

INTRODUCTION

W. T. Kirk and R. B. Neal, Editor

Design and construction of the Stanford Linear Accelerator Center (SLAC) and its principal instrument, a two-mile linear electron accelerator, occurred over a period of approximately 4 years. The first electron beam was accelerated through the entire length of this machine on May 21, 1966. Altogether, including the efforts of SLAC and subcontractor personnel, several thousand people contributed to this major undertaking. Documentation of these efforts exists in many forms including internal criteria and design reports; technical notes and laboratory notebook entries; engineering drawings and specifications; and published laboratory reports, journal articles, and conference papers. While these documents are and will continue to be valuable sources of detailed information, they are obviously inconvenient to use for general reference purposes. Moreover, these documents do not provide consistent coverage over all phases of the work and they were prepared over an extended period of time; thus many of them do not represent the final description of a particular component or system, or the final result of a test program or theoretical study.

The definite need for a single comprehensive document about SLAC at the time of completion of the accelerator has been recognized. It has been decided to prepare the document in the form of this book. It is being published approximately 1½ years after the acceleration of the first beam through the machine. Thus, it describes the various technical features of the accelerator and the laboratory in a reasonably "final" state of completion, although it must be acknowledged that accelerators are never really complete until they approach obsolescence. Their design must continue to evolve in minor and sometimes in major ways to respond to the changing requirements of physics.

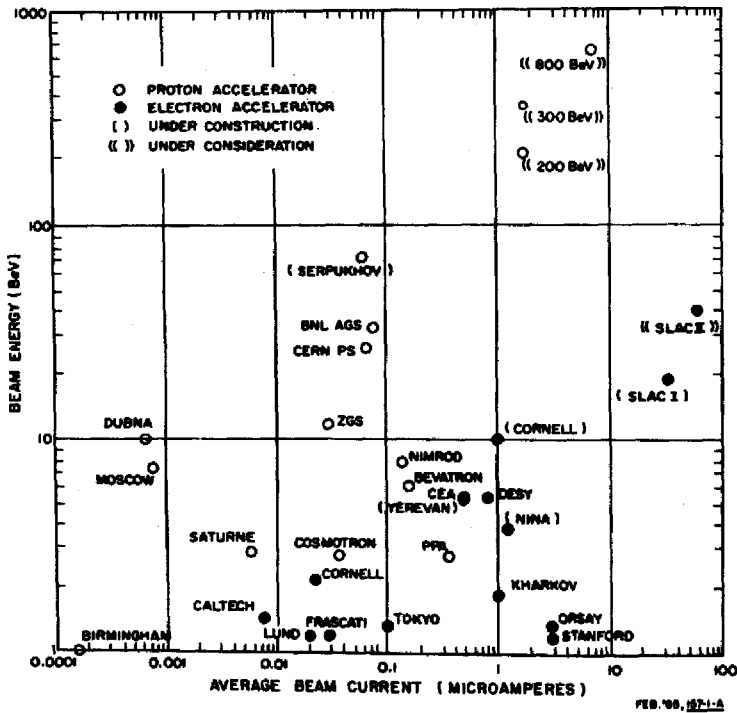
In addition to its usefulness to the SLAC staff as a ready reference and as a compendium of essential material for indoctrination of new staff

members, it is also expected that workers outside of SLAC will find this volume a repository of useful information on accelerator design and performance and on special engineering problems. Pertinent references are provided at the end of each chapter.

1-1 Comparison of SLAC accelerator with other particle accelerators (RBN)

The relative position of the SLAC machine in the international family of particle accelerators is shown in Fig. 1-1. Not noted on this graph but of interest is the fact that all of the proton machines shown accelerate their particles along approximately circular orbits. This is also true of the majority of the electron machines. But the four highest-current electron accelerators (Orsay, Kharkov, Stanford, and SLAC) accelerate their electrons along a straight path. The existing Stanford machine referred to here is the 1.2-GeV Mark III accelerator which began operation in 1950. The largest and most energetic machines now in operation are the alternating-gradient synchrotrons at the Brookhaven and CERN Laboratories, each of which accelerates protons to about 30 GeV. They will be surpassed when the Russian 70-GeV machine at Serpukhov starts operations. Two "super-energy," circular, proton accelerators of 200 to 400 GeV are presently under consideration in

Figure 1-1 Comparative graph of various accelerators.



the United States and in Europe. Even larger proton machines are in initial concept stages in America and in Russia.

The two-mile Stanford accelerator is distinguished not only by its length and high energy (Stage I, 20 GeV), but also by its high current, which exceeds by an order of magnitude that of any other machine of any kind now operating. Moreover, provisions have been made in the design of this machine which permit its later expansion (Stage II) to twice the energy (40 GeV) and twice the current (60 μ A) by connecting additional or higher-power radio-frequency (RF) sources along its length. If desirable, the energy increase can be accomplished in a gradual manner.

1-2 SLAC as a national facility (WTK)

The study of elementary particles through the use of high-energy accelerators became a separate and distinct aspect of physical research shortly after the end of the Second World War. During the 20-year period that has since elapsed, and as new accelerators have been built and brought into operation, there have evolved two general patterns or styles of carrying out experimental research which may be called the "university accelerator" pattern and the "national laboratory" pattern. Since SLAC does not readily fit into either category, these two "traditional" patterns will first be described so that SLAC may be compared with them.

Broadly speaking, university accelerators are those machines which are conceived and proposed by a technical group from one or two universities, are built at a university site, and are operated by the home university with the understanding that a major part of the machine's research program will be carried out by its own physicists and graduate students. This pattern began with the small group of 300- to 500-MeV accelerators that were built between 1945 and 1950; continued during the 1950's with the construction of the 1-GeV electron machine at CalTech, at Cornell, and at Stanford; and is most recently exemplified by the 3-GeV Princeton-Pennsylvania Accelerator (1961), the 6-GeV Cambridge Electron Accelerator (1961) undertaken jointly by Harvard and MIT, and the 10-GeV Cornell Electron Synchrotron (1967).

In contrast, the national laboratory pattern is associated with accelerators which at the time of their construction appear to have such exceptional research potential that extensive participation by physicists from many different institutions is expected and planned for. A further characteristic of this pattern is that each of these "forefront" accelerators is located at an Atomic Energy Commission (AEC)-supported National Laboratory which also carries out a broad program of basic and applied research in a number of scientific and technical fields other than elementary-particle physics. Three American machines fit this second pattern quite precisely: the 3-GeV Cosmotron (1952) and the 33-GeV AGS (1961) at Brookhaven National Laboratory; and the 12-GeV ZGS (1962) at Argonne National Laboratory. A fourth machine, the 6-GeV Bevatron (1953) at Lawrence Radiation Laboratory, fits

the pattern somewhat less closely than the others chiefly because of the fact that the major part of the machine's research program, particularly in its early years, was carried out by the exceptionally strong physics group at Berkeley.

It was evident from the beginning that the pattern of operation and experimental use best suited to SLAC would be neither that of the University Accelerator nor that of the National Laboratory, but rather some middle way. This was recognized in the original proposal,¹ which stated that

. . . the unique nature of the proposed facility puts the laboratory in the role of a national facility. Even though its formal operation would remain as the responsibility of the University . . . it shall be the policy of [Stanford] to make the facilities of the laboratory available to qualified scientific workers from any institution, subject only to maintaining the quality of the research program as limited by the available facilities and funds.

As envisioned in this proposal, the concept of SLAC as a "national facility" has evolved. In this facility the pattern of the university accelerator may be seen in the fact that SLAC is a single-purpose laboratory, built and operated by one university on its own campus. At the same time similarity to the national laboratory pattern is evident. Because of SLAC's exceptional research potential and its high cost, combined with the countrywide interest in high-energy physics involving more than forty universities, it is clear that SLAC has a real responsibility to make its unique facilities available nationally and to adjust the size of its scientific staff in relation to its facilities to permit effective outside use. Effective outside participation in the experimental program by qualified physicists throughout the United States and abroad has thus been anticipated and planned for, both in terms of facilities and staff.

1-3 General policies for experimental use of the SLAC accelerator (WTK)

As a planning guideline, it has been assumed that the division of the experimental program between Stanford and outside physics groups would eventually level out at about 50% for each, with outside user participation increasing toward this level during the first year or two of operation. Early experience (as of July 1967) indicates that this working assumption is probably quite reasonable.

The SLAC Scientific Policy Committee

A key part in working out suitable policies and procedures for SLAC in its role as a national facility has been played by SLAC's Scientific Policy Committee (SPC), which was established in 1962 under the terms of Stanford

University's contract with the AEC. The terms of reference under which the SPC operates are as follows:

1. Membership of the Committee is to be between ten and twenty scientists actively engaged in the field of high-energy physics. These scientists are to be appointed for 4-year terms arranged in overlapping tenure. The composition of the Committee is to be chosen so as to strike a reasonable balance between experimental and theoretical physicists and also between scientists affiliated with universities and those affiliated with major government laboratories.
2. The members of the Committee are to be nominated by the director of SLAC and approved by the Board of Trustees of Stanford University and by the AEC.
3. The Committee will set its own agenda with the staff of SLAC providing the necessary services. The Committee should have maximum flexibility to consider all scientific and technical matters pertaining to SLAC. The Committee may include in its considerations also those administrative problems which in its view affect directly the scientific and technical work of the Laboratory.
4. The Committee will review the work of the Laboratory as well as initiate for discussion topics which it considers to be of concern to the work of the Laboratory. A major concern of the SPC is to ascertain that the facilities of the accelerator center are made available to qualified scientists from other institutions as well as Stanford University, subject only to the quality and productiveness of the research program.
5. The Committee will report to the president of Stanford University. He will transmit the findings with respect to paragraph 4, above, immediately to the director, Division of Research, AEC; he may, at his option, transmit any other findings of the Committee to the director, Division of Research, AEC.

Experimental scheduling policy

In 1965, with the advice and approval of SLAC's Scientific Policy Committee and of the Atomic Energy Commission, SLAC prepared a general statement of the policies and procedures that would be used in scheduling the assignment of time for experimental use of the accelerator's beam and the major research devices that were then being constructed. This general statement was embodied in a memorandum called "Scheduling of the SLAC Facilities," from which the following information has been extracted.

RESPONSIBILITY FOR PROGRAM. The Stanford linear accelerator is a national facility and, as such, is available to all qualified experimenters. Stanford University has the responsibility for programming the research use of this national facility according to certain basic conditions set forth in a contract

between the University and the AEC. The director of SLAC has the responsibility for decisions on all matters relating to schedules, including the administration and interpretation of these policies and procedures.

The functioning of the scheduling, and the experimental operations in general, will be reviewed periodically with the SPC, which may suggest changes in the procedures. The procedures may be amended from time to time by agreement between SLAC and the AEC.

PROGRAM ADVISORY COMMITTEE. The director will appoint a Program Advisory Committee (PAC) which will meet with him to assist him in establishing the program commitments for the use of the accelerator. It is expected that the meetings of the PAC will be scheduled at intervals of 2 to 4 weeks. The PAC will consist of eight members, at least four of whom will be high-energy physicists not employed at Stanford. The director will also appoint from the SLAC staff a program coordinator, who will act as secretary to the PAC. Appointments to the PAC will be for terms of 2 years with the possibility of reappointment. The SPC and the AEC will be informed of all changes in the membership of the PAC. At each meeting of the SPC the director will report on all scheduling decisions which have been made in the interval between meetings. It is anticipated that the SPC will also wish to review once each year the scheduling records and the operation of these scheduling procedures.

PROPOSALS FOR EXPERIMENTS. Proposals for experiments which would use beam time or for the use of any of the major research facilities intended for general use will be received by the program coordinator who will present them to the PAC on the next suitable occasion. The program coordinator will also be prepared to present to the PAC information regarding the availability and suitability of the Laboratory's resources for carrying out any particular proposal.

Proposals from staff members of SLAC will be handled on the same basis as proposals from research workers at any other institution.

CRITERIA FOR SELECTION. Stanford is contractually obligated to program the use of the linear accelerator so as to achieve "a vigorous, forward-looking research program in high-energy physics." It is further stipulated that "Scientific priority shall generally govern the allocation of machine time"

ACCEPTANCE FOR THE PROGRAM. All firm decisions to accept or reject a particular proposed experiment will be made by the director or his assigned deputy with the advice of the PAC at a scheduled meeting of the PAC, and will be announced after the meeting. A particular experiment may be discussed at several meetings of the PAC before a firm decision is reached.

An experiment accepted for the long-range operation plan will normally be assigned a specific amount of running time. Experiments will, in general, *not* be scheduled in the order of their submission or their acceptance.

EXECUTION OF THE PROGRAM. The administration of the short-range schedule, including all specific arrangements for the use of SLAC facilities will be the responsibility of the Operations Staff of SLAC. The Operations Staff will be responsible for arranging the detailed schedules so as to provide the allocated beam time to a particular experiment during a particular running period, but otherwise will be free to make adjustments in the light of day-to-day problems.

RECORDS. Records will be kept of all experiments proposed to SLAC and of the disposition of the proposals. The records will include the dates of submission and the dates of acceptance or rejection. For proposals accepted, the records will show the amount of beam time assigned and of the ultimate execution of the program, including the beam time actually received. These records will be reviewed annually with the SPC, will be transmitted to the AEC, and will be publicly available.

Early scheduling experience

As of July 1967, SLAC had received twenty-four proposals for particle-physics experiments. Of these, seventeen had been accepted for the approved experimental program, four had been rejected, one had been withdrawn, and the remaining two had not yet been acted upon. Of the seventeen approved experiments, seven were to be carried out by physics groups from Stanford, two by groups from other universities, and the remaining nine as collaborative efforts between Stanford and outside users groups. Three experiments had been completed by this time, and the results of these had been published or were being written up for publication.

1-4 Relationships among SLAC, Stanford University, and the U.S. Atomic Energy Commission (RBN)

The functional relationships among SLAC, Stanford University, the AEC, and the various advisory and coordinating committees are illustrated in Fig. 1-2. The Stanford Linear Accelerator Center has been constructed and is now being operated by Stanford University as a national facility under contracts with the U.S. Atomic Energy Commission. The AEC carries out its role as the responsible government agency administering SLAC affairs through its program and fiscal approval procedures. Contracting responsibility at Stanford resides in the Board of Trustees of the University. Construction and operating responsibility for SLAC extends from the Trustees to the president of Stanford University who has, in turn, delegated this responsibility to the director of SLAC. The director is assisted by a deputy director and by four associate directors who administer the four main divisions of SLAC: Technical Division, Research Division, Business Services Division, and Administrative Services Division.

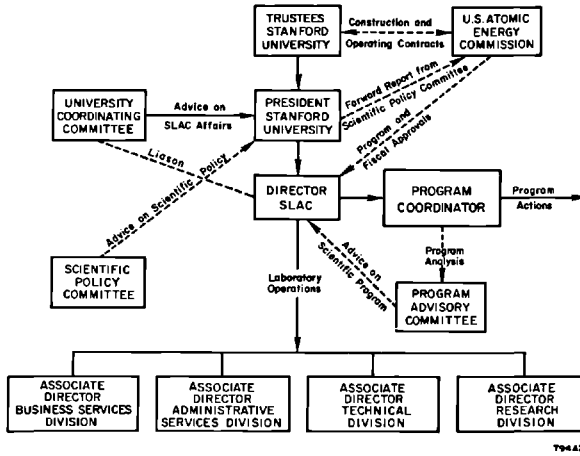


Figure 1-2 Functional relationships among SLAC, Stanford University, the U.S. Atomic Energy Commission, and various advisory and coordinating committees.

Coordination of the SLAC experimental program and liaison with the PAC are the responsibilities of the program coordinator.

The administration of the short-range schedule, including all specific arrangements for the use of SLAC facilities and for the safety of any proposed installation is the responsibility of designated members of the SLAC operating staff. The detailed day-to-day scheduling of operations of the accelerator is also the responsibility of the Operations Staff of SLAC, and is determined in consultation with the experimenters who are working on the scheduled experiments.

A University Coordinating Committee advises the president regarding the interrelationships between SLAC and the University. This Committee meets monthly.

Reference

- 1 *Proposal for a Two-Mile Linear Electron Accelerator*, Stanford Linear Accelerator Center, Stanford University, Stanford, California (April 1957).

AIMS AND PURPOSES

W. T. Kirk and R. B. Neal, Editor

Although it is not within the scope of this book to describe the physics research program at SLAC in any great detail, some knowledge of the objectives of this research and of the ways in which SLAC expects to pursue these objectives should prove helpful in understanding the reason for SLAC's existence and the general role it is likely to play as a center for particle-physics research. The intent of the present chapter, therefore, is to set out brief descriptions of the following four subjects: (a) the objectives of elementary-particle physics, (b) the machine characteristics that determine the SLAC accelerator's experimental utility, (c) the initial research program planned at SLAC, and (d) the research equipment used in conjunction with the accelerator to carry out experiments. The description of objectives given here is historical and nontechnical, since it is intended only to give the general reader a speaking acquaintance with some of the background of elementary-particle physics. The following four sections, though introductory in character, do assume some modest prior knowledge of accelerators, experimental physics techniques, and related research apparatus.

2-1 The objectives of particle physics research (WTK)

In this section a brief description of the objectives of particle physics research is presented.¹ Perhaps the simplest statement of the central goal of this work is that it is an attempt to understand how nature works on its most fundamental level. What is the basic stuff of the universe and how does it behave? These profound questions have occupied men's thoughts for as long as history has been recorded. Although the evidence of our senses presents us with an apparently limitless variety of natural objects and events in the world around us, man always sought an understanding of this rich profusion of forms

through an attempt to find some underlying simplicity—some basic pattern. Is it possible that the incredible diversity we see in nature is simply the elaborate arrangements and combinations of only a few basic substances? For the past 2500 years, starting with the Greek philosophers, men have first speculated, then later demonstrated, that the answer to this question is “yes.”

Toward simplicity

About 100 years ago, the Russian scientist Mendeleev devised a comprehensive classification scheme, the Periodic Table of the Elements, which succeeded in relating to each other the seventy-odd elements that were then known, on the basis of their chemical properties and relative weights. Although the patterns of relationship revealed by the Periodic Table were striking and suggestive and, in fact, led to the prediction and subsequent discovery of several new elements, an explanation of *why* the elements should fit into such a periodic system was not given until about 1910 when Rutherford, Bohr, and others worked out the theory of the nuclear atom. This new view of matter made it clear that the chemical elements (which are now known to number about 100) were in fact not “elemental” at all, but rather were themselves composite states built up from various simple combinations of only two truly elementary particles: protons and electrons. This recognition marked a point of extreme simplicity in the search for the basic stuff of nature, and for a time it appeared that physicists would be able to describe most small-scale phenomena on the basis of only these two particles and the known electrical forces with which they acted upon each other. It was a time when so astute an observer of science as Bertrand Russell could remark that “Physical science is thus approaching the stage when it will be complete, and therefore uninteresting. Given the laws governing the motions of electrons and protons, the rest is merely geography—a collection of particular facts telling their distribution throughout some portion of the world’s history.”

But nature has turned out to be a good deal more elusive than that.

Toward complexity again

By the 1930’s, the simplicity of the earlier view had begun to give way to a deeper and more intricate picture. The discovery of the neutron, in 1932, helped to explain several discrepancies in the earlier view; and by that time it had also been recognized that the quantum of electromagnetic radiation, the photon, could equally well be thought of as a particle or as a wave (this is true of all “particles”). Even earlier, in 1930, the theory of the electron worked out by Dirac had implied the possible existence of antiparticles (specifically, a positively charged electron), and this was soon confirmed with the discovery of the positron. It was thus believed, and later verified, that both antiprotons and antineutrons should also exist.

To be brief, the period between 1930 and the present time can be summed up as one in which each new penetration to a deeper level of nature has disclosed an unsuspected richness and subtlety. Whole new classes of particles, new properties, and new principles of conservation and symmetry have been discovered. By 1960, the list of elementary particles had increased to about thirty, and at the present time the number of different particle states that have been discovered or are predicted is about 200. Given this rich profusion, it is no longer clear which of the particles, if any, is in fact “elementary,” nor even if this word still has much meaning.

The present objectives

To repeat, the central aim of elementary-particle physics is the search for an understanding of the ultimate nature of matter. Although it is somewhat misleading to divide what is essentially a unified activity into smaller parts, it is possible to describe several different aspects of the subject.

INTRINSIC PROPERTIES OF THE PARTICLES. The particles are distinguished from each other by differences in a number of intrinsic properties: mass, electric charge, spin, stability, and several others. One objective then is to determine the quantitative values of these intrinsic properties as accurately as possible.

CLASSIFICATION SCHEMES. A second objective is to devise a consistent classification scheme, perhaps analogous to the Periodic Table of the Elements, which will indicate how their intrinsic properties logically relate the particles to each other. Much progress has been made in this work in recent years. One of these recent classification schemes, called “The Eightfold Way,” which is based on the mathematics of group theory, has had striking success in demonstrating that the particles occur in “families” and in predicting both the properties of known particles and the existence of new particles. A possible consequence of this scheme is that there may yet be an underlying simplicity to the variety of particle states that are now observed. In this regard, physicists are presently searching for a postulated set of three “truly” elementary objects called “quarks,” which may be the building blocks from which most of the known particles are constructed.

INTERACTION FORCES. Four kinds of forces are now known in nature (see Table 2-1). The objective here is to determine the characteristics of these forces (range, strength, particles acted upon, etc.) in as much detail as possible. The electromagnetic force seems to be well understood—no discrepancies between theory and experiment have been observed so far in cases where only this force is involved. The large-scale effects of the gravitational force are well known, but its mechanism is not. Because of its relative weakness, the gravitational force is assumed to be negligible in the small-scale world of

Table 2-1 Types of forces

<i>Force</i>	<i>Relative strength</i>
Strong or nuclear force	1
Electromagnetic force	10^{-2}
Weak or Fermi force	10^{-14}
Gravitational force	10^{-38}

particle physics. The weak or Fermi force may be a point-force, that is, its effects may not extend over any measurable range. Recent work has made it possible to predict the effects of the weak force much more accurately than before. The strong or nuclear force appears to act through only a very short range (roughly one nuclear diameter, or 10^{-13} in.); although an understanding of this force is of critical importance, and much of the work in the field is devoted to this end, there does not yet exist any satisfactory theory for it.

THE BASIC LAWS. The ultimate objective is to formulate the basic mathematical laws that will precisely describe the behavior of matter in its most elementary forms. Except for the purely electromagnetic interactions, the present attempts to formulate such laws are approximate, speculative, and often not self-consistent. Certain conservation laws and symmetry principles appear to be broadly applicable. Although these may point toward some underlying uniformity in nature, in their present form most of them simply state what is observed to happen without greatly illuminating either mechanisms or significance.

2-2 Machine characteristics important to research (RBN)

For maximum research utility, it is essential that a particle accelerator have certain characteristics which are well matched to the experimental requirements. Among the most important characteristics are the following:

Kind of particle accelerated

Machines have been built to accelerate protons, electrons, deuterons, alpha particles, and various heavy ions. In the energy range above 100 MeV most of the existing machines accelerate either protons or electrons. Proton and electron machines are complementary in terms of applicability to research, principally because these particles interact with other particles in different ways. Electrons interact through the electromagnetic force, whereas protons interact with other particles principally through the strong nuclear force. The electromagnetic force is better understood than the strong nuclear force. Thus, the resulting interaction is in general easier to analyze when the incident particles are electrons rather than protons. However, because the nucleus force is about 100 times as strong as the electromagnetic force, the number

of events in a proton-induced interaction is correspondingly larger than in an electron-induced interaction. This situation would tend to place electron machines at a disadvantage compared to proton machines when studying processes of low cross section. However, linear electron machines usually more than compensate for this discrepancy by accelerating larger numbers of particles per second than proton machines.

For the same incident kinetic energies, electrons produce higher kinetic energies in the center-of-mass system than protons. This is because the rest mass of the electron is only about 1/1846 of the rest mass of the proton. For example, when a 10-GeV electron is incident upon a stationary proton target, the kinetic energy in the center-of-mass system is 5.3 GeV. The corresponding center-of-mass energy when the incident particle is a proton is 4.5 GeV.

Beam energy

In particle research, high energies are important for several reasons:

1. The resolution of a particular instrument used to examine the detailed structure of matter is limited by the wavelength of the "light" which illuminates the object under study. Thus, in the employment of high-energy particles for research it is not possible to resolve details which are much smaller than the de Broglie wavelength ($\lambda = h/p$), where p is the momentum of the incident particle and h is Planck's constant, 6.6×10^{-27} erg-sec. This wavelength varies inversely with the particle energy. For example, at an incident electron energy of 20 GeV, the de Broglie wavelength is 6.2×10^{-15} cm, which is roughly 1% of the diameter of the proton or neutron. In principle, this energy then permits detailed study of the fine structure of the fundamental particles.
2. In general, the number and variety of the secondary particles which are produced in a nuclear reaction increase as the energy of the bombarding particle increases. The heaviest "long-lived" particle (the Ξ^- , which has a rest mass of 1321 MeV) can be produced at an electron energy of about 6 GeV and at a proton energy of about 9 GeV. However, higher energies than these are usually desirable when studying the heavier secondary particles in order to increase the yield and to study the production of these particles at energies well above their threshold values.
3. History has shown that the advance to higher and higher energies has consistently led to interesting and often unexpected results. It is expected that such will also be the case with the SLAC two-mile accelerator.

Electron energies above 10 to 12 GeV are difficult and expensive to obtain with circular accelerators because radiation losses increase as the fourth power of the energy (for fixed radius). Since linear accelerators are not subject to radial acceleration losses, it seems quite likely that *electron* energies of 20 GeV or more will be achieved only with the linear-type machine.

Beam intensity

Many phenomena of great interest in high-energy physics occur with very low probability. Thus, a very large number of particles must be incident on the target in order that enough events occur to be statistically significant. In such cases, a large number of incident particles per unit time, i.e., a beam of high intensity, must be available if a meaningful experiment is to be accomplished in a reasonable length of time. The SLAC accelerator has a beam intensity higher by about two orders of magnitude than any other machine with energy greater than 10 GeV now in existence. Somewhat more than 10^{14} electrons/sec are available. When all of this intensity is not needed for a single experiment, the inherent capability of sharing it among several experiments simultaneously is a great advantage.

Spectrum width

When the momentum of the incident particle plays a direct role in the kinematics of an experiment, e.g., scattering experiments, it is necessary to define this momentum with great precision. This is accomplished by setting the opening of momentum-defining slits in the beam-analyzing system to a suitably small value. Only those incident particles of which the momenta lie within the desired narrow acceptance band are then able to pass through the system. Other particles with momenta outside the acceptance band are absorbed in the metallic structures forming the boundaries of the slit and are thus excluded from the experiment.

It is desirable that the spectrum width of the incident beam be as narrow as possible for the following reasons: (1) A larger fraction of the incident beam can be accepted and utilized in the experiment; (2) there is less absorbed beam and hence less trouble with unwanted background radiation; and (3) the experimental requirements can be satisfied by an accelerated beam of lower intensity; hence, there is less energy loss due to beam loading and less direct radiation and residual radioactivity along the machine and in the beam-analyzing system.

Beam duty cycle

The beam duty cycle is the fraction of the total time the beam is on.* It is given by the product (PRR) (t_p), where PRR is the pulse repetition rate and t_p is the duration of the pulse. For the SLAC machine the PRR (maximum) is 360 pulses/sec and t_p (maximum) is 1.67 μ sec; thus, the maximum duty cycle is 0.06%.

* In this context, it is the macroscopic time characteristics of the beam which are referred to, not the time structure determined by the microwave (i.e., "bunched") nature of the beam.

A particular number of incident particles is required to obtain a desired number of experimental events. The average time separation of these events is proportional to the duty cycle of the machine producing the incident particles. Thus, for most counting experiments a large duty cycle is desired so that the counting equipment can discriminate between successive events and thus count all or nearly all of them. This data rate problem is even more serious when on-line computers are being used in conjunction with experiments. The limitation in this case becomes the rate at which data can be introduced into the computer.

In most counting experiments, the momentum of a particle under study is measured by requiring that it follow a precisely determined trajectory through an array of magnets. The momentum of the accepted particles is proportional to the strengths of the magnet fields which are known with great accuracy. Therefore, with a given spatial arrangement of the elements of the transport system, a wide range of momenta can be measured by variation of the fields. The fact that a particle has followed the required trajectory is ascertained by the simultaneous indication (i.e., coincidence) of counters along the path. For a given discrimination time, τ , of the counters, the probability of an accidental coincidence in two counters from two separate particles ("events") varies as $(S\tau)^2$, where S is the instantaneous counting rate. Thus, the probability of accidental events may be reduced by the use of a high beam duty cycle so that the instantaneous counting rate is low. Another way of reducing accidentals, though at added experimental complication, consists of increasing the number of counters in coincidence along the particle trajectory. For n counters in coincidence, the probability of an accidental coincidence is $(S\tau)^n$.

From the above discussion it is clear that a high duty cycle is very beneficial for most counting experiments. Duty cycle in an accelerator is limited by cost considerations. Increased duty cycle requires larger power supplies and higher average ratings of all modulator components. Operating costs are also increased roughly in proportion to the duty cycle.

In some experiments, a particle of known momentum, p , is identified by determining its relativistic mass, m , from the time, t , required for the particle to traverse a fixed distance, l , between two counters. Thus, the mass is obtained from the expression $m = pt/l$. To apply this technique successfully it is necessary to distinguish particles which truly have different transit times (because their velocities are different) from particles of the same velocity but which *appear* to have different transit times. These apparent differences in transit time can arise in either of two ways: because two or more particles pass through the counters at different instants during the pulse length or because they originate from two different pulses and are indistinguishable. Thus, to avoid confusion, it is desirable that the pulse length be short and the separation between pulses long compared to the difference in transit times of the particles being distinguished. Fortunately, it is relatively simple to adjust the injector of a high duty cycle, linear accelerator so as to obtain low beam

duty cycle conditions. The inverse situation is, of course, not possible. As an example, suppose that it is desired to distinguish among 3-GeV/c, e^- , μ^- , π^- , k^- , and \bar{p} particles by time-of-flight measurements over a 45-meter distance. The transit time over a distance l for a particle of total energy E (rest energy plus kinetic energy) and rest energy mc^2 is given by:

$$t = \frac{l}{\beta c} = \frac{l}{c} \left[\frac{\gamma^2}{\gamma^2 - 1} \right]^{1/2}$$

where $\gamma = E/mc^2$.

From the known rest masses of the particles under study Table 2-2 can be calculated. The normal length of the beam in the two-mile accelerator is 1.67 μ sec. However, by the use of a *beam knockout* device in the injector system, it is possible to shorten the pulse so that only single bunches are accelerated. Assuming bunching to a phase spread of 5° , the pulse length is then $1/2856 \times 5/360 \mu$ sec = 0.0049 nsec. The beam knockout system also allows only 1 bunch out of each 36 to be accelerated. The bunch separation is thus 12.6 nsec. Under these conditions, it is possible to distinguish the particles in Table 2-2 by time-of-flight techniques.

Table 2-2 Transit times of various particles with 3 GeV/c momenta

Particle	Rest energy (MeV)	t (nsec) for $l = 45$ meters
e	0.51	150.000
μ^-	105.7	150.093
π^-	139.6	150.162
k^-	494	152.020
\bar{p}	938.2	157.164

Geometrical properties of the beam

It is desirable that the beam emerging from the accelerator have a small lateral cross section and a small angular divergence. Since these qualities can be traded to some extent, a characteristic of the beam called the *transverse phase space* occupied by the beam is more generally applicable. The phase space is given approximately by the product of the beam diameter at the beam minimum times the angular divergence of the beam. Measurements show that about 80% of the beam emerging from the SLAC accelerator is contained in a phase space of 0.03 (MeV/c) (cm). Thus, for a beam diameter of 0.4 cm the angular divergence at an energy of 20 GeV is somewhat less than 10^{-5} radian.

A small phase space is desired so that beams of good optical quality can be transported simply, inexpensively, and without excessive loss in intensity to widely separated experimental areas. A small phase space permits the use of magnets and other beam transport devices of relatively small aperture. It also requires less initial collimation of the beam. Excessive collimation results

in reduction of mean intensity and in unwanted background radiation and large residual radioactivity in the beam transport components.

A small beam cross section upon entrance into the transport and energy analyzing system is also desirable to enable precise determinations of the beam energy to be made. The characteristics of the SLAC analyzing system are such that a 6 mm diameter of the beam entering the transport system allows a $\pm 0.1\%$ energy spread in the beam accepted through an infinitely narrow energy-defining slit. (This figure applies to the A side of the transport system; the corresponding figure of the B side is twice as large.) A diagram of the beam transport system is shown in Fig. 5-23. A more complete description and design details are given in Chapter 17.

Operational flexibility

The research utility of an accelerator is greatly enhanced by the provision of certain operational features and capabilities. Examples are as follows:

1. Ease and speed of changing beam energy and intensity
2. Adjustable pulse repetition rate
3. Adjustable pulse length
4. Interlaced multiple beams, each independently controllable in pulse length, intensity and energy
5. The ability to increase the time gap between electron bunches (beam knockout)
6. Preservation of bunched beam phase quality as beam passes through beam transport system (isochronism)
7. Good beam stability in energy, current, and optical characteristics
8. Good beam transmission through accelerator (low background radiation)
9. Capability of accelerating other particles as well as primary particle (e.g., positrons)

Attention to all of these features has been given in the design of the SLAC accelerator.

2-3 The SLAC research program (WTK)

When SLAC was first proposed in 1957, it was expected that its eventual research program would have an emphasis quite different from those of the large proton accelerators. As stated in the Proposal: "Studies made with electron beams yield information which ideally complements that obtained with proton beams. In general, processes induced by electrons and photons are simpler in character than the corresponding proton reactions, and are thus more readily understood in fundamental terms." Although it was recognized at that time that the SLAC accelerator could be used to produce intense beams of secondary particles, it was assumed that experiments such as electron-scattering and photoproduction studies would tend to dominate the

SLAC program in much the same way as the work of the proton machines is dominated by strong-interaction studies done with secondary beams.

During the intervening 10 years, several factors have conspired to alter, to some extent, SLAC's original research expectations. The first factor is the increasing emphasis on strong-interaction physics brought about by the discovery of particle resonances and the subsequent proliferation in the number of meson and baryon states that have been observed, and also by the successes of such classification schemes as SU_3 in grouping the observed states into families which share certain properties. The second factor is based on a prediction by S. Drell, later confirmed experimentally, that the process of photoproduction of secondary particles would proceed, in part, through a mechanism which would result in more intense beams of high-energy secondaries at SLAC than had been previously supposed.² These two factors have increased the prospective importance of strong-interaction physics at SLAC.

The early program at SLAC

The first use of the SLAC accelerator for physics research began in late 1966. By the time of this writing (July 1967), many of the inevitable bugs have been worked out of the accelerator and the research equipment, and an increasingly large fraction of the machine's running time has been given over to routine production of electron and positron beams for the experimental program. The experiments that have been approved for the program as of July 1967, are listed in Table 2-3 in order to indicate the scope and variety of this initial block of work. In the remaining parts of this section, these experiments have been divided into several classes and a brief description of each class is given.³

Elastic scattering of electrons and positrons

One of the early experiments that will be carried out at SLAC is a study of the elastic scattering of electrons from protons. This work is an extension to higher energies of the study of the electromagnetic structure of the proton that began with the fundamental work of Hofstadter at Stanford and was continued by groups at Cornell, at the Cambridge Electron Accelerator, and recently at the Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany. In general, the proton's structure is described in terms of two form factors, G_E and G_M , which refer, respectively, to the distribution of the proton's electric and magnetic properties. The values of G_E and G_M are a strong function of q^2 (q is the four-momentum that is transferred to the proton in the scattering process), and the chief purpose of the planned experiment is to extend the form factor measurements out to regions of very large q^2 . Both the cross sections and the corresponding values of the form factors drop rapidly with increasing q^2 ; at $q^2 = 16(\text{GeV}/c)^2$, for example, a typical cross section is 7×10^{-39} cm²/steradian. However, the high intensity of the SLAC accelerator should make it possible to obtain counting rates of 2 to 3 per hour even at this extremely small cross section.

It is also of interest to compare the scattering of positrons on protons with the scattering of electrons on protons. Most of the theoretical predictions of electron-proton scattering assume that only one photon gets exchanged in the process. This is partly because most experimental results corroborate this assumption and partly because some of the two-photon exchange calculations have not been carried out. One way to resolve this experimentally is to measure the ratio of the scattering cross sections for electrons and positrons.

Table 2-3 Approved SLAC experimental program (July, 1967)

<i>Experiment</i>	<i>Facility used</i>	<i>Participating groups</i>
Electron/proton elastic scattering	8-GeV/c spectrometer	Stanford, MIT, CalTech
Electron/proton inelastic scattering		Stanford, MIT, CalTech
Comparison of e^-p and e^+p elastic scattering		Stanford, MIT, CalTech
Inelastic spectrum of electrons scattered from carbon-12		Stanford, MIT
Photoproduction at forward angles	20-GeV/c spectrometer	Stanford
Photoproduction of asymmetric muon pairs		Stanford, MIT
Survey of photomeson production processes at backward center-of-mass angles	1.6-GeV/c spectrometer	Stanford
Photoproduction of neutral mesons		Stanford, CalTech, Northeastern
Photoproduction in a streamer chamber	2-meter spark chamber magnet	Stanford
Production of wide-angle electron pairs		Stanford, Harvard
Survey of $\mu-p$ inelastic interaction at high energy	54-in. spark chamber magnet; muon beam	Stanford
Setup of monochromatic photon beam to study photon interactions in the SLAC hydrogen bubble chamber	Positron beam	Stanford
ρ^0 photoproduction from complex nuclei at forward angles	Monochromatic photon beam	Stanford, U.C. (Berkeley)
Study of possible CP violation in f^0 photoproduction		Stanford, U.C. (Berkeley)
Flux measurements of neutral particles, and K_S^0 decay asymmetry	—	Stanford, U.C. (Berkeley)
Search for new particles	—	Stanford
Measurements pertinent to the design of a 12-GeV/c RF separated beam	—	U.C. (Berkeley)
Emulsion study of electromagnetic interactions	—	U.C. (Riverside)
A search for fractionally charged particles (quarks)	—	Stanford

If two-photon processes are observed, this will indicate a need for revision in our understanding of electromagnetism. The required accuracies have not been attainable in the past, in part because it is difficult to obtain intense positron beams. At SLAC, previous experiments can be redone with only a few hours running time with high accuracy ($\approx 1\%$). Furthermore, a two-photon contribution, if it exists, can be investigated out to higher values of momentum transfer.

Photoproduction experiments

A large number of photoproduction experiments are scheduled for the research program at SLAC. In most cases, the photon beam will be formed by letting the main electron beam strike a thin target in the beam switchyard and then deflecting the electron downward into an energy-absorbing device called a "beam dump." The gamma rays go straight ahead into a target in the end station.

The 20-GeV/c spectrometer will be used to examine photoproduction of single new particles as a function of production angle and the photon energy. This is a difficult energy-difference experiment which depends on precision measurements to isolate, by kinematics alone, processes that differ from each other in minor ways. An experiment to measure photoproduction of anti-protons is also scheduled. Counting rates as high as several per minute for 15-GeV antiprotons with a momentum spread of 1% are expected.

More complicated photoproduction events will be studied with streamer spark chambers. These include the production of very short-lived "resonance" particle states such as ρ^0 and ω . Additional photoproduction studies will make use of a quasi-monochromatic photon beam obtained from positron annihilation to look at ρ^0 production in great detail. From the knowledge of the properties of the incoming photon, it is now possible to do a photon experiment similar to that which has been done with incident pi mesons. The experiment is done with nuclei as well as protons as the target to see if at high energies the ρ^0 continue to be produced in a diffractionlike process. Such a production mechanism has been inferred from observations at lower energies.

Two other classes of photoproduction experiments will be carried out at SLAC. In the first of these, the 1.6-GeV/c spectrometer will be used to study the photoproduction of strange particles at large angles. In production processes where one of the created particles recoils in the backward direction, the momentum of the recoil particle is typically 1 GeV/c or less, which is a good match to this spectrometer. Since these low values of momentum can be measured with high precision, it is possible to specify with considerable accuracy the "missing mass" that was created in the reaction. Thus, if a resonant state is being produced, it can be detected in this way.

The last series of photoproduction experiments presently planned for the SLAC program will be carried out in the 40-in. hydrogen bubble chamber which is expected to come into operation in the latter part of 1967.

Strong-interaction experiments

As noted at the start of this section, the creation and experimental use of beams of strongly interacting secondary particles is an important part of the research program at most accelerators. Several of the early experiments that have been completed at SLAC were designed to measure the yields of these particles at various angles and momenta. A specific purpose of this work was to specify the design parameters for the high-energy beam of charged secondaries that will be used with the 82-in. hydrogen bubble chamber which is being moved from the Lawrence Radiation Laboratory in Berkeley to SLAC in the summer of 1967. In more general terms, the results of these secondary yield experiments have been published so that the information will be available to physicists outside of SLAC who may be planning to prepare proposals for experiments on the SLAC accelerator.

Muon scattering

The existence of the muon, or mu meson, is an outstanding puzzle in high-energy physics because a whole series of experiments has failed to show any difference between this particle and the electron except that the former is about 200 times heavier and that each has a different associated neutrino. At SLAC, exploration of the muon will continue by comparing electron and muon scattering at high energies. At energies where there exists no detectable difference in scattering properties, the muon is inherently a better nucleon probe than the electron because it does not radiate much energy when accelerated. The calculation of the so-called "radiative" corrections of electron scattering is both difficult and tedious.

The muons will be scattered in a liquid hydrogen target, and their momenta will be measured to within 2% at 10 GeV/c by a large-volume magnet. The muon is identified by its range or lack of interaction in a thick-plate spark chamber and iron slab, and the elastic events can be isolated by looking at the recoil proton in an opposing spark chamber. The main limitation is the intensity of the muon beam, but at SLAC this is high enough for cross sections of several microbarns to be measured in a reasonable time. For example, some 100,000 inelastic events are expected in several hundred hours of running time.

New particle search

A search for new particles will be one of the first efforts at SLAC. According to the Bethe-Heitler theory of electromagnetism, any particle having either or both electric charge and magnetic moment can be created in pairs from the field quantum (photon). The cross section for this process falls inversely as the square of the mass, so that electron-positron pair production is by far the predominant process. However with SLAC intensities it is possible to see a

“long-lived” ($> 10^{-9}$ sec) beam particle in a background of 10^6 muons/particle. These may have escaped detection with proton accelerators because all experiments reported have concerned themselves with particles either made in strong interactions or decayed from such particles. If a new particle had only weak or electromagnetic interaction, it would not have been seen. Cosmic radiation, on the other hand, could contain such particles, but previous experiments would not have detected them in a ratio to muons as small as is possible in this experiment.

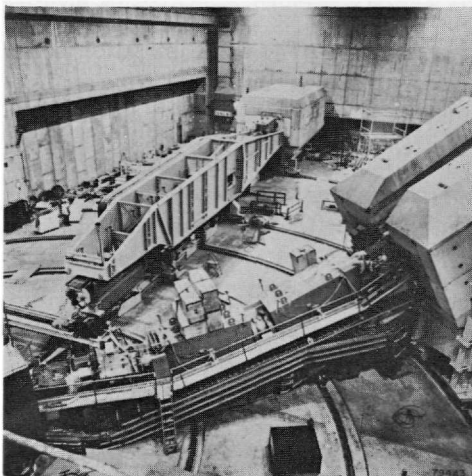
2-4 Initial research equipment (WTK)

In this section we give a brief description of the large experimental facilities (spectrometers, large-volume analyzing magnets, and bubble chambers) that have been built at SLAC. All this equipment is intended for general use by both SLAC and outside experimental groups. An idea of the size of these devices can be obtained from Figs. 2-1, 2-2, and 2-3.

Spectrometers

Three large magnetic spectrometers have been built for use in scattering and photoproduction experiments. The usual idea conveyed by the word “spectrometer” is perhaps inappropriate to the scale of these instruments, the largest of which is about 160 ft long and weighs 1700 tons. The three spectrometers are designed to complement each other in covering the momentum range up to 20 GeV/c and the angular range from 0° to 180° . The largest

Figure 2-1 The 8- and 20-GeV/c spectrometers.



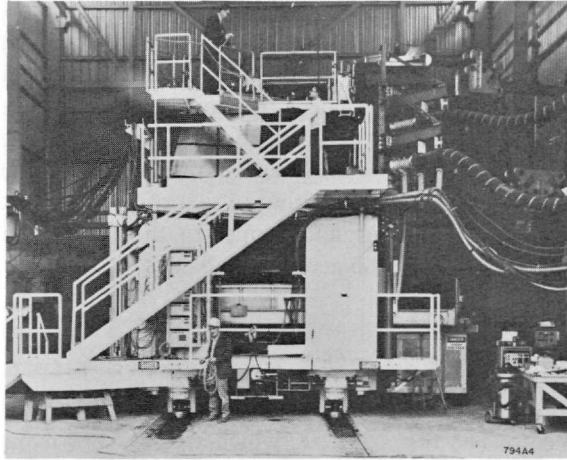
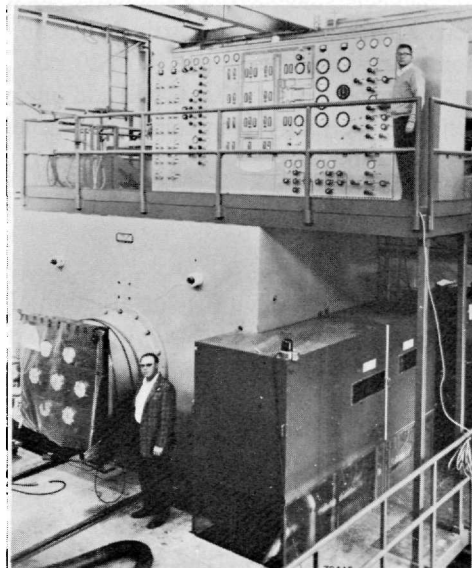


Figure 2-2 The 2-meter spark chamber magnet.

instrument can resolve momenta up to $20 \text{ GeV}/c$ (the maximum accelerator energy) and is intended to work the forward angles from 0° to about 20° in the laboratory frame of reference. The $8\text{-GeV}/c$ spectrometer will handle the middle range of angles from approximately 15° to 100° . The $1.6\text{-GeV}/c$, spectrometer will cover the backward angle range from about 90° to 180° .

Figure 2-3 The 40-in. hydrogen bubble chamber.



All three instruments are mounted on a common pivot point so that they can view a common target. The momentum resolution of each of the instruments is about 0.1%, and the angular resolution is about 3×10^{-4} radian. This precision is sufficient to allow the spectrometers to distinguish between elastic scattering events and those in which one or more pions are produced. Since the total solid angle and momentum acceptance of these instruments is much larger than the resolution that can be achieved, it will be common practice to use counter hodoscopes in the focal planes to resolve angles and momenta within the acceptance band.

Large analyzing magnets

Two large-volume magnets have been built for use in spark chamber experiments. The first of these, which weighs approximately 500 tons, has a pole diameter of 2 meters and can be assembled in several different configurations with gaps up to about 1 meter. The first use of this magnet will be in a photoproduction survey, where it will contain a very large streamer spark chamber, a device which permits stereophotography, has a rapid response time, and can be triggered by surrounding counters.

The second large-volume magnet has a pole diameter of 54 in. used in several configurations with gaps ranging up to about 3 ft. The first intended use of this magnet is with conventional spark chambers in an experiment to study the inelastic scattering of muons from protons.

Both of the large-volume magnets noted above are designed to permit a good deal of flexibility in setting up various field configurations. The use of movable struts and plugs simplifies access for spark chamber installation in the magnets, and provides suitable openings for stereo viewing of the chambers. Depending on the particular setup, these magnets can provide rather nonuniform fields of about 10 to 20 kG.

It is expected that SLAC will add one or two smaller magnets of this same general type to its complement of general use analyzing magnets during 1968 or 1969.

Bubble chambers

SLAC has undertaken the construction of a hydrogen (or deuterium) bubble chamber having a cylindrical volume 40 in. in diameter and 20 in. deep. It is a conventional chamber with a bellows-connected piston designed to pulse at 2 cycles/sec in a magnetic field of 20 kG. An early intended use of this chamber is in a series of photoproduction experiments in which the incoming photon beam, obtained from positron annihilation, will contain a preponderance of monochromatic photons.

The second bubble chamber is a modified version of the famous 72-in. chamber which has served so well at the Lawrence Radiation Laboratory.

The modifications, which are being carried out at Lawrence Radiation Laboratory, include extending the length of the chamber to 82 in., and increasing its cycling rate to 2 expansions/sec.

A point of interest in regard to bubble chambers at SLAC is the fact that a chamber may require very little scheduled running time. Since the accelerator delivers 360 pulses/sec, the 1 or 2 pulses/sec needed to feed a chamber can be switched, under favorable circumstances, to the chamber without noticeable effect on any other experiments that may be running.

References

- 1 For the general reader interested in pursuing this subject beyond the greatly simplified description given here, two recent books are especially recommended: C. N. Yang, *Elementary Particles*, Princeton Univ. Press, Princeton, New Jersey, 1961; and Kenneth W. Ford, *The World of Elementary Particles*, Ginn (Blaisdell), Boston, Massachusetts, 1963. Ford's book contains an extensive bibliography.
- 2 See the reports by J. Ballam and S. Drell, "Some Aspects of Target Area Design for the Proposed Stanford Two-Mile Linear Electron Accelerator," Rept. No. M-200, W. W. Hansen Laboratory of Physics, Stanford University, Stanford, California (Summer 1960).
- 3 Much of the information given in the remainder of this section has been adapted from Joseph Ballam, "SLAC: The Program," *Physics Today* (April 1967).

HISTORY AND DEVELOPMENT

D. W. Dupen

The development of linear accelerators at Stanford originated with the late W. W. Hansen's interest in x-ray problems in the mid-1930's. He sought an inexpensive way of obtaining high-voltage electrons for use in the production of x rays. The idea of a linear accelerator was an old one but required considerable advances in available techniques as well as a detailed understanding of the theory of the various components. Professor Hansen believed that the resonant-type accelerator held great promise because resonant cavities could be built with very low losses, making it possible to provide unusually high voltages with the consumption of only moderately high power. Nevertheless, in the late 1930's, the voltages of interest to the physicist could not be obtained by cavity methods even with the highest power available. The limitation on electron energy by the available RF power did not discourage Hansen in his aspirations toward higher energies. However, in 1938 and 1939, two events caused Hansen to pause in this work. The first was his participation with the Varian brothers in the invention and development of the klystron (which was destined to play an important role in the forthcoming war). The second event was Kerst's successful development of the betatron. Kerst's methods, so eminently successful, made it appear that the RF linear accelerator could not compete with the simple transformer action of the betatron, certainly not without finding unprecedented sources of power.

Technical advances during the course of the war indicated that a change in this situation might be imminent. The British development of the magnetron for radar demonstrated that new horizons of power generation were in sight.

At the end of the war, Hansen together with E. L. Ginzton and J. R. Woodyard reexamined earlier conclusions regarding the feasibility of linear accelerators. This group, among several others, recognized that the

war-developed magnetron made it practical to build linear electron accelerators in the range of several million electron volts using these available RF sources. However, it was also apparent that higher energies would require further developments in order to obtain powers in the range of several hundred megawatts.

3-1 Early developments at Stanford

In 1946, Woodyard¹ and Hansen began to explore methods of accelerating electrons using waveguide accelerator structures. Although the general concept was relatively simple, a great many details were in doubt, especially in regard to orbit stability. Equally critical was the problem of fabrication of large numbers of resonant cavities with sufficient accuracy and low loss. During 1946-47, Hansen aided by E. L. Chu, E. L. Ginzton, E. T. Jaynes, S. F. Kaisel, and W. R. Kennedy studied these problems. Hansen was able to demonstrate, both theoretically and practically, that the acceleration process was feasible.² In 1947, electrons were successfully accelerated in a machine known as the Stanford Mark I Accelerator which eventually became 12 ft long. This machine produced 6-MeV electrons when powered by 0.9 MW at 10-cm wavelength. A description of this accelerator was given by Kennedy³ and later on, after various improvements, by Becker and Caswell.⁴ (See Fig. 3-1.)

The early successes in acceleration of electrons at Stanford and elsewhere did not obscure the fact that sources with higher peak power were badly needed. With this in mind, and aided and encouraged by the Office of Naval Research, E. L. Ginzton and M. Chodorow began to explore possibilities of generating higher power. Being most familiar with the klystron approach, the Stanford group decided to use these tubes. Chodorow investigated the theory of operation of klystrons at relativistic velocities and found no fundamental obstacles to their operation in the multimewatt range. Assisted by K. L. Brown, A. L. Eldredge, A. E. Harrison, N. P. Hiestand, Jr.,

Figure 3-1 The original Mark I Electron Linear Accelerator photographed in the Stanford quadrangle and being held by, left to right, S. Kaisel, C. Carlson, W. Kennedy, and W. W. Hansen.



J. H. Jasberg, C. B. Jones, R. C. Messimer, R. B. Neal, I. R. Neilsen, J. C. Soderstrom, S. Sonkin, and others, Chodorow and Ginzton demonstrated the first successful high-power klystron in the spring of 1949.

Meanwhile in 1948 a proposal was submitted to the Office of Naval Research, presenting in considerable detail arguments in favor of a gigaelectron volt linear accelerator. This proposal, framed by Hansen, Ginzton, and Chodorow, was supported by the Office of Naval Research. The project obviously involved a considerable risk because no previous experience in generation of high RF power and in accelerating electrons to high energies was available.

In the period that followed, Hansen and Chu further developed the theory of the acceleration process and the theory of disk-loaded waveguides.⁵ W. W. Hansen proceeded to develop the detailed design of a gigaelectron volt machine. He was aided by many people, some of whom were responsible for major phases of this work.

E. L. Chu completed the theoretical work on many aspects of accelerator performance.⁶ R. F. Post constructed the prototype machine using components designed by Hansen and others and, eventually, obtained an energy of 35 MeV with a 12-ft accelerator, the Stanford Mark II.^{7,8} P. A. Pearson designed and developed power supplies, pulsers, trigger gaps, and pulse transformers suitable for a 1-GeV accelerator.⁹ Ginzton, Chodorow, Sonkin, and others developed successful high-power klystrons.¹⁰ Under the supervision of R. L. Kyhl, who was creatively assisted by F. W. Bunker, A. L. Eldredge, L. H. Franklin, W. S. Geisler, J. H. Jasberg, C. B. Jones, K. B. Mallory, R. B. Neal, and others, a complete accelerator system was planned and developed.

3-2 The Mark III 1-GeV Linear Accelerator

The construction of the 1-GeV accelerator (Stanford Mark III) began in the winter of 1949. The accelerating waveguide for the Mark III was constructed in 2 ft long subsections, each containing twenty-two cavities assembled from annular disks and 4-in. diameter tubing of selenium-copper. Five such subsections were then clamped together to form the 10-ft long accelerating waveguide sections. Each 10-ft section in the machine was to be fed by one klystron amplifier. All the klystrons were to be driven by a common magnetron oscillator.

The Mark III first operated on the night of November 30, 1950. At that time, a length of 30 ft of accelerator had been assembled, supplied by three klystrons. With each klystron providing an average of 8 MW of power, this assembly delivered an electron beam of about 75 MeV.

In the following months, the machine grew in 10-ft steps. The 4-in. diameter accelerator tube was supported on I-beams. These units were mounted on the floor of the long accelerator building. Concrete shielding blocks were piled along each side and across the top. The klystrons and their

pulse-control modulators were housed in oil baths and high-voltage cages, respectively, along one side of the resulting concrete bunker.

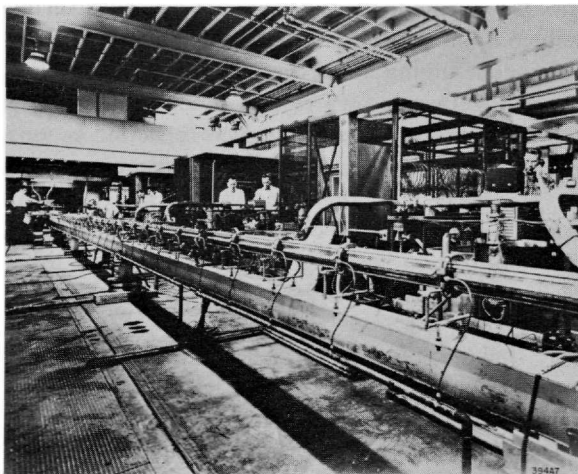
By April 6, 1951, the Mark III reached 80 ft in length and eight klystrons had been installed. On that date this arrangement delivered a beam of 180 MeV. During this time the klystrons were operating at no more than half their design value of 18.5 MW. The highest energy obtained with the 80-ft Mark III was about 200 MeV on January 14, 1952.

The accelerator was operated at the 80-ft length until May 8, 1952. At that date, it was disassembled. The used subsections were cleaned and assembly of the final 220-ft machine was begun. (See Fig. 3-2.)

By the end of November 1953, the Mark III had twenty-one 10-ft sections in place, but there were not yet enough reliably operating klystrons to power the entire machine. The maximum electron energy up to that time was 400 MeV with fourteen klystrons operating. At this time, Stanford Professor R. Hofstadter and his collaborators began their investigation of nuclear structure by means of electron scattering using the Mark III beam. By December 1955, the accelerator was operating routinely with a full complement of twenty-one klystrons to yield an energy of about 600 MeV.¹¹

Professor Hofstadter's electron scattering program was one of many kinds of nuclear research carried out in the experimental areas of the Mark III during this time. A high point for the Laboratory was the awarding of the 1961

Figure 3-2 The first sections of the Mark III Accelerator, as seen looking in the opposite direction to beam motion (looking toward the injector). The twisted waveguide delivers power from the klystrons to the accelerator tube which is supported by the I-beams. After construction, the accelerator and I-beams were surrounded by concrete shielding.



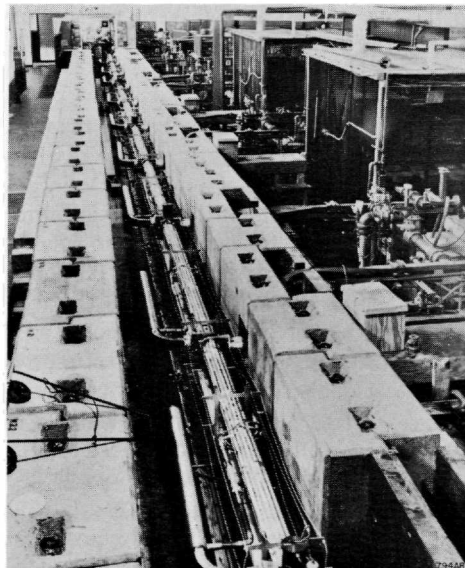
Nobel prize in physics to Professor Hofstadter “for his pioneering studies of electron scattering in atomic nuclei, and for his thereby achieved discoveries concerning the structure of the nucleons.”

By December 1957, a 90-ft extension of the Mark III Accelerator was under construction. This extension was completed by July 1960, and from this time on, routine operation at energies of 900 MeV was possible. One gigaelectron volt could be obtained if all thirty klystrons along the 300-ft machine were effective and well processed.

During the latter half of 1963, the Mark III was dismantled. New accelerator sections, produced to the improved design of those to go into the two-mile machine, replaced the original Mark III sections. (See Fig. 3-3.) By March 1964, the Mark III was producing electron beams up to 1.2 GeV. The High Energy Physics Laboratory continues to operate this accelerator.

A number of other electron accelerators have also been built by Stanford for medical and other applications. During the mid-1950's, Stanford constructed a 10-ft, 35-MeV accelerator for cancer therapy at Michael Reese Hospital in Chicago, a 20-ft, 60-MeV accelerator for cancer research at Argonne National Laboratory, and a 6-ft, 5-MeV accelerator for cancer therapy at Stanford University Hospital. These machines, powered by Stanford klystrons, are used to produce electrons or x rays by electron beam

Figure 3-3 The Mark III after replacement of its accelerator sections in 1964. In this photograph all that remained was to replace the concrete shielding blocks on top of the concrete shielding walls.



target bombardment. Many private industrial firms now specialize in building small accelerators of the Stanford design for medical research.

During the same period, Stanford built several other accelerators including two 3-ft, 2-MeV machines for radiation research, one of which was put into use at Oxford University, and a 6-ft, 5-MeV accelerator for medical research by the General Electric Company.

In 1954, with the support of the U.S. Atomic Energy Commission, Stanford started to build a 20-ft, 80-MeV accelerator. This machine, which became known as the Mark IV, was designed as a vehicle for improving accelerator components. However, it was also used at times for beta-ray cancer therapy. Under the direction of R. B. Neal, the Mark IV was invaluable in establishing many improved methods of design and construction of linear accelerators. In the early 1960's the Mark IV was used extensively testing prototype components for the two-mile accelerator. In 1964, after the big machine was well along in construction, the Mark IV was dismantled.

3-3 The beginning of the two-mile project

The immediate and resounding success of the Mark III in the early 1950's, both in operation and in application, started Stanford people thinking about a much larger accelerator.¹² Beginning in 1955, Stanford Professors, L. Schiff, R. Hofstadter, W. Panofsky, F. Bloch, and E. Ginzton met informally several times to discuss the possibilities of a "Multi-GeV" electron linear accelerator. This group decided that such a machine had good scientific justification and that the possibilities should be further investigated.

To this end, the first "Project M Meeting"* was held in the home of Professor Panofsky at 8:00 p.m. on April 10, 1956. In attendance, in addition to the five named above, were K. Mallory, W. Barber, K. Brown, R. Debs, R. Neal, R. Mozley, F. Pindar, S. Sonkin, and J. Jasberg. From the minutes of this meeting,

The purpose of this gathering, the first in a series of weekly meetings, was to discuss plans and form objectives which will ultimately lead to a proposal for the construction of a multi-GeV linear electron accelerator. The participation of the members of this group is entirely voluntary and on their own time as there are no funds available to support this program . . . should such a program materialize, it should be administratively distinct from the Hansen Laboratories and the Physics Department. Professor Ginzton has agreed to serve as Director of the proposed accelerator activity during the design and construction phases, and Professor Panofsky as Assistant Director for at least one year.† Professors Schiff and Hofstadter would act as consultants.

* Opinion is equally divided as to whether the letter M in this early unofficial name of the project stands for Multi-GeV or for Monster.

† As things turned out, Professor Panofsky soon became Deputy Director of Project M, a post he held until assuming the directorship late in 1961, after Professor Ginzton became chairman of the Board of Varian Associates following the death of Russell Varian.

The primary objective of the proposed large accelerator was declared to be basic physics research. There should be no security measures except to protect personnel and property, no classification and freely publishable results; the facilities should be available to qualified research visitors The following possible accelerator characteristics were listed to orient future thought: length, two miles; energy 15 GeV, expandable to 50 GeV

During 1956, much exploratory work was done by this study group* with the assistance of several other organizations. Detailed studies were made of the general problems that would be involved in the construction of such a machine. Special studies were carried out on beam dynamics, accelerator structures, and other systems and components. The Utah Construction Company and the Bechtel Corporation made voluntary independent studies of the site and tunnel problems, and submitted complete reports on their respective solutions. Technical specifications for many aspects of the project were generated. Planning and cost estimates were made for the construction and operation of a facility to design and build the huge number of klystrons which would be required. The University of California Radiation Laboratory (later the Lawrence Radiation Laboratory) provided financial and administrative information based on its experience in the operation of large accelerators. At Stanford, Professors C. Oglesby of Civil Engineering and B. Page of Geology provided civil engineering and site geology and other information.

3-4 Stanford's proposal

From these endeavors, a formal proposal for a two-mile accelerator resulted on April 18, 1957. This proposal was submitted by Stanford University President, J. E. Wallace Sterling, to the U.S. Atomic Energy Commission, to the National Science Foundation, and to the Office of the Secretary of Defense for Research and Engineering.

The proposal received consistent and impressive scientific support. The first formal endorsement of national significance came in 1958 when a panel convened by the National Science Foundation recommended that the project be initiated. Later in 1958, a joint panel drawn from the General Advisory Committee of the U.S. Atomic Energy Commission and from the President's Science Advisory Committee recommended the project. In 1960, the same joint panel, after updating its review of high-energy physics, strongly reiterated its support of the Stanford proposal. Hearings before the Joint Committee on Atomic Energy of the Congress were held in July and August 1959 and in April 1960.¹³

Two related investigations were carried out during the early planning days. One was for the selection of a suitable site. The other was for a mode

* During the year, the Project M Study Group was augmented by the addition of F. Bunker, M. Chodorow, E. Chu, D. Dedrick, L. Franklin, C. Jones, J. McIntyre, C. Olson, and H. Soderstrom.

of construction which would result in an accelerator housing shielded by 25 ft of earth.

Several methods of construction of a housing were considered. The general requirements were for two structures, each 2 miles long, one to house the accelerator itself and one to contain the klystrons and associated auxiliary equipment. The two structures were to be separated from each other by 25 ft of earth shielding. This parallel configuration was required so that equipment could be operated and maintained by personnel in one structure while the beam was on in the accelerator housed in the other structure. All equipment connections between the two structures were to be made via interconnecting penetrations in the earth shield at somewhat regular intervals along the entire machine.

One method considered was to bore two parallel tunnels through a hilly area. Another was the boring of one tunnel for the accelerator housing with the construction of a parallel building on the surface of the ground. A third plan, the one finally adopted, was to excavate a trench to the depth of the floor of the proposed accelerator housing and to construct that housing in the open trench. Then some of the excavated earth was to be dumped back into the trench to cover the completed housing. This fill was to be compacted, layer by layer, until the earth shielding was 25 ft thick. Finally, the second structure was to be built on top of this fill, parallel to, and directly over the buried accelerator housing.

Several sites were investigated, including three on Stanford University property and three on shore lands around San Francisco Bay. Because of the requirement for a bedrock foundation, the selection was narrowed to the Stanford sites. Economic considerations eventually led to the final selection of the "Sand Hill" site.

3-5 Congressional authorization

In late 1960, under congressional authorization, a contract was negotiated between the U.S. Atomic Energy Commission and the Board of Trustees of Stanford University. This contract called for Stanford to perform initial engineering and design of the accelerator, at an estimated cost of \$3,000,000. Under this contract, a building on the Stanford campus to house the initial staff was planned, further studies and design work were carried out, and Stanford entered into contract to acquire architect-engineer-management services for the project. The contractor selected for this work was a joint venture known as Aetron-Blume-Atkinson (ABA). This joint venture comprised people from the Aetron Division of Aerojet-General Corporation, John A. Blume and Associates, Engineers, and the Guy F. Atkinson Construction Company. ABA began work on architectural design and planning for site and building construction.

The Congress on September 15, 1961 authorized the AEC to enter into negotiations with Stanford University for the ultimate realization of the two-

mile accelerator. In this action the amount of \$114,000,000 was authorized for design and construction. Finally, in April 1962, a contract between Stanford and the U.S. Atomic Energy Commission was executed.

Although the 5 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 5-year preconstruction 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 ft in length, and the entire accelerator comprised forty such sectors. It was felt that it might be necessary to operate the klystrons initially at the conservative level of 6 MW peak in order to obtain a tenable life (2000 hours). During the preconstruction period the requirement for the initial complement of tubes was reduced to 240, organized into thirty sectors, each of 333-ft length. The corresponding beam energy for the same klystron output range became 10–20 GeV. The RF pulse length of the klystrons was increased from 2.0 to 2.5 μ sec. This 25% increase resulted in a 43% increase in beam duty cycle. 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.^{14–17}

In general terms the contract executed in 1962 between Stanford and the U.S. Atomic Energy Commission called for the University to design and construct the two-mile accelerator. Besides authorizing \$114,000,000 for design and construction of the machine, it also included provisions for spending up to \$18,000,000 in preconstruction research and development. This latter sum was used for investigation of alternative methods of various design and fabrication techniques, as well as for component testing and development on the small Mark IV accelerator.

3-6 Under way

Ground breaking at the site about 2 miles west of the Stanford campus took place in July 1962. While the site was being prepared, the buildings constructed, and the underground accelerator housing built, fabrication of the

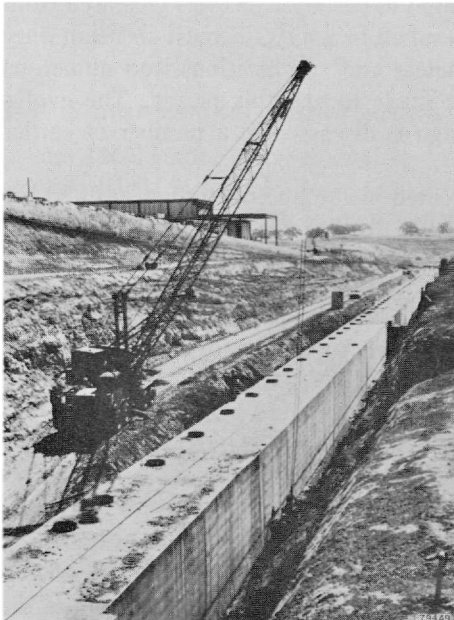
10-ft accelerator sections was begun, first in temporary quarters on the Stanford campus, then eventually in the special fabrication facility at the site.

At about the same time, SLAC's Scientific Policy Committee, chaired at that time by Professor Roger Hildebrand of the University of Chicago, held its first meeting.

By the end of 1963, two office and laboratory buildings had been built and occupied, the entire 2-mile trench had been excavated, the first 2000 ft of accelerator housing had been constructed, and filling operations had begun. (See Fig. 3-4.) In July 1964, the accelerator housing was finished and the installation of accelerator sections was begun. In the same month, the first 1000 ft of above-ground, klystron gallery was completed.

During January 1965, enough of the accelerator had been installed in the housing to permit acceleration of a 1.5-GeV electron beam through the first 666 ft. In the spring of 1965, the staff numbered 1100 people, who by then were all located on the site. In October of that year, the first "Users Conference" was held at SLAC, attended by 150 people interested in using the accelerator when completed. Installation of accelerator sections proceeded at a rate of about 40 ft/day. By the end of 1965, the entire accelerator had been installed.

Figure 3-4 SLAC accelerator housing construction continued eastward while western portions were being covered with compacted fill.



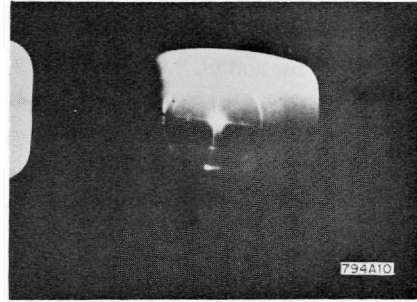


Figure 3-5 Two-mile beam centered on Cerenkov cell PR 2 (May 21, 1966).

In February 1966, the Program Advisory Committee met at SLAC to review experimental proposals and to approve and schedule the experiments to be performed at SLAC after achievement of the beam. On May 21, 1966 the entire accelerator was operated, and a 10-GeV beam was delivered to the beam switchyard.¹⁸ (See Fig. 3-5.) Two weeks later, the beam energy had been increased to 18.4 GeV.

During the remainder of 1966, a second “Users Conference” was held at SLAC (June 22), positrons were accelerated through a portion of the machine (July 13), the electron beam was delivered through one of the end stations to the beam dump at the eastern extremity of the site (September 20), interlaced beams of different energies were delivered to the beam switchyard (October 17), and experiments with the beam began. The first experiments, carried out in November and December of 1966, were primarily concerned with measuring the intensity of the secondary particle beams produced.^{19–21}

In January 1967, a beam energy of 20.16 GeV was achieved and the full research program was underway. It was just 10 years since the Stanford proposal had first been drafted. The Stanford Linear Accelerator Center was operational, completed on schedule, and within the originally authorized budget.

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