



STANFORD LINEAR ACCELERATOR CENTER

A NATIONAL HISTORIC ENGINEERING LANDMARK

DESIGNATED 1984, STANFORD CALIFORNIA

*THE AMERICAN SOCIETY OF
MECHANICAL ENGINEERS*

*THE INSTITUTE OF ELECTRICAL
AND ELECTRONICS ENGINEERS —
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The Stanford Linear Accelerator Center is a national laboratory for subatomic physics, the study of the smallest building blocks of matter. The two-mile-long accelerator starts near the top in this aerial photograph and ends in the research area at the bottom.

ENGINEERING THE SUBATOMIC MACHINES

Man's wonder at things too small to grasp is as old as his fascination with things too far to reach. The ancient Greeks looked up to name constellations and chart planets, but they also looked inward to imagine tiny and indivisible atoms at the heart of all matter.

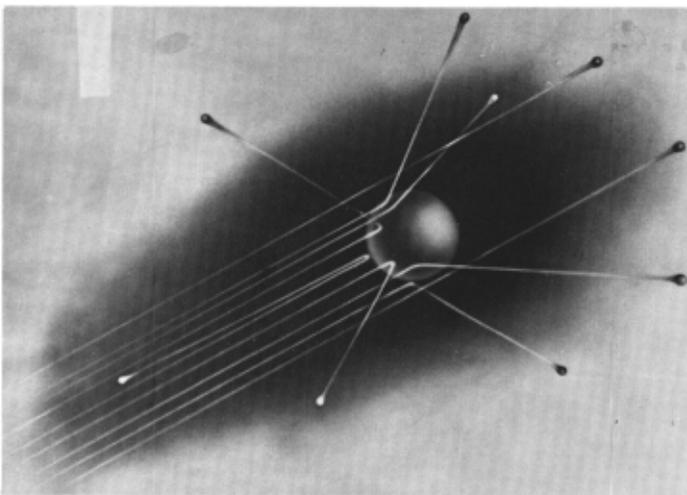
Imagination inspires science, but measurement must give it substance. The sciences of both the outer and inner worlds waited for machines to bring them closer. Lenses assembled into telescopes marked the beginning of modern astronomy. Rearranging those lenses produced microscopes, and the unfolding of the world began.

While advances in all the basic sciences have followed the development of instruments of exploration and measurement, the fundamental role of engineering and technology in science is particularly evident in subatomic physics, the study of how the world is put together.

At the Stanford Linear Accelerator Center, *SLAC*, beams of electrons are accelerated to the very high energy needed to explore the structure of matter at its very smallest and simplest. The machines which make it possible to produce and control these beams have made *SLAC* an engineering landmark.

EXPLORING THE SUBATOMIC WORLD

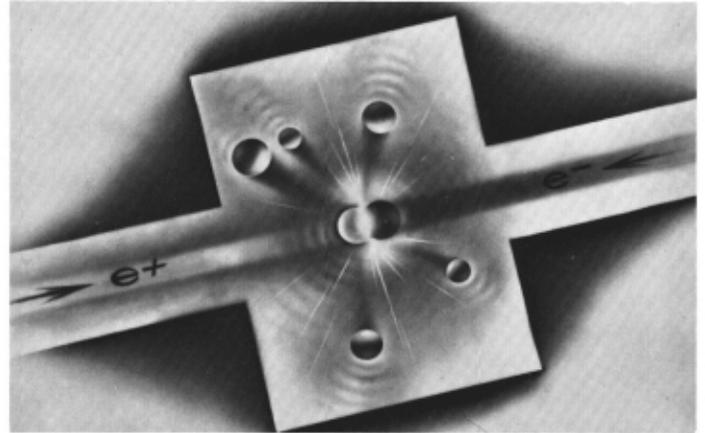
The fundamental particles and forces of nature have been explored in two kinds of experiments. In the first, a beam of electrons is shot at a more complicated object like a proton, as shown in this sketch.



The pattern produced by the scattered electrons is something like an x-ray picture of what is inside the proton.

In the second kind of experiment, an electron collides head-on with its antimatter equivalent, the

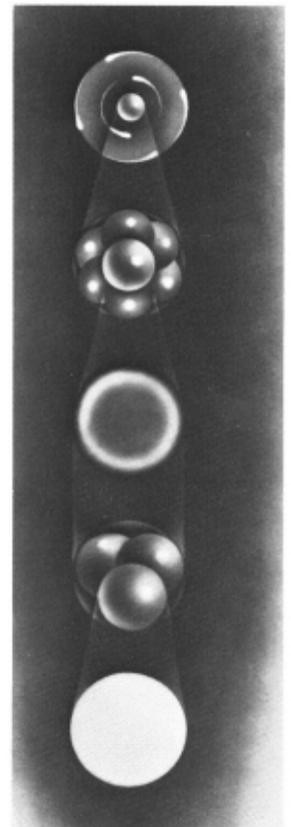
positron. The two particles disappear in a flash of energy in which new particles are created, as shown here.



WHEELS WITHIN WHEELS

The basic idea of the atomic model is that matter is made of simple pieces simply held together. The search for this basic construction has led to a series of discoveries in which simple pieces turn out to be built of still simpler, and smaller, pieces. The progression is shown in the five stages of this figure starting at the top with the smallest quantity of a chemical element, the atom.

The sketch of the atom shows that it is composed of electrons circling a larger object. This central nucleus is magnified in the next step, which shows a tightly packed group of smaller particles, called neutrons and protons. The middle stage of the figure shows an individual neutron or proton as a fuzzy sphere, ready for a closer look. This came in the late 1960s when experiments at *SLAC* showed that the proton and neutron were composed of smaller objects. The fourth enlargement in the sketch shows these particles, called quarks. The blank circle in the final enlargement is a statement of uncertainty about the nature of quarks. For the moment the quark, like the electron, seems to be an ultimate particle.



FAMILIES OF PARTICLES

The idea of quarks explained many complicated phenomena in a straightforward way. Eventually, however, problems began to crop up, both in theoretical models and other experiments. Something appeared to be missing.

Within a decade, another experiment at *SLAC* found the problem. Colliding-beam experiments in the mid 1970s uncovered both a new kind of quark and another particle very similar to the electron. This work, together with discoveries at other laboratories, has led to the present picture of three complete ‘generations’ of the quark and electron families. Only the first generation seems to be directly involved in ordinary matter, and the additional particles are parts of an important puzzle.

STICKING PARTICLES TOGETHER

Quarks and electrons are only half the story; three forces — called the electric, the strong, and the weak — are needed to build up matter from the particles. The electric force, which is familiar in the everyday world, keeps the electrons circling the positive nucleus. The strong force keeps quarks together to make up protons and neutrons. The weak force allows changes within the quark and electron families, such as one kind of quark changing to another.

This is the idea, but it does not explain very much about how those forces work. In the subatomic world, a force is produced by another kind of particle which travels between two particles of matter. In the illustration below, the exchange of a particle-of-force causes two passing particles to repel each other.



These force particles are incorporated in theories that may intimately relate the three subatomic forces. One particularly promising step involves the electric and the weak force. In this model the two forces are basically the same but are carried by different particles. The electric force is carried by the massless photon (familiar as light and x-rays), while the weak force is carried by particles, called the *W* and *Z*, which are nearly 100 times heavier than the proton.

Since it is much harder for two particles to exchange the heavy *Z* than a photon, the weak force is indeed much weaker than the electric force. Nevertheless, since the weak and electric forces are so similar in behavior, the effect of the weak force should show up in electron-scattering experiments. An exquisitely sensitive experiment at *SLAC* detected this slight effect in 1978, confirming this part of the theory.

The *W* and *Z* particles, which have been recently discovered in experiments at the European laboratory *CERN*, are the key to understanding the connection between these two forces. A new kind of collider now being built at *SLAC* will begin to produce thousands of *Z* particles per day at the end of 1986.

BUILDING THE MACHINES

Just what does it take to explore this subatomic world of small objects and exotic forces? How do the engineers, who live in a larger world with partial tools, go about building these machines and experiments?

The extension of microscopy to ever smaller scales requires probes that are smaller than the specimen. A basic principal of physics assigns any particle, such as an electron, an apparent size that depends on its energy; the higher the energy, the smaller its size. This intrinsic connection between size and energy sets the primary requirement for subatomic experiments: beams of very high energy. But there is another, related problem.

As the distance scale decreases it becomes more difficult to get two particles to collide, and enormous numbers of electrons are required to have a chance at one good collision. Not only must the beams be of very high energy, they must also be very intense.

There is a third feature to subatomic experiments, one which runs counter to the need for high energy and high intensity. The individual subatomic collisions themselves involve minuscule amounts of energy, yet the features of these individual events must be precisely measured. This requires instruments sensitive to the passage of a single subatomic particle.

Thus, the job is to accelerate an intense beam of electrons to very high energy, direct this beam on a target or against another beam, and then detect the particles which are produced. Some of the machines and devices which do this are described next. These unique devices have required the application of several technologies involving high vacuum, low temperatures, high-speed electronics, precision small-scale mechanical fabrication, computation, special magnets, and unconventional materials. The success of the engineers in building these machines has helped make *SLAC* a world leader in subatomic research.

THE TWO-MILE LINEAR ACCELERATOR

The basic research tool at *SLAC* is an intense beam of electrons that have been accelerated by an electric field equivalent to 30 billion volts, making this the most powerful electron beam in the world.

The two-mile linear accelerator produces this field using high-power microwaves traveling through an evacuated waveguide. Electrons injected into one end of this pipe are continuously accelerated by this traveling field to very high energies.

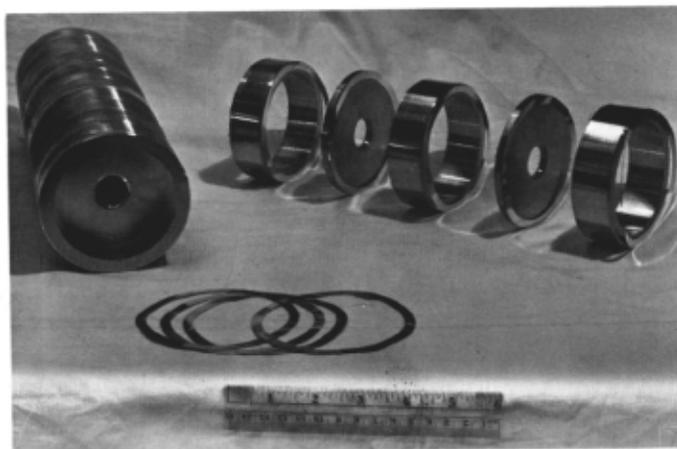
Although the principle is straightforward, the application is not. The engineering problems included manufacturing a thousand sections of precision copper waveguide, aligning these sections over a two-mile length, producing high-power pulsed microwaves, and safely handling the intense high-energy beam of electrons.

The accelerating waveguide, which is basically a long conducting tube about four inches in diameter, was assembled from cylinders and disks that formed individual microwave cavities as shown in the photograph at right.

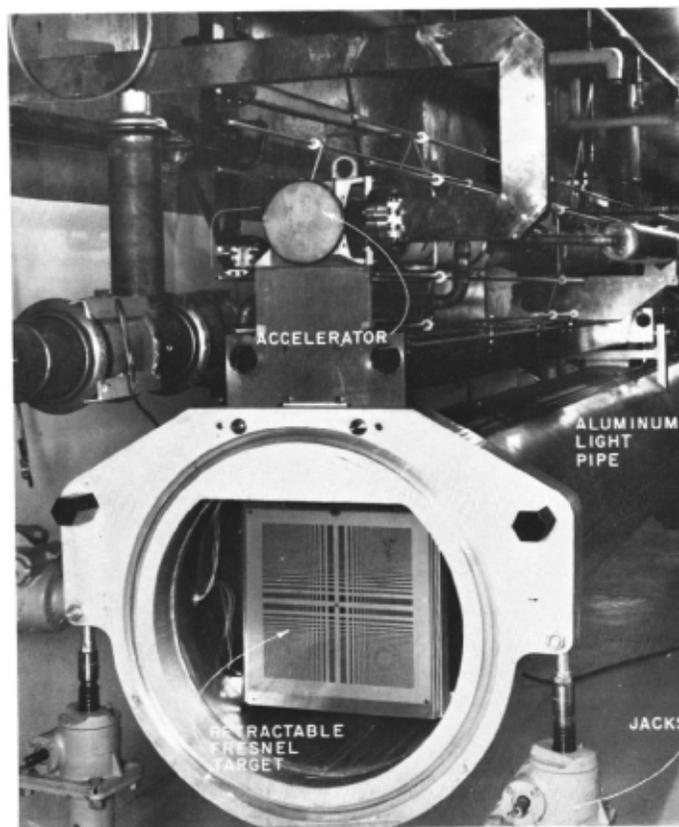
These cavities, made of high-purity copper, were machined to a precision of about two ten-thousandths of an inch and then brazed in a hydrogen furnace into ten-foot-long sections. Each cavity was then 'tuned' by slightly deforming the outside using hydraulic rams. In the complete accelerator there are nearly 100,000 of these cavities, each brazed to hold high vacuum. This operation required new techniques for mass production to very high standards.

If any section of the accelerator is out of line, the electromagnetic fields produced in the walls by the passing beam can severely limit the intensity. Controlling this 'beam breakup' effect required precision alignment of the two miles of accelerator. This was solved by mounting four ten-foot accelerator sections on one large aluminum pipe and aligning these four sections with an optical transit in the laboratory. These 40-foot-long sections were then transported into the underground tunnel of the accelerator and connected together.

Fresnel targets, which were built in the end of each 40-foot section, intercepted a laser beam traveling down the center of the pipe. Each 40-foot section was then aligned separately using its own jacking screws. Using this method the accelerator was aligned to be straight within twenty-thousandths of an inch over its two-mile length.



The components of the accelerator cavities, rings of brazing material, and a small assembled section. There are nearly 200,000 individual pieces in the two-mile long linear accelerator.



A short section of the linear accelerator and support in the underground tunnel. The rectangular waveguide near the top brings in microwave power.

MAGNETIC SPECTROMETERS

SLAC has many different kinds of experimental apparatus which use the direct electron beam or other particle beams produced from it. Some of the most important experiments at *SLAC* measure precisely the angle and energy of electrons scattered from a target in the primary electron beam. Experiments with these instruments in the late 1960s showed that the proton is composed of smaller individual particles, now identified as quarks.

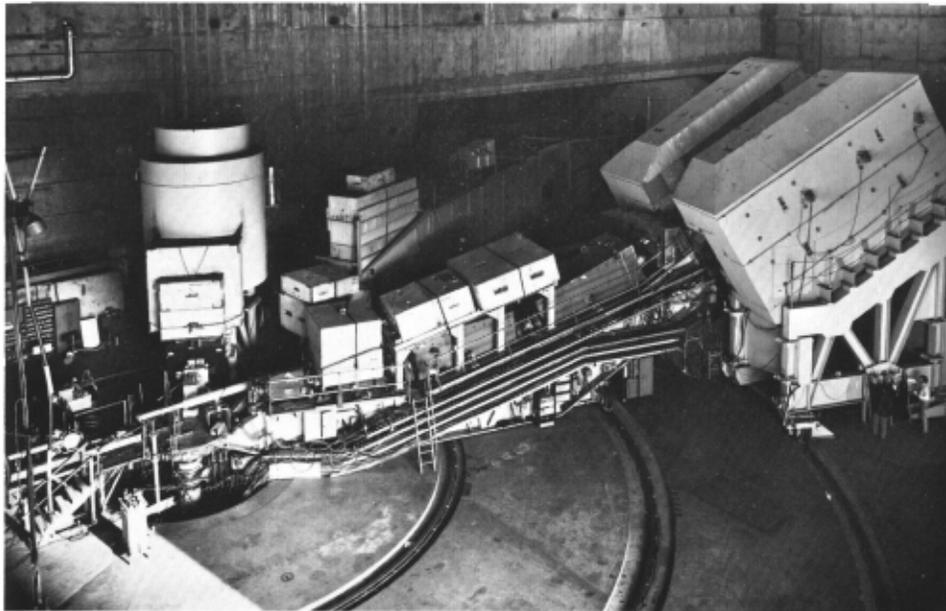
The traditional way to measure a particle's energy is by deflecting it with a magnetic field and measuring the effect with a sensitive detector of charged particles. The same scheme is used at these very high energies, but the instruments are of vastly different scale.

The sensitive instruments which detect the electrons must be shielded from the background radiation of the primary beam by massive amounts of concrete and lead. Large bending and focusing electromagnets are required to deflect the beam enough to make precise measurements at such high energy. In order to measure energies to the required accuracy of one part in a thousand, the magnets must be aligned to five thousandths of an inch on the carriage.

The entire spectrometer is pivoted about the target and must roll smoothly, reproducibly, and quickly to desired angles within a hundredth of a degree.

The conflicting requirements of precision and size have been met by three spectrometers covering different ranges of angles and energy. The mid-sized spectrometer, shown in the foreground of the photograph below, is nearly 100 feet long and weighs 500 tons.

The ideal target for these experiments would be a collection of protons, packed densely enough to scatter a reasonable fraction of the electrons in the beam. Liquid hydrogen has the right composition and density, but it must be kept at about 250 degrees below zero Centigrade. Such cryogenic liquids are normally stored in multiwalled, heavily insulated containers, but in these targets the intense electron beam must pass through without encountering any significant material, and the scattered electrons must be similarly unimpeded to avoid measurement errors. The designers of the liquid-hydrogen targets at *SLAC* solved problems of cryogenics, thin windows, safety, and remote control.



A view of the three magnetic spectrometers in their acre-sized shielded building. These three instruments swivel about the common pivot at the left. A beam of high-energy electrons enters from lower left and passes through a target of liquid hydrogen on the pivot (not in place in the picture). Individual electrons scatter from protons in the target and emerge at large angles and with reduced energy. These three instruments detect and measure electrons over different ranges of angle and energy. The spectrometer in the foreground weighs about 500 tons and is nearly 100 feet long.

COLLIDING-BEAM MACHINES

One of the most important tools in subatomic experimental physics is the storage ring, in which an electron beam collides with a similar beam of positrons, the antimatter equivalent of electrons. These collisions, or annihilations, probe subatomic matter much more deeply than can be done by directing a single beam onto a complex target. One of the most productive of these machines, *SPEAR*, was built at *SLAC* in 1972. In 1974 an experiment at this machine uncovered a completely new kind of quark, now called 'charm.' One year later an unexpected new particle very similar to the electron was found.

Positrons are produced by directing the primary electron beam into a heavy target about one third of the way down the accelerator. The rest of the machine is adjusted to accelerate these positively charged particles to high energy. After leaving the linear accelerator, electrons and positrons are injected in opposite directions into a common ring in which 142 magnets guide the beams around the thousand foot circumference. These bunched beams cross through each other at two places, called interaction regions, containing the experimental apparatus.

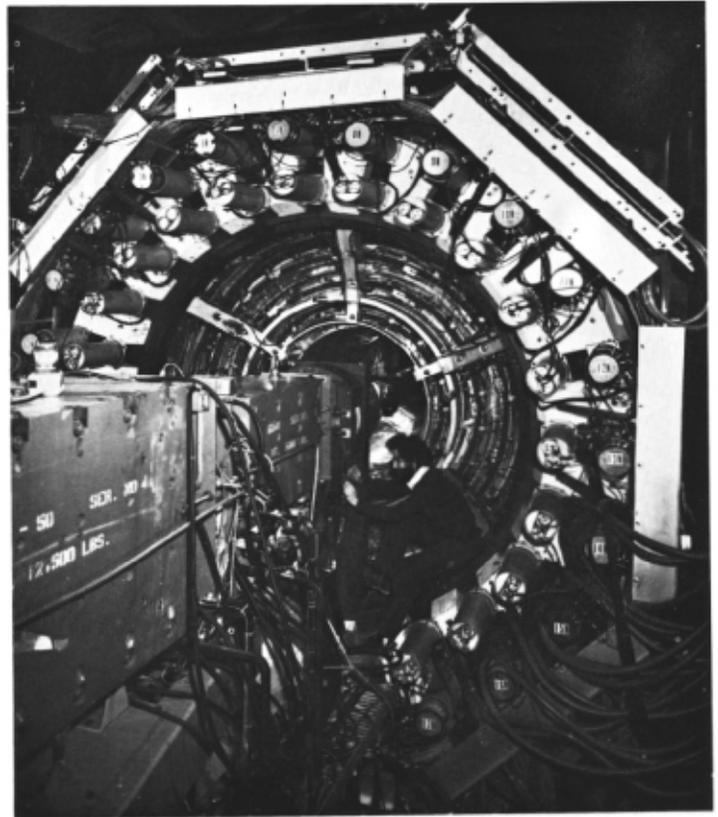
Experiments require that the beams circulate undisturbed for hours at a time, corresponding to about ten billion trips around the ring. This requires very tight tolerances on the magnets, stable power supplies, and a vacuum equivalent to a millionth of a millionth of one atmosphere.

The experiments which use the colliding beams present their own special problems. Head-on collisions between particles of equal energy produce many new particles which fly out in all directions, and experiments must identify and measure as many of these as possible. The experimental equipment must surround the collision point completely instead of concentrating on a particular direction. The magnetic field required to measure particle energies must be solenoidal and along the beam direction to avoid interfering with the circulating beams. The space inside and outside the large magnet coil is filled with the various kinds of particle detectors.

The Mark I detector illustrated at right was one of the first 'general-purpose' instruments built for storage rings. This device, built jointly by *SLAC* and the Lawrence Berkeley Laboratory, weighed about 500 tons and had a magnetic field volume of about one thousand cubic feet.

A successful collision produces hundreds of separate electronic signals, which describe the path and other characteristics of the particles in the event. This information must be partially sorted in less than a microsecond to decide before another collision whether this is an interesting event to record for later analysis. Online computers and special fast electronics make these decisions, record the data, and monitor the operation of the many components of the experiment.

Analyzing the data produced in experiments of this kind required the development of sophisticated programs for complex pattern recognition. Even very large commercial computer systems are nearly overwhelmed by this work and specialized small computers have been developed to preprocess data.



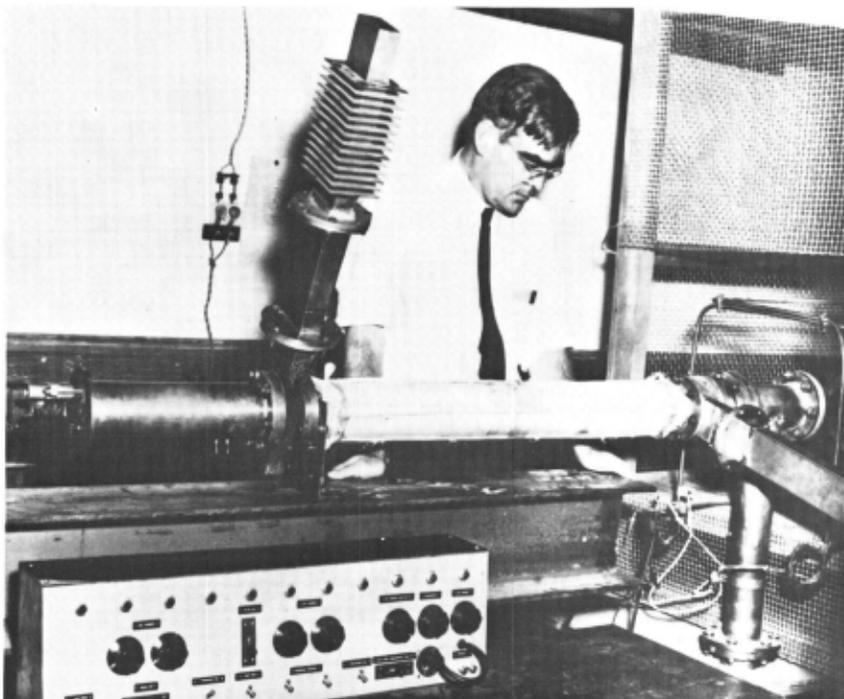
The Mark I detector at the SPEAR storage ring. Two of the magnets of the ring are visible in the left foreground. The physicist is resting against the magnet coil which surrounds one component of the detector.

SLAC — A BRIEF HISTORY

Experiments to make high-energy beams of charged particles for subatomic physics began early in this century and were carried on in several laboratories and universities. Stanford joined this search nearly fifty years ago when W.W. Hansen began to look for new ways to accelerate electrons. This work eventually produced the twelve-foot linear electron accelerator in the photograph below.

Encouraged by the success of this device, the Stanford researchers proposed a new machine, some thirty times larger, which would accelerate electrons to an energy equivalent to one billion volts. This 300-foot-long machine, named the Mark III, was funded by the Office of Naval Research. It began operation in 1950 with a first stage of 30 feet and was increased in several steps to full size and energy. The Mark III was used in frontier physics research for a great many years at Stanford University.

In 1956 physicists began planning for the next machine, proposing another jump of thirty in size and energy to a machine nearly two miles long. In 1961 a contract between Stanford University and the Atomic Energy Commission established the Stanford Linear Accelerator Center, *SLAC*. The laboratory, built on a new site near the university, was to be operated by Stanford as a national facility for subatomic research. On May 21, 1966, the first beam was delivered to the research area, and the experimental program began.



Another development in the late 1950s at Stanford considered a new way of using high-energy beams, in which one beam collided with an opposing beam instead of striking a heavy target. Physicists from Princeton and Stanford built a machine, called a storage ring, in which two beams of high-energy electrons from the Mark III accelerator collided. The first experimental work was begun with this machine in 1962.

The advantage of the storage ring could be considerably enhanced if the two beams were oppositely charged. In 1961 design began on a storage ring at *SLAC* that would collide positrons and electrons. In 1970 construction began on this machine, named *SPEAR*, and the first beams were collided in April 1972.

While construction was under way on *SPEAR*, design studies began on the next machine. This new ring, named *PEP*, was a joint undertaking of *SLAC* and the Lawrence Berkeley Laboratory of the University of California, and was funded by the US Department of Energy. Construction began in 1976 and colliding beams were obtained in 1980. *PEP*, which is nearly one and a half miles in circumference, is in a tunnel located underneath the circular road surrounding the research area at the bottom of the photograph on the cover.

A new project, called the *SLC* for *SLAC* Linear Collider, was approved in 1983. The new tunnel required for this machine is about the same size as the *PEP* ring. When completed in late 1986, this addition will extend the physics reach of the laboratory by about three times, putting it squarely in the region where the simplification of the subatomic forces will begin to emerge. At the same time this new machine will test a completely new idea in colliding beams, one which will make possible the continuation of the search to still higher energies.

Professor W. W. Hansen with his first operating linear accelerator. This 12-foot-long machine, was running at Stanford University in 1947 and is the ancestor of the two-mile accelerator at SLAC.

ACKNOWLEDGEMENTS

The Stanford Linear Accelerator Center is the 67th National Mechanical Engineering Landmark to be designated since the *ASME* program began in 1973. In addition, sixteen International and seven Regional Landmarks have been recognized. Each represents a progressive step in the evolution of mechanical engineering, and each reflects its influence on society, either in its immediate locale, nationwide, or throughout the world.

The landmarks program illuminates our technological heritage and serves to encourage the preservation of the physical remains of historically important works. It provides an annotated roster for engineers, students, educators, historians, and travelers and helps establish persistent reminders of where we have been and where we are going along the divergent paths of discovery.

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The *ASME* Santa Clara Valley Section gratefully acknowledges the assistance of all who cooperated on the landmark designation of the Stanford Linear Accelerator Center, particularly the staff at the laboratory.

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The *IEEE* San Francisco Bay Area Council is pleased to co-sponsor the designation of the Stanford Linear Accelerator Center as a National Historic Engineering Landmark and salutes those who have made this award possible and those who have earned this honor.

The Stanford Linear Accelerator Center, *SLAC*, is a national laboratory for basic research in high-energy physics. Its facilities are used by scientists from universities and other laboratories in this country and abroad. Stanford University operates *SLAC* under contract with the US Department of Energy through the Department's San Francisco Operations Office in Oakland.

This brochure was prepared for the engineering societies as a special issue of the laboratory's newsletter, the *Beam Line*, Special Issue Number 5, February 1984. Edited by W.W. Ash and H.A. Weidner; graphics by W. Zawojski.