COMPLETION OF CONSTRUCTION AND INITIAL OPERATION OF THE SLAC ACCELERATOR*

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Introduction

Since construction of the SLAC accelerator is now essentially complete and initial operations are underway, it is perhaps appropriate to pause briefly and look backward in time to view our various successes and failures in the light of advancing project maturity.

The idea of constructing a very long high energy accelerator was first discussed in early 1955 by a few physicists and accelerator scientists who had been associated directly or indirectly with the 1-GeV Mark III linear accelerator at Stanford. These included F. Bloch, E. L. Ginzton, R. Hofstadter, W.K.H. Panofsky and L. I. Schiff. Starting in April 1956, a somewhat larger group (about 22, half of whom are presently at SLAC) of Stanford people began more detailed studies on a part-time basis. The studies as a whole were under the general direction of Professors E. L. Ginzton and W.K.H. Panofsky. These efforts plus those of several outside organizations which volunteered their services resulted, in April 1957, in a proposal[1] for the construction of a two-mile linear electron accelerator.

Several years then passed during which the 1957 proposal was considered and endorsed by several scientific advisory committees (President's Science Advisory Committee, General Advisory Committee to the Atomic Energy Commission, Advisory Panel on High Energy Accelerators to the National Science Foundation, Technical Committee on High Energy Physics of the Federal Council for Science and Technology) and was reviewed on several occasions before Congressional Committees (Hearings before the Joint Committee on Atomic Energy, Congress of the United States, February 3-14, 1958; July 14-15, 1959; August 26, 1959; March 8-11, April 5-7, 1960; April 5-6, May 16-29, 1962). Several independent engineering and cost reviews[2] were sponsored by the U.S. Atomic Energy Commission. In October 1961, Congress authorized the construction of the two-mile machine and appropriated $114 million for this purpose. Contractual negotiations between Stanford University and the U.S. Atomic Energy Commission, the sponsoring agency, began shortly thereafter and resulted in a firm contract in April 1962.

While the five years between the proposal date and the contractual date seemed quite long to those closely identified with this program and many cycles between states of elation and near-despair transpired during this period, the time was not wasted. Under support from the AEC, a small development program continued during this interval and progress was made in the development of klystrons, modulators, accelerator structures and general instrumentation. Time was available for the fabrication and testing of several generations of prototypes of these basic components. In retrospect, it appears quite clear that this period of relatively small scale but basic work contributed greatly to the performance and reliability of the accelerator as it finally materialized.

Moreover, the principal parameters of the accelerator did not remain static during the five-year pre-construction period. For example, the 1957 proposal envisioned a two-mile accelerator powered initially by 480 klystrons giving an energy capability of 15 to 30 GeV. These tubes and the associated accelerator sections and other components were to be organized into sectors, each 250 feet in length and the entire accelerator comprised 40 such sectors. It was felt that it might be necessary to operate the klystrons initially at the conservative level of 6 megawatts peak in order to obtain a tenable life (2000 hours). During the pre-construction period the requirement for the initial complement of tubes was reduced to 240 organized into 30 sectors, each of 333-foot length. The corresponding beam energy for the same klystron output range became 10 to 20 GeV. The rf pulse length of the klystrons was increased from 2.0 to 2.5 microseconds. This 25% increase resulted in a 43% increase in beam duty cycle. It was originally planned that the accelerator would be located in an underground tunnel and the klystrons and other auxiliary components would be situated in a parallel tunnel at the same depth below the surface. During the pre-construction period, it was realized that a much more economical design would be realized by placing the two housings in a vertical orientation with the klystron housing above at surface level. This permitted the employment of less expensive "cut-and-fill" procedures rather than more costly tunneling construction techniques. Many other changes in parameters and specifications, too numerous and detailed to be given here, were made during this period. The evolution of the two-mile accelerator design is discussed in a number of earlier reports.[3-7]

Manpower and Fiscal Experience

Manpower

The total manpower involved in the design, construction, and operation of the SLAC site including the accelerator, the buildings and facilities is shown in Fig. 1. The lower curve shows the manpower associated with Aetron-Blume-Atkinson (ABA), the architect-engineering-management organization (a joint venture of three companies) under contract to SLAC for the design of the conventional buildings and facilities (including the accelerator and klystron housings, the beam switchyard, and the research area buildings). The second curve from the bottom gives the total of ABA employment plus their subcontractors' on-site personnel. ABA reached a manpower peak of about 140 at the end of FY 63 and then began a gradual

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phase-out over a 3-1/2-year period. On the other hand, the manpower of ABA's subcontractors did not reach a peak until early in FY 66 and then declined rather rapidly over a one-year period.

Direct SLAC employment and the total of SLAC plus SLAC subcontractors' on-site employees are shown in the third and fourth curves from the bottom in Fig. 1. The bumps on the SLAC curve at the beginning of FY 65, FY 66, and FY 67 represent student summer employment (typically about 60-75). SLAC subcontractors' employment is approximately 100 even at the present date due principally to the continuing installation and activation of the research area facilities and equipment, but is expected to decline sharply between now and July, 1967.

The upper curve in Fig. 1 represents the total employment at the SLAC site. It reached a peak of just over 1900 in July 1965, and has declined to about 1200 by the present date.

Direct SLAC employment in terms of man-months of effort is shown in the upper curve of Fig. 2. This is similar to the center curve of Fig. 1 but reflects the effects of vacations, overtime, and the exclusion of summer employment. The direct SLAC effort started with a nucleus of about 30 people of all classes from the Hansen Laboratories at Stanford. A serious effort was made to avoid excessive build-up of the long-term SLAC staff during the periods of peak manpower demand. In general, it was the intent to acquire staff members who would participate not only in the design and construction phases of the project but who would also remain as effective, continuing staff during the operating and research phases. While complete success in carrying out this objective was not achieved, the upper curve Fig. 2 shows a reasonable approach to this goal. Methods used to control direct SLAC staff build-up included: (a) the hiring of approximately 140 people with appointments terminating at the end of construction (up to 6 weeks' termination pay was stipulated in the offer of employment provided the worker remained until his employment was terminated by SLAC), (b) the use of engineering services from outside engineering firms, contract draftsmen and designers, and several outside "captive" machine shops. These contract services, which reached a peak level of approximately 180 people, extended over a period from FY 64 through FY 67 as shown in the lower curve of Fig. 2.

The SLAC man-month effort reached a peak of 1170 in October 1965, and remained approximately constant at this level until August 1966, when it began to decline slowly. A drop to approximately 1050 by June 1967 is planned. During FY 65 and FY 66 the project monthly turnover rate averaged about 2%. The rate was lower than this figure prior to FY 65 and higher (up to 4% per month) during the first half of FY 67 as the end of the construction phase approached. During the latter period , the high turnover resulted in part from the dismissal of a substantial portion of the employees with temporary appointments. A few of the latter class of workers proved to be so effective that they were offered permanent positions.

Fiscal Experience

Financial support of SLAC has come principally from three funds administered by the U.S. Atomic Energy Commission: (a) a \$114 million design and construction fund authorized by Congress in October 1961; (b) a \$20.3 million preconstruction R and D fund; and (c) a pre-operation R and D fund totaling \$22.7 million through FY 66. The latter fund changed character from "pre-operations" to "operations" starting in FY 67. Expenditure rates for each of these funds are shown in Fig. 3.

Expenditures under the pre-construction R and D fund started in January 1961, about nine months in advance of construction authorization. This work was initially a continuation of earlier R and D activities on accelerator structures and associated components already being supported by the AEC at the Hansen Laboratories. The expenditure of pre-construction R and D funds continued over a 5-1/2-year period, reflecting that the development activities associated with some of the components for the accelerator were completed and the designs frozen early while the development of other components and systems, particularly those utilized in the beam switchyard and research area, could not start until the programs and conceptual designs of these areas were formulated. Such considerations, stemming from the diversified nature of the accelerator and its associated research facilities, show that it is not at all strange that the pre-construction R and D program extended almost the whole of the construction period, although its scope was considerably diminished during the two final years.

Expenditure of construction funds began in March 1961, about seven months in advance of construction authorization. The early expenditures consisted principally of money advanced by the AEC to support master planning of the accelerator site, buildings and utilities.

This preliminary planning was very important in enabling the project to get off to a fast start after the contractual agreement between Stanford and the AEC for construction of the two-mile accelerator was reached in April 1962. For example, initial ground-breaking at the accelerator site took place on July 9, 1962, and actual construction of the first two buildings, the Test Laboratory and the Administration-Engineering building, commenced on August 2, 1962, and September 25, 1962, respectively.

In FY 63, the construction costing rate began to increase rapidly. It continued to climb during FY 64 and FY 65, reaching a peak rate of approximately \$4 million per month early in FY 66. The rate remains about \$0.2 million per month at the date of this report but is expected to decline almost to zero by July 1967. Even then, it will remain finite for some time due to modifications and extensions of facilities and settlement of contractor claims.

The number of procurement actions, i.e., subcontracts, purchase orders, and change orders per six-month period is plotted in Fig. 4. These actions reached a maximum rate of approximately 2000 per month in late FY 66. The corresponding cost incurred during each six-month period are also shown in Fig. 4 for SLAC only and for SLAC plus ABA. Note that the SLAC cost rate reached peak about one year after the peak of ABA's cost rate.

The integrated overall project construction costs and costs plus commitments versus time are shown in Fig. 5. These are in the form of the classical "lazy S" curves applicable to most construction projects. These curves represent the sum of SLAC and ABA cost experiences.

The breakdown of the $114 million construction budget into the principal categories of Engineering, Design, Inspection, and Management (EDI and M), Direct Construction, Indirect Costs, and Escalation and Contingency is shown in Table 1. For comparison, these costs are given for two points in time: (a) November 1962, shortly after the systems criteria were established and preliminary designs completed, and (b) January 1967, when construction was substantially completed. At the earlier date, the escalation and contingency reserve was kept intact and was not apportioned to the systems and components budgets in advance of proven needs for these funds. In fact this policy was followed throughout the construction program. As noted in the table, the cost of EDI and M, the cost of 12 of the direct construction items, and indirect costs increased during this period. On the other hand, the cost of four of the direct construction items decreased. The reasons for these changes upward and downward include: (a) poor initial estimating, (b) changes in scope, and (c) changes in local or national labor or materials costs. The relative weight of these factors varied from system to system and will not be given here. From the sub-total, it may be noted that the total project estimated cost increased about 25% during the four-year construction period. Fortunately, it was possible to sustain this increase completely out of the escalation and contingency reserve.

Schedule and cost information for the principal SLAC buildings and structures is shown in Table 2. This table gives the starting and completion dates of each facility, the total construction cost, the gross area and the cost per square foot. Engineering, design, inspection, and management costs are not included in this table. It may be noted that the cost per square foot ranged between $10 and $85 for the various structures. Altogether, the total gross area listed in the table is 897, 289 square feet at an average cost of $25.43 per square foot.

General Description

Principal Buildings and Structures

The Stanford Linear Accelerator Center is located on 480 acres of land about two miles west of the main Stanford Campus. In Fig. 6, an air view of the site shows the research area in the foreground, the principal laboratories, offices, and shops in the center, and the accelerator and klystron gallery running west to east (diagonally across the photograph). The injector is located at the west end of the accelerator (upper right corner of the photograph).

Two-Mile Accelerator

A schematic diagram illustrating the entire two-mile accelerator is shown in Fig. 7. The overall specifications of the accelerator are given in Table 3. The accelerator has been authorized and built in accordance with the Stage I (20 GeV) specifications. Provisions have been made in the design to permit later expansion to Stage II (40 GeV) by connecting additional rf sources along its length. If desirable, the energy increase can be accomplished in a step-wise manner. The accelerator proper[8] is a cylindrical copper disk-loaded structure fabricated by a brazing technique from basic disk and ring elements. The fabricated accelerator sections are each 10 feet long. Each of the 87 cavities comprising the section has its own unique dimensions. The cavity dimensions are varied in order to achieve a constant axial electric field over the length of each section. The injector[9] consists of an 80-kV gun[10] followed by a cavity-type pre-buncher, a disk-loaded buncher 10 cm long having a phase velocity of 0.75 c, and a standard 10-foot accelerator section.

Just 40 feet downstream from the injector at the west end is a beam analyzing station (No. 1) which is used to set up and to make precise measurements of the characteristics of the injected beam. An instrument group is located in a 9-foot drift space at the end of each 333-foot sector of the accelerator. It contains monitoring devices which measure the beam current, transverse beam position and beam profile. This information from each of the 30 sectors is transmitted to the Central Control Room located opposite Sector 27. The same drift space also contains the quadrupole doublets which are used for focusing the beam. These drift space components are important elements in the overall instrumentation and control system for the two-mile accelerator. The overall I and C system is described in a separate report[11] to this conference. At the one-third point, a branch in the accelerator housing is provided to allow future construction of a reduced energy experimental facility at this position. A facility to house a future intermediate injector is provided just downstream from the beam take-off point. Only a short distance farther downstream, at the beginning of Sector 11, is the positron source. Electron bombardment of the target at this point produces positrons which can then be accelerated through the remaining length of the accelerator, thus achieving up to 2/3 of the full energy potential. At the two-thirds point is located beam analyzing station No. 2. This station permits testing of up to 2/3 of the length of the machine without involvement of the beam switchyard at the end of the accelerator. Just downstream from the analyzing station, another branch in the accelerator housing provides a second intermediate beam take-off point. It is at this location that the proposed 3-GeV electron-positron storage ring[12] will be located if its construction is authorized by Congress. A second future injector facility is located just downstream from the storage ring take-off.

A view of the cross section of the accelerator housing and the klystron gallery is shown in Fig. 8. These housings are separated by 25 feet of earth for radiation shielding. Service shafts, 27 inches in diameter and spaced 20 feet apart, allow passage of waveguides, vacuum manifolds, cooling water piping, and instrumentation cables between the two housings. Man accessways are provided between the two levels at 333-foot intervals along the length.

The Beam Switchyard

At the east end of the accelerator, the beam switchyard contains the magnets, collimators, energy-defining slits, and other special beam handling and monitoring instrumentation required to determine the characteristics of the beam and to direct it into any of the three experimental areas. Details of the beam switchyard equipment and its performance to date are given in several reports to this conference.[13-18] An overall layout of the beam switchyard is shown in Fig. 9.

The Research Area

Layout of the Research Area is shown in Fig. 10. At this time, it is divided into two general areas. One of these areas centers around End Station A. This area includes three spectrometers, rated at 20, 8, and 1.6 GeV, which are used to measure the angles and momenta of particles resulting from scattering incident electrons and positrons on nuclei. This area also includes a two-meter streamer chamber for use in photoproduction experiments. The second existing research area centers around End Station B. This area is concerned with creation of secondary particles and experiments to determine the characteristics of these particles. At the present time, three beams have been constructed: a muon beam, a K^0 beam, and a monochromatic gamma beam. Two major instruments which will be used in these experiments are a one-meter hydrogen bubble chamber and a spark chamber with its associated 54-inch magnet. Plans are underway to develop a third (central) experimental area. An 82-inch hydrogen bubble chamber will be moved from LRL, Berkeley, and will be used in conjunction with experiments in the central research area starting in late 1967.

Initial Operating Results

Key Dates

Perspective regarding the operating results obtained to date may be gained from an examination of the "Key Dates" given in Table 4.

An early plan called for construction of a prototype length of the machine (one or two sectors) to verify and test the mechanical, electrical, and instrumentation design features. This plan was not followed because of the associated high costs and difficulty of fitting this sub-project into the design and production schedules. Instead of building separate prototype sectors, the completion of the first two sectors (666 feet) of the accelerator was pushed ahead of the rest. By January 1965 it was possible to accelerate a 1.5-GeV beam through these two sectors. As a result of these tests a number of important but not fundamental changes were made in the remaining sectors. Sectors 1 and 2 were later modified to correspond to the other sectors in most respects.

It was decided after these first tests to move the beam analyzing station originally located at the end of Sector 2 to a new location near the beginning of Sector 20. Recent operating experience has proved that this relocation was wise in that it has permitted testing up to 2/3 of the machine with a beam even when the beam switchyard is unavailable as a result of installation or maintenance activities.

The beam was first accelerated through all 30 sectors on May 21, 1966. A beam energy of approximately 10 GeV was obtained at that time. Less than two weeks later, on June 2, 1966, the energy was increased to 18.4 GeV by turning on more klystrons at somewhat higher levels and by better phasing of the available klystrons.

On September 20, 1966, the beam was run for the first time to Research Area A and to Beam Dump East (beyond End Station A). The beam was first sent to End Station B on November 1, 1966, and the experimental program on the B side started immediately after this date.

On December 20, 1966, positrons were first accelerated from the positron source at the 1/3 point in the accelerator housing to beam analyzing station No. 2 at the 2/3 point.

The two most recent achievements shown in Table 4 are concerned with maximum energy and maximum beam power. On January 10, 1967, a beam energy of 20.16 GeV was obtained with all but four of the klystrons participating. On this occasion, the klystrons were operated about 5% below their rated voltage level. On January 21, 1967, a beam having an average power of 170 kilowatts was transmitted to the A beam dump. The corresponding parameters were an energy of about 16 GeV, a peak current of 18.5 mA, 1.6-μsec beam pulse length, and a repetition rate of 360 pulses per second.

Beam Characteristics: Energy, Spectrum Loading and Power

The electron energy gained in the multi-section accelerator of constant gradient design is given by:

$$V = (1-e^{-2\tau})^{1/2} \sum_N (P_n \ell r)^{1/2} - \frac{irN\ell}{2}\left(1 - \frac{2\tau e^{-2\tau}}{1-e^{-2\tau}}\right)$$

where

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
τ = RF attenuation in acceleration section in nepers

The first term in this equation is the "no-load" energy, i.e., the energy for negligible beam current. The second term is the energy correction due to the presence of peak beam current i. Inserting the design parameters of the SLAC accelerator ($N = 960$, $\ell = 3.05$ meters, $r = 53$ megohms/meter, and $\tau = 0.57$ nepers) into the above equation 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 ± 0.1 dB) is dissipated in the waveguides connecting the klystrons to the accelerator, the result is

$$V_{GeV} = 0.020 \sum \left(P_{MW}\right)^{1/2} - 0.035\ i_{mA}$$

This equation is plotted in Fig. 11 for the case where the outputs of all klystrons are assumed to be the same and equal to 21 megawatts. In this case, the no-load energy is seen to be 22.0 GeV. The beam energy decreases from the no-load value at the rate of 35 MeV/mA (independent of input power level). Also shown in the same figure is the average beam power obtained by multiplying the above energy equation by the peak beam current i and then by the beam duty cycle. Theoretically, the power transferred to the beam is maximum when the peak current is such that the beam energy is reduced to one-half of the no-load value, i.e., in this case to 11 GeV. The peak current corresponding to maximum average beam power (≈ 2.1 MW in this example) is equal to ≈ 312 mA. The design current and the corresponding design energy and average beam power for the SLAC accelerator are 50 mA, 20 GeV, and 600 kW, respectively. These design values are indicated in Fig. 11. Design values of beam current and beam power have not yet been achieved due to the onset of beam break-up phenomena as discussed in a later section. However, the coefficients in the energy design equation have been verified within experimental accuracy (about 2%).

Typical energy spectra are shown in Fig. 12. The higher energy spectrum resulted from relatively light beam loading (i = 2.0 mA). A higher beam current (i = 25 mA) led to a lower energy beam spectrum having 0.80 GeV less energy than the first. The lower energy spectrum is broader than the higher energy spectrum due to the presence of electrons in a high energy tail. This tail is due to those electrons which pass through the accelerator early in the beam pulse before the beam has extracted a significant amount of stored rf energy. Broadening of the spectrum in this manner is usually undesirable in physics applications of the beam. One useful method of compensating for this effect consists of delaying the time of triggering one or more of the accelerator sectors. Then the first electrons during the pulse pass through the sector when it is not completely filled and therefore gain less than the maximum energy potential. Later electrons encounter a situation where the sector is completely filled but some of the stored energy has been extracted by the pioneering electrons. By properly adjusting the trigger delay to the sector it is possible to achieve near equality in the energies of the earlier and later electrons. Compensation obtainable with this technique is indicated in Fig. 13 where the dotted curve represents the uncompensated spectrum and the full curve is the compensated spectrum achieved by trigger delay to one sector.

The spectrum width at half maximum for the cases shown in Fig. 12 is approximately 1.3%, of which about 0.9% is attributable to resolution of the measurement devices. In more recent runs with careful adjustment of beam parameters, spectra with widths of $\approx 0.2\%$ have been measured.

Beam Transmission

Careful measurements have shown that more than 90% of the beam current measured near the injector, say at beam analyzing station No. 1 located at the 40-foot point, is preserved during passage through the entire machine. This favorable result arises from the effective performance of the beam position and intensity monitors, the steering and focusing systems, and the long ion chambers.[19] The microwave position monitors located in the drift space at the end of each sector are capable of indicating the transverse position of the beam within ± 0.5 mm. The long ion chamber, which is an argon-filled coaxial line installed alongside the accelerator, enables the operator to detect beam losses and from the times of arrival of the ionization signals to resolve their location within one to two hundred feet.

Beam optics measurements at beam analyzing station No. 1, located 40 feet from the injector, have shown that 80% of the injected beam is contained in a transverse phase space of 1.2×10^{-2} (MeV/c)(cm). A second measurement in the beam switchyard at the end of the accelerator indicates that the same fraction of the beam is contained in a transverse phase space of about 3×10^{-2} (MeV/c)(cm). Since the beam diameter at that point is roughly 0.4 cm, the angular divergence of the beam in the energy range of 10 to 20 GeV is less than 10^{-5} radians.

Tests to date have demonstrated the capability of accelerating at least three beams in a time-interlaced manner. Spectra of three low energy interlaced beams measured at beam analyzing station No. 2 in Sector 20 are shown in Fig. 14. Independent control of the energy, intensity, and pulse length of each beam is feasible.[20] This capability permits the simultaneous performance of several independent experiments in physically separated areas. The trigger "pattern" for these beams is set by the operator in the Central Control Room and is sent to the appropriate areas: the injector, the accelerator sectors, the beam switchyard pulse magnets, and to the experimental areas. The beam intensity presentation observed by the operator for two interlaced beams of energies 11 and 5.65 GeV is shown in Fig. 15. Two base line traces are shown. The height of each dot above the corresponding base line is proportional to the beam intensity at the end of a particular sector. These signals originate at toroid-type intensity monitors located in the drift space at the end of each sector. Similar displays are viewed by the operator to ascertain vertical and horizontal beam position relative to the accelerator axis at the end of each sector. In this instance, the dots lie on the base line when the beam is perfectly centered. Displacement of the dot above or below the base line implies a right or left, or upward or downward displacement of the beam from the axis.

Beam Break-Up and Remedial Measures

Phenomena associated with beam break-up in the SLAC accelerator and the theoretical explanation of these phenomena have been given elsewhere.[21, 22] In addition, the most recent results are being presented to this conference in a separate invited paper.[23] A summary of the present status is as follows: Beam break-up phenomena have limited the maximum peak current through the entire two-mile accelerator to approximately 20 mA at the maximum energy gradient. This is about 40% of the design current level. Higher currents can be accelerated to intermediate points along the accelerator. Higher currents at a given position along the accelerator are also achievable by reducing the beam pulse length. Lower energy gradients lead to reduced threshold current levels. In general, the product

$$\frac{i\, t_p z}{\delta V/\delta z} \cong \text{constant, where}$$

i is the peak beam current at which beam break-up occurs, t_p is the length of the beam pulse as limited by break-up, z is the distance from the injector to the closest position where current is lost at time t during the beam pulse, and $\delta V/\delta z$ is the average energy gradient in the accelerator.

While the presently available current is adequate for all presently scheduled experimental purposes, it is highly probable that future experiments will require higher current. Therefore, means of increasing the beam break-up current threshold are now being incorporated in the accelerator.

Present steps which are being taken consist of strengthening the focusing along the accelerator. The original focusing system consisted of 30 quadrupole triplets, with one triplet being located at the end of each 333-foot accelerator sector. In addition, 14 special triplets were used for focusing positrons produced by the positron source at the 1/3 point along the accelerator. Each triplet consists of a coaxial set of two A-type quadrupoles at the ends and one B-type quadrupole in the center. The B quadrupoles are twice as long as the A quadrupoles and thus for a given current have twice the focusing strength. Originally, triplets were chosen rather than doublets because calculations showed that they would introduce less steering errors in the presence of short-term misalignments due to thermal effects in the support structures. However, actual measurements with the completed accelerator have shown that misalignment effects are small enough that doublets can be used without difficulty and that the focusing effect of the doublets is equal to that of the triplets. This permits rearrangement of the quadrupoles as follows:

a. Remove all of the longer (B) quads from Sectors 1 through 29 and from special positron triplets.

b. Install doublets consisting of B-type quadrupoles in the drift sections of Sectors 10 through 29. Procure larger regulated power supplies capable of 15 amperes output for these doublets.

c. Install doublets consisting of A-type quadrupoles in the drift sections of Sectors 1 through 9. Use standard power supplies (7 amperes maximum current) with these doublets.

d. Install the remaining A-type quadrupoles as singlets between 40-foot girders in the first six sectors; use standard power supplies with these singlets.

With the quadrupole arrangement just described, it will be possible to taper the quadrupole current linearly from Sector 1 through Sector 29 so as to obtain the same effective betatron wavelength for the electron orbits over the entire accelerator length. Previously, it was possible to taper only up to 7 amperes quadrupole current. When the plan just discussed is completed it should be possible to taper up to an effective value of 30 amperes. It is expected that these measures will result in an increase of peak beam current to the design value of 50 mA. Preliminary tests with partial completion of the rearrangement described above has resulted in an increase of beam break-up threshold current in accord with theoretical expectations.

In addition to the straight-forward or "brute-force" technique described above, other schemes for alleviating beam break-up phenomena are also being studied. These include microwave filter and feed-back schemes and injector noise reduction schemes. Work in these areas is still preliminary and no significant progress can yet be reported.

Klystron Status and Performance

Among the principal accelerator components, klystrons are being singled out for special review because of their significant role in accelerator performance and reliability and their high costs. Because of these factors, the early decision was made to procure these tubes from several sources so that there would always be back-stops against technical and production difficulties involving one or two vendors. In addition, SLAC itself chose to fabricate a reasonable number of the production tubes both for insurance purposes and also to afford a ready means of developing and testing improved models of klystrons.

A total of 245 klystrons is required to fill all the sockets along the accelerator. These tubes are rated at 21 MW peak and 21 kW average power output. Their design capability is somewhat higher than these ratings.

A basic tube design with permanent magnet focusing was first developed at SLAC. Later, four commercial firms developed models based upon the SLAC design but differing in design and fabrication details. All of these tubes were mechanically and electrically interchangeable. Klystron models fabricated by SLAC and the four commercial companies are shown in Fig. 16. These developments led to three production contracts. The present status of these procurements and the SLAC in-house program is given in Table 5. These procurements did not all start at the same time. All tubes being procured are designed to be repairable. Thus, the total number of tubes being procured allows both for a quantity sufficient to fill the repair cycle and a suitable quantity of spares. SLAC has negotiated an extended warranty agreement with one of the vendors wherein, after initial purchase of a tube, SLAC pays a fixed hourly rate for the first 1500 hours of operation of the tube and a decreased rate thereafter. Under this arrangement, the manufacturer agrees to replace a failed tube with a tube meeting original specifications at no additional cost to SLAC.

Klystron operating experience to date is summarized in Table 6. Tube operating hours by quarter and cumulative tube hours are given. Also given are the number of failures and average life at failure on both a quarterly and a cumulative basis. In terms of the cumulative values, one klystron failure has occurred for each 6000 operating tube hours. This is, of course, not an accurate measure of tube life expectancy except after many generations. An attempt to predict mean life on the basis of the present meager experience is shown in Fig. 17, where life at failure for each tube has been plotted against the fraction of tubes which have failed. The horizontal scale is constructed so that a normal failure distribution will result in a straight line when life at failure is plotted as indicated above. The data plotted omits all failures of the tubes of one of the manufacturers since the failure rate for this company is about seven times the average failure rate for the other two companies and SLAC. Both optimistic and pessimistic prediction lines are shown in the graph. Where these lines cross the 50% failure coordinate, the corresponding mean time to failure may be read on the vertical scale. The optimistic and pessimistic values of mean time to failure are 7000 and 4000 hours, respectively. A better prediction of tube life must await more operating results.

SLAC has continued to do development work on klystrons during the construction and operating periods. Recently, an experimental SLAC klystron, when operated at a beam voltage of 300 kV, produced a peak power output of 42 MW with an efficiency of 45%. While tubes having these improved characteristics are a long way from production, this result indicates that at some time in the future a significant increase in power output of production klystrons may be possible. Many questions relating to stability and life must, of course, first be resolved.

Operating Statistics

Operating statistics for the first seven months of FY 67 are shown in Fig. 18.

The number of klystron hours depends not only upon the total hours of operation but also upon the beam energy. Allowing about 5% reserve, approximately 13 klystrons are needed for each GeV. By the end of January 1967, a total of approximately 365,000 klystron hours had been run in FY 67. The rate of usage has continued to rise, exceeding 21,000 klystron hours in recent weeks. It now appears that the total for all of FY 67 will be approximately 750,000 klystron hours.

Useful beam hours are also shown in Fig. 18. Approximately 1900 useful hours were run in the first seven months of FY 67. Flat regions of the beam hour curve correspond to weeks when the accelerator was shut down for modifications.

The cumulative number of trouble reports for all types of failures reported during the seven-month period reached a level of approximately 3300. From the graph it appears that the number of trouble reports is rising more rapidly than either klystron hours or useful beam hours. This gloomy indication is believed to be suspect since the listing of troubles has become more thorough and efficient as the year has gone on.

During the last quarter of calendar 1966, the accelerator was manned for a total of 156 eight-hour shifts. This total manned time was utilized as follows:

Useful high energy beam	40.2%
Useful low energy beam	22.1%
Search/shutdown time	7.7%
Tune-up time	6.8%
Scheduled maintenance	8.8%
Accelerator failure	5.3%
Beam OFF at experimenter's request	9.1%
TOTAL	100.0%

This was the first quarter in which physics research took place. It is expected that the fraction of the total manned time resulting in useful beam operation will increase as more experience is accumulated.

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Table 1. Accelerator Construction Costs.

	11/62	1/67
E D I & M	$7,907,800	$13,794,713
Direct Construction:		
Improvements to land	1,476,000	2,277,622
Buildings	18,778,900	24,627,765
Utilities	7,575,400	8,115,242
Equipment	6,121,200	5,731,494
Modulators	8,332,500	4,687,545
RF Systems (phase/drive)	2,197,200	2,030,821
Accelerator Structures	6,326,000	6,953,036
Electrical System	1,117,400	1,606,725
Mechanical Systems	5,619,500	5,992,111
Injection System	357,500	596,900
Instrumentation & Control	4,295,800	4,922,658
Klystrons	2,496,000	3,498,985
Test Stands (Constr. & Operation)	2,126,700	1,994,194
Beam Switchyard Equipment	2,624,500	8,526,794
End Station Equipment	2,436,000	2,905,065
1-meter Hydrogen Bubble Chamber		117,400
Total Direct Construction	$71,880,600	$84,584,357
Indirect Costs	11,392,300	15,246,576
Sub-Total	$91,180,700	$113,625,646
Reserve for Escalation & Contingency	22,819,300	374,354
Total	$114,000,000	$114,000,000

Table 2. Principal SLAC Buildings and Structures.

Name	Date Construction Started	Date of Completion	Construction Cost $	Gross Area (Ft.^{2})	Cost (\$/Ft.^{2})
Test Laboratory	7/62	6/63	892,101	40,000	22
Administration-Engineering Bldg.	9/62	9/63	774,625	44,023	18
Construction Office Bldg.	12/62	6/63	188,305	15,000	13
Electronics Bldg.	2/63	11/63	341,238	26,000	13
Fabrication Bldg.	2/63	12/63	751,041	31,855	24
Accelerator Housing	6/63	10/64	4,710,417	124,355	38
Klystron Gallery	10/63	6/65	3,604,290	361,483	10
Central Laboratory	12/63	4/65	1,582,345	59,372	27
Heavy Assembly Bldg.	12/63	10/64	764,469	32,000	24
Control Bldg.	6/64	3/65	288,332	13,842	21
Beam Switchyard	9/64	3/66	4,257,476	50,000	85
Cafeteria	1/65	8/65	129,844	3,780	34
Auditorium	1/65	8/65	186,620	7,300	26
End Station A & B D E	3/65	7/66	2,515,781	32,300	78
End Station B	3/65	7/66	961,562	17,000	57
Cryogenics Bldg.	8/65	5/66	295,749	8,060	37
Fire Station	4/67	10/67	87,660	2,500	35(est.)
General Services Bldg.	7/67	3/68	486,000	28,419 (est.)	17(est.)

Table 3. General Accelerator Specifications.

	STAGE I	STAGE II
Accelerator length	10,000 feet	10,000 feet
Length between feeds	10 feet	10 feet
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 μsec	2.5 μsec
Filling time	0.83 μsec	0.83 μsec
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 μA	30 - 60 μA
Electron average beam power	0.15 - 0.6 MW	0.6 - 2.4 MW
Electron beam pulse length	0.01 - 2.1 μsec	0.01 - 2.1 μsec
Electron beam energy spread (max)	± 0.5%	± 0.5%
Positron Energy	7.4 - 14.8 GeV	14.8 - 29.6 GeV
Positron average beam current*	1.5 μA	1.5 μA
Multiple beam capability	3 interlaced beams with independently adjustable pulse length and current	
Operating frequency	2856 Mc/sec	2856 Mc/sec

*For 100 kW of incident electron beam power at positron source located at 1/3 point along accelerator length.

Table 4. Key Dates.

April 1957	Proposal for two-mile accelerator
September 1961	Authorization by Congress
April 1962	Contract with AEC
January 1965	1.5-GeV beam through two sectors
April 21, 1966	Beam to 2/3 point (Sector 20)
May 21, 1966	Beam through 30 sectors to Beam Switchyard
June 2, 1966	18.4-GeV beam in Beam Switchyard (tune-up dump)
September 16, 1966	Beam to A-Beam Dump in Beam Switchyard
September 20, 1966	Beam to Research Area A and Beam Dump East
November 1, 1966	Beam to Research Area B
December 20, 1966	Accelerated e^+ beam from Positron Source
January 10, 1967	20.16-GeV achieved
January 21, 1967	170 KW of average beam power into A Beam Dump

Table 5. Klystron Status as of February 1, 1967.

Supplier	Total Contract	Accepted to date	Installed
RCA	216	187	99
Sperry	80	80	29
Litton	144	88	68
SLAC	54	54	44
Litton *	6	6	3
Eimac*	6	5	2
TOTAL	506	420	245

*Special 6-tube contract
245 Klystrons are required to fill all accelerator sockets.

Table 6. Klystron Usage and Failures.

Dates	Operating Hours		Quarter		Cumulative	
	Quarter	Cumulative	No. of Failures	Avg. Life @ Failure	No. of Failures	Avg. Life @ Failure
To 12/31/65		27,000			10	297
To 3/31/66	11,000	38,000	13	252	23	272
To 6/30/66	118,000	156,000	16	234	39	256
To 9/30/66	127,000	283,000	15	594	54	350
To 12/31/66	176,000	459,000	23	1070	77	575

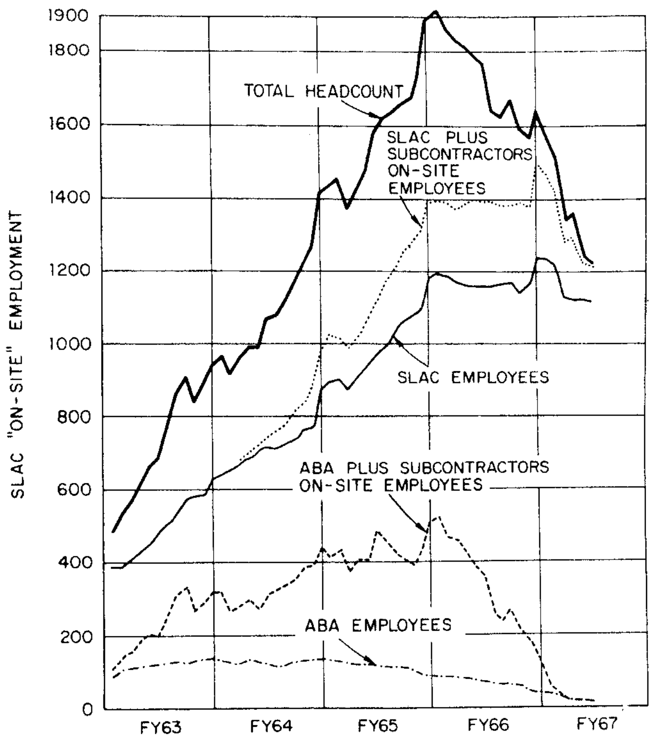


Fig. 1. SLAC "On-Site" Employment.

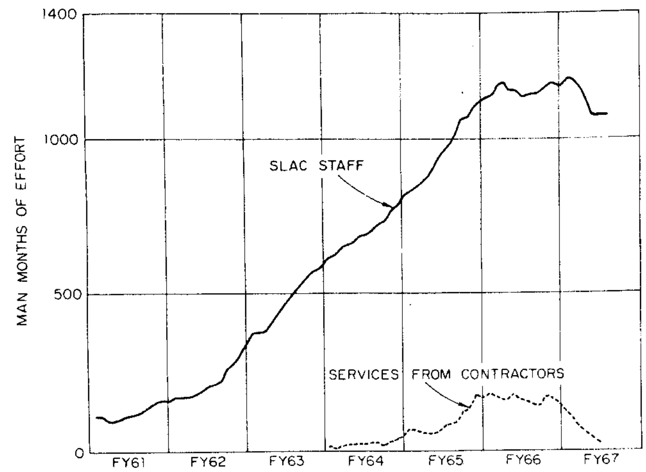


Fig. 2. SLAC Staff Effort and Services from Contractors.

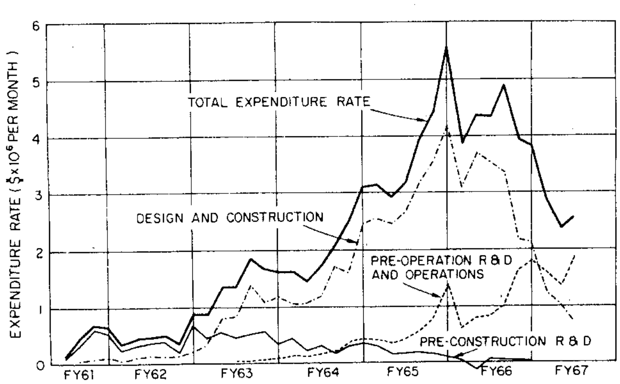


Fig. 3. Expenditure Rates for Pre-Construction R and D, Design and Construction, and Pre-Operation R and D Funds.

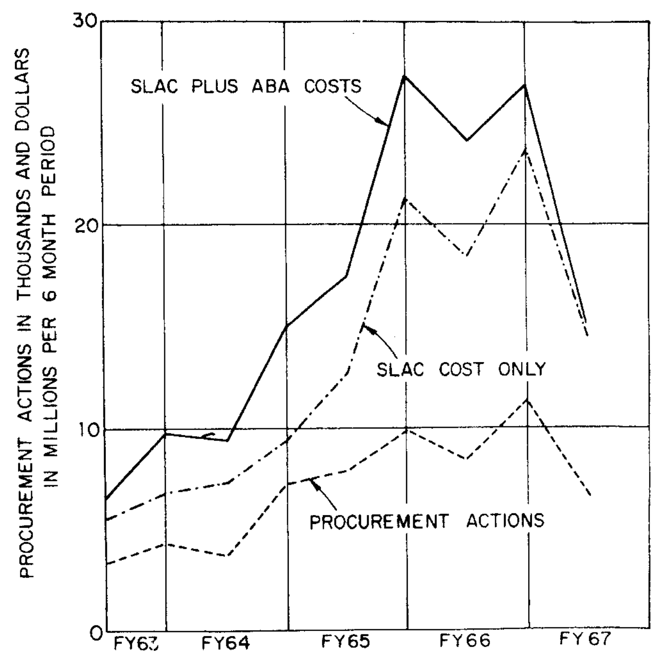


Fig. 4. Number of Procurement Actions and Associated Costs.

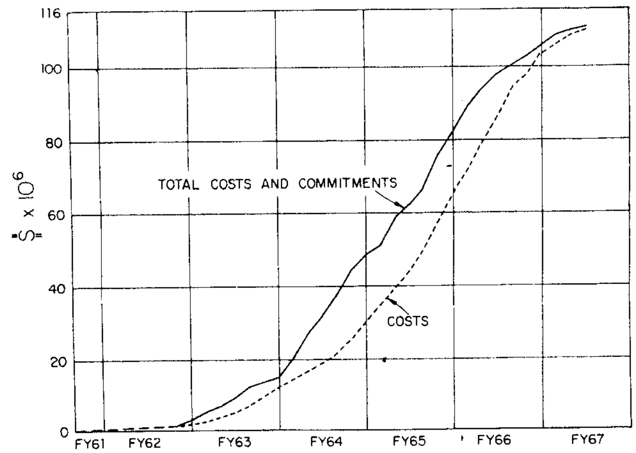


Fig. 5. Integrated Total Costs and Commitments for Overall SLAC Construction Project.

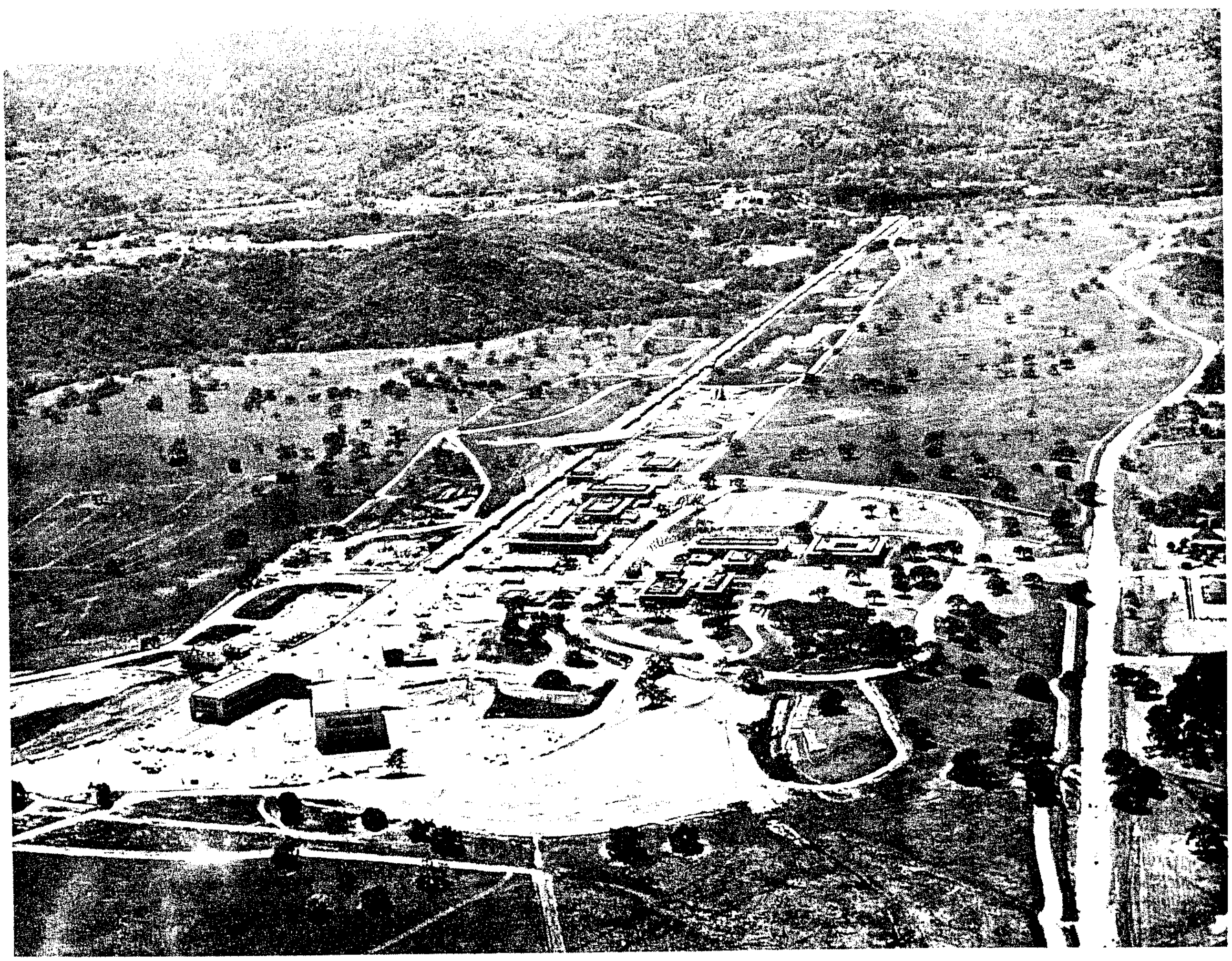


Fig. 6. Air View of SLAC Site Showing the Two-Mile Accelerator, the Research Facilities, and the Principal Laboratories and Shops.

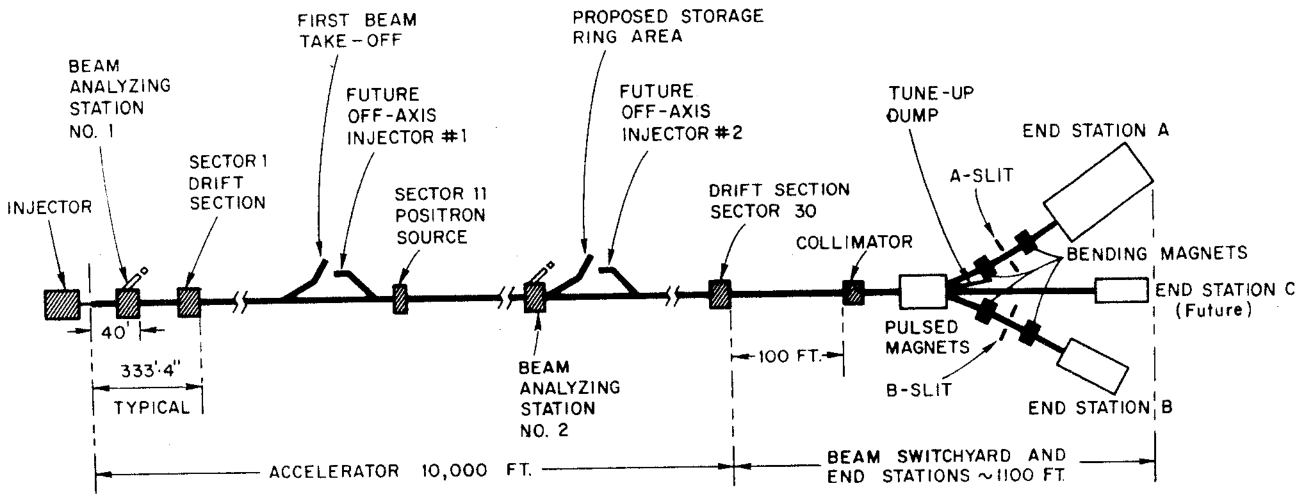


Fig. 7. Overall Layout of the Two-Mile Accelerator.

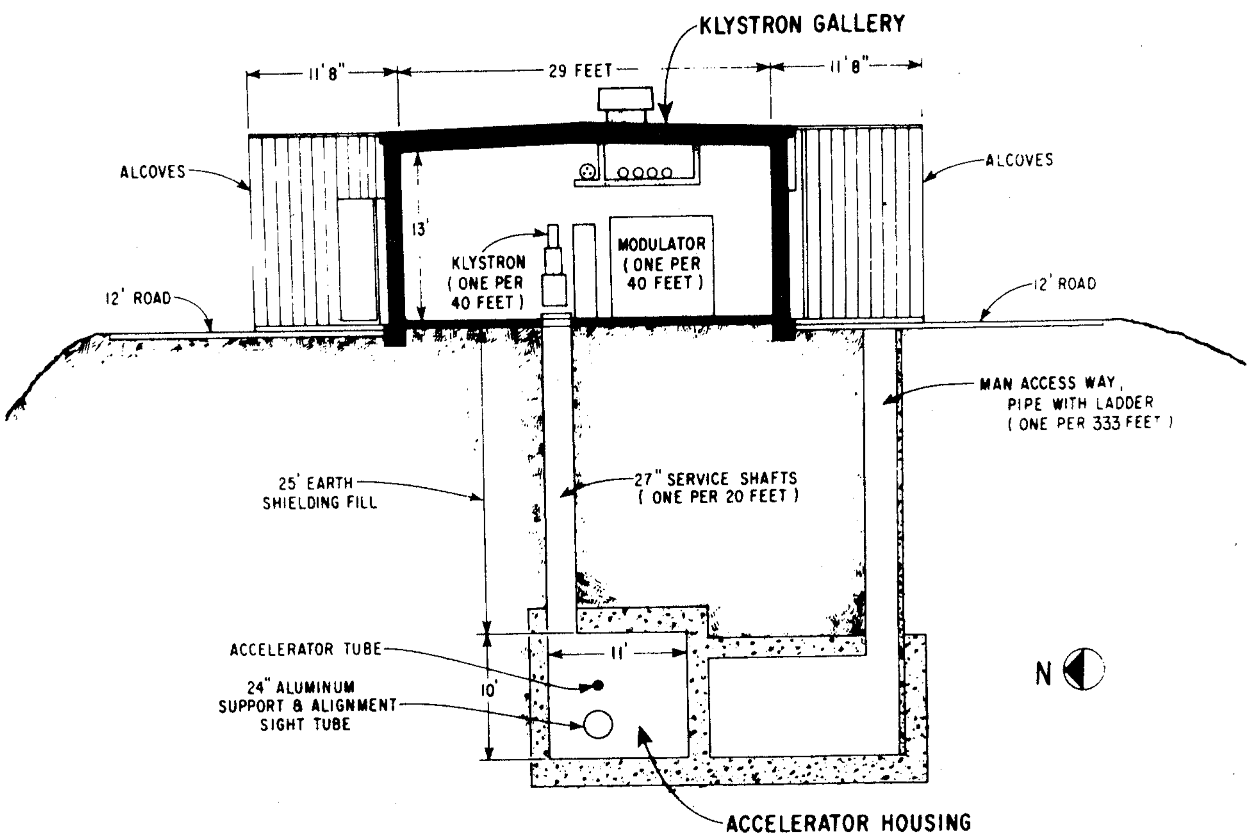
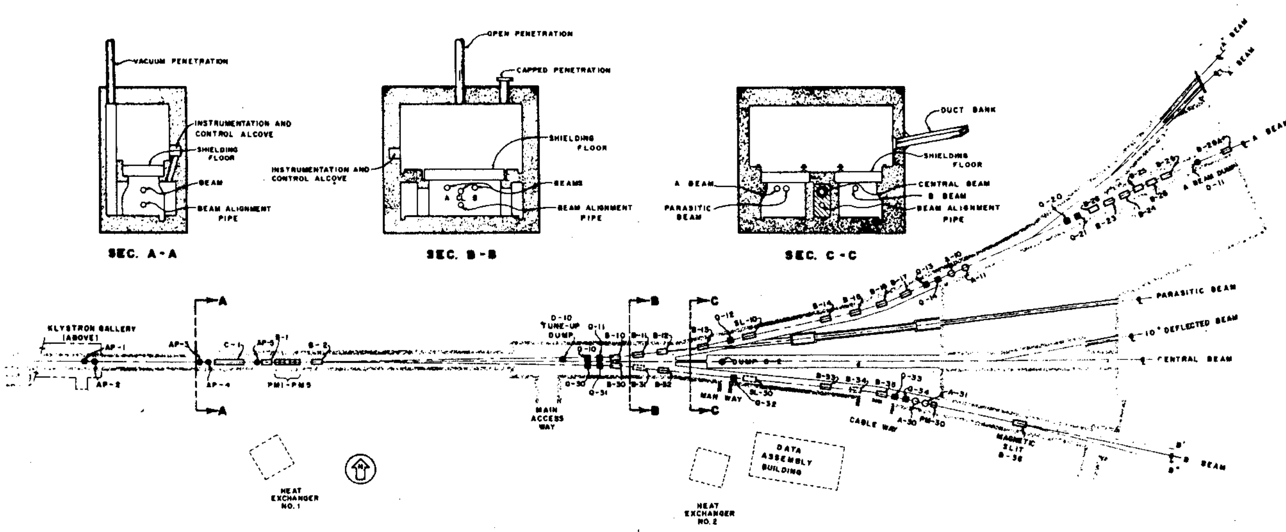


Fig. 8. Cross Section of Accelerator Housing and Klystron Gallery.



AP - Pulsed Steering Magnet
C - Collimator
B - Bending Magnet
PM - Pulsed Magnet

D - Beam Dump
Q - Quadrupole
SL - Energy Defining Slit
A - dc Steering Magnet

Fig. 9. Overall Layout of Beam Switchyard.

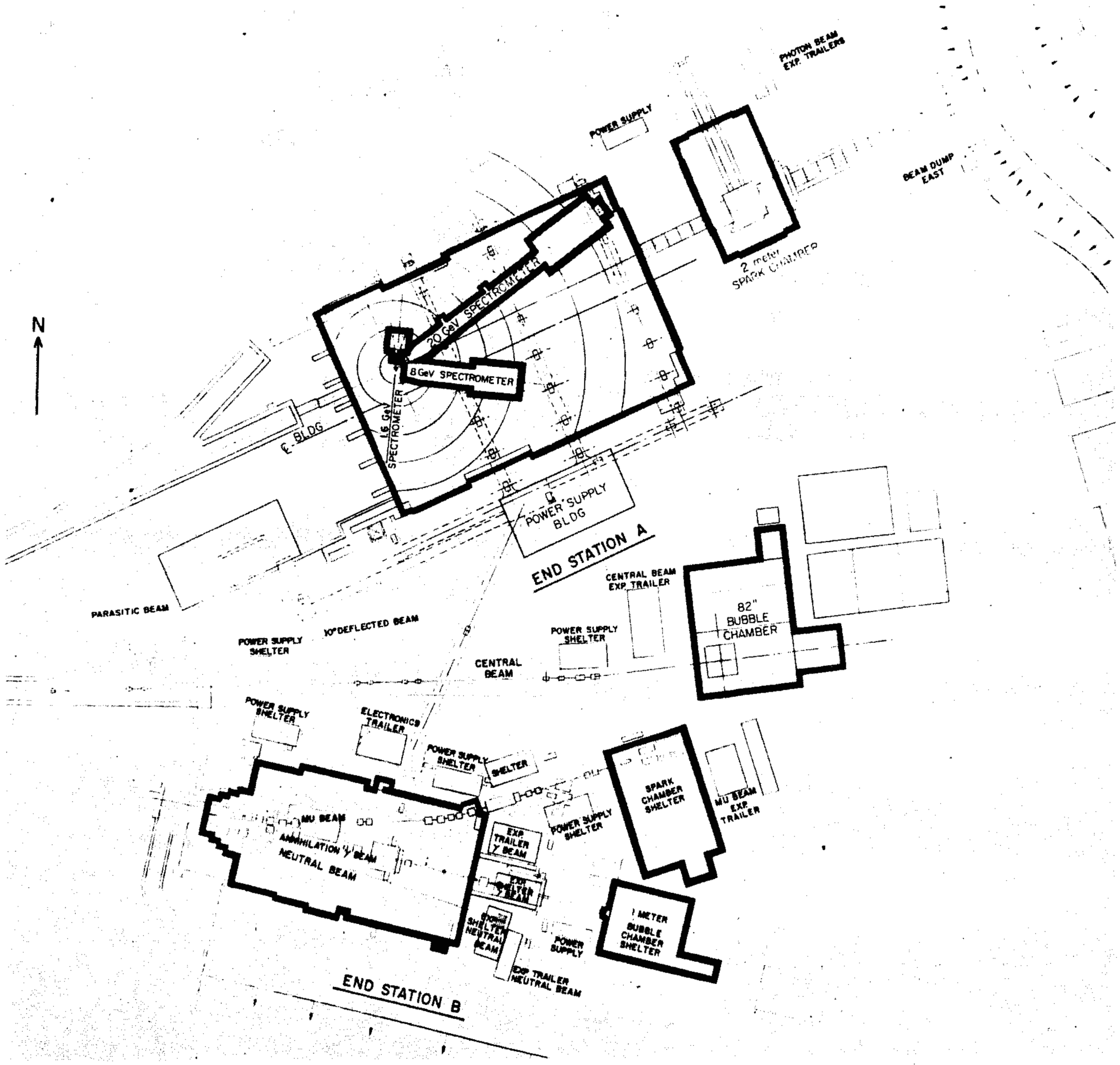


Fig. 10. Layout of Research Area.

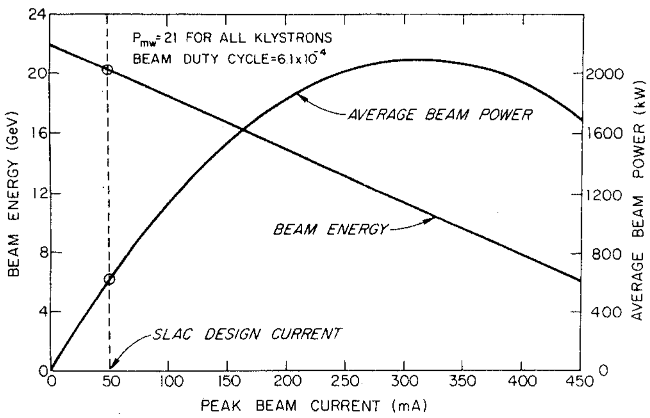


Fig. 11. Beam Energy and Average Beam Power vs Peak Beam Current for the SLAC Accelerator.

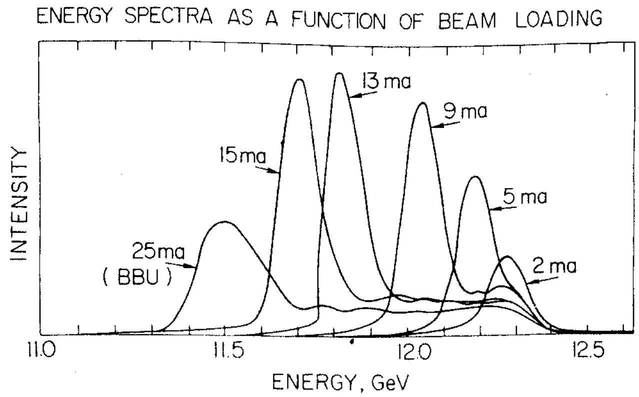


Fig. 12. Energy Spectra Under Different Beam Loading Conditions.

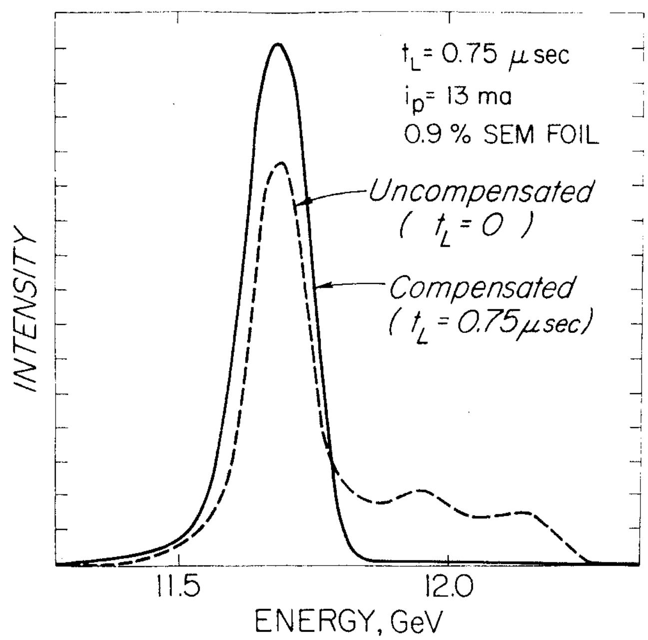


Fig. 13. Compensation of Spectrum Broadening Due to Beam Loading by Trigger Delay to 1 Sector.

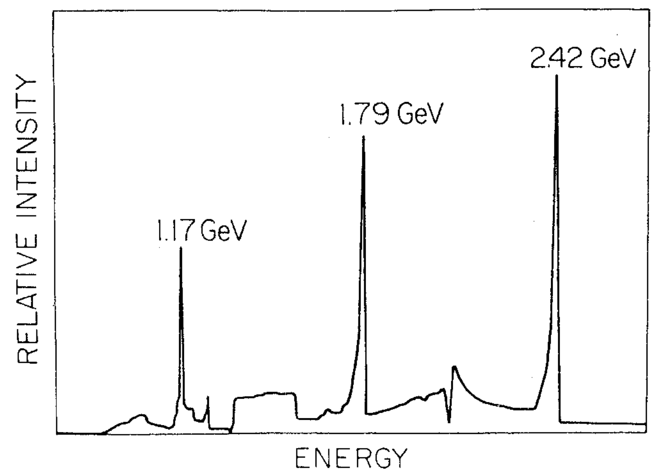


Fig. 14. Spectra of 3 Time-Interlaced Beams.

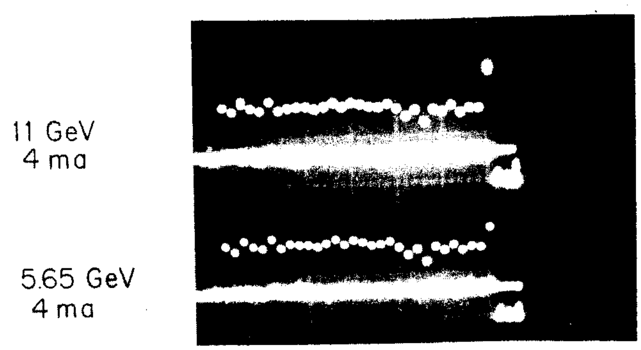


Fig. 15. Beam Intensity at End of Each Sector for Two Interlaced Beams.

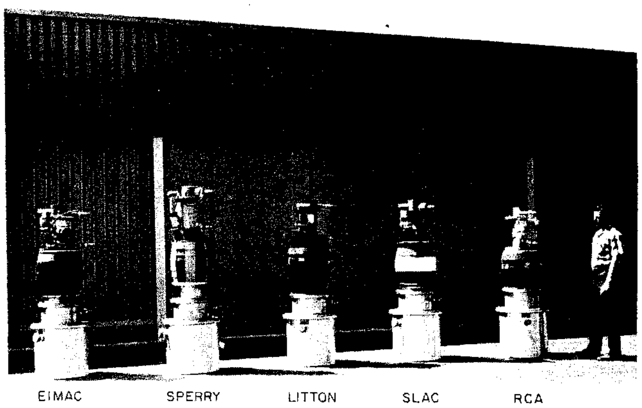


Fig. 16. Klystron Models Manufactured by SLAC and Four Commercial Companies.

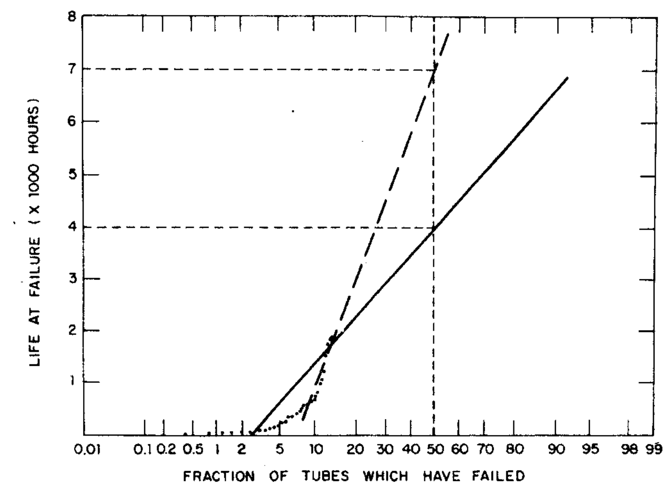


Fig. 17. Predicted Mean Time to Failure of Klystrons.

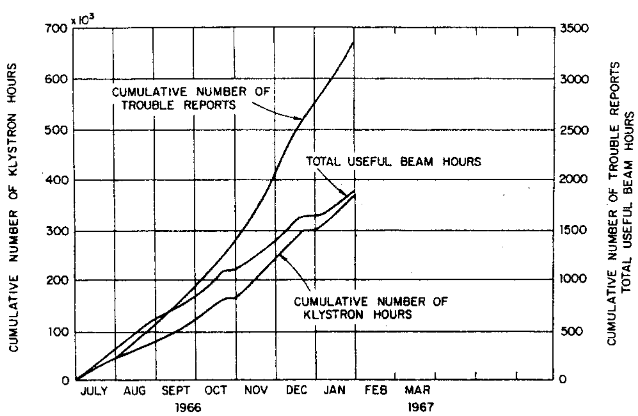


Fig. 18. Operating Statistics.