SLAC BEAM LINE

Like artists, creative scientists must occasionally be able to live in a world out of joint.
— Thomas Kuhn

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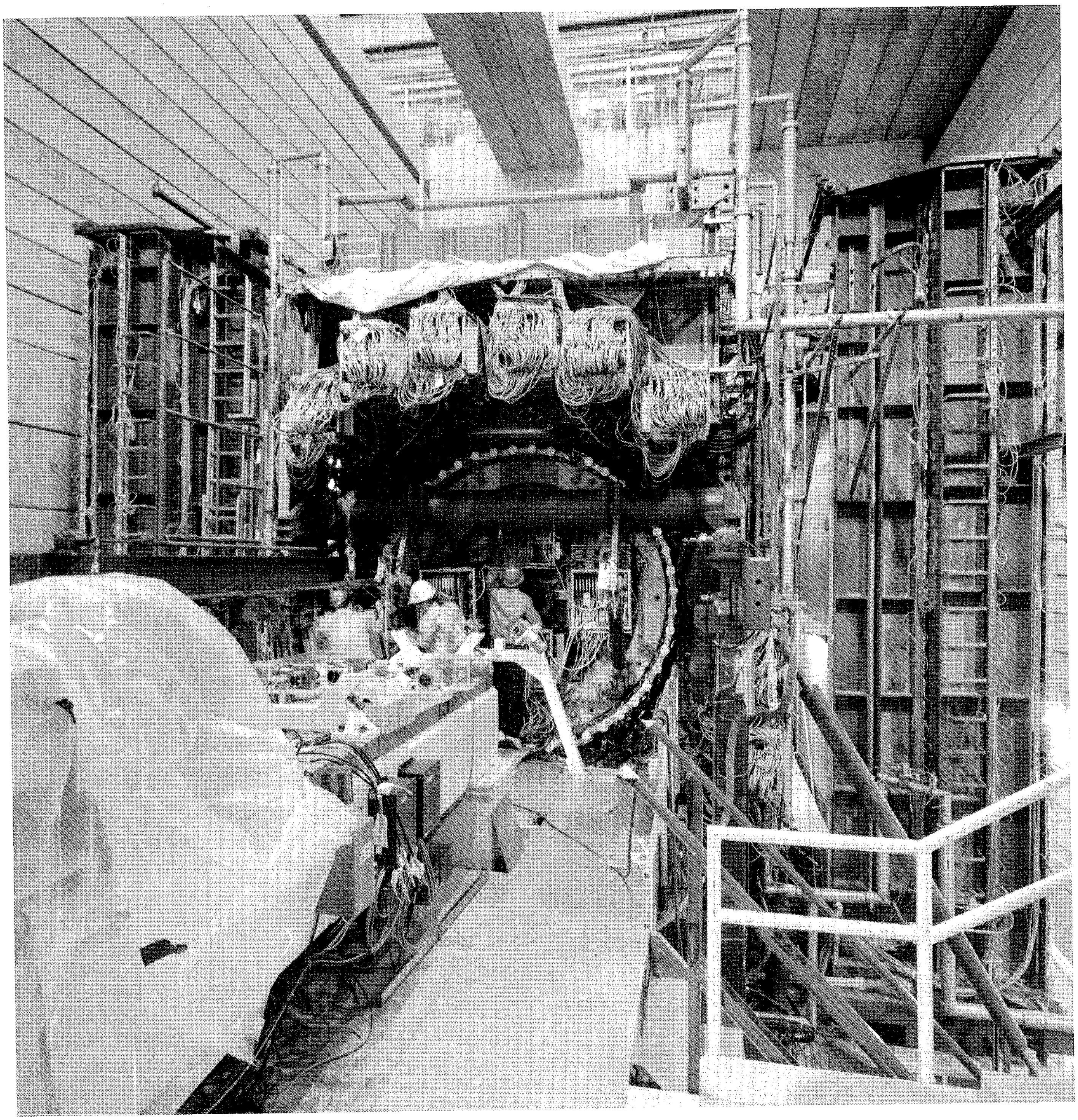

The Mark II Detector at the SLC

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IN THIS ISSUE:

Stanford University operates SLAC under contract with the U.S. Department of Energy.

With this issue the *SLAC Beam Line* begins a small shift in direction. We will be attempting to reach a slightly different audience than in past years. The community of physicists from other institutions who use the SLAC facilities need a publication that addresses their interests, too. Therefore readers will find increasing emphasis in these pages on scientific matters. Other topics of interest purely to SLAC staff will be reserved mainly for the Personnel Newsletter edited by Marian Wehking.

Heading this issue is an article beginning on page 3 about the Mark II detector and how it will extract information on the Z° particle. Following that are a piece by Malcolm Browne excerpted from the *New York Times* and a survey of the recent SLAC Summer Institute. On the last two pages are several short articles of general interest to the community.

We invite contributions from SLAC physicists, staff, and visitors. Deadline for the December issue is Monday, October 31. Special thanks on this issue are due Shirley Boozer for typesetting and Sylvia MacBride for illustrations and paste-up work. Unless otherwise indicated, all photos are by Joe Faust.

—the Editors

COVER PHOTO: The Mark II detector being prepared for its first data-taking run at the SLC interaction point. Bunches of high-energy electrons enter from the lower left and collide with positrons inside this detector, which records the tracks and energy deposits of particles emerging from these collisions. (Photo by Joe Faust)

FIRST SLC RUN ENDS

The initial colliding-beam run on the Stanford Linear Collider (SLC) ended on Monday, September 12. Work began immediately to retune the linac so that it can again inject electrons and positrons into the PEP and SPEAR storage rings. High-energy physics research at these facilities resumes this fall while extensive improvements are in progress at the SLC.

Major advances in accelerator physics occurred during the recent SLC run. For the very first time ever, bunches of electrons and positrons smaller than 5 microns in radius were collided successfully. The slight deflection of one beam by the other, first witnessed in June (*SLAC Beam Line*, June 1988, p. 2), has now been developed into a powerful steering aid that can be used to aim the beams to a relative accuracy of 1 micron. And in early September strong, clear signals were observed for a phenomenon unique to the SLC called *beamstrahlung* — bursts of electromagnetic radiation thrown forward by two compact bunches as they cross.

Although the basic principles of a linear collider have been demonstrated, the SLC must maintain its beams in collision for long periods of time in order to serve as a useful tool for physics research. In all, beams collided for about 60 hours this summer, and 34 hours worth of data were logged on the big Mark II detector, but no Z°'s were observed during this period. Hardware problems and untimely component failures, together with the long time presently required to retune the collider, have been the principal reasons for this performance.

An important development that occurred during August was the successful test and subsequent use of a subtle technique known as "BNS damping." Never before attempted, it restricts the growth of transverse bulges in the particle bunches as they travel down the two-mile linac, leading to large reductions in the size of their troublesome tails. Other promising techniques have helped the SLC achieve smaller spots (3–5 microns) at the interaction point and control slow drifts seen there in the beam positions.

While improvements are under way at the SLC, attention turns to the SPEAR and PEP rings. Physicists working on the Mark III detector at SPEAR plan to search for rare objects in decays of the ψ' particle and hope to study the production and decays of the rare F meson at a combined energy of about 4 GeV. At PEP the TPC collaboration plans extensive studies of the τ lepton and B mesons at an energy of 27 GeV. After the improvements have been completed in January, top priority will return to the SLC, which will run through August 1989.

—Michael Riordan

THE MARK II DETECTOR AT THE SLC

by Kathy O'Shaughnessy

For over a decade the Mark II has been a familiar, successful particle detector at SLAC. Originally built by the SLAC-LBL collaboration in 1977 to replace the Mark I detector at SPEAR, it was designed to study in detail the ψ and τ particles discovered there.

Meanwhile SLAC was building the PEP storage ring with a higher energy, expecting the first beams to be available in 1980. The collaboration proposed to upgrade and move the Mark II detector to PEP after it had finished taking data at SPEAR. The idea was that a seasoned, well-understood detector could be moved to PEP and be able to analyze data soon after beams began colliding. The Mark II finished running at SPEAR, was moved to PEP during the summer of 1979, and started logging data in 1980. Although no new particles were discovered with the detector, the experimenters were able to study the b quark (discovered at Fermilab in 1977) and fulfill other important goals.

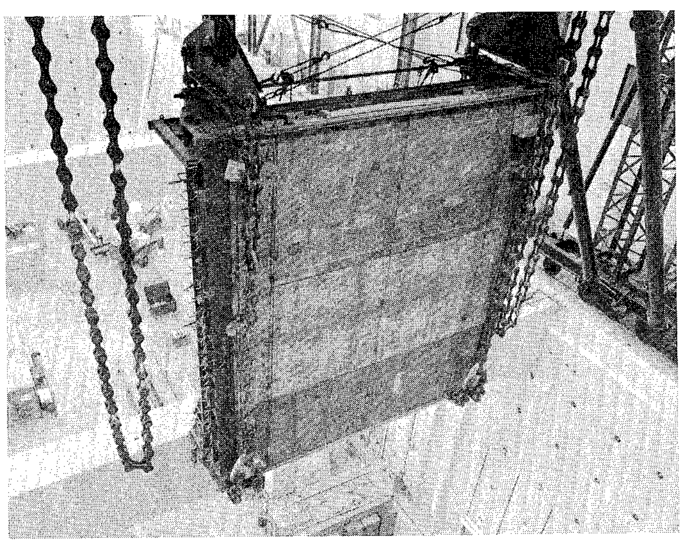


FIGURE 1. Part of the Mark II detector being lowered into the Collider Experimental Hall.

A similar sequence of events happened several years later. In 1983, SLAC officially began building a new type of collider. The Stanford Linear Collider (SLC) would reach energies over three times higher than PEP. The original SLAC-LBL team joined with six other universities* and proposed still another upgrade for the Mark II, to be used for initial experiments at the SLC. After the proposal was accepted, the major new parts were built and installed for a check-out run at PEP in 1985. During the summer of 1986, the 1800-ton detector was disassembled and moved, piece by ponderous piece, to the Collider Experimental Hall. The reconstructed detector was tested using cosmic rays from the fall of 1986 until November 1987, when it was finally rolled into the SLC beamline.

The main physics goal of the Mark II collaboration is to study the Z° particle, the heaviest known elementary particle. The total electron-positron collision energy of the SLC was designed to be approximately 92 billion electron volts (92 GeV), the energy needed to create the Z°. Largely because of its huge mass-energy, only about 100 events containing Z°'s have been observed so far at CERN and Fermilab.

As one of the particles that carries the weak nuclear force, the Z° lives only for a very short time, decaying into the elementary particles that make up matter. There are two types of matter particles — called *quarks* and *leptons*. The Z° decays into a quark or lepton plus its corresponding antiparticle (see Figure 2). All of the Z° events observed so far have been its decays into leptons: $Z^\circ \rightarrow e^+e^-$ or $Z^\circ \rightarrow \mu^+\mu^-$. Mark II physicists will have the first opportunity to see the Z° decay into quarks.

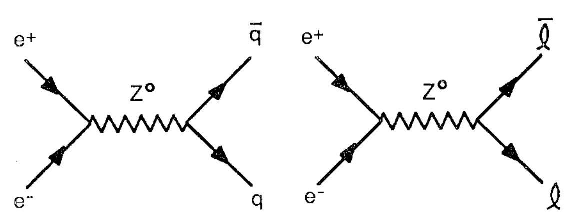


FIGURE 2. Diagrams illustrating production of the Z° particle and its subsequent decays into either quarks ($q = u, d, s, c, b, ...$) or leptons ($l = e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau, ...$) and their antiparticles.

Quarks never appear in nature as single particles; rather they come in groups of two or three. These groups of quarks, called *hadrons*, are the particles we can actually detect. There are many different hadrons, but the ones that commonly leave tracks in detectors are among the lightest — pions, kaons and protons. Heavier hadrons that contain the initial quarks from the decay of the Z° (the primary quarks)

*Caltech, UC Santa Cruz, University of Colorado, University of Hawaii, Johns Hopkins University and the University of Michigan. Indiana University joined later.

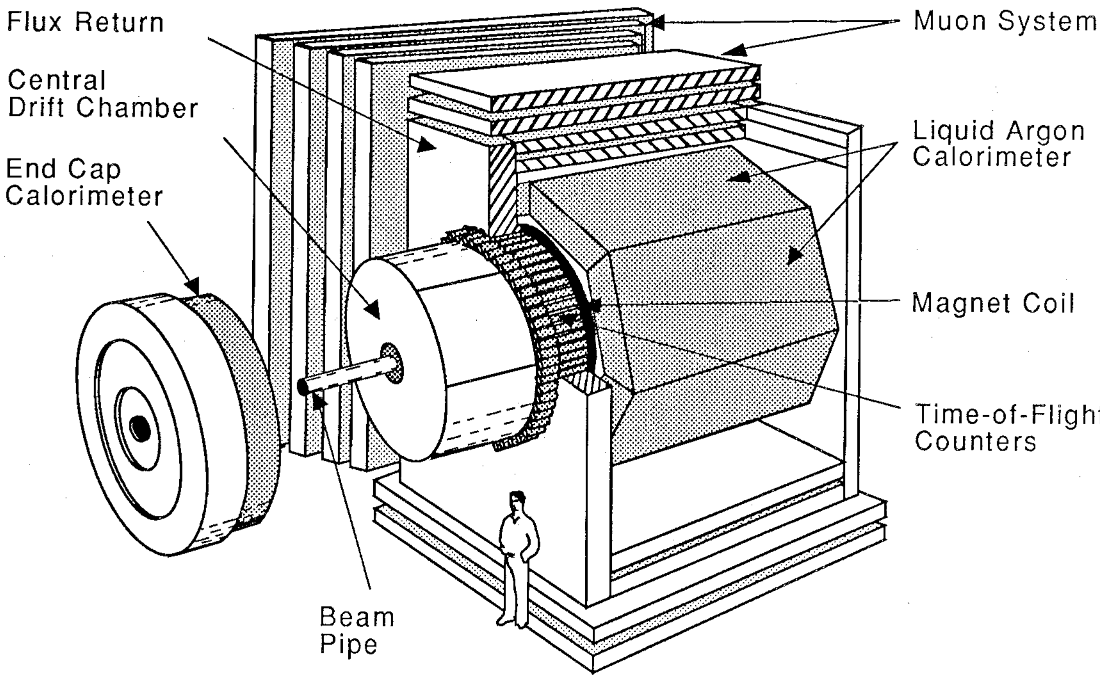


FIGURE 3. Cut-away view of the Mark II detector, with the end cap removed and the central drift chamber shifted left along the beam axis.

quickly decay into these hadrons and sometimes into leptons as well. So we have a difficult task, trying to work back to the primary decay using the end products of all of the subsequent decays.

The result of a Z° decay will be anywhere from two to fifty particles spraying out radially from the collision point. The purpose of the Mark II detector is to measure the energies and trajectories of all of these particles, as well as to try to identify them. These tasks are accomplished by putting together many different types of devices that individually measure some of the needed information. Ideally, they would spherically and completely surround the point where the electron and positron collide. However, it is easier to build the detector in the shape of a cylinder with doors on the flat ends and the beams passing through along its axis. Such a design can be seen in the schematic drawing of the Mark II detector in Figure 3 above.

As with any real object, there are imperfections. For example, where sections of the detector join together there are "cracks" through which particles can escape undetected. We also have more difficulty measuring the properties of particles that pass through the ends. We have tried, however, to minimize any effects these problems might have on the physics measurements we want to make.

In the following sections I give brief descriptions of each of the main components of the current Mark II detector. I will describe the separate pieces of the overall puzzle each provides, and outline how these pieces fit together to give us a complete picture of the Z° particle and its decays.

Magnet

We need to measure the momenta of the particles emerging from a decay of the Z°. To do so we use the fact that a charged particle travels along a curved path when it passes through a magnetic field. The radius of curvature depends on the particle's momentum — the greater the momentum, the larger the radius. Therefore, a large part of the detector sits inside a magnetic field which is generated by passing a current through a cylindrical coil of wires, as shown in Figure 4. Made of aluminum conductor, the Mark II coil is about 3 meters in diameter and measures 3 meters from end to end. The magnetic flux lines

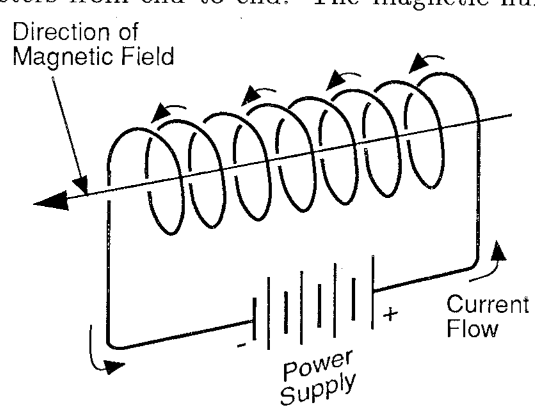


FIGURE 4. Solenoidal magnetic field generated by an electric current flowing through a coil.

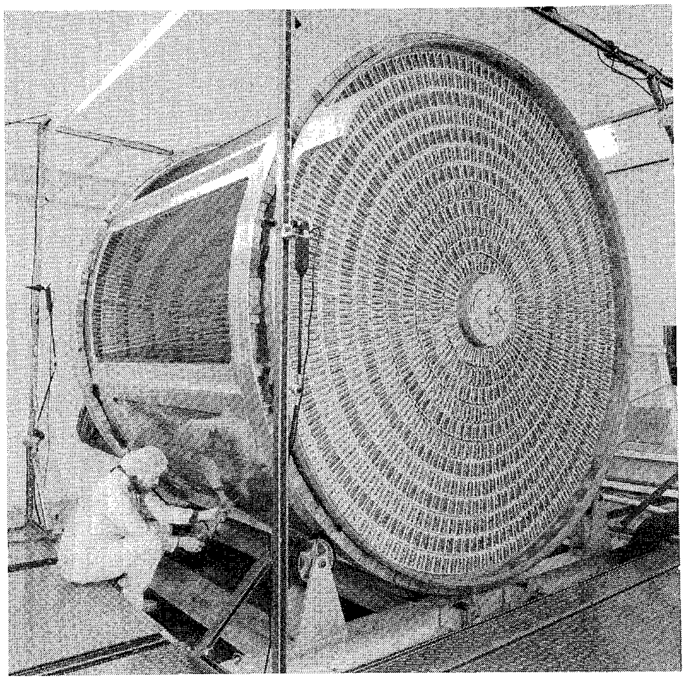


FIGURE 5. The Mark II central drift chamber.

pass through the center of the detector and loop back through the steel housing that encloses most of the detector. This "flux return," a part of the original Mark II detector at SPEAR, has been a physical constraint for the recent improvements.

Central Drift Chamber

We need to have some way of recording the paths taken by the particles as they speed through the detector. A common device for tracking the paths of charged particles, called a drift chamber, is a volume (usually cylindrical in shape for colliding beam applications) filled with a special gas and lots of wires. As a charged particle passes through the gas, it knocks electrons out of the gas molecules. This process is called ionization. The freed electrons drift through an electric field onto special purpose wires, called "sense wires," which generate a signal. The amount of time that the electrons drift is proportional to the distance between the particle track and the sense wire. By combining this information from many sense wires, we can reconstruct the paths of the charged particles.

The reconstructed tracks allow us to measure the momenta of the particles. As discussed above, charged particles travel on curved paths in the magnetic field, with curvature related to momentum. Slower particles bend a lot whereas fast, energetic particles leave straighter tracks. The reconstructed tracks also help us tie together information from the rest of the detector. We extrapolate the tracks into

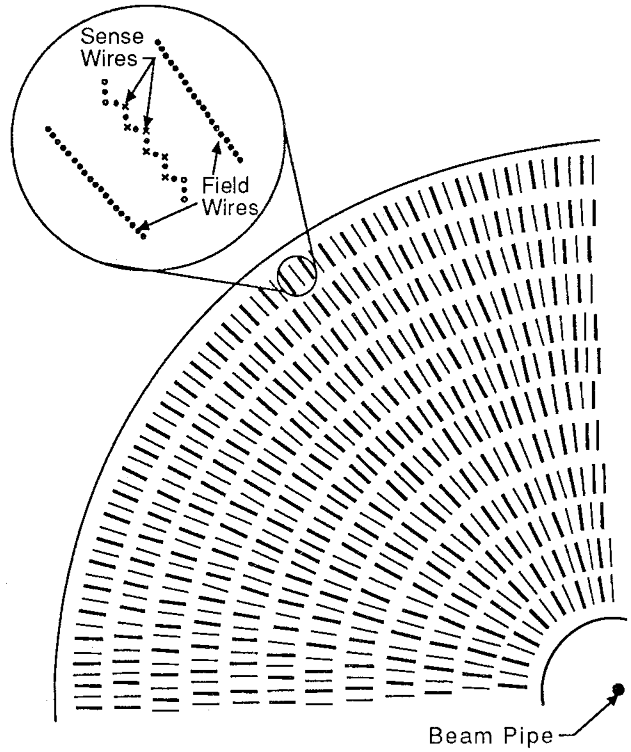


FIGURE 6. Physical arrangement of the cells and wires inside the Mark II drift chamber.

the other components and match them with the information found there.

Drift chambers can also be used to help identify particles. By measuring the amount of charge deposited on each wire, we can determine the energy loss (dE/dx) of the particle. The dE/dx, mass and momentum of the particle are related. Therefore when we know the dE/dx and the momentum, we can estimate the mass of the unknown particle, which helps us identify it.

The Mark II has been refurbished with a new central drift chamber (see Figure 5). This drift chamber is cylindrical in shape with an inner radius of 19 centimeters and outer radius of 152 centimeters. It is 2.5 meters long with about 37,000 wires strung between the two ends, parallel to the beam axis.

The wires are grouped in logical units called cells. Each cell contains several different types of wires, all of which play a different role in making the drift chamber work. Some of the wires are used to isolate the cells from each other electrically. Others are used to define a uniform electric field in the cell so that the ionization electrons will drift in a well determined way. And then there are the sense wires mentioned above, which collect the drifted electrons and record a signal. There are six sense wires in each cell (see Figure 6), and 972 cells are arranged in twelve concentric layers. With this design, we are able to measure track positions to an accuracy of about 200 microns (1000 microns is 1 millimeter), or 0.008 inch.

Vertex Detectors

Some of the primary hadrons are very short-lived, decaying into lighter, more stable particles before they reach the detectors. If we can measure tracks accurately close to the e^+e^- interaction point (IP), then we can better study the properties of the original particles. This would also give us a good starting point for determining the trajectories of the more stable particles. The devices that make these kinds of measurements are called "vertex detectors."

For the Mark II detector at the SLC, we are building two new vertex detectors. Neither was installed for the trial running during the summer of 1988. The innermost one, the Silicon Strip Detector (SSD), is a solid state device designed to measure track positions to an accuracy of 5 microns. The detector consists of three layers of thin strips of doped silicon with voltages applied at the ends to set up electric fields. A charged particle traveling through a strip liberates electrons, which drift to the electrodes and generate a signal. Because it is very thin, this kind of detector is well suited for placement close to the beam pipe. Current plans call for placing the innermost strips 2.8 centimeters from the beam axis.

The second vertex device, the drift chamber vertex detector (DCVD), is a cylinder approximately 17 centimeters in diameter and 71 centimeters long with an inner radius of about 5 centimeters. Shown in Figure 7, it has 38 sense wires in each of ten tilted radial sections.

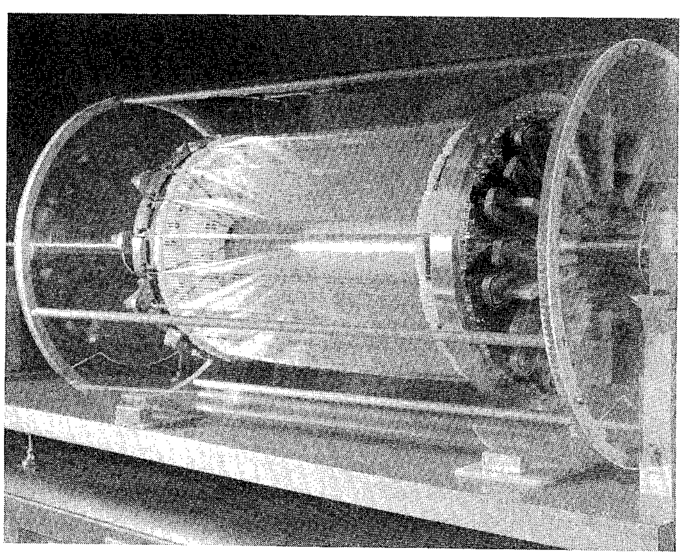


FIGURE 7. The Mark II drift chamber vertex detector. (Photo by Margaret Farwell.)

The gas inside the DCVD is kept at three times the atmospheric pressure, which helps improve the accuracy of its position measurements. We expect that this accuracy will be about 40 microns. The DCVD will surround the SSD and sit inside the central drift chamber. Both vertex devices will be installed in late 1988.

Time-of-Flight Counters

The particles created in the decay of a Z° spray out from the interaction point with varying momentum and take a measurable amount of time to travel through the drift chamber. Slabs of plastic scintillator forming a barrel around it are used to determine this time. When the particles travel through the special plastic they induce light emissions called scintillations. This light is channelled to both ends of the counter and converted to signals by photomultiplier tubes.

We want to know the time t the particle takes to travel to the counters because a combination of that time and the track information from the drift chamber can sometimes identify the particle. The velocity v can be calculated from

$$v = L/t$$

where L is the total distance the particle travelled to reach the time-of-flight (TOF) counter. For relativistic particles, the velocity and the momentum p are related by

$$p = \frac{mv}{\sqrt{1 - v^2/c^2}}$$

where c is the speed of light and m is the mass of the particle. Knowing a particle's velocity from the time-of-flight measurement and its momentum from its radius of curvature, we can use this relation to determine the mass and thus identify the particle. This method of identifying charged particles only works if the particular TOF counter hit is matched to a drift chamber track and if the particle is travelling slow enough.

Liquid Argon Calorimeter

The liquid argon calorimeter (LAC) is used to measure the energy of photons, electrons and positrons emerging from a collision. These particles interact with lead sheets and produce a cascade of e^+e^- pairs and photons. These "shower" particles pass into gaps between the lead and ionize the liquid argon filling them, continuing on into the next lead sheet until they lose most of their energy. The ions in the liquid argon are collected on the lead, and the size of the resulting signal is proportional to the energy of the particle initiating the shower.

The LAC is one of the components remaining from the original Mark II detector at SPEAR. It consists of eight modules that form an octagonal barrel surrounding the magnet coil (see Figure 3). Each module contains 36 layers of 2 millimeter thick lead sheets alternating with 3 millimeter gaps for the liquid argon, which is kept at a temperature of 87°K (−186°C). The lead in every other layer is segmented into 3.6 centimeter wide strips, which have a voltage applied to them to collect the ions from the liquid argon. By aligning the strips in different directions in different layers to form a grid, we can reconstruct the shape and position of the shower.

The shower process yields varying amounts of deposited energy for a given incident energy. The "resolution" of a calorimeter indicates how well we can match the energy we measure with the actual incident energy of a particle. For the LAC we have an energy resolution of approximately

$$\frac{\Delta E}{E} = \frac{13\%}{\sqrt{E(GeV)}} \quad .$$

That is, the energy of a 4 GeV electron, positron or photon can be measured to within 6.5%. Other particles such as hadrons also interact with the lead but generally will not be captured. Therefore, it is not possible to measure their energy in the LAC.

Endcap Calorimeters

We also want to measure the energy of electrons, positrons and photons that leave the detector through the ends, areas not covered by the LAC. To achieve this, we have added two "endcap" calorimeters (ECCs), which are mounted on removable steel doors that are part of the magnet flux return.

The principle used to measure the energy of the particles is the same as used in the LAC; however, in this case the gaps between the lead sheets contain proportional tubes instead of liquid argon. These are tubes filled with a gas, having a sensing wire strung along the axis of each tube. The shower particles generated in the lead sheets ionize the gas in the tube, and the ions drift to the sensing wire in an electric field. The amount of charge collected on the wire is proportional to the energy deposited in the tube. The total signal from all tubes is proportional to the energy of the particle initiating the shower.

The endcap calorimeters are toroidal in shape with an inner diameter of 67 centimeters and an outer diameter of 295 centimeters. Each endcap consists of 18 layers of 3 millimeter thick lead sheets interleaved with the rectangular proportional tubes. The tubes vary in length from 44 centimeters to 280 centimeters and are aligned at different angles in different layers to allow position measurements. The resolution of this calorimeter is about 11% for a 4 GeV electron, positron or photon.

Muon System

Muons are heavy cousins of electrons; they have similar properties but weigh about 200 times as much. Their heaviness and lack of strong nuclear interactions means that they penetrate material very easily. A muon with only 1.2 GeV of energy can travel through a meter of iron whereas a hadron with that energy would be absorbed in about half that distance. We use this penetration property to distinguish muons from other particles.

When a muon is created in a Z° decay, it will travel through the drift chamber (leaving a track because it is a charged particle), a time-of-flight counter and the liquid argon calorimeter. Then it encounters four layers, each of approximately 22 centimeter thick steel interleaved with proportional tubes. The tracks in the drift chamber are extrapolated out to the muon system to define an area to look for matching muon tracks. If signals are seen in all four of the detection layers, then there is better than 99% probability it is a muon.

For the later runs at the SLC, we are supplementing the muon system that was in use at PEP. Previously, the muon walls covered the top, bottom and sides of the detector, leaving a large area on the ends

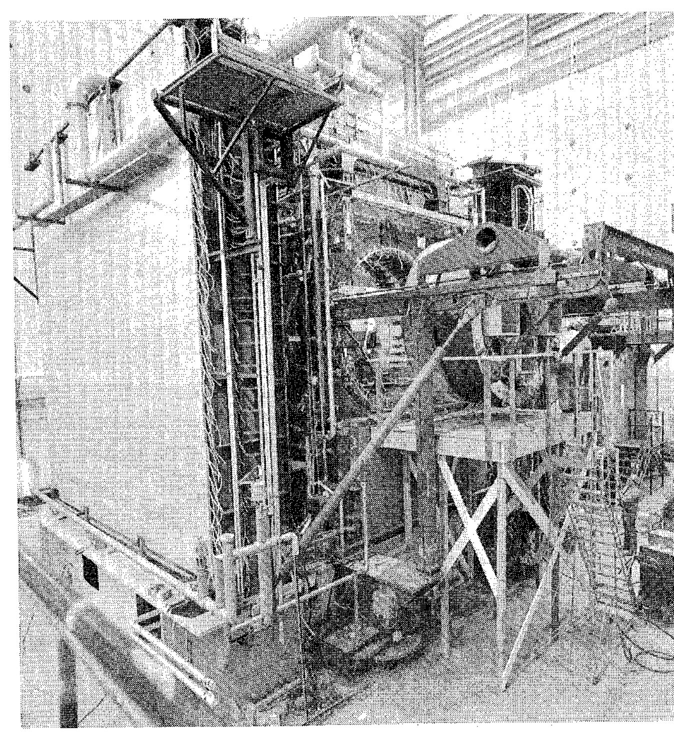


FIGURE 8. The Mark II detector on the floor of the Collider Experimental Hall. One of the muon walls stands at left; the endcap calorimeter sits inside the circular door just right of center.

where muons could escape the detector without being identified. The upgrade involves mounting 2 layers of steel and proportional tubes along both ends of the detector to cover some of that area. This will significantly enhance our ability to identify muons.

Luminosity Monitors

The measurements we want to make about the properties of the Z° particle require that we know the number of collisions the accelerator has provided — a quantity called the "luminosity." We take advantage of a well-understood e^+e^- interaction called Bhabha scattering, illustrated in Figure 9. The electron and positron usually glance off one another and emerge close to the beampipe; therefore the best location for measuring these types of events, called "Bhabha events," is at small angles.

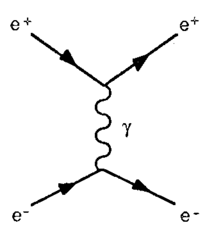


FIGURE 9. Diagram illustrating Bhabha scattering between an electron and a positron.

We have two such devices in the Mark II to measure the SLC luminosity; the small-angle monitor (SAM) and the mini-SAM. The Bhabha electron and positron leave the interaction point in opposite directions, so both the SAM and mini-SAM must have instrumentation on each side of the IP. The SAM has layers of proportional tubes to track particles and a back section of interleaved layers of tubes and lead to make a crude energy measurement. The mini-SAM is composed of six alternating layers of plastic scintillator and tungsten with each layer of scintillator divided into four quadrants. A back-to-back Bhabha pair would leave signals in diagonally opposite quadrants. We expect to see Bhabha events in the SAM at the same rate as we see Z°'s in the detector. Because the mini-SAM is closer to the beampipe than the SAM, it should record seven times as many Bhabha events.

Performance

The first test of the upgraded Mark II detector was a run made at PEP from November 1985 to February 1986. Its primary purpose was to check out the new detector components and to integrate the information into the data analysis, but we have also been able to extend some of the physics results that had been obtained with the old detector. All of the major additions (the new drift chamber, new time-of-flight counters, new magnet coil and new endcap calorimeters) performed as expected.

One of the events from the PEP data sample is illustrated in Figure 10. This shows a computer-generated cross-section of the Mark II detector, looking along its axis from the vantage point of an incoming positron. Particles spray out radially from an e^+e^- interaction at the center, leaving traces in the various detectors. The curves inside the inner octagon are charged particles leaving tracks in the central drift chamber. Those with more curvature have lower momenta. Time-of-flight counters hit by these particles appear as small boxes distributed about a circle.

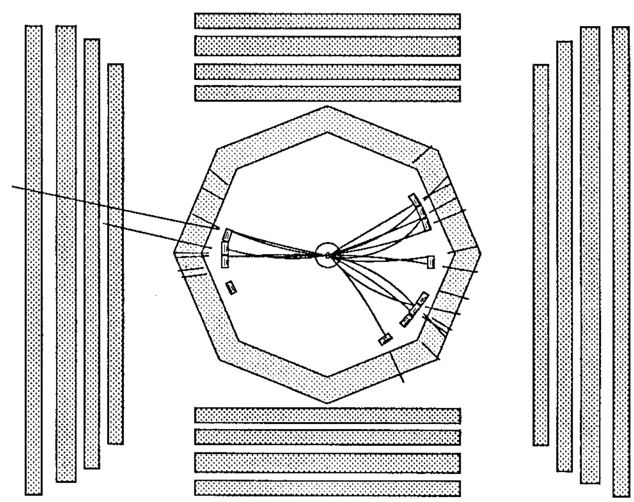


FIGURE 10. Computer reconstruction of a three-jet event witnessed by the Mark II at PEP.

Both charged and neutral particles then deposit varying amounts of energy in the liquid argon calorimeter, represented by short lines in the shaded space between the two concentric octagons. The energy deposits of all these particles are small, consistent with their interpretation as hadrons. But one, the very straight track at left that continues on through all four layers of the muon system, is obviously due to a fast, high-energy muon. The long track just below it, which penetrates only one layer of steel, is probably that of a hadron.

The most likely interpretation of this event is the production of three sprays or "jets" of hadrons. Two of these jets are due to a quark and its antiquark, one of which makes a meson that subsequently undergoes a "semileptonic" decay into a muon, one or more hadrons, and an unseen neutrino.

After initial testing with cosmic rays at the collider hall, the Mark II was moved onto the beamline last November and has helped with commissioning the SLC. With the detector surrounding the interaction point, we have identified some beam-related sources of background radiation. This knowledge has led to the installation of new collimators in strategic points along the SLC arcs.

Summary

The different devices that make up the Mark II detector combine to give us the information we need about a decay of the Z° particle. The momentum of charged particles is calculated from the curvature of tracks in the drift chamber, where this curvature is induced by the magnetic field in the interior of the detector. The energy of electrons, positrons and photons are measured in the liquid argon and endcap calorimeters. The time-of-flight counters, the muon system and the dE/dx information from the central drift chamber aid in identifying particles.

The recent improvements in vertex detection, solid angle coverage and tracking and particle identification in the central drift chamber will enable the Mark II detector to make significant measurements in this energy regime. The approximately 140 members of the Mark II collaboration hope to continue its tradition of excellent physics.

Kathy O'Shaughnessy is a Stanford University graduate student in physics. She works with Group H on the Mark II detector.

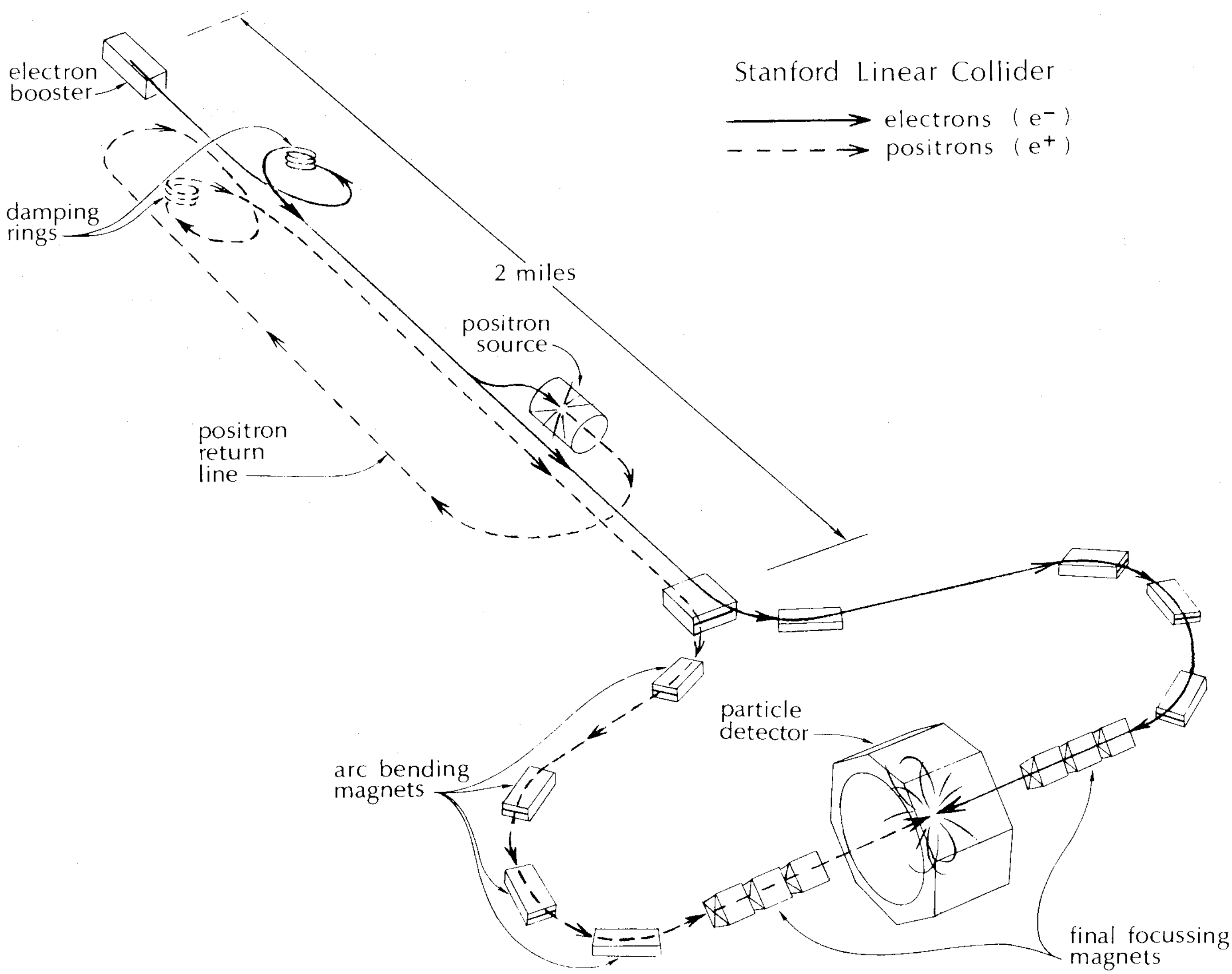


FIGURE 11. Artist's conception of the SLC. Electrons and positrons are accelerated to almost 50 GeV in the linear part, then guided and focussed by magnets until they collide head-on. Surrounding the interaction point, the Mark II detector records the tracks and energy deposits of particles emerging from these collisions. (Drawing by Walter Zawojski.)

SEARCH QUICKENS FOR ULTIMATE PARTICLES

Two new American colliders start up, with a European one to follow

by Malcolm W. Browne

(Editor's note: The following is a shortened version of an article that appeared in The New York Times *on July 19, 1988. It gives an excellent overview of the new colliders coming online at SLAC, Fermilab and CERN, and the physics they are aiming for. It is reprinted in the* Beam Line *by permission.)*

For the first time in five years, high-energy physicists in the United States are poised to seize the lead from colleagues in Europe as they bring powerful new particle accelerators to bear on mysteries shrouding the ultimate basis of matter. Full-scale experiments have begun at America's two largest accelerator laboratories, in California and Illinois, both of which recently completed machines even more powerful than their European counterparts.

The Stanford Linear Collider (SLC) in California, the Stanford Linear Accelerator Center's new entry in the high-energy physics race, began its ambitious experimental program in June. The machine hurls clusters of negatively charged electrons into oncoming clusters of their antimatter counterparts, positrons. Scientists at Stanford hope these collisions will soon produce large numbers of Z° particles — ephemeral particles whose properties illuminate some of the enigmas that underlie material existence.

At America's other leading high-energy accelerator, the Fermi National Accelerator Laboratory (Fermilab), scientists are also expecting important results soon. "We have just started our first real series of experiments using the new Tevatron Collider," said Dr. Leon M. Lederman, its director.

'The Missing Quark'

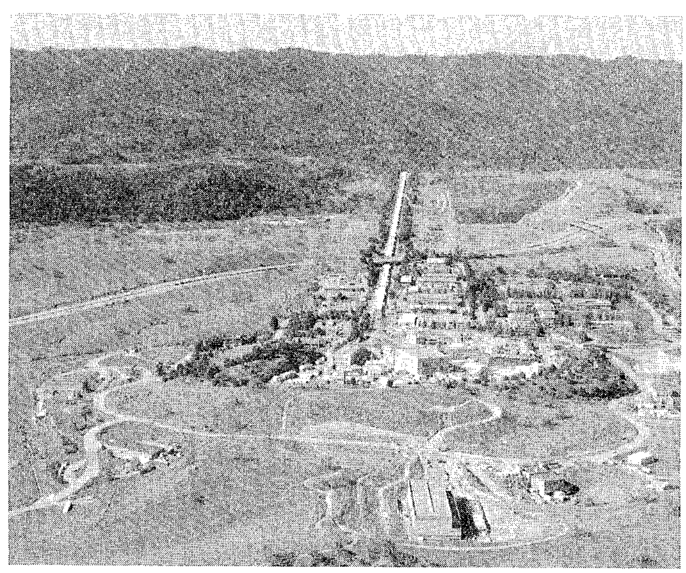
One object of their work is to make progress toward testing the theory that everything in nature is made up of some combination of 16 ingredients: four classes of "vector" particles, six "leptons" and six heavier "quarks," one of which, called the top quark, has not yet been detected. "We think we will soon have the top quark in the bag — the missing quark physicists have been looking for," said Lederman. "But in this business you learn to keep your fingers crossed."

But the technological supremacy the SLC and Tevatron offer may be short-lived. A Western European scientific consortium is nearing completion of an underground accelerator 17 miles in circumference, by far the largest such machine in the world. Last Wednesday scientists successfully tested the first two-mile segment of the Large Electron-Positron collider (LEP), prompting acclaim from scientists at competing institutions in the United States. The LEP will not be ready for experiments until 1990, however, and until then U.S. physicists are pressing their temporary advantage.

"This will be a very interesting summer but a very tense one," said Dr. Burton Richter, director of SLAC, in a telephone interview. "While we wait," he added, "I've asked my department leaders to go to their church or synagogue and pray for divine help."

Dr. Richter's uneasiness stems from the fact that the SLC represents an accelerator design that has never been tried. A conventional particle collider spins counter-rotating clusters of particles around a ring. In the machine Dr. Richter conceived, however, the opposing beams — each thinner than a human hair — are initially accelerated together down a straight, two-mile-long linear accelerator. At the end of the line, the two beams diverge and are ducted around two semicircular arms resembling crab claws. The tips of the claws point toward each other, aiming the two beams directly at one another.

The Z° particle that scientists hope the SLC will soon produce in large numbers is a very heavy, short-lived particle that conveys the weak nuclear force from one subnuclear particle to another. Five years ago, physicists in Europe created and observed Z° particles and two other carriers of the weak force, the W^{+} and W^{-} particles. Measurements of these



Aerial view of SLAC.

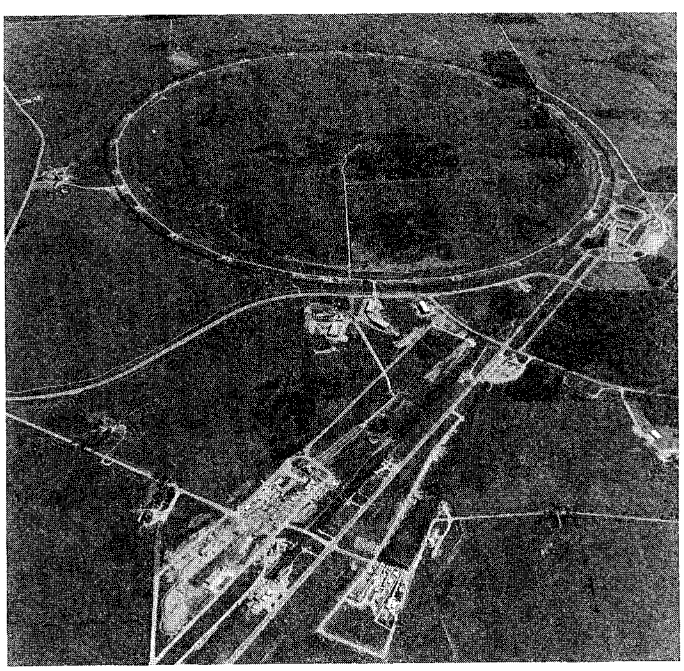
particles provided dramatic confirmation of a theory that the weak force is actually equivalent to the more familiar electromagnetic force.

The discovery of the Z° in 1983, one of the great experimental milestones of modern physics, was the work of the 14-nation European consortium called CERN. The result was achieved by a powerful CERN accelerator near Geneva. For this triumphant experiment, Dr. Carlo Rubbia and Dr. Simon van der Meer were awarded the 1984 Nobel prize in physics.

The Standard Model

One of the immediate objectives of high-energy physics is to create and observe large numbers of Z° particles, and by studying their behavior, to perfect a unifying theory that would explain how all the ingredients of the universe are related to each other. "The first few hundred SLC collisions producing Z° particles should suffice to measure the mass of the Z° precisely," said Dr. Richter. "We must know that mass to judge the validity and accuracy of what we call the Standard Model."

The Standard Model is the theory that assumes there are four fundamental forces — gravity, electromagnetism, plus the strong and weak nuclear forces (although gravity is not explained by the theory). Each force is transmitted by its own vector particle or set of particles. Besides the vector particles there are the six leptons and six quarks, too. The Standard Model holds that everything in nature is made of some combination of these ingredients.



Aerial view of Fermilab, showing the main ring in the background. (Photo courtesy of Fermilab.)

But there are problems with the Standard Model, and physicists agree that it must be refined and tested much more rigorously than has been possible with the accelerators of the past. In Dr. Lederman's words: "If you want to reach up for the Golden Fleece — the ultimate theory of everything — you want to make sure that your theoretical base, the Standard Model, doesn't fall apart. Right now, it needs some shoring up."

Among the weaknesses of the Standard Model to which Dr. Lederman alluded was the possibility that it omits one or more families of as-yet-undiscovered particles. Physicists are also troubled by the seemingly arbitrary masses of the fundamental particles. They believe that a complete theory must explain why these masses are what they are.

Dr. Richter believes that by creating and observing a few thousand Z° particles, scientists can determine whether there is a so-far undetected fourth "generation" of leptons and quarks, in addition to the three generations encompassed by the Standard Model. Further in the future, the creation of a few hundred thousand Z°'s, he said, could tell experimenters whether "supersymmetric" particles exist: particles spanning the gulf between the force-carrying kind on the one hand and the leptons and quarks on the other.

Finally, Dr. Richter noted, the production and study of a few million Z° particles "should tell us whether the Higgs particle lies in our mass range." Named for the physicist Peter Higgs, this particle exists with certainty only as a mathematical consequence of the Standard Model. But the particle may exist in more tangible form as well, and the physicists who found it would be strong candidates for Nobel prizes. The discovery of a real Higgs particle would go far toward explaining why other fundamental particles have the specific masses they do, one of the basic open questions of physics.

Electrons Versus Protons

The electrons and positrons SLAC uses as projectiles are scarcely larger than mathematical points, and are not believed to have any internal structure. The spray of particles created from the energy released by collisions of electrons and positrons is therefore "clean," relatively free of compounds that typically form after heavier particles collide. These confusing fragments, which physicists regard mostly as useless debris, can mask important events.

By contrast, the Fermilab Tevatron collides large protons and antiprotons, each made up of three quarks. Their collisions produce enormous sprays of debris. Nevertheless, proton colliders have an important advantage over conventional electron-positron colliders. When magnets in the latter force electrons or positrons to change direction continuously as they speed around a circular course, they emit energy in somewhat the way the tires of a skidding car emit heat, smoke and noise. Instead of smoke, the electrons emit intense x-rays called synchrotron radiation, and this radiation robs the electrons of energy. To reduce synchrotron losses, Dr. Richter designed an entirely new type of collider based on a linear accelerator.

The problems created by synchrotron radiation do not apply to protons and antiprotons, however. These particles can be accelerated along a circular path with no appreciable loss of energy. Proton accelerators can therefore boost particles to far higher energies than are attainable with electron machines. The SLC and the Tevatron therefore play complementary roles.

In June, after more than a year of trials and preliminary experiments, Fermilab's collider, built inside a four-mile-long circular tunnel, began its main work, what Dr. Lederman describes as the "physics phase." The Tevatron, which has begun colliding counter-rotating beams of protons and antiprotons at a combined energy of nearly two trillion electron volts (2 TeV), is by far the most powerful particle collider in the world. In a typical collision, most of this immense energy is dispersed in sprays of comparatively uninteresting debris, but some of the energy goes into creating rare particles that scientists are eager to study.

While U.S. physicists enjoy their new technical advantage, their European counterparts at CERN are assembling their LEP collider inside a circular tunnel that spans the French-Swiss border. This gigantic 17-mile tunnel, begun in 1983, was completed last February, and the accelerator it will house is scheduled to be ready for experiments by the end of next year. Eventually, the LEP collider is expected to accelerate particle beams to a combined energy of 200 billion electron volts. This will make it by far the most powerful electron-positron collider ever built.

Dr. Emilio Picasso, the Italian physicist who directs the LEP facility, believes its electron-positron collider will be the last accelerator of its kind built in the form of a ring. "We adopted a proven design to simplify our work," he said in an interview. "But future electron-positron colliders will have to be head-on linear colliders," he continued. "At the energies of the future colliders, the losses due to synchrotron radiation would rule out ring accelerators completely. Burt Richter has the right idea."

16th SLAC SUMMER INSTITUTE

Probing the Weak Interaction was the theme of the 1988 SLAC Summer Institute on Particle Physics. The sixteenth in a series that dates back to 1973, this year's conclave took place from July 18 through 26 in the SLAC auditorium and surroundings. A total of 342 physicists (including 198 from 93 other institutions) heard lectures on CP violation, rare decays of K, D and B mesons, and searches for dark matter. Following that was a three-day topical conference on recent results in particle physics, which closed with tributes to deceased physicist Richard Feynman.

As before, this year's Institute was organized by Gary Feldman, Fred Gilman and David Leith — who also served as chairmen of the pivotal morning sessions. Program Coordinator Eileen Brennan and her staff, particularly Lilian Vassilian, watched after the myriad details involved in actually running such an enterprise.

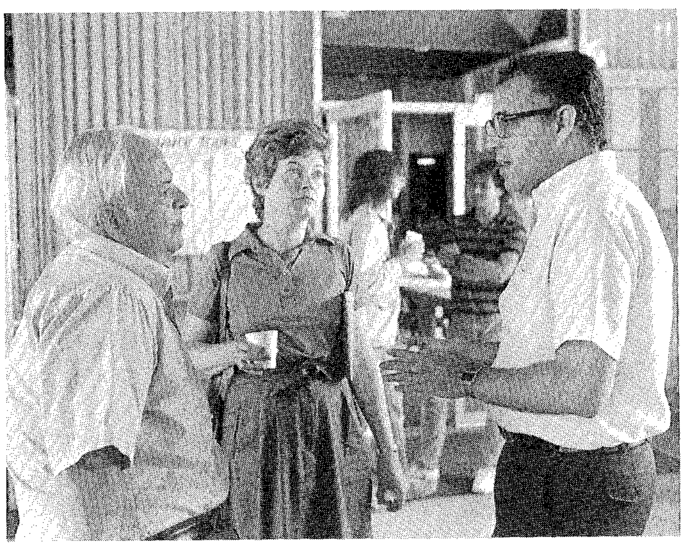
In Stanford's Rodin Sculpture Garden, Program Directors Gary Feldman and David Leith plot strategies for the upcoming sessions.

The affair got underway on a sultry Sunday afternoon, July 17, with a reception held in Stanford University's Rodin sculpture garden. Participants sipped wine and Calistoga water, talked physics, listened to a string quartet playing Mozart, talked physics, and debated the merits of Modernism as the mercury soared to a record 105°F (40°C).

Core Lectures

Ikaros Bigi of the SLAC Theory Group kicked off the lectures on Monday and Tuesday mornings with a survey of what he called "precious rarities" – rare meson decays that should still occur at some small, non-negligible level. Such decays can constrain as-yet unknown parameters of the Standard Model like the mass of the top quark. Other decays are sensitive barometers of completely new physics. If the kaon were observed to decay into an electron and a muon ($K \rightarrow e\mu$), for example, it could not be explained within the Model.

Stewart Smith of Princeton followed Bigi with three lectures on successive days about the extensive Brookhaven program on experimental searches for rare kaon decays. With its intense beams of charged and neutral kaons, Brookhaven continues to be a major center for such work, which is enjoying a rebirth recently. The best limits so far on interesting decay modes like $K \rightarrow e\mu$ and $K \rightarrow \pi\mu e$ are on the order of a few parts per billion, but hopes are high that they can be reduced to the level of parts per trillion. One of the most ambitious of the Brookhaven experiments is E-791, which includes a large contingent from SLAC/Stanford led by Stan Wojcicki and Jack Ritchie.



Haim Harari (right) tries to convince a skeptical lab director of his latest theoretical predictions, as Gail Hansen of SLAC looks on.

Karl Berkelman of Cornell surveyed the measurements at colliders of B-meson mixing and decays that have spurred plenty of excitement and activity during the past year. Principal among the results he noted were the discovery of B°–$\overline{B}^\circ$ mixing by the ARGUS collaboration at DESY and its confirmation by the CLEO collaboration at the Cornell Electron Storage Ring. In this process a B° meson spontaneously converts into its antiparticle, or vice-versa. Berkelman ended his thorough, well-organized lectures with a discussion of the on-going search for CP violation in B-meson decay.

On Thursday and Friday mornings, Jack Sandweiss of Yale spoke about the prospects for b-quark physics in fixed-target experiments. With pion, proton and photon energies in the hundreds of GeV, he explained, there is copious production of $b\bar{b}$ pairs; but extracting this signal from huge backgrounds of hadronic debris is going to be difficult. Nevertheless, groups of experimenters at Fermilab are game to try, because fixed-target experiments can measure accurate values for B-meson lifetimes and will be sensitive to rare B decays.

In an extremely well-prepared and very lucid set of lectures, Haim Harari of Israel's Weizmann Institute (and a frequent SLAC visitor) put everything together for his listeners. Using limits from B°–$\overline{B}^\circ$ mixing plus B-meson and kaon decays, he showed why the top quark must have a mass greater than 50 GeV. This would put it almost beyond the range of the SLC, because one would then need at least 100 GeV to produce a $t\bar{t}$ pair. His own best guess was that its mass lies between 80 and 100 GeV, making it accessible in $p\bar{p}$ collisions at the Fermilab collider. Harari wagered that top would finally be found during the current collider run there. He proudly displayed a page from the SLAC Theory Group "Book of Bets" dated June 22, 1987, on which he bet Michael Peskin that the top quark discovery "will be announced by the CDF collaboration not later than March 31, 1989."

Dark matter was the topic of lectures by Larry Hall of UC Berkeley and Blas Cabrera of the Stanford Physics Department. Hall presented a summary of the reasons cosmologists give for the existence of this mysterious, invisible stuff that seemingly pervades the universe. Then he described its expected characteristics, emphasizing that the possible forms of dark matter are tightly constrained by cosmological considerations. Cabrera surveyed recent attempts to detect dark matter directly in the laboratory, concentrating on his own research involving superconducting materials and techniques.

The next Monday and Tuesday, July 25 and 26, Lincoln Wolfenstein of Carnegie Mellon University explained why theorists are interested in the subject of neutrino mass. Without embellishments, the Standard Model is content with absolutely massless neutrinos, but most of its extensions require small, nonzero masses. Thus neutrino mass is another good barometer of new physics. Following Wolfenstein, Michael Witherell of UC Santa Barbara surveyed recent work in double beta decay of selected atomic nuclei, which provides one way to search for evidence of neutrino mass.

Topical Conference

The last three days of this year's Summer Institute were devoted to a topical conference in which physicists from the various experimental collaborations presented their recent data. As this writer could only attend a few of these sessions, what follows is necessarily a somewhat personal selection of key results.

Nobu Katayama of SUNY Stony Brook presented the CLEO evidence for B°–$\overline{B}^{\circ}$ mixing, confirming the ARGUS find, which was summarized by David MacFarlane of McGill University. The two collaborations *disagree* on whether charmless B-decay has been observed: ARGUS says yes, CLEO says no. Resolving this difference is important because such decays would represent the first concrete evidence for $b \rightarrow u$ quark transitions.

John LoSecco of Notre Dame reported on his more detailed analysis of the eight neutrinos from the 1987 supernova that were witnessed in the IMB underground detector. These events show a forward peaking, he claimed, that cannot be explained by low statistics. LoSecco speculated that perhaps the experiment had witnessed the telltale effects of muon or tau neutrinos.

Reporting the results from the Kamiokande underground detector, Masatoshi Koshiba of Tokai University rhapsodized about what he regards as "The Birth of Neutrino Astronomy." Because of its low, 7 MeV trigger, Kamiokande is sensitive to neutrinos emanating from the Sun. Preliminary results appear to confirm the long-standing deficiency of solar neutrinos reported over the past decade by Ray Davis of Brookhaven.

Topical Conference speaker Masatoshi Koshiba of Tokai University (right) talking between sessions with Michel Davier of LAL Orsay.

Junpei Shirai of KEK summarized the most recent results from Japan's e^+e^- collider TRISTAN. In March it finished running at a center-of-mass energy of 56 GeV, accumulating 5–6 inverse picobarns of luminosity on each of its three main detectors — AMY, VENUS and TOPAZ. The latest data show no surprises at all. The top quark mass is obviously greater than 27 GeV.

Despite the absence of any surprising new results, one could not help but be impressed by the quality of new data issuing from TRISTAN and Kamiokande. This year certainly marks the emergence of Japan as a first-rate power in elementary particle physics.

Daniel Amidei of Chicago capped the experimental portion of the program with a report from the CDF collaboration at Fermilab. He showed data from its 1987 run at 1.8 TeV, comparing it with data measured earlier at 630 GeV by CDF and by the UA1 collaboration at the CERN $p\bar{p}$ collider. A suggestive (but hardly earth-shaking) result was the observation of almost a hundred events with five or more jets in them, including ten six-jet events — an expected signature of top quark production. Perhaps Harari is about to win his bet with Peskin!

Feynman Memorial

The Institute ended with two tributes to Richard Feynman, who died in February after a long bout with stomach cancer. Matt Sands of UC Santa Cruz recalled Feynman's decision to teach the freshman physics course at Caltech, and his inimitable teaching style. At the end he showed a film clip from Feynman's Cornell University lectures on "The Character of Physical Law." One could close his eyes and imagine he was listening to Jackie Gleason discoursing on quantum mechanics!

Following Sands, Sid Drell of SLAC closed out the Institute by recounting Feynman's pivotal mid-1940s work on quantum electrodynamics and his development of the quark-parton model of the nucleon during the late 1960s. Sid, who chose these two contributions because he "had a ringside seat" on both, stressed Feynman's intuitive approach to doing physics.

One departed the 1988 Institute with a broad understanding of the importance of rare meson decays and CP violation experiments in the general scheme of high-energy physics. These will clearly remain interesting research areas for years to come. Not only are they helping us to resolve some of the important open questions about the Standard Model, but they also give us potential windows on new physics beyond this model.

— *Michael Riordan*

TWENTY YEARS AGO . . .

On September 2, 1968, Pief Panofsky delivered an address at the 14th International Conference on High-Energy Physics. Held in Vienna at the Imperial Palace of the Hapsburg dynasty, this key biannual meeting had attracted particle physicists from all over the world. Following a talk by Burton Richter, Pief spoke at 10 o'clock in the morning session on Electromagnetic Interactions, summarizing some of the important new experimental results in the field.

In an earlier session on August 28, Jerry Friedman of MIT had already presented preliminary data from SLAC Experiment 4B, the first of the now-famous MIT–SLAC experiments on deep inelastic electron scattering. The fraction of electrons ricocheting from protons (known as the "inelastic cross section") had come in far larger than expected, a great surprise. But Friedman's paper had generated little interest. Resonances and the strong interaction were the favorite topics at Vienna.

It was Pief who finally called attention to what must certainly be regarded as the most important new high-energy physics result of 1968. His talk is recounted here in an excerpt from *The Hunting of the Quark*, by Michael Riordan.

Panofsky, an old hand at these affairs, delivered the plenary session talk that eventually became the surprise of the Conference. As one of the "rapporteurs," he was responsible for summarizing all the experimental work on electromagnetic interactions that had occurred during the previous year. He had spent a good portion of his time at Vienna cooped up in his hotel room, poring over the many publications submitted for his review. Finally it came time for his summary talk to the more than 800 scientists from forty countries assembled in the chandeliered conference hall at the Hofburg, the grand Imperial Palace of the Hapsburgs. Hardly visible behind the lecturn, his head just peering over the top, his voice barely audible, Panofsky dutifully recounted all the year's salient results—coming finally to the MIT–SLAC paper. Turning at long last to the deep inelastic scattering, he announced:

> The qualitatively striking fact is that these cross sections . . . are very large and decrease much more slowly with momentum transfer than the elastic scattering cross sections and the cross sections of the specific resonant states. Therefore theoretical speculations are focused on the possibility that these data might give evidence of point-like charged structures within the proton.

Although his audience did not realize it then, this was the dawn of a new age in particle physics. Fitting it was that Panofsky should be the one to usher it in.

RIORDAN WINS AIP SCIENCE WRITING AWARD

Michael Riordan of SLAC has won the 1988 American Institute of Physics Science Writing Award for his recent book, *The Hunting of the Quark*. This award is given annually by the AIP "to stimulate and recognize distinguished writing that improves public understanding of physics and astronomy." The award includes a certificate, a check, and an inscribed Windsor chair. It will be officially presented to Riordan at a banquet October 25 in Yorktown Heights, New York, in conjunction with the annual AIP Corporate Associates Meeting.

Michael recently joined the SLAC staff as Science Information Officer, and serves as Editor of the *SLAC Beam Line*. Before that he was a Research Scientist with the University of Rochester, in which capacity he served as spokesman for SLAC Experiment 141, a beam dump search for short-lived axions. He completed the manuscript of *The Hunting of the Quark* while working for Rochester.

Michael earned his Ph.D. in physics from MIT in 1973, submitting a dissertation on measurements of the nucleon structure functions. His book is derived largely from his experiences while working here at SLAC as an MIT graduate student and postdoc on the MIT–SLAC inelastic electron scattering experiments, which resulted in the discovery of quarks.

His book was published in 1987 by Simon & Schuster. It is of particular interest to SLAC readers because of its emphasis on the pioneering work done here during the late 1960s and throughout the 1970s with the two-mile linac and the SPEAR storage ring.

The Hunting of the Quark has already received wide critical acclaim. "Mr. Riordan enables us to behold exactly how physicists work and the tortuous paths that experimentalists must take to gain just a scrap of insight into the puzzling laws of nature," wrote Marcia Bartusiak in the *New York Times Book Review*. "Mr. Riordan understands the physics," commented Jeremy Bernstein in *The New Yorker*, "but he also has an eye for the human comedy associated with the work."

— *Bill Kirk*

Dates to Remember

SSRL Users Meeting . .	October 27–28, 1988
Annual SLAC Race	November 3, 1988
EPAC Meeting	November 4–5, 1988
Linear Collider Workshop	Nov 28–Dec 9, 1988

JOE FAUST RETIRES

This is one retirement story of special interest to *Beam Line* readers, for Joe Faust's photographs have graced every issue of this newsletter for more than ten years. The photo below, in fact, is one of the few that we can guarantee he didn't take.

As the lab's technical photographer, Joe shot everything from 1-inch-square hybrid circuit chips for engineering publications to aerial photos of the site during construction projects. The indoor shots were safe, but not the aerials. Joe used to fly the plane while shooting them — until we insisted that he hire a separate pilot!

No matter what the subject, every photograph was a studied piece of work, and it showed. The *CERN Courier* has had a Faust photo on its cover at least once a year. Some of his framed pieces hang in the *SLAC* auditorium lobby as art. The man is good.

Working with Joe began with the task of finding him, not an easy matter until we learned to call him at the darkroom in his home. The next step was to describe the needed picture, which was often difficult without actually visiting the site and looking it over. By this time the physicist would be fidgeting, but Joe's calm is infectious. He would quietly pad around in jeans and sneakers and start handing you equipment from the trunk of his old orange Datsun.

SLAC Photographer Joe Faust. (Photo by Tom Nakashima.)

He would listen to what you wanted and then figure out how to set up.

The last time I worked with him, Joe climbed onto the roof of the tool crib in the collider hall, pushed a scrap piece of plywood onto the joists, waited for the swaying to stop, and then started shooting. He had the job done while I was still looking around for a ladder to help him.

Joe has actually had two complete careers at SLAC, the first as an electrical engineer. He came here in 1962 from Princeton's plasma physics laboratory, and joined the Light Electronics Group. He was responsible for the accelerator trigger system as the leader of a subsystem group that included Dale Horelick and Bill Pierce.

Joe gradually developed his photographic hobby into a profession by practice, workshops, and more practice. The electronics group's loss was photography's gain. And now retirement takes him away from both.

Enjoy it, Joe.

— *Bill Ash*

CORTEZ HEADS DOE OFFICE

On July 3 Dr. Jose Luis M. Cortez became the new Director of the Stanford Site Office of the Department of Energy (DOE), succeeding William Gough, who retired in April. Dr. Cortez comes to SLAC representing the DOE San Francisco Operations Office (SAN), which manages the Stanford office.

Prior to joining SAN, Dr. Cortez was Senior Research Program Coordinator for the Office of Nuclear Regulatory Research, Nuclear Regulatory Commission, in Washington. Prior to that he held positions at DOE as Program Manager of the Photovoltaic Energy Research Program, Director for Technology Programs in the Office of International Programs for Conservation and Solar Energy Technology, and Senior Management Specialist in the office of the Assistant Administrator for Nuclear Energy.

Before DOE, Dr. Cortez spent twelve years as a research scientist at Livermore and Los Alamos. He also worked for six years as a space scientist for NASA's Marshall Space Flight Center during the early unmanned lunar exploration and the Saturn V rocket development programs.

Dr. Cortez received Bachelor of Science and Master of Science degrees in Physics from Texas A&I University. He holds a Master of Science in Nuclear Physics (1965) and a Ph.D. in Theoretical Physics (1967) from the University of Michigan.

— *Bill Kirk*