Deeper and Deeper into the Atom

Step by step over the last three decades, Stanford physicists have devised larger and more powerful machines in pursuit of the simplest particles of matter.

Deep within the rolling ground of the Stanford Linear Accelerator Center, revolutionary research in elementary particle physics is taking place. First, a beam of electrons and a following beam of their antiparticles, the positrons, are accelerated to nearly the speed of light down a slender two-mile-long copper tube. The two beams are then circulated in counter-rotating directions in a vacuum storage ring more than a mile in circumference. When giant magnets cause the racing beams to meet head-on, some of the opposing particles collide with and annihilate each other in infinitesimally small fireballs of pure electromagnetic energy that is hotter and more densely concentrated than almost anything else known in the universe. This concentrated energy instantly rematerializes into showers of subnuclear particles whose properties are measured and recorded by huge electronic detectors.

The storage ring, called PEP (Positron Electron Project), is new. Parts of it were first tested late in 1979. The two-mile accelerator, in terms of the fast-moving world of high-energy physics, is old. It has been operating with great success since 1966. Hooked in tandem, PEP and the accelerator are expected to advance the new age of quantum dynamics, perhaps providing a key step forward in the search begun by Einstein for a single set of equations to explain all of nature's basic forces.

PEP is a big brother of SPEAR (Stanford Positron Electron Asymmetric Ring), a colliding beam facility ten times smaller, which began operation in 1972. SPEAR really started the revolution. A team of physicists from SLAC and the University of California's Lawrence Berkeley Laboratory used the SPEAR ring to discover in November 1974 a wholly new and unsuspected family of subnuclear particles, the psions, which opened a view of the structure of matter more fundamental than ever seen before. The finding set off an epidemic of excitement among those working in the field.

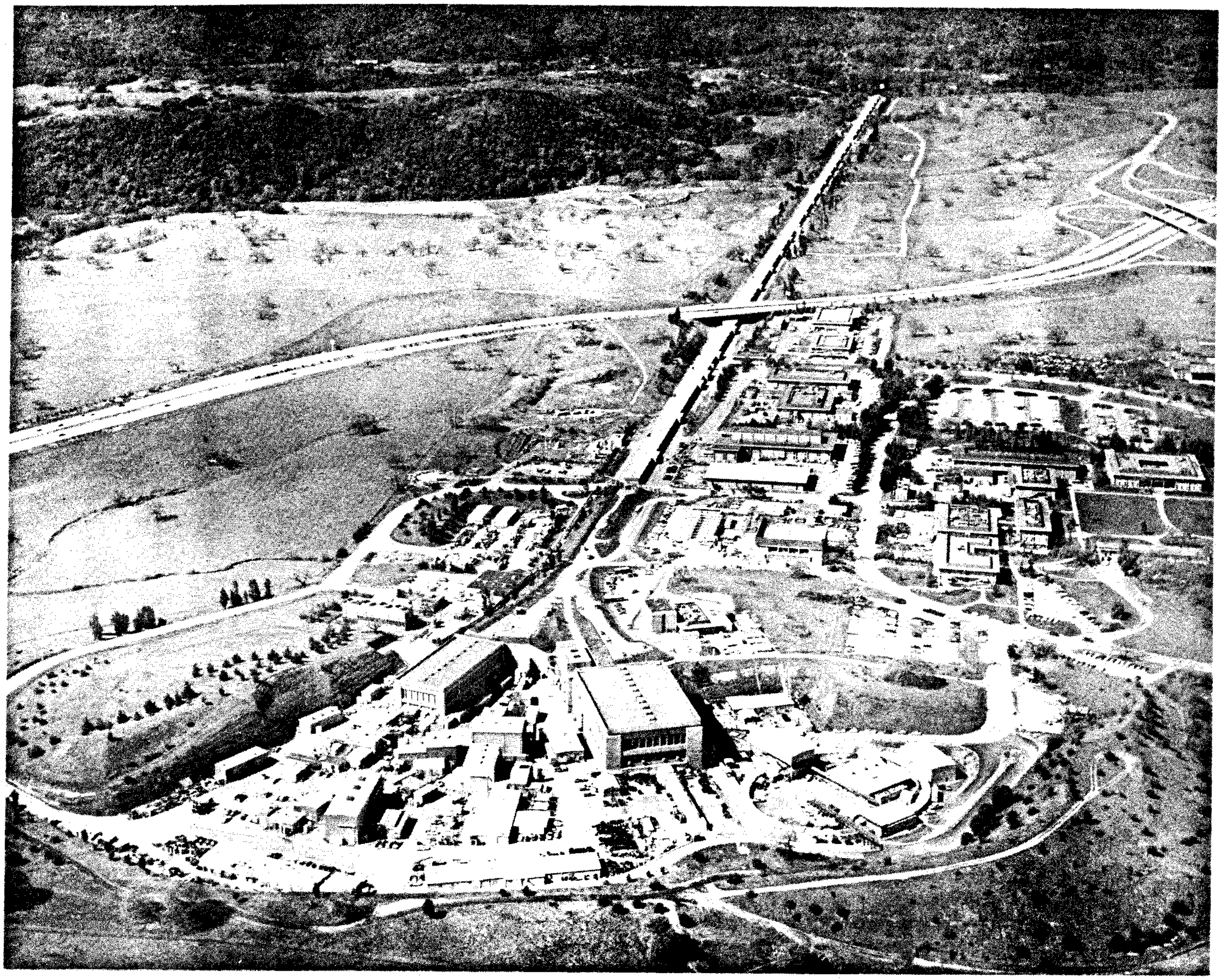
SLAC's Professor Burton Richter, head of the SPEAR experimental group, spent more than ten years on the design, funding, and construction of SPEAR. For his part in the discovery of the first psi particle, he shared the 1976 Nobel Prize for physics. The discovery "has changed the work-style of laboratories throughout the world," according to a spokesman for the Swedish Royal Academy, which awards the Nobel Prize. "A new field of research has been opened."

If SPEAR is so good, why PEP?

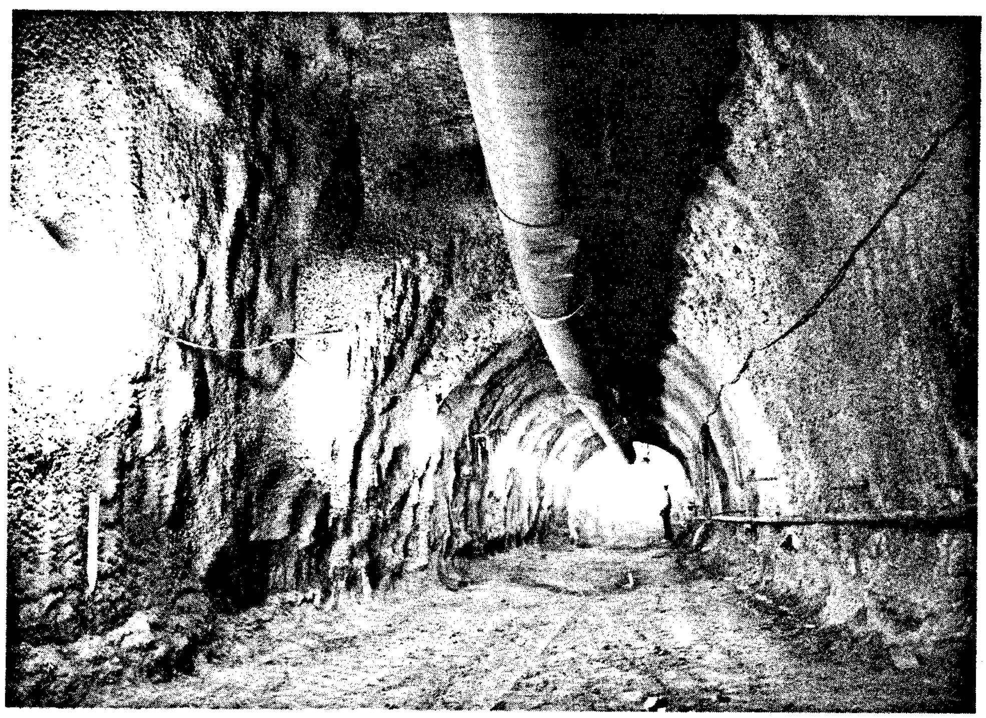
PEP exists because, as with most major scientific discoveries, SPEAR's findings raised almost as many questions as they answered. The basic puzzles remain: What is the nature of matter at its simplest level? What are the fundamental particles of matter, and how do they interact? The answers require higher interaction energies, and PEP will provide more than four times the energy of SPEAR.

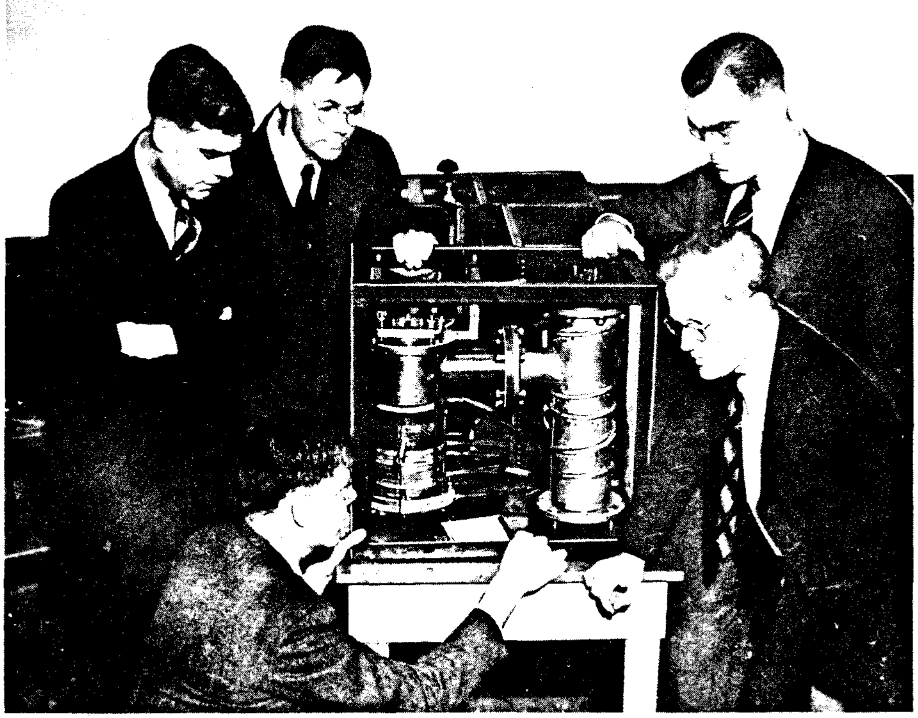
"In high-energy physics you have to have bigger and bigger machines to see smaller and smaller things," SLAC's director, W. K. H. Panofsky remarked some 20 years ago when the two-mile accelerator was under construction, and the statement still holds true.

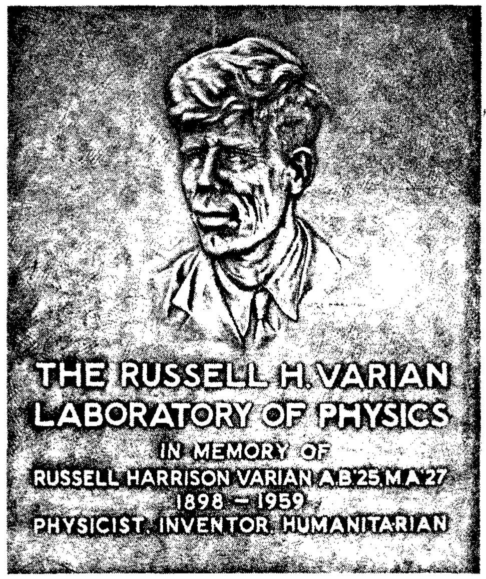
Although the ideas developed by a good many scientists over a good many years were involved, it is correct to say that the electron linear accelerator was invented at Stanford shortly after World War II and that William Webster Hansen was the man chiefly responsible. Hansen, a member of the Stanford physics faculty, and his associates were searching for a simpler and more powerful type of accelerator for bombarding the atom in order to deduce its



The SLAC tunnel stretches two miles from the target area and research yard in the foreground to the distant point where electrons are shot into its slender copper tube. Midway, Highway 280 makes a crossing. The underground PEP ring, more than a mile around, completely encircles the research yard. Left: More than 2,000 feet of tunnel were bored beneath the hilly SLAC terrain as part of the PEP undergrounding.







Stanford physicists inspect an early model of the klystron. Clockwise, from lower left: Russell Varian, Sigurd Varian, Professor David L. Webster, Professor William W. Hansen, and John R. Woodyard.

The klystron connection

Russell and Sigurd Varian came to Stanford University in 1937 with an idea and a creative urge. The University, financially strapped by the Depression, appointed them research associates without salary in the Department of Physics, set them up with basement laboratory space, and gave them $100 a year for materials and supplies.

Within seven months the Varians had conceived and built a device that was to make airborne radar feasible, thus helping to crush Hitler's Luftwaffe and destroy the German submarine fleet in World War II. In the postwar period their invention, the klystron tube, became a cornerstone for microwave research and development throughout the world.

Russell, who had earned two degrees in physics at Stanford in the mid-twenties, was the theorist. Incorporating a cavity resonator newly invented by William W. Hansen, a brilliant young faculty member, Russell worked out the tube's design on paper. Sigurd, a skilled mechanic and former Pan American Airways pilot, built the prototype tube, Model A. (The improved Model B is now in the Smithsonian Institution.) The brothers named their creation klystron, from the Greek verb *klyzo*, expressing the breaking of waves on the beach, a metaphorical reference to the critical bunching of electrons in the tube.

The klystron turned out to be more than an important wartime development. Edward L. Ginzton, who worked with the Varians as a graduate student assistant, has written: "It helped make commercial air navigation safe, it opened the possibility of worldwide communications by satellites, and it led to a variety of high-energy particle accelerators useful in medicine and in nuclear physics." The brothers established Varian Associates in 1948, and the firm soon became the first to build in the Stanford Industrial Park. Ginzton became a professor at Stanford in 1946 but eventually left to become chairman of the board of Varian Associates.

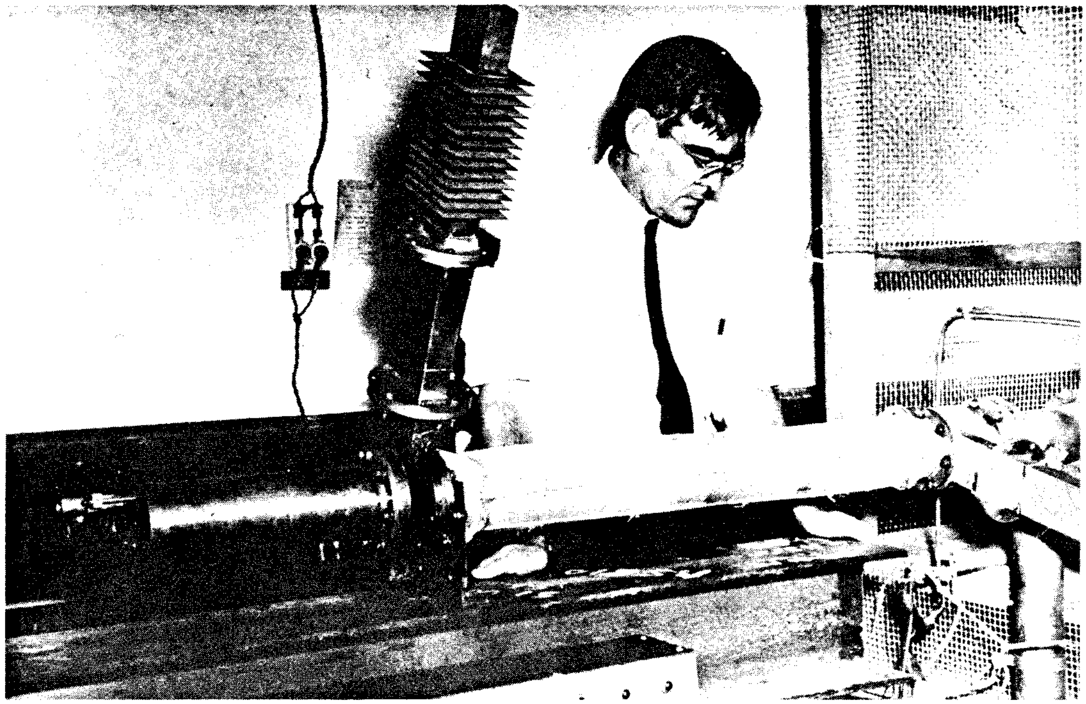
When the Varians began their experiments on the campus, they agreed to share financial returns with the University. Stanford has received more than $2.5 million in klystron royalties, a large part of which was used in the construction of the Russell H. Varian Laboratory of Physics, dedicated in 1962. Russell died of a heart attack in 1959 while on an Alaskan cruise, and Sigurd perished in a private plane crash off the coast of Mexico in 1961.

structure. In 1947 they operated their first model, a three-foot-long tube that generated a 1.5-million-electron-volt beam. Hansen put his whole report to his sponsor, the U.S. Office of Research and Inventions, into four words: "We have accelerated electrons."

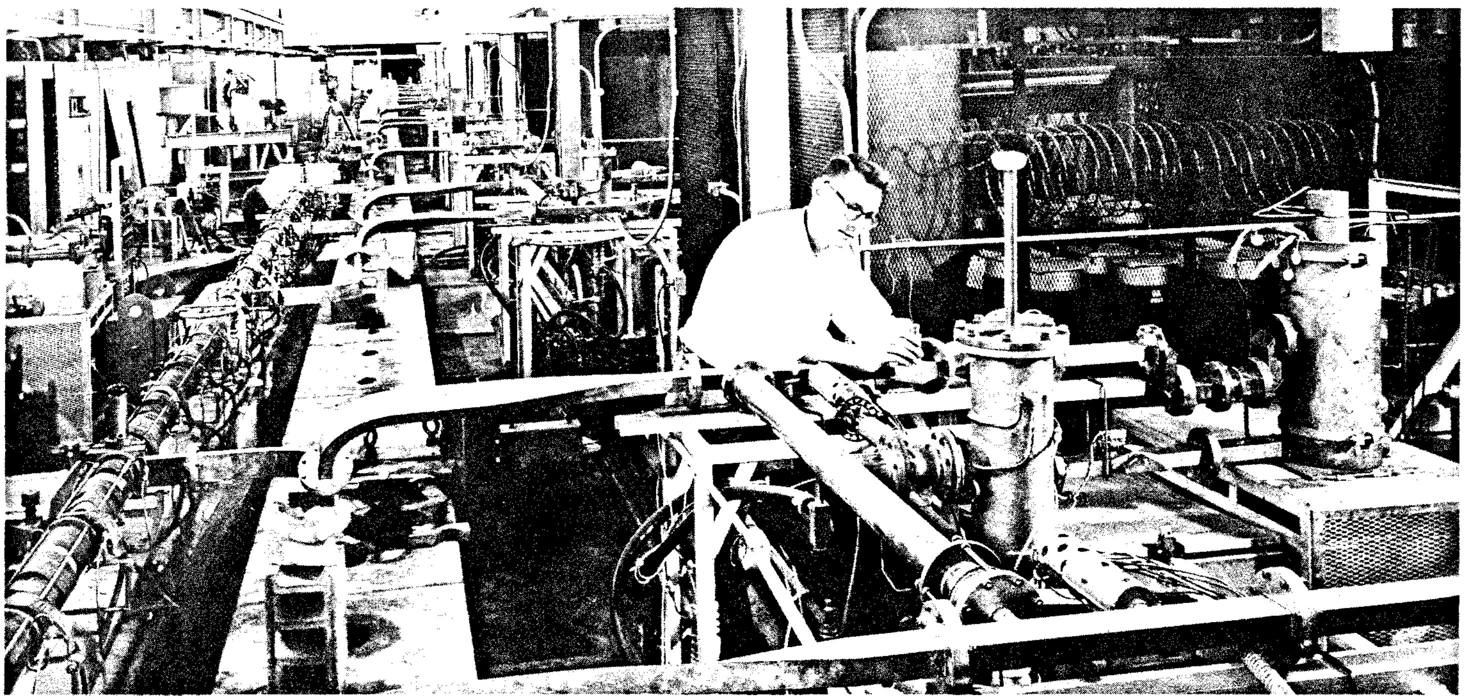
Meanwhile, Stanford professors Marvin Chodorow and Edward L. Ginzton had succeeded in dramatically increasing the power of the klystron, the microwave tube invented at Stanford by the Varian brothers. In 1950 a billion-electron-volt accelerator, using klystrons as the source of the high-frequency radio waves which push the electrons down the tube, was put in operation. (Hansen, just entering his forties, had died the year before and Ginzton became the project leader.) Using the new machine, called the Mark III, Professor Robert Hofstadter of the Stanford Department of Physics won the Nobel Prize in 1961 for his studies of electron scattering in atomic nuclei and for his discoveries concerning the structure of nucleons.

It was Hofstadter who first suggested that an accelerator 10 to 20 times more powerful than the Mark III be considered. The awesomeness of the proposed machine, which would be two miles in length, can be detected in its first nickname, "The Monster," later changed to "Project M." The first formal Project M meeting was held on April 10, 1956, in the home of Professor Panofsky, who had

William W. Hansen in a Stanford physics laboratory with the first three-foot-long electron linear accelerator, developed in 1947.



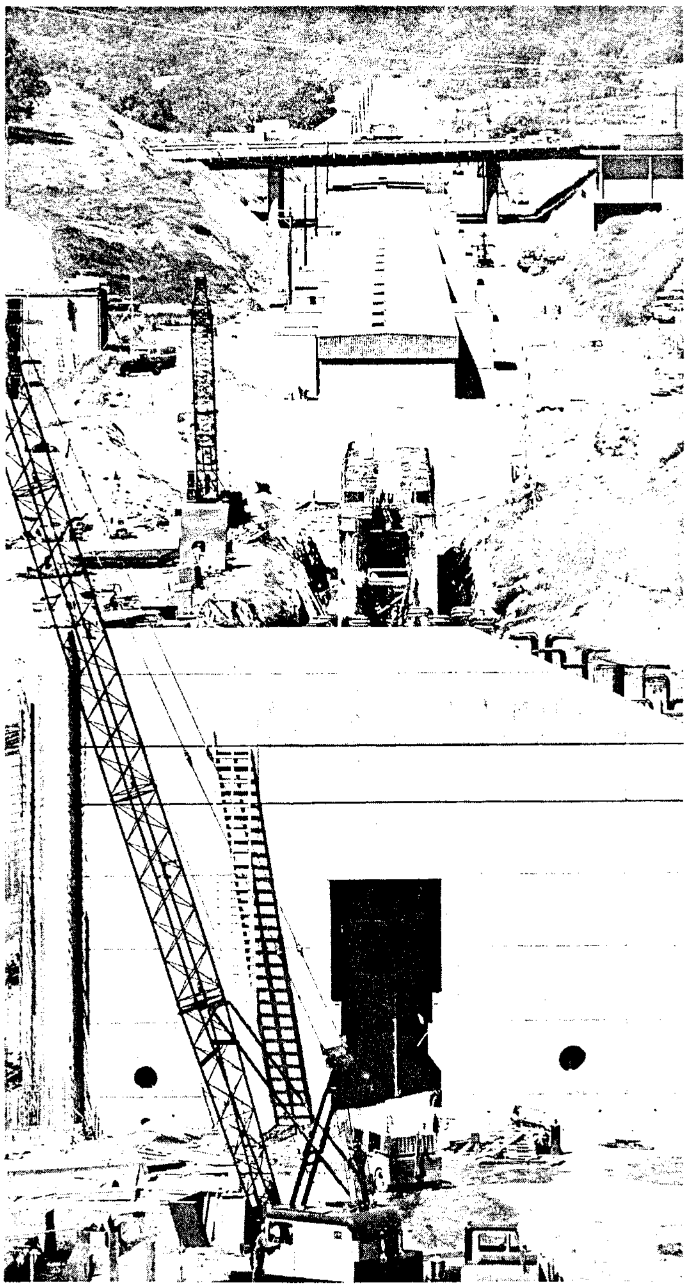
The Stanford Mark III accelerator, without its customary concrete-block radiation shielding, in the High Energy Physics Laboratory. This billion-electron-volt machine was used by Physics Professor Robert Hofstadter to win the 1961 Nobel Prize.



joined the Stanford faculty in 1952 and was to become director of SLAC in 1959. The minutes of this meeting record an interesting sentence: "The participation of the members of this group is entirely voluntery and on their own time as there are no funds available to support this program."

A detailed proposal for construction of Project M on Stanford land was presented to the federal government by President Wallace Sterling in 1957. After prolonged investigations and hearings—punctuated by President Eisenhower's endorsement in a nationally broadcast radio address—Congress authorized the Stanford Linear Accelerator Center project in 1961. A contract was signed between the Atomic Energy Commission and Stanford calling for the University to design the accelerator, build it on a 480-acre strip of land in the low foothills behind the campus, paralleling Sand Hill Road, and operate it. The huge job was completed in 1966, on schedule and within the allocated budget of $114 million.

Within a few months after the first beam of electrons was transmitted over the accelerator's full two-mile length, the projected energy of 20 billion electron volts was achieved. This has since been boosted to 24 billion. The electrons, injected at the beginning of the accelerator pipe, are driven constantly forward by microwaves fed into the pipe by regularly spaced klystron tubes. Answering to laws



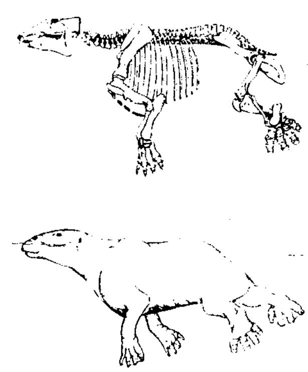
Watchmaker precision on massive scale

A 10,000-foot-long concrete tunnel, 10 feet by 11 feet in cross section and buried under 25 feet of soil compacted to bedrock density, houses the copper tube of SLAC's accelerator. Parallel to the tunnel and directly above it at ground level is perhaps the longest and slimmest shed in existence. This structure contains 240 klystron tubes at spaced intervals for accelerating the subterranean beam.

The extreme requirements for strength and linearity turned construction of the tunnel and the accelerator tube into one of the most exacting large-scale projects ever undertaken. The varying soil bases encountered in the lengthy land cut made for construction of the housing were brought to uniform density. A special concrete formula was devised to minimize shrinkage. Ice was manufactured on the site and added to the concrete mix on warm days to reduce the effect of temperature changes. And all joints were grouted with epoxy, turning the concrete housing into a two-mile monolith.

The accelerator tube, four inches in diameter, was fabricated of more than 80,000 copper cylinders alternated with a like number of copper disks. Copper-silver alloy washers were melted under heat to fuse the pieces together. Each disk has a center hole about ⅞ inch in diameter. The electron beam, with a diameter of about ½ inch, is injected into the tube by an "electron gun" and of its own accord travels in an absolute straight line. The beam must pass through the holes in the disks without touching, so the designers specified that the tube must deviate no more than four-hundredths of an inch from center over its two-mile length. The tube was built in 240 modules, and worm screw jacks at each coupling permit realignment, using a laser beam as a reference.

The first scientific discovery at SLAC was a skeleton unearthed during construction. It proved to be that of a heavily built amphibious mammal 15 million years old, now called Paleoparadoxia. Only one other of its skeletons had been found before—in Japan in 1961.

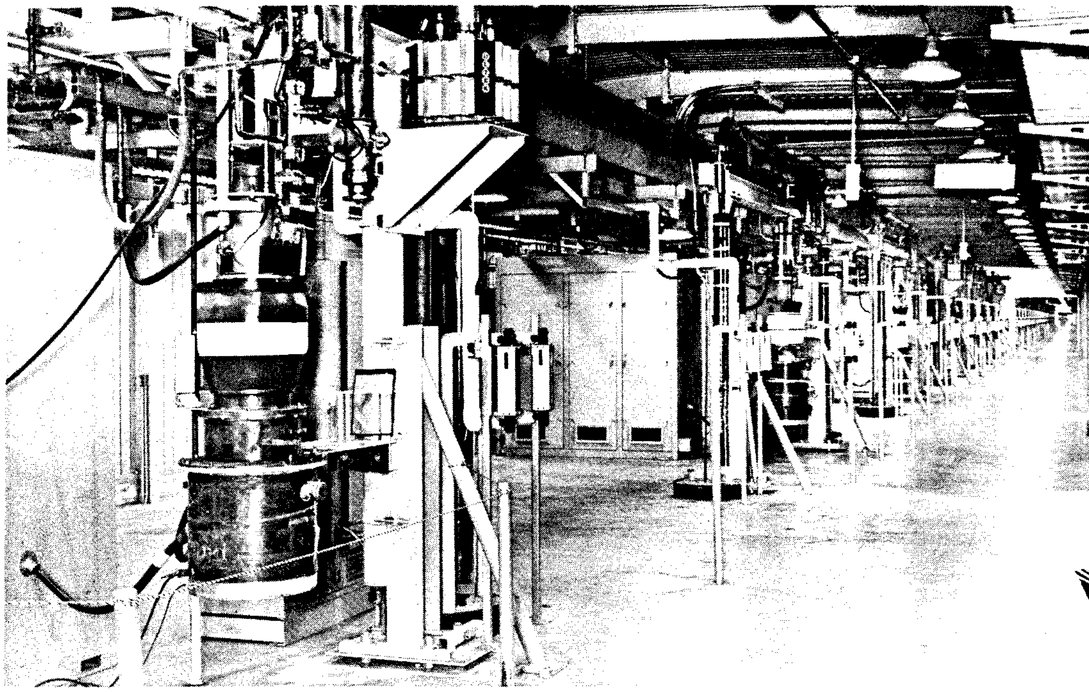


of physics, the electrons quickly approach the barrier speed of light (within 0.0000001 percent) and then increase in mass some 40,000 times. These superelectrons crash into the nuclei of stationary target material in two large end-station buildings, and the telltale scattering of subnuclear particles created is studied in optical and electronic detectors. A SLAC experiment of this kind provided the first clear evidence that protons and neutrons in the nucleus of the atom are not the smallest particles of matter but rather are formed from particles which have come to be called quarks.

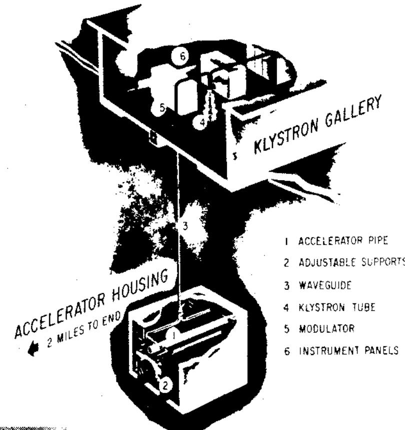
The coupling on of the SPEAR and PEP colliding beam rings has added a new dimension of power to the linear accelerator. Energy, as highway accidents demonstrate, is doubled in head-on collisions. Thus PEP is able to deliver 36 billion electron volts initially and a considerable increase is expected after trials.

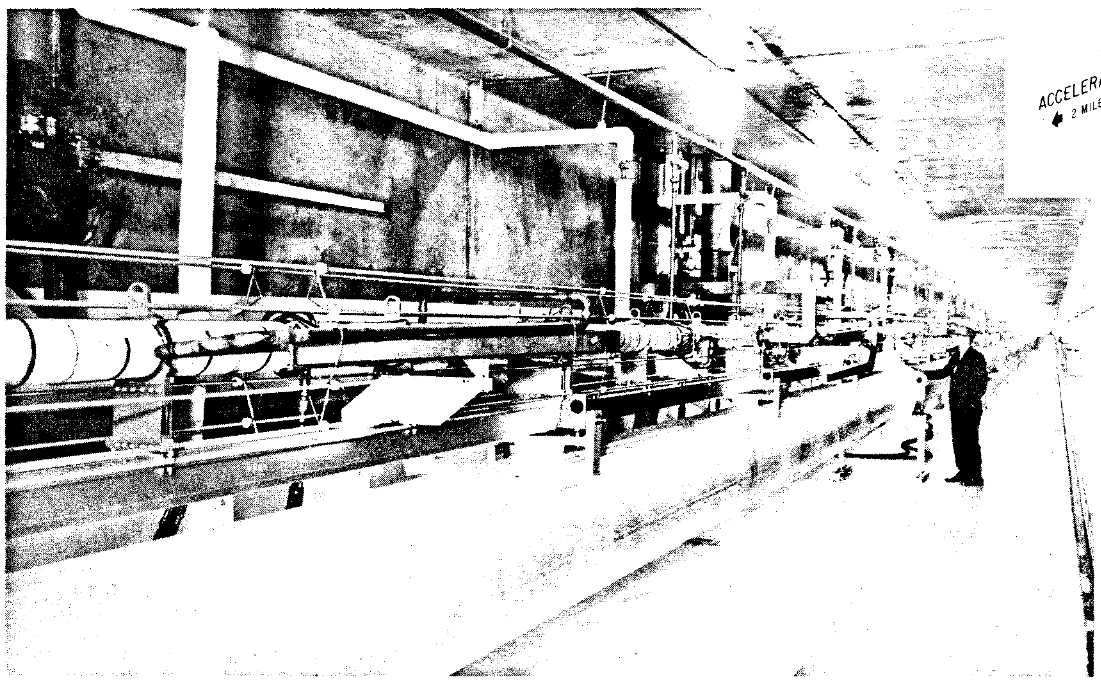
Yet each technique—the bombardment of fixed targets and the collision of beams—has its special uses and SLAC research will continue to use both of them.

The storage ring story began in 1958 when a Stanford-Princeton team constructed a machine in Stanford's High Energy Physics Laboratory that brought two electron beams into collision. Burton Richter, a recent M.I.T. Ph.D., was a junior member of the team. He became convinced that an electron-positron collision would be more produc-



This is the klystron gallery, a two-mile shed running along the top of the accelerator tunnel. The striped cylinders are the klystron tubes which deliver intense bursts of microwave radiation to the accelerator below.





In the underground tunnel, the accelerator tube, four inches in diameter, is supported by the large lower pipe. The lower pipe contains optical targets and a laser beam which are used to align the accelerating structure to minute tolerances over its entire length.

tive than the electron-electron mode. (He said at the time of receiving the Nobel Prize: "I have been led on by a naive picture: positron and electron, particle and antiparticle, annihilating and forming a state of simple quantum numbers and enormous energy density from which all of the elementary particles could be formed.")

Richter and a colleague, Professor David Ritson, designed SPEAR for SLAC but could not get a federal agency to back it. The funds were finally squeezed out of SLAC's budget. The Stanford group, joined by Lawrence Berkeley Laboratory physicists who concentrated on devising the detection equipment, placed SPEAR in operation in 1973. A year later, they discovered the psi particle. Richter has described SPEAR's $5.3 million price tag as "the biggest bargain in physics."

It became an even bigger bargain when the Stanford Synchrotron Radiation Laboratory was formed to take advantage of a SPEAR by-product—the extremely pure and intense X-ray and ultraviolet radiation thrown off by the electron beam as it is bent by magnets into its circular orbit. This radiation is siphoned off through slits in the ring and is used as an ideal illuminating source for looking at the structural details of all kinds of materials, including biological samples such as nerve, retinal, and muscle tissues. Some 300 scientists from around the country soon were using the facility. Although closely allied with SLAC,

Burt and Psi and Sam and J

Burton Richter of SLAC and Samuel C. C. Ting of M.I.T. were jointly awarded the Nobel Prize in 1976 for their simultaneous discovery of an entirely new elementary particle.

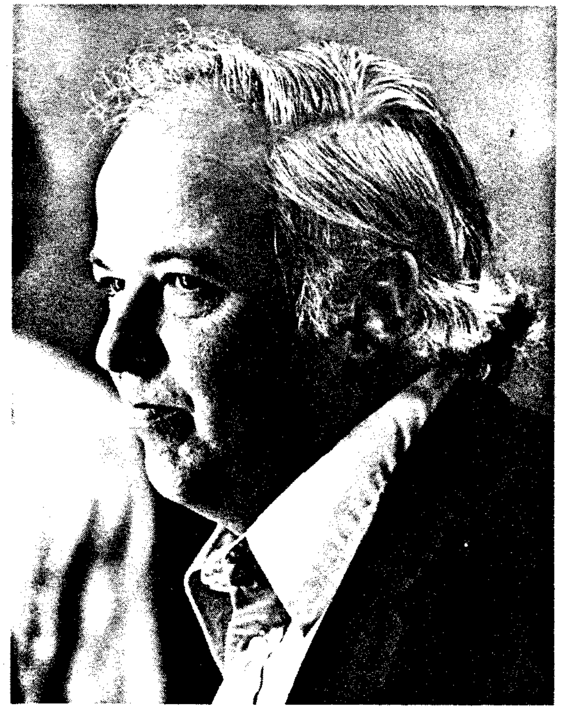
The fact that their two teams, using different methods and working on opposite coasts, made identical discoveries of a revolutionary nature is a strange enough story. But the way they found this out is even stranger.

Ting arrived at SLAC for a committee meeting the morning after the SLAC/Lawrence Berkeley Laboratory group had verified its finding. Richter picks up the story:

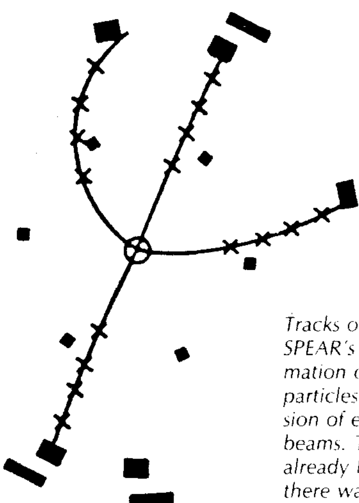
"When I met Sam early that morning, he said to me, 'Burt, I have some interesting physics to tell you about.' My response was, 'Sam, I have some interesting physics to tell you about!'

"What this conversation lacked in sparkle it more than made up for in astonishing coincidence, for it soon became clear that Ting's group had discovered the very same particle in their statement at Brookhaven."

The M.I.T./Brookhaven group called the particle "J" and the SLAC/LBL group named it "psi." After some friendly competition, in which emblazoned T-shirts played a part, the particle is now usually referred to as "J-psi."



Burton Richter



Tracks on the oscilloscope of SPEAR's detector show the formation of previously unknown particles following the collision of electron and positron beams. The new particles had already been named "psi"—there was a precedent for calling particles after Greek letters—before anyone noticed that the tracks themselves formed a perfect "psi."

W. K. H. Panofsky

SSRL is an independent unit within the University and is supported by the National Science Foundation. Arthur I. Bienenstock, professor of materials science engineering, is director.

Today SLAC has 1,200 employees—one-third scientists and engineers, one-third technical and support personnel, and one-third administrative, clerical, and other workers. Its sponsoring agency is the Department of Energy. As a national facility engaged in no classified research, SLAC is open to researchers from all over the world, and usually at least half of the users are from outside Stanford. Panofsky expects this outside usage to increase because SLAC, the Brookhaven National Laboratory on Long Island, and Fermi National Accelerator Laboratory in Illinois have survived to become the three major centers for elementary particle physics experimentation in the United States.

So it has turned out that SLAC, in operation since 1966 and once thought by some to be too much "The Monster" to be able to adapt to emerging conditions, has kept very much in the front line of elementary particle physics. In his "state of SLAC" message for fiscal year 1980, Director Panofsky said, "There is no other electron accelerator in the world that even approaches SLAC's performance."