SLAC BEAM LINE

Faith is a fine invention, When gentlemen can see.
But microscopes are prudent, In an emergency.
—Emily Dickinson

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BEGINNING THE SLC TUNNEL

Shortly after this photograph was taken in mid February, the two machines in the foreground disappeared into the face of the hill through the wooden walled port. This first section of the eventual 9000 feet of *SLC* tunnel starts near *PEP* region 12 and goes back toward the linac. (Photo by Joe Faust.)

THE STATE OF SLAC

W. K. H. Panofsky

The following talk describing the present budget, the past accomplishments, and the future prospects for SLAC was given by the Director to the staff on February 6, 1984.

This will be the last of the series of annual talks that I customarily have given to the *SLAC* staff soon after the President's budget for the next fiscal year has been unveiled.

The President released his budget on February 1, 1984, and as usual I will try to tell you how this budget will affect our laboratory. This time I hope you will bear with me if in addition to talking about this subject I also give a brief review of what *SLAC*'s role in physics has been in the past. I will also speculate about the role *SLAC* may play in times to come, and the changes in *SLAC* which this implies.

Let me remind you again that *SLAC* was started with considerably more modest and narrow scientific goals than the program that we are pursuing today. When *SLAC* was first proposed to various agencies of the government in 1957, we planned for an experimental program in which the primary beams were to be used for electron scattering experiments, and in which high-energy x-ray beams generated by electron impact on heavy foils would permit the study of the production of various families of new and old unstable particles by high-energy photons. It was also clear at that time that the *SLAC* linac could produce quite respectable secondary beams of such particles as pi and K mesons, but this was not then thought to be a very important part of the prospective program.

Figure 1 shows a schematic map of our facilities corresponding to those original limited objectives.

As you know, the actual program turned out to be a great deal broader than what was initially envisaged. There are many reasons for this expansion in research, not the least of which were the ingenuity and accomplishments of many people here at *SLAC*. Let me give specific examples. The flux of secondary particles concentrated in the forward direction was predicted by subsequent theoretical analysis to be much larger than originally assumed, and this prediction was soon confirmed by an experiment at the Cambridge Electron Accelerator. This result greatly broadened *SLAC*'s program to include not only electron, positron and x-ray beams but also very useful beams of pi-mesons and K-mesons (both charged and neutral) as well as muons and antiprotons. From all this blossomed a variety of large and complex detection instruments including a streamer chamber, several generations of magnetic particle spectrometers, and two important bubble chambers. This program of secondary beam physics at *SLAC* led to many important discoveries.

Next came the electron-positron storage ring *SPEAR*, which began operating in 1972, and which is shown in Figure 2. *SPEAR* is probably the single most fruitful and cost-effective high-energy physics collider ever built. I need only mention here a few of its successes in physics. You all know that *SPEAR* was the brainchild of our future Director, Burt Richter, and that the discovery of the psi particle in 1974 was rewarded with a Nobel Prize in 1976. Going beyond this first discovery, *SPEAR* turned out to be unusually productive in unveiling a whole spectroscopy of these new particles.

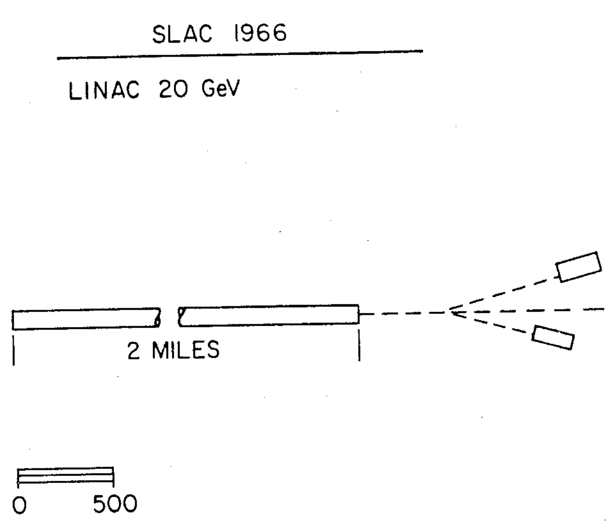


Figure 1. The original scope of SLAC provided only for experiments with the primary and secondary beams.

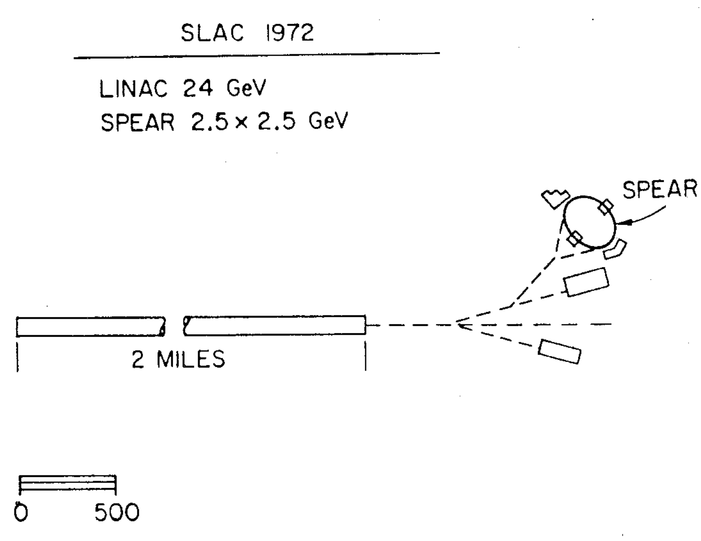


Figure 2. In 1972 SLAC added the storage ring SPEAR.

In addition, through the work of Martin Perl and his collaborators, the equally important discovery of the tau lepton, which is the third member of the family of particles hitherto consisting only of the electron and muon, was made.

Even today work with the *SPEAR* storage ring remains extremely productive, as again new or only barely suspected phenomena are exhibiting themselves. Not all of these have lent themselves to interpretation within our current understanding.

It was the success of *SPEAR* that made it possible to secure the endorsement of the scientific community, followed by government support, for the next stage of our development — the construction and operation of the *PEP* storage ring, which first turned on in 1980. Figure 3 shows the schematic map of *SLAC* with the *SPEAR* and *PEP* rings added — the present era.

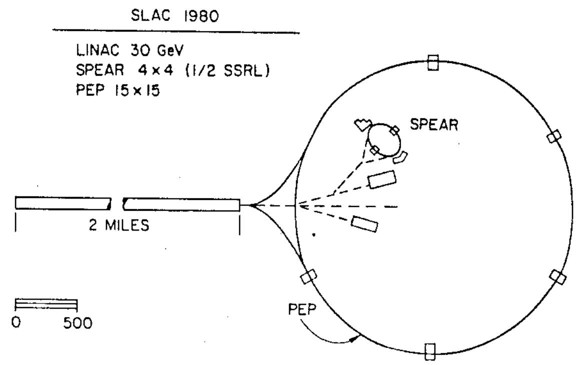


Figure 3. The present era of SLAC: the linear program, SPEAR, and PEP.

It is characteristic of large, government-supported laboratories like *SLAC* that funding does not necessarily follow along with either the available scientific opportunities or with the demonstrated success of the research. Other, external factors — the state of the economy, public attitudes toward science, and compelling national needs — also have a large effect.

This point is well illustrated in Figure 4, which gives a history of the funding that *SLAC* has received from the government, adjusted for inflation. The figures in this chart are given in equivalent *FY*85 dollars, that is dollars adjusted to the buying power those dollars are expected to have during the fiscal year starting September 1, 1984.

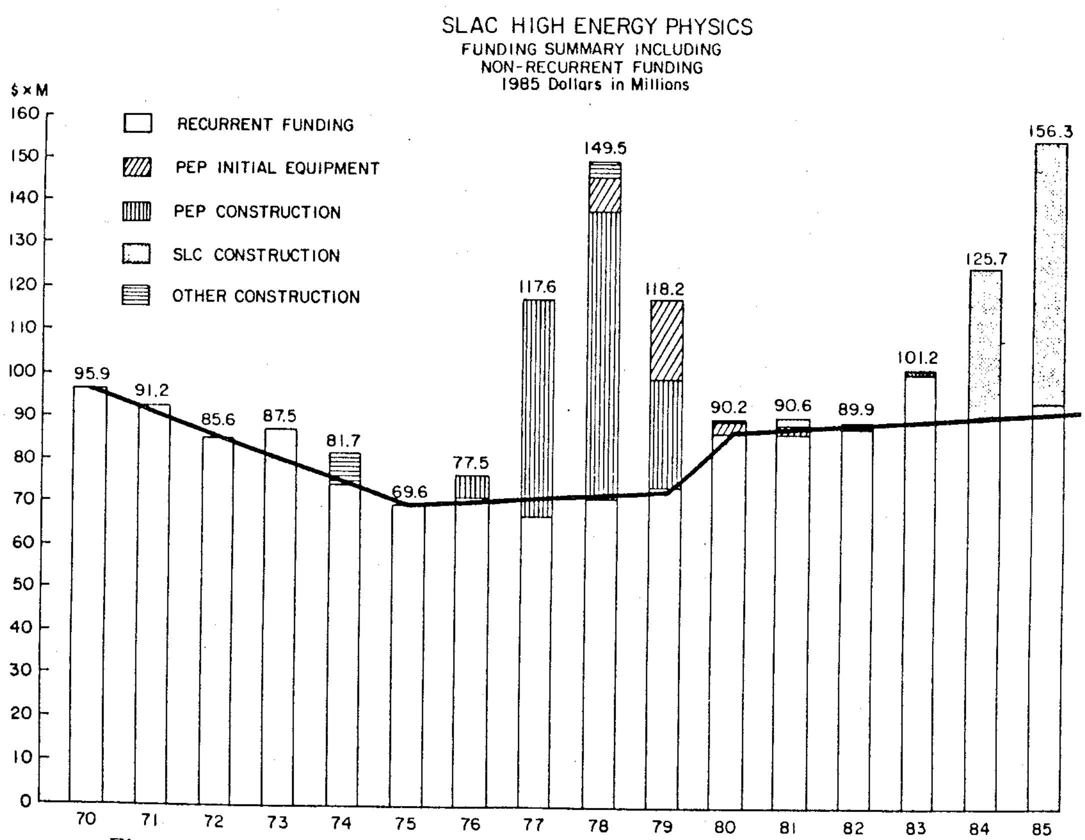


Figure 4. Annual funding of SLAC over the years in 1985 dollars. The white rectangles are the normal operating budget, the vertical and cross-hatched rectangles are for PEP equipment and construction, and the shaded rectangles are for SLC construction.

You have probably read in the newspaper and heard in speeches by government representatives that inflation is almost over. You may not have felt this in your own pocketbook to the same level of conviction, and *SLAC* has certainly not experienced it in terms of the purchasing power of its dollars. Figure 5 shows *SLAC*'s experience during the past few years in respect to inflation, and also our inflation forecast for the current fiscal year (*FY*1984 to *FY*1985). We are still expecting a considerable inflationary bite out of our support dollars since we expect to follow the peninsula pattern in providing reasonable salary increases during the next fiscal year, and we are also expecting sharp increases in electric power rates from the Western Area Power Administration which continues to be the principal supplier of electricity for *SLAC* from public power sources.

As you saw in Figure 4, government support for operating the laboratory decreased initially in real terms, even though our program opportunities, as shown in the first few figures, have continued to increase. This pattern was in no way discriminatory against *SLAC*; on the contrary, if anything, *SLAC* fared somewhat better during the 1970s than many other activities in basic science. This pattern followed the general trend of government support of science during the early 1970s.

The situation took a turn for the better with the authorization and construction of *PEP*. After completion of that construction project, the level of *SLAC*'s operating funds took a jump upward by an amount almost but not quite commensurate with the increased cost involved in operating the new facility and its research program. After *PEP* our funding had its small ups and downs from year to year, but remained fairly level on the average.

During the last several years we have been able to persuade the scientific community, and then the government, to support our next major initiative — the *SLAC* Linear Collider, or *SLC*.

This has led to a sharp increase in our total funding, because of the new construction funding from the *SLC*. At the same time, however, the support for our regular operating program during the current fiscal year (*FY*84) has been decreased in real terms. In other words, the cost of building the challenging new *SLC* facility — which will provide a great new tool for science and also extend the expectations for the future of *SLAC* — is partially coming out of our own hide.

As a result of this support pattern for *FY*84, *SLAC* is currently living in a 'good news - bad news' situation. The good news is that construction of the *SLC* has begun vigorously; ground has been broken and earth moving is in progress; and thus far in our technical work nothing has as yet 'raised its ugly head' to threaten the turn-on of the *SLC* by the end of 1986 or early 1987. The bad news is that the stringency in operating funding has severely curtailed our operating schedule; we will have to shut down regular machine operations by the end of April, and funding for maintenance and for many of our other activities is under severe pressure. At the same time, the total funding of *SLAC* in all categories, including construction, has made it possible to support and in fact somewhat augment our regular staff.

SLAC Cost Index
Base Year = 1967
Composite and Major Commodity

	FY1982	FY1983	Est. FY1984	Est. FY1985
Labor	330.3	371.2	399.0	420.9 - 420.9
Operating Supplies	230.5	237.5	246.3	258.6 - 263.6
General & Metal Stores	303.4	304.4	314.1	329.9 - 336.2
Capital Equipment	301.5	307.5	309.2	324.7 - 330.8
Electrical Power	234.5	231.2	447.6	573.5 - 573.5
Composite (With Elec. Pwr)	314.7	339.3	366.7	395.2 - 397.9
Index Change	24.0	24.6	27.3	28.6 - 31.3
% Change	8.3	7.8	8.1	7.8 - 8.5
Composite (W/O Elec. Pwr)	316.9	341.8	362.0	384.3 - 387.3
Index Change	24.3	24.9	20.3	22.3 - 25.3
% Change	8.3	7.9	5.9	6.2 - 7.0
Other Economic Indicators				
Consumer Price Index (Bay Area - Jan. or March)	297.3	298.3	316.8	332.6 - 339.0
% Change Over 12 Months	12.0	.3	6.2	5.0 - 7.0
Wholesale Price Index (Industrial Commodities - Jan. or March)	311.0	313.5	323.1	339.3 - 345.7
% Change Over 12 Months	4.0	.8	3.1	5.0 - 7.0

Based on index run of 11/11/83

Figure 5. Recent and expected changes in the cost of supplies and services at SLAC, compared to other economic indicators.

The situation that we are anticipating for *FY*85 is not all that different from this year. Figure 6 shows the funding for *SLAC* that is contained in the President's proposed budget for *FY*85. As you can see, support for our regular operations is proposed to increase by an amount that is almost exactly equal to the expected inflationary increase. Our support for equipment is also increasing somewhat, but more about this later. There is a very large increase in the support of *SLC* construction, and I am pleased to report that this amount is just what we estimate is needed to keep construction on schedule during the next fiscal year. Let me remind you that last year at this time I announced with pleasure and gratitude that the President's budget, which covered the funding for the fiscal year in which we are today, authorized the initiation of *SLC* work and covered funding for the first year of *SLC* construction. The amount provided for that purpose in the President's budget was subsequently cut in Congress by $8 million. However, we were still able to keep the project on schedule by shifting some of the work into the next year. In order to compensate for the loss of first-year funding for the *SLC*, the funding required for *FY*85 to keep us on schedule has to be larger than originally anticipated. Thus our ability to keep *SLC* on schedule depends critically on the conviction of Congress that the funding pattern contained in the President's budget for *FY*85 must be maintained.

This story is only one part of the general caution that I would like to emphasize here again. The President's proposed budget is only a submission introduced into the Congress. Before actual appropriations are made, the budget undergoes a long process involving hearings before several committees and final appropriating action by the two Houses of Congress. This can take many months, and at some times in the past the process had not even been completed before the next fiscal year had begun! In an election year we do not expect such a delay, but at the same time there is no way to predict in detail how the specific items within the President's budget will be modified during the next few months.

As we proceed with actual construction of the *SLC*, we will gradually decrease the effort that we are now putting into research and development aimed at fixing the basic design of that machine. After all, if we are to build the *SLC* on schedule, we have to quit designing and proceed to build it on the basis of decisions made. This will free some of the funds in the general field of accelerator R & D for a new line of work not specifically dedicated to the *SLC*, but rather aimed at longer-range ideas that just might be extremely useful for another generation of colliders.

SLAC Funding Comparison
($ x 1,000)

	FY1984 Financial Plan	FY1985 President's Budget
High Energy Physics		
Operations	$ 73,900	$ 80,700
Capital Equipment	8,000[1]	10,900
AIP/LINAC Improvement	1,900	2,700
GPP	1,300	1,500
SLC Construction	32,000	60,500
Subtotal High Energy Physics	117,100	156,300
Nuclear Structure Physics		
Operations	95	1,090
AIP/Nuclear Physics Injector	1,650	—
Subtotal Nuclear Physics	1,745	1,090
Total Financial Plan	$118,845	$157,390

1) Includes $ 1 million transfered to LBL for Mark II Detector fabrication.

Figure 6. The present SLAC budget and the funding proposed in the President's budget for the next fiscal year.

A successful program of using the *SLC* demands a lot more than just making the machine work, however important this may be. We need detectors, and we have to plan for research. We made the decision that two detectors should be built, although there is only one point at which the electrons and positrons of the *SLC* will collide. As most of you know, the first detector will be a modification of our old work horse — the Mark II detector — which has done heroic service at *SPEAR* and which was then moved to *PEP* and will again be moved to the *SLC*. Each one of these moves is preceded by an upgrading program — that is, pulling out those components for which improved designs have become available, and replacing those components with new devices. As a result the 'new' Mark II that will go into the *SLC* has a relationship to the 'old' Mark II that we used at *SPEAR* something like a blanket which has been mended so often that none of the original cloth remains.

The decision to improve the old Mark II, and then to test the improvements at *PEP* before using this detector in the *SLC*, was made because we wanted to have one 'tried and true' detector ready at the time the *SLC* turned on. However, such a converted old detector cannot possibly do justice to the full potential of the *SLC* (provided, of course, that the *SLC* works according to design).

Thus with the advice of the outside user community we decided to initiate construction of a second, wholly new detector, which will not be ready at the time the *SLC* turns on, but which will give reasonable assurance that whatever physics can be done with the *SLC* will in fact be eventually forthcoming. This second detector is now being designed; it will be quite expensive. The group that will plan, design and build this instrument is a collaboration among many physicists from many institutions. Marty Breidenbach of *SLAC* and Charlie Baltay of Columbia University are those responsible for managing this project. It is intended that this new detector will be ready to take data in 1988.

The President's budget as now submitted does not provide enough money in the equipment category to permit a fast start for this second detector. This is because *DOE* has found that the demand for high-energy physics Equipment money for the next fiscal year is greatly in excess of what can be made available. There are needs at Fermilab stemming from the recent successful conversion of their machine to operate as a superconducting magnetic ring at higher energy, and there are many other equipment needs throughout the nation's laboratories and universities. Thus some difficult decisions will have to be made, and a special meeting of the High Energy Physics Advisory Panel to the Department of Energy has been called in February to provide advice about these various conflicting requirements. I cannot give you a definite prediction about whether the outcome of these considerations will be to increase the equipment money allocation to *SLAC*, but I remain optimistic as usual.

Let me summarize. The President's budget gives us the good news that construction of the *SLC* can go ahead full steam, paced only by our ability here at *SLAC* to do the work and by the tractability of the very difficult technical problems that have to be solved as we proceed to build this challenging machine. Our operating activities will continue to be constrained by fiscal pressures; if the President's budget does not get cut in the Congress, the situation will not be worse than it is today. Equipment money shows an increase, but definitely not enough to live up to our obligations to construct competitive detector systems for the use of the *SLC* on a reasonable time scale. As far as *SLAC*'s staff level is concerned, I predict a small growth to match our total obligations during the coming year.

Figure 7 shows the schematic map of *SLAC* with the *SLC* sketched in. As you can see, *SLAC* has now grown from its initial configuration using just two beams to a 'three-ring circus' involving many beams, and exploiting *SPEAR*, *PEP*, and soon the *SLC*. How has this dramatic change come about?

I believe that the basic reason is that our initial hunch that the future of high-energy physics would be deeply intertwined with the use of electron beams has proven to be correct. When *SLAC* was started there was general acquiescence to the idea of building a very large electron accelerator on the part of the scientific community, but there was not much enthusiasm. Through the mid-1960s the mainstream of high-energy physics followed the development of proton accelerators. The decade of the 1970s turned out to be the golden years of high-energy physics using what we call 'lepton' beams, that is electrons, muons and neutrinos. The work was paced by electron accelerators and colliders, both at *SLAC* and at the *DESY* laboratory in Germany; proton accelerators made some of their biggest contributions through the use of secondary neutrino and muon beams.

There are good physical reasons why this happened. Leptons are not affected by the strong or nuclear force that holds the nucleus of the atom together; instead, leptons interact through electromagnetism and to a lesser extent through the so-called weak interaction. Thus when leptons collide with nuclei, one is exploring unknown structures with relatively well known forces, and the resulting events are easier to understand than when protons with their complex internal structures collide with other protons. To go even further, when electrons collide with positrons they can annihilate into a single 'quantum' of pure electromagnetic energy, which then materializes into any of those particle states that can be created under the applicable rules. The events that result from this process exhibit new physics with remarkable clarity.

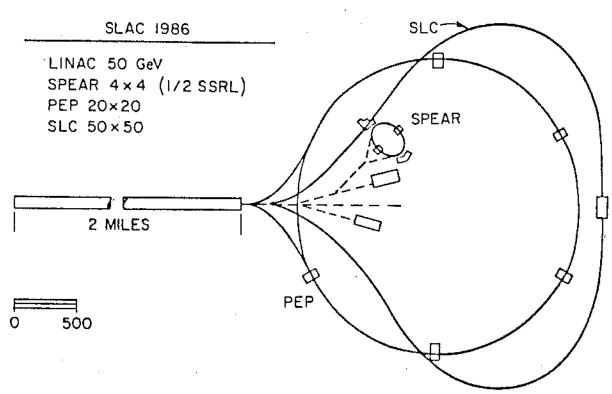


Figure 7. A schematic of SLAC including the Linear Collider.

Hours before this State of SLAC talk was given, machine physicists succeeded in a critical test of the Linear Collider. A high-intensity beam was stored in the damping ring, extracted, and accelerated to a measuring station one-third of the way down the linac.

Largely as a result of this 'golden age of leptons' of the 1970s, we now understand the fundamental building blocks of nature much better than before. The world as we know it today is made up of leptons, on the one hand, and quarks which are the carriers of the strong interaction and the building blocks of nuclei, on the other. We now know that protons and neutrons are each composed of three quarks, and that the forces among these quarks are carried by objects known as gluons which have characteristics that give rise to the known properties of the strong interaction. Most of this was initially uncovered through lepton experiments and has been confirmed by the behavior of protons, neutrons, and other particles; *SLAC* has played a truly crucial role in achieving this great leap in understanding. The key to this role has been the technical achievements made by *SLAC* in building and using its accelerators and colliders. The question now facing us is for how long this role of electron machines will continue into the future. We know that the *SLC* in the United States and the *LEP* machine in Europe will advance the energy of electron-positron colliders to 100 GeV center-of-mass collision energy, and eventually to perhaps twice that value at *LEP*. But what will happen thereafter, perhaps in the mid-1990s?

The energy of proton machines promises to be advanced by the mid-80s to a collision energy of 2,000 GeV, building on the recent successes at Fermilab in bringing a large superconducting proton synchrotron into operation. The 270 GeV per beam proton-antiproton collider at *CERN* has been a great success; it has provided the first direct conclusive evidence that the carriers of the weak interaction actually exist — a great achievement indeed.

Does this mean that the pendulum will swing back again? Will the dominance of the high-energy physics world that moved from proton machines in the '60s to lepton physics in the '70s swing back to proton machines in the '80s? We cannot be sure. The essential simplicity and analyzability of the events produced by electron colliders will continue to provide an enormous advantage to experimenters using those machines. At the same time, the energies that can be reached with proton machines will continue to outstrip the energies attainable with electron machines at comparable cost, at least for the time being. However, even this last remark must be tempered. Since protons are complex objects consisting of quarks and gluons, the energy of each of the colliding protons is divided among these elementary constituents. Therefore the energy available to generate truly new phenomena is really that carried by the individual elementary constituents; these carry on the average only one-sixth or so of the energy of the proton. Thus the 2,000 GeV collision energy attainable at Fermilab by the mid-'80s translates into an equivalent collision energy for electrons of about 300 GeV, which is still above the energy limit attainable by *LEP* and the *SLC* but not by much! For these and other reasons the results of electron machines and proton machines will continue to be complementary in the future, with no such thing as a single 'best machine.'

The dominant reason why electron machines — in spite of the inherent simplicity of the physics they produce — have not thus far matched the reach into the unknown projected for proton machines is simply one of technology and of cost. We can extrapolate the established technologies of proton machines into the future to energies of perhaps as high as 20 TeV or 20,000 GeV of proton energy per beam. A comparable advance for an electron machine requires development of new technology for which the *SLC* will point the way, but which has not as yet been demonstrated. Thus the next logical step for the US high-energy physics program is the proposed superconducting supercollider *(SSC)*, which is envisaged as a colliding beam proton-proton machine with each beam having an energy of 20,000 GeV. If the current hopes of the community materialize, such a machine will operate by the middle of the '90s. This hope can only be realized if this new machine can be built as a truly national effort — that is, an effort to which all laboratories in the US contribute, including *SLAC*. Thus while operation of *PEP* and *SPEAR* and the construction of the *SLC* now comprise and will continue to comprise the large bulk of our work, we are already beginning to be involved, albeit to a very small extent, in the planning process for this very large proton machine.

Nevertheless, it is not at all clear that electron machines will also not be able to attain the same or an even larger reach of discovery as is now planned for proton machines. But we simply do not know today how to do this at a cost that appears affordable. No one can be sure now whether this cost disadvantage of electrons versus protons will continue indefinitely, or whether progress in technology will erase or reverse it. Using the new linear collider technique opened up by the *SLC*, there are several possible approaches towards building better and cheaper very high energy electron colliders. As construction of the *SLC* approaches completion, we will dedicate an increasing fraction of our work towards exploring these new technologies that may carry us beyond the *SLC*.

If the *SLC*, in addition to making valuable contributions in terms of its own physics program, also leads to an exciting and supportable proposal for a large-scale electron-positron collider, then this avenue should and will certainly be pursued. Whether it could be pursued on the *SLAC* site, or whether exploitation of such a machine would require more space than can reasonably be made available locally, I simply do not know. Neither do I know whether such a large linear collider would be best pursued as a national or as an international high-energy physics program.

In other words, in parallel with *SLAC*'s increasing participation in the national program for the *SSC* we will at the same time explore the opportunities of making a high-energy linear electron-positron collider a competitive or even superior machine in the long run.

All of these issues relate, of course, to the question that is closest to many of your concerns: What is the long-range future of *SLAC*? I would be uncomfortable in facing that question today if it were not for the fact that the very same question has been asked of me ever since the founding of this laboratory. If has always been true that the future program of *SLAC* was relatively well-defined for a large fraction of the decade ahead, but beyond that little or nothing could be said. The situation is the same today. We can look towards a secure future (or a least a future as secure as a reasonable level of support of science by the federal government) for the rest of this decade and perhaps somewhat beyond. What happens after that depends on our ability to exploit new ideas and initiatives. The director of *SLAC* after Sept. 1, 1984 is a past master in this respect. One of the many reasons why I believe that a change of leadership for this laboratory is a good idea, and why I believe that the leaders of this lab should relinquish their administrative responsibility at a fixed age, is that we want to create the best climate for the generation of new ideas and their fullest exploitation.

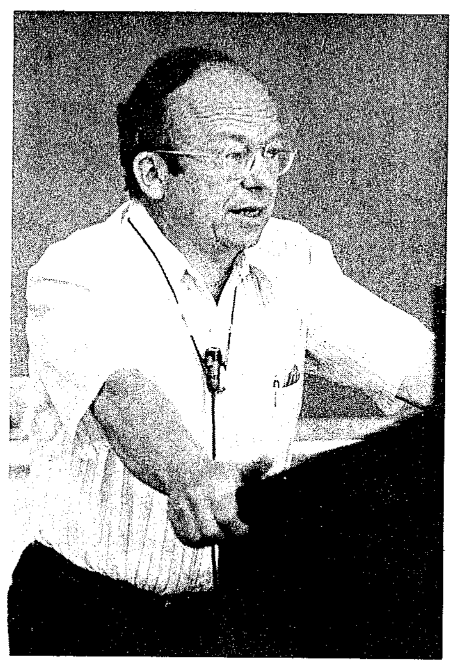
Finally, we do not know when and if *SLAC* will depart from its traditional exclusive role of pursuing high-energy physics to the exclusion of all other disciplines. Even if the quest at *SLAC* for electron-positron colliders of energies beyond the reach of the *SLC* is not successful, *SLAC*'s role will continue as a collaborator in the effort towards generating the superconducting super collider for protons and as a base for high-energy physics experimental users.

It would be illusory to believe that the style of carrying out physics research will ever become again what it was when *SLAC* started. We have seen at *SLAC*, and even more at other laboratories, a change from a concentration of work at many experimental stations to experimentation concentrated into only a few interaction regions where beams collide. The result is that detection instruments become larger and larger engineering enterprises in their own right, and that the scientific teams to exploit such detectors also become larger. The only reason why this is a lesser change for *SLAC* than it is for other laboratories is that our work has always been centered around relatively large facilities.

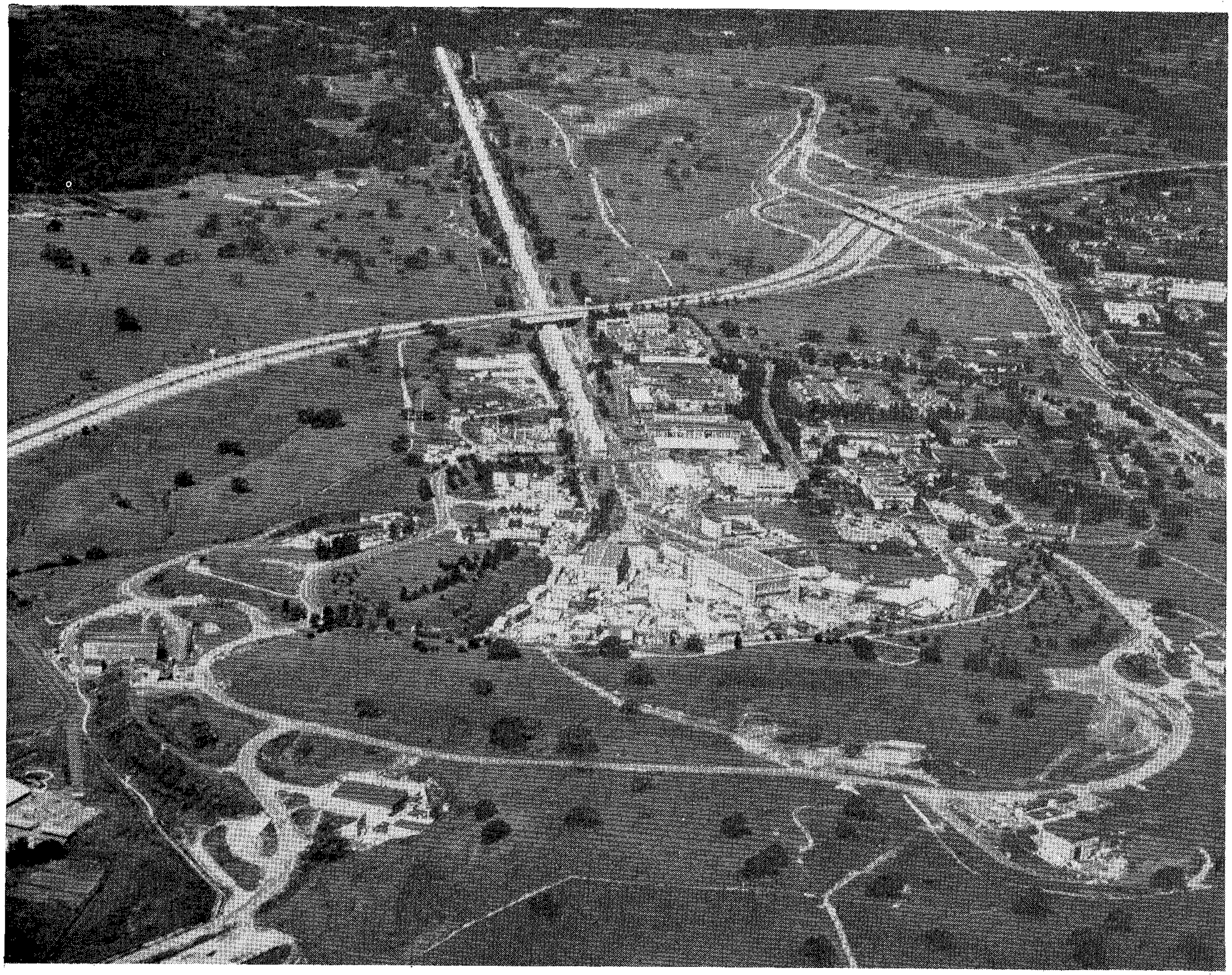
The title of this talk is 'The State of *SLAC*.' While thus far I have spoken of the past and of expectations for the future, I have not said much about where we are right now. I am happy to report that the present state of *SLAC* in the world of high-energy physics is excellent:

- We remain the world's highest energy and intensity electron accelerator
- We are the only laboratory with facilities in high energy physics for high intensity electron and photon beams on stationary targets
- *PEP* is the highest luminosity, and the second highest energy, electron-positron storage ring now operating.
- *SPEAR* has a worldwide monopoly on electron-positron collisions in its energy range — a range that continues to produce important and surprising results.
- *SPEAR* remains the most productive source of synchrotron radiation worldwide
- The *SLC* promises to be the first 'intermediate boson factory,' and it opens up a whole new direction for high-energy collider technology as well as for particle physics.

This should be a good base on which to build.



W.K.H. Panofsky



STANFORD LINEAR ACCELERATOR CENTER

A NATIONAL HISTORIC ENGINEERING LANDMARK
DESIGNATED 1984, STANFORD CALIFORNIA

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.

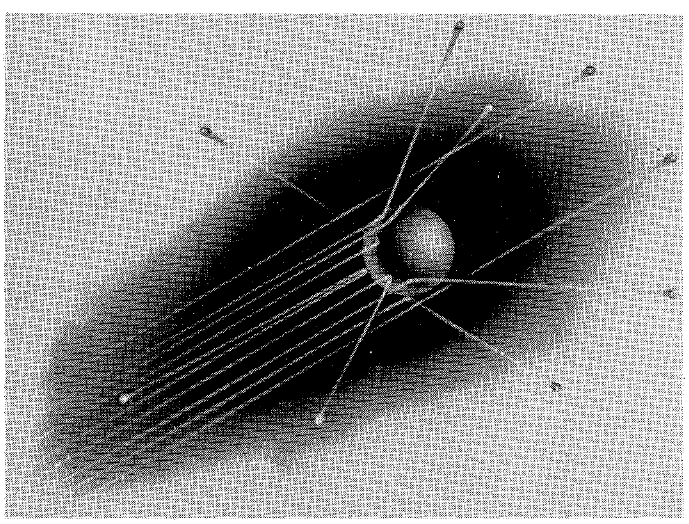
Imagination inspires science, but measurement must give it substance. The sciences of both the outer and inner worlds waited for machines to bring them closer. Lenses assembled into telescopes marked the beginning of modern astronomy. Rearranging those lenses produced microscopes, and the unfolding of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

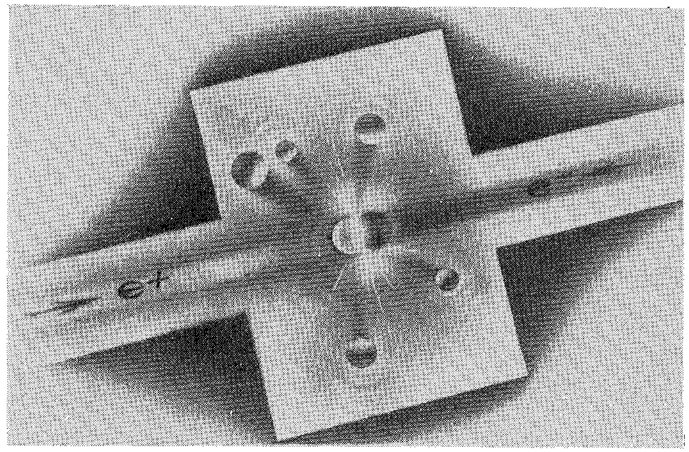
EXPLORING THE SUBATOMIC WORLD

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.



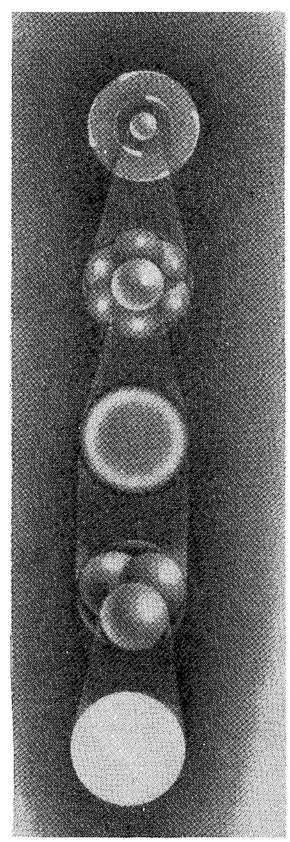
The pattern produced by the scattered electrons is something like an x-ray picture of what is inside the proton.

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

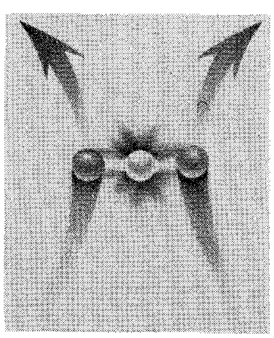
The idea of quarks explained many complicated phenomena in a straightforward way. Eventually, however, problems began to crop up, both in theoretical models and other experiments. Something appeared to be missing.

Within a decade, another experiment at *SLAC* found the problem. Colliding-beam experiements 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 practical 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.

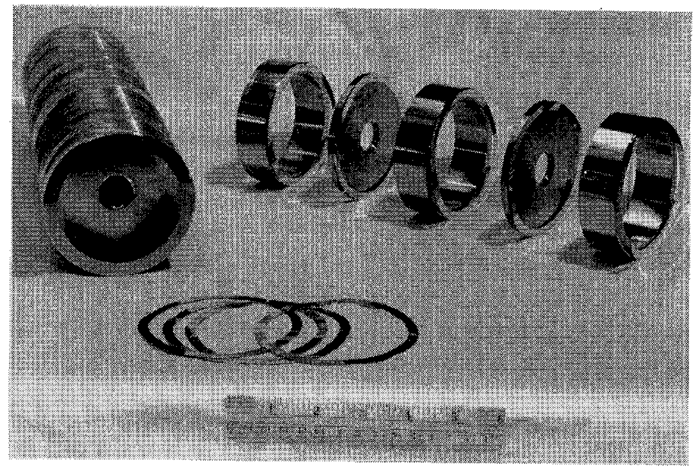
Although the principle is straightforward, the application is not. The engineering problems included manufacturing a thousand sections of precision copper waveguide, aligning these sections over a two-mile length, producing high-power pulsed microwaves, and safely handling the intense high-energy beam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

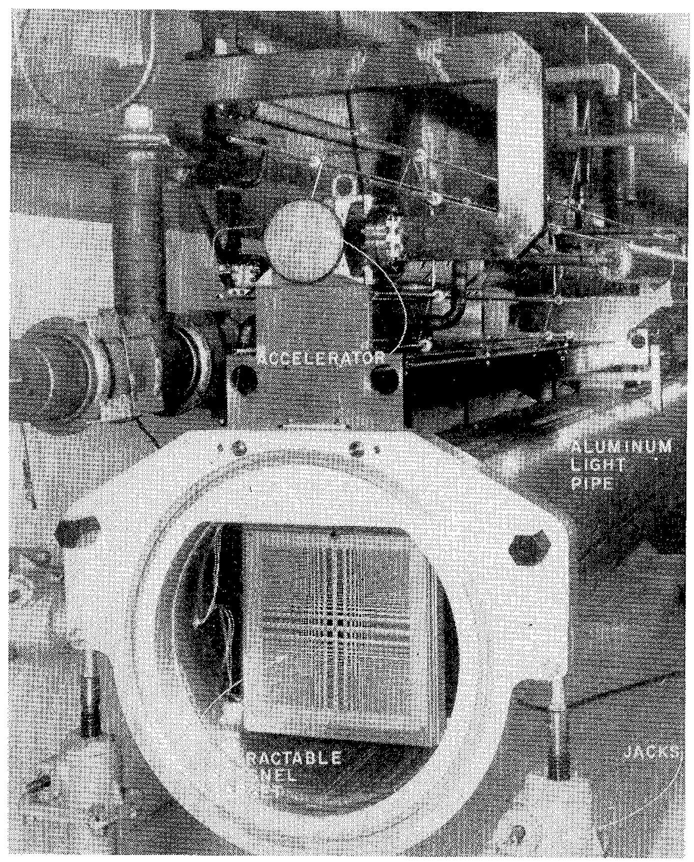
These cavities, made of high-purity copper, were machined to a precision of about two ten-thousandths of an inch and then brazed in a hydrogen furnace into ten-foot-long sections. Each cavity was then 'tuned' by slightly deforming the outside using hydraulic rams. In the complete accelerator there are 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.

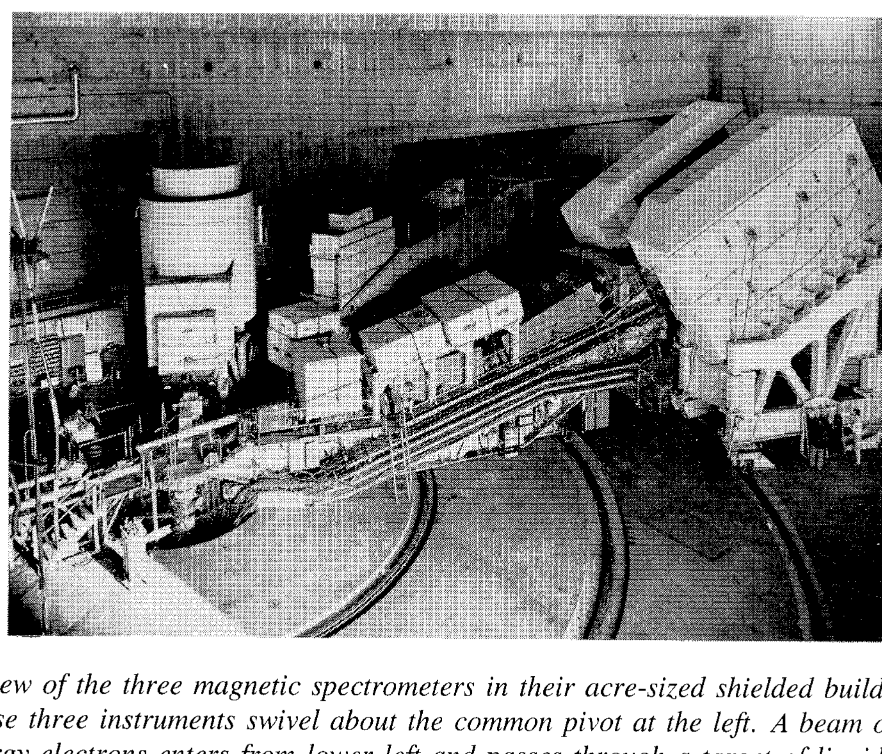
The traditional way to measure a particle's energy is by deflecting it with a magnetic field and measuring the effect with a sensitive detector of charged particles. The same scheme is used at these very high energies, but the instruments are of vastly different scale.

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.

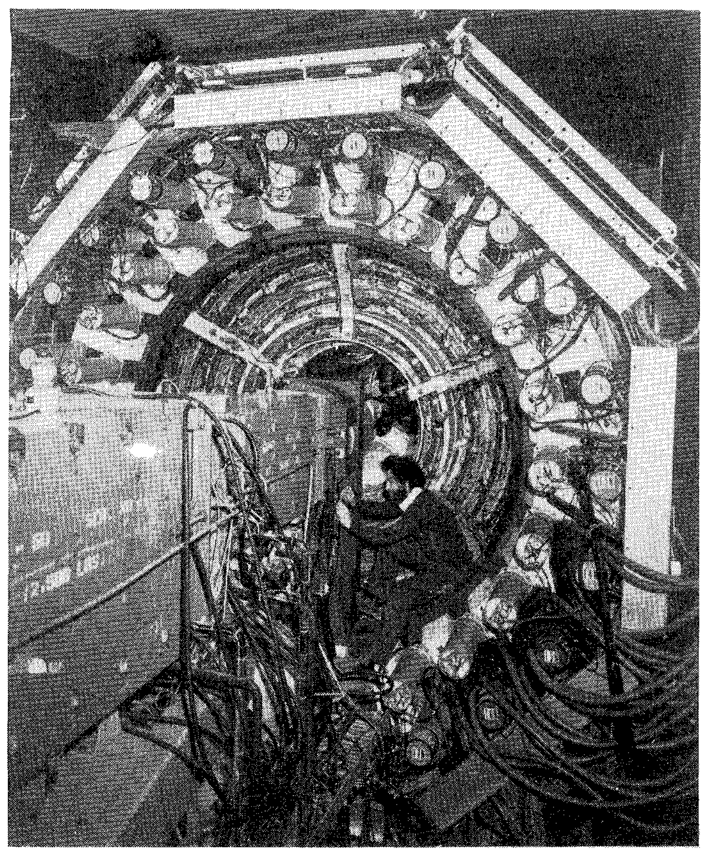
Experiments require that the beams circulate undisturbed for hours at a time, corresponding to about ten billion trips around the ring. This requires very tight tolerances on the magnets, stable power supplies, and a vacuum equivalent to a millionth of a millionth of one atmosphere.

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.



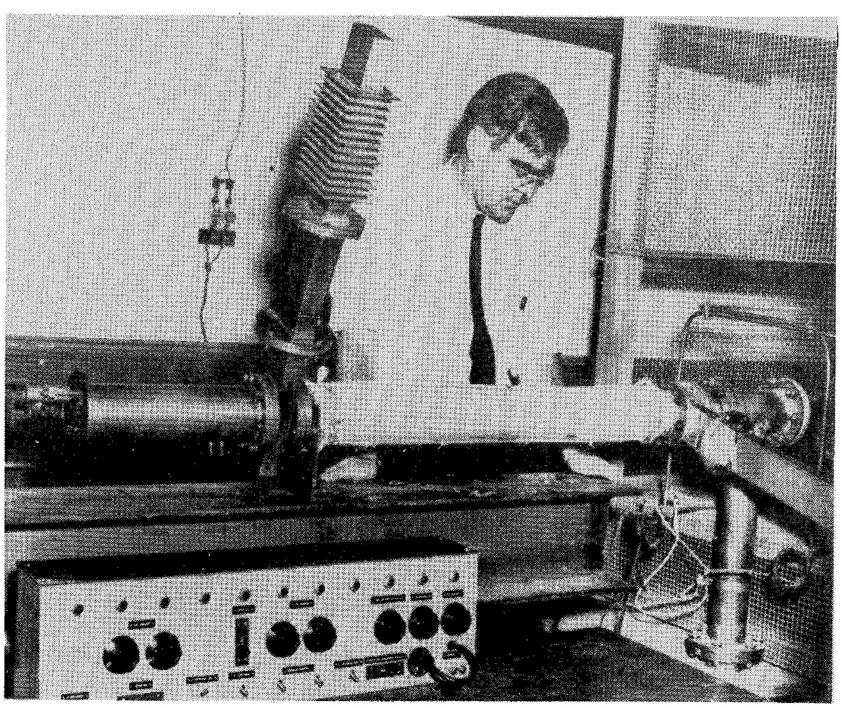
The Mark I detector at the SPEAR storage ring. Two of the magnets of the ring are visible in the left foreground. The physicist is resting against the magnet coil which surrounds one component of the detector.

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.

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.

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