Stanford Pulls Off a Novel Accelerator

A 600-meter-diameter loop at the end of an upgraded 3-kilometer-long linear accelerator is aimed at lassoing the fabulous Z^0 particle

Although federal money is never certain until Congress appropriates it (and sometimes not even then), the Stanford Linear Accelerator Center seems likely to be the home of the next high energy physics accelerator to be approved in the United States. The Stanford Linear Collider (SLC) is an add-on to the West Coast laboratory's famed electron linear accelerator that will pave the way for a future generation of "colliding linacs" and simultaneously allow U.S. physicists a crack at the highly sought Z particle ahead of their European competitors. If the SLC were ready to run in the fall of 1986 (the most optimistic date), its total cost including R & D, inflation, and possibly two detectors would be just over $186 million.

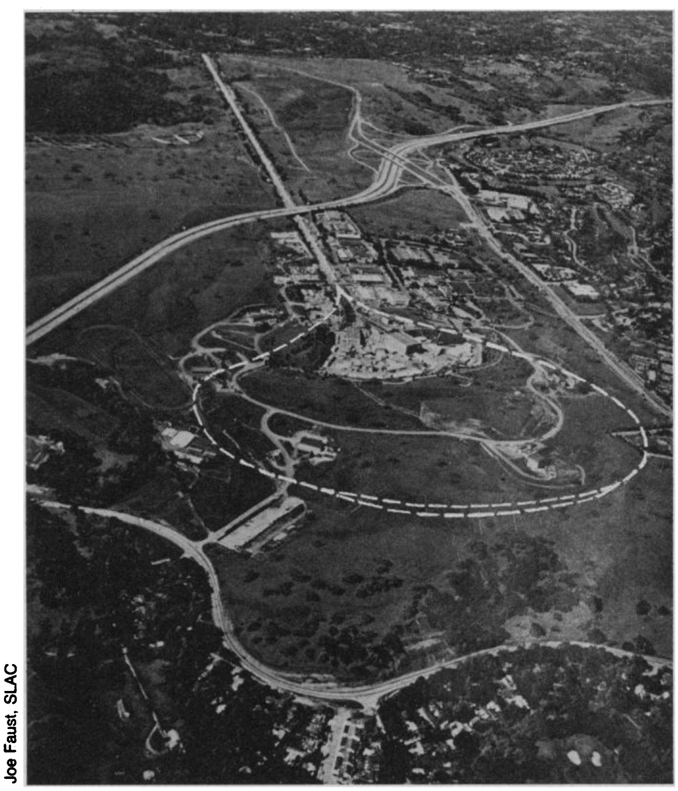
Time was becoming a matter of some concern at Stanford. The SLC was first proposed to the Department of Energy (DOE) for inclusion in its fiscal 1982 budget but did not make it. A try for fiscal 1983 (the budget now working its way through Congress) also fell short, although in both years some R & D money was made available. About $26 million will have been spent through fiscal 1983. The concern was that if major construction did not begin in 1984 at the latest, SLC's completion date would slip to 1988 or later, and a chance to beat the Europeans to a detailed examination of the Z particle would be lost. The European Organization for Nuclear Research (CERN) is building a giant machine named LEP and is aiming at a late 1987 start of operations (*Science*, 4 June, p. 1088; 31 July 1981, p. 528).

Now things are looking rosier for Stanford. The High Energy Physics Advisory Panel (HEPAP) that counsels DOE released a report this January on long-range planning in the field endorsing the SLC for a 1984 start. At its most recent meeting on 10 and 11 May, panel members reacted strongly against a suggestion by DOE officials that the likelihood of a lean fiscal 1984 budget might mean delaying SLC until the following year. This apparently was enough for Stanford, which on 18 May put out a call for letters of intent for SLC experiments. "While there are always uncertainties in future year fundings for high energy physics," read the letter, "we feel that the probability of having the SLC completed in 1986 or early 1987 is sufficiently large that it is advisable to now begin the process of selection of the first experiments for the physics programs of the project."

The cause of all the competition, the Z particle, or more properly the Z^0 because it is electrically neutral, is a resonance. When electrons and positrons collide head on, they annihilate, and the energy released is turned into other elementary particles. However, if the collision energy is equal to the mass of the Z^0, this particle is produced in great profusion, about a thousand times more frequently than all other possibilities put together. If the collision energy deviates slightly above or below the Z^0 mass, the rate of production drops precipitously, hence the resonance character of the particle. Moreover, the Z^0 is expected to decay into a host of other particles of great current interest, such as the Higgs and mesons containing the top quark. It is a true particle factory.

Such a resonance would be a bonanza for experimentalists who usually have to sift through large backgrounds to dredge out meaningful "signals." But the real value of the Z^0 lies in its implications for particle theory. It is one key to the so-called standard model of the world of elementary particles, which includes quantum chromodynamics as the theory of the strong nuclear force and a unified field theory that ties together the weak and the electromagnetic forces. It may also be possible to encompass all three forces into one "grand unified" theory, if the details of the electro-weak theory are proved out by experiment.

With a perverse sort of pride, experimental physicists probably would be just as happy disproving the standard model (and thereby make theorists just a little more humble) as verifying it, for the standard model has a powerful grip on current thinking. For one thing, the electro-weak theory has only one free parameter, and experiment has already placed tight limits on its value. The value of the Z^0 mass predicted by the standard model is just over 90 billion electron volts (GeV). Alternatives to the standard



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Stanford Linear Accelerator Center

Electrons start their 3-kilometer-long journey down the linear accelerator at the top of the photograph. The fan-shaped array of buildings at the bottom house fixed-target experiments. The winding but loop-shaped road around the fan roughly outlines the trace of the underground PEP electron-positron storage ring. The dotted line indicates the position of the SLC loop when completed. Originally, there were to be two collision points, hence the two arcs.

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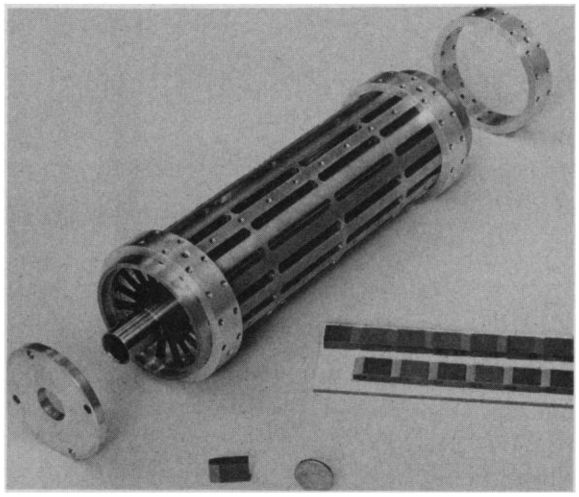
Beam focusing lens

In order to obtain a usefully high collision rate, the electron and positron beams must be squeezed down to a radius of about 1.4 micrometers at the collision point. A system of magnetic lenses is used to accomplish this. The final focus is by way of quadrupole magnets, which must be placed about 3 meters on either side of the collision point, whereas the particle detector may extend 10 meters in each direction. A $SmCo_5$ permanent magnet, a prototype of which is shown, is small enough and has other properties that allow it to be placed inside the detector.



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model, which are numerous and also consistent with all existing experiments, have several free parameters. As a result, they have little predicting power, and purists might not even consider them theories at all.

Letting of civil engineering contracts for construction of the machine the Europeans will use to study the Z^0 will get under way this winter. LEP, which stands for large electron-positron storage ring, is most modestly named. In fact, LEP is enormous, 27 kilometers in circumference or about four times the size of the biggest existing circular accelerators. It will cost $500 million (excluding four particle detectors, which will add another $125 million; staff salaries, which will add a comparable amount; and R & D). The reason for the mind-boggling dimensions is synchrotron radiation, which grows as the fourth power of the particle energy. Synchrotron radiation causes the particle beam to lose energy, which must be replaced on each turn around the ring. High energy, circular electron accelerators are voracious consumers of electricity. To reduce synchrotron radiation, which also varies as the inverse of the ring radius, physicists can build physically larger machines. The final size is a balance between the cost of building a large structure and the cost of operating a small one.

Burton Richter, leader of the SLC project, has argued that the cost of a circular electron accelerator scales as the square of its beam energy. From the financial standpoint alone, circular machines of higher energy than LEP, which will start out with 50-GeV electron and positron beams and work eventually up to 130-GeV beams, are unlikely to be built. Scaling up from the cost of LEP, Richter estimates the price of a machine with 350-GeV beams as $10 billion. Even LEP project director Emilio Picasso has said that his is probably the last accelerator of its kind.

In what may or may not be a coincidence, there is also a technical argument against circular electron accelerators of higher energy than LEP. LEP is a colliding beam storage ring in which counter-rotating bunches of electrons and positrons (about 10^{12} per bunch) meet at fixed points around its circumference. In any given meeting, at most one electron-positron pair will annihilate, and the stored beams circulate for hours. But, when the beam energy gets into the hundreds of GeV range, according to the calculations of machine engineers, nonlinear interactions between the particles in the bunches cause them to "blow up," so that the beams are lost.

One cure would be to reduce the number of particles in each beam, but then the collision rate would be too low to be of any use. The solution that Richter and his colleagues at Stanford have been championing (as has Alexander Skrinsky at the Institute of Nuclear Physics at Novosibirsk in the Soviet Union) is replacing the circular storage ring with two linear accelerators or linacs, one for electrons and one for positrons, aimed head to head. Since the beams do not recirculate, no one cares what happens to them after they pass through one another. Linacs also address the financial issue, according to Richter. Because there is no synchrotron radiation, their costs should scale only linearly with energy. "Sooner or later the curves have to cross over, and it will be cheaper to build linear machines," he says. "The only question is where the crossover lies, near LEP or far beyond."

Stanford's existing 3-kilometer-long electron linac, which now has a beam energy of 32 GeV, is the second most expensive machine ever built in the United States (when corrected for inflation). So, it clearly would not do to brashly try out the colliding linac concept, which would require two such machines, without a great deal of confidence that it would work. Stanford's masterstroke has been selling the SLC simultaneously as a development project leading someday to a very high energy machine and as a relatively inexpensive way to compete with Europe for Z^0 physics.

In essence, the SLC consists of a 600-meter-diameter loop affixed to the end of Stanford's linac. The latter would be modified to produce positrons and accelerate both these particles and electrons as high as 50 GeV. Electrons would follow one arm of the loop, positrons the other, and they would collide on the far side, releasing up to 100 GeV in each annihilation. The particles not annihilating would not recirculate, but new bunches of 5×10^{10} positrons and an equal number of electrons would be created and accelerated in the linac 180 times per second. Richter told HEPAP at its recent meeting that the SLC running at 50 percent efficiency for 40 weeks a year in this mode would generate about 3.5 million Z^0's annually, about the same as LEP would make for each of its four detectors.

Unlike LEP, the SLC would service only one detector. Once Stanford had a plan to switch the pulses of electron and positron beams alternately between two collision points, thereby permitting two experiments simultaneously. But the January HEPAP long-range planning report was cool to this idea because of the SLC's untried nature and counseled a more limited initial venture. In its call for letters of intent, Stanford indicated that current thinking is for two detectors that could be exchanged in the space of a few days by wheeling them in and out of the collision area in a push-pull arrangement. If the SLC did not work as planned, the second detector would not be built at all.

Also, unlike LEP, there are no plans to boost the SLC beam energy past 50 GeV. Doing so would have to be by the brute force method of adding radio-frequency power (klystrons) to the linac, and this would quickly become very expensive. "Only if the theorists are wrong and the Z^0 is heavier than expected would we be tempted to increase the SLC energy this way," says Richter.

The first detector is likely to be an upgraded version of one of the instruments now running at Stanford's 17-GeV per-beam storage ring PEP. The idea is to get to the Z^0 physics as fast as possible, and a new detector that needs months of debugging would not help with this. There are several options for the second detector, which Stanford's experimental policy advisory committee will sort through. Although the call for letters of intent promises a decision by next April for the first detector, it allows for a deferral on a recommendation for the second of several months "if that seems advisable." On other occasions, Richter has said that if the proposals are "dull, uninteresting, and all alike," none may be chosen right away.

Insofar as it is in the bag, Stanford has managed quite well to steer a careful course in these troubled times. Two years ago, when the SLC was proposed for the first time for funding as a construction project, a HEPAP subpanel headed by Sam Treiman of Princeton University was very favorably disposed to the innovative new machine. But, at that time, the Isabelle project at Brookhaven National Laboratory was in full swing, and the proton synchrotron at the Fermi National Accelerator Laboratory, which was to be upgraded to 1000 GeV (the Tevatron), was next in line for funding. There were "simply no funds available for new initiatives at this time." In addition, the panel members had a number of technical reservations. The recommendation in its July 1980 report was to reconsider the situation in 1 to 2 years.

Since then, Isabelle's well-publicized woes have caused that project to be put temporarily—perhaps permanently—on the back burner. Stanford physicists found that the collision rate of electrons and positrons would be higher than expected at first, making the SLC more comparable to LEP. And a new HEPAP subcommittee under George Trilling of the Lawrence Berkeley Laboratory recommended the inclusion of the SLC for construction beginning in 1984 under both the high- and the low-budget scenarios it considered.

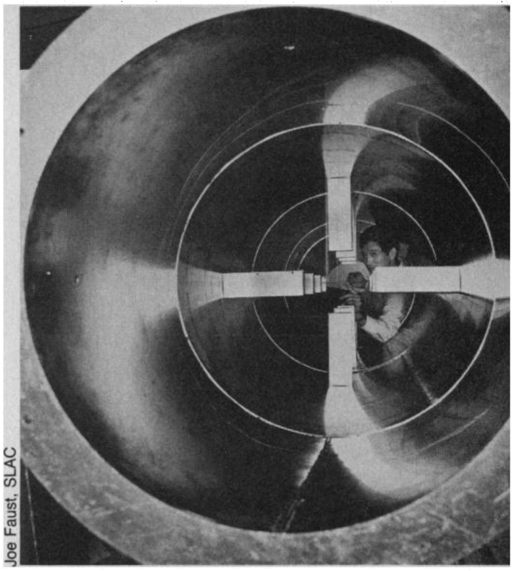
The subcommittee emphasized that its support of the SLC was not meant to endorse the Stanford machine as a replacement for Isabelle. That the SLC will have only one or two detectors ensures that the accelerator will serve only a limited portion of the high energy physics community, whereas Isabelle, along with the Tevatron at Fermilab (now scheduled for use starting in 1985), was to be a workhorse. Officially, DOE views the SLC as mainly an R & D project directed toward a future machine. High energy physicists are still looking for a "major new facility" for the early 1990's, whether an Isabelle greatly reduced in cost or some altogether new accelerator. What has happened is that the SLC and the new facility have exchanged places in the construction timetable.

How much money Stanford will get to begin building will, of course, not be known until next year when the fiscal 1984 budget comes out. At the May HEPAP meeting, DOE high energy physics chief William Wallenmeyer tossed out two scenarios roughly equivalent to those considered by Trilling's subcommittee. The lower-budget scenario showed the SLC being delayed until 1985. HEPAP members unanimously rejected slowing SLC this much. The overall sentiment seemed to be to recommend a 1984 start on construction, but HEPAP members were less united on recommending the full amount of money needed to meet the fall 1986 completion date.

A minor hurdle that was overcome came from residents in the affluent neighborhoods near the accelerator center. The first layout of the SLC had an unsightly building over the experimental hall and a chain link fence running across an oak tree–studded hillside in full view of a new housing subdivision. "Does it have to look so industrial?" The easy solution, which had the added benefit of lowering construction costs, was to realign the SLC so that the building sat in a hollow, out of sight.

More substantial problems lie in the SLC technology. The pulse repetition rate of 180 per second is about a thousand times lower than the frequency of the beams circulating in storage rings. The collision rate is proportional to the product of the number of particles in each beam, the frequency at which the beams cross, and the inverse of the beam cross section. For a collision rate in the SLC to be comparable to that in a storage ring, the SLC beam must be squeezed down to a much smaller cross section by the same factor of 1000. Thus, Stanford physicists must learn how to make and control a beam with a radius of about 1.4 micrometers.

Another challenge is modifying the linac to produce 50-GeV beams that are much more intense, by a factor of 100, than now is the case. A source to produce the intense beams has been developed already. In progress is work on the linac that will allow testing of the intense beams over one-third of its length by next March and over the entire length by the following year. To reach 50 GeV requires the development of new klystrons or the addition of more of the existing conventional devices. Three different ways to make more powerful kly-



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Wake field experiment

An electron in the waveguide of a linear accelerator induces an "image" charge in the waveguide walls. This charge in turn generates an additional electric field in the waveguide. When a bunch of electrons travels down the accelerator, the fields, called wake fields, due to the first electrons in the bunch tend to deflect the electrons toward the tail of the bunch from their straight path. In colliding beam linacs, the bunches must be densely packed with a larger than normal number of electrons (or positrons), and the wake fields can break them up.

strons are under investigation, and a decision as to which option to choose will come in about 2 years.

Finally, there is the positron source. The scheme for making positrons is to accelerate electrons two-thirds of the way down the linac, where they will bombard a metal target. Positrons streaming out from the target will be collected and brought back to the head of the linac. From there, the particles go into a "damping ring," whose purpose is to compress the physically large positron pulse to a smaller size that the linac can handle. The ring is quite small, with a circumference of only 34 meters, so that the 1.2-GeV stored beam will emit large quantities of synchrotron radiation, which is the compression mechanism. Construction of an underground building to house two damping rings, one for electrons and one for positrons, has been completed. The electron ring will be ready for testing on the high-intensity electron beam by this October.

When all is completed, each machine cycle will involve three pulses of particles, two of electrons and one of positrons. One electron pulse will be used to generate the next positron bunch. The second electron pulse and the positron pulse will meet in the collision region of the SLC and, Stanford physicists hope, spew out Z^{0}'s.—Arthur L. Robinson