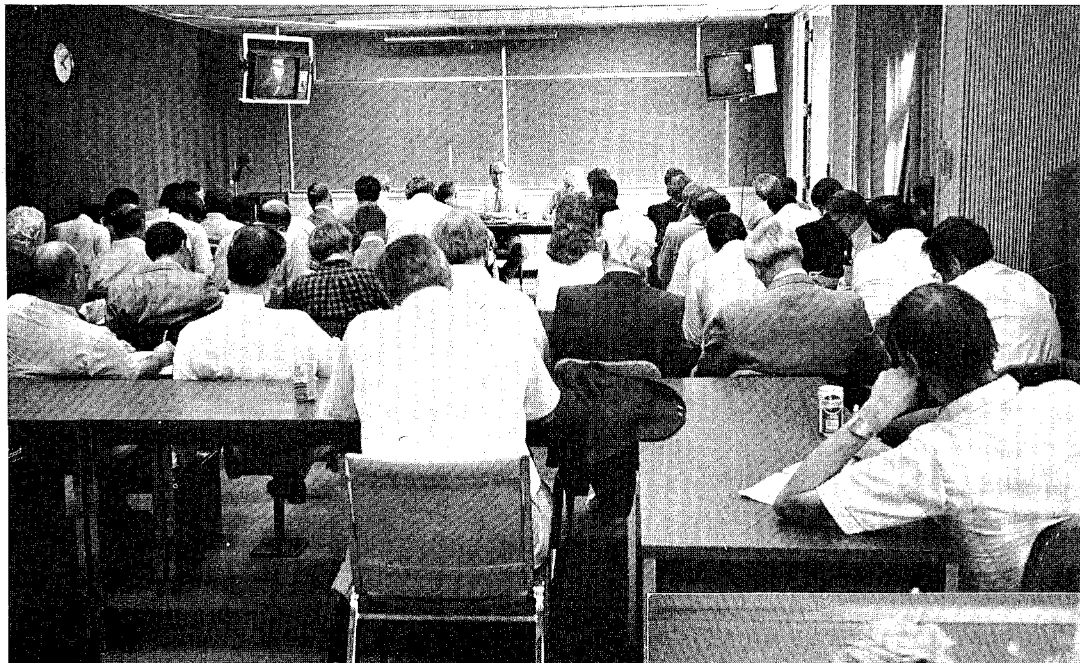
SLAC BEAM LINE

High-energy physics is an intoxicating subject — every generation has felt that it has nearly scaled the truth ... and every generation has been proved wrong in the past. —Abdus Salam.

Volume 14, Number 10 October 1983



THE FIRST SLC BIDS

Gordon Ratliff faced a roomful of hopeful bidders on Thursday, 15 September, in the Orange Room of *SLAC*. The 16 bids ran from just under 8M$ to just over 16M$ for the nearly 9000 feet of collider tunnel and the linac junction. Bob Bell and Matt Allen go over the details of the bid after the opening. The successful bidder, Gates and Fox Company, began work early this month. (Photos by Joe Faust.)

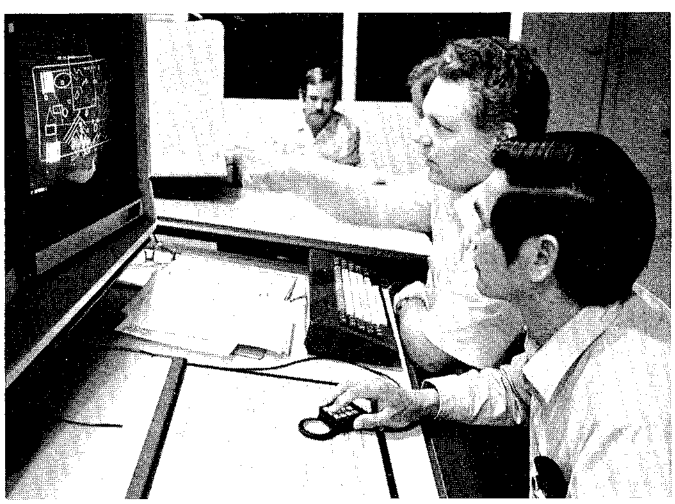
INSIDE ...

COMPUTER AIDED DESIGN

In the last week of June *SLAC* acquired its first equipment for computer-aided design, commonly known as *CAD*. A *CAD* system does for drawing and design what a word processor does for typing and writing. The skill, thought, and initial work are still there but corrections and repetitive work are made enormously easier.

The designer works at a kind of electronic drafting table where the motions of a hand-held 'pen' are picked up by the computer and displayed on a screen. Corrections are made by simple commands, the drawing can be changed in size, standard small pieces of design can be added with commands instead of redrawing, and much more. At the end of the session the computer stores the design and, if desired, prints a copy of the drawing. When the design is complete, the computer can produce commands for manufacturing the piece, such as a paper tape which drives a special drilling machine. This last step is usually called computer-aided manufacturing, or *CAM*.

What are the potential benefits of *CAD*? One obvious benefit, with which we have some direct experience, is in printed circuit design. Many of the routine and repetitive tasks can be performed more simply and more accurately using a computer. For example, many mechanical or electronic designs often involve blocks of circuitry or the use of standard mechanical components that have been used before in other designs. The computer can copy such components or blocks in a matter of seconds from an existing model, compared with perhaps many minutes for each copy if drawn by hand. In addition the computer can store images of commonly used components in a library, so that schematics or mechanical drawings may be quickly assembled from a collection of building blocks, as opposed to having to recreate each new building block each time a new drawing is begun.



Ed Austin and Joseph Yu of the Printed Circuit Design Group sit by a CAD workstation.

Another major advantage of a *CAD* system is that the computer can help verify the accuracy of drawings. In a mechanical application where several parts have to fit together, the computer allows the assembly of these parts in a model form to check whether any of the parts interfere. In architecture similar processes can be used to check whether pipelines are interfering with electrical utilities or plumbing. In electronic design the computer verifies the schematic by checking each line drawn between components. It then points out unusual features in the schematic, which in turn will usually reveal errors in the drawing or in the original design. Some of the more sophisticated programs will even alert the designer to some errors, such as 'non-wired-or' outputs wired together.

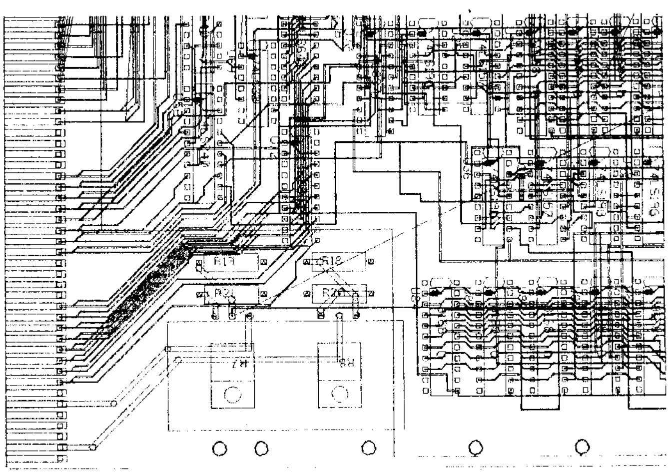
A further major advantage in the electronics application is that the computer can generate the net list of connections from the schematic. This can then be used as an input file for the printed circuit board design. This eliminates a very tedious process where the 'design file' is independently created by a draftsman drawing the schematic and again by the person designing the board. This now becomes one continuous process, although it is clearly easy to split the function so that draftsmen continue to design schematics, and printed circuit designers continue to design printed circuit boards.

Once the printed circuit design file is created, the computer refers to an existing library of components to produce images of the physical components against the printed circuit *(PC)* board. A program called Constructive Initial Placement does a semi-intelligent placement of components on the board to minimize trace lengths. The designer interacts with this placement to optimize it, and then turns the design file over to the 'autorouter.' The autorouter basically has several strategies for routing the connections on the board, but in general it performs the function of connecting the nets as specified by the net list to the proper components. On a multilayer board the autorouter can typically route 75 to 80 percent of the board, in a matter of a few hours. If the board density is sufficiently loose, one may expect 100% completion of the routing. Since *SLAC* tends to design very high density *PC* boards, in general this will be rare, and the *PC* designer will have to interact strongly with the design, especially toward the end of the task.

The combination of computer entry of the schematic, verification of the net list, and routing of the board is expected to reduce overall design time greatly. Since placement and routing accounts for the majority of *PC* design time, improvement factors of 3 or more are expected.

The overall objective in the *SLAC* Electronics Shop is to produce the initial prototype designs and one or two copies of the final boards as quickly as possible after receipt from the designer. The *CAD* system is expected ultimately to remove the last major bottleneck in *PC* board turn-around, a process which currently takes two or more months for a difficult design. The shop already can make multilayer boards in pre-production prototype quantities (one or two) in one or two days, compared to 3 to 8 weeks for an outside vendor to do the same job. This capability, coupled with faster design, should significantly shorten the time between completion of the engineering design and final production of large quantities of boards, modules, or systems.

Although the above discussion has used the electronics problem for illustration, similar arguments apply and similar gains in productivity can be expected with the other applications such as system wiring and architectural or mechanical designs.



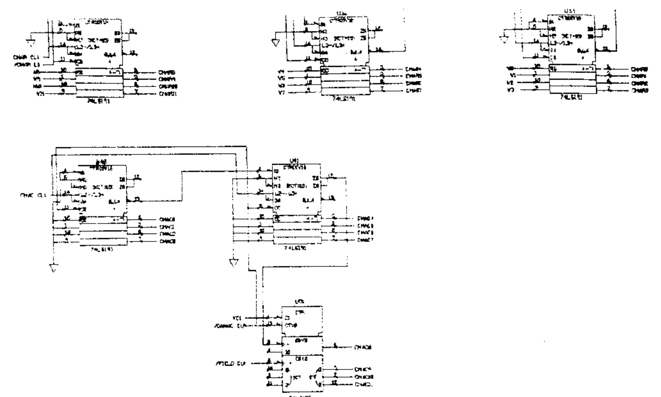
A corner of a partially routed Camac multilayer board showing completed traces and unrouted single-line interconnects.

Buying the Right Machine

The new *CAD* system was the result of two-year search for a system which would best meet the various needs of the *SLAC* Engineering and Production Groups. Many people participated in determining the requirements for the system and in evaluating the many different systems available. The committee that was charged with making the final specification and selection of the system consisted of Joe Fish, *PED* Drafting (Chairman); Ken Crook, I&C; Bill Johnson, Computation Group; John Steffani, Computation Research; Chuck Perkins, Mechanical Engineering; and Ray Larsen, Electronics Department. Dave Downing provided liaison with Business Services.

The committee discovered that there are basically three kinds of vendors: those who sell specialized *CAD* hardware and software to do restricted tasks such as printed circuit design; those who sell a piece of a large system but do not offer a full integration of hardware and software to cover multiple disciplines; and those who offer 'fully' integrated systems which combine multiple engineering and manufacturing disciplines in a single integrated system.

After surveying a large number of available systems, the selection committee decided that an integrated system would work best at *SLAC*, since project designs here inevitably involve many different disciplines, such as



A much-reduced section of an electronic schematic drawing produced using CAD.

Ben Revillar, Vic Itani, and Jim Cabading of the Electronic Department Drafting Group practice with the electronics schematic and PC menu tablet.

electronics and printed circuit layout, mechanical package design, architectural design, and wiring systems. Another reason for integration is that *SLAC*'s existing documentation system is managed by a central office, namely Plant Engineering, and there were strong arguments for purchasing a system which could gracefully complement and absorb it.

The Initial System

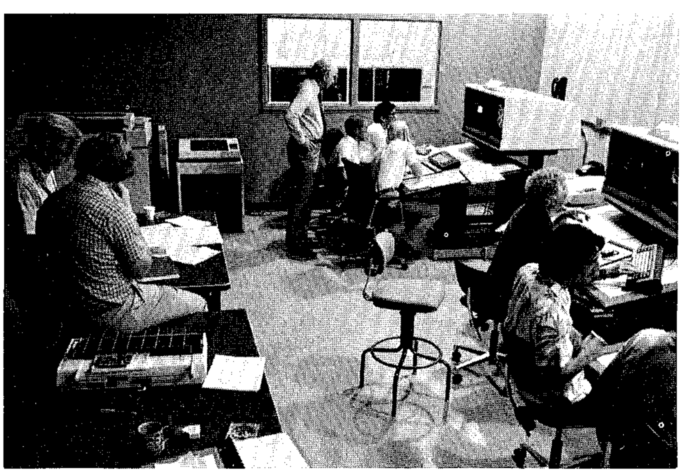
The system finally selected is made by Intergraph of Huntsville Alabama, and is based on the Digital Equipment's *VAX* computer line. The company manufactures the work station, which includes its own 68000 processor, and also offers a line of hardware enhancements to the *VAX*, such as a high speed graphics processor. The software system is designed to accommodate multiple enginering disciplines under a common data base.

The inital system procured by *SLAC* consists of five dual screen color work stations, each with a digitizing table and each with a 68000 local processor. The work stations are connected to the central processor via a looped 2 megabit per second coaxial cable. The cable can be up to 2 miles long. Peripherals on the system include 2 84-MB disc drives, one 675-MB disc drive, dual tape drives, and a 4-pen color plotter. Future additions planned include several more work stations, one or two engineering work stations (a new compact single screen work station with the same capability as the dual screen), a flatbed electrostatic roll plotter, and the high speed graphics processor.

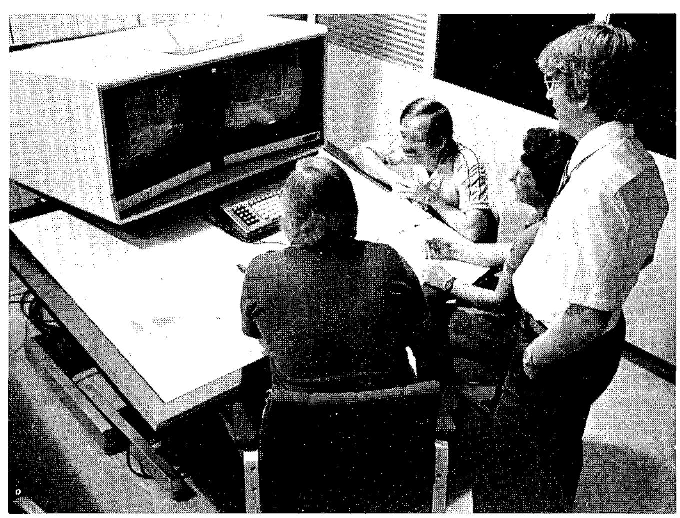
The basic software procured with the system includes electronic schematic and printed circuit design, two- and three-dimensional mechanical design, an architectural package, and an electronic system wiring package. In addition, software has been purchased to create machine outputs for the Gerber photoplotter, Excellon drill, and various numerically-controlled *(NC)* machines used in the Mechanical Fabrication Shop. Software for various engineering disciplines may be added in the future; this is under evaluation by a number of different groups with different needs.

The first work stations are located in the old *SLAC* Control Building *(CCR)* and in the Vacuum Assembly Building. Eventually, work stations will be located in the A&E Building, Electronics Building, and the new Electronics Building Annex (I&C). Presumably the system will grow and work stations will appear in other locations as well. A high speed graphics processor attachment can reduce the load on the central processor caused by intensive jobs associated with printed circuit routing and three-dimensional modeling. This would allow the system to handle at least 16 work stations, and possibly more.

One of the features included in the original specifications but not purchased was a data link to the *IBM 3081*. It has not been determined what the optimum connection might be for future needs, but the general idea was to have a future capability to perform engineering analyses of various kinds (such as *SPICE, TEGAS,* or stress analysis) on the *3081,* and then be able to download a design file to perform detailed mechanical or electronic design on the *CAD* machine. There is a strong interest in adding to our computer-aided engineering design capabilities in the near future, and to allow these new components to work smoothly with the new *CAD* system.



The CSD training center in the old CCR building at SLAC. Two work stations are shown and the VAX 780 computer is visible through the windows.



A CAD work station showing the dual screens (monochromatic at left, color at right) and the large digitizing table.

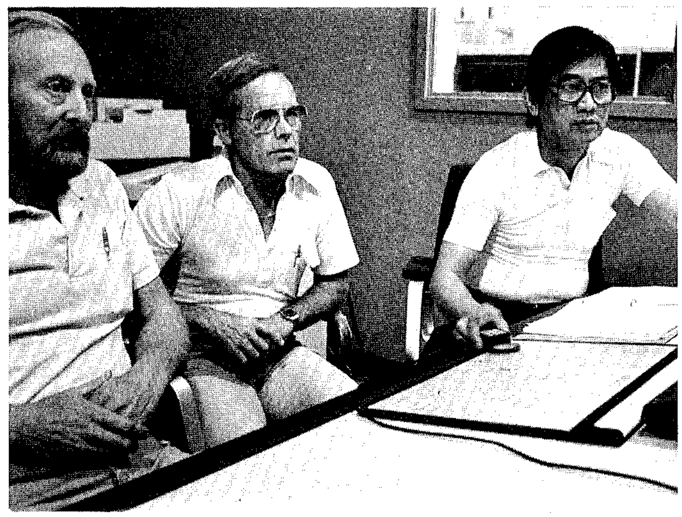
Tests and Organization

Currently the *CAD* system is undergoing acceptance tests. In conjunction with this, a number of people have taken basic training and some have taken advanced training in the various disciplines. Over the next few months, a larger number of people will be trained, and those with the most advanced training will be dedicating themselves full time to the system. In conjuction with this, all of the trainees will participate in creating the necessary library components which will serve as the standard set of design modules for the various disciplines. Six months from now we should probably be in full production with all work stations being used 1 1/2 to 2 shifts per day and with some of the production goals outlined above being met.

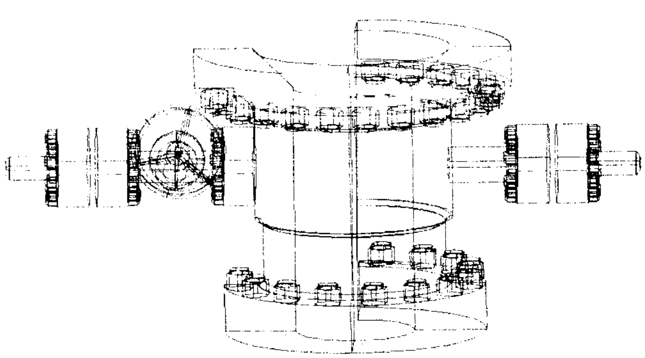
John Steffani of the Computation Research Group has been appointed System Manager to introduce this large scale system into the mainstream of *SLAC* design and production work. John is charged with acquiring or creating the interconnections between the various software and hardware tools needed to perform all phases of the *SLAC* design and manufacturing tasks. This includes the components to create magnetic or paper tape for driving various plotters and *NC* machines. Interfaces to future engineering software may be required. Anyone wanting to look at the system or see a demonstration should call John at extension 2289.

–Ray Larsen

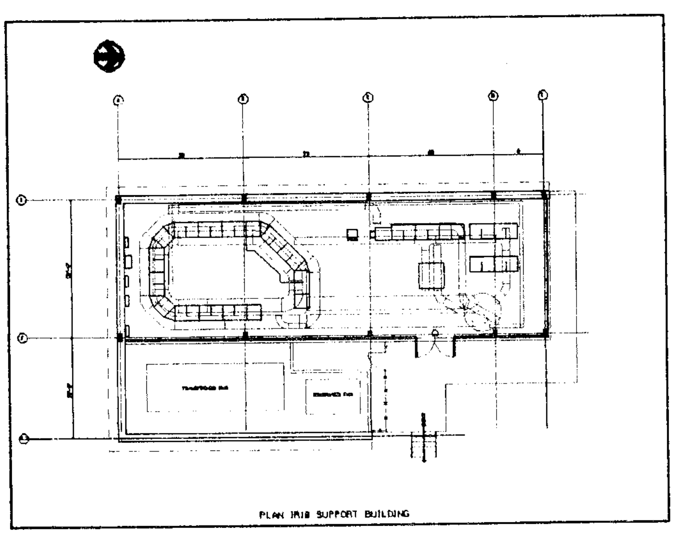
Chuck Perkins and Nancy Palmer of the Mechanical Engineering Department explore the wonders and pitfalls of the mechanical design package.



Les Johnson, Bob Laughead, and Romy Castro of the Plant Engineering Drafting Group riveted to the CAD screen.



A perspective drawing of a piping assembly produced using CAD.



A much-reduced copy of a drawing of the PEP IR-10 support building produced using CAD.

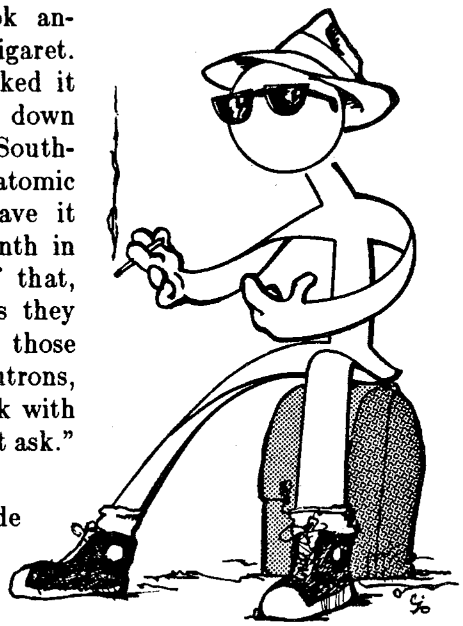
Jon Carroll

OUR MR. QUARK

It was revealed last week that a team of dogged scientists at Stanford had discovered a hitherto-elusive quark. For the quark, it was a disappointment—and a relief.

"Imagine what it's been like these past few years," said the short, beautiful so-called 'Fifth' quark in an exclusive interview with this correspondent. "Constantly on the run, sleeping in electron fields, scrabbling for bits of Key lime pi-mesons in the bottom of garbage bins. I move pretty fast, but I guess not fast enough."

The quark took another drag on a cigaret. "Filthy habit, Picked it up from a proton down at Caltech. Those Southern California subatomic particles really have it easy. Once a month in the accelerator, if that, and all the gluons they can eat. And all those tanned young neutrons, looking for a quark with a steady job. Don't ask."



How, I asked, had he managed to evade the scientists for as long as he did? He smiled.

"I guess you could say I lead a charmed life." He smiled. "As a matter of fact, I told that joke to the scientists, and they couldn't stop laughing. Dummies."

I pressed him to reveal his secrets.

"It ain't easy. I can tell you that. Everywhere you go, there's some scientist peering through an electron microscope, or wanting to rotate you until your brains turn to brie, or pinning you down and asking you questions about your childhood."

Well, what about his childhood?

"Poor but honest. Dirt poor and too honest, I guess. I'm a 'bottom' quark, you know. We didn't get the vote until after the Particle Revolution of 1910. My father was in that; those were the days. Cosmic ray battles outside the union halls; liberal 'up' quarks bringing food packages; everyone chanting 'We Want a Spin' and wearing 'Split Wood not Atoms' buttons."

What happened?

"What always happens. The 'top' quarks kept collaborating with the scientists; nothing changed. I read in the paper where the scientists say they still haven't discovered the 'top' quarks. Bullpuckey. They want to find one, they don't have to look any farther than a faculty cocktail party."

How, I asked, did he become an outlaw?

"Well, the word was out, you know? Find that quark! My Daddy didn't raise a quitter, though. If they wanted me, they'd have to find me — that was my attitude ...

"The worst part was that I couldn't see my friends. A lot of them had chosen to stay in Palo Alto, pretending to be hadrons or some damn thing. They'd hide in the bowels of the Positron Electron Project machine — they call it *PEP;* isn't that cute? — sleeping with one eye open, ready for an energy alert. I understood, but it wasn't the life for me."

So how did he finally get caught?

"I don't like to talk about it. Let's just say I had a ... friend, a beautiful little B-meson. Before the big quark hunt, we'd planned to make a life together, settle down in New Mexico, raise a few fractional charges. I heard she was sick, so I hitched a ride on a cross-country electron out of *MIT.* Fetched up in Palo Alto, wormed my way into the goddam *PEP* doohickey.

"So there I was, whispering sweet nothings, when all of a sudden the juice went on and all these antimatter positrons began whooshing past my head and suddenly ka-bammo, there I was. My cover was blown. The scientists were slapping each other on the back and sending out for bottles of imported wine."

He paused.

"I never did see that B-meson again. Oh, I've asked a hundred times, but you know scientists. These are quantitative guys, purely. They only know from numbers."

The quark lit another cigaret.

"I've learned to be philosophical. Life is short — in my case, about 2 picoseconds — and you've got to learn to take the bitter with the sweet."

Columnist Jon Carroll wrote the preceding whimsical account of the life of a quark after reading one of the more conventional reports of the measurement of the lifetime of B-mesons by two teams at SLAC. He agreed to our reprinting his account and later visited SLAC, writing another column about our work here. The above piece first appeared in the August 8 issue of the San Francisco Chronicle. We have taken the liberty of illuminating the manuscript with a cartoon of Our Mr. Quark as seen by SLAC illustrator Conrad Ouellette.

SSRL DECISION

A research proposal to the Stanford Synchrotron Radiation Laboratory (SSRL) from scientists at three laboratories involved in nuclear weaspons testing has produced considerable discussion and controversy at Stanford and SLAC over the past several months. The questions raised have now been settled as explained in the following excerpted memo to all SLAC staff of 27 September from Acting Director Sidney Drell.

Dr. Arthur Bienenstock, Director of *SSRL*, has announced that he is accepting the proposal from scientists at the Lawrence Livermore National Lab, the Los Alamos National Lab, the Sandia National Lab and the University of California to build two new beamlines at *SPEAR* to carry out a program of basic research at *SSRL*. This decision by *SSRL* has come after agreement was reached between *SSRL* and the proponents on a number of basic points that confirm that this program of research, in all respects, will be in accord with Stanford University research policy; that is, all work will be unclassified and will be freely and openly disseminated, and access to the *SSRL* facilities will remain open as at present. In addition, beam time will be shared in full accord with University research policy.

Many of you have expressed concerns about *SLAC*'s being drawn into participating in work directly related to the nuclear weapons program. You should know that the revised Construction Project Data Sheet (i.e., the construction proposal to the Department of Energy) for this project and the letter from Dr. Bienenstock to the Provost's Office accepting the research proposal make clear that its basic science measurements will be performed at *SSRL*, while "all routine calibration of instruments for the weapons tests will be performed at *LLNL*, rather than *SSRL*."

I welcome this clarification of the proposed work. As stated in an earlier memo by Dr. Panofsky, with the clear determination that this proposal is in accord with Stanford policy, *SLAC* is prepared to cooperate fully with *SSRL* on this project.

JIM MOSS RETIRES

Jim Moss retired on September 30, 1983, after a twenty year career at *SLAC* in mechanical and electrical support of several large projects.

Jim came to *SLAC* in January 1963 from the University of Chicago's cyclotron project. His first project here was with the large Spark Chamber for Experimental Group E. Six years later he began a 12 year stint with Experimental Group D and their Streamer Chamber.

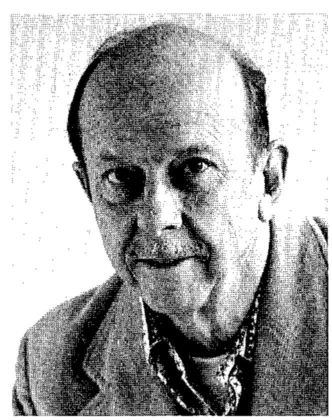
In 1981 he joined the Magnetic Measurements Group to run the production magnetic measurements system for the *SLC* and damping ring magnets.

In retirement Jim plans to pursue hobbies of gardening and golf. We wish Jim the very best of everything in his much deserved leisure time. It has been a great pleasure working with him.

–Joe Cobb

BOB LAURIE RETIRES

The call of the highlands has finally lured Bob Laurie away from *SLAC* .



As he lounges in his mountain cabin he can while away the hours reminiscing about the early days of the Accelerator Structures Group of Project M which he joined in 1961. This group ultimately evolved into the Mechanical Engineering Department and Bob has been with it the whole way.

In addition to his work on the beam line design for *EFD* and various accelerator improvement projects, most notably *SLED*, Bob has acted as the resident expert on the curing of olives and the bagging of pipes. His yearly ritual of greeting the new year in the best Scots tradition will certainly be missed but he can be sure that his acquaintance will ne'er be forgot by his large group of friends at *SLAC*.

NEWS AND EVENTS

FEYNMAN FILM SERIES

"The Character of Physical Law," a series of six filmed popular lectures by physicist Richard Feynman, will be shown at *SLAC* during the lunch hour on Wednesdays over the next six weeks.

The first lecture, "The Relation of Mathematics to Physics," will be shown on Wednesday, October 19, at 12 noon in the Yellow Room of the A&E Building. The succeeding five lectures will be shown in the Auditorium as follows: "The Great Conservation Principles" (October 26), "Symmetry in Physical Law" (November 2), "The Distinction of Past and Future" (November 9), "Probability and Uncertainty—the Quantum Mechanical View of Nature" (November 19), and "Seeking New Laws" (November 23).

BENEFICIAL BLOOD DRIVE

Heartfelt thanks to the many donors at the Mobile Blood Drive for the Stanford University Blood Bank held at *SLAC* last month. In a letter of thanks Rhoda Burns, Supervisor of Recruitment, stated: "The success of this recent blood drive has been an enormous aid to the Blood Center in meeting an emergency situation this week. There is a 16 year old patient at Stanford ... requiring over 100 transfusions of platelets per 24 hours for over one week." Donations credited to the *SLAC* Donor Club are good for one year for the use of the *SLAC* community. If you need replacement credits, please contact Nina Adelman, Blood Drive Coordinator, ext. 3113.

SLAC Beam Line, x2979, Mail Bin 94

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Photography: Joe Faust, Walter Zawojski.
Illustrations: Publications Department.

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

SLAC ACCELERATORS

Pictured above are the *SLAC* Accelerators - Bob Nicholson, Bryan Harris, Nate Peairs, Jim Minich, Tom Kamakani(manager/coach). Below: Gus Stevenson and Rod Harrison. The team now holds first place in the C-1 league and several of the Accelerators are playing in the league All-Star Game.

FLU SHOTS

Influenza vaccine is available in the *SLAC* Medical Department. Flu shots are recommended for those at high risk. This category includes individuals with chronic health problems such as diabetes, disease of the heart, lungs, or kidneys, severe anemia, or chronic illness. It is also recommended for those 65 and over. If you have any questions, call Medical, ext. 2281.

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Z^0 COME TO THE SLC GROUNDBREAKING Z^0

Z^0 *OCTOBER 31, 3:00 PM* Z^0

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Join your colleagues at the *SLC* Groundbreaking Ceremony, October 31 at 3:00 pm, on the green at *SLAC*. The principal speaker at this in-house celebration will be the US Secretary of Energy, Donald Hodel. William Kimball, Chairman of the Stanford Board of Trustees, and Dr. Alvin Trivelpiece of *DOE* will give brief talks.

SLC Project Director John Rees will host the festivities and Pief will conclude the program. Refreshments will be served after the ceremony.

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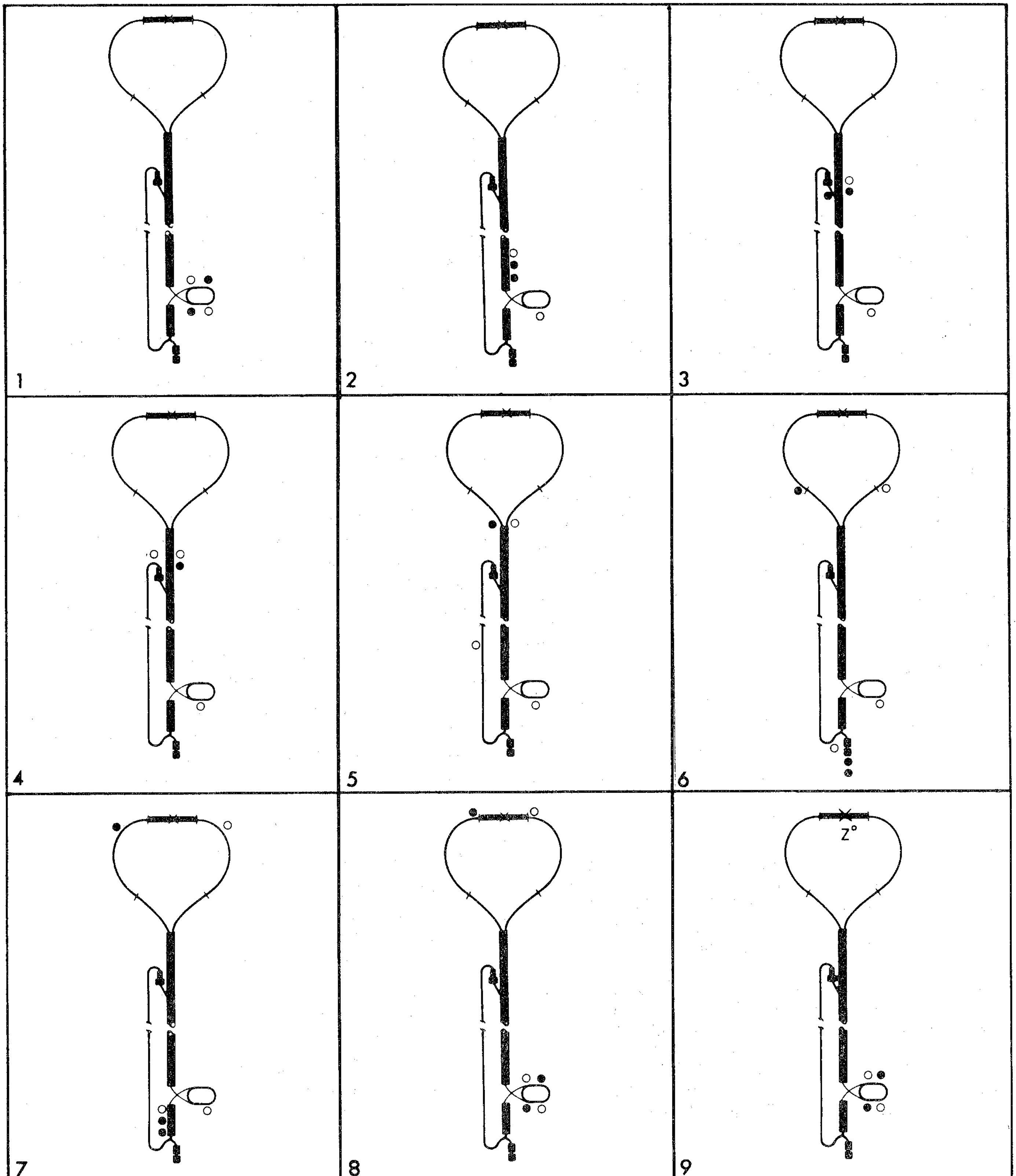
SLAC BEAM LINE

OCTOBER 31, 1983

SLAC LINEAR COLLIDER GROUNDBREAKING



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THE SLAC LINEAR COLLIDER

High-energy physics is the study of how the world is put together: what are the simplest particles of nature and how do they behave? Producing these particles and studying their behavior in simple conditions requires very high concentrations of energy. This apparent paradox of using more leverage to pry into tinier objects is a result of a fundamental principle of physics which relates distance and energy. Roughly speaking, the smaller the object, the bigger the microscope needed to see it.

The result of this coupling of small size and high energy has been a series of large and sophisticated machines, or accelerators, which produce the high-energy beams of particles that are used to explore the very small structure of the world. The *SLAC* Linear Collider, or *SLC,* is a big step in this march of machines at *SLAC.* In fact it is more like two steps: one step as a completely new kind of machine and another in entering a new realm of physics.

STEP ONE—THE NEW MACHINE

A direct way of producing a large concentration of energy is to collide an electron with its anti-matter equivalent, a positron. These particles annihilate into a flash of energy in which other subatomic particles are created. The higher the energy of the two particles, the more is available in their collision.

The first application of this idea was the electron-positron storage ring. In this technique a beam of electrons and a beam of positrons circulate in a ring in opposite directions and collide at several points. These machines, of which *SPEAR* and *PEP* are examples at this laboratory, have been extraordinarily productive tools for high-energy physics in the past decade. Unfortunately, there is a practical limit to building storage rings of much higher energy than now planned.

In a *linear* collider the very intense and highly focused beams of electrons and positrons from two linear accelerators collide directly. Such machines allow the technique of electron-positron collisions to be carried on to higher energies. The *SLC* will be the first application of the principles of the linear collider.

STEP TWO—THE NEW PHYSICS

The subatomic world appears to be composed of two classes of simple particles which are held together and interact through three kinds of force.

The basic particles are the quarks and leptons. Quarks combine in twos and threes to form the familiar (and many unfamiliar) heavy particles such as the proton and neutron. The leptons appear individually, with the electron being the most familiar example. Discovering new members of the quark and lepton families and exploring their properties has been the focus of experiments in the past decade.

The basic subatomic forces are the electromagnetic, the weak, and the strong. Finding out how these forces work is as important as cataloging the particles which make up matter, but experimental advances have come harder.

The electromagnetic force is very well understood, even in the subatomic world. The strong force is not very well understood at all, but at least its function of holding together quarks and in holding together the nucleus is a familiar concept. The weak force, however, is unfamiliar; it does not hold things together but instead allows particles to change from one kind to another.

Many of the properties of the weak force have recently been explained by an elegant theory proposing that the weak and electromagnetic forces are two parts of a single, simpler force. One consequence of this idea is that the force must be 'carried' by three special particles. The three carriers of the weak force (the W^+, the W^-, and the Z^0) were recently discovered in experiments at the European laboratory, *CERN.*

The *SLC* will have enough energy and intensity to produce millions per year of the Z^0, giving physicists their first detailed look at how the weak force works.

SLC: The SLAC Linear Collider

The *SLAC* Linear Collider is a program to increase the energy, intensity, and precision of the *SLAC* linear accelerator so that pulses of electrons and positrons may be bent around and collided. The 113 million dollar project was approved for construction beginning in October 1983. First operation is expected in late 1986.

This introduction to the *SLC* is the first in a planned series describing the principles and operation of the new machine, its technical components, and the expected physics program. This first section traces the evolution from the accelerators of high-energy physics to the first colliding beam machines, and then to the first in the new breed of linear colliders.

THE SLC—A NEW MACHINE

Exploring the structure of matter has required the development of a series of machines to produce high-energy beams of particles. Important breakthroughs in physics have come both by building machines of higher energy and by exploiting the energetic beams in new ways. Since the *SLC* is an important turning point in this evolution, a brief review of the history of the machines of high-energy physics will be useful.

ACCELERATORS

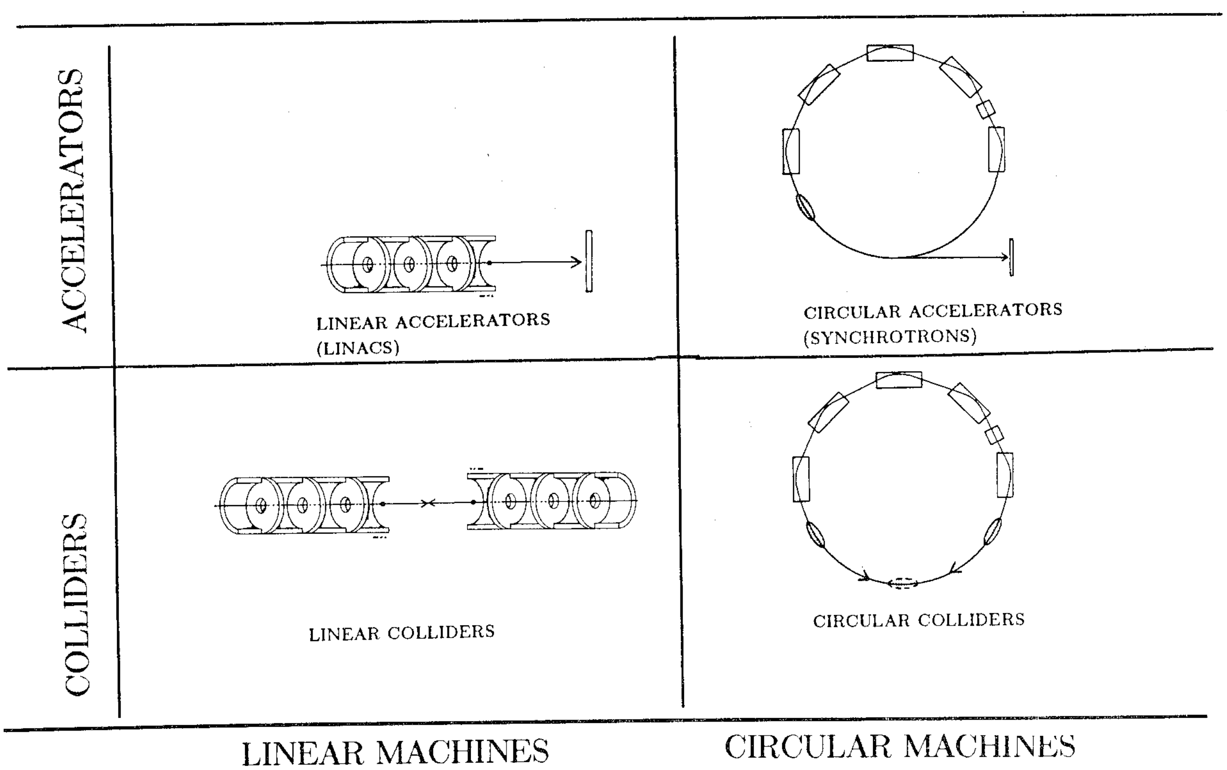
In the 1930's the first machines were built which could accelerate particles to the energy needed for exploring the nucleus. These accelerators, which launched the present era of high-energy physics, can be divided according to the chart at the bottom of the page. This review will concentrate on the family of electron accelerators, with occasional references to parallel work with proton machines.

All of the machines have the same basic mechanism for accelerating charged particles: an electric field. The most familiar particle accelerator (and certainly the most watched) is the television picture tube. The high voltage applied to plates in the neck of the tube accelerate a beam of electrons toward the screen. The source of particles is basically an electrically heated wire which 'boils off' electrons.

The simplicity of the basic accelerating mechanism shows up in the unit used to measure the energy of beams. One electron volt, or *eV*, is the energy given to a beam by a field producing one volt. The typical picture tube produces a beam of about 20000 eV, or 20 keV. The *SLAC* linear accelerator routinely delivers beams with one million times this energy, or 20 GeV. (The *G* stands for *Giga*, or one billion.)

This factor of one million in energy implies that such machines are going to be very big; indeed, the *SLAC* accelerator is two-miles long. On the other hand, two miles is only about ten thousand times the length of a picture tube, not one million times, so there is more to these machines than just building something larger.

Before going on to the techniques that make accelerators practical, it is worth another look at the unit of energy, the GeV. When one high-energy particle collides with another, new particles are produced; the energy of the collision has been converted to mass. The arithmetic of these collisions requires that the beam energy and the particle masses be measured in equivalent units. Most subatomic particles have masses around one GeV, some less and some more. Thus, the collision energy in GeV is simply related to the number of subatomic particles that can be produced. Physicists think in terms of GeV directly, not in billions of electron volts.

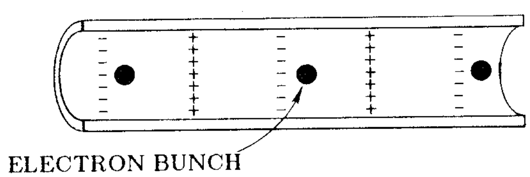


LINEAR ACCELERATORS

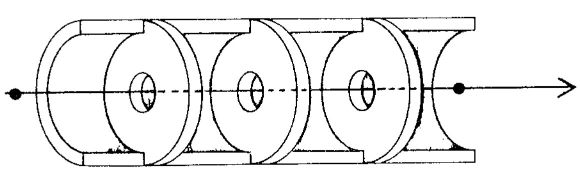
In an electron linear accelerator, like *SLAC's*, the basic electric field which accelerates particles is not produced by a voltage applied to metal plates. Instead, the field is produced by high-frequency radio waves, called microwaves, which travel down the long copper tube of the machine. Electrons are injected into the end, are caught up in this traveling wave, and are continuously accelerated by the field as they travel down the machine.

The final energy of the electron beam depends on the strength of the accelerating field in the microwaves and the length of the machine. The *SLAC* linac gets its microwave power from 240 high-power amplifiers, called klystrons, spaced along the machine. Since the amount of power put into the machine for acceleration is very large, electron linacs usally run with short intense pulses of beam instead of continuously. The *SLAC* linac typically turns on for about one millionth of a second and pauses for a few thousandths of a second before pulsing again.

The schematic of the linac shows the basic simple structure of microwave source and accelerating tube.



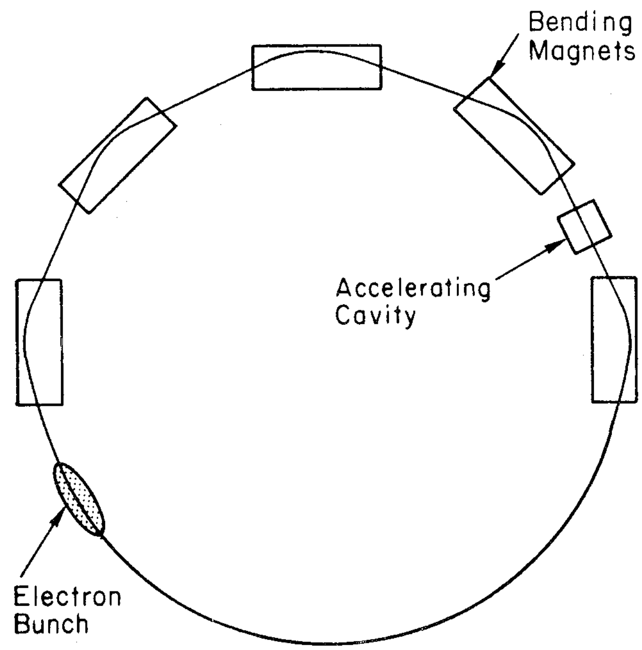
The electric field carried by the microwaves is shown as if it were produced by lines of positive and negative charges. The bunches of electrons follow the motion of the field. The actual linear accelerator tube contains periodic metal disks which are necessary to control the velocity of the microwave power down the tube.



One section of a linear accelerator looks very much like any other. Nothing happens as the electrons gain more energy that requires a more elaborate beampipe or a change in the microwave system. (In fact, the trickiest part of a linac can be at the low energy end where the electrons are more susceptible to stray fields.) As a result, simply doubling the length of a linac gives twice the energy.

CIRCULAR ACCELERATORS

Instead of running a beam through a long accelerating field, circular accelerators use a shorter field over and over again. Short accelerating sections are placed at a few points along the circumference of a ring and bending magnets keep the beam confined to the circle, as shown in the schematic. As the beam circulates it gains energy on each turn in a way that is just matched to the increasing field of the magnets necessary to keep the beam on the orbit.



USING THE BEAMS

There are many kinds of experiments which use the beams of electron accelerators, with electron-scattering being the most direct example. In these experiments a high-energy electron beam hits a target of liquid hydrogen. The small fraction of electrons which strike the protons in the target are detected at different angles and energies, and the pattern of scattering is the key to what is inside the proton. The more energy in the collision between the electron and the proton, the more deeply is the structure probed.

Linacs and synchrotrons have been complementary tools for exploring matter in these scattering, or 'fixed-target,' experiments. The linac has a much more intense beam, but it is delivered in a short pulse. The synchrotron has a less intense beam, but it can deliver it over a longer time, making some experiments easier to do. The crucial difference shows up when these machines are used for a different class of experiments: colliding beams.

COLLIDERS

Colliding beam machines are not new kinds of accelerator, but rather new ways of using accelerated beams: instead of colliding a beam with a target, collide it with another beam.

The idea of colliding beams has always been attractive. Two particles striking head on give up all their energy to the collision. When a beam particle strikes a particle in a stationary target, however, most of the energy is carried away by the particles moving away together after the collision. The advantage is not just a factor of two; it can be enormous and it gets even larger for higher energy beams.

The first experiment with colliding beams was performed by Stanford and Princeton on the Stanford campus in the early 60's. The experiment collided two 0.5-GeV electron beams, to find out whether the theory of the electromagnetic force worked at very high collision energies. The energy scale of these collisions was three or four thousand times what could have been obtained by letting the highest-energy electron beam of the day strike atomic electrons in a solid target. This made an enormous difference to the physics significance of the experiment.

This comparison between colliding-beam and fixed-target experiments can be made more vividly. How big would a fixed-target experiment have to be to get the same collision energy available by colliding beams of a particular energy? Fermilab near Chicago is completing modifications which will produce collisions of 1 TeV (1000 GeV) protons with antiprotons in the existing 4-mile circumference ring. The equivalent fixed-target experiment would require a proton synchrotron so large it would encircle the United States and a good part of Mexico and Canada!

With so much to gain, why weren't colliding beams introduced long before? The biggest problem was that a beam makes a very poor target. No matter how great the benefit in the energy of a collision, an experiment cannot be done unless there is a collision to begin with.

Compared to a solid target a beam of electrons is an airy thing. In fact, in a dense electron beam the particles are spaced about a hundred times farther apart than air molecules. The holdup in colliding beams was in producing beams dense enough to give a useful number of collisions.

This property can be compared with a similar one in optical microscopes. The strength and arrangement of the lenses of the microscope determines the power or magnification. The diameter of the lenses and the strength of the light determine the brightness. Both factors must be considered, for it does no good to have a very high-power microscope with an image too dim to see.

Just as energy in a beam compares with magnification in the microscope, the collision rate compares to the brightness of the image. This property of brightness is called luminosity and must be considered along with energy in comparing and designing colliders.

CIRCULAR COLLIDERS

Synchrotrons offered the quickest way to achieve colliding beams with good luminosity by using the ring both to accelerate the beams and then to 'store' them. In most circular machines the beam is extracted from the ring after acceleration and sent to various experiments. If the beampipe vacuum is good enough and the magnets are kept stable, however, a beam can be stored in the ring for hours. Electrons and positron beams can even be stored in the same ring, circulating in opposite directions, with the beams passing through each other every turn. The rate of interesting collisions is then increased by the number of times the beams cross each second—a factor of up to one million.

The first colliding-beam experiment was performed with the Princeton-Stanford collider in 1963. This machine used two electron beams, so two separate rings with a common intersection point were required. Most of the machines which followed stored electrons and positrons in a single ring. The chief reason for this choice was not the economy of one ring, but the richness of the physics from the complete annihilation of the electron with its anti-matter equivalent, the positron.

These electron-positron storage rings, including *SPEAR* and *PEP*, have been extraordinarily productive. *CERN* is now building an electron-positron storage ring called *LEP* (Large Electron-positron Project). *LEP* will be about 17 miles in circumference and will have 50 GeV beams in its first phase.

Colliders have not been confined to electrons and positrons. *CERN* built a two-ring proton-proton collider in the early 1970's, and has a proton-antiproton system now running using their proton synchrotron. Fermilab is completing modifications to its synchrotron to give proton-antiproton collisions with 1 TeV beams. The German laboratory *DESY* is building a hybrid electron-*proton* collider.

LINEAR COLLIDERS

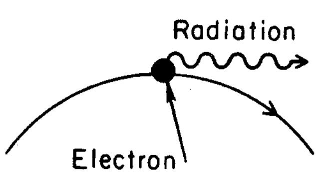
The march of machines to higher energy is running into a serious problem, one whose dimensions can be seen already in the two storage rings at *SLAC*. *SPEAR*, an electron-positron storage ring with beams up to about 4 GeV, is about 800 feet in circumference. *PEP*, with beams up to around 18 GeV, is about one and a half miles in circumference.

Something is strange here: the size has increased much more than the energy. In fact, it's even worse than it looks in this example. This unusal growth of cost and size with energy is explained by a basic physical process which dominates the design of all circular electron machines.

Synchrotron Radiation

When electrons are jerked hard, or accelerated, they lose energy. In an antenna, for example, the current of electrons oscillating up and down loses energy in the form of the radiated radio waves.

The continuous bending of the electron beam in a circular machine is also an acceleration; the electrons would go straight if there were no force making them curve. As a consequence the electrons constantly lose energy to what is called, aptly enough, synchrotron radiation. This loss is made up on each turn by the same devices which accelerated the beam to running energy to begin with: the short section of linear accelerator built into the ring.



The amount of energy lost on one turn of the ring depends on how hard it is to bend the beam into the circle, just like turning a car. The difficulty of a turn depends both on the speed of the car and the tightness of the curve. When a ring is run at higher energy, much more power must be put in to make up the steady losses. The practical limit to how much power can be put in sets the maximum energy at which a particular ring can run, so the only way to work with higher energy beams is to build a bigger ring. Unfortunately, this tradeoff is not very even. The radiation loss depends much more strongly on the beam energy than it does on the size of the ring. As a result a machine with *ten times* the energy must be *one hundred times* bigger. A hypothetical circular machine built like *SPEAR* and *PEP* but with 50 GeV beams would be more than fifteen miles around. This scaling is shown in the sketch at right.

In a linear collider the beams from two linear accelerators are collided directly. Since the beams are not bent and stored in circular rings, there is no radiation loss and the scaling problem of circular machines is avoided.

This difference shows up in the sketch. The 50 GeV *SLAC* Linear Collider will be about the same scale as the lower-energy *PEP* and a lot smaller than a circular machine of the same energy.

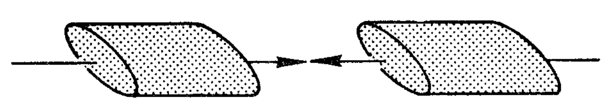
The smaller size of linear colliders compared to circular machines at energies of 50 GeV is very nice, but the principle will be even more important at higher energies. Collisions with ten times the energy will require linacs ten times longer or circular machines a hundred times bigger. A twenty-mile linac is not out of the question as a next step, but a 1500-mile circumference circular machine would be.

Problems of Luminosity

The solution seems too good. What's the catch and why wasn't it done sooner? The catch is in luminosity. The storage rings achieve a good part of their luminosity from the fact that the beams cross each other hundreds of thousands of times per second. This is like seeing by the light of a weak, flashing light; if the light flashes often enough, the visibility is still good. A linac, however, is able to produce beams only a few hundred times per second. If a linear collider is to compete, it must increase its luminosity by brightening the individual flashes.

The luminosity of one beam crossing depends on the number of particles and the area through which they are squeezed during the collision. Clearly a more powerful flash (more particles) helps. But if the light can be focused to a tinier spot, it will also appear brighter. It is hard to pack more particles into a bunch than is already done. The *SLC*, in fact, will have about a tenth the number of electrons in a bunch as *PEP*. So, the only way left to get a high luminosity is to focus harder. This is what brings linear colliders into the game.

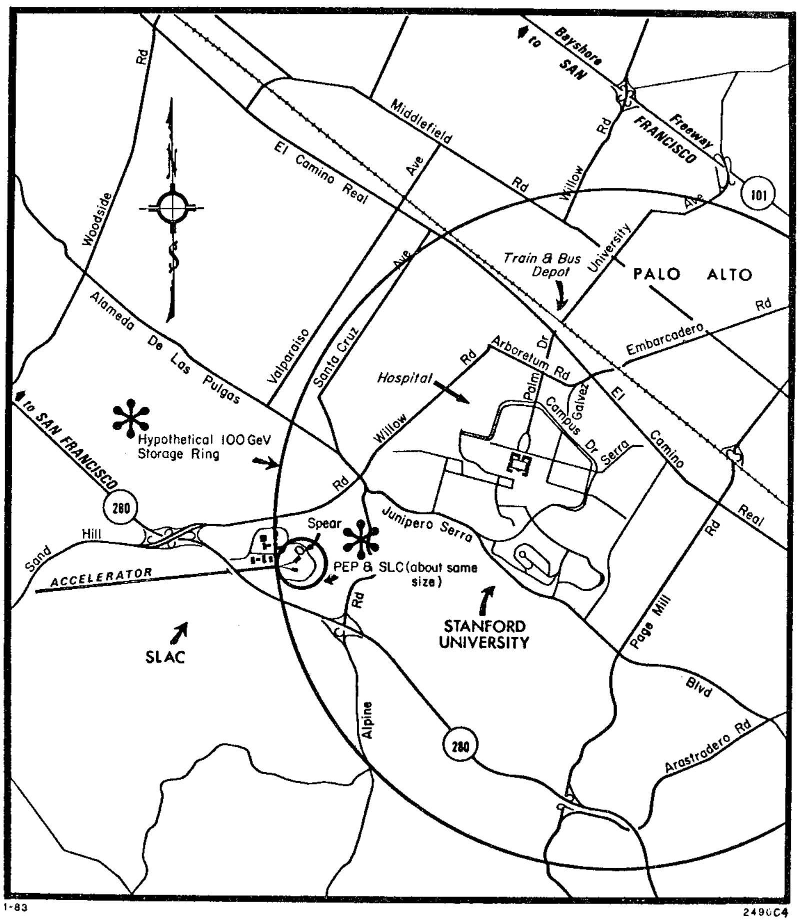
The *PEP* bunches are focused to a collision spot about 1 mm by .1 mm size, about one tenth the size of the drawing below.



The *SLC* spot will be about 1.4 microns in diameter, about a hundred times smaller than the *dots* in the sketch above. This is where the linear collider makes its money. The very tiny spot of the *SLC* makes it very bright and helps compensate for its much lower rate of flashing.

Why not use this fine idea of tight focusing in storage rings to increase their luminosity too? Unfortunately, the fact that storage rings recirculate the beams to get their high luminosity also prevents their using this additional handle. The beams in the storage rings circulate millions of times per minute for hours at a time. Small disturbances on one turn would quickly build up and kick out the beam. One source of such a disruption is the collision of the beams themselves. The simple electric and magnetic forces produced by the electric charge of one of the beams can disturb the other beam so much that it wanders off course and is eventually lost from the ring. This 'beam-beam' interaction gets stronger as the beams are squeezed tighter, and the typical spot sizes discussed above for storage rings are about the best one can get.

Strong beam-beam forces in the *SLC*, on the other hand, are not a problem since the beams do not get reused. In fact the instantaneous magnetic field produced by one bunch is about a hundred times stronger than the field used to bend the particles in the ring of *PEP*. Not only is this force tolerable, it even has a nice side effect. During the collision these forces squeeze the beams together a little more so that the luminosity can actually increase significantly.



THE SCALE OF MACHINES: This map of the Stanford area shows the relative sizes of a 4 GeV storage ring (SPEAR), an 18 GeV ring (PEP), and a hypothetical ring with 50 GeV beams. This dramatic increase of size with energy sets a practical limit to storage rings for colliding electrons and positrons. The SLAC Linear Collider, by contrast, will collide 50 GeV beams using the two-mile linac and a transport system about the size of PEP.

THE SLAC LINEAR COLLIDER

A linear collider consists of two linear accelerators pointed at each other and each firing an intense and finely focused beam at the collision point midway between the ends.

Since *SLAC* only has one linear accelerator, the first hurdle of the *SLC* project is to make one linac do the job of two. The linear accelerator can accelerate both a positron bunch and an electron bunch in a single pulse, so the trick is to separate these two bunches at the end of the machine, turn them around, and collide them. Simple enough, but several technical problems stand between these words and the deed.

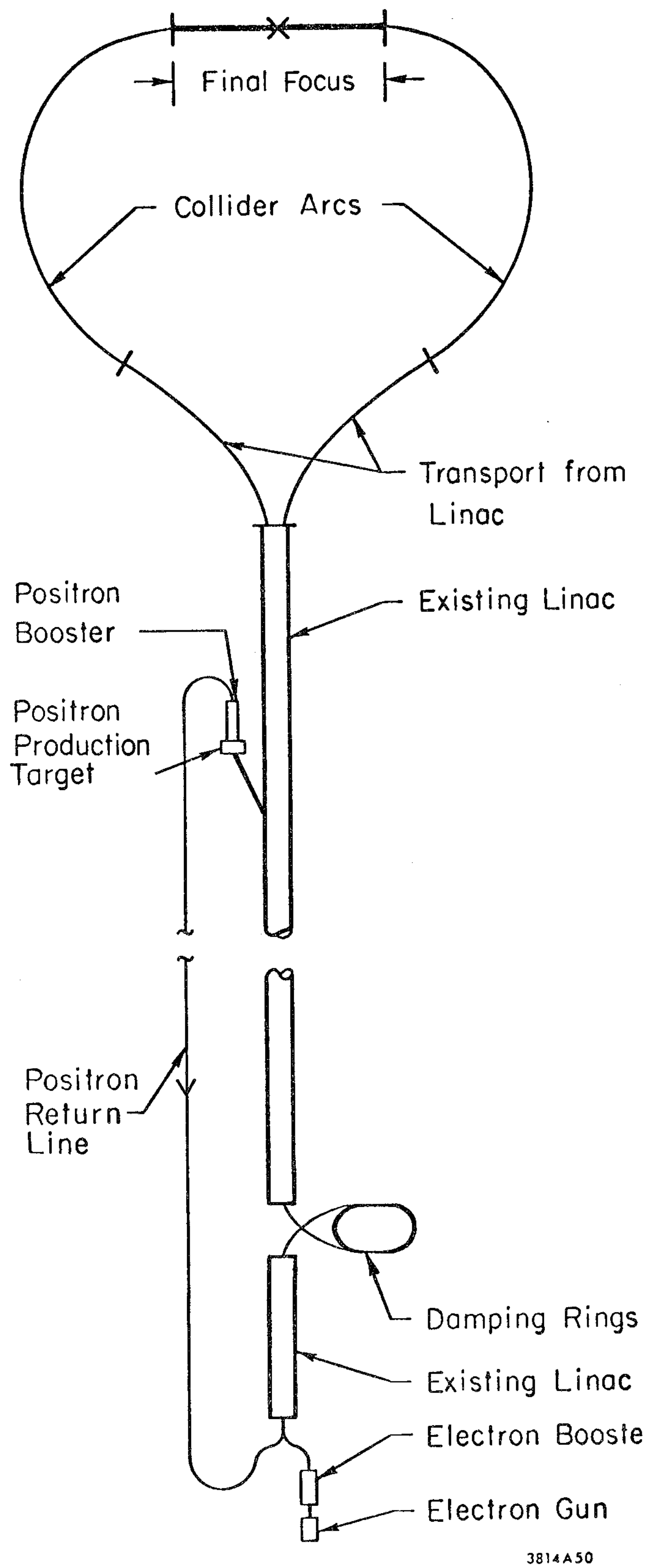
TECHNICAL CHALLENGES

The biggest apparent piece of the project is the pair of 4500 foot beamlines which bring the two bunches to a collision point. These two collider arcs are the pincers at the top of the schematic at right. The arcs consist of a string of bending magnets much like those in the storage rings *PEP* and *SPEAR* but more densely packed. The underground tunnels containing these magnets enclose the research yard at *SLAC* and most of the *PEP* ring.

These arcs make the project look like a storage ring, but the similarity is only superficial. A high-energy beam can be brought around such a tight arc once, but circulating a beam in a continuous *ring* of that size would be impossible. As it is, the beams lose about 1 GeV of their 50 GeV in the half-turn. The arcs are just the best way to make the beams collide once and are not part of a closed ring.

The second hurdle is to get a beam of positrons. Positrons are not part of ordinary matter and must be produced in high-energy collisions. When a beam of electrons strikes a heavy target, it produces a 'shower' of lower energy electrons, positrons, and photons. Positron beams have been produced this way at *SLAC* both for direct beam experiments and for filling the storage rings. In practice a target is flipped into the linac beam partway down the machine. The rest of the accelerator is then adjusted to accelerate these positrons.

The positrons basically start out from rest and only get the benefit of the part of the linac between the target and the end of the machine. Thus, the positron beam will have a significantly lower energy than that of the normal electron beam. Placing the target earlier in the machine would give a higher-energy positron beam in exchange for a lower-energy electron beam on the production target. This in turn would decrease the intensity of the positron beam since the yield depends on the electron energy. The solution for the *SLC* is to place the target two-thirds of the way down to give a



high yield, collect the positrons, and carry this beam all the way back to the beginning of the linac for re-acceleration.

There are still problems. The beams must be finally focused down to incredibly small spots about two microns in diameter. This is less than one tenth the diameter of a human hair. Magnets can be made to do this, but only if the original beam is very small and very nearly parallel to begin with. Typical beams from a linac can only be focused down to about a millimeter, or a thousand times bigger than desired for the *SLC*. Doing better requires two new things: damping rings and precision beam control.

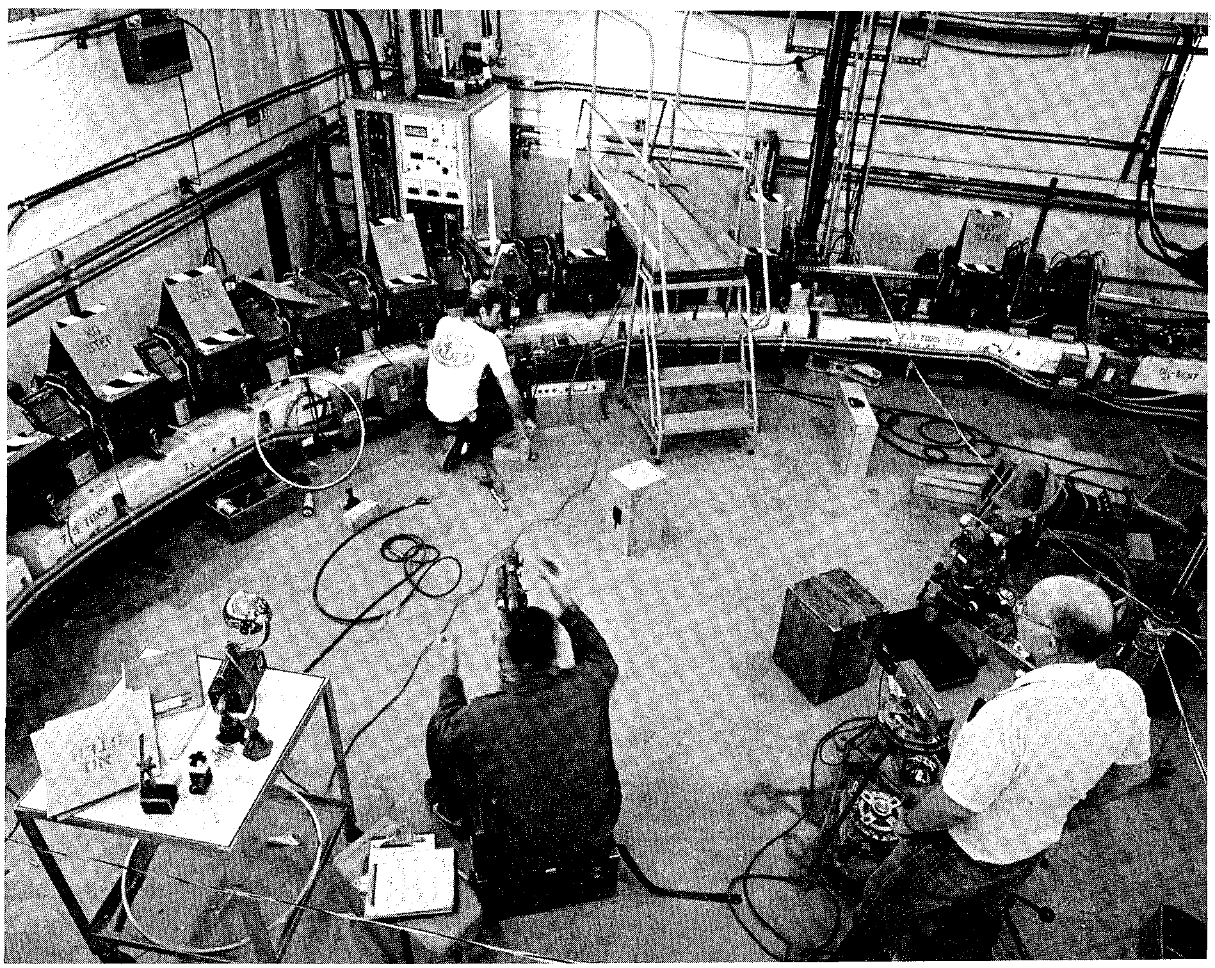
A damping ring is a small circular electron machine, like a little storage ring. As electrons circulate in the ring, the synchrotron radiation (which at high-energy is such a nuisance) causes the beam to shrink down to a smaller size. There will be two such rings, stacked one above the other, located at the injector end as shown in the schematic. These rings will separately store positron and electron bunches and act as the sources of beams for the accelerator.

The other half of providing dense beams is in the linac control. If the beams are not kept very close to the centerline of the accelerator, the electrical and magnetic fields which the beam produces in the copper tube of the linac will act back on the beam and enlarge it. New monitors of beam position, new focusing magnets, and new computer controls are part of controlling this problem.

The new machine requires beams of about 50 GeV, compared to the 30 GeV presently available. This increase can be made by putting more microwave power into the linac. This in turn requires more powerful klystron tubes along the machine.

The new machine also requires a very intense beam of particles in very short pulses. This means a new and special electron injector for the linac.

In all there are seven subprojects for the *SLC* which pose technical challenges: the electron injector, the new klystrons, the positron target system, the damping rings, the linac controls, the collider arcs, and the final focusing system.



Surveying the first SLC Damping Ring.

THE SLC CYCLE

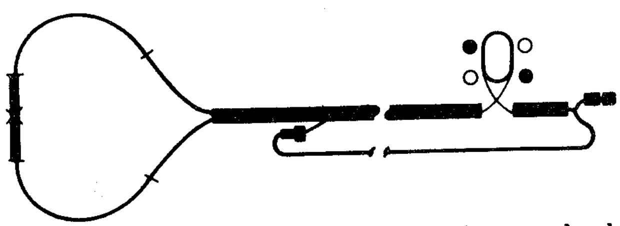
The *SLC*, like the accelerator itself, runs not with a continuous beam but in pulses. The action is like that of a single-shot rifle. The firing of the bullet is a series of steps which happen very fast compared to the steps of reloading.

The *SLC* operation also has two distinct parts, one very fast and one relatively slow. The firing corresponds to the acceleration of the electron and positron beams to their collision. This happens very quickly, in about 15 millionths of a second. The reloading corresponds to the recovery of the linac and its microwave supplies and takes much longer, several thousandths of a second. The complete operation repeats 120 or 180 times per second.

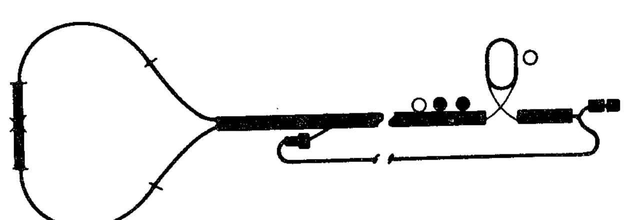
The recovery period of the machine is uncomplicated. The power supplies for the klystrons charge up for another voltage pulse to the tubes and the beams stored in the damping rings settle down. Neither of these processes can be rushed. The damping takes time and the klystrons cannot withstand a high rate of the very intense pulses.

The short firing period, on the other hand, is very complicated indeed and requires the delicate orchestration of many bunches. This part of the cycle is best described by the nine small figures on the front cover showing the collider at different stages.

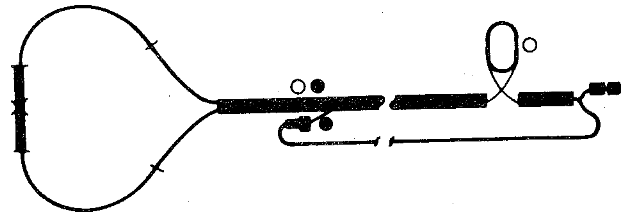
The process starts in Step One with the machine just ready to fire and ends in Step Nine with the machine just beginning its recovery. The electron bunches are the solid dots, the positron bunches are open circles, and the approximate times are in millionths of a second (μs).



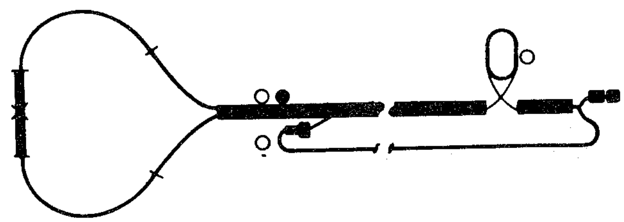
(Step One; t $\leq$ 0) The two damping rings are loaded with two bunches each and the beams have damped down to injection specifications.



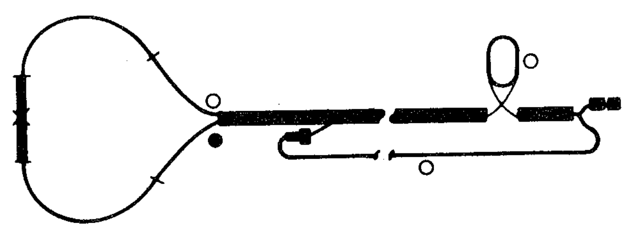
(Step Two; t = 0) The two electron bunches and one of the positron bunches are ejected from the damping ring into the linear accelerator. The remaining positron bunch continues to damp in the ring.



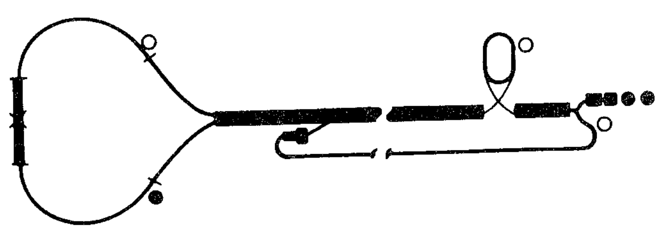
(Step Three; t $\sim$ 7 μs) The trailing electron bunch is deflected into the positron target channel about two-thirds of the way down the linac. The lead positron and electron bunches continue down the accelerator.



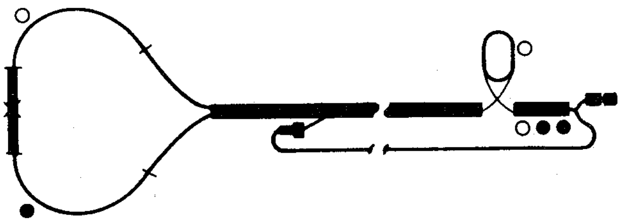
(Step Four; t $\sim$ 7 μs) The trailing electron bunch strikes the positron production target, producing a flood of lower energy electrons, positrons, and photons. Low energy positrons are collected, accelerated up to 200 MeV, turned around, and sent into a transport line located inside the main tunnel.



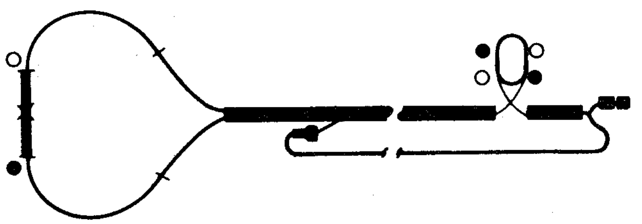
(Step Five; t $\sim$ 10 μs) The low-energy positron bunch is about halfway back to the injector end of the linac. The electron and positron bunches have now been accelerated to 50 GeV and have reached the end of the linac.



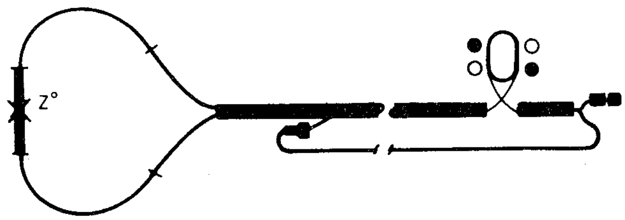
(Step Six; t $\leq$ 12μs) The low-energy positron bunch is ready for injection into the linac. The electron gun has produced two electron bunches to follow the positron bunch. The high-energy bunches have traveled about one-third of the way around the collider arcs.



(Step Seven; t $\sim$ 12μs) The first sector of the linac fires and accelerates the low-energy positron and two low-energy electron bunches up to about 1 GeV. The high-energy bunches are approaching the final focusing system.



(Step Eight; t $\geq$ 12 μs) The low-energy bunches have been injected into the damping ring, joining the positron bunch which had been left there. The high-energy bunches are being focused toward the collision point.

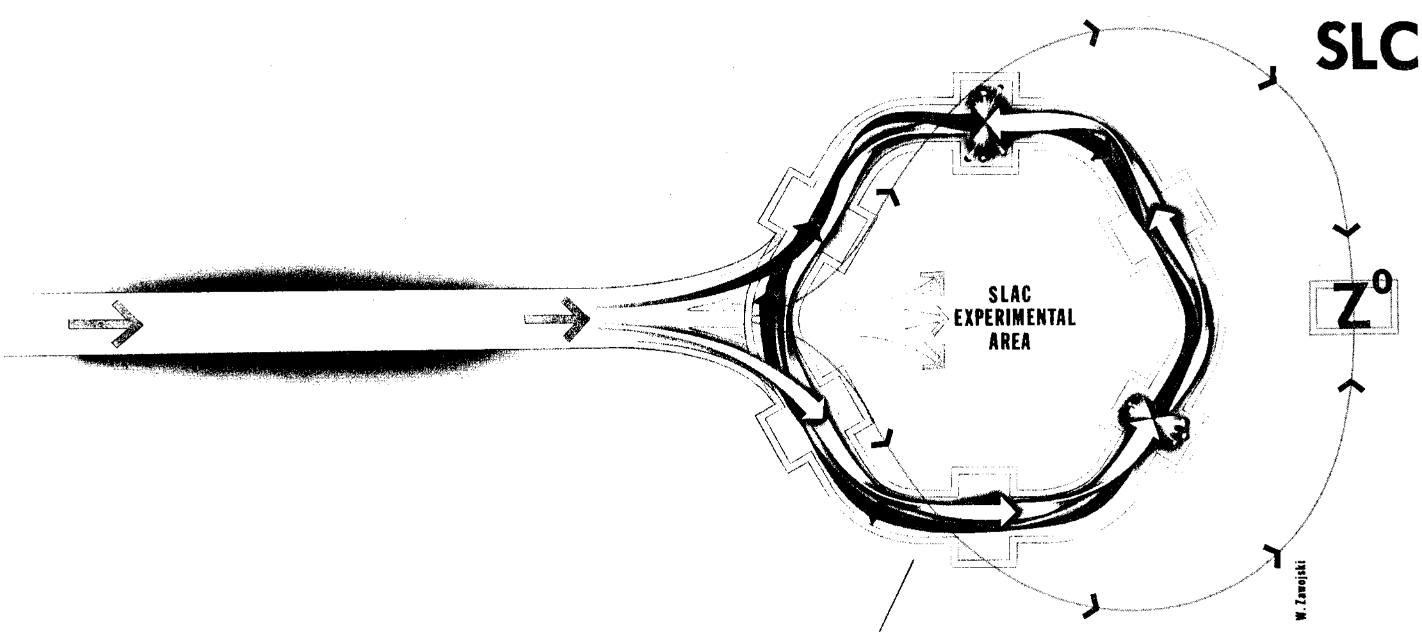


(Step Nine; t $\sim$ 15 μs) The high-energy bunches collide. The fast part of the cycle is now complete and the recovery phase begins.

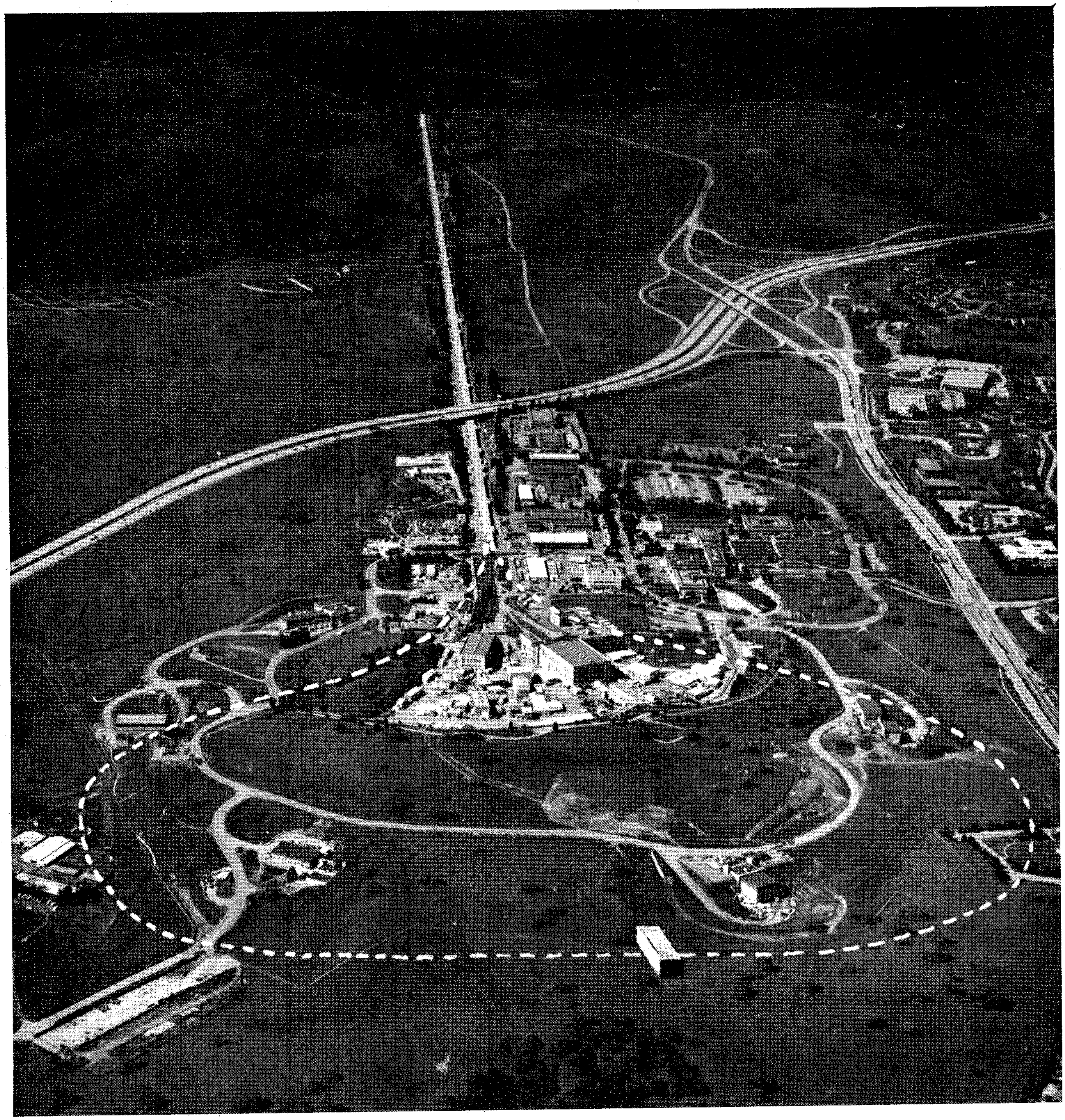
There is one further note. Only one positron bunch is used from the ring at the start of each cycle and only one is added at the the end. Why are two stored? Using two allows each positron bunch to damp for two complete cycles as follows. At Step Nine the 'old' positron bunch, which was not used the last time has been left over from the previous cycle and has already damped for one period. On the next firing, that bunch will have damped for two complete cycles. It will be extracted and the new one left to age. This extra damping compensates for the relatively unrefined state of the positron beam as delivered from the positron-production target.

The next parts in this introduction to the *SLC* will deal with the physics that will be studied using all those Z^0's and the seven elements of the project that will have to work to such precision and reliability to produce them.

–Bill Ash



PEP, 30 GeV ELECTRON-POSITRON COLLIDING BEAM
2.2 km (1.37 miles) STORAGE RING



SLC Groundbreaking

This special issue of the *SLAC Beam Line* commemorates the groundbreaking ceremony for the *SLAC* Linear Collider, 31 October 1983.

The main speaker for the occasion was US Secretary of Energy, Donald Hodel. Brief talks were also given by William Kimball, Chairman of the Stanford Board of Trustees, and Dr. Alvin Trivelpiece of *DOE*.

SLAC Beam Line, x2979, Mail Bin 94

Special Issue Number 4

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