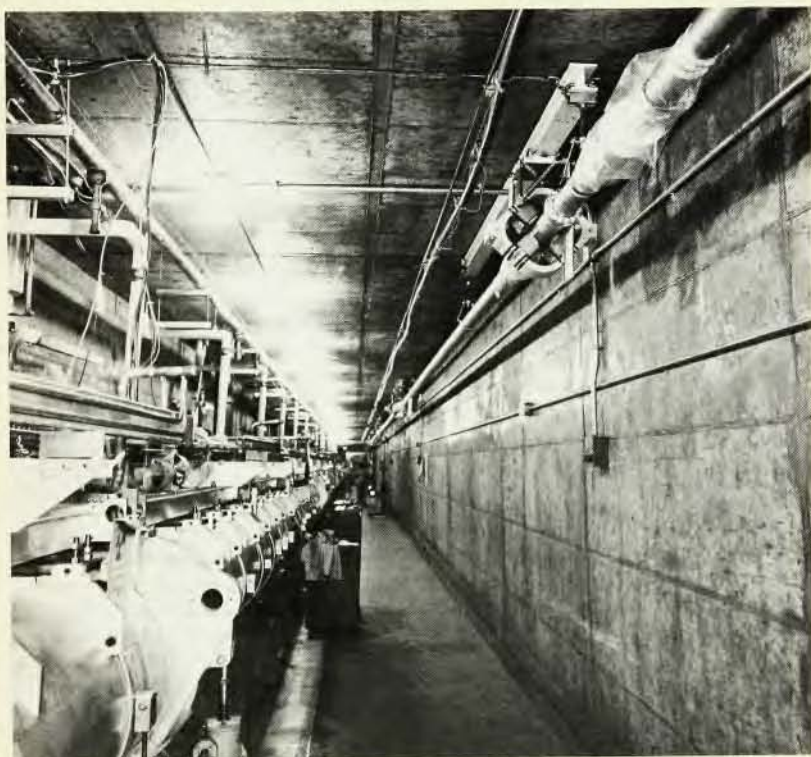


## Stanford linear collider scheduled to operate in 1986

Construction of the Stanford Linear Collider is well under way. The SLC is the crucial testing ground of a new accelerator technology, widely thought to be indispensable if we are to push electron-positron collision energies much beyond what LEP will make available. LEP, the Large Electron-Positron storage ring under construction at CERN, near Geneva, is scheduled to provide  $e^+e^-$  collision energies of 100 GeV by the beginning of 1989. But this gargantuan \$400-million ring, 27 km in circumference, is regarded by many as the largest practicable  $e^+e^-$  collider one can base on the well-tried storage-ring technology. Significantly higher  $e^+e^-$  energies, it is believed, will require linear colliders.

Why do  $e^+e^-$  (or  $e^-e^-$ ) storage rings have to be so outlandishly large? The Fermilab Tevatron, by contrast, will soon be providing us with proton-antiproton collisions at 2000 GeV (2 TeV) in a storage ring less than one fourth the size of LEP. The problem is synchrotron radiation. The rate at which a relativistic charged particle of mass  $M$  and energy  $E$  circulating in a storage ring of radius  $R$  dissipates its energy by synchrotron radiation is proportional to  $(E/M)^4/R^2$ . Thus for a given beam energy and radius, electrons (or positrons) radiate away  $10^{13}$  times more power than the much heavier protons (or antiprotons). Trying to mitigate the synchrotron radiation problem by increasing the radius of curvature, one soon runs up against a roughly quadratic growth of the cost of  $e^+e^-$  storage rings with increasing beam energy. Injecting a small note of skepticism into such calculations, Maury Tigner (Cornell) recalls the expert who announced 25 years ago that, because of synchrotron radiation, the Cornell 1-GeV synchrotron was the end of the line for circular electron machines.

Linear colliders would get around the synchrotron radiation problem by eliminating the offending circular beam path. Linearly accelerated beams of electrons and positrons would be fired at one another head on. In such a scheme the cost grows more



The 2-mile-long SLAC linac will provide 50-GeV electrons and positrons for the Stanford Linear Collider, now under construction. Looking down the tunnel, one sees the main accelerating structure at left and, along the upper right, the newly installed return line that will bring back low-energy positrons from the positron-production target near the downstream end, to be injected into the linac.

linearly with energy, implying that, above some crossover energy, linear colliders must become progressively cheaper than storage-ring colliders. But linear colliders have problems of their own. Because the particle bunches collide only once—in contrast to the repeated collisions of countercirculating bunches stored in a ring—one must make the bunches extremely dense to ensure a reasonable luminosity (event rate per unit scattering cross section). This requires bunch diameters on the order of a micron—incredibly small by the standards of conventional accelerator technology.

In February, the upstream portion of the SLC, with its electron damping ring

already in place, passed a crucial test indicating that the collider should be able to provide bunches of sufficient density with acceptably small dispersion in phase space. But because the technology is so new, it will probably be at least a year after SLC is completed in the fall of 1986 before the machine is operating at its full design luminosity of  $6 \times 10^{30}$  events/sec  $\text{cm}^2$ .

SLC is much more than just a proof-of-principle experiment for linear colliders. Five years ago, Burton Richter (who replaces the retiring Wolfgang Panofsky as director of the Stanford Linear Accelerator Center this month) proposed it as a way of providing the world's first abundant source of  $Z^0$

particles, while at the same time testing linear-collider technology (PHYSICS TODAY, January 1980, page 19). Incorporating the existing 2-mile-long SLAC linac, SLC could be built faster and much cheaper than LEP. The  $Z^0$ , the vector boson that mediates the neutral-current weak interaction, was first seen by Carlo Rubbia's UA1 group at the 540-GeV CERN  $\bar{p}p$  collider in the summer of 1983 (PHYSICS TODAY, November, page 17). But the grand total of  $Z^0$  events observed in a year of running by the UA1 and UA2 groups is fewer than two dozen. "We would hope to see that many in less than a single day's running at SLC," Richter told us. "I've always said that the CERN collider would probably be the first to find the  $Z^0$ ; but with a  $\bar{p}p$  collider you can't do much more than just discover it."

The observed mass of the  $Z^0$ , about 93 GeV, is in excellent agreement with the prediction of the Glashow-Salam-Weinberg theory that unifies the weak and electromagnetic interactions (PHYSICS TODAY, December 1979, page 17). But one wants to do much more than simply confirm its predicted existence and mass. An abundant source of clean  $Z^0$  events will permit one to determine its decay width, a crucial measure of the number of "generations" of elementary particles. It will also make possible detailed examination of the decay modes of the  $Z^0$ , putting the "standard" electroweak theory through severe tests. CERN director Herwig Schopper points out that with the few  $Z^0$  events now in hand we already have an upper limit of 7 on the number of particle generations permitted by the standard model.

SLC is designed to collide 50-GeV electrons with 50-GeV positrons. This is also the planned energy of the first (nonsuperconducting) phase of LEP. But the LEP tunnel is designed to accommodate beam energies up to 100 GeV. This will require eventually installing superconducting rf cavities, now under development at CERN. The high-energy community eagerly awaits the availability of 75-GeV beams because recent  $\bar{p}p$  collider data from the UA2 group suggest there may be some interesting, unanticipated physics at 150 GeV (see August, page 17). With colliding 85-GeV beams one reaches the threshold for producing the  $W$ , the charged cousin of the  $Z^0$ , which must be produced in  $W^+W^-$  pairs in an  $e^+e^-$  collider.

Once it reaches its design luminosity, SLC should be observing about three million  $Z^0$ 's a year. Not only is this five orders of magnitude higher than the  $Z^0$  production rate at the CERN  $\bar{p}p$  collider, the  $e^+e^-$  colliders should also provide much cleaner  $Z^0$  events than does the  $\bar{p}p$  machine. 270-GeV hadrons (protons and antiprotons) colliding

with one another inevitably produce a profusion of pions and other hadronic debris that makes it difficult to detect and study the production and decay of the  $Z^0$ . Furthermore hadrons are composites of quarks, while electrons and positrons (leptons) are thought to be structureless point particles. Whereas one cannot pinpoint the energy and momentum of the elementary quark-antiquark annihilation that creates a  $Z^0$  in a hadron collider, these quantities are fixed in the electron-positron annihilations of an  $e^+e^-$  collider. A typical constituent quark carries only  $1/3$  the proton's momentum; hence the need for very energetic  $\bar{p}p$  colliders.

**Getting there faster and cheaper.** The formal starting date for the SLC construction project was 1 October 1983. The construction is scheduled to take three years, at a cost of \$112 million. Richter expects that the first of the SLC detector systems—the upgraded Mark II—should be in place at the beginning of 1987, ready to do physics a few months later.

Construction of LEP began early in 1982. Because LEP is a much larger machine, starting essentially from scratch, SLC should be providing 100-GeV  $e^+e^-$  collisions in less than half the time and at one-fourth the cost. The SLC accelerating system—the SLAC linac—has been around for two decades, originally as a 20-GeV electron accelerator, upgraded to 30 GeV in the late 1970s.

The operation of SLC will require that the linac accelerate electrons and positrons to 50 GeV. To this end, the 240 thirty-megawatt klystron tubes that now supply the rf accelerating power will all have to be replaced by 50-MW klystrons. These 50-MW tubes, the world's most powerful pulsed klystrons, are currently under development at SLAC. "Some of the new klystrons we've built have already passed the 50-MW test," we were told by John Rees, who leads the SLC construction project. "But our big problem right now is the ceramic output windows." They must maintain the klystron vacuum while passing 50 megawatts of 3-GHz rf power out into the linac waveguide structure. The problem is to protect the windows from intense x-ray bombardment (from stray electrons), which tends to overheat and crack them. Various protection schemes are currently under study. Rees is confident that all 240 high-power klystrons, manufactured at SLAC, will be in place and operational by 1 October 1986.

**With only a single linac,** SLC is not really a full-fledged linear collider. This makeshift prototype is perhaps better described as a "single-pass" collider. The downstream end of the 2-mile linac puts out a single bunch of 50

GeV electrons, followed closely by a similar bunch of positrons. The major new construction for SLC is a pair of curved arcs, each about a mile long, emerging from the end of the linac much like the arms of a stethoscope. The electron bunch is steered through one of the collider arcs, the positron bunch through the other. The far ends of the two arcs are joined by a short straight section in which the final beam optics focus the two bunches down to their ultimate 1.3-micron transverse dimensions in preparation for the single head-on collision. To provide the very strong magnetic-field gradients needed to focus the beams to such an extraordinary degree, the last triplet of focusing quadrupoles on either side of the collision point will be superconducting magnets.

The collider arcs approximate a ring with a diameter of 1 km, somewhat larger than the five-year-old PEP  $e^+e^-$  storage ring, underneath which they make their way to the trench housing the collision point. A circulating 50-GeV electron beam stored in so tight a ring would radiate away about 2% of its energy per (10- $\mu$ sec) revolution—a totally impractical situation. But one can easily afford the 1% of its energy that each electron and positron bunch loses in its single half circuit, en route to their one and only encounter.

**Progress.** By midsummer of the first year of construction, the underground tunnels for the two collider arcs are more than half dug, and the vault that will house the positron damping ring has been dug, walled and joined to the linac housing. The electron damping ring, which sits on the other side of the linac, has already been in testing operation for a year and a half. Both damping rings, located near the upstream end of the linac, are required if one wants to compress the electron and positron bunches to micron dimensions—a thousand times smaller than the bunch dimensions required for the traditional operation of the SLAC linac. They are essentially miniature storage rings that exploit synchrotron radiation damping to reduce the phase-space spread of the particle bunches before they reenter the linac to complete their acceleration. Great care must also be taken lest the phase-space compression achieved in the damping rings be degraded in the subsequent three miles of beam transport. To that end, a special monitoring system will be required to keep the beam very close to the centerline.

SLC passed a significant milestone last winter, when a sufficiently compact electron bunch from the damping ring was accelerated  $1/3$  of the way down the linac. The luminosity of a collider depends on the number of particles in a bunch and on its emit-

tance, the product of its angular and spatial spread in a given direction normal to the beam axis. To provide reasonable confidence that SLC can yield a luminosity of at least  $10^{29}$   $\text{sec}^{-1}\text{cm}^{-2}$ , it was felt that at this stage one must demonstrate the acceleration of bunches containing  $10^{10}$  electrons to 6.5 GeV with horizontal and vertical emittances of no more than about  $3 \times 10^{-9}$  mrad. This was accomplished, with some fanfare, shortly before dawn on 4 February.

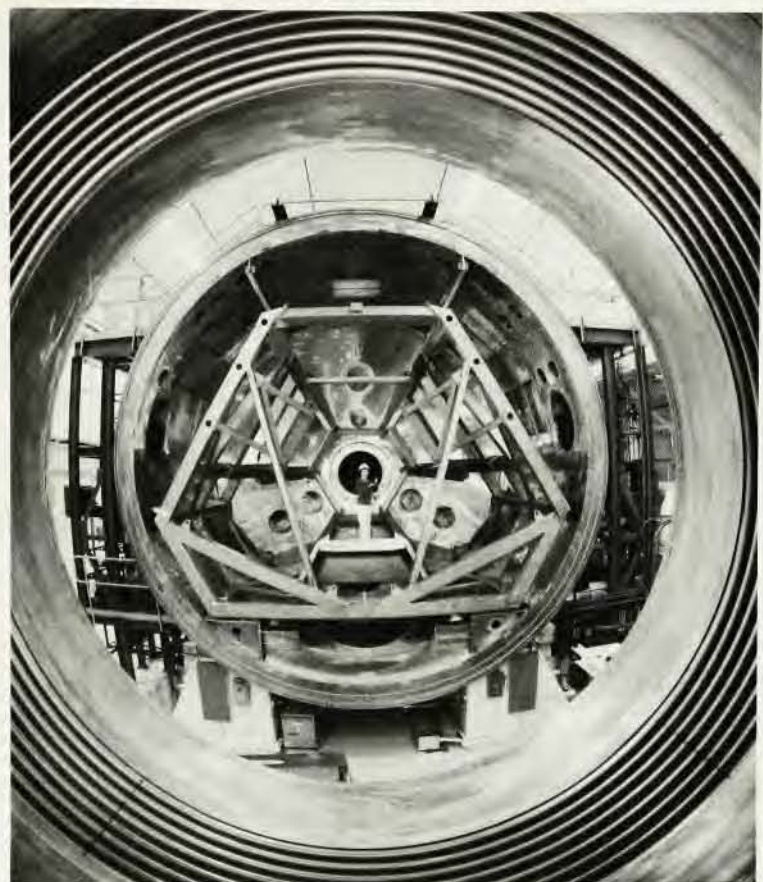
The ultimate goal is to run with electron and positron bunches each containing  $5 \times 10^{10}$  particles. A high-current electron gun capable of producing such large bunches was already in place at the time of the February test, but the extra-strong focusing needed to transport them to the first accelerating stage of the linac was not installed until July.

**How will the positron bunches be produced?** The SLAC linac traditionally accelerates only electrons. SLC will operate at a repetition rate of 180 cycles per second. In each of these cycles, the linac will accept two new electron bunches from the injector. After a respite in the electron damping ring, both bunches are accelerated down the linac, but one is diverted near the far end to strike a "positron-production" target. Among the debris produced in this high-energy collision with the tungsten-rhenium target is a profusion of low-energy positrons, which are collected, accelerated to 200 MeV, and then transported back to the injection end of the linac through a separate return line now under construction in the main linac tunnel.

After a further acceleration in the first stages of the linac, the positron bunch spends two machine cycles in the positron damping ring—twice as long as the electron bunches because its initial phase-space spread is so much greater. After damping, the positron bunch continues down the linac, joined by one of the two electron bunches from the subsequent machine cycle. Separated by 17 meters, the two oppositely charged bunches are accelerated to 50 GeV by opposite phases of the 3-GHz rf wave propelling them down the linac. Emerging from the 2-mile linac, the  $e^+$  and  $e^-$  bunches go their separate ways in the collider arcs, finally colliding after being focused down to micron size.

The luminosity of a collider is of course proportional to its effective repetition rate. Having to accelerate fresh bunches every cycle limits SLC to a rather slow rate of 180 Hz. This must be compared with the hundred times faster rate at which countercirculating bunches stored in the LEP ring complete their 27-km course, passing through one another again and again. The linear collider compensates by

## Fusion experiments have begun at Antares



Antares, the world's highest-power  $\text{CO}_2$  laser, was ceremonially dedicated at Los Alamos in January. Experiments had in fact begun a month earlier. The purpose of Antares is to evaluate the feasibility of  $\text{CO}_2$  lasers as drivers for inertial-confinement fusion. The system's 24 laser beams are focused onto a 100-micron-diameter deuterium-tritium target pellet, delivering 25-kilojoules of 10.6-micron, infrared light in nanosecond pulses. It is anticipated that Antares will eventually run at 40 kJ.

The picture shows the space frame inside the Antares target chamber. Although the shorter wavelengths put out by neodymium glass lasers such as Nova (page 20) are expected to couple more efficiently to D-T fusion pellets,  $\text{CO}_2$  gas lasers are of particular interest for practical laser fusion because they can sustain much higher repetition rates, tolerating heat levels that a solid-state lasing medium probably could not survive.

having much denser bunches.

In this regard the fact that linear-collider bunches are discarded after one pass is something of an advantage. When very dense charged-particle bunches pass through one another, their reciprocal electromagnetic interaction is a serious source of "beam-beam" perturbation. In a single pass, this perturbation does little harm; but with the repeated passes of a storage ring it puts an upper limit on the tolerable charged-particle density in a bunch. LEP could not increase its luminosity by compressing its bunches to anything like micron dimensions.

The design luminosity of LEP is 1 to  $2 \times 10^{31}$   $\text{sec}^{-1}\text{cm}^{-2}$ , two or three times that of SLC. But, Richter points out, this is the *peak* luminosity. In a

storage ring, the beam intensity, and hence the luminosity, begins a steady decay from the moment the ring is filled. From experience with similar, albeit much smaller,  $e^+e^-$  rings, Richter argues, one must divide the peak LEP luminosity by a factor of two or three to compensate for filling time and beam decay in arriving at the effective time-averaged luminosity. Thus, he concludes, the time-averaged design luminosities of LEP and SLC are about the same.

With four experimental collision points, compared to only one for SLC, LEP can of course observe four times as many interesting events per unit time even if both machines have the same luminosity. Furthermore, "you'd have to be an even crazier optimist than I'm

known to be," says Richter, "to believe that SLC will come close to its design luminosity in its first year." LEP, on the other hand, with its essentially traditional technology, should reach its design parameters more promptly. But Richter is confident that the SLC detectors will see at least a hundred thousands  $Z^0$ 's in the first year.

Two detector systems have already been selected for the early operation of SLC. The first to go into the collision area will be the seven-year-old Mark II detector, veteran of the SPEAR and PEP  $e^+e^-$  rings at SLAC. For its new role at SLC, the Mark II will be extensively upgraded. It will get a new drift chamber and end-cap detectors that will permit the detection of particles within  $5^\circ$  of the beam direction.

Because the SLC beam width at the collision point is much narrower than that of storage rings such as PEP or LEP, one has the opportunity to begin tracking charged particles very close to the collision point. This is particularly important for the direct observation of bottom- and top-flavored heavy mesons (see August, page 17), whose lifetimes are as short as  $10^{-12}$  or  $10^{-13}$  seconds. To exploit this closer access to the collision point, the Mark II will get a small, moderately high-resolution vertex detector, which will permit tracking within 1 cm of the  $e^+e^-$  collision point. Whether this vertex detector will employ charge-coupled-device elements or silicon microstrips has not yet been settled.

The second detector, called SLD, is being built from scratch by an 18-group consortium headed by Charles Baltay (Columbia) and Martin Breidenbach (SLAC); it will not be ready until 1988. This state-of-the-art detector, costing \$50 million (twice what it would cost to build the Mark II today), "will have all the bells and whistles needed to do a complete  $Z^0$  physics program," Richter told us. Breidenbach hastened to assure us that these "bells and whistles" are to be accomplished within a reasonably austere budget.

Whereas Mark II has no hadron calorimetry, SLD will have a "fission-compensated" hadron calorimeter—alternating layers of uranium and liquid argon. Bill Willis (CERN) has demonstrated that replacing the traditional iron by uranium in a hadron calorimeter permits one to exploit fission processes to improve the energy resolution by a factor of two. SLD will also have a Cherenkov ring-imaging detector for particle identification, and an ultra-high-precision vertex detector with a resolution of 10 or 20 microns.

The two detectors will reside on opposite sides of a "push-pull" platform in the experimental area, devised so that one can switch detectors at the collision point with relative ease. In

addition to  $Z^0$  physics, it now looks as if the new Stanford collider will be doing extensive top-quark spectroscopy. Richter stresses the fact that the single-pass collider, unlike  $e^+e^-$  storage

rings, can provide polarized-electron collisions. Even though it cannot offer polarized positrons, the polarized electrons will greatly facilitate the study of electroweak processes at SLC. —BMS

## Nova nears completion



Inertial-confinement fusion experiments at Livermore's 10-armed Nova laser are expected to begin early next year. With the capacity to deliver 100-kilojoule, nanosecond pulses of 1.05-micron infrared light, Nova will have the highest peak power (exceeding 100 terawatts) of any laser yet built. In July, eight of the ten Nova beams were fired, delivering a 57-terawatt, nanosecond pulse. Eventually such pulses will be directed at millimeter-sized deuterium-tritium pellets, exploring the density and temperature region of D-T fusion ignition.

The photo shows the optical switchyard, through which the ten 74-cm-diameter beams are transported from the laser room (rear left) to the evacuated target chamber room, where they are focused and made to converge on the pellet. The large aluminum tubes (5 of the 10 are visible here, in various stages of completion) assure the cleanliness and thermal uniformity of the air through which the beams travel. Baffles on the inner tube walls remove stray light from the beam.

The lasing medium is neodymium, doped into a special phosphate glass designed to tolerate the extraordinary light-density levels of Nova. KDP crystals will be incorporated to provide second-harmonic (green) and third-harmonic (ultraviolet) output in addition to the fundamental infrared neodymium lasing frequency. Experiments on Novette—an experimental setup employing the two arms still to be transferred to Nova—have shown that the coupling of the laser light to the pellets is enhanced at these shorter wavelengths.