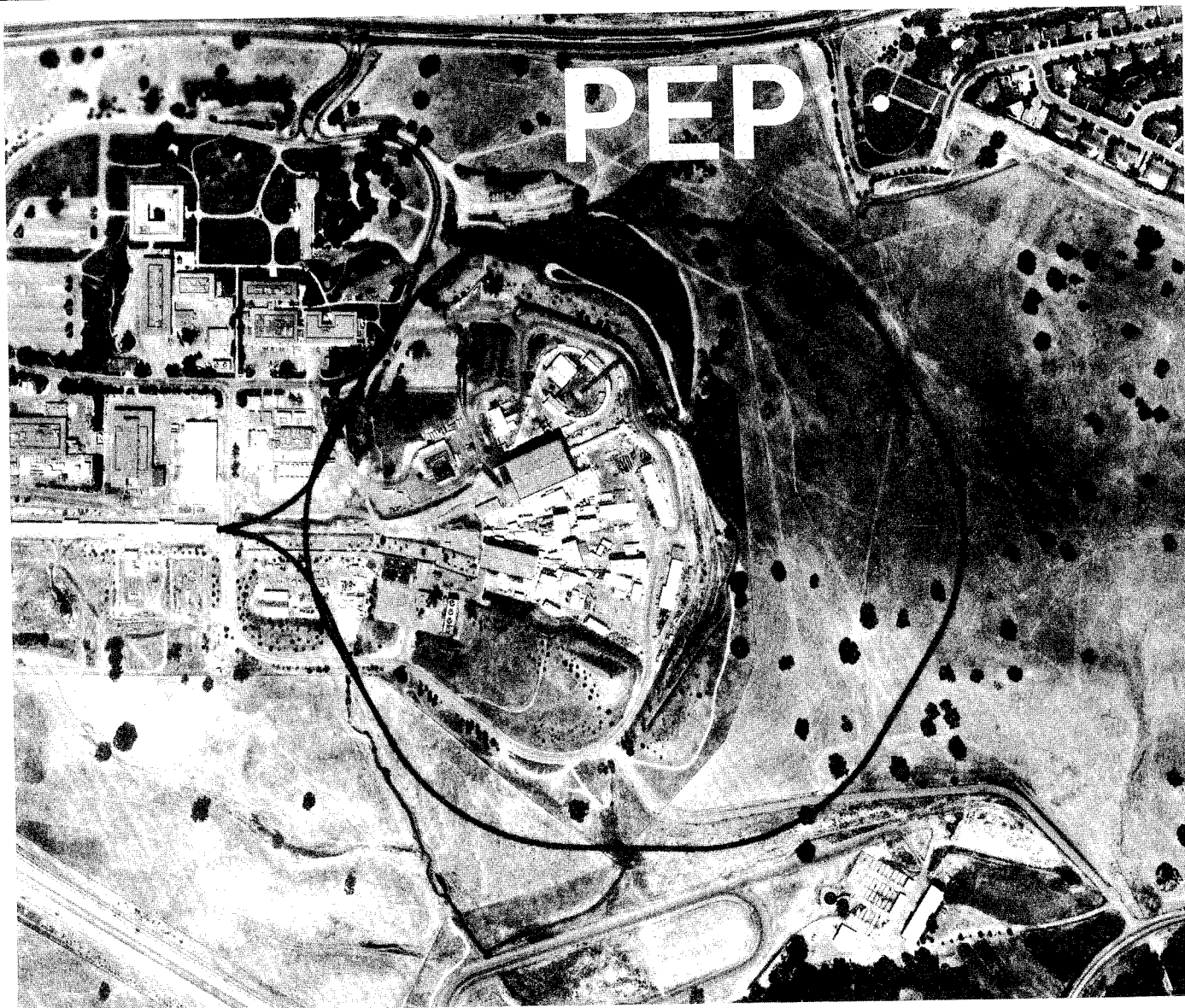


SLAC BEAM LINE

"There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out." - Isaac Newton, Opticks (1704)

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ELECTRON LINACS AND STORAGE RINGS

The first large linear electron accelerator was the 1 GeV Mark III machine, which began operating in 1950 in the Hansen Laboratories on the Stanford campus. Electron storage rings were built at Stanford in the early 1960's. In 1966 the SLAC 20 GeV electron linac was completed, and the SPEAR electron-positron storage ring at SLAC first ran in 1972. This issue of the *Beam Line* contains the first of a two-part article about the next machine in this evolutionary

development at Stanford: the PEP storage ring project that is now being built as a joint SLAC-LBL undertaking at SLAC.

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Special Article:

PEP: An Introduction

PEP-1/PEP-20

PEP NOTES

CLEAN MACHINE

The extraordinary requirements of the PEP vacuum system are described on page 10 of the special article on PEP in this issue of the *Beam Line*. A little dirt or a fingerprint on a surface within the system would be intolerable. Although the culprit could in principle be caught out in the latter case, the idea is to avoid the problem from the beginning, so a rather elaborate cleaning and handling procedure has been developed.

This is where the new Chemical Cleaning Facility comes in. Located behind the light fabrication shops, this first new building for PEP will be completed this month. The 14-meter-long vacuum-chamber sections and some of the RF components that are too large for the existing cleaning tanks at SLAC will be prepared in this new facility for eventual installation at PEP.

A day in the life of a PEP vacuum-chamber section will begin with a steam bath and a tap-water rinse on the concrete pad outside the new building. (So far it sounds pleasant.) Then, together with 7 of his fellows, the long, slightly curved section of extruded aluminum pipe will be trundled into the new facility on a special cart. The sections will then be lifted by a crane, one at a time, and dunked into a long trough filled with an alkaline solution for a 10-minute soak. (The fun is clearly over.)

After that, the vacuum-chamber section is put through the following steps: a rinse in tap water, an acid bath to remove the oxide coating or mill scale, another rinse, a soak in an alkaline etching solution, yet another rinse, and then back to the acid bath. This last step is intended to remove "smut"--and sounds more effective for this purpose than the techniques of the Palo Alto City Council. However, to an experienced hand like Jim Pope, head of SLAC's cleaning and plating shop, "smut" is the residue of copper and manganese from the aluminum alloy that remains on the surface after the etch has removed the aluminum itself. Anyway, the now thoroughly clean and righteous vacuum-chamber section is rinsed twice more in distilled water, blown dry with nitrogen gas, capped off to prevent further contamination, and finally placed on a cart at the opposite side of the building.

This whole cleaning process will require about 45 minutes. When the 8 sections have been cleaned, they will be moved by cart to the PEP Vacuum Assembly Building (another story) for flange-welding, bakeout, and leak-testing.

Only 8 of the 10 long vats installed in the new building will be used for aluminum parts. The remaining 2 will be used for soaking and pickling stainless steel components.

The various acid and alkaline baths sound pretty rough, but in fact they will be rather mild by the standards of the craft. A fast, violent etching procedure such as that commonly used in outside shops would be inappropriate for the long, hollow sections, which must be rocked in the bath and slowly drained. For example, a copper penny would last for about a week in the acid bath that will be used, compared to about one hour in a stiff acid solution (or, according to some data I took last week, about 0.6 seconds in the aisles of Safeway).

THE GOOD NEWS

In his "State of SLAC" talk in January, Director W. K. H. Panofsky described the "junction" project for PEP--the construction of the tunnel stubs on either side of the Beam Switchyard structure through which the electrons and positrons will begin their journey to the PEP ring (see the January 1977 issue of the *Beam Line*). At the end of March, five firms specializing in underground construction sent representatives to SLAC for a pre-bid conference and a tour of the Switchyard to learn more about this particular project.

The bid opening is scheduled for mid-April, with the work to begin in stages in May and, coordinated with the 4-month shutdown of the accelerator, in late June. This will be a significant step in the early PEP construction, and we'll report more on this and on the other features of the construction schedule next month.

THE BAD NEWS

During the work on the junction project, there will be only one lane of traffic past the Sector 30 gate--with a 35-foot precipice on one side for a time!

Not much later, the site work at PEP will also interrupt traffic on the loop road near the "magnet yard" (by the entrance road to the Beam Switchyard). Still later, site work for interaction regions 4 and 6 of PEP will cut through the spur road that runs from the loop road to Alpine Road gate.

So why are we saying all this? Well, what we're leading up to is an "unfortunate inconvenience" (translated as a pain in the neck): the Alpine Road commuter traffic will have to be shut off from early May until the end of major PEP site construction--probably sometime in 1979. This will certainly be a nuisance for a lot of people, but there doesn't seem to be a safe alternative. Anyway, if it's any consolation, PEP still loves you.

--Bill Ash

SLAC WOMEN'S ASSOCIATION

April Activity

On April 13, Sally Kladnick of the Institute of Professional Development will speak in the Orange Room, Central Laboratory, at noon. Her topic will be an accelerated route to the Bachelor's Degree in Business Administration. If you are unable to attend at that time, she will repeat the discussion on April 20 at the Medical Center.

On April 18, Nancy Martin, Assoc. Professor of Computer Sciences at the University of New Mexico, will be talking on "Women in Science and Technology--An Historical Approach." This talk will also be in the Orange Room at noon.

Film Reviews

On March 7 and 8, we sponsored two films that proved to be entertaining, informative and inspiring. *Pack Your Own Chute* dealt with many kinds of fears that people experience. It suggested that many of these fears were "self-inflicted," and that the growth and nurturing of these fears is propagated in the greenhouse of one's own mind. Meeting these fears head-on, particularly in business situations, often proves that they were unfounded or at least unreasonably intense.

51% was a less professionally polished film, but nevertheless provided a certain amount of impetus to use in our business roles. It was nicely paired with *Chute*, each film addressing a different aspect of business goals, problems and needs.

On March 28, we sponsored another film, *Other Women, Other Work*, which dealt with women working in non-traditional jobs. The film covered a spectrum of working situations, from a woman roofer to a woman commercial pilot, from a woman truck driver to a woman veterinarian. Each woman in the film spoke about her reasons for doing what she was doing, the particular problems associated with doing it, what she gained personally, and her motivations. After the film, four women from SLAC who hold (or have held) non-traditional jobs spoke briefly about their jobs, their problems, their motivations, and support and encouragement/discouragement from their friends and families. A very special acknowledgement and thank you to Michelle Bondi, PS&E Technician; to Jackie Huntzinger, truck driver emeritus; to Mary James, Accelerator Physics Engineer; and to Cherrill Spencer, Physicist. Their openness and willingness to share their experiences was very much appreciated.

--Vicki Bosch

Stan Stamp has recently been appointed as Director of ERDA's newly established SLAC Site Office.

SSRP NEWS: THE WIGGLER WORKSHOP

A three-day workshop on the subject of Wiggler magnets was held at SLAC on March 21-23, 1977, and was attended by about 60 scientists from 17 laboratories around the world. The objective of the workshop was to provide a forum for study, discussion and exchange of information about Wiggler magnets among those promoting their use for synchrotron radiation research and other applications and those concerned with storage ring design and operation.

This is the first time that a large group of accelerator physicists and others have concentrated their attention on increasing and enhancing the production of synchrotron radiation. In the past, their aim has generally been the reduction of synchrotron radiation losses--hence the large radius and low magnetic field of PEP.

Wiggler magnets are devices which produce particularly intense synchrotron radiation from high energy electrons. Those interested in utilizing this radiation in research, at SSRP and in similar programs elsewhere, are planning to install Wigglers in existing storage rings and in new machines now being constructed or planned. Also, the designers of colliding-beam storage rings, such as PEP, plan to use the effects of the extra synchrotron radiation produced by Wigglers to control the damping rates and cross-sectional area of stored beams with a resultant improvement in luminosity.

Simple Wigglers consist of a few sections (3 or more) of alternating polarity magnets that produce a relatively strong (16-50 kilogauss) transverse magnetic field. Such magnets are fitted into a straight section of a storage ring, and they produce no net deflection or displacement of the circulating beams. Because their magnetic field is considerably stronger than that of the normal ring bending magnets, they produce intense synchrotron radiation, which extends up to higher photon energies.

Wigglers with a large number of alternating poles, or with a rotating helical field, are also being considered for producing interference effects, which can result in very high intensity radiation at certain particular wavelengths or energies.

The Workshop began with a general survey of Wiggler magnets and their applications by Andy Sessler, Director of the Lawrence Berkeley Laboratory. Part of the Workshop was devoted to presentations of magnet designs that are being developed at several laboratories, and analyses of the effects of these magnets on the behavior of stored beams. Wigglers for SPEAR were discussed by Bill Brunk and Dick Helm of SLAC, and by Klaus Halbach of LBL. The PEP Wiggler design

(Continued on next page)

was described by Helmut Wiedemann of SLAC. John Blewett and Bill Sampson of Brookhaven National Laboratory described the superconducting Wiggler magnets that are being considered for use in the synchrotron radiation storage rings proposed for Brookhaven. Sergio Tazzari presented the plans for the Italian ring ADONE, and Vic Suller and Elwyn Baynham described the Wiggler planned for the Daresbury (England) 2 GeV synchrotron radiation source now under construction. Jim Spencer of Los Alamos discussed alternative Wiggler designs which also produce some focusing of the beams. Terry Martin of SLAC and Sam Krinsky of Brookhaven outlined the severe problems of handling the high power densities than can be produced by Wigglers.

Another part of the Workshop was devoted to the exciting possibilities of interference and coherence effects. Albert Hoffman of CERN discussed the intense peaks that are expected at certain wavelengths from magnetic structures with many periods. Coherent radiation by very short electron bunches and the production of coherent X-rays were discussed by Hans Motz of Oxford and by Paul Csonka of the University of Oregon and SSRP. As a matter of historical interest, Motz was the first to produce radiation from a Wiggler structure. He observed interference peaks in the millimeter-wavelength region in the early 1950's, using 100-MeV electrons from the Stanford Mark III accelerator and an array of alternating polarity permanent magnets.

In related talks, the Free Electron Laser was described by John Madey, Dave Deacon and Bill Colson. They covered the theory of its operation, the recent experimental results (which demonstrated lasing) utilizing a 43 MeV beam from the superconducting linear accelerator at HEPL (Stanford), and the possibility of including the device in a small (100-200 MeV) high current storage ring to produce a very powerful tunable laser extending into the ultraviolet region of the spectrum.

After these talks, the participants divided into several smaller groups for more detailed analyses of various subjects. These groups met

in the office space that has recently been completed, but not yet occupied, on the mezzanine of the Electronics Building at SLAC. Our thanks go to Glenn Tenney and to Dorothy Ellison for making this space available.

The Workshop closed with summary talks presented by spokesmen for each of the individual working groups. There was considerable optimism that Wiggler magnets could be made to work in storage rings with little or no adverse effects on the ring performance. Part of this optimism is based on the successful use of a pair of damping-magnet Wigglers at the Cambridge Electron Accelerator to permit beam storage in the alternating-gradient structure of that ring. However, some problems still remain to be solved (particularly the handling of high power densities), and detailed analysis will be needed to optimize the designs of particular Wigglers for particular machines, and to minimize and compensate for their effects upon the beams.

Also, the use of structures with many periods to produce interference and coherence effects, as demonstrated by the work of Motz and Madey with linear accelerators, has not yet been tried in storage rings. One of the conclusions of the Workshop was that cross-coupling, thought to be unavoidable in helical Wigglers, can probably in fact be avoided. The Free Electron Laser in a high current storage ring is capable in principle of producing enormous power levels (perhaps one megawatt) of tunable ultraviolet radiation. Achieving this, however, will certainly not be an easy task.

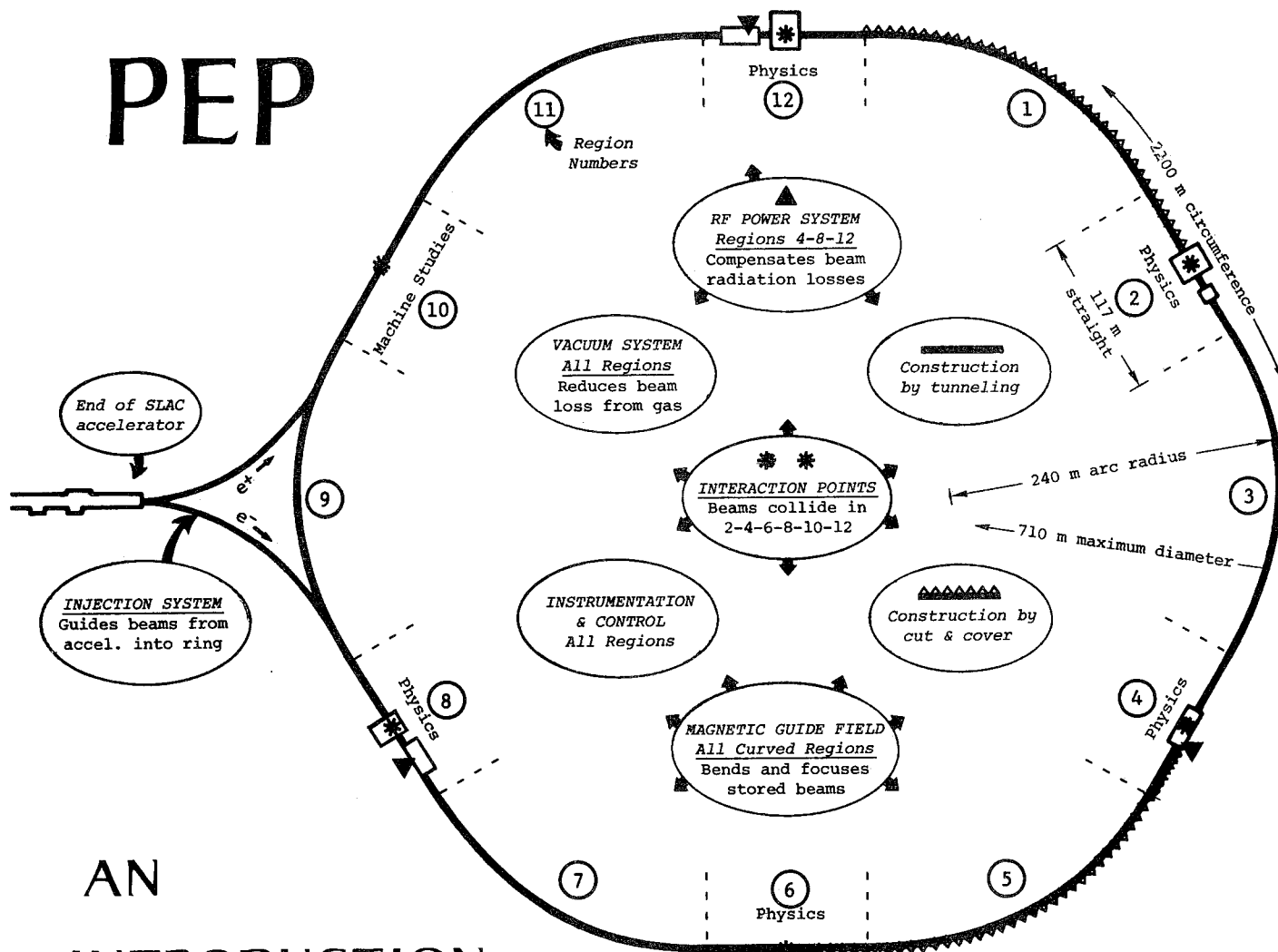
The Wiggler Workshop was sponsored jointly by Brookhaven National Laboratory, the Energy Research and Development Administration, the Stanford Synchrotron Radiation Project, and the Synchrotron Radiation Center of the University of Wisconsin at Madison. The Workshop was organized by Herman Winick, SSRP, Chairman; John Blewett of Brookhaven; Albert Hoffman of CERN; Phil Morton of SLAC; Claudio Pelligrini of Frascati; Ed Rowe of Wisconsin; and Andrew Sessler of LBL.

--Herman Winick

<p><i>SLAC Beam Line</i> <i>Stanford Linear Accelerator Center</i> <i>Stanford University</i> <i>Stanford, CA 94305</i></p> <p>Published monthly on about the 15th day of the month. Permission to reprint articles is given with credit to the <i>SLAC Beam Line</i>.</p>						<p>Joe Faust, Bin 26, x2429 } <i>Photography &</i> Walter Zawojwski, Bin 70, x2778 <i>Graphic Arts</i></p> <p>Ada Schwartz, Bin 68, x2677 <i>Production</i></p> <p>Dorothy Ellison, Bin 20, x2723 <i>Articles</i></p> <p>Bill Kirk, Bin 80, x2605 } <i>Editors</i> Herb Weidner, Bin 20, x2521</p>						
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AN INTRODUCTION

TO THE SLAC - LBL POSITRON - ELECTRON
COLLIDING - BEAM STORAGE-RING PROJECT



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This is the first of a two-part article about the PEP storage ring project now being built at SLAC. This description of PEP, though quite long, should be fairly easy to read, with the possible exception of some parts of the sections on the technical components of the ring, and on its prospective physics uses. In such cases, we have tried to give both a simple and a more technical description of the basic ideas that are involved.*

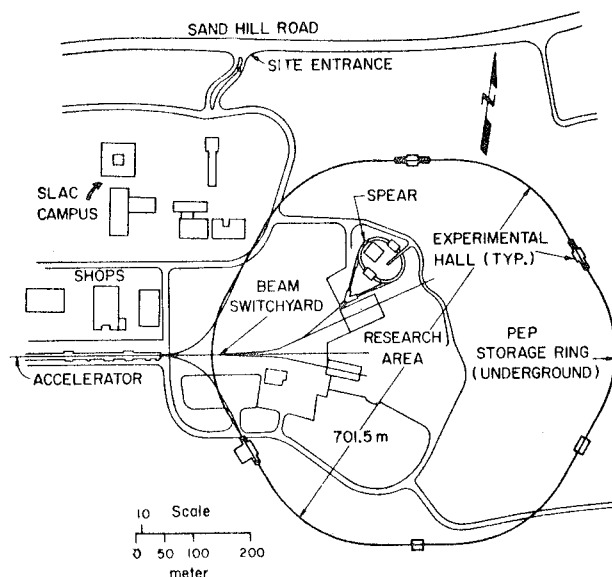
A. A BRIEF SUMMARY

General. The name "PEP" is an acronym for Positron-Electron Project. It is a joint undertaking of SLAC and of the University of California's Lawrence Berkeley Laboratory (LBL), which was first proposed to the AEC (now ERDA) in April 1974. The PEP machine is designed to store beams of electrons and positrons circulating in opposite directions at single-beam energies between 4 GeV and a nominal maximum of 18 GeV. The source of these beams will be the present SLAC accelerator. The estimated cost of the PEP construction project (in 1975 dollars) is about \$62 million; an additional sum of \$16 million has been included to cover the cost escalation that is expected to occur during the four-year construction period. First operation of the completed PEP facility is scheduled for early 1980.

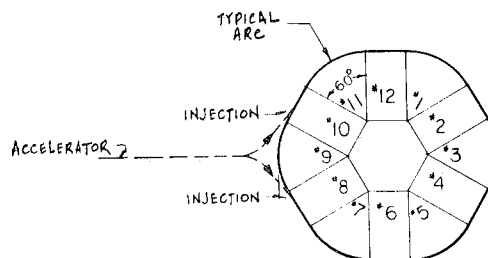
Some History. PEP will be the third colliding beam storage ring built at Stanford University. The first was a figure-8-shaped set of 500 MeV electron-electron rings built as a collaborative project between Stanford and Princeton University at the High Energy Physics Laboratory on the Stanford campus. These rings were used, starting in 1965, to carry out the first successful colliding-beam experiments. This early machine was followed by the SPEAR electron-positron storage ring at SLAC, which first operated in 1972 at single-beam energies up to 2.5 GeV, and which was modified in 1974 (SPEAR II) to achieve energies up to about 4 GeV per beam. The remarkable physics discoveries made at SPEAR and at other electron-positron storage rings have provided a good deal of the scientific motivation for building PEP. SPEAR has also served as a valuable prototype machine for testing new components and for operational studies that are directly applicable to the design of PEP.

Site, Buildings, Etc. About 40% of the cost of PEP will be connected with the work that is called "conventional" construction. This includes access roads, utilities, buildings that will house experimental research areas and other functions, and also an underground tunnel in

which the storage ring itself will be located. The general layout of the six-sided PEP ring tunnel is shown in the following sketch:



The Storage Ring. PEP can be thought of as six curved regions or arcs that alternate with six straight regions to form a rounded hexagonal figure. For convenience in specifying the locations of the various components, these 12 regions have been assigned identifying numbers like those of a clock:



The counter-rotating beams of electrons and positrons in PEP will collide with each other at the mid-points of the six straight regions of the machine. Five of these six collision or beam-interaction points will be used for high-energy physics experiments, while the sixth (Region 10) will be reserved for studies of the storage ring itself.

The technical components of the storage ring can be grouped into five major systems--beam injection, magnetic guide field, vacuum, radiofrequency power, and instrumentation and control--which together account for the remaining 60% of the estimated construction cost of the project. Beams from the SLAC accelerator will be transported through the two curved channels of the beam injection system and will enter the PEP ring at the points where Region 9 joins onto Regions 8 and 10. Nearly all of the magnets that make up the magnetic guide field of PEP will be located in the six curved regions

*A detailed technical description is given in the "PEP Conceptual Design Report," SLAC Report No. 189 and LBL Report No. 4298, February 1976.

of the machine. The vacuum system will extend throughout the full circumference of the ring, while the radiofrequency power system will be located at three different points in Regions 4, 8 and 12. The functions of the instrumentation and control system will be distributed throughout the machine where needed, but with connections to a central station in a control building near Region 8.

One Reason For PEP. Perhaps the main reason for the growing interest in colliding-beam storage rings is that they provide a comparatively economical way to achieve very high effective particle-collision energies. As an example, a beam of 22 GeV electrons from the SLAC accelerator striking a stationary proton target (hydrogen) can produce a maximum effective collision energy (or "center-of-mass" energy) of only about 7 GeV. This means that only $7/22$ or about 32% of the beam energy is "useful" for producing new particles or for studying the structure of the target particles. In contrast, the collision between 4 GeV electrons and 4 GeV positrons in the SPEAR storage ring can produce an effective energy of 8 GeV--that is, 100% of the sum of the energies of the two colliding beams. And the disparity between conventional accelerators and colliding-beam machines becomes rapidly more pronounced at higher and higher energies. In the case of PEP, two colliding 18 GeV beams will produce a center-of-mass energy of 36 GeV, whereas even the largest conventional accelerators (the 400 GeV proton machines at Fermilab and at CERN) can yield a maximum collision energy of only about 28 GeV, or 7% of their beam energy.

A Second Reason For PEP. The second important physics-related characteristic of PEP is the fact that the basic collision process that occurs between electrons and positrons, which is called *annihilation*, offers a unique method for exploring the submicroscopic world of the elementary particles. The annihilation of an electron with its antimatter counterpart, a positron, proceeds in two steps. First there is created for a brief instant an intermediate state of pure electromagnetic energy. Then this dense bundle of energy rematerializes into any of a great variety of newly created elementary particles. Since the electromagnetic force is by all odds the most completely understood of the fundamental interactions that occur in nature, electron-positron annihilation is the ideal starting point for studying the properties and behavior of the many different kinds of particles that have been discovered during the last 25 years of high-energy-physics research. The power of this technique--now to be extended to the higher PEP energies--has been convincingly demonstrated during the past several years by the discoveries of the new "psion" family of particles at SPEAR and at the electron-positron storage rings in Germany (DESY) and Italy (Frascati).

Experiments At PEP. As is the case with the SLAC accelerator and with SPEAR, PEP will be a national facility for particle-physics research, available to any group of qualified scientists. Proposals for the use of the facility will be evaluated by the PEP Experimental Program Committee (EPC), which consists of senior physicists from many different institutions. The EPC will then advise the Directors of SLAC and of LBL of their findings, and decisions will be made by the two Directors acting jointly.

Preliminary planning for the PEP experimental areas and for some possible major research devices was carried out during the PEP Summer Study programs that have been held during each of the last four summers. An invitation to the physics community to submit proposals for the first round of experimentation at PEP was sent out last year, and nine such proposals were received by the December 30 deadline date. The schedule calls for decisions on these proposals by May of this year, with only three to be accepted (two other experiments will be approved at a later time).

A Friendly Competition. The DESY laboratory in Hamburg, Germany, is presently building a large electron-positron storage ring called PETRA that is very similar in scope to PEP. In a sense, the DESY laboratory is the "SLAC" of Western Europe, and close cooperation between the two labs extends back for many years. DESY has a 7 GeV electron synchrotron, and also a SPEAR-like storage ring called DORIS. The construction of PETRA began about a year earlier than that of PEP, and as with these earlier machines there will continue to be not only close cooperation but also a friendly and spirited competition between the two labs both in building the new machines and in getting the most out of them in the way of productive experimental research.

Future PEP Options. The design of PEP makes it possible at some future time to expand the facility in one or more of the following ways:

1. The maximum energy could be increased from 18 GeV to more than 20 GeV per beam by adding more accelerating cavities and klystrons.
2. A second, separate storage ring for protons of energies up to 200 GeV could be installed in the same tunnel.
3. A different, separate storage ring for either electrons or positrons could be installed in the same tunnel.

Options (2) and (3) would make it possible to have collisions between electrons and protons, positrons and protons, electrons and electrons, and positrons and positrons. Needless to say, these possible future options will not be seriously considered until such time as the results from the initial electron-positron experimentation may warrant.

B. THE STORAGE RING

Sections B.2 through B.6 contain rather detailed descriptions of the main technical systems of the PEP storage ring: magnets, vacuum, RF power, beam injection, and I&C. In Section B.1 below, we try to set the stage for these later sections by giving a rundown of basic storage ring processes. The idea is to look briefly at the storage ring as a whole before focusing in on its several parts.

1. BASIC STORAGE RING PROCESSES

The sketch on this page shows a much simplified version of a storage ring for electrons (e^-) and positrons (e^+). We make use of this sketch in the following paragraphs to consider the functions of the various systems and the problems encountered in trying to carry out these functions.

Getting The Beams: The Injector

The electron and positron beams are first produced by a conventional accelerator and then transported to the ring. Most e^-/e^+ accelerators, including the SLAC machine, can deliver a much more intense beam of electrons than of positrons, so a typical procedure is the following: (1) Positrons are injected through one leg of the Y-shaped injection channel; the time required to "fill" the ring is perhaps 5-10 minutes. (2) The accelerator switches over to electrons, which are injected through the other leg of the Y; the ring is filled in 1-2 minutes. (3) The counter-rotating e^+ and e^- beams are brought into collision with each other at two or more points around the ring and experiments are carried out. (4) After the stored beams have lost a certain fraction of their original intensity, a new injection cycle is begun, either by "topping" off the existing beams, or by "dumping" them and starting all over again.

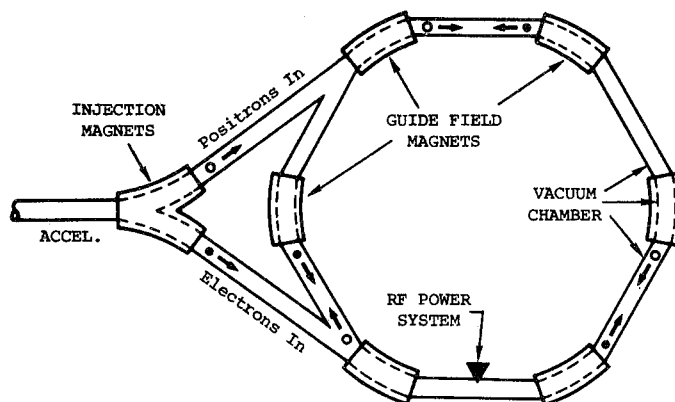
The main function of the injection system is to act as an efficient means for transferring the beams from the injector accelerator to the storage ring. Its principal components are a passable vacuum system, some standard magnets for guiding the beams accurately toward the ring, and a few very special magnets (switching, septum, kicker) that must act extremely rapidly and/or with great precision.

Storing The Beams: The Magnetic Guide Field

As the bunches of electrons or positrons enter the ring, they pass from the influence of the injection magnets to that of the ring's magnetic guide field. Two kinds of guidance are needed:

Dipole or bending magnets *deflect* the beams so that they follow a more-or-less circular path or orbit around the machine.

Quadrupole (4-pole) magnets *focus* or "squeeze"



The basic components and systems of an electron-positron storage ring

the beams in order to overcome their natural tendency to spread out or diverge--like the beam of a flashlight. [Some machines also use sextupole (6-pole) magnets for focusing.]

Since counter-rotating beams of electrons and positrons of equal energies are deflected and focused by the magnets by equal amounts and in the same direction, both beams can be stored within the same magnetic guide field. In some e^+e^- storage rings, the beams are stored in two separate magnetic guide fields that have only the beam-crossing or beam-interaction regions in common. For proton-proton storage rings, separate guide fields are required. Both SPEAR and PEP are single-guide-field machines, although the earliest SPEAR design (1964) was based on two separate rings.

Clearing The Beam Path: The Vacuum System

Even a very intense, high-energy electron beam will be completely dissipated if it is made to travel through the atmosphere for, say, the length of a football field. The problem is that there are so many air molecules (oxygen and nitrogen) in the path of the beam that nearly every beam particle is certain to collide many times with these molecules. And each such beam-gas collision causes the particle to lose energy and to be deflected from its original direction. In the SLAC accelerator this problem is solved by evacuating the beam pipe so that the air pressure is reduced to a level about 100 million times lower than normal atmospheric pressure (10^{-8} atmosphere*). This allows the SLAC electron beam to travel through its two-mile journey without significant interference. At PEP, however, a beam that has been circulating for three hours in the ring will

*The common unit for low gas pressures is the "Torr," named after Evangelista Torricelli (1608-1647). One atmosphere is equal to 760 Torr, so very roughly one Torr = 10^{-3} atmosphere. The pressure in the SLAC accelerator is thus about 10^{-5} Torr. For the rest of this article we'll give pressures in Torr (T) units.

have traveled a distance not of two miles but of two *billion* miles. This means that the PEP beams will meet with as little interference from air molecules as the beams in the SLAC accelerator only if the PEP vacuum is a billion times better than SLAC vacuum: $10^{-9} \times 10^{-5} = 10^{-14}$ Torr.

But such low pressures are simply not technically possible in machines like e^+e^- storage rings. The best that can be done is about 10^{-8} Torr. As a consequence, many beam-gas collisions will in fact occur at PEP, and these are one of the main reasons why the stored beams will gradually dwindle away.

A storage ring's vacuum system consists of two parts: (1) A vacuum chamber that runs completely around the ring and provides a sealed-off, air-tight loop for the beams to travel in. (2) Vacuum pumps capable of "pulling" and holding as low a pressure as is practically possible within the chamber. As will become evident, achieving a level of 10^{-8} Torr is very difficult, and will require special kinds of pumps and plenty of them, in a system that strains the vacuum art to the utmost. Even the best possible system will only hold down the beam-gas collisions to a dull roar.

Boosting The Beams: The RF Power System

If a storage ring were provided with both a perfect magnetic guide field and a perfect vacuum system, that would still not be enough to store the beams for more than a fraction of a second, for the following reason. When electrically charged particles such as electrons and positrons are forced by magnetic fields to follow a curved trajectory, they respond by repeatedly throwing off bits of their energy in a form called *synchrotron radiation*. The process has a certain centrifugal character that superficially resembles mud being thrown off from a spinning wheel, or sparks from a grinding wheel. (More accurately, an observer moving with the beam would see a radiation pattern like that of a dipole antenna. However, the very high velocity of the particles causes nearly all of the radiated energy to be concentrated in the forward lobe, and also causes this lobe to be very narrow.)

As a practical matter, the emission of large amounts of synchrotron radiation by the beam particles in a storage ring causes the following three kinds of problems:

Gassing. Synchrotron radiation striking the inner wall of the vacuum chamber desorbs or knocks loose gas molecules that jump out into the path of the beams. Thus the chamber acts as though it has a large, steady leak that is letting air in. The solution to this problem is not subtle--pump harder.

Heating. At full operation the beams in PEP will radiate energy against the vacuum cham-

ber wall at a rate of 3 megawatts. A water-cooling jacket is built-in as an integral part of the vacuum chamber to dissipate this heat load.

Dropping out. Again at full PEP operation, the circulating beam particles will lose energy at a rate of about 27 MeV per particle on each revolution around the machine. This is about 1/500 of their total energy, and it occurs 136,000 times per second. So it's *phhhht!* and gone unless some corrective action is taken. The cure for this radiation-caused deceleration of the particles is a steady shot of acceleration, which is provided by the radiofrequency (RF) power system. At one or more points around the ring, a powerful source of high-frequency radio waves (a klystron, for example) feeds energy into a beam-coupling device called a "cavity," where the strong electric fields that are created deliver a sharp accelerating "kick" to the beam particles each time they pass by. The strength of the accelerating kick is adjusted so that it just compensates for the energy lost through synchrotron radiation. In addition to this compensation function, the RF power system is also used for actual acceleration of the beams when their energy is being increased to a higher level in the ring.

Sensing And Acting: Instrumentation & Control

The simplified storage ring sketch on page 4 does not show any I&C components, although a complex I&C system is essential to the operation of all but the most rudimentary storage rings or accelerators. We postpone discussion of I&C details to Section B.6, with only the note here that I&C is an elaborate set of interconnected devices that serve to sense and analyze the storage ring's operation, and that also make use of that analysis to effect changes in the operation.

The following chart summarizes some of the basic storage ring processes we've just looked at:

"Natural" Particle Behavior	Desired Behavior	Means Of Achieving	Device Or System Used
Beams travel straight	Follow circular path	Magnetic deflection	Bending magnets
Beams spread out	Maintain stable size	Magnetic focusing	Quadrupole (and other) magnets
Beams scatter from gas	Fewer beam-gas collisions	Vacuum system	Vacuum chamber & pumps
Beams radiate energy	Restore lost energy	Electric field acceleration	RF power system

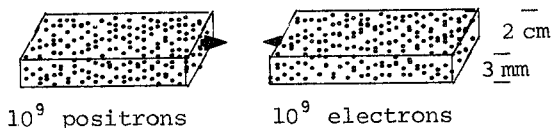
2. MAGNETIC GUIDE FIELD

Magnetic guide field is the name given to the complete system of magnets that forms the magnetic structure of a storage ring (or of any circular accelerator). These magnets fall into three main classes: the bending or dipole (2-pole) magnets; the focusing or quadrupole (4-pole) magnets; and the sextupole (6-pole) magnets, which are also used for focusing purposes. In this section we plan to describe these kinds of magnets in some detail, after first looking at the reason for "storage" in a storage ring.

Beam Storage

In the usual circular accelerator, the beam is accelerated from low to high energy during a cycle that lasts anywhere from 1/60 of a second to several seconds. The accelerated beam is then extracted from the machine and directed against a target, after which the acceleration cycle is repeated. In contrast, the beams in a colliding-beam storage ring are maintained in stable, circulating orbits for periods ranging from a few to many hours. What is the purpose of such long periods of beam storage?

The brief answer to this question is that interesting collisions between electrons and positrons in a storage ring are relatively rare events, and long beam-storage times are needed in order to collect a decent number of the important kinds of interactions. We can emphasize the "rare event" problem in the following way. Let's suppose that we build a "linear" colliding beam machine by construction another linear electron accelerator just like the present SLAC machine, with the two monsters aiming at each other. Now we accelerate a burst of one billion (10^9) electrons in one machine, and 10^9 positrons in the other, with each beam having the same 15 GeV energy that the PEP beams will have. At the interaction region we arrange to squeeze down the cross-sectional areas of the two beams to narrow ribbons of the same lateral dimensions that PEP will have, 2 cm by 3 mm. Then we let 'er rip, and a billion billion particles go zooming through the same skinny ribbon of space in opposite directions:

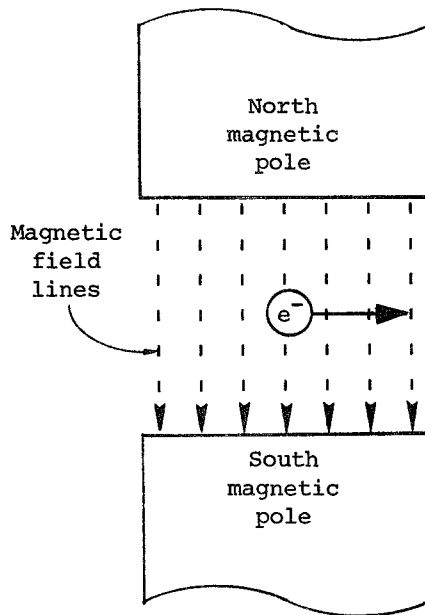


What happens? It must be Gangbusters, right? Well, not exactly. In fact, on the average what happens in such a situation is that one lousy electron collides with one lousy positron and produces one not very interesting interaction. So the reason for building colliding-beam rings, rather than colliding-beam linacs, is that you can keep on trying each time the beams circle around and pass through each other

again. At PEP, for example, there will be 3 separate bunches of electrons and 3 of positrons circulating, with each bunch making a complete loop 136,000 times a second. So the general idea is that if you deal fast enough and long enough, sooner or later four aces will turn up, or 13 spades.

Bending Magnets

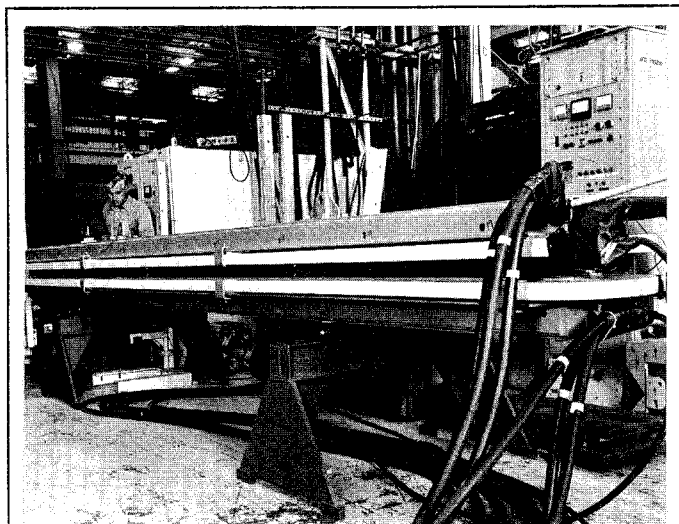
The path or orbit followed by the particles in a storage ring is more or less circular. This orbit results from a series of sideways deflections that the particles receive as they pass through the magnetic field produced by an array of dipole or bending magnets. As shown in the sketch, the deflecting or bending force exerted on the particles is in a direction perpendicular to the particles' path, and also perpendicular to the direction of the magnetic field. How strongly the particles are in fact deflected by the magnetic force depends on how much energy (actually momentum) the particles have--high energy beams are deflected less and are therefore "stiffer" than beams of low energy.



A charged particle passing through the magnetic field of a dipole or bending magnet will be deflected in a direction perpendicular to the field direction and perpendicular to the direction of its motion. In this sketch an electron (e^-) traveling into the paper is deflected to the right. For the same field configuration, a positron traveling out of the paper will also be deflected to the right, and the amount of deflection will be equal for both electrons and positrons if they have equal energies. This is what makes it possible to store counter-rotating beams of electrons and positrons within the same magnetic structure in a storage ring.

Deflection also depends on a particle's electric charge, both the amount of charge and its *sign*. Electrons and positrons carry exactly the same quantity of basic electricity (most other charged particles also carry this same unit charge), but of opposite sign: -1 unit for electrons, and +1 unit for positrons. Because of this, electrons and positrons of equal energy will be deflected by equal amounts in a magnetic field. This is one of the two main reasons why it is possible to guide and control beams of electrons and positrons together in the single, common magnetic structure of a storage ring like SPEAR or PEP. The second reason is that the sideways deflection of electrons and positrons in a bending magnet is in *opposite* directions if they are traveling along the same path, but in the *same* direction if the two beams have opposite paths. Thus the counter-rotating beams of negatively charged electrons and positively charged positrons respond to the magnetic bending field in a storage ring equally both in amount and direction of deflection.

The magnetic guide field for PEP will consist of a total of 669 magnets, of which 216 will be bending magnets of two different designs. A prototype of the "standard" bending magnet (192 required) is shown in the accompanying photograph. These C-magnets (so named because of their C-shaped cross section) are big dudes, each about 5 meters long and weighing in at about 10 tons apiece. The steel frames are built up by stacking together a long series of thin laminations, then welding the stack together. The magnet coils are made of aluminum conductor

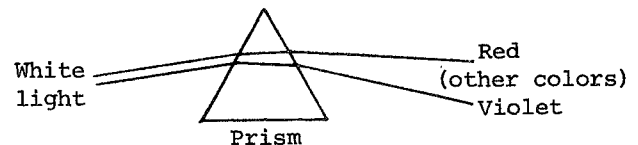


Chief of PEP mechanical systems Bob Bell is shown here with an engineering model of the dipole or bending magnet that will be used in PEP. This is the "standard" dipole, 5.4 meters long and weighing about 10 tons. The PEP ring will use 192 of these magnets, plus an additional 24 bending magnets of different design. (Photo by Joe Faust.)

with a cooling-water hole running along its center. The bending magnets will be energized by large power supplies, with each magnet carrying a maximum of about 650 amperes to produce the bending field required for PEP operation at 18 GeV.

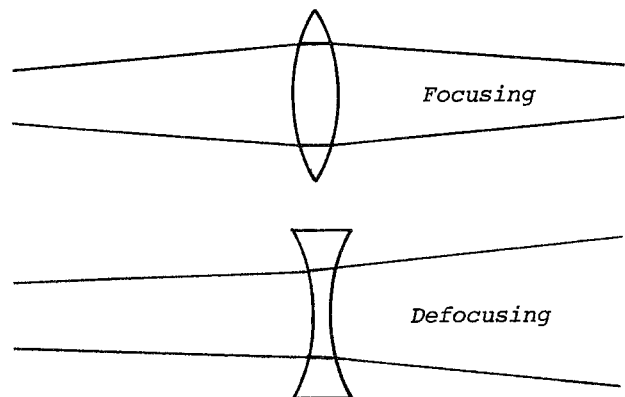
Quadrupole Magnets

A storage ring whose guide field consisted only of bending magnets wouldn't work. This is because the particles in the stored beams have small differences in energy, in direction of travel, and in the position they occupy in the particle bunches. These small differences mean that the particles are deflected by the bending magnets in very slightly different ways, with the net result that the beams gradually tend to spread out in space (diverge). This situation is closely similar to what happens when a beam of white light is passed through a prism:



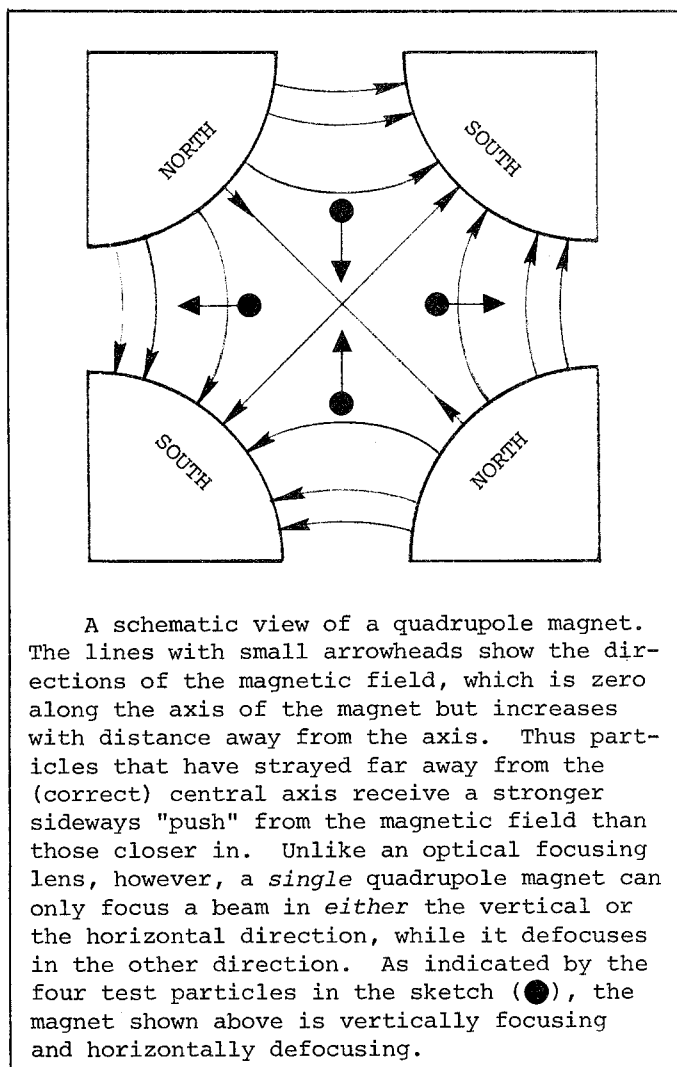
The light beam spreads out into a rainbow of the individual colors of light that appeared to be white when they were all together. Each of the colors of light has an energy (or wavelength) slightly different from the others, and for this reason each color within the white light beam is bent (refracted) through a different angle in passing through the prism.

A prism, then, acts on light in the same way that a bending magnet acts on electrically charged particles. This analogy with optics can be profitably extended to the problem of spreading or diverging particle beams. The spreading beam of light from a flashlight, for example, can be gathered back together--can be *focused*, that is--by using a convex lens, and *defocused* by a concave lens:



What the lens is to optics, the quadrupole magnet is to particle "optics." (In fact, "quadrupole lens" and "magnet optics" are com-

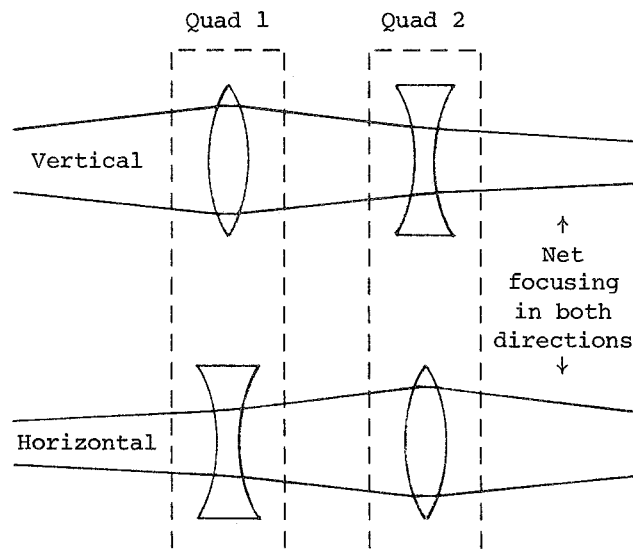
monly used phrases.) The four-pole configuration of a quadrupole magnet is shown in the following sketch.



A schematic view of a quadrupole magnet. The lines with small arrowheads show the directions of the magnetic field, which is zero along the axis of the magnet but increases with distance away from the axis. Thus particles that have strayed far away from the (correct) central axis receive a stronger sideways "push" from the magnetic field than those closer in. Unlike an optical focusing lens, however, a single quadrupole magnet can only focus a beam in either the vertical or the horizontal direction, while it defocuses in the other direction. As indicated by the four test particles in the sketch (●), the magnet shown above is vertically focusing and horizontally defocusing.

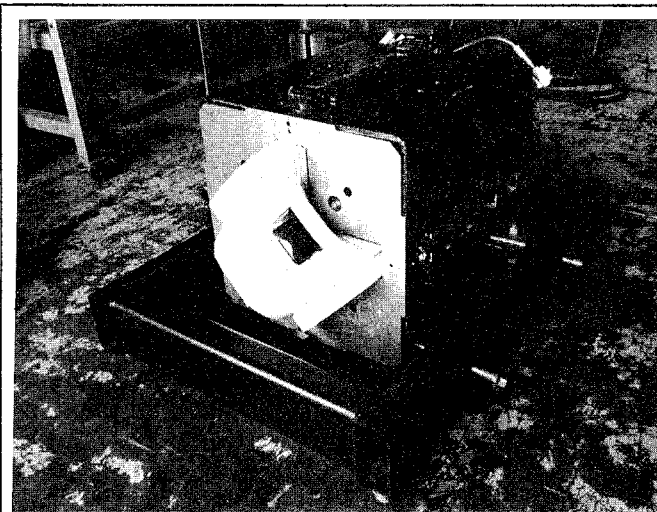
As noted in the caption, a quadrupole differs from an optical focusing lens in that it can focus a beam in only the vertical or the horizontal direction, with defocusing in the other direction. It turns out, however, that there is a simple solution to this apparent problem. The solution is to use two quadrupoles together, with the first focusing vertically and the second horizontally (or vice versa). Such a quadrupole pair has the property, perhaps surprisingly, that it produces an overall net focusing in both the vertical and horizontal sizes of the beam. This is illustrated (by its optical analog) in the sketch in the next column.

A prototype of one of the five different designs of quadrupole magnets intended for use at PEP is shown in the accompanying photograph. Quadrupoles tend to be shorter and chunkier than bending magnets (up to two meters long for PEP), although the largest of them weighs in at about the same 10 tons as the standard bending magnet.



PEP will use a total of 240 quadrupoles, of which 180 will be the "standard" or most common design.

To summarize, then, the bending magnets constrain the beams to travel in a roughly circular orbit. The quadrupoles act to keep the beams from spreading out over too large an area--or, alternately, from straying too far from the ideal central orbit of the ring. The focusing action of the quadrupoles can also be thought of as a sort of repeated "squeezing" of the beams whenever they start to get giddy and wander away from the beaten track. We should emphasize here that the beam particles do indeed



An engineering model of one of the five different designs of quadrupole focusing magnets that will be used in the main PEP ring and in the regions immediately adjacent to the six beam-interaction points. A total of 240 quadrupoles will be used in the PEP magnetic guide field (with an additional 46 in the injection system). (Photo by Walter Zawojwski.)

skitter around a lot in various kinds of oscillatory motions (the most common called "betatron oscillations"). But all of these fancy maneuvers are confined to a certain doughnut-shaped volume around the ring. If this volume has to be made large in order to accommodate particle ripple motions with wide excursions away from the ideal orbit, this will have a very strong effect on a storage ring's cost--larger vacuum chamber and pumps, larger magnets, very much larger magnet power costs because of the greater volume of magnetic field required, and so on. These factors have led, over the years, to the development of circular accelerators and storage rings in which the aperture (the required "beam stay-clear region") has gradually been reduced to present typical cross-sectional areas of perhaps 5 by 10 cm. This has largely been made possible by the use of magnetic guide fields that strongly focus the beams at frequent intervals.

Sextupole Magnets

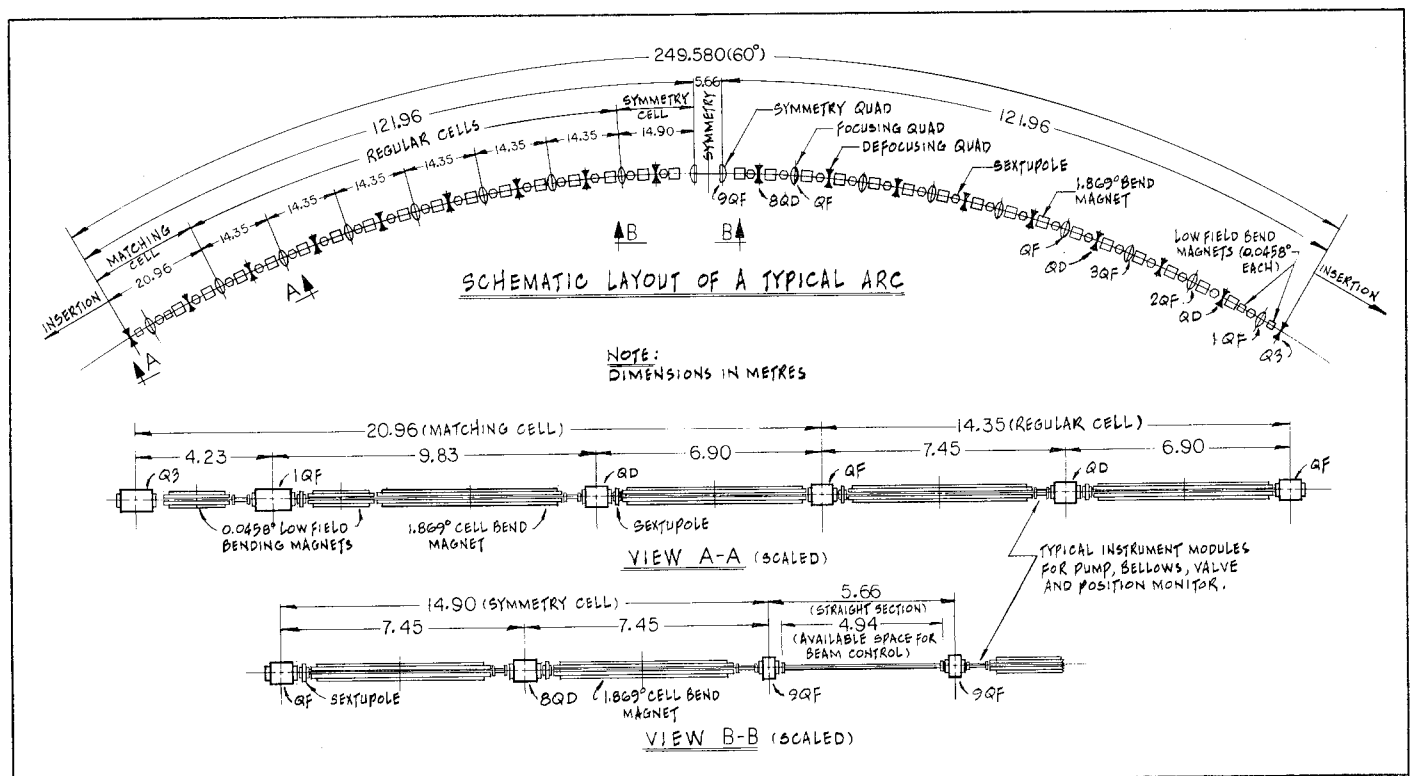
We've been a little cavalier so far in implying that the dipoles take care of the bending and the quadrupoles take care of the required focusing. Not quite. As it turns out, some of the beam particles can get into an off-energy situation in which the focusing of the quadrupoles is not sufficiently effective to squeeze them back into line. This hangup can be overcome through the use of special six-pole or sextupole magnets. Like quadrupoles, the sextupole magnets consist of a symmetric arrangement of alternating north and south magnet poles around a null axis (N-S-N-S-N-S spaced apart by 60°

around a circle). Although a large number of sextupoles--204 of two designs--will be needed for this special focusing function at PEP, the individual sextupoles are only a foot or so long and weigh about 450 pounds.

Layout Of The Magnet Lattice

Nearly all of the magnets that form PEP's magnetic guide field, or magnet "lattice," are located in the six curved regions or arcs of the machine. The figure at the bottom of this page shows the layout of the components within one of the arcs, and also within the smaller modular units called "cells." Each of the six arcs is made up of a total of 16 cells: 12 "standard" cells, 2 "symmetry" cells (on either side of the midpoint), and 2 "matching" cells (at the ends). The standard and symmetry cells are about 15 meters long, and each contains 2 bending magnets, 2 quadrupoles, and 2 sextupoles, with the bending magnets accounting for more than 70% of the total length. The matching cells are about 21 meters long and have a somewhat different complement of magnets. Each type of cell has a small amount of space available for various vacuum and instrumentation components.

The most notable magnets not located in the curved regions are the 24 special "insertion" quadrupoles that will be used in pairs on either side of the six beam-collision points at the center of each straight region. These quadrupoles will be used to focus the beams down to the very small ribbon-like cross sections, 2 cm by 3 mm, that were noted earlier. (About 60% of the beam particles will actually be contained within an even smaller cross section of 2 mm by



0.3 mm.) This very small beam size at the collision points is important for maximizing the number of interactions that occur between particles in the two beams. In contrast, when the beams are traveling through the curved regions of the machine, their cross section is expanded up to as much as 6-cm wide and 3-cm high.

The following table summarizes the main facts about the magnets that make up the ring.

MAGNETIC GUIDE FIELD SUMMARY				
Type Designation	Number Used	Magnetic Length (m)	Weight Of Iron (kg)	
<u>Bending magnets</u>				
Standard 70C5400	192	5.40	8580	
Low-field 70C2000	24	2.00		
<u>Quadrupoles</u>				
Standard 120Q750	180	0.75	1700	
120Q1000	24	1.00	2315	
120Q380	12	0.38	790	
Insertion 160Q2000	12	2.00	9000	
160Q1500	12	1.50	6700	
<u>Sextupoles</u> 140S250	204	0.25		
<u>Wigglers</u> 50H400	9	0.40		
		669		

3. VACUUM SYSTEM

As we mentioned briefly earlier, even a perfect magnetic guide field will not store particle beams unless we provide an obstacle-free environment for the beams to travel in. In this section we consider the chief potential obstacle--the molecules of nitrogen, oxygen and various other gases that form the earth's atmosphere or that may come from some other source to clutter up the beam path. High energy electrons traveling in free atmosphere will be scattered and lost through collisions with air molecules in a distance of less than 100 meters. Our goal at PEP, however, is to store circulating beams of electrons and positrons for periods of, say, three hours, during which time the particles will travel approximately 3 billion kilometers (or about 2 billion miles). The ratio of the two distances we've just mentioned is

$$\frac{3 \text{ billion kilometers}}{100 \text{ meters}} = 30 \text{ billion}$$

So our task is to try to make the air in the vacuum chamber at least 30 billion times "thinner" than the normal atmosphere. In physical terms, this means reducing the gas pressure in the vacuum chamber to a level of about 10^{-11} atmospheres, or 10^{-8} Torr. And this must be achieved even though the circulating beams of

electrons and positrons are constantly bombarding the chamber walls with an intense flood of radiation.

Clean And Bake

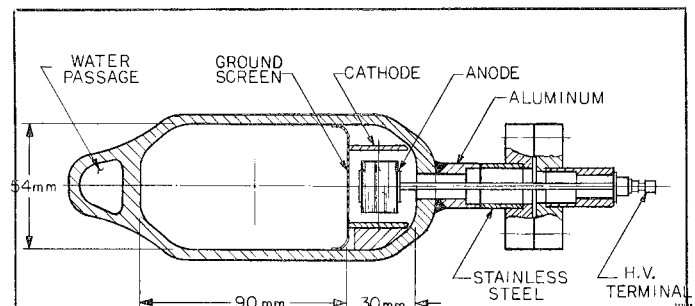
To attain and hold this level of ultrahigh vacuum is a tough business. The first step is to carry out a thorough chemical cleaning of the inner surface of the aluminum beam pipe, after which the pipe is then heated and baked for a time at a temperature of 180°C. These treatments will remove nearly all of the materials such as oil and grease (and even fingerprints!) that would eventually evaporate and thus form gas within the chamber.

A Skinny Straw

With a clean vacuum pipe in hand (the hand better be wearing a silk glove), the next step is to consider what sort of pumping will be required to attain the desired low pressure. The vacuum pipe itself, shown in the drawing below, has a relatively small inner cross section of about 5 by 9 cm, but its total length around the circumference of the ring will be about 2200 meters. With these dimensions, any attempt to evacuate the air by pumping from a single location would work about as well as trying to suck molasses through a 50-foot straw. So the first conclusion is that many pumps will be used, distributed around the ring where they are needed. In fact, for both SPEAR and PEP the idea of putting the pumps where they are needed has been carried to its logical limit in the following system.

Where The Action Is

Most of the gas that is desorbed from, or



The PEP vacuum chamber in cross section. The basic structure is an aluminum extrusion that is formed in 14-meter lengths. At the right, the cathode/anode/high voltage fittings form a part of the special sputter-ion pumping system that will be contained within each bend magnet. The water-cooling passage is located behind the chamber wall against which the bulk of the synchrotron radiation will strike. The individual 14-meter sections will be joined together by a common bellows located between magnet cells in order to allow for expansion and contraction of the chamber sections.

knocked out of, the walls of the vacuum chamber appears at those places where the blast of synchrotron radiation from the circulating beams is most intense. Since the beams radiate most strongly when they are being deflected by the magnetic field, the vacuum-pumping problem is most severe in the curved regions of the machine, and in particular within the fields of the bending magnets. Conventional vacuum pumps cannot be located any closer to these prime sources of gas than the spaces between magnets, but a special kind of pump--a "sputter-ion" pump--has been developed that can be built as an integral part of the aluminum vacuum chamber itself. How such pumps work is beyond the scope of this article, but it is worth noting that each of the PEP bending magnets will have a built-in pump section of this special kind.

These distributed sputter-ion pumps will carry most of the vacuum-pumping load, but there will also be more than 100 additional pumps of more conventional design attached to the vacuum pipe at many between-magnet locations.

Water Cooling

At beam energies of 15 GeV and with full beams of electrons and positron circulating in PEP, the synchrotron radiation from the beams will deposit energy on and into the inner wall of the vacuum chamber at a rate of about 3 million watts. Since this large load of energy is manifested mostly in the form of heat, an efficient water-cooling system will be required to carry it away. As shown in the drawing of the vacuum pipe, a passageway for circulating water has been incorporated within the extruded aluminum section that will be used.

Reducing Experimental Noise

One other vacuum problem merits attention. Assuming that the PEP vacuum system is good enough to permit beam-storage times of 3 hours or so, it is still nevertheless true that particles will be lost from the circulating beams through beam-gas collisions at a rate of something like 100 million per second. Although this loss is a drop in the bucket when compared to the total number of stored particles (a maximum of about 4 million million, 4×10^{12} , in each beam), it does create the following problem. Many of the beam-gas collisions will occur in the straight sections of the machine where the experiments are to be carried out, and some of the particles thus lost will strike the experimental detection devices. Such "hits" result in a background of extraneous detector data that is at best irrelevant and at worst a volume of "noise" that may drown out whatever subtle physics message the experimenters were trying to listen to. For this reason, a number of special pumps will be located in the areas immediately adjacent to the beam-interactions points in order to achieve a local reduction in gas pressure,

and thus fewer lost particles and a reduced level of background events.

Vacuum Pipe Sections

The 2200 meters of PEP vacuum pipe will be made up of a large number of individual sections joined together. For practical reasons, it is convenient to have individual pipe sections that are long enough, about 14 meters, to fit through one complete cell of the magnet lattice. These 14-meter pipe sections will be pre-curved in a bending fixture, then fitted into the magnets of a cell. The individual pipe sections will then be joined through a common bellows between cells, thus allowing for the expansion and contraction that will occur in the pipes with changes in temperature. In particular, the bellows must be able to accommodate a longitudinal expansion of about 5 cm that will occur in each pipe section when the vacuum chamber is baked at a temperature of 180°C, as described earlier. This bake-out process may have to be repeated from time to time in the event of a vacuum failure that causes contamination of the inner surface of the vacuum chamber.

4. RADIOFREQUENCY POWER SYSTEM

High-power radio waves are used in conventional accelerators to provide the strong electric fields that actually push the particles along to higher energies during the acceleration process. This also happens in electron-positron storage rings when the energy of the circulating beams is being increased, but that is only half of the story. The other half is the use of powerful radio waves not to accelerate the beams, but rather to prevent them from decelerating.

Synchrotron Radiation Again

We've just seen how the strong flux of synchrotron radiation given off by the circulating electron and positron beams causes heating and outgassing problems within the vacuum chamber. The energy that is carried away by this radiation is carried directly away from the beam particles that were its source. That is, the emission of synchrotron radiation causes the energy of the emitting particle to be reduced by just the amount that was emitted. And if nothing were done to compensate for these energy losses, the electron and positron beams would very quickly spiral in against the inner wall of the vacuum chamber and be lost. With PEP operating at 15 GeV, for example, each beam particle loses on the average 27 MeV or about 1/500 of its total energy every time it makes one complete revolution around the ring; and at 136,000 revolutions per second, the losers don't take long to drop out.

Before we go on to a description of the radiofrequency power system which solves this deceleration problem, we should make a brief re-

mark or two about the good side of synchrotron radiation. Such radiation includes a wide range of energies or wavelengths: thermal, infrared, visible light, ultraviolet, and X-rays. And because a great deal of power is involved in this radiation, storage rings such as SPEAR and PEP are among the most intense sources available for research which makes use of this radiation. Although the attitude of high-energy physicists toward synchrotron radiation tends to be annoyance at the problems it creates for them, solid-state physicists, chemists, biologists, and many other kinds of scientists have become very enthusiastic about the experimental studies that it makes possible. (The January 1975 and February 1977 issues of the *Beam Line* contain articles about synchrotron radiation research in general and the Stanford Synchrotron Radiation Project, SSRP, located at SPEAR in particular.)

Sizing Up The Need

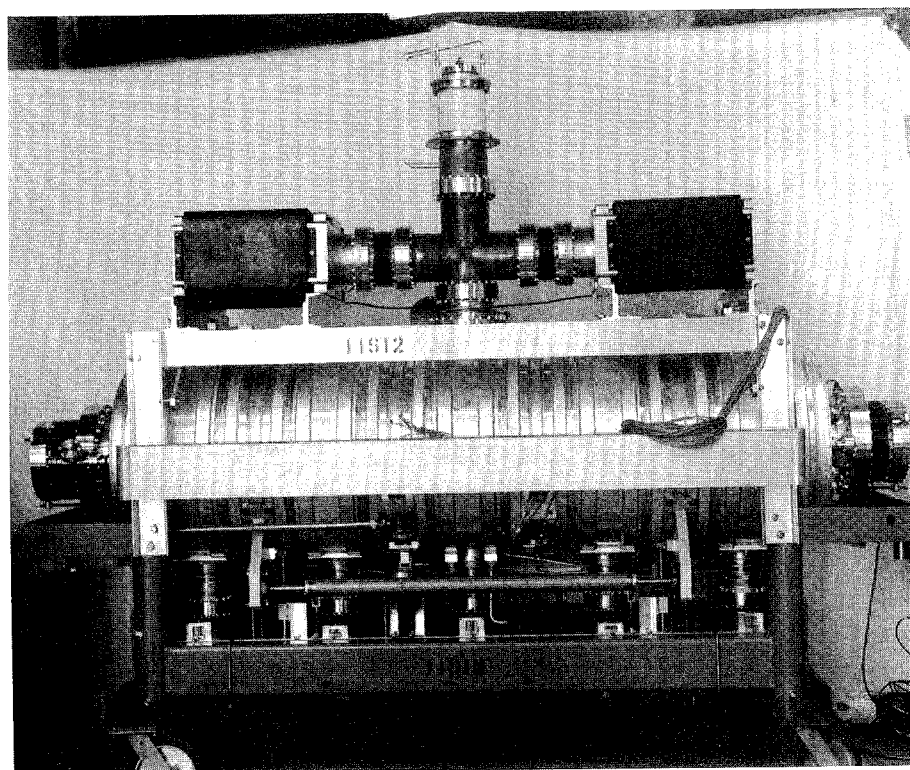
The circulating beam particles in the storage ring emit bursts of radiation (photons) in a random manner, which means that the exact loss of energy by each of the individual particles during any one turn around the machine cannot accurately be predicted. What is readily predictable, however, is the average energy lost by many particles during many revolutions, and it is this very well known quantity that is used to design a radiofrequency (RF) power system that will exactly compensate for lost radiant energy. If we were able to observe one of the beam particles during its travels, we would notice several abrupt, stepwise energy decreases

of different amounts as it passed, most probably, through bending magnets. Then it would reach one or more sections in which it would feel the accelerating force exerted by a strong, carefully timed, oscillating electric field. And the net effect of many such radiative losses and electric-field gains of energy during many revolutions would average out to zero--the gains exactly offsetting the losses.

The Planned PEP RF System

Knowledge of the average energy loss, then, establishes the scope of the RF system that will be needed to offset those losses. At PEP there will be three separate RF stations, located in Regions 4, 8 and 12. At each of these stations there will be an accelerating structure about 20 meters long. This structure is a series of coupled "cavities" or resonant boxes within which high-frequency radio waves generated by a large klystron produce very strong electric fields, and through which the beam particles pass on each revolution around the ring. The PEP RF structure is quite similar in function to the disc-loaded waveguide that was used as the accelerating structure for the SLAC linac. The chief difference is that the PEP structure has linear dimensions about 8 times larger than the SLAC machine, because the frequency used at PEP will be about 8 times lower than that of the linac (353 MHz vs. 2856 MHz).

Each of the three 20-meter-long accelerating sections at PEP will be subdivided into eight subsections, with each subsection containing five individual cavities. (Enough uncommitted



One of the RF accelerating structures developed at SLAC for use at SPEAR. This section, about 8 feet long, contains 5 coupled cavities. At PEP, eight such sections will be used in each of three locations to compensate for beam energy losses through synchrotron radiation. The total RF power available at PEP will be about 6 MW (supplied by 12 500-kW klystrons), of which 3 will feed the beams. Most of the remaining 3 MW will be dissipated on the inner surfaces of the cavities, or will make up for parasitic mode losses (see text).

Photo by Walter Zawojski.

space has been reserved at the accelerating stations to allow for the addition of the extra cavities that would be required to increase the maximum PEP single-beam energy to greater than 20 GeV at some future time.) Radiofrequency power will flow to the cavities through waveguides that run down through vertical penetrations from the klystron shelters located above the ring tunnel at surface level.

Klystron Power Sources

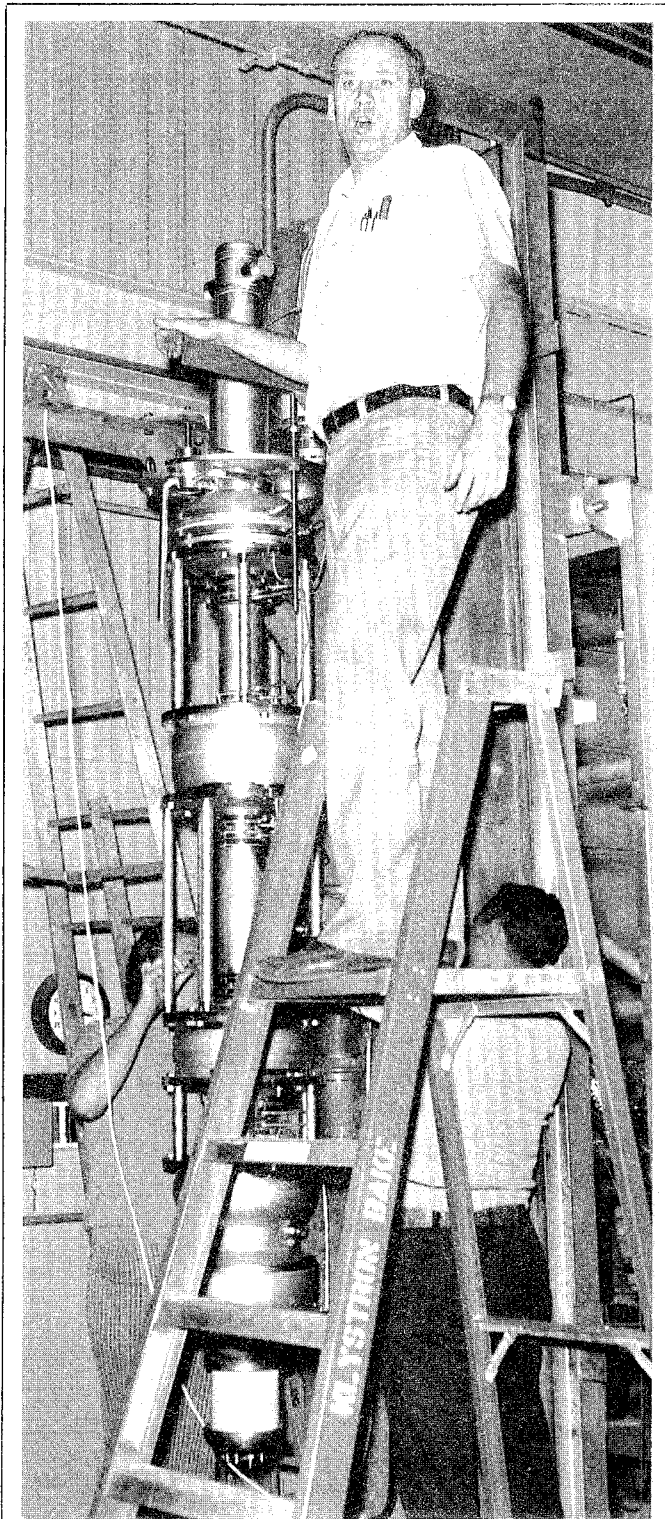
To sustain the maximum circulating beam current of 54 milliamps in each beam at an energy of 15 GeV, a total of about 6 million watts (6 MW) of radiofrequency power will be required. 3 MW will be needed to compensate for the synchrotron radiation losses suffered by the circulating beams, about 0.5 MW will be dissipated in "parasitic mode" losses (more on this later), and about 2.0 MW will be lost in the accelerating structures themselves owing to the finite conductivity of the cavity material.

This total of 6 MW of required RF power is so large that it was decided to try to develop a special high-power klystron at SLAC for this PEP service. One approach to this problem would have been simply to scale up the SPEAR klystrons previously developed at SLAC from their average-power output of 125 kilowatts to about 500 kilowatts per tube. However, there is another klystron parameter, the efficiency, that has become increasingly important with the rising costs of electrical energy. The efficiencies of commercially available tubes tend to run about 40%, while those of the SLAC-built klystrons for SPEAR are about 55%. For PEP, the design goal for efficiency was set at 70%. The significance of these different levels of klystron efficiency can be seen from the following comparison. For a total klystron output power of 6 MW, the required input power to the klystrons would be 15 MW at 40% efficiency, or 11 MW at 55% efficiency, or only 8.6 MW at 70% efficiency. Thus very significant savings in electrical power consumption will accrue if the efficiency of the PEP klystrons can be increased.

At the present time the design work on the PEP klystrons has resulted in tubes that can deliver 500 kilowatts of output power at an efficiency of about 63%. This is an achievement that is unparalleled anywhere in the world, and it is expected that further design refinements will raise the efficiency even closer to the 70% design goal.

Parasitic Mode Losses

The present SPEAR storage ring at SLAC has served and will continue to serve as a very valuable test machine for understanding storage ring operation, and for testing out new components. One important example of this has been the observation during the last year or so of a phenomenon called "parasitic mode losses."



Klystron group members Bob Boesenberg (top) Blaine Hayward (left) and Willie Roberts are shown here with one of the klystrons developed for SPEAR. The PEP tubes are very similar but have an output of 500 kW rather than 125 kW, and their efficiency will be at least 63% (which is unprecedented) and perhaps as high as the design goal of 70%. (Photo by Walter Zawojski.)

What happens is the following. As the amount of stored beam in SPEAR is increased above a certain level, some of the vacuum components that surround the beams begin to heat up. In fact, on one occasion a vacuum bellows heated to the point where it broke, thus causing a complete loss of vacuum.

What causes this heating? Well, although the circulating beam currents in SPEAR are measured in milliamps (thousandths of an ampere), this is only the average current that is stored in the machine. In fact all of the current in each beam is packed into a single, short bunch that is only a few centimeters long. And this means that the peak current in SPEAR (the current packed into the short bunch) is about 200 amperes. Such a short, very intense pulse of current creates a strong electromagnetic field within the vacuum chamber whenever there is an abrupt change in the inner size of the chamber--as in a bellows or vacuum flange, etc. At such size-change points, the energy of the induced electromagnetic field is absorbed by the vacuum components, thus causing them to heat up. And if these components are not cooled adequately from the outside, the temperature will continue to rise until the weakest part of the structure fails.

At SPEAR, the maximum beam current that can be stored (and thus the rate at which collisions occur) is limited by this parasitic-mode effect. For PEP, the effect of parasitic-mode losses would be significantly worse--about 40 times worse--if the same kinds of vacuum components were used. Because of this experience

at SPEAR, there are two kinds of corrective measures that can be taken for PEP. The first is simply to design the vacuum system so that it has as constant an inner cross-section as possible, with any necessary changes in cross-section being made through smooth rather than abrupt transitions. This will definitely be done. The second measure is to devise a means for artificially lengthening the circulating beam bunches, thus decreasing the peak current and also the strength of the resulting electromagnetic field. Such means are presently being explored.

5. BEAM INJECTION SYSTEM

So far we've described many of the good and bad things that happen to the particles as they go round in the storage ring, but we haven't yet talked about how the particles get into the ring (beam injection), nor where the particles come from in the first place (the injector). We'll begin by discussing the beam-injection process, since this will tell us a good deal about the kind of particle-source or injector we'll need.

The Beam-Injection Process

Injecting particles into a storage ring is a more complicated problem than injection into an electron synchrotron. The main difficulty results from the fact that no accelerator in the world is able to deliver as many particles as we need in a storage ring in a single burst of about one billionth of a second duration. The SLAC accelerator can produce about 10^8 positrons or 10^9 electrons during a single pulse, but the PEP machine will need about 10^{12} particles in each of its two beams. The beam-injection system for PEP will therefore have to be designed to allow for the injection of thousands of SLAC pulses during each filling cycle in order to build up the stored beams to the required level.

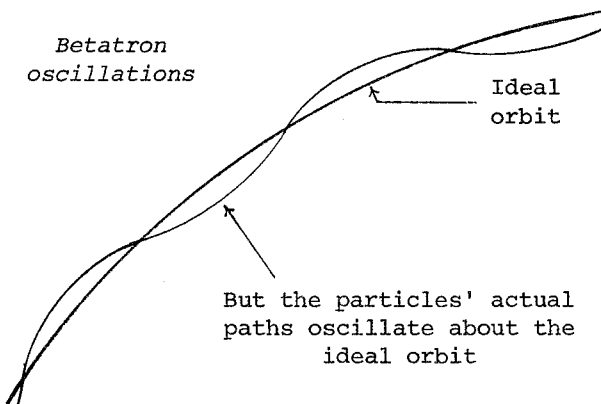
How will this be done? Well, first let's visualize the situation in which there is a partial beam circulating in the ring, and the next injection pulse is on its way from the SLAC accelerator (that is, approaching the ring from the outside). At the point where the incoming beam pulse meets the ring, there must be a bending magnet that will deflect the incoming particles into a path that is parallel to that of the stored beam. But now we've got a problem, because we don't want that bending magnet to deflect the partial beam that is already safely stored in the ring. There is a solution to this problem, but it will take another paragraph or two of explanation before we can describe just what that solution is.

Betatron oscillations. In the curved regions of PEP, the ideal orbit of the circulating beams is simply a line that runs through each magnet along its central axis, and that overall

RADIOFREQUENCY POWER SYSTEM SUMMARY

Beam orbital frequency	136.2693 kHz
Radiofrequency	353.2102 MHz
Harmonic number ($2^5 \times 3^4$)	2592
Length of accel. structure	51 m
No. of accel. sections	24
No. of cavities per section	5
No. of klystrons	12
Output power per klystron	500 kW
Total available RF power	6 MW
Peak RF voltage	78 MV
<u>Operating at 15 GeV:</u>	
Synchrotron radiation loss/turn	27 MeV
Circulating current/beam (max.)	54 ma
Particles/beam	2.3×10^{12}
Synchrotron radiation power/beam	1.5 MW
Bunch length	~ 4 cm

has approximately a circular shape. But as we noted earlier, the beam particles weave back and forth around this ideal orbit in a motion called "betatron oscillation," which looks something like this (the wiggle size is exaggerated):



This oscillatory motion is largest (moves farthest from the ideal orbit) for those particles that have just entered the ring, and its amplitude gradually decreases with time as a result of the emission of synchrotron radiation by the particles. This is described by saying that the betatron oscillations are "damped down" by synchrotron radiation.

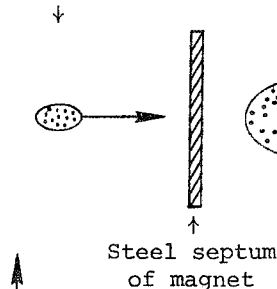
The solution. Our problem was to find a way to deflect new pulses of particles into the ring with a bending magnet without affecting the beam already there. The solution is to choose a path for the new pulses that is displaced sideways from the ideal beam orbit by a certain distance. This distance is determined by two factors:

1. It must be large enough to allow the use of a special (septum) magnet that will deflect the incoming pulses but not the stored beams.
2. It must be no larger than the largest amplitude of betatron oscillation that the beam particles can undergo without being lost from the beam.

As a practical matter, the distance between the ideal orbit and the beam-injection path is about 2 or 3 cm. The sketch in the next column shows schematically what happens at the beam-injection point.

Damping time. Having thus found a way to feed a succession of pulses of new particles into the ring in order to build up the stored beams to the required level, our next step is to find out how rapidly we can feed in these new pulses. Before a new pulse is sent in, we have to wait until the betatron oscillations of the previous pulse have damped down by a certain amount, which means that the total time required to fill the ring completely will depend very strongly on the damping time of the betatron oscillations. For PEP the damping times are

Incoming beam pulse is deflected by septum magnet



Stored beam after damping is not deflected by septum magnet

Particles undergoing horizontal betatron oscillations within these limits will not be lost from the stored beams

A schematic cross-sectional view of the beam-injection point. The ideal orbit of the storage ring runs through the center of the larger ellipse. The area of this ellipse represents the cross-sectional size of the stored beam after the betatron oscillations of the particles have been damped down through the emission of synchrotron radiation. The incoming beam pulse is displaced from the ideal orbit of the ring by a distance that is less than that of the largest horizontal betatron oscillations that can occur without losing the oscillating particles. The special injection magnet used at this point has a divided throat, or septum, which allows the incoming beam pulse to be deflected by the magnetic field, as is required, but which does not cause an unwanted deflection of the beam particles that are already stored in the ring.

calculated to be as follows:

Beam Energy	Betatron Oscillation Damping Time
15 GeV	0.008 second
5 GeV	0.22 second
1 GeV	28 seconds

The incredible difference in damping times between high and low energy beams tells us something very important about the kind of injector we should use to produce the beams. For example, suppose we decided to build a small, 1 GeV linear accelerator as the source of the beams for PEP. It would be possible, in principle, to inject the positron and electron

beams at 1 GeV and then to use PEP's RF power system to "ramp up" the beam energy to 15 GeV or whatever value was needed. Feeding 1 GeV pulses into PEP at a rate of one pulse every 28 seconds would result in a total filling time of about 26 hours. However, since the expected "unfilling" time (beam lifetime) for PEP is only about 3 to 6 hours, the bottom line is that we never would get the damn thing filled.

The Injector

From the preceding discussion it should be clear that there are certain advantages in building the PEP storage ring at a laboratory that happens to have a 22 GeV linear electron accelerator kicking around in its back yard. With the SLAC accelerator as the injector for PEP, we will be able to inject 15 GeV positrons, followed by 15 GeV electrons, at a rate of 360 pulses per second. With an assumed injection efficiency of 25%, the ring would be filled in only 4 minutes. There are a number of factors that may cause the injection efficiency to be less than 25%, but even at 10% the filling time would be a perfectly acceptable 10 minutes.

The electrons that enter the SLAC accelerator to become its electron beam are obtained from a simple source--essentially a heated metal surface that is not much different from the filament wires in an ordinary light bulb. The source of positrons, however, is not so simple, since they are the antimatter counterparts of electrons and are not ordinarily present in nature (at least not in our local region of the universe). Briefly, the positrons for the SLAC accelerator are obtained in the following way. An electron beam is accelerated through 1/3 of the SLAC machine and is then ploughed into a metal target. The ~7 GeV electrons strike the atoms in the target and produce gamma rays, which then make further collisions in which an electron and a positron are created. The positrons that emerge from the back of the target are focused down to a small beam size and are then accelerated through the remaining 2/3 of the machine to energies ranging up to a maximum of about 15 GeV.

The PEP Beam Injection System

The system that has been designed for beam injection at PEP must handle a number of complex problems that we haven't even touched upon here. We'll ignore these, however, and conclude this section with only a few remarks about what is being planned. The beam injection components will be housed in the two legs of a Y-shaped tunnel structure that leads from a point at the end of the SLAC accelerator to two different joining points at the PEP machine. Within these north and south injection tunnels the separate electron and positron beams will each travel through a vacuum pipe and will be acted upon by a series of bending and focusing magnets. At

or near the points where the injection channels join the PEP ring there will be a number of special magnets to kick, bump and generally move the beams around in the complex patterns needed for efficient injection. The design of the system has been spiced up a bit by the fact that the plane of the PEP ring will be located at an elevation about 12 meters lower than that of the SLAC accelerator, which means that the injection tunnels must slant down to meet the ring. The first actual construction at PEP will be the digging required to build the accelerator ends of the two injection tunnels where they join into the existing beam switchyard structure. This work should be in evidence at SLAC by June or July of this year.

The following table summarizes the main facts about the beam injection system.

INJECTION SYSTEM SUMMARY	
Injection accelerator	SLAC linac
Injection energy	4-15 GeV
Pulse length	10^{-9} sec
<u>No. particles/pulse</u>	
Positrons	1.3×10^8
Electrons	1.3×10^9
Time to fill ring (both beams)	4 - 10 min
Pulse repetition rate	up to 360 pps
Assumed injection efficiency	25%
Injection system vacuum	10^{-3} torr
Injection magnets	96
Bending	32
Quadrupole	46
Switching, septum, kicker & bump	18

6. INSTRUMENTATION & CONTROL

The PEP storage ring will be made up of a very large number of individual components and systems of varying degrees of technical sophistication, all of which must operate in a coordinated way. In fact, it is very likely true that large accelerators and storage rings are the most complex instruments ever made. Such instruments would never operate successfully unless they were continuously instructed in what to do, and this is the purpose of the instrumentation and control (I&C) system. The central brain of the PEP I&C system will be a good-sized computer located in the control room, which will be linked to seven smaller computers--one for each sextant of the storage ring, and the seventh for the beam injection system. Each of these small computers will collect information from many passive mon-

itors which sense, for example, the behavior of the stored beams; and each will also transmit instructions for setting and correcting such parameters as the currents flowing through the magnets. All of the information collected by the small computers will be sent on in condensed form to the main computer, where it can be displayed to the machine operators.

An I&C Example: Starting Up The Ring

Since we can give no more than a general notion of the PEP I&C system here, we describe briefly the role of I&C in starting up the storage ring as an example of its functions. The operator begins the process by punching into the main computer the desired beam energy and some information about the configuration of the magnetic guide field. The main computer will then calculate what magnet currents are required and the correct set of RF system parameters. These are passed on to the smaller computers, which then send out action instructions to the controls of the magnet power supplies and the RF system. The monitors on these components report back to the small computers, which check to see that each instruction has been executed and the specified operating levels achieved.

After confirmation, the process of beam injection is begun. A master clock of very high precision generates signals that are used to trigger the accelerator so that its many thousands of beam pulses each arrive at the ring at the exact time required for them to be added to the particle bunches already stored in the ring. During this beam-fill operation, a current monitor measures the stored beam current and displays the result through the computer. When the filling cycle is completed, the circulating beams (which had not previously interacted with each other) are made to pass through each other at the interaction points. Monitors at these points measure the rate at which electron-positron collisions are occurring (the "luminosity"), and if this rate is satisfactory the ring is ready for the scheduled physics experiments to begin.

After several hours, the number of particles in the stored beams will have gradually dwindled away to a point where the experimental users and the machine operators agree that more particles should be added. And at that point the beam-injection cycle is begun again.

Instrumentation Example: Beam Monitors

Because of small errors in the alignment of the magnets, or of small deviations in magnetic fields, the equilibrium orbit of the beam (its average actual path) may be slightly displaced from the ideal orbit which lies along the central axis of vacuum chamber. To detect such displacements, a total of 80 beam position monitors will be located around the ring. The beam-position measurements from these monitors

will be sent to the computer, which will then calculate the magnetic field strength that each correcting coil must provide in order to move the stored beams back to the ideal orbit.

A second example is a situation in which a stored beam increases its cross-sectional area significantly, or is even lost, after a certain level of stored current is reached. It would be helpful in this situation to be able actually to see the beam as this unstable behavior occurs. This is in fact possible because the emitted synchrotron radiation actually makes the beam luminous, and all that is needed is to let the light exit from the vacuum chamber through small windows at several different locations. The beam is then viewed by television cameras which send their pictures back to a display screen in the control room.

C. SITE & BUILDINGS

1. BEAM HOUSING AND SHIELDING

The shape and size of the machinery--magnets, vacuum chamber and RF cavities--that makes up the PEP storage ring are determined by physics and engineering constraints. As we saw in Section B, the end-product is a ring comprised of six 117-meter straight sections joined together by six long arcs with a total circumference of 2200 meters (about a mile and a half). The first problem is where to put it.

The main constraint in finding a location is that it must be reasonably convenient to feed it with beams from the SLAC accelerator. There are several ways this could be done, but it is most convenient to take the beams from the accelerator either upstream or downstream of the beam switchyard area, in order to avoid conflicts in that area.

The next points to be considered are related to the geography of the SLAC site. The PEP storage ring should, if possible, fit within the existing SLAC leasehold; and the beam-interaction regions, which will have rather large buildings and must be readily accessible to heavy equipment, should be fairly close to the surface level of the terrain to minimize the amount of dirt that has to be moved. The structure that houses the storage ring itself needs to be covered with about 5 meters of dirt to provide radiation shielding.

The optimization of these several points resulted in the choice of location that is shown on the next page. Several compromises had to be made. One of the interaction regions (Region 10) ended up so deep underground that plans to develop it for physics experiments were abandoned, and it has since been dedicated to experimental studies of the behavior of the storage ring itself. One other interaction region (Reg-

ion 4) is also deeply buried in a steep slope, and its planned building and related facilities have been reduced in scope to decrease costs.

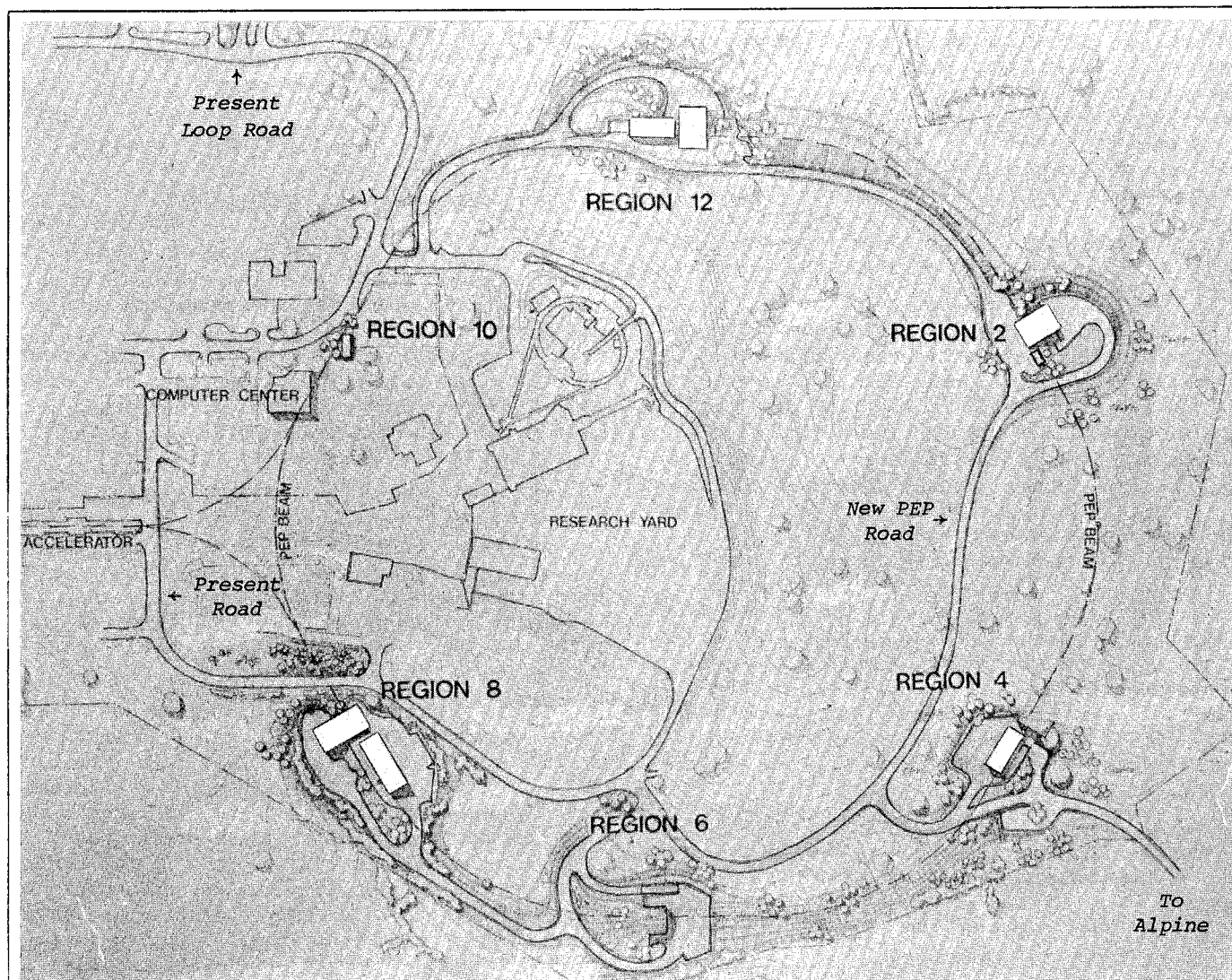
The elevation chosen for the storage ring, 218 feet above sea level, is about 26 feet below the elevation of the end of the SLAC linac. As a result, the injection beam lines must run downhill fairly steeply on their way to the ring.

Excavation for the ring housing itself will consist partly of tunneling and partly of cut-and-cover construction. Since the magnets and associated support structures and utilities are relatively small in cross section, the ring

housing will have an inverted "U" shape about 10-feet high and 11-feet wide (next page).

2. EXPERIMENTAL AREAS

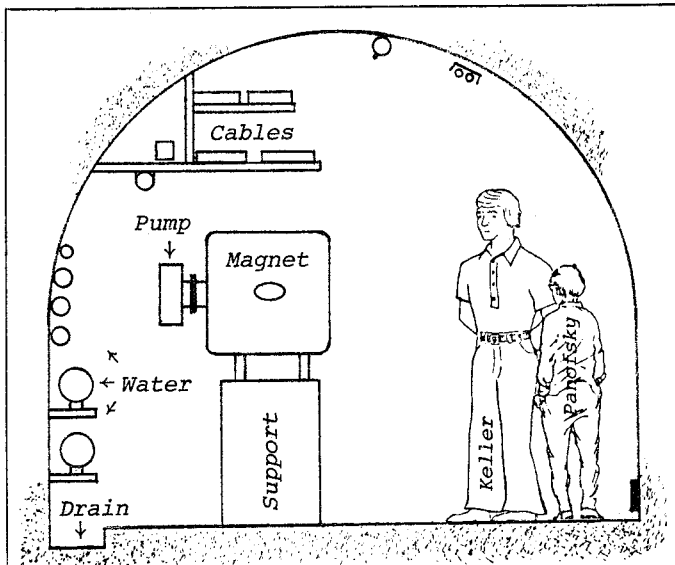
The purpose of the PEP storage ring is, of course, to do physics. Consequently, the design of the interaction-region buildings, where the physics will be done, is an important matter. Choices made now on the size and shape of these buildings may place constraints on the kinds of physics apparatus that can be used in the future. Furthermore, the operating efficiency of the storage ring will be affected strongly by the fact that the beams cannot be



General site plan for the PEP project. A new loop road will take off from the existing road leading to SPEAR (at Region 10) and will turn clockwise down to Region 6, where it will join the existing road that leads to the research yard. Two branches will lead to PEP Regions 6 and 8. The control building for PEP is the slender rectangle at Region 8. The experimental areas in Regions 2-4-8-12 will be housed within buildings of similar design but different sizes. Region 6 will initially have only a large concrete pad at its experimental area, with future structures to be erected on an ad hoc basis as the need arises. The klystrons and related power supplies used in the PEP RF power system will be housed at surface level in the buildings at Regions 4-8-12, and will be connected to the PEP tunnel by vertical penetrations.

"on" when people are working on one or more of detectors in the interaction regions. The detectors that have been proposed for use at PEP are large, complex devices that will each cost several million dollars and will take many months to assemble and test.

These considerations have resulted in a building design that consists of two quite different parts -- a heavy concrete region surrounding the beam-interaction point in which the actual experiments will be done, and a separate light steel structure that will be used as an assembly and work area. The sizes of these two-part buildings will vary somewhat from one interaction region to the other. The largest will be in Region 8, with 20 meters along the beam direction and 35 meters in the radial direction. Region 4 will have the smallest of the buildings, being 15 meters along the beam and 28 meters radially. However, the Region 4 building will have heavy concrete construction for both of its sections because it will be largely underground.



A schematic, cross-sectional view of the PEP ring tunnel in one of the curved regions of the machine. Power, signal and control cables will run in the cable-trays shown. Cooling water for the vacuum chamber (two large pipes) and for the magnets (three smaller pipes) runs along the wall at the left. The magnet shown is a quadrupole; the dipole and sextupole magnets used in the ring have smaller cross sections. Most of the tunnel excavation will be done by a special boring machine; the remainder, by conventional cut-and-cover techniques. The ring magnets must be aligned to high accuracy; vertical alignment will be aided by a liquid-level system in the tunnel (lower right-hand wall). Not labelled in the sketch are lights, fire protection, nitrogen piping, an ion pump, and a small duct for beam-monitoring cables.



Designer Glenn Hughes is shown here working on a large layout drawing of the PEP site. The site-elevation contour lines on the drawing are a clue to the fact that the new roadwork planned for PEP will have some fairly steep ups and downs to negotiate as it loops around from region to region. (Photo by Joe Faust.)

No building is planned for Region 6 during the initial construction period. A flat concrete pad will be provided, and any buildings and shielding will be erected on an ad hoc basis to suit the particular needs as they arise.

The structures planned for Region 8 are shown in the drawing on the next page.

3. CONTROL ROOM AND OTHER BUILDINGS

The control room for PEP will be located at a point on the surface above the ring tunnel in Region 8. This location is reasonably close to the Main Control Center (MCC) of the accelerator. The spot chosen, however, is just outside the fence that presently marks the boundary of the SLAC site, and is in an area that is currently used as a horse pasture. (Arrangements have been made to move the fence and the horses.) A two-story building is planned, with the control room on the first floor. The second floor will have offices and additional space for electronics labs and for storage of some spare parts. The building will eventually turn out to be home for about 30 people, after the work to be done there gets fully going. More than half of the control room space on the first floor will be occupied by the computer system that is the focus of the instrumentation and control functions.

The PEP control building will also house the power supplies for some of the magnet systems, as well as the klystrons and their associated power supplies which feed the RF cavities in Region 8. The klystrons and power supplies for the RF cavities in Regions 4 and 12 will be housed in other, smaller surface buildings at those locations.

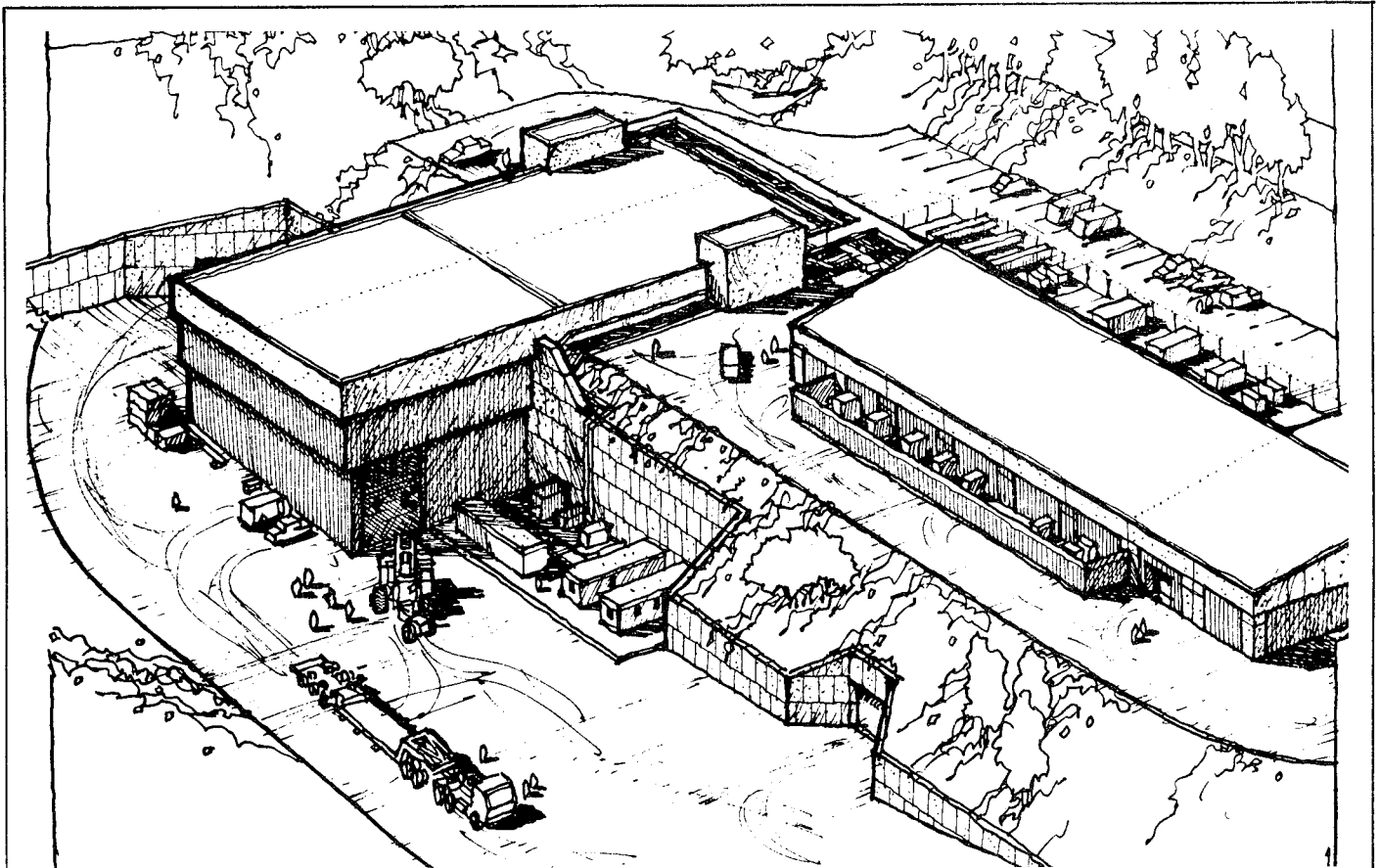
4. ROADS

To interconnect all the interaction regions and surface buildings, a loop road will be built starting from the present parking lot next to the north gate of the research yard (the gate that leads down to SPEAR). Running clockwise, the run will go north, then east, skirting the toe of the shielding berm to the north of the research yard. From Region 12 to Region 2 it will wind around a bit to take advantage of the topography. As it approaches Region 4 it will drop down sharply and run along the face of a steep slope, after which it will join into the present access road that leads into SLAC from

Alpine Road for about a hundred yards. Just south of the present south entrance to the research yard a spur road will head down toward the present horse pasture, with a left branch going to Region 6 and a right branch going to Region 8.

The PEP road system will bring along with it a certain fringe benefit--an exciting and picturesque route for bicycle races that should be much more fun to ride than going back and forth along the klystron gallery. However, automobile drivers will need to exercise caution, because the new roads will have steep grades as they dip down to the level of the interaction regions (which are 4 meters below beam height) and then rise up again to get over the hills behind the present research yard. The road from Region 4 will climb 80 feet in less than 250 yards, for example. It would be wise to have your brakes checked before you go driving at PEP.

(Part II of this article will appear in about two months.)



The structures planned for Region 8. On the upper level is the control building for PEP, which will house the storage rings' central I&C functions, and will also have room for offices and some light laboratory space. Cut into the side of the slope is the experimental area building for this region. The right-hand side of this building encloses the actual beam-interaction point and will be of heavy concrete construction, while light steel framing will be used for the assembly section of the building on the left. This building will be the largest of the experimental area housings at PEP. The buildings at Regions 2-4-12 will be somewhat smaller but of generally similar light-heavy sectional design.