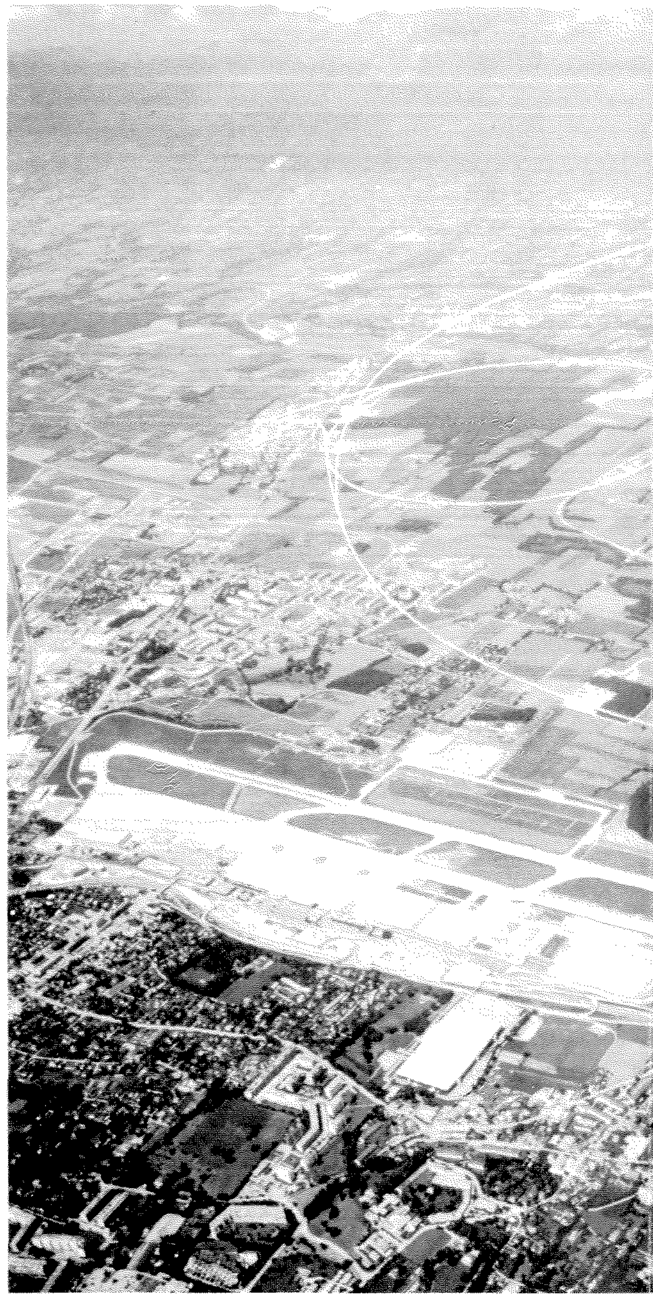
Quark Quest



THE BESTIARY OF subatomic physics draws its denizens from a world where energy and mass are one, where time slows down as speed increases, and where particles conjure new particles from the void or transmute themselves through interactions with other particles—by tossing still more particles back and forth at each other. In this world where energy transforms into mass, a particle can only appear when the available energy is more than its rest mass, with a little something left over to give the newborn particle some velocity (kinetic energy). In the search for these particles, physicists continue to build bigger and more powerful particle colliders. The particle hunters, armed with computerized detectors, hope to find ever more massive particles in a generous pool of free energy.

Research teams from Caltech are participating in several experiments. One group, headed by Associate Professor of Physics Harvey B. Newman, hopes to find new particles in the wreckage of electron-positron collisions. Newman's group is helping design an experiment to be installed at the LEP (Large Electron Positron) collider, currently under construction at CERN, the European Laboratory for Particle Physics, in Geneva, Switzerland.

Newman hopes to find the top quark and the Higgs particle. Both particles are believed to lurk in the 150 - 200 GeV range. (GeV stands for giga [read billion] electron volts. An electron volt is the kinetic energy gained by an electron passing through a one-volt electric field in a vacuum.) Both particles have tantalized physicists for years, and a false sighting of the top quark has been reported at least once. But, in fact, they have remained just beyond the view of today's accelerators.

Physicists want the top quark for aesthetic reasons, as its discovery would bolster the fundamental theory's internal consistency. Quarks bind together to form protons, neutrons, and most other particles, just as protons and neutrons form atomic nuclei. As things currently stand, five quarks have been found. The fifth, the bottom quark, represents a loose end. Quarks and another set of particles, the leptons, appear to be fundamental: they behave as points, with no signs of internal structure. There are six known leptons, not counting antiparticles: the electron, the electron neutrino, the muon, the

muon neutrino, the tau, and the tau neutrino. The leptons divide neatly into three pairs or "generations," each containing a particle and its neutrino. Each generation is more massive than its predecessor, but resembles it in all other properties. Quarks display a similar grouping, pairing "up" and "down," "charmed" and "strange," but the bottom quark sits in splendid isolation in the heavyweight division. The top quark would round out the roster, making the quark and lepton families symmetric. This would cause several intractable processes predicted by the theory to cancel each other out, leaving a self-consistent theory of quark and lepton interactions.

The Higgs particle would confirm the standard theory of electroweak interactions—the Weinberg-Glashow-Salam (WGS) theory. The electroweak theory unifies electromagnetism and the weak nuclear force, and is a big step toward a Theory of Everything describing the four forces of nature—gravity, electromagnetism, and the weak and strong nuclear forces—as different aspects of one fundamental force. Just as quanta of electromagnetic force are carried by photons, the weak force is carried by three particles, the W^+, W^-, and Z^0. But while photons are massless, these other particles have been found to have masses 90 to 100 times the mass of a proton. The WGS theory meets the challenge

Aerial view of CERN with underground rings drawn in. LEP is the largest ring. (CERN's aboveground complex is at left, surrounding the smallest ring.) The Jura Mountains are in the background.

of describing how two forces can be aspects of one force when the particles that carry them appear so different. The mathematics is quite complex; but once the smoke clears several sets of infinite terms cancel each other out. The residue is a solvable set of equations with finite terms, but when all the terms describing the photon, W^+, W^-, and Z^0 have been sorted out, a set of terms is left over. These terms describe a new particle, christened the Higgs after the physicist who developed the math that creates it.

The particle collider is to high-energy physics what the telescope is to astronomers. Just as many astronomers use one telescope for different purposes, several experiments can be run on the same accelerator. In order to understand Caltech's role in the LEP project, therefore, we shall look first at the LEP itself, then at the experiment, and finish with a closer look at one of Caltech's contributions.

The idea behind a particle collider is quite simple. Take equal measures of electrons (e^-) and positrons (e^+), or protons (p) and antiprotons ($\bar{p}$), or protons and protons. Put them in a high-vacuum tube (two tubes for proton-proton collisions), goose them with a powerful electromagnetic field to rev them up to a very high kinetic energy—to a velocity close to lightspeed—and then send them headlong at each other. The collisions will have twice the kinetic energy of either particle alone, plus all the energy released in the matter-antimatter annihilation of e^+e^- or $p\bar{p}$ collisions. This energy creates new particles, which fly off in directions whose distribution may be determined by their charges, masses, and the initial collision parameters. An array of detectors around the collision zone determines the trajectories and charge/mass ratios of the departing particles. The interesting particles often don't reach the detectors, but decay into something else almost immediately. The physicists match their quarry's predicted decay patterns with observed particle distributions and energies.

Putting this simple scheme into practice is another matter. Each component has numerous parts and subassemblies of its own. Institutions around the world provide the parts, which must fit more tightly than the pieces of any jigsaw puzzle. The whole is run by a vast array (a hierarchy, really) of computers whose software was assembled the same way. The entire operation requires so much complex equipment and sophisticated computing that there are only a handful of high-energy particle accelerators in the world. The accelerator complex at CERN, LEP's future home, is one of the world's largest, most sophisticated collections.

LEP should be operational by 1989. It will operate in the 44-200 GeV range, where the top quark and Higgs particles are expected to appear. It will be the largest electron-positron accelerator in the world, and will incorporate many novel design features. The LEP ring, 27 kilometers in circumference (approximately 9 km in diameter), is buried under the French-Swiss border between Lake Geneva and the Jura Mountains.

LEP will accelerate electrons and positrons in opposite directions around a circular track. Electron-positron pairs were chosen because they have no internal structure, unlike protons, which are made up of quarks. The collisions are therefore easier to reconstruct, as there are no secondary reactions among the component quarks to confuse the picture. The price to be paid, and the reason LEP is so big, is that any particle radiates photons (called synchrotron radiation) when accelerated. The electrons and positrons in LEP radiate vast amounts of high-energy photons, requiring many megawatts of power to make up for the energy losses. If the ring were smaller, forcing the beam around tighter corners, the power loss to synchrotron radiation would be much higher.

The electrons and positrons are confined in a high-vacuum pipeline only inches in diameter. The pipe passes through a series of radiofrequency (RF) cavities and magnets. Since electrons and positrons are oppositely charged, a single RF pulse will push them in opposite directions. Similarly, a single magnetic field will bend the two beams in equal but opposite directions. The beams collide head-on at the four experimental halls.

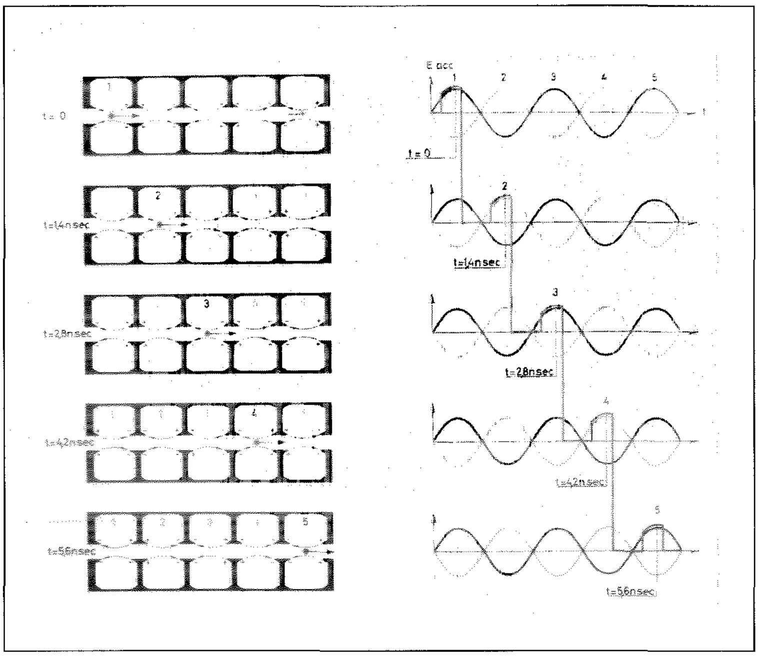
Each beam is 500 microns (μ, 10^{-6} meters) wide and 25 μ high at the interaction points, less than the thickness of a human hair. That space contains approximately 90 percent of the beam's particles. Since the number of collisions is proportional to the beam's density, or "luminosity," the accelerator physicists are working to make the beam even tighter. Initially, LEP will circulate two e and two e^+ bunches, each 1.6 mm long.

Like all particle accelerators, LEP uses the behavior of point charges in electromagnetic fields to accelerate subatomic particles. LEP uses resonance cavities—hollow, copper-lined cylinders divided into chambers by a series of plates. The plates are perpendicular to the beam line, which passes through their center. An oscillating RF field in the cavity, synchronized with the particles' passage, gives them an energy boost with every plate due to interactions with the field's electric component. The oscillations are timed so that the RF field is decreasing while the particles are passing through it. This helps keep the bunches together, as particles arriving early—having slightly less energy and thus following a slightly smaller orbit—see a stronger field and get a bigger push. Overenergetic latecomers get a smaller push, slowing them down.

The LEP has 128 RF cavities of five chambers each. They produce an acceleration of 1.5 MeV(million electron volts)/meter using an RF field of 352 megahertz (MHz) at 16 megawatts of power. The total ring will be able to produce up to 110 GeV initially. It can be upgraded by adding 64 niobium superconducting cavities producing 7 MeV/m. LEP II will eventually replace all the RF cavities with superconductors and the ring will operate at 186 GeV with no additional power consumption. According to Newman, "that's actually less than at PETRA [a 46.8-GeV machine in Hamburg, Germany]. When I was there we could draw 50 megawatts from the local net. This machine is much bigger, but it will use less power."

The LEP ring broke new ground in its RF cavity design. Conventional RF cavities keep the field at constant strength between bunches, even though the cylindrical design does not store the field efficiently. The time between succeeding bunches is much too small (44 microseconds for LEP) to turn the power supplies feeding the field on and off. Unfortunately, power losses from the RF cavities add a significant surcharge to the operating cost. The LEP designers added a spherical chamber atop each resonance cavity, connecting the two with a magnetic "gate." The sphere stores the RF field very efficiently. The magnetic gate opens to let the RF field down into the resonance cavity as each bunch passes, and closes again in its wake. Newman estimates the new design will save 40 percent on LEP's electric bill.

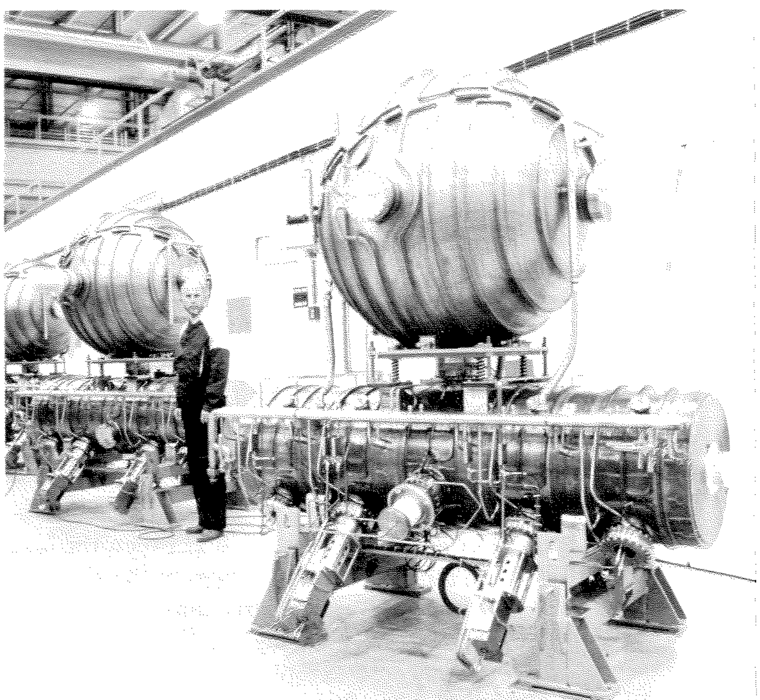
Powerful electromagnets guide the particle beams between RF cavities. Magnets exert a force perpendicular to both the field's orientation and the particle's path. Dipole magnets



A particle moving through an RF cavity (left) and its RF field (right). The field gives the particle a boost with each chamber.

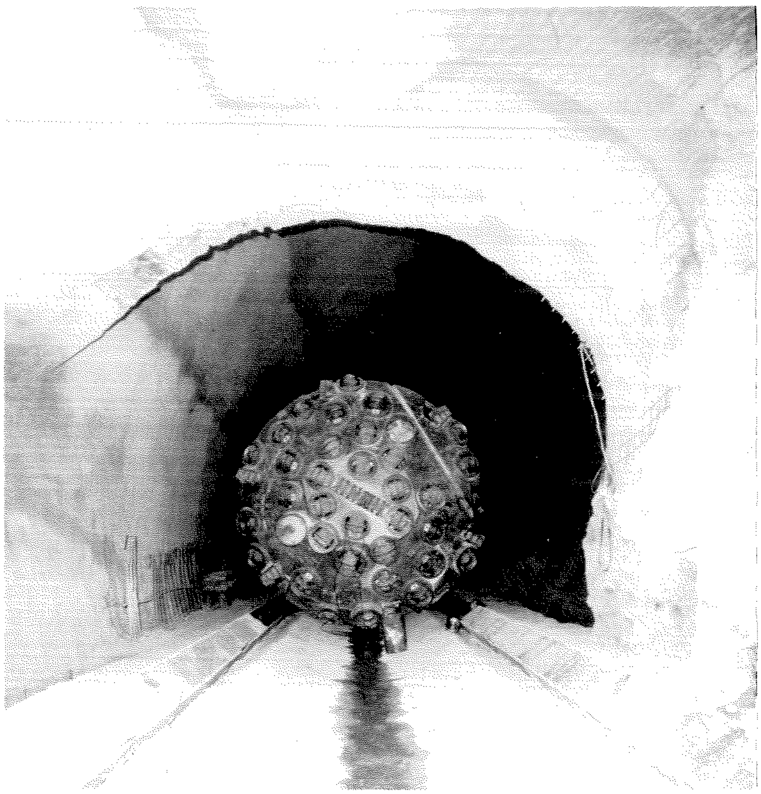
steer the beam around the ring. Quadrupole magnets (magnets with two opposing sets of north and south poles, and hence two opposing fields) keep the beam tightly focused. Otherwise, the repulsion between like charges within a beam would cause it to spread out as it travels. Fine adjustments to the beam's shape often require sextupole magnets. The LEP ring has 3,304 dipole magnets, 776 quadrupoles, and 504 sextupoles.

LEP's steering magnet design is another first. The magnets don't have to be very



RF cavity assemblies with storage spheres.

powerful, but they must be absolutely rigid to keep the particle beam properly aligned. The designers substituted concrete for the metal core used in conventional electromagnets. The result is an electromagnet with thin metal stampings embedded in concrete, with the concrete making up most of the structure. "The concrete magnets turned out to be very rigid, with very good geometric integrity," Newman said. "We saved over 50 percent of the cost of normal magnets."



The tunneler's cutting head. The machine bores a hole 4 meters in diameter.

Most of the ring's site has already been excavated by a tunneling machine. The machine clawed a 4-meter borehole through the local sandstone at up to 60 meters per day. Preliminary designs had a good portion of the ring under the mountains, but test borings soon revealed that the limestone there was more than a match for the tunneler. The designers were reluctant to make the ring smaller because of the synchrotron radiation problem. They couldn't put the ring under downtown Geneva or the lake, either. They wound up setting the ring on a 1.5 percent grade in order to shoehorn it between the lake and the mountains. A portion of the ring still passes under the mountains' periphery. As of December, 1987, the ring has been completely excavated except for 80 meters in a dense limestone formation, where the work proceeds by pick, shovel, and explosives.

In the meantime, the experimental halls have been excavated, and work proceeds on the magnets, detectors, and computers needed to make it all work. All the magnets have been built and are on-site. Detector components are being built around the world. Some portions are already in the final assembly and testing stage on-site. LEP3NET, an international computer network, is up and running. Administered by Caltech, LEP3NET connects American and European research centers with the first transatlantic data communications link dedicated to high-energy physics. Physicists worldwide are contributing control and analysis programming.

The LEP ring will host four experiments, ALEPH, DELPHI, L3, and OPAL. The Caltech group is part of the L3 project. While the other three experiments' names are acronyms generated by applying intense heat and pressure to a phrase describing the experiment, "L3" simply means this experiment was the third proposal submitted to run on the LEP ring.

"The L3 experiment is designed to emphasize very-high-resolution energy and momentum measurements of photons, electrons, and muons," Newman said. "We are aiming for resolutions of 1 percent at 50 GeV.

"We will make very precise measurements of the electroweak theory. LEP collides electrons and positrons in a very small energy spread, so in just a few days' running you can get a very precise mass for the Z^0. The experiment is so precise, it's a bit of a theoretical challenge. You have to do third-order calculations in order to obtain theoretical predictions as good as the experimental precision. The Z^0 mass is the most precise quantity that can be measured. It will serve as the refer-

MUON PAIR ASYMMETRY

Muon pair asymmetry is a consequence of the weak force, which is responsible for neutron decay, among other things. Weak interactions do not conserve parity, which has profound mathematical consequences. On the observable level, it means that particles formed in weak force reactions tend to be ejected in certain directions relative to an external magnetic field. If parity were conserved, muons of a given electric charge would have equal probability of being ejected "forward" or "backward" relative to one of the incoming beams. The electroweak theory predicts the degree of asymmetry that should be observed at a given energy.

ence point for further tests of the theory.

"We can then measure something else against that: the asymmetry of muon pair production. We will run for 200 days and collect about 6,000,000 Z^0s. Of these, 200,000 produce muon pairs. Then we can measure the asymmetry with a statistical accuracy of 0.2 percent.

"If the top quark has a mass of 180 GeV, it will affect the asymmetry by 0.8 percent, so that's detectable at our experimental accuracy of 0.2 percent. As the particles get heavier, they have a greater effect on the symmetry. But if the top quark gets too massive, when you go back to the low-energy experiments that have been done and reinterpret them in order from low energy to high energy, putting in corrections for the mass of the top quark, the experiments no longer agree with each other. If the mass gets very large—like 400 GeV, 450 times the mass of the proton—the whole self-consistent picture of the unified electroweak theory that occurs for a more reasonable top quark mass falls apart.

"After we study the Z^0, we'll go on to higher energies. One of the best ways to see the Higgs is to look for certain rare events. For example, at 165 GeV, electrons and positrons can collide to make a Z^0 and a Higgs. The Z^0 goes to a muon pair, which you detect, and by precise measurements of the muons you can measure the mass of the Higgs recoiling against that pair. This probably will require two years of continuous running at 4,000 hours per year, from which we may get twenty events. (This depends on the mass of the Higgs, and—of course—on its existence!)"

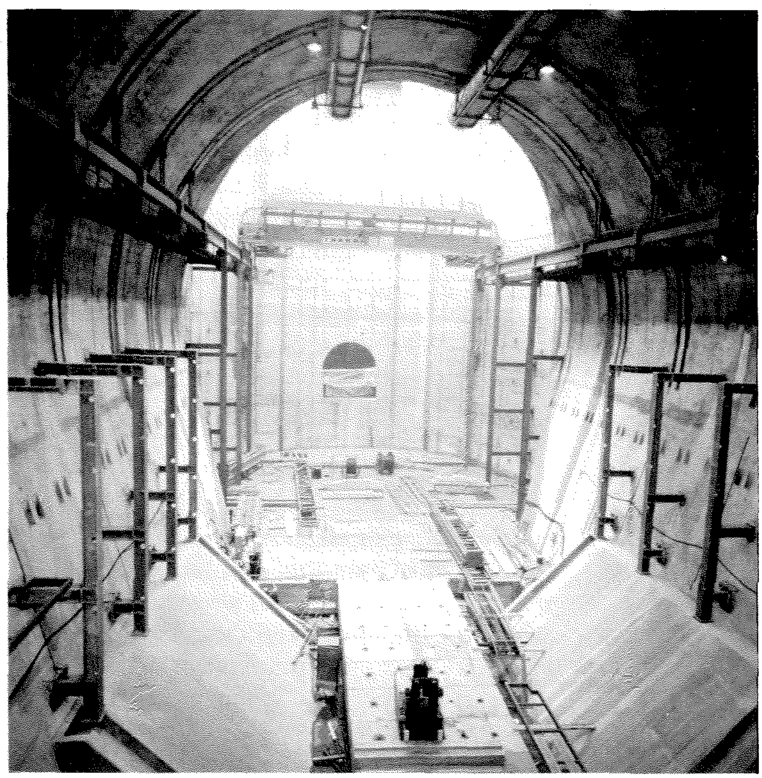
The cavernous L3 experiment hall lies 50 meters below the French countryside. That hall is the shallowest of the four; the hall under the foothills of the Jura Mountains is a vertiginous 150 meters (approximately 500 feet) below ground. ("It doesn't sound like much," Newman said, "but when you look down this hole 500 feet deep, it's a long way down. And people had to go up and down stairs. The elevators have only recently come into service.")

L3's massive detector assembly, bigger than a two-story house, almost fills the hall's 21.4 m diameter by 30.5 m length. The detector components must be lowered piecemeal down an access shaft, to be reassembled below. A crane traveling on rails high under the vaulted roof wrestles components weighing tons into positions accurate to fractions of a millimeter. Some components require an 800-ton crane at the surface to lower them down the shaft. There are only two cranes that big in all Europe, one of which will soon visit CERN. These cranes are itinerant specialists, always on the move from job to job.

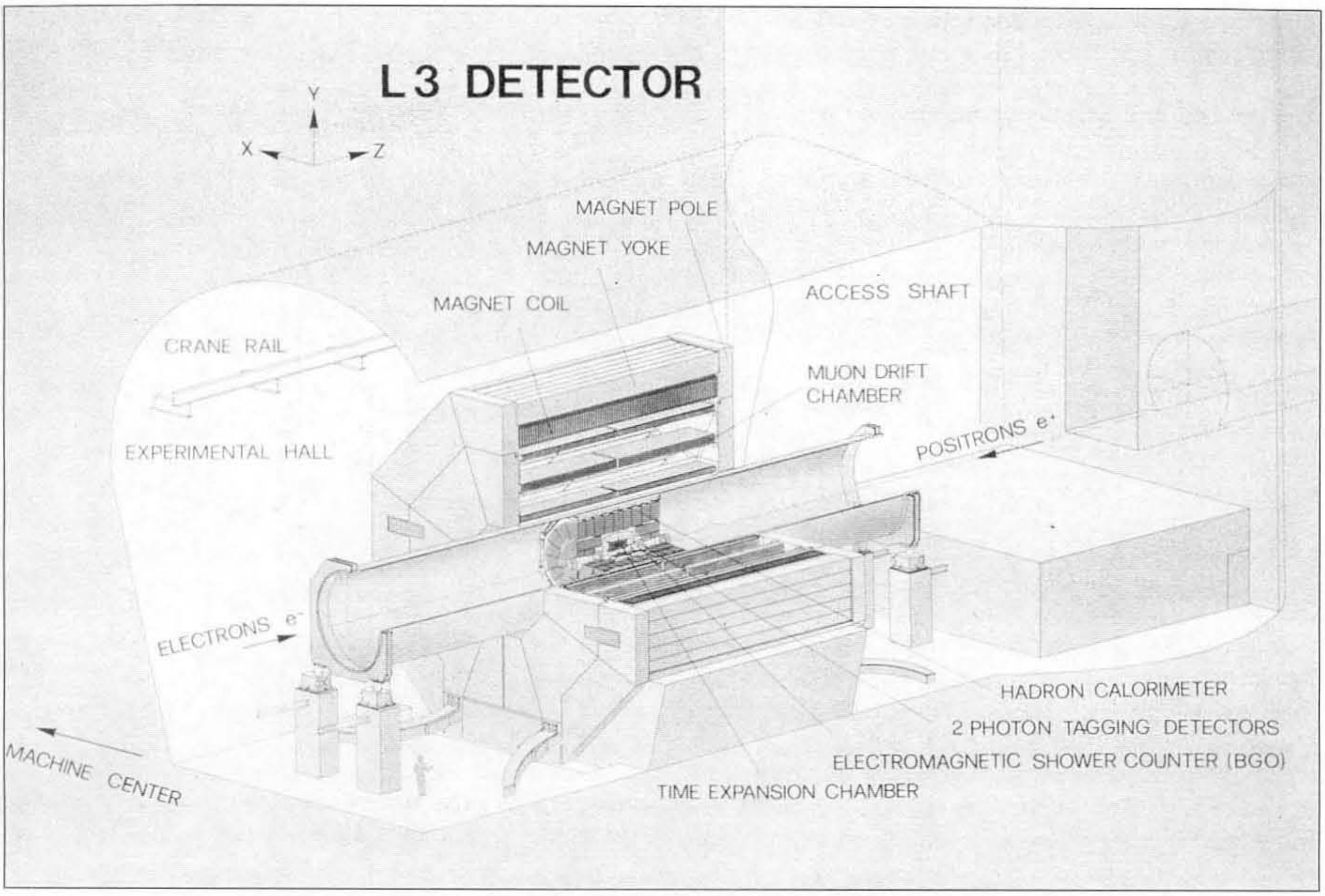
The detector assembly contains four different detectors nested around the collision point like Russian puzzle dolls. Each detector completely surrounds the beamline, so only particles leaving at very small angles, and the elusive neutrinos, will escape undetected. (All particles must be accounted for to balance the mass-energy books. If the books are too far out of balance, it can indicate that new, unpredicted particles are being formed.) The time expansion chamber (TEC) is innermost, surrounded by the electromagnetic calorimeter, the hadron calorimeter, and the muon drift chamber.

A gargantuan electromagnet surrounds the detectors. This electromagnet, the largest ever built, provides the powerful magnetic field needed to separate particles by their charge/mass ratio. The electromagnet weighs 7,600 tons. It creates a magnetic field 5,000 gauss strong, constant over a volume of 1300 cubic meters.

The TEC, according to Newman, is "a very-high-precision detector for tracking the trajectories of charged particles and measuring their momentum. It measures all the



The L3 experiment hall, looking toward the access shaft. Note the forklift in the foreground for scale.



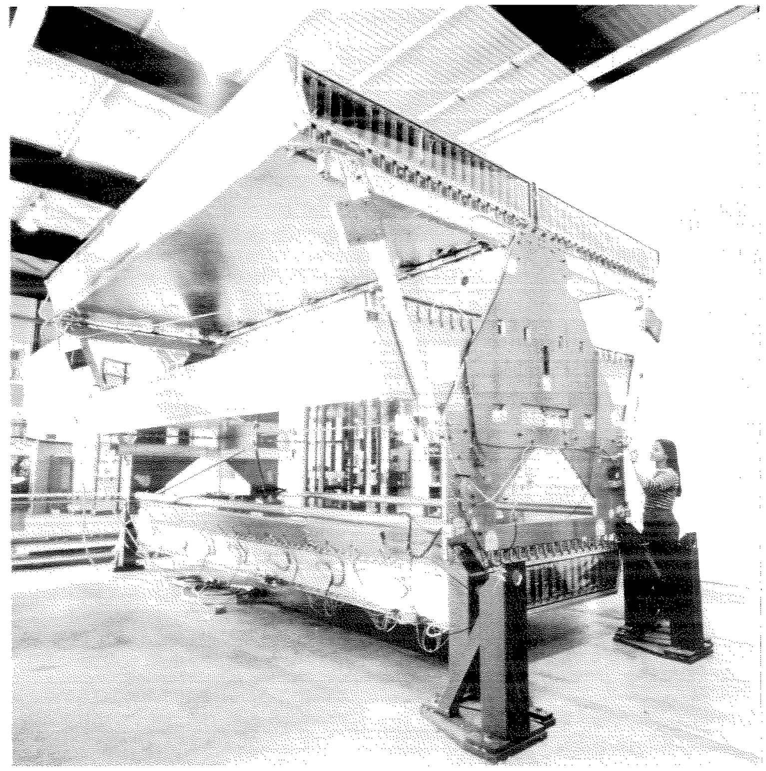
charges within 10 microseconds after an e^+e^- collision, and its hardware integrates them into particle tracks in real time." Further analysis determines how the magnetic field has deflected the particle. The direction shows whether the particle has a positive or negative charge, and the curvature gives the charge-to-mass ratio. The combination reveals the particle's identity.

The particles pass through the TEC and into the electromagnetic calorimeter. The "calorimeter" doesn't actually measure heat. It's a scintillation counter on a grand scale. A barrel-shaped array of 12,000 bismuth germanate (BGO) crystals detects photons, electrons, and positrons. A single photon penetrating the crystal dissociates into an electron-positron pair. Each particle interacts with the crystal to produce photons, creating additional electron-positron pairs. The resulting avalanche of electrons and positrons produces a lot of light that eventually reaches a photodiode on the crystal's rear surface, where the photons signal their arrival with an electrical pulse. The amount of light produced is proportional to the energy deposited in that particular crystal.

The hadron calorimeter doesn't detect heat, either. It intercepts protons, neutrons, mesons, and hyperons, all comparatively massive particles that interact with heavy nuclei. It also absorbs the small part of the electromagnetic "cascade"—electrons, positrons, and especially photons—that may slip past the BGO crystals. The densely packed nuclei in the calorimeter's 600 tons of depleted uranium—^{238}U from which all ^{235}U has been removed—are so many sitting ducks for the hadrons from the collision zone. A particle will probably ricochet off a nucleus as it passes through the detector. The particle will change direction and lose some kinetic energy with each collision. It will also produce new particles, which may interact in turn, forming a cascade of particles. Approximately 60 concentric sets of 5-millimeter-thick uranium plates alternate with parallel tubes containing a mixture of 80 percent argon and 20 percent carbon dioxide. As a particle zips through a tube, it ionizes the gas and generates a signal on a detector wire. Computer analysis of signals from successive layers of tubes helps recreate the particle's path. A particle's track length is proportional to its initial energy, which can then be deduced. The modules are being built in Michigan, Aachen, Bombay, and Beijing, with production scheduled to be completed in December 1987.

Muons, having only about one-tenth the mass of hadrons, and being immune to the blandishments of the strong nuclear force, whizz unscathed through the hadron calorimeter and into the muon drift chamber. This is actually three concentric sets of chambers. Each chamber is a long, flat box made of thin aluminum sheets. The boxes contain a total of 116 kilograms of argon and ethane. Again, as the muons pass through the gas, they leave ionized trails that are detected on a three-dimensional wire array. The innermost box has 16 wire layers perpendicular to the particle's path. The center box has 24 layers, and the outer box has 16. Each particle thus leaves a trail of 56 data points. Optically flat glass sheets keep the wires in perfect alignment down to 10-micron tolerances. The entire drift chamber system is dynamically stabilized to the same tolerance. "With the very-high-energy particles we'll be looking at, high precision is critical," Newman explained. "For example, with a 45-GeV muon the deviation from a straight line, by which you can measure the momentum, is only 4 millimeters in 6 meters. We want to reach 1 percent accuracy for the muon pair's mass reconstruction, which means 1.5 percent for each muon. To do this, we need to measure the deviation from a straight line to the order of 50 microns. The total systematic error, i. e., the total error in the computer's knowledge of the location of the detector wires in space at any instant, has to be less than 30 microns." The muon chambers will be assembled into 16 "half-octants" of five chambers each. Most of the octants have already been built and tested at CERN.

The data from the TEC, the BGO array, the hadron calorimeter, and the muon drift chambers go through a massive on-line parallel processing system. The computer has a complete picture of the detector arrays in its memory. Each component's location and orientation in space is known to a precision dictated by the physics, which in some cases is within 10 microns. The system takes all the signals from all the detectors, over 100,000 channels of data, and integrates them into a three-dimensional "picture" of all the particle tracks. Some of the computational power goes into deciding what particles came from uninteresting events, and discarding them before too much computational time or storage space is wasted on them. These decisions must be made in real time while the detector is running. Soon after, LEPICS, an off-line computer at CERN, sifts through the stored particle tracks, identifies the particles, and winnows out those combinations that could not have been produced by the particles or decay modes of interest. The off-line analysis can take many months to complete. Thanks to LEP3NET, the analysis can be coordinated among participating institutions, and some computer work can be done locally.



Muon drift chamber "half-octant" assembly. The two upper rows have two chambers each.

Most projects at CERN are international collaborations, and the L3 experiment is the largest and most widespread. Four hundred physicists from forty institutions in thirteen countries are contributing to the project. The list of American participants includes Caltech, Carnegie-Mellon, Harvard, the University of Hawaii, Johns Hopkins, M.I.T., the University of Michigan, Northeastern, Ohio State, the University of Oklahoma, Princeton, Rutgers, and Yale. Other contributors include groups from China, France, East and West Germany, Hungary, India, Italy, the Netherlands, Spain, Sweden, Switzerland, and the Soviet Union.

L3's Caltech contingent numbers only one associate professor, one senior research fellow, two postdocs, and assorted undergraduates. Yet this small group has been responsible for key elements of the basic design of the muon drift chamber; for developing LEPICS; for developing and operating LEP3NET; and for developing a calibration technique for the BGO crystals used in the electromagnetic calorimeter.

The BGO subproject preserves the international flavor of the whole. The USSR supplied some of the raw materials. The Shanghai Institute of Ceramics is making the crystals. France provided the technology to cut, grind, and polish the crystals to tolerances of 100 μ in 24 cm. West Germany furnished the photodiodes. An Italian firm specializing in helicopter rotors built the supporting barrel. Caltech is calibrating test arrays of 20 and 49 crystals.

Each BGO crystal is a long, thin, truncated pyramid. The crystal's front face is 2 × 2 cm. The back face, where the photodiode is mounted, is 3 × 3 cm, and the crystals are 24 cm long. When the crystals are assembled into a barrel, their tapered shapes aim their long axes at the barrel's center—the collision point.

Besides having the requisite transparency and scintillation properties, BGO is quite dense, almost as dense as iron. The heavier the atoms in a material, the more likely incoming particles are to interact with its nuclei. The crystals are long enough to absorb 99 percent of the energy from an electromagnetic cascade produced by incoming high-energy electrons, positrons, or photons.

Unfortunately, great density also means great weight. Each crystal weighs a kilogram. But the supporting structure between crystals must be as thin as possible to minimize the odds of any particle from a cascade missing the crystals. The support must also be very rigid to keep the crystals aligned accurately. The final design uses a lightweight grid of molded carbon fibers. The grid is only 0.2 mm thick between crystals. The grid weighs a mere 400 kg, yet it supports ten tons of crystals.

The BGO crystal array is designed to measure energies in the neighborhood of 100 GeV with a precision of 0.5 percent. The array will require frequent calibration while in use to maintain such high resolution. The Caltech group developed a calibration method using a Radiofrequency Quadrupole (RFQ) proton accelerator.

The RFQ would be installed underneath the LEP ring. An angled beamline would connect the RFQ to a lithium target in the collision zone. The RFQ would bombard the target with high-energy hydrogen atoms, producing a high-intensity flux of 17-MeV photons. The crystals' response can be calibrated to the photon's known energy. The entire system, including the vacuum line carrying the hydrogen beam, is completely independent of the LEP ring.

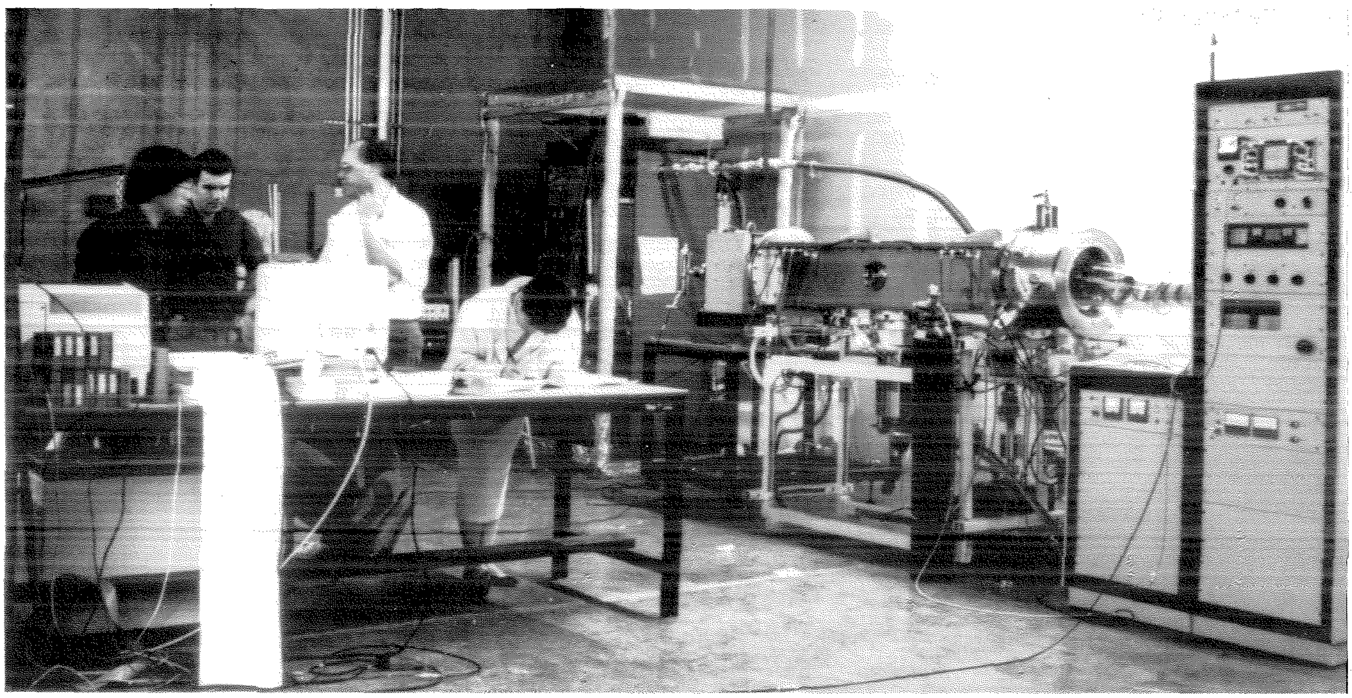
The system can operate between runs, or even while the LEP is running. The RFQ's electronics will be strobed to an external trigger. The RFQ will emit a high-intensity pulse, one to three microseconds long. The intensity must be carefully controlled: high enough that photons hit an appreciable number of crystals, yet not so high that two photons hit the same crystal. The pulse length is no less important—it must be short enough for the crystals' response to be measured accurately, and for the detector's electronics to work with a high ratio of signal to electronic noise. A single pulse calibrates only 200 to 300 of the 12,000 crystals, but at 200 pulses per second the entire array can be calibrated in an hour or two. Although RFQs running at low pulse rates have been used as proton sources in the first, or preinjector, stages of high-energy proton accelerators, no one had ever attempted to run one at 200 Hz *within* a physics experiment before.

The Caltech group tested their idea on a 20-crystal array in the first week of November 1987. They had originally planned to do it at the Los Alamos National Laboratory, but it seems international cooperation only goes so far. Graduate students Hong Ma and Renyuan Zhu, who designed the calibration setup and built the readout system, were denied security clearances. Both are from mainland China. So they wound up at a commercial RFQ manufacturer, AccSys, Inc., of Pleasanton, California, instead.

Since the calibration occurs while the experiment is running, the lithium target cannot be set up at the collision point. With an offset target, though, some photons would hit crystals at angles of up to 55° from the long axis. The test showed that good results can still be attained at 60°. Thus the entire barrel can be calibrated from a single location.

The experimenters also let the system pulse continuously for two days at an intensity equivalent to a couple of weeks' running in the LEP ring. The system proved quite stable.

Although the test was successful, the experiment hit one not-unexpected glitch. The unshielded RF source generated a power-



ful field that interfered with the detector's sensitive electronics. (This shouldn't happen at LEP, where the entire RF system will be well shielded, and the RFQ will be much farther away from the controls.) Unfazed, the team slapped an RF shield together from wood slats, chicken wire, and generous swatches of aluminum foil. This four-hour exercise in low technology reduced the RF interference tenfold. They gained another tenfold reduction by moving the RFQ away from the rest of the system. This was no mean feat—the RFQ weighs about 800 pounds. Six people and a one-ton hoist were needed to push it across the floor. Furthermore, the vacuum system had to be opened to the air while the team inserted a ten-foot extension into the RF conduit. The conduit itself is a two-inch copper pipe containing a smaller pipe held in alignment by teflon spacers. The system acts as a high-power coaxial cable, carrying the RF power to the RFQ accelerator.

Even before the calibration test was arranged, BGO crystal production entered high gear. As these are the largest BGO crystals ever made, early production runs were by trial and error. The system is up to speed now, with more than 100 people working around the clock to produce 420 finished crystals every month. The first half-barrel of 4,000 crystals has been shipped to CERN, where it was set up and precalibrated in July through August, 1987. Crystal production for the second half-barrel will be finished by early 1988, and production of the two end caps (of 2,000 crystals each) will then begin. Overall, it will take another year and a half at current production rates to finish the assembly.

And so it goes. There's still a lot to be done before L3 is up and running. The chief French mechanical engineer said it best. With elegant calligraphy, he painted an old Chinese proverb on the finished half-barrel's housing. Roughly translated, it says, "In a journey of 100 miles, 90 miles is halfway."

Will the results be worth the wait? Newman is confident. "We've been searching for the last ten years for the top quark. My last experiment was actually built to find the top quark, and in eight years of running we didn't find it. With L3, we have achieved very ambitious technological goals in electron, muon, and photon resolution. We have to be rather unlucky, or nature has to be almost perverse, for us not to see the top quark. If the standard theory is working, the top quark should be in the LEP range. And if we don't see the top quark, the self-consistency of the unified electroweak theory will be in jeopardy. Either way, we will have a new, exciting situation for the experimenters and for the theorists."□—*DS*

Newman will give the Caltech Associates President's Circle a two-day tour of CERN and L3 this May. The President's Circle will tour Europe May 3 through May 12.

H. Ma, R. Mount, H. Newman and an AccSys employee (l. to r.) testing the BGO calibration system (along right-hand wall, from left:) RF source (in wood and wire enclosure), RFQ accelerator (on white cart—BGO array [not shown] would go at left end), detector electronics. The RF conduit emerges near the top of the enclosure and passes down behind the RFQ.