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)

Volume 8, Number 6 June 1977

--*Photo by Joe Faust*

PEP GROUND BREAKING

During the June 2nd ground-breaking ceremonies for the PEP storage ring now being built at SLAC, the exuberance of the shovel-wielders unfortunately screened out Robert D. Thorne, Manager of ERDA's SAN Operations Office, and Paul H. Gilbert, President of Parsons Brinckerhoff Quade and Douglas. The four visible ground-breakers are, L to R, Lawrence Berkeley Laboratory Director Andrew M. Sessler; California Senior Senator Alan Cranston; Acting Assistant Administrator Donald A. Beattie of ERDA's Solar, Thermal and Advanced Energy Systems division; and SLAC Director W. K. H. Panofsky. The speakers and distinguished guests present on this auspicious occasion are listed on page *2*, and Senator Cranston's remarks as principal speaker are given on page *3*. Now that PEP is formally launched, the dirt should really begin to fly.

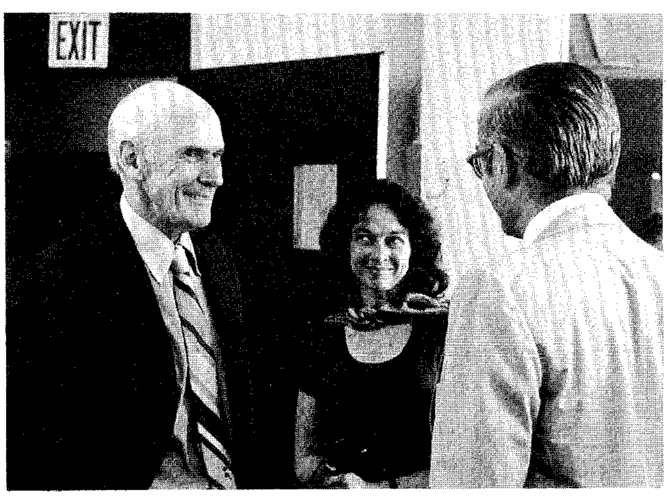
Contents Of This Issue

**Part II of the two-part article on PEP is being distributed separately. (Part I appeared in the April 1977 issue.)*

PEP GROUND-BREAKING CEREMONY

On the afternoon of June 2, ground was formally broken for the PEP storage ring project in a ceremony near the PEP site. PEP Director John Rees acted as Master of Ceremonies, introducing the speakers and guests (listed at the right) to the large crowd that attended. The principal speaker was The Honorable Alan Cranston, Senior Senator from California (and a graduate of Stanford). The text of Senator Cranston's remarks appears on the following page. Refreshments were served after the ceremonies, and we hear that the PEP crew all went directly home at 6:30 PM to rest up for the hard times ahead. Or maybe it was AM.

Senator Cranston is shown addressing the large crowd that turned out for the ground-breaking ceremony, with the other speakers and guests seated on the platform. *(Photo by Joe Faust.)*



From the left, Senator Cranston, Gladys Sessler, and Stanford President Richard W. Lyman. *(Photo by Joe Faust.)*

SLAC Director W. K. H. Panofsky and Senator Alan Cranston. *(Photo by Joe Faust.)*

SPEAKERS

John Rees, Director of PEP
Master of Ceremonies

Richard W. Lyman
President, Stanford University

C. O. McCorkle, Jr.
Vice-President, University of California

Robert D. Thorne, Manager
San Francisco Operations Office
Energy Research & Development Administration

Donald A. Beattie, Acting Asst. Administrator
Solar, Thermal and Advanced Energy Systems
ERDA

The Honorable Alan Cranston
Senior Senator, State of California
United States Senate

GUESTS

Philip D. Bush, Vice President
Kaiser Engineers

Thomas Elioff, Deputy Director of PEP

Paul H. Gilbert, President
Parsons Brinckerhoff Quade and Douglas, Inc.

James F. McCloud, President
Kaiser Engineers

Henry L. Michel, President & Chief Exec. Off.
Parsons Brinckerhoff Quade and Douglas, Inc.

W. K. H. Panofsky, Director
Stanford Linear Accelerator Center

Andrew M. Sessler, Director
Lawrence Berkeley Laboratory

Stanley R. Stamp, Director
SLAC Site Office, ERDA

SENATOR CRANSTON'S REMARKS

We are here today to begin an exciting new venture in our quest to understand the basic building blocks of nature--and in so doing, perhaps, to seek to better understand ourselves.

Basic research into the nature of matter, as carried out here at Stanford and at the University of California, represents one of the fundamental aspirations of man.

Understanding nature is an essential ingredient in the shaping of our decisions, in making our institutions more responsive and humane, and in preserving and protecting the natural world which nourishes us all.

Unfortunately, too few of our research and development dollars are now dedicated to such peaceful and basic physical research.

Worldwide, some forty percent of all research expenditures are spent to design and develop weapons. In the United States alone, public spending for military research and development during 1975 was $10 billion, while research and development for all other purposes combined--both pure and applied--amounted to only $8.8 billion.

This means that more than half of the public's research and development dollars were spent to improve the tools of war.

By contrast, this figure for Western Europe is about 25 percent.

That imbalance must be corrected.

I am delighted that the PEP project--locat- here in my home state and not far from my early home in California--represents a new initiative in peaceful and basic physical research.

There are those who criticize basic research, but I believe it is absolutely necessary.

It should be fostered and nourished with stable funding. For there is a continuous chain which leads from the most basic physical research, such as that practiced here, to the eventual development and production of useful products.

Thus our economy and our national well-being ultimately draw upon the storehouse of knowledge that has accumulated from the basic research of the past.

The United States lags behind other nations in this regard. Western Europe, for example, is currently investing about twice the effort of the U.S. in the field of basic research--high energy particle physics--to which this laboratory is dedicated.

There has been a ten-year gap between the new construction initiative we begin here today and the last major new facility for the exploration of the fundamental properties of matter. That was the huge accelerator in the state of Illinois, named after the great physicist, Enrico Fermi.

Much of the early history of the creation of new tools for atomic and particle physics stems from California--the early work on the cyclotron at Berkeley, the work on nuclear magnetism and linear accelerators at Stanford, and the linkage between astronomy and nuclear structure at Pasadena.

The results of these pioneering efforts have enriched man's understanding of nature, while at the same time producing material and economic benefits.

But the tools of physical research have become increasingly expensive, and those institutions which formerly operated their own smaller accelerators and other research equipment must now share in the use of the larger machines at few locations.

I am pleased that two of the truly outstanding universities of our state--one public, the University of California, and one private, Stanford--have decided to construct jointly this new research tool rather than to compete with each other for this opportunity.

I am even more pleased that this new storage ring, PEP, will follow the tradition of the Stanford linear accelerator and the Brookhaven and Fermilab machines in being operated as national and even international facilities.

The scientific opportunities which exist here and which will be enriched by this facility will be available to qualified scientists from all over the world. Thus with this installation, California can serve the nation and the world.

As a layman, I can only remotely appreciate the importance of the recent discoveries --with both SLAC and the Berkeley lab playing such dominant roles--which have demonstrated beyond reasonable doubt that there are building blocks of matter smaller and more fundamental than the neutron and proton.

But these new and fundamental discoveries capture the imagination of us all, providing windows of insight into the nature of man himself.

It is in the hope that this new facility will contribute even further to our basic knowledge, and to help make this world of ours one of peace and common purpose, that I am pleased to wield my shovel in this groundbreaking ceremony.

SLAC WOMEN'S ASSOCIATION

June marks the end of the term of office for the slate of officers elected in January. The past six months have helped to surface a spectrum of matters of concern to women which is so broad in scope that we have only begun to deal with them.

Because so many women at SLAC are working in the clerical field, the problems of clerical women are of prime importance. This is reflected in the fact that our program for the early part of June was headed by a film and panel discussion about these matters:

June 1: The documentary film *Nine to Five*, about clerical workers, was followed by a panel discussion. This program was co-sponsored by the Affirmative Action Task Force.

June 6: The agenda items for this Business Meeting included nominations of candidates for Association Officers for the term beginning July 1; a report from Affirmative Action Officer Carl Banks on an ERDA-sponsored meeting on concerns of women held at Argonne National Laboratory; and several information items.

June 13: Miriam Machlis of the LBL Affirmative Action Office discussed the history of the formation of the LBL Women's Association.

The meetings planned for the latter part of June are the following (Orange Room at noon):

Monday, June 20: Election of Officers.

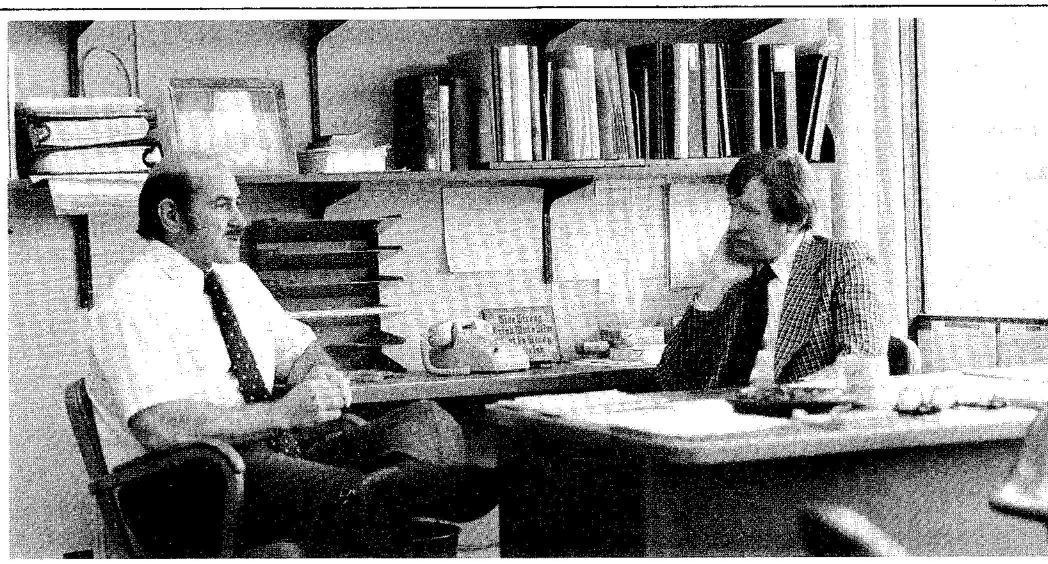
Monday, June 27: Betsy Horn of the San Mateo County Child Care Coordinating Council will present information of existing child care facilities.

We thank SueVon Gee for demonstrating meeting facilitation techniques at our meeting on May 16. The organizational and time-keeping methods she taught us can be usefully applied to many situations in addition to our Association meetings. Thank you, SueVon!

--Martha Zipf

CORRECTION

A correction in last month's article on "Women In Science And Technology": the discoverer of pulsars is Jocelyn Bell *Burnell*, not Bennett.-- Cherrill Spencer.



PEP Deputy Director Tom Elioff (left) of LBL and Director John Rees of SLAC are seen during a quiet moment in this photo by Joe Faust.

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PEP: PART II*

D. PEP AS A RESEARCH INSTRUMENT

In the next three pages we plan to give a brief description of how PEP's characteristics as a research instrument compare with those of conventional accelerators and of other storage rings. In doing so, we will give only a compressed version of the physics background information on which the comparison is actually based. Those who wish to explore the subject in more detail may find some of the earlier *Beam Line* articles listed on page *40* to be useful.

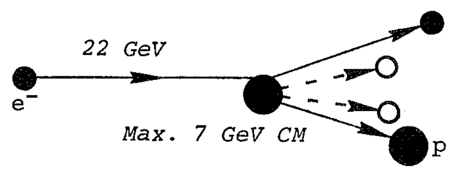
1. ACCELERATORS & STORAGE RINGS

The two most important characteristics of a conventional accelerator are its *beam energy* and its *beam intensity*. For a storage ring, the analagous characteristics are *center-of-mass energy* and *luminosity*. In the following paragraphs we discuss how these accelerator and storage ring properties differ from each other, and why the differences are important.

Beam Energy vs. Center-Of-Mass Energy

When the beam from a conventional accelerator strikes a target particle, the amount of energy that is actually "useful" in making something happen in the collision is always less than the total energy carried by the beam particles. This useful part of the total energy is most often called the *center-of-mass* (CM) *energy*, but several other names such as *effective collision energy* or *available reaction energy* mean exactly the same thing. As an example, a 22 GeV electron from the SLAC accelerator striking a proton target (a bottle of liquid hydrogen) will produce a maximum useful or CM energy of about 7 GeV.

Why is this so? What happens to the other 15 GeV of beam energy? The answer is that all of the remaining 15 GeV is used up in giving a strong forward push to the target particle and to any new particles that happen to be created in the collision--something like this:



Now let's suppose that we want to have more than 7 GeV of CM energy available from the SLAC accelerator (or more CM energy from any conventional accelerator). The most obvious way to get this extra CM energy is simply to increase the total energy carried by the incoming beam. This solution will work, all right, but it has a serious snag that is illustrated in the following table:

Conven. Accel.	Beam*	Beam Energy (GeV)	CM Energy (GeV)	% of Beam Energy Avail. as CM Energy
DESY	e^-	6	3	50%
SLAC	e^-	22	7	30%
BNL AGS	p	32	8	25%
Serpukhov	p	76	11	15%
FNAL/CERN	p	400	28	7%
FNAL plan	p	1000	40	4%

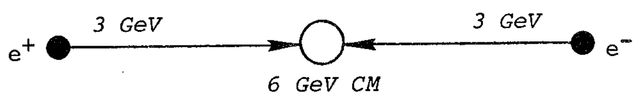
*e^- = electron; p = proton.

What happens, then, is that going to higher and higher beam energies results in a smaller and smaller fraction of that energy being available as useful CM energy. (The CM energy increases only as the square root of the beam energy.) And because of this, there has been a strong incentive to find some other, less expensive way to achieve very high CM energies--which is where colliding-beam storage rings come in.

The problem with conventional accelerators is that the stationary target that is used is too easily pushed around by the high-energy beam. (It's like punching a balloon--the impact is not very forceful no matter how hard the blow.) In a storage ring, the stationary target is replaced by a *second* high-energy beam

*This is the second of a two-part introductory article on PEP. Part I appeared in the April 1977 issue of the *Beam Line*. Some extra copies of the complete article, Parts I and II bound together, will be available soon for those who may wish to have them.

traveling in the opposite direction. Then, with two beams of equal energy colliding head-on, there is no "forward" or "backward" direction in the collision, and the result is that *all* of the energy carried by *both* of the beams in available as useful center-of-mass energy. For example:



The next table shows the CM energies of several different storage rings (existing, in construction, or proposed), and in the last column the beam energies that a conventional accelerator would have to have in order to achieve equal values of CM energy.

Storage Rings	*Beams**	*Single Beam Energy (GeV)*	*CM Energy (GeV)*	*Conv. Accel. Energy Req. To Equal CM Energy†*
ADONE	e^+e^-	1.5	3	6 GeV
SPEAR	e^+e^-	4	8	36 GeV
PEP	e^+e^-	18	36	690 GeV
CERN ISR	p p	30	60	2000 GeV
ISABELLE (proposed)	p p	200	400	85,000 GeV

*e^+ = positron; e^- = electron; p = proton.

† These figures assume that a stationary proton target is used, which is somewhat confusing for the e^+e^- rings. But electrons in a stationary target have so little mass that to achieve large CM energies would require impossible beam energies. To equal PEP's 36 GeV CM energy, for example, using an electron target, a conventional accelerator would have to produce a positron beam of about 1,250,000 GeV (about 50,000 SLAC machines end-to-end).

The good news, then, is that colliding beam storage rings are a first-class solution to the problem of how to get very high center-of-mass energies--and thus very important physics possibilities--without going bankrupt in the process. Next comes the bad news.

Beam Intensity vs. Luminosity

If the high CM energies that storage rings can produce are such a big deal, then why haven't they made conventional accelerators obsolete? This question has several different answers, but here we'll discuss only two of these answers (and the first only briefly):

1. Versatility. Conventional accelerators are much more versatile research devices than storage rings because they can produce a variety of different kinds of particle beams, and also because these beams can be directed to several different experimental areas away from the accelerator itself. This makes possible a broadly diversified program of experiments. In contrast, the experiments at storage rings are necessarily based on electron-positron or proton-proton collisions, and they must be located directly in the few regions around the ring where the stored beams interact with each other.

2. Interaction rate. The beam intensity of a conventional accelerator is simply the number of beam particles it can deliver to a target during a certain period of time, and it is usually expressed, for example, as "10^{12} protons per pulse" or "30 microamps of average current." In the case of storage rings, the analagous factor is called the *luminosity*, which we'll define in the following somewhat simplified way:

> Luminosity is a measure of the rate at which the beam particles in a storage ring collide with each other.

The key point here is that the "target" for each of the two beams in a storage ring is the other beam, and these beams contain so little actual "stuff" that there's almost nothing there to hit. For comparison, let's cut out a little cube of material from a typical accelerator target and also a cube of the same size (one cubic millimeter) from a typical electron beam in an e^+e^- storage ring:

1 mm³ of "target" →

Machine	Accelerator	Storage ring
Target mtl.	Liq. hydrogen	Electrons
No. particles	10^{20} (atoms)	10^8
Rel. density	1,000,000,000,000	1

So a real target is about 10^{12} or one trillion times more packed full of things to hit than a storage ring beam. In fact, storage ring beams have just about the same density of electrons or positrons in them as the density of gas molecules in an ultrahigh vacuum system.

So where does that leave us? Well, the designers of storage rings go to a great deal of trouble to try to pack as many particles as possible into the beams. The limits on this beam-packing are sometimes set by the amount of RF power you can afford to pay for to keep the beams circulating, and more fundamentally by the onset of what are called "instabilities," which cause the beams to drive themselves or each other out of stable orbits and thus be lost. As was discussed back on pages *6* and *9*, the luminosity can also be increased to some extent by squeezing the beams down to narrow ribbons at the interaction points. But this and certain other technical tricks that are possible are beyond the scope of this article, so we'll just settle here for the following summary: The luminosity of the SPEAR and DORIS (DESY) storage rings has been good enough to produce a small revolution in physics during recent years, and PEP's luminosity is expected to be higher than SPEAR's.

2. THE ANNIHILATION PROCESS

For more than 40 years it has been realized that each basic form of matter (particles) has an "antimatter" equivalent (antiparticles). The difference between particle and antiparticle is that they possess properties that are either opposite or complementary to each other. The electron, for example, carries one unit of negative electric charge, while the "anti-electron" carries one unit of positive electric charge (which is why it was given the special name *positron*). Because of this oppositeness or complementarity, a collision between an electron and a positron can result in a particular kind of interaction called *annihilation*, which occurs as a two-step process. In the first step, the two particles disappear and a state of pure electromagnetic energy is formed--a *virtual photon* or *virtual gamma ray* (its symbol is γ_V). Then, after an unimaginably brief period of time (about 10^{-25} second), the virtual photon "materializes" into one or more newly created particles. This two-step process can be expressed in the following symbolic form (in which the newly created particles $\pi^+\pi^-\pi^o$ are pi-mesons or pions):

EM: $$e^+e^- \rightarrow \gamma_V \rightarrow \pi^+\pi^-\pi^o$$

We've drawn a circle around the virtual photon intermediate state and added the letters "*EM*" to emphasize the fact that this is an *electromagnetic* process for creating new particles. Now we want to compare this process with what happens at proton accelerators when the high-energy proton beam strikes a stationary proton target and creates new particles:

Strong: $$pp \rightarrow ? \rightarrow \pi^+\pi^-\pi^o pp$$

In this case the same new particles are created ($\pi^+\pi^-\pi^o$), but the creation process is different from that shown above in the following two ways:

1. The more obvious but less important difference is that the two protons (pp) that created the new particles are still left hanging around afterward, whereas the e^+e^- pair has disappeared (been annihilated). If our purpose is to study the pions that are created, then the remaining "spectator" protons serve only to complicate the analysis of what is happening. This is a moderate disadvantage when compared with the "clean slate" left by the e^+e^- annihilation process.

2. The critically important difference occurs in the middle of these processes where the circles are drawn. In the second process, new particles are created through the *strong* or *nuclear* force, and the circled ? expresses the very limited understanding we have of how such strong interactions actually happen. In contrast, the electromagnetic force which governs the first process is by all odds the most completely understood of the fundamental forces in nature. The theory that describes the workings of electromagnetism in the microscopic world of the elementary particles is called *quantum electrodynamics*, or "QED" for short, and it is not an exaggeration to say that QED has been found to be almost perfectly accurate over an enormous range of physical phenomena. So the message here is this:

> The ideal way to explore the *unknown* structure and properties of particles is with the *known* electromagnetic force.

3. WHERE PEP FITS IN

Although there is more that might be said in comparing PEP with conventional accelerators and other storage rings, the foregoing discussion should make it evident that the research carried out with accelerators and storage rings tends to be complementary, with each focusing on what it does best. To end this section, we list below the world's past, present and future collection of large electron-positron storage rings.

ELECTRON-POSITRON STORAGE RINGS

Machine	*Location*	*First Oper.*	*Max. CM Energy (GeV)*	*Note*
ACO	Orsay, France	1966	1.0	syn*
ADONE	Frascati, Italy	1969	3.1	
CEA	Cambridge, Mass.	1971	5.0	gone
SPEAR	Stanford	1972	8	
DORIS	Hamburg, Germany	1974	9	
VEPP-2M	Novosibirsk, USSR	1975	1.3	
DCI	Orsay, France	1976	3.4	
VEPP-4	Novosibirsk, USSR	1978	15	const
PETRA	Hamburg, Germany	1979	38	const
PEP	Stanford	1980	36	const
CORNELL	Ithaca, New York	1980	16	const
CERN LEP	Geneva, Switz.	?	200	study

*Now used as a synchrotron radiation source.

E. EXPERIMENTS AT PEP

As is the case with the present SLAC linear accelerator and research facilities, PEP will be a national facility, available to any qualified scientist or group of scientists on the basis of the scientific merit of the proposed experiment. For some years now, there had been a gradual reduction in the number of accelerator laboratories at which "forefront" high-energy physics research could be done. Most of the important new results in this field have recently come from about five such labs in the US, and perhaps another half-dozen or so in the rest of the world. And the prospect is that even this small number will eventually be reduced even further. This places a strong responsibility upon the remaining labs --the "survivors"--to work not only for the most productive local research program but also for the most productive national and even international program. It's nice to be among the chosen few. Our task at SLAC is to see to it that the choice was a good one.

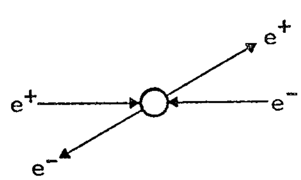
In this section we'll begin by describing in some detail the basic physics of electron-positron collisions at the energies expected for PEP. With this background, we'll then move on to a description of the plans that are now being made for the first round of PEP experiments, including the large new detection devices that are being built for this work.

1. THE BASIC PHYSICS

Lepton Production: Two In/Two Out

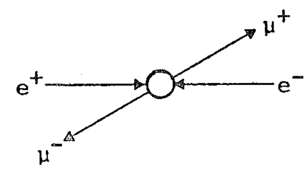
The simplest physical processes that occur in electron-positron annihilation are those in which lepton pairs are created. In the first example, an electron (e^-) and a positron (e^+) collide, and after the collision an electron and a positron emerge. This kind of reaction is called "Bhabba scattering"--named after the Indian physicist who calculated the rate at which it should (and does) happen. Because this reaction is well-understood, it does not have a great deal of physics interest in itself, but for that very reason it is used for calibrating the detection efficiencies of experimental equipment and also for determining the luminosity of the storage ring. The characteristic pattern, or "signature," for Bhabba scattering is e^+ and e^- emerging from the interaction region back-to-back, each particle having the same energy as that of the incoming beam particles.

$\boxed{e^+e^- \rightarrow e^+e^-}$



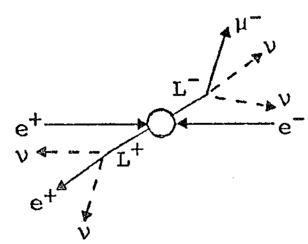
The second example of lepton-pair production is one in which e^+e^- annihilation leads to the creation of two mu-mesons or muons ($\mu^+\mu^-$). In all of their properties except mass, muons appear to be identical to electrons, and it has long been an intriguing question why nature has provided the electron with a big brother some 200 times as massive as itself. The signature for muon-pair production is the same as that for Bhabba scattering, except that we have to distinguish between outgoing electrons and muons. That is, we need to have *particle identification* as well as measurement of the paths following by the outgoing particles.

$\boxed{e^+e^- \rightarrow \mu^+\mu^-}$



The mystery of the muon's role in nature may be connected with the third possible example of lepton production. During the last several years, the SLAC-LBL experimental group working at SPEAR has observed a number of so-called "e-μ" events that are difficult to explain in any conventional way. Over time the evidence had gradually grown stronger that these events result from the production and subsequent decay of a pair of "heavy leptons" not previously known. The symbol τ (tau) has recently come into use as a designation for the SPEAR heavy lepton, but we use "L^+L^-" here in order to include any new lepton more massive than the muon that may exist.

$\boxed{e^+e^- \rightarrow L^+L^-}$



The experimental signature of heavy lepton production is a complex problem. Such particles will not be directly detectable because they will have lifetimes that are too short--on the order of 10^{-14} second. So their existence will have to be inferred by analyzing the patterns of the particles into which they decay. In the case of the SPEAR events, the observed $e^\pm$ and $\mu^\mp$ are assumed to appear from the decays

$$\tau^\pm \rightarrow e^\pm \nu\nu \quad \text{and} \quad \tau^\mp \rightarrow \mu^\mp \nu\nu,$$

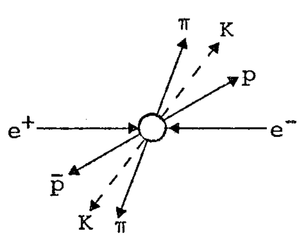
so we've shown these same decay modes for the general heavy-lepton pair $L^\pm$ in the sketch above. A good deal of the difficulty in trying to identify any new heavy leptons unambiguously results from the neutrinos (ν) that appear in the decay products. (There are actually two kinds of neutrinos and two kinds of antineutrinos: ν_e and $\bar{\nu}_e$ go with e^+ and e^-, and ν_μ and $\bar{\nu}_\mu$ go with μ^+ and μ^-. But mostly we just use ν for any or all of them.) These particles have no electric charge, no mass, and nearly no nothing, and for this reason are almost impossible to detect.

Hadron Production: Two In/Many Out

"Hadron" is the name given to any of the large family of particles that are affected by the strong or nuclear force (leptons are those which are not so affected). The best-known members of this family are the proton and neutron that together make up the nuclei of atoms, and the pions (π) and K-mesons (K) that play a role in binding the protons (p) and neutrons (n) together. The hadron family consists of well over a hundred particles or "states," and the search for a simple pattern that may underlie this apparent complexity continues to be one of the central themes in particle-physics research.

In comparison with the two-in/two-out lepton production processes, the creation of hadrons in e^+e^- collisions most often occurs in *multiparticle* or *multibody* reactions. At PEP, it will not be uncommon for a single collision to yield 10 to 20 newly created particles, most of them unstable, and about half of them having no electric charge that can be used as a handle for tracking or particle identification. (The sketch at the right shows a simpler example of the many different possible combinations that can be produced. The dashed line is meant to indicate electrically neutral particles.) Thus hadron-production is too multiple and too various a collection of different processes to have any single experimental signature, and as we'll see later, much of the effort and ingenuity that is going into the new detectors for PEP is directed toward combining several different detection techniques into overall systems of broad versatility.

$$\boxed{e^+e^- \rightarrow 2\pi 2Kp\bar{p}}$$

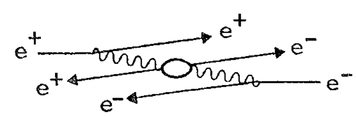


A point of interest in this connection is the fact that multiparticle hadron production at PEP is expected to have a very strong tendency to occur in the form of two oppositely directed clusters of particles called "jets"--as is suggested by the back-to-back pattern of the two groups of particles in the sketch above. The specific directions in which the jet sprays of particles are emitted will vary randomly from event to event, with no one direction preferred over any other. This means that the big PEP detectors must be designed to cover as much of the "solid angle" (the spherical volume surrounding the interaction point) as possible. However, since the bulk of the emitted particles in any particular event will be concentrated in the narrow cone-shaped jets, the detectors must also be designed with enough segmentation or separate little pieces to respond to the individual closely spaced particles within each jet. Thus the problem is not only to cover the whole volume but also to cover each little piece of the volume in detail.

Two-Photon Annihilation: Something New

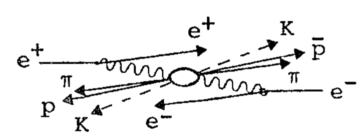
In all of our earlier discussions, both in this and previous articles, we've said that the electron-positron annihilation process proceeds in two steps, with the first step being the creation of a short-lived intermediate state called a "virtual photon" or "virtual gamma ray," which in the second step then materializes into newly created particles. We'd better now give this process a name, *one-photon annihilation* (1γ), because at the higher PEP energies we have to start worrying about an alternate process called *two-photon annihilation* (2γ). Although this 2γ process does occur at SPEAR, it is relatively much less important there than it will be at PEP. The difference between 1γ and 2γ annihilation can be illustrated by comparing the processes in which an e^+e^- pair is created in the two cases. In the 2γ case, the incoming e^+ and e^- are not themselves annihilated. Instead, each emits a photon or gamma ray (∿∿∿), and it is these photons that annihilate, with subsequent production of a new e^+e^- pair. Thus the final state consists of four particles ($e^+e^-e^+e^-$): the incoming e^+e^- which are scattered but not annihilated, and the newly created e^+e^- which emerge from the annihilation of two photons.

$$\boxed{e^+e^- \rightarrow e^+e^-e^+e^-}$$



Two-photon annihilation can also result in the production of hadrons in a way that may, within certain limits, mimic their production by the 1γ process previously described. At the right we show a 2γ event that is similar to that on the left. An event of this kind is possible but very unlikely, because only rarely will the two photons radiated by the beam e^+ and e^- have enough energy to create as many, and as massive, new particles.

$$\boxed{e^+e^- \rightarrow e^+e^- 2\pi 2Kp\bar{p}}$$



It will be important at PEP to understand the 2γ process for two reasons: (1) The physics is quite different from that of 1γ annihilation, is largely unexplored, and for these reasons may be intrinsically important of itself. (2) As a practical matter, 2γ events at PEP will constitute a large "background" that is mixed in with the usual 1γ physics, and which therefore must be separated out in a known way before the 1γ physics itself can be confidently interpreted.

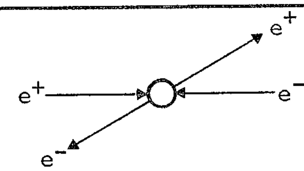
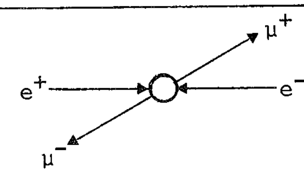
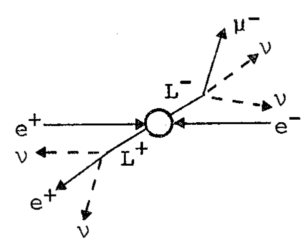
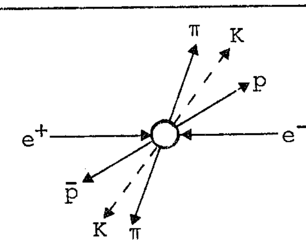
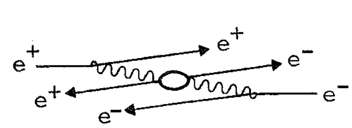
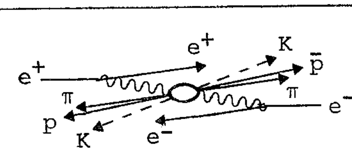
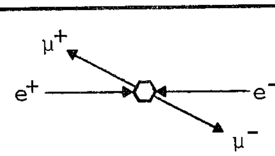
In this connection, the 2γ events will have a characteristic experimental signature that can be used to good advantage: the final particles will be directed preponderantly within narrow cones along the line of the beams. Thus these limited regions can be specially instrumented to assure adequate detection.

Weak-Interaction Effects

The process $e^+e^- \rightarrow \mu^+\mu^-$ (and others) can occur not only through the electromagnetic force, as we've already seen, but also through the *weak* force. At present storage ring energies, such weak-force events are swamped by the much stronger electromagnetic interactions, but at PEP energies the relative strengths will be much closer together. Because of this, it will be very important to try to observe the effects

(The chart below summarizes the basic physics processes we've been describing here.)

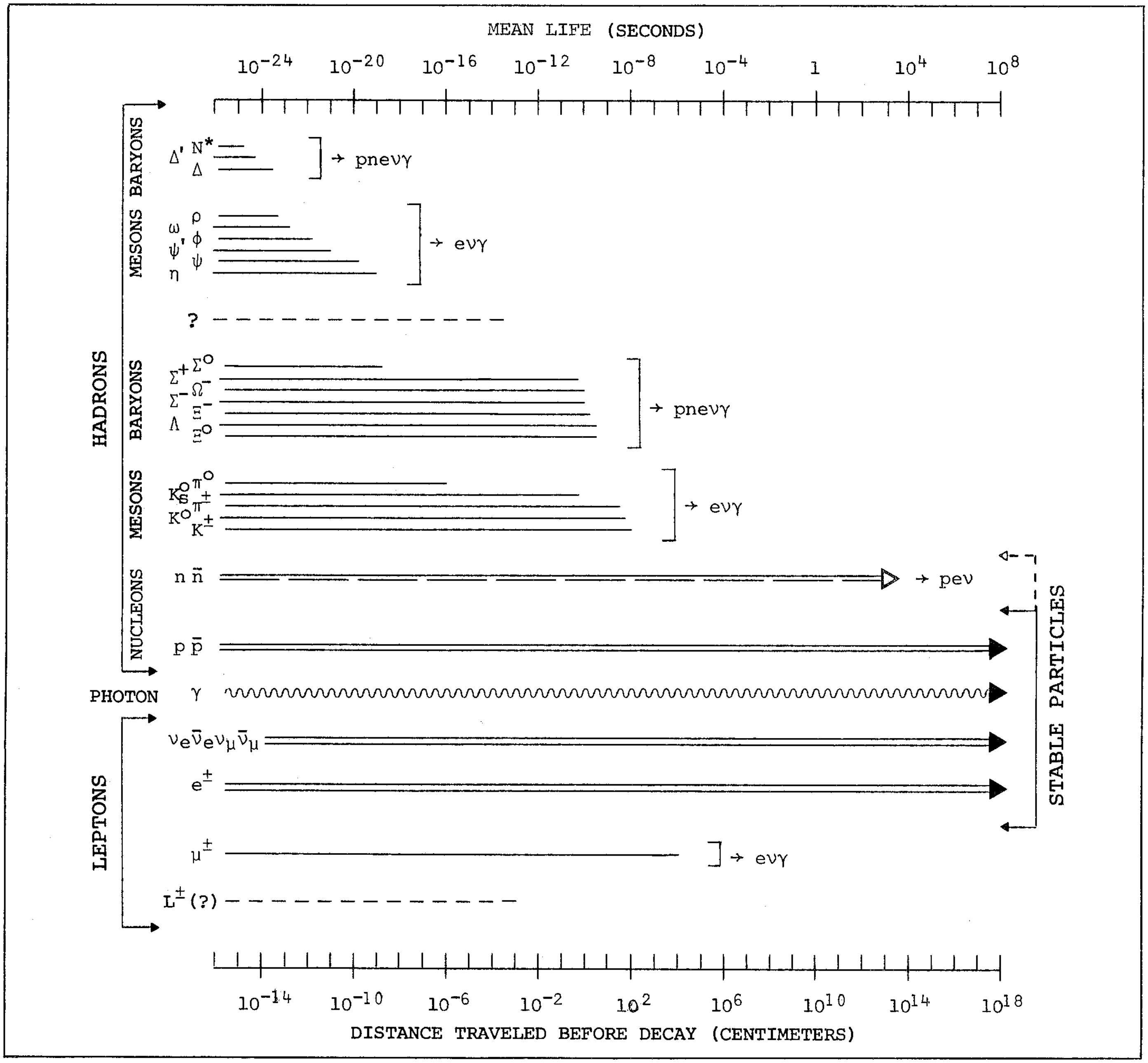
THE BASIC PHYSICS AT PEP

PROCESS			REACTION	DIAGRAM	EXPER. "SIGNATURE" (PATTERN) NOTES & COMMENTS
ONE-PHOTON ANNIHILATION	LEPTON PRODUCTION	ELECTRONS	$e^+e^- \rightarrow e^+e^-$		e^+e^- emerge back-to-back, each with 1/2 total CM energy. Identified through "showers" of gamma rays and e^+e^- pairs created. Used to calibrate ring luminosity and detector efficiencies.
ONE-PHOTON ANNIHILATION	LEPTON PRODUCTION	MUONS	$e^+e^- \rightarrow \mu^+\mu^-$		Same signature as above, except muons identified by measuring deep penetration through matter. Search for weak-force effects at PEP (see below). Used as a comparison standard in hadron prod.
ONE-PHOTON ANNIHILATION	LEPTON PRODUCTION	HEAVY LEPTONS	$e^+e^- \rightarrow L^+L^-$ $L^+ \rightarrow e^+\nu\nu$ $L^- \rightarrow \mu^-\nu\nu$		Lifetime too short for direct identification; inferred from e-μ events at SPEAR, which are thought to result from the leptonic decay modes shown at left. Is there a sequence of leptons: e, μ, L . . . ? Fundamental issue. SPEAR search for L . . . will continue at PEP.
ONE-PHOTON ANNIHILATION	HADRON PRODUCTION		$e^+e^- \rightarrow 2\pi 2Kp\bar{p}$ (+ many others)		At PEP, often 10-20 particles per event. All particle types possible. Strong tendency for particles to cluster around two back-to-back "jet" axes. Need maximum detection power to track and identify multiparticles. Backbone of SPEAR program and probably also PEP program.
TWO-PHOTON ANNIHILATION	LEPTON PRODUCTION		$e^+e^- \rightarrow e^+e^-e^+e^-$		Most particles emerge at small angles centered around the beam axis. (In contrast, one-photon events have no preferred angular distribution). Important to measure two-photon events because: (1) the physics is quite different and may produce some surprises; (2) must be able to subtract the 2γ "background" in order to understand the 1γ physics.
TWO-PHOTON ANNIHILATION	HADRON PRODUCTION		$e^+e^- \rightarrow e^+e^-2\pi 2Kp\bar{p}$ (+ many others)		
WEAK FORCE	LEPTON PRODUCTION		$e^+e^- \rightarrow \mu^+\mu^-$		Interference between weak & electromagnetic production of $\mu^+\mu^-$ may be seen at PEP as asymmetry in angular distribution. Search for weak-force effects is vital ("carried" by W particles).

of the weak interaction at PEP, and muon-pair production is an experiment that would be well-suited to this purpose. The reason is that weak-force production of muon pairs is expected to interfere with electromagnetic production in a way that will distort the symmetric angular distribution of the latter process. Such an asymmetry would show up, for example, as an excess of positive over negative muons observed at certain production angles. This interference asymmetry is expected to grow with increasing energies, but may still be only marginally detectable even at 18 GeV. This is one of the main reasons for planning an eventual expansion of PEP's beam energy to 23-24 GeV. We'll describe this possible energy-increase program in the last section of this article.

The Particles To Be Detected

We conclude this section by listing, in the following chart, the more common of the hadrons, the photon, and all of the leptons, together with their lifetimes and decay distances (at speeds near that of light). We judge the 938-second life of the neutron to qualify it as "stable." Although the various complex decay modes for the unstable particles are not shown, the end result is that all of them decay into stable particles within about one-millionth of a second. The big detectors are designed to cope directly with these stable particles, and directly or indirectly with the most frequently produced unstable particles: muons, pions and K mesons.



2. DECISIONS, DECISIONS

All going well, the PEP storage ring will begin to operate early in 1980, or perhaps late 1979. To do physics at a machine like PEP will require several large new pieces of experimental equipment similar in scope to such present detectors as the LASS spectrometer, the Mark I magnetic detector at SPEAR, and the Streamer Chamber. The costs of these new detectors for PEP will easily run into the millions, and the time required to design, build and test them will be on the order of 2 to 3 years. A little arithmetic leads to the conclusion that work on these major new detectors should already have started if they are to be ready when PEP is. And in fact the work has already started.

Back in mid-1976, the Directors of SLAC and the Lawrence Berkeley Laboratory (LBL) sent out an invitation to the 1000 or so high-energy experimentalists in the US to prepare and submit proposals for new experimental facilities to be used in the first round of PEP experiments. By the specified submission deadline of December 30, 1976, a total of 9 such proposals had been submitted, representing the work of about 180 physicists from 25 different institutions. These proposals are listed in summary form on the next page.

How to decide? Concurrent with this proposal period, a special advisory group called the PEP Experimental Program Committee (EPC) had been established. The EPC consists of 15 senior physicists from many different institutions, and its first task was to assess the relative scientific merit of the 9 proposals and then to advise the SLAC and LBL Directors on which of the proposals should be chosen. As a part of this evaluation process, a couple of open general meetings were convened at SLAC during the first three months of 1977 to present, discuss and criticize each proposal; to coordinate the planning of cryogenic facilities; and so on. In addition, various sub-committees of the EPC sought out more detailed information from the individual proposing groups, sent out questionnaires to be answered, and invited the groups to submit any additional material they wished as supplements to the original proposals.

D-day arrived when the EPC met at SLAC on April 14 and 15. Tentative recommendations were reached, slept on, rehashed, and finally made firm. The recommendations of the EPC were accepted by the two Directors, and in short order a series of phone calls and formal letters were sent out to each of the Spokesmen for the 9 proposals--winners and losers alike.

The Winners

The proposals that were approved for this first round of PEP experiments were the following:

PEP-5
PEP-6
PEP-4 + PEP-9

(PEP-2 is a much more modest proposal than the others, and it will not be acted upon until a later time.) Although four proposals were approved, PEP-4 and PEP-9 will be combined into a single large detection system (as PEP-9's proponents had proposed) for use in one of the interaction regions. Thus 3 of the 6 PEP interaction regions were committed by these decisions, as had been intended. This leaves 2 interaction regions still available for experiments that are yet to be chosen, while the 6th is being reserved for studies of the PEP storage ring itself.

A call for the second round of PEP proposals has recently gone out to the experimental community, with the deadline for submission set for October 30, 1977, and with decisions on this second round to be reached no later than February 1, 1978.

3. THE FIRST-ROUND DETECTORS

An ideal experimental detection system for PEP would be able to measure with high precision both the energies of and the paths followed by all of the particles that emerge from the beam-interaction regions. This would include both charged and neutral particles, and it would also be able to identify unambiguously each particle by type. In addition, the ideal system should be able to collect data at a very rapid rate, carry out some rough analysis of the data with a local computer as it comes in, and and perhaps also pass on the data for permanent recording to the SLAC central computer facility. The system to accomplish all this should be designed, built, tested, debugged and christened in time to receive the first PEP beams some 30 months from now, and the whole project from soup to nuts should preferably cost something less than Disneyland.

Although there ain't no such thing, there have been some ingenious compromises worked out by the proponents of PEP-4,5,6 and 9, and the instruments they have imagined seem likely to milk a great deal of interesting physics out of PEP. Here they are.

PEP-6: MAC

"MAC" or "Big MAC" is the unregistered trademark of the physics group from five different universities that plans to build a magnetic calorimeter for use in muon physics, new particle searches, and total cross section measurements. We consider first their general approach to the problem of identifying muons. Muons are distinguishable from other particles by their ability to penetrate deeply into matter with

PEP EXPERIMENTAL PROPOSALS - FIRST ROUND

PEP-1:	A GENERAL MUON DETECTOR FOR PEP	U. Washington	Cook, Mockett, Rothberg
		U. Wisconsin	Williams, Young, Benvenuti, Camerini, Cline, Learned, March, Morse, Reeder, Resvanis, Rhoades
PEP-2:	SEARCH FOR HIGHLY IONIZING PARTICLES	SLAC	Fryberger
		UC-Berkeley	Price
PEP-3:	PEP SPECTROMETER FACILITY	Argonne Nat. Lab.	Cho, Derrick, Jaeger, Singer, Schreiner, Ward
		Indiana U.	Brabson, Gray, Neal, Ogren, Rust
		U. Michigan	Akerlof, Meyer, Thun
		Northwestern U.	Buchholz, Gobbi, Miller
		Purdue U.	McIlwain, Loeffler, Miller, Shibata
PEP-4:	TIME PROJECTION CHAMBER FACILITY	LBL	Clark, Dahl, Eberhard, Fancher, Galtieri, Garnjost, Kenney, Loken, Kerth, Madaras, Nygren, Oddone, Pripstein, Robrish, Ronan, Shapiro, Strovink, Wenzel, Urban
		UC-Los Angeles	Buchanan, Hauptman, Slater, Stork, Ticho
		Yale U.	Marx, Nemethy, Zeller
		UC-Riverside	Gorn, Kernan, Layter, Shen
		Johns-Hopkins	Barnett, Chien, Madansky, Matthews, Pevsner
PEP-5:	GENERAL SURVEY OF PARTICLE PRODUCTION	SLAC	Alam, Boyarski, Breidenbach, Dorfan, Feldman, Fischer, Hanson, Hitlin, Jaros, Larsen, Luke, Martin, Paterson, Perl, Richter, Schwitters, Tanenbaum, Taureg, Weiss
		LBL	Abrams, Broll, Carithers, Chinowsky, DeVoe, Goldhaber, Johnson, Kadyk, Pang, Shannon, Trilling
PEP-6:	LEPTON/TOTAL-ENERGY DETECTOR	U. Colorado	Bartlett, Ford, Nauenberg, Smith
		Northeastern U.	Faissler, Gauthier, Gettner, Gottschalk, Mallary, Moromisato, Pothier, Potter, von Goeler, Weinstein
		Stanford/SLAC	Ash, Gustavson, Rich, Ritson
		U. Wisconsin	Aronson, Johnson, Morse, Prepost, Wiser
		U. Utah	Groom, Loh
PEP-7:	A PEP STREAMER CHAMBER FACILITY	UC-Santa Cruz	Dorfan, Flatte, Heusch, Schalk, Seiden, Smith
		LBL	Ely, Gidal
		U. Michigan	Chapman, Seidl
		SLAC	Bunnell, Mozley, Odian, Wang
PEP-8:	A MAGNETIC DETECTOR FOR PEP	Brown U.	Cutts, Lanou, Massimo, Dulude
		CalTech	Barish, Bartlett, Gomez, Pine, Linsay
		MIT	Brandenburg, Busza, Friedman, Halliwell, Kendall, Nelson, Osborne, Rosenson
		SLAC	Atwood, Carroll, Chadwick, Cottrell, DeStaebler, Moffeit, Prescott, Rochester, Sherden, Sinclair, Taylor, Kirkby, Wojcicki
PEP-9:	PEP FORWARD DETECTOR FACILITY	UC-Davis	Klems, Ko, Lander, Pellett, Lander
		UC-San Diego	Lyon, Masek, Miller, Vernon, Wallace
		UC-Santa Barbara	Caldwell, Eisner, Morrison, Yellin

Underline indicates spokesmen.

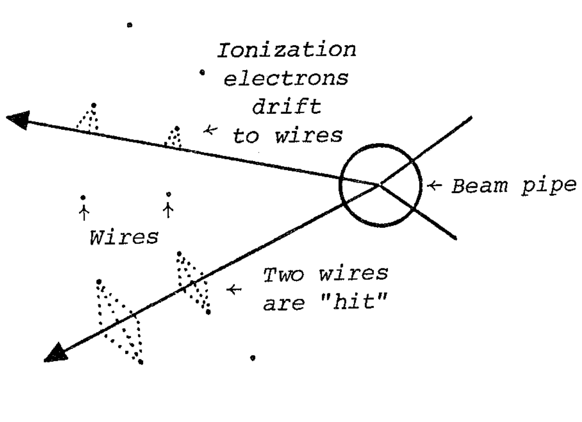
comparatively little loss of energy. So the obvious solution is simply to surround the interaction region with a shell of material that is thick enough to stop everything but the muons, and then to count the muons that actually come through with a suitable array of detectors.

But there are some problems. One is the fact that the region immediately surrounding the interaction point has to be used for finding the tracks of the particles, rather than for absorbing them, and so the shell of material needs a fairly large hollow core. And at PEP energies the shell thickness needed to discourage everything but muons is about 3 feet if the shell is made out of the customary iron. After making some other allowances for various odds and ends, the end result of a simple idea turns out to be the ≈ 500-ton iron barrel that is shown in the MAC layout sketches on the next page.

Referring to this figure, let's now look briefly at the functions that are served by each of the main sub-systems in MAC, starting at the beam and working our way radially outward.

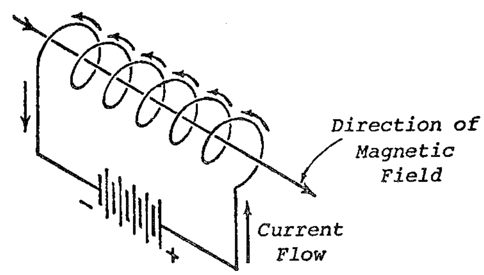
Core Drift Chamber: Tracking & Momentum Analysis

Surrounding the beam pipe is a cylindrical chamber about 2.3 meters (m) long and 1 m in diameter. Inside this chamber are four concentric layers of fine wires that are stretched along the length of the cylinder to form a drift chamber. The purpose of this drift chamber is to measure the paths or tracks followed by the charged (and thus ionizing) particles that emerge from the beam pipe. Schematically, what happens is the following:



In an actual wire drift chamber of this kind, the wires are spaced much closer together (typically 1 cm) than the sketch implies. In addition, the electronics measures the time required for the electrons produced by ionization to drift to each of the wires that is "hit," so the actual particle trajectories can be determined more accurately than the spacing between adjacent wires.

The drift chamber has wrapped around it a coil of heavy alumininum conductor that is used to produce a magnetic field up to about 5 kilogauss throughout the volume of the chamber. A magnetic configuration of this kind is called a "solenoid," and it produces a magnetic field whose direction is parallel to the axis of the coil and thus of the beam path:

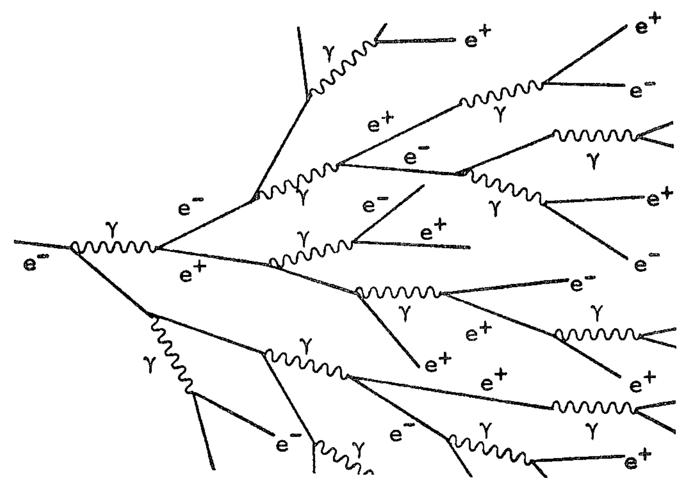


This solenoidal magnetic field causes the charged particles passing through the chamber to be deflected and thus to follow curved rather than straight trajectories. It is difficult to draw a two-dimensional picture of the tracks because they have a complicated helical form, but what happens can be summarized in the following way: (1) Positive and negative particles are deflected in opposite directions. (2) Particles with high momentum are deflected less than those of low momentum. (3) Particles emerging at 90^0 with respect to the beam direction are deflected more than those emerging at smaller angles.

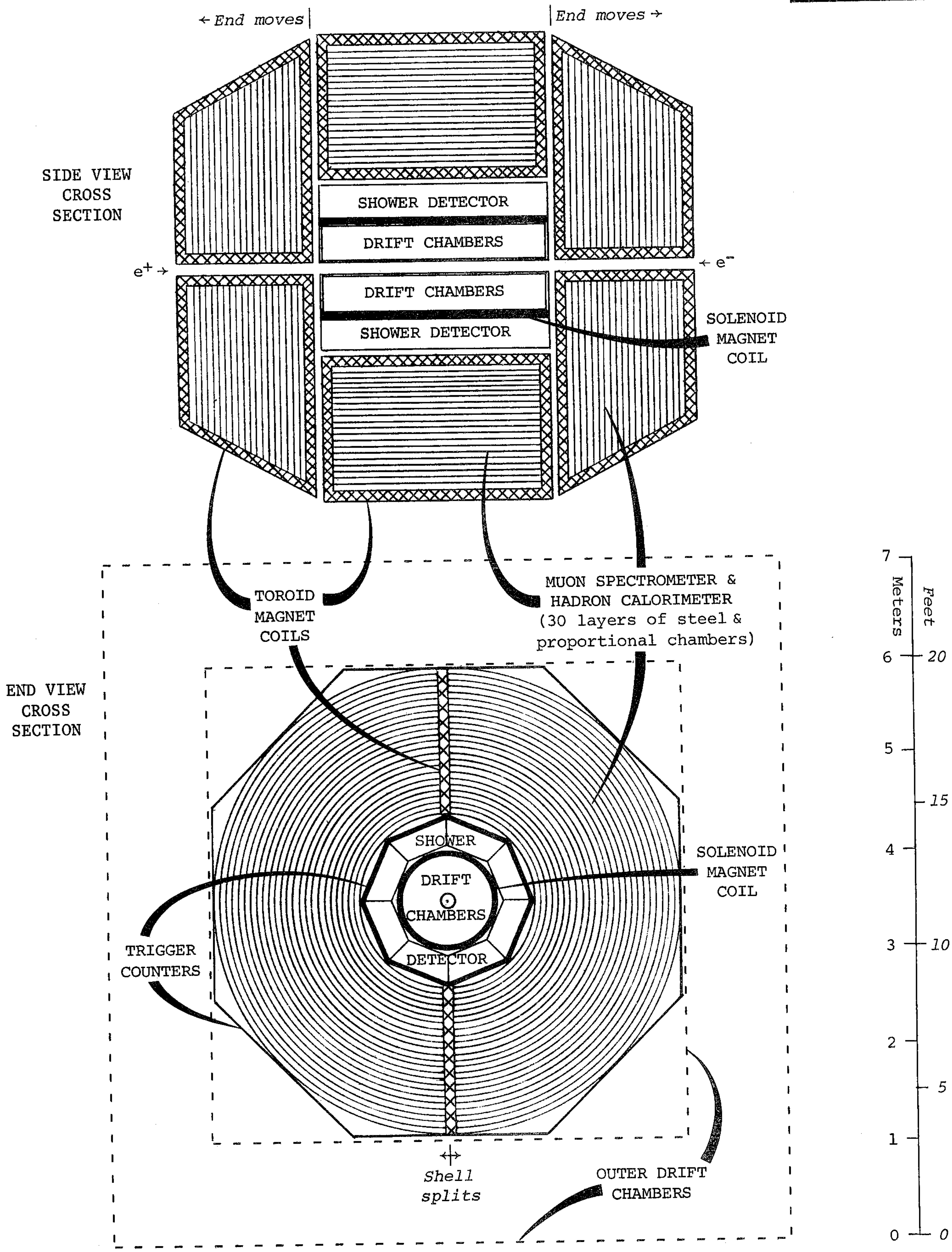
The curvature of the particle trajectories, as determined by the succession of hits on the drift chamber wires, thus provides information that can be used to deduce the momentum of each of the observed particles.

Shower Detector

Moving outward from the drift chamber and solenoid magnet coils, we come next to the system that is designed to identify electrons (e^-), positrons (e^+) and gamma rays, and also to measure their energies. The experimental signature for these particles is an *electromagnetic shower*, and what is meant by "shower" is the following:

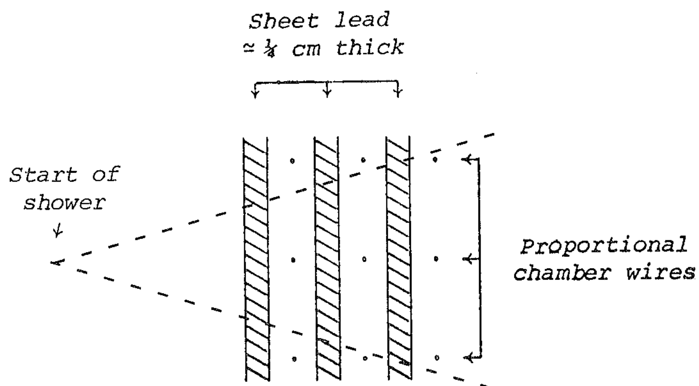


PEP-6: MAC


← End moves
End moves →
SIDE VIEW
CROSS
SECTION
SHOWER DETECTOR
DRIFT CHAMBERS
DRIFT CHAMBERS
SHOWER DETECTOR
e+ →
← e−
SOLENOID
MAGNET
COIL
TOROID
MAGNET
COILS
MUON SPECTROMETER &
HADRON CALORIMETER
(30 layers of steel &
proportional chambers)
END VIEW
CROSS
SECTION
SHOWER
DRIFT
CHAMBERS
DETECTOR
SOLENOID
MAGNET
COIL
TRIGGER
COUNTERS
Shell
splits
OUTER DRIFT
CHAMBERS
Meters
Feet
7
6
5
4
3
2
1
0
20
15
10
5
0

This multiplying cascade can be initiated by e^-, e^+ or γ. The higher the energy of the initiating particle, the larger the shower will be in both the number of particles created and the depth to which they penetrate.

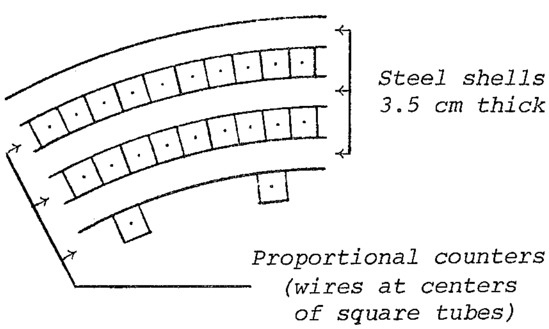
In MAC these electromagnetic showers will be detected in an eight-sided structure that consists of 30 alternating layers of dense material (lead) and electronic counters (proportional wire chambers). A small section of this 30-layer sandwich will look something like this.



Proportional wire chambers work in about the same way as drift chambers do--that is, by collecting the ionization electrons that are knocked loose by the charged particles in the shower. What is "proportional" about these chambers is the fact that the magnitude of the output signal from each wire depends upon how many electrons it collected. (Some wire chambers simply scream "I've been hit!" rather than calmly stating "I have received a hit of the following size.") Thus by adding up the signals from each of the wires that responded to a shower, a reasonably accurate indication of the energy of the initiating particle can be obtained.

Muon Spectrometer & Hadron Calorimeter

The bulk of Big MAC consists of a massive laminated iron-and-detector barrel that surrounds the central core region of the device. As before, there will be 30 interleaved layers of dense material and electronic counters, with the structure shown in the following partial cross section:



The total thickness of the 30 layers will be about 150 cm, with the iron (steel) shells making up about 2/3 of this thickness. Detection of charged particles is again done with proportional counters, but this time each wire is enclosed within its own section of square tubing.

Muons. The first of the two functions served by the big barrel is to identify muons and to measure their momentum. Muons will be distinguished from other charged particles by the fact that they lose energy less rapidly than the others--and thus produce smaller signals in the proportional tubes--as they pass through the successive layers of the barrel. The magnetic field needed to provide momentum information (by deflecting the particles) is provided by the set of "toroid magnet coils" shown on page *31*. The direction of the magnetic field produced by these coils is again parallel to the beam axis, but its overall form is something like that of a doughnut (toroid). At any rate, by following the curved trajectories of the muons through the barrel, their momenta can be determined to an accuracy of about 20%.

Hadrons. The second of the barrel's two functions is to measure the total energy that is carried by hadrons in each event. In contrast to muons, many of which will penetrate completely through the barrel's 30 layers, all of the hadrons will be stopped sooner or later within the iron (including the neutral ones). What happens is that the hadrons undergo a series of collisions with both the nuclei and the electrons of the iron atoms, and these collisions eventually result in the initial energy being spread over a large number of low-energy charged particles or ions. Although different in character from an electromagnetic shower, this hadron-induced spray of secondary particles can be measured in a similar way by the proportional counters interleaved between the steel sheels.

(Total absorption of the hadron energy within the laminated barrel structure has led to the name *Hadron Calorimeter*, which literally means "calorie measurer." The analogy is with an old tried-and-true technique for measuring difficult forms of energy--light, mechanical, chemical--by absorbing it totally in some heavy body and measuring the resulting rise in temperature. This is not exactly what MAC will do, but the idea seems close enough to permit the use of a good name.)

The calorimeter should respond to almost all of the events in which hadrons are created, but not to the usual background events because they will not in general produce a large enough signal. This characteristic will provide a useful technique for measuring the total cross-section (probability) for electron-positron annihilation, and it will do so in a way that is different from (and thus complementary to) that of any of the other detectors at PEP or at PETRA.

PEP-5: MARK II

The Mark II magnetic detector, shown below, is the same device that is now being readied for installation at SPEAR during the next few months. In the discussions leading to the selections of the first-round detectors for PEP, it was perhaps natural that Mark II got special consideration. Apart from its inherent abilities, which are substantial, the Mark II will have two unique advantages going for it: (1) it is certain to be ready on time, and (2) it will have accumulated about 18 months of operating experience by the time it moves to PEP. (During the meetings it was a little odd to hear this experience factor alluded to by describing the still-unfinished Mark II as "the old warhorse.")

The Mark II detector was described at some length in an article in the June 1976 issue of the *Beam Line*, so in the following we'll give only a brief description by using some of the information from this earlier article.

Tracking and *momentum measurement* of charged particles in Mark II is handled by a cylindrical drift chamber immersed in a solenoidal magnetic field in a system much like that of Big MAC.

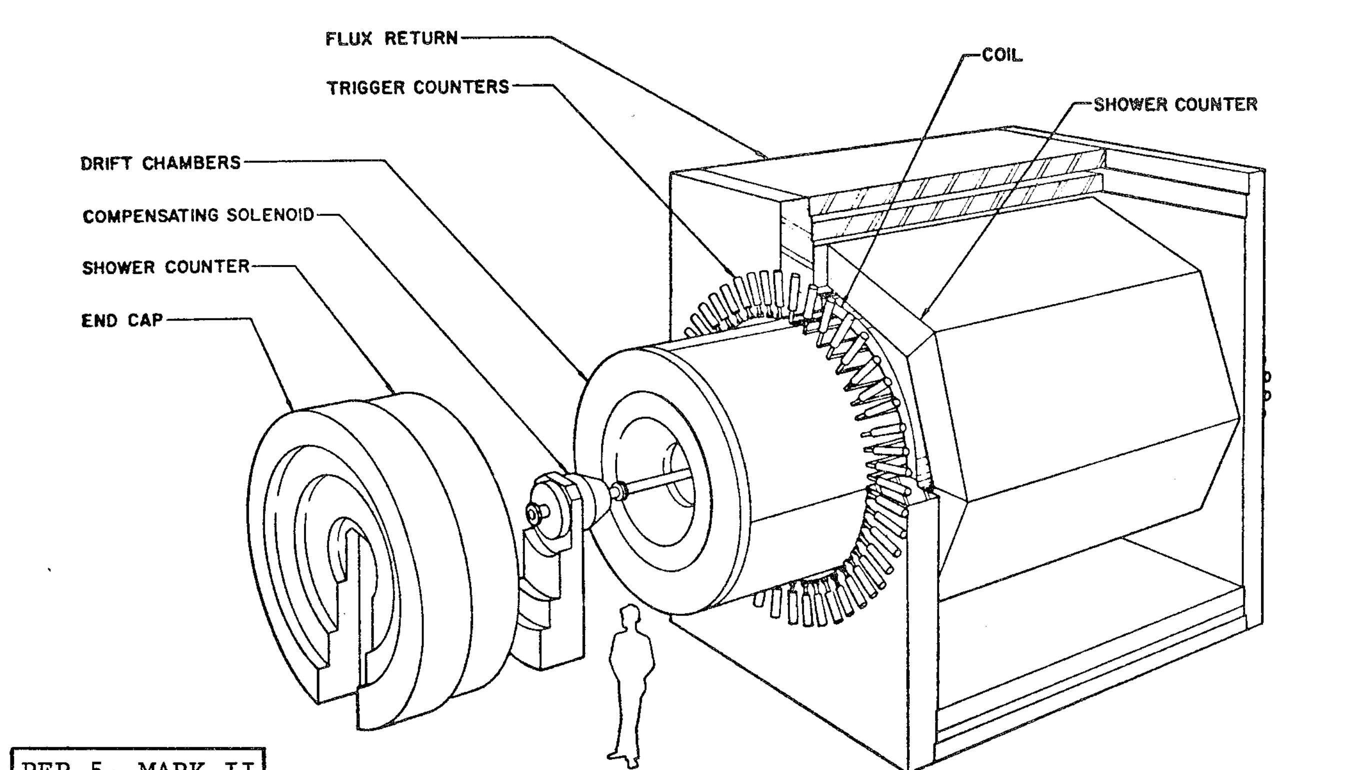
Shower Counter

The method for identifying electrons, positrons and gamma rays in Mark II is distinctive enough to merit separate attention. As with MAC, Mark II's shower counter will be contained within an eight-sided structure (plus two end-cap sections), but the shower will develop in a series of lead sheets alternating with lead collection strips (rather than sensing wires), and the ionizing medium will consist of a liquid-argon bath rather than the more common mixture of gasses. The ionization electrons produced in the argon will generate proportional signals in the strip sensing elements, and these signals can be analyzed to give an accurate measurement of both the direction and the energy of the initiating particle.

The energy resolution that can be obtained with this lead/liquid argon shower detection system is not as good as that of such special materials as sodium iodide crystals or lead-loaded glass, but the cost of these materials becomes prohibitively high when the whole region around the interaction point has to be covered. An important virtue of the lead/liquid argon technique is that it provides a very accurate picture of the spatial development of the shower as it spreads through the layered structure of the counters.

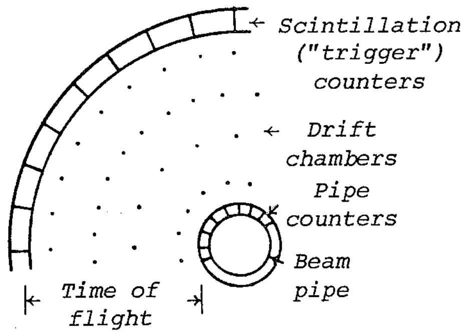
Hadron Identification

The lead/liquid argon counters just described will be useful within certain limits in distinguishing between electromagnetic showers and the "hadronic showers" we talked about in con-



PEP-5: MARK II

nection with MAC's hadron calorimeter. But the chief method for identifying charged hadrons in Mark II will be the technique known as "time-of flight." The general idea is the following:



We've already seen how track curvature can be used to determine a particle's momentum. The time-of-flight system provides an accurate measurement of the time required for a particle to travel from the inner pipe counter to any of the 48 "trigger" counters that form a cylindrical array around the drift chambers. Knowing time and distance, this measurement thus determines the particle's velocity, and the combination of velocity and momentum uniquely determines the mass of the particle and thus its identity:

$$\text{mass} = \text{momentum} \div \text{velocity}$$

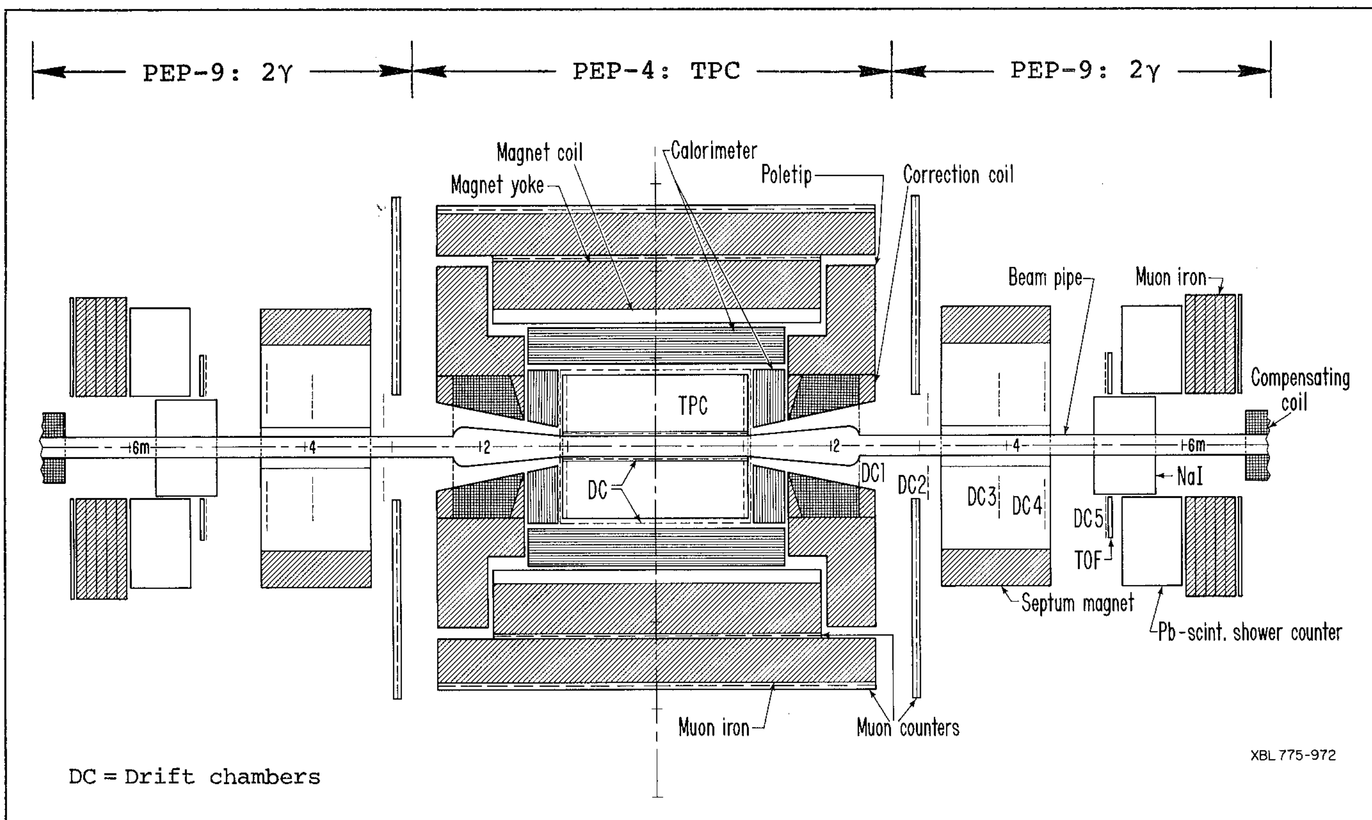
The trigger counters are actually long slabs of a special plastic material that emits flashes of light or *scintillates* when struck by a charged particle. Such scintillators are well suited to the fast timing needed in this system.

PEP-4: TPC + PEP-9: 2γ

We come last to the combined PEP-4/PEP-9 experimental facility for PEP. The designation "2γ" for PEP-9 expresses the fact that this facility is intended to handle the *two-photon annihilation* physics that we talked about back on page *25*. The PEP-9 proponents specifically intended that their facility should form the 2γ "bookends" on either side of a large central detector designed mainly for 1γ physics, and PEP-4 was chosen as that central detector. A general layout of the combined facility is shown below. We'll discuss PEP-4 first, then take up PEP-9.

TPC

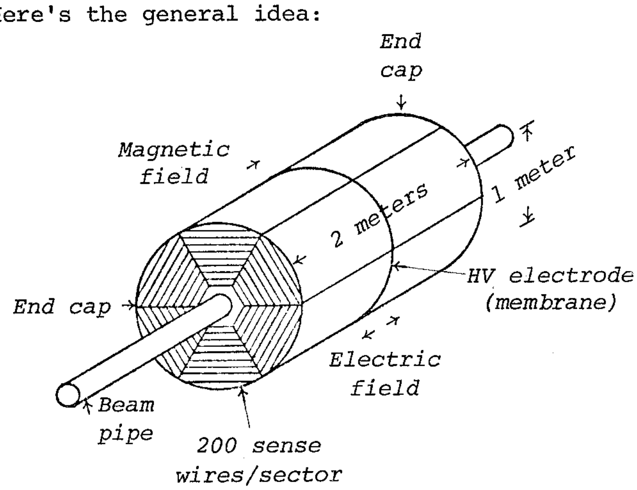
"TPC" stands for "time projection chamber," which is the heart of the PEP-4 facility. In the drawing below, note that several sub-systems within the complete PEP-4 package are similar to those we've already described: muon counters located behind thick sections of iron absorber, a calorimeter, and a number of drift chambers (labelled "DC" in the drawing). The central chamber is also immersed in a solenoidal magnetic field, as before, but in this case the magnet is superconducting. What is new about PEP-4,



essentially, is the time projection chamber itself, and it is this remarkable device that we will focus on.

Time Projection Chamber

The TPC is an imaginative variation on the theme of drift and proportional wire chambers in which charged particles pass through a large volume of high-pressure gas, leaving an ionized trail. The chamber is divided in the center by a thin membrane which is used as a negative high-voltage electrode and thus creates an electric field within the volume of the chamber, with the field direction being opposite on the two sides that are separated by the membrane. Here's the general idea:



Each of the six sectors of the end caps contains about 200 sense wires, rather than the few shown in the sketch.

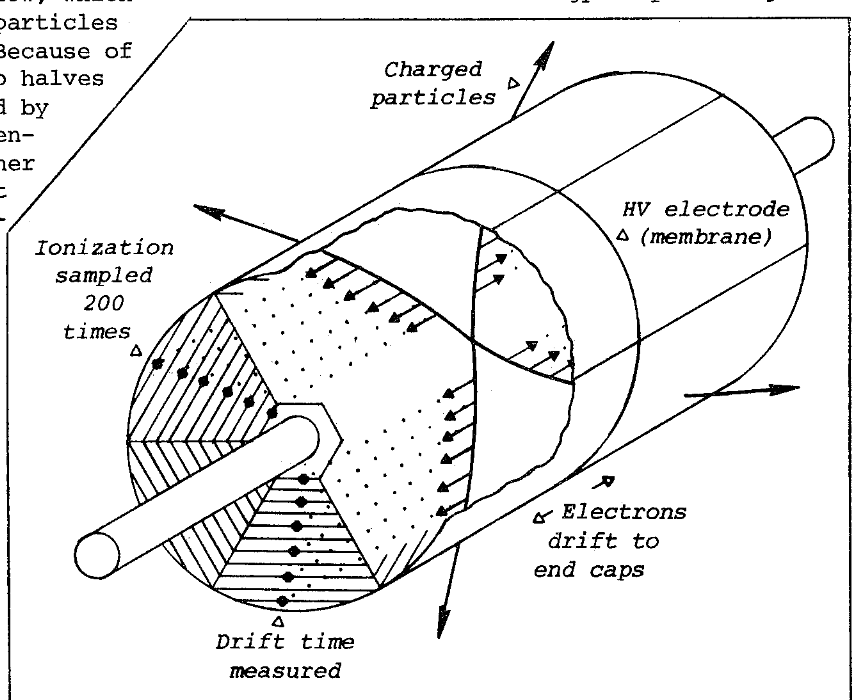
We can get a picture of what happens inside the TPC by using the larger sketch below, which shows an event in which four charged particles emerge from the interaction region. Because of the reversed electric field in the two halves of the chamber, the electrons produced by ionization will drift away from the center membrane and toward one or the other of the end caps. With such long drift distances (as much as 1 meter in either direction), it might be expected that the drifting electrons would disperse, but the parallel magnetic and electric fields constrain the electrons to travel toward the end-cap wires in fairly straight trajectories. At the end of the drift, the ions are collected by the wires and thus produce an output signal. (Note in the sketch that "hits" are shown only on alternate wires for clarity. In fact the hits would occur on each of the ≈ 200 sense wires in a sector for the particle trajectories shown here.)

We can now summarize the kinds of information that result from the TPC system in the following way:

Three-dimensional tracking. The path followed by the particle through the chamber is immediately given in two dimensions by the sequence of hit-locations along the wires. (The location on each wire is actually determined by signals induced in a series of ground-plane pads that are not shown in the sketches.) The third dimension is added by measuring how long it takes the electrons from the different parts of the particle track to arrive at the the respective wires that record them.

Momentum measurement. As with the other detectors we've discussed, the TPC uses a solenoidal magnetic field to deflect charged particles into curved trajectories, and the degree of curvature and thus the particle's momentum is given automatically by the three-dimensional reconstruction of its track.

Particle identification. The time projection chamber would be an impressive device if it did no more than provide tracking and momentum measurement in the novel way described above, but it actually has yet another very important feature. It turns out that the end-cap wire arrays can also measure the amount of ionization that occurs at each of ≈ 200 different points along the track, and this information can be used in the following way. The amount of ionization produced by a particle in a certain distance of travel depends not only upon its momentum but also its mass. If we take as an example the particles e^+, π^+, K^+ and p, with each having exactly the same momentum, then it will generally be easy to distinguish the e^+ from the three hadrons by the significantly different rate at which it loses energy in producing ions.



The differences among π^+, K^+ and p are much smaller, and they also change in a complex way at different values of momentum. The great advantage of the TPC in this regard is that it will sample the ionization many times along each track, and by averaging all these samples together even very small differences can be pinned down as statistically significant. Thus by relating ionization to mass, the TPC will accomplish particle identification within the same system that also gives three-dimensional tracking and momentum measurement. Wow.

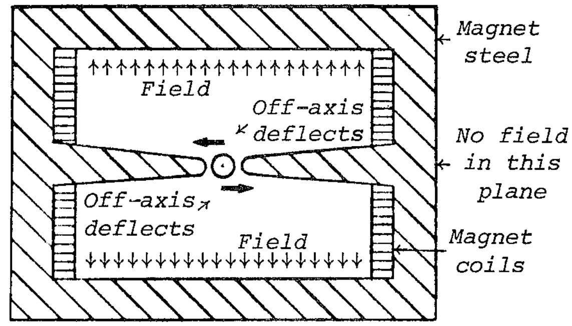
2γ

The drawing at the lower right shows a cross section view, in perspective, of one of the two identical detection systems that will be provided by PEP-9 for coverage of events in which the particles emerge at small angles with respect to the beam direction. Working from the left in toward the interaction region (I.R.), muons will be identified with a conventional system consisting of several layers of counters and iron absorbers. Then comes a composite shower-counter system, the septum magnet, and a series of drift chambers (DC-1, etc.) placed between successive elements in the system. We single out for special attention the septum magnet and the shower counter systems.

Septum Magnet

As we noted earlier, the usual experimental signature for the events resulting from two-photon annihilation is that the beam electrons and positrons that emit the two photons are themselves deflected only slightly as a result. This means that in many cases the scattered e^+ and e^- will emerge along trajectories so close to that of the beams that it will be difficult or impossible to detect them. But such detection (called "tagging") is important if 2γ processes are to be recognized, and the purpose of the septum magnet is to reach in close to the beam and pull the particles out to a position in which they can be detected.

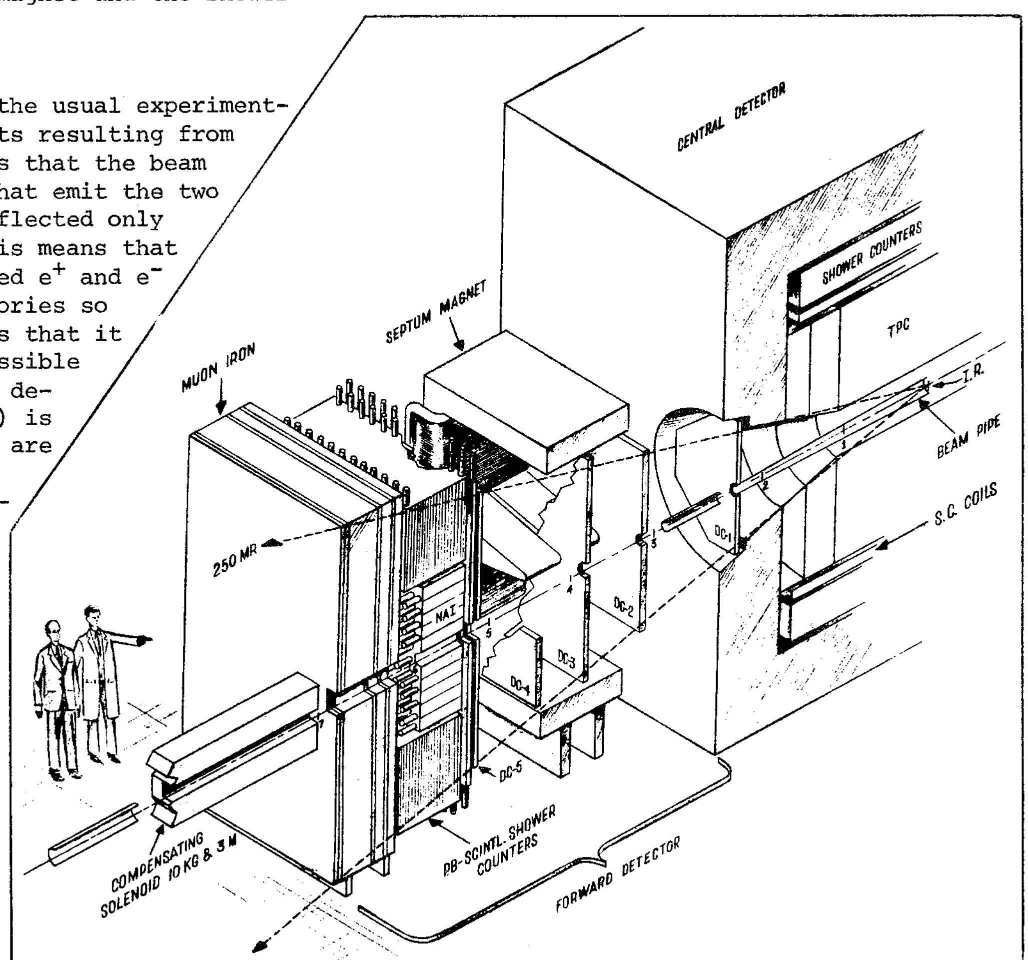
The sketch at the top of the next column shows how this is accomplished. In full cross section, the septum is a modified form of "H" magnet (this one is often called the "beltbuckle") in which one of the two coils is wired backwards. This has the necessary result that the



magnetic field along the axis is zero, so the stored beams themselves are not affected. But particles that are off-axis, either above or below the center, will be deflected sideways farther away from the axis, and will thus move out to where the following devices can see them.

Shower Counters

This composite system consists of a core section of sodium iodide (NaI) crystals, and an outer section of scintillation counters loaded with lead (Pb). These are the best and most expensive materials for the purpose, as we noted earlier, and their use in this application is affordable because only reasonable quantities are needed for the small-angle coverage.

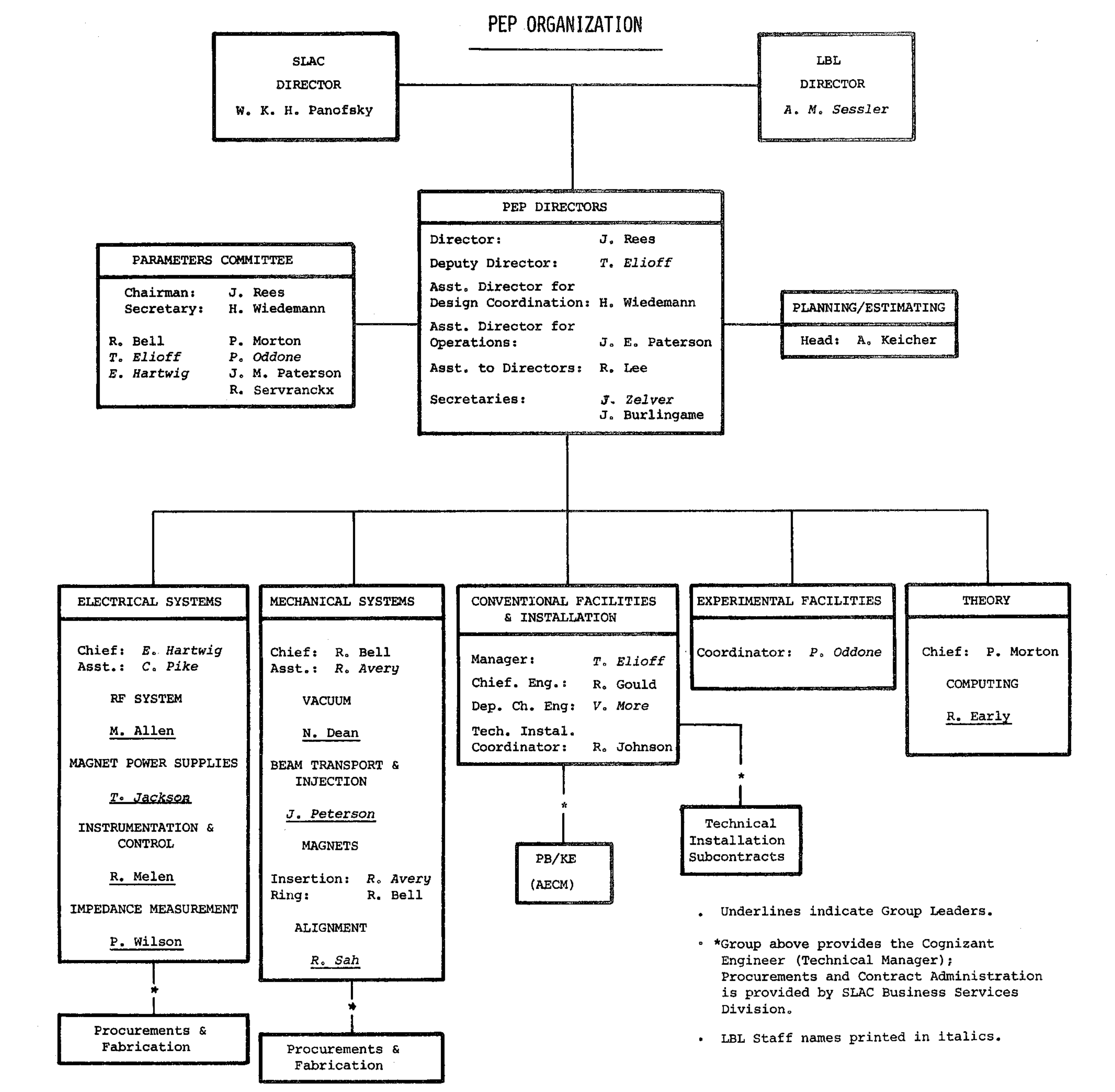


F. ADMINISTRATIVE & MISC.

In this concluding section, we give some information about the PEP organization, and about project management and costs. Then we'll also give a brief description of the possible future options that exist for expanding the research potential of PEP.

1. PEP ORGANIZATION

PEP is a joint undertaking of SLAC and of the Lawrence Berkeley Laboratory (LBL). The chart below shows the individuals from SLAC and from LBL (names in *italics*) who form the core of the PEP organization. There are other persons who work in the groups that are shown, and at any given time PEP work is also being done in the shops, drafting rooms, engineering departments, etc., of the two laboratories. Some of the reasons for this method of organizing the project--in which a relatively small central group draws upon the services of the other parts of the two labs as needed--are discussed in the fol-



NOTE: This chart shows structure to the level of the system group. For a list of personnel working in the groups, and for any organizational structure internal to the groups, a separate listing is maintained in the PEP Director's Office.

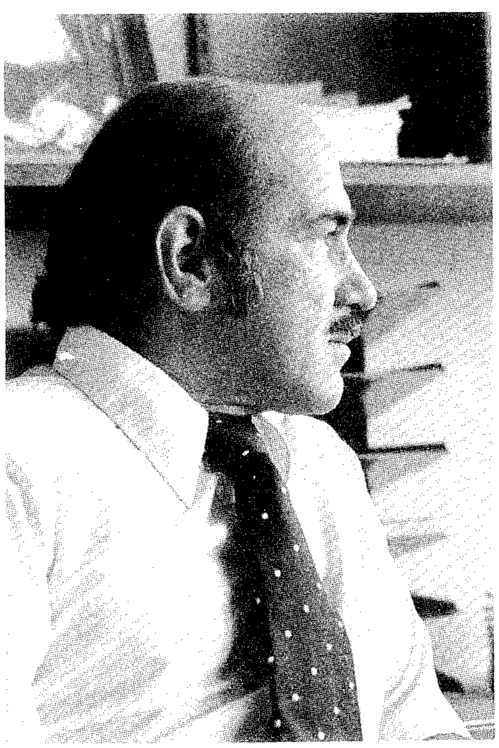
lowing section.

2. PROJECT MANAGEMENT & COSTS

Building a big machine like PEP presents management problems as well as technical problems. The particularly rigorous dimension of the management problem is control of the budget. Consider the case of PEP: a $78 million construction program spanning four years. Unlike many other expenditures of public funds, it is the tradition in high-energy physics that big machines get built "on budget." That is, you don't go back and ask for more money to finish the project. And this is true despite the fact that each large new machine is a unique device, with many innovative technical systems, and also despite the fact that the money to build the machine has to be asked for before the machine itself has been designed.

In addition to the technical uncertainties, there are also market uncertainties--the construction industry in particular has recently been experiencing rapid cost inflation. On the other hand, some parts of the construction industry may be temporarily depressed, and a contractor may choose to bid low just to keep his organization afloat until business picks up. In short, when the construction bids come in, there may be some surprises, both good and bad.

A third cost-management problem comes from the sheer rate of spending that is necessary to get the work done. In the peak spending year



PEP Deputy Director Tom Elioff of LBL.
(Photo by Joe Faust.)

PEP Director John Rees of SLAC.
(Photo by Joe Faust.)

for PEP, Fiscal Year 1978 (which starts in October 1977), the project will be committing money at the rate of about $120,000 *every working day*. At that rate, even the most accurate and prompt accounting system may not pick up potential problems before things go seriously awry.

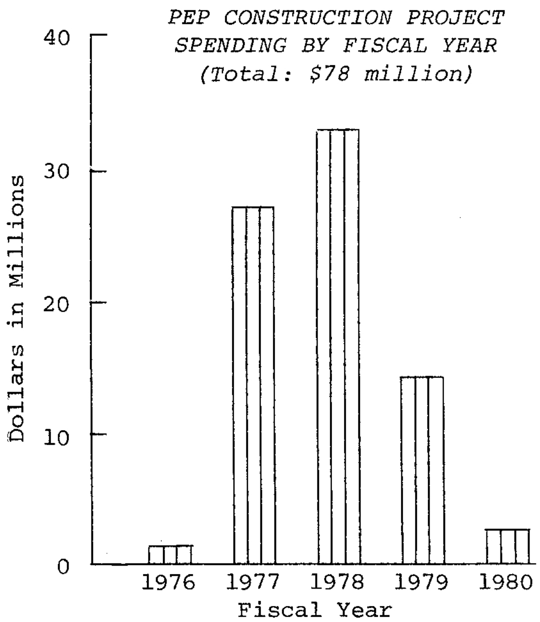
What to do about all these problems and uncertainties? On approach is to form a vast bureaucracy to keep track of everything, right down to the last nut and bolt. There are plenty of examples, often in military projects, which show that the bureaucratic approach doesn't work very well. And even worse is the fact that, at the end of it all, you are still stuck with the bureaucracy that you created to keep control of things. Then pretty soon it becomes evident that the bureaucracy is eating up all the money that might have been spent on hardware.

The alternative to the bureaucratic approach is one of keeping your options open.

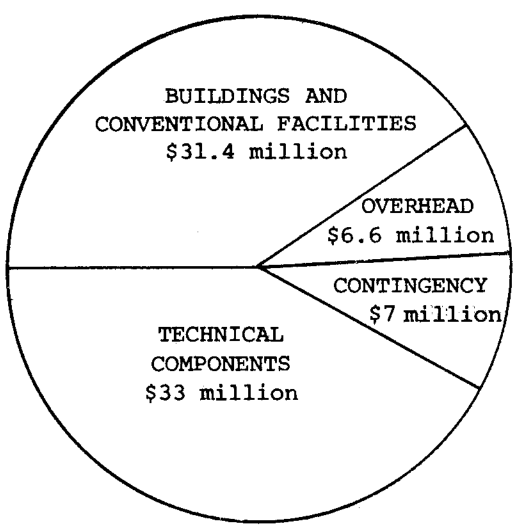
In the case of PEP, this is being done in two ways. The first is the conventional way of setting aside a certain fraction of the total funds as contingency, to be used as late in the game as possible and only to cover emergencies. For PEP, this contingency amounts to about $7 million, or about 9% of the total cost.

The second approach is to be willing to forego certain conveniences or operational possibilities that do not affect the essential scope of the project. As an example, the experimental area in Region 6 at PEP is presently planned for only partial development, with additional facilities to be added only as the funding picture and the program needs become clearer. If the cost experience looks good, it may be possible to move ahead with some additions of this kind.

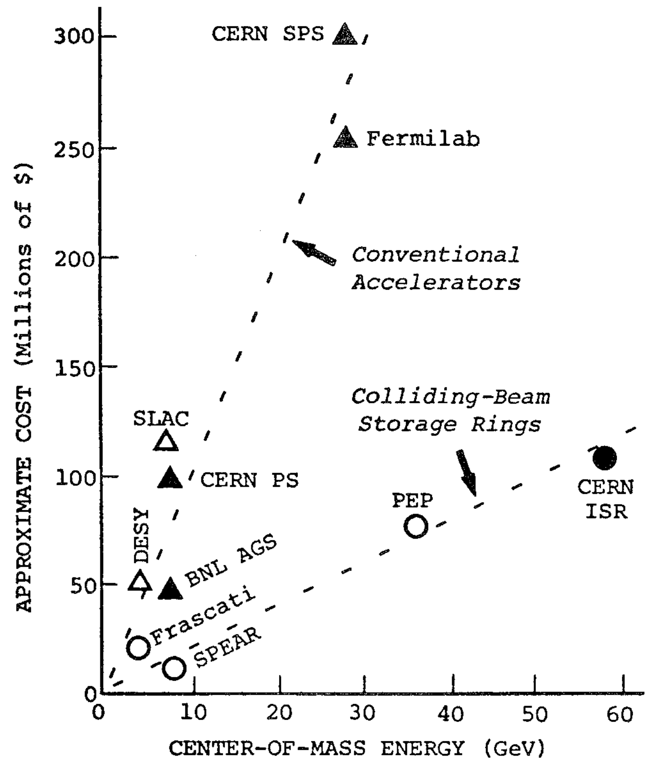
The total cost of PEP, as noted, is estimated to be $78 million. The heaviest spending years will be this year and the year following. This spending schedule is shown in the following figure:



The way in which the money will be spent can be divided into two large pots and two small pots. The two large pots of almost equal size are the "conventional facilities" (tunnels, buildings, roads, utilities) at $31.4 million; and the magnets, electronics, vacuum and RF components, etc., at $33 million. The two smaller pots are also of almost equal size: the overhead costs of administrative services, fringe benefits and other indirect costs at $6.6 million; and the contingency fund of $7 million. All of which looks like this in terms of slices of the pie:



In a more general vein of cost comparison, it may be of interest to amplify our earlier remarks about storage rings being a relatively economical way to achieve high center-of-mass energies in relation to conventional accelerators. In the following figure we show a number of large accelerators and storage rings plotted according to their CM energies and approximate costs.



Conv. accel: ▲ proton beam; △ electron beam
Collid. beam storage ring: ● pp; ○ e^+e^-

The relative costs given in this figure may be inaccurate to a certain extent, since it is sometimes difficult to translate different currencies and different accounting practices. But this should not significantly alter the clear trend: storage rings really are a good way to get more bang for a buck.

3. FUTURE PEP OPTIONS

Although high-energy physics research has a way of making predictions about the future eventually look silly, we'll risk taking a flyer here on the two main possibilities for expanding PEP's research potential that now appear most promising:

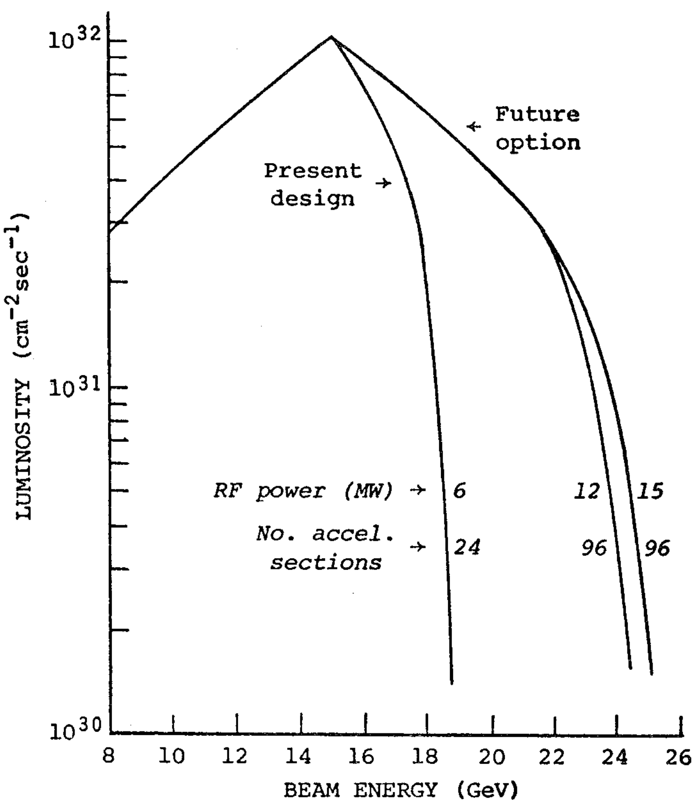
(1) Increasing the maximum single-beam energy from the present design goal of 18 GeV to 23-24 GeV.

(2) In the longer term, adding a separate storage ring for 200 GeV protons in the same tunnel structure, thus allowing electron-proton collisions.

In the space remaining, we shall pass up any discussion of the physics motivation for these two future possibilities in favor of a brief summary of the main technical matters.

23-24 GeV Beam Energy

The main cost in increasing the maximum beam energy of PEP would be that associated with RF power. The present design makes use of 24 accelerating sections to which power is fed from 12 500-kW klystrons for a total RF power of 6 MW--about 1/2 of which is used by the circulating beams. By increasing the number of accelerating sections to 96 and the number of klystrons to 24, the resulting total RF power of 12 MW would provide a maximum beam energy of about 23 GeV at a luminosity of $10^{31}cm^{-2}sec^{-1}$. If klystrons capable of 625 kW per tube can be developed, the maximum beam energy would be about 24 GeV at the same luminosity. The RF situation is summarized in the following figure.



At the present time there are two different, self-consistent designs for the magnetic guide field of PEP, one limited to beam energies of 18 GeV, and the other able to sustain ≃ 24 GeV. The construction schedule permits deferring the decision between these two alternates until the Fall of this year, when the accumulating cost experience with PEP will make the choice clearer. It may thus be possible eventually to go to the higher beam energies without replacing any of the ring guide-field magnets.

Some relatively minor additions to power-supply capacity and utility systems would be the only other requirements of this program.

200 GeV Proton Ring

The eventual addition of a separate storage ring for protons to the PEP facility would be a major program, comparable in construction cost to that of PEP itself. The technical feasibility of such a project depends strongly upon the successful development of superconducting magnets that can be fabricated in quantity with reliable results. It now appears that this difficult technology will have matured sufficiently within the next several years to make the proton-ring option for PEP a realistic possibility.

The proton-ring guide-field magnets would be installed in an alternating over-and-under arrangement within the existing tunnel, with the proton and electron (or positron) beams crossing through each other at the six present interaction regions. The collision of 200 GeV protons with ≃ 24 GeV e^+ or e^- would produce center-of-mass energies up to about 140 GeV--far beyond anything that is imaginable from a conventional accelerator.

3. SOME RELATED READING

To conclude, we list below some articles from earlier *Beam Line* issues that are related in one way or another to PEP. Copies of these articles (in small quantities) can be obtained from Bill Kirk or Roslind Pennachhe (ext. 2605, Bin 80), or from Herb Weidner (ext. 2521, Bin 20).

1. "An introduction to colliding-beam storage rings," Aug & Sep 1974.

2. "We have observed a very sharp peak...," Dec 5, 1974. [*Discovery of the psi particles*.]

3. "More new particles," Oct & Nov 1975. [*More psions; jets; heavy leptons; quarks*.]

4. "Charmed particles," July 1976. [*The charmed D mesons; the charmed quark*.]

5. "SPEAR: A review of the facility and the SLAC-LBL experiments," Nov 1976. [1-4 *summary*.]

6. "SPEAR Mark II magnetic detector," June 1976.

7. "The hunting of the quark," by Sheldon Lee Glashow, Sep 1976. [*NYTimes reprint*.]

Acknowledgements. Our thanks to Dave Fancher of LBL, George Masek of UC-San Diego, and John Rees for their contributions, and to Wolfgang Panofsky and Roy Schwitters for their clarifying comments.

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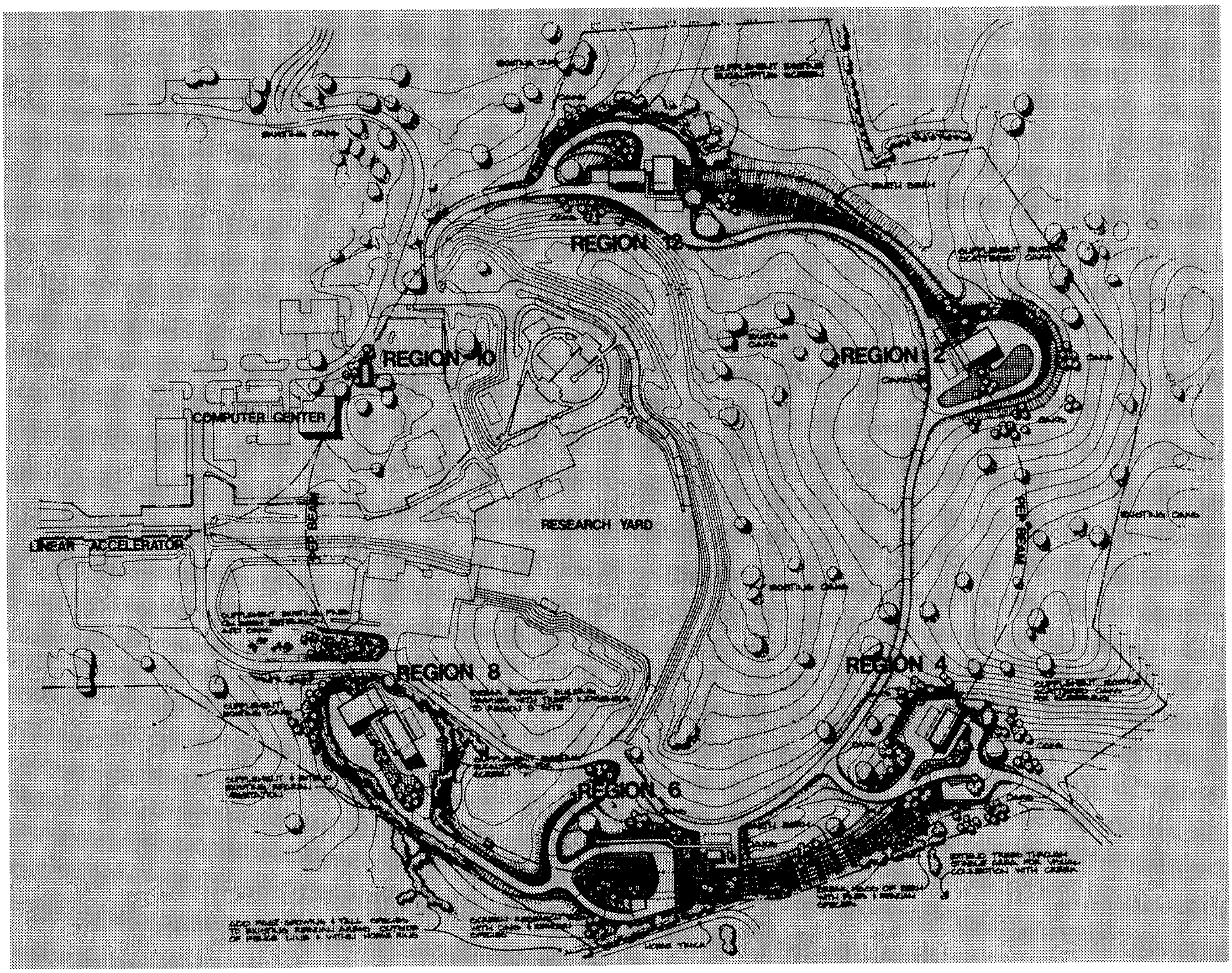
SLAC Beam Line Report No. 6 June 1977
Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, Calif. 94305

PEP: AN INTRODUCTION



PARTS I & II COMBINED

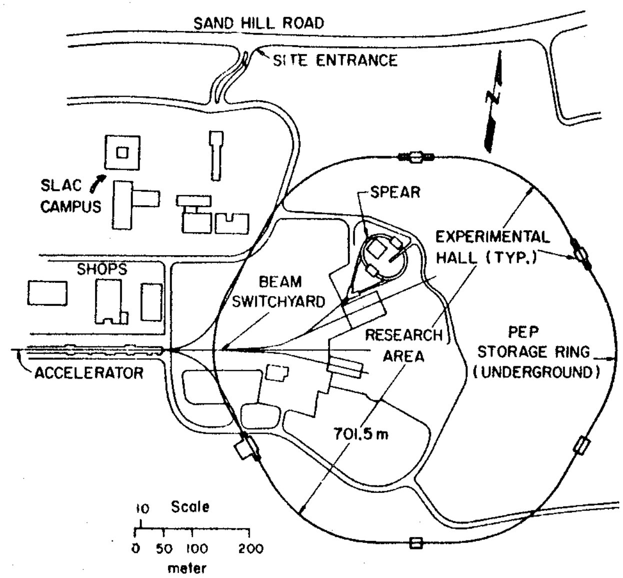
This is the complete article on PEP that originally appeared as two separate parts in the April (Part I) and June (Part II) 1977 issues of the *Beam Line*. Although this description of PEP is intended as a general introduction, the reader may find parts of Sections B, D and E too technical to cope with. This is because we are trying to reach both technical and non-technical readers, and for the latter we hope enough will come through to make it worth the effort.*

A. A BRIEF SUMMARY

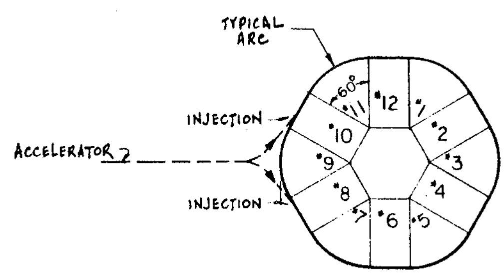
General. The name "PEP" is an acronym for Positron-Electron Project. It is a joint undertaking of SLAC and of the University of California's Lawrence Berkeley Laboratory (LBL), which was first proposed to the AEC (now ERDA) in April 1974. The PEP machine is designed to store beams of electrons and positrons 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 45% 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 PEP ring is shown on page *1* and 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 55% 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. The schedule calls for decisions on these proposals by May of this year (see Section E for a description of the approved proposals).

A Friendly Competition. The DESY laboratory in Hamburg, Germany, is presently building a large electron-positron storage ring called PETRA that is very similiar 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 about 23-24 GeV per beam by adding more RF power and certain other changes.

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.

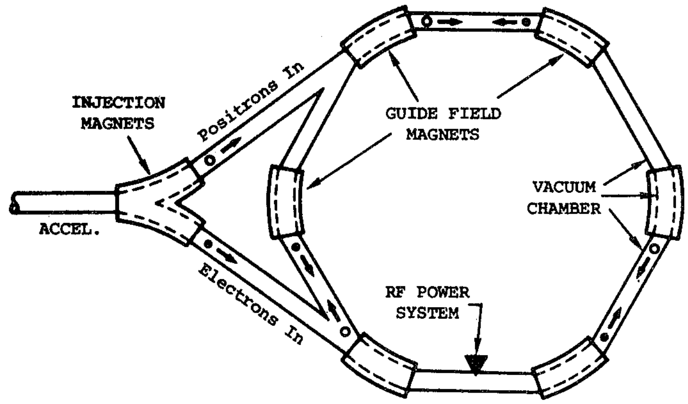
Options (2) and (3) would make it possible to have collisions between electrons and protons, positrons and protons, electrons and electrons, and positrons and positrons. Recent physics developments have made Option (1) seem quite important, and at present there are studies in progress to explore this possibility more thoroughly.

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.



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

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 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 chamber 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 *phhhtt!* 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

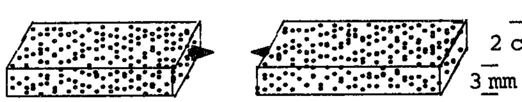
2. MAGNETIC GUIDE FIELD

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?

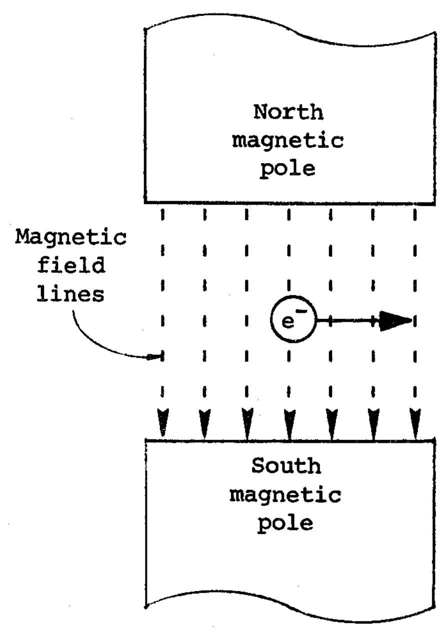
The brief answer to this question is that interesting collisions between electrons and positrons in a storage ring are relatively rare events, and long beam-storage times are needed in order to collect a decent number of the important kinds of interactions. We can emphasize the "rare event" problem in the following way. Let's suppose that we build a "linear" colliding beam machine by constructing 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

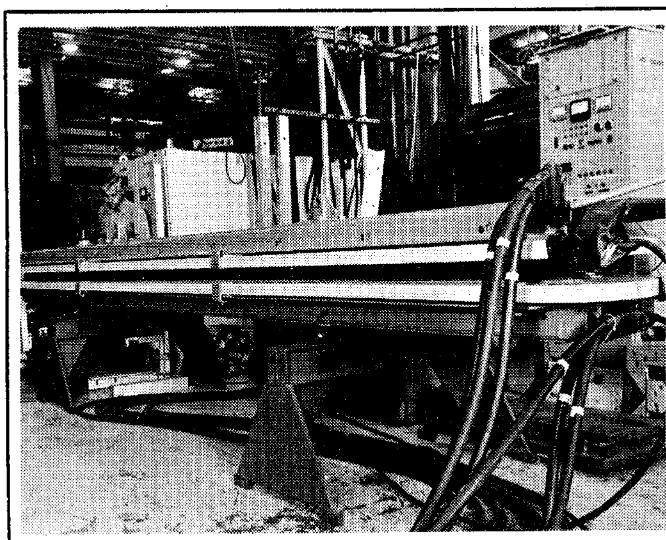
The path or orbit followed by the particles in a storage ring is more or less circular. This orbit results from a series of sideways deflections that the particles receive as they pass through the magnetic field produced by an array of dipole or bending magnets. As shown in the sketch, the deflecting 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.

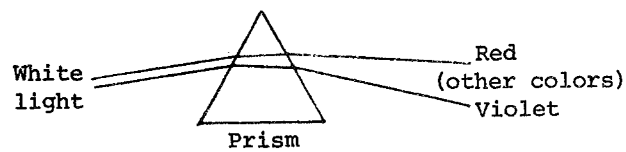
The magnetic guide field for PEP will consist of a total of 669 magnets, of which 216 will be bending magnets of two different designs. A prototype of the "standard" bending magnet (192 required) is shown in the accompanying photograph. These C-magnets (so named because of their C-shaped cross section) 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 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.



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.)*

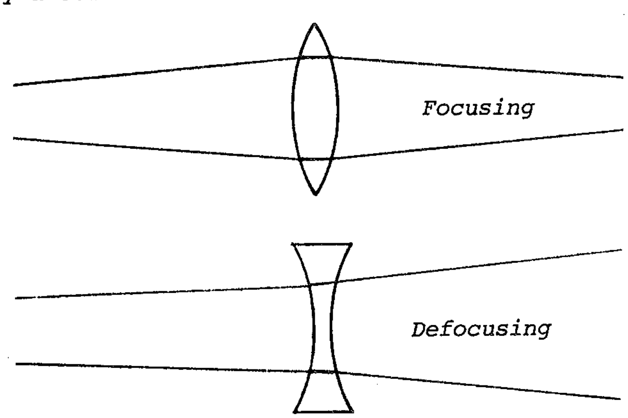
Quadrupole Magnets

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:

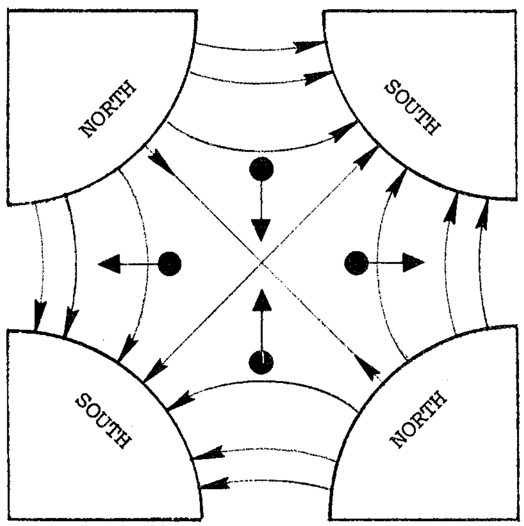


The light beam spreads out into a rainbow of the individual colors of light that appeared to be white when they were all together. Each of the colors of light has an energy (or wavelength) slightly different from the others, and for this reason each color within the white light beam is bent (refracted)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



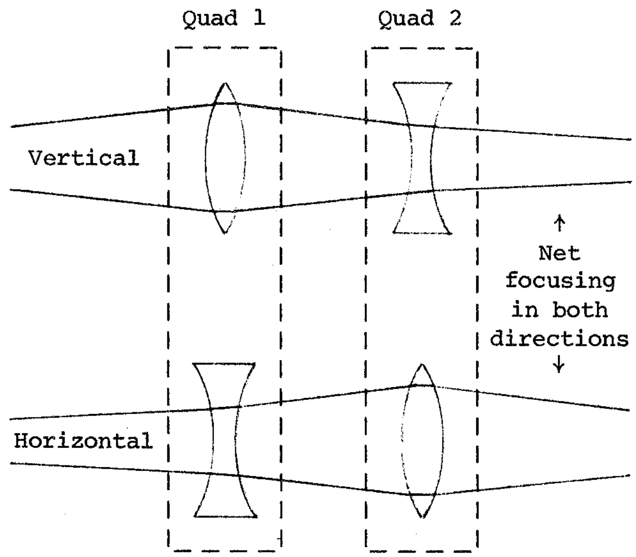
What the lens is to optics, the quadrupole magnet is to particle "optics." (In fact, "quadrupole lens" and "magnet optics" are commonly used phrases.) The four-pole configuration of a quadrupole magnet is shown in the following sketch.



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.

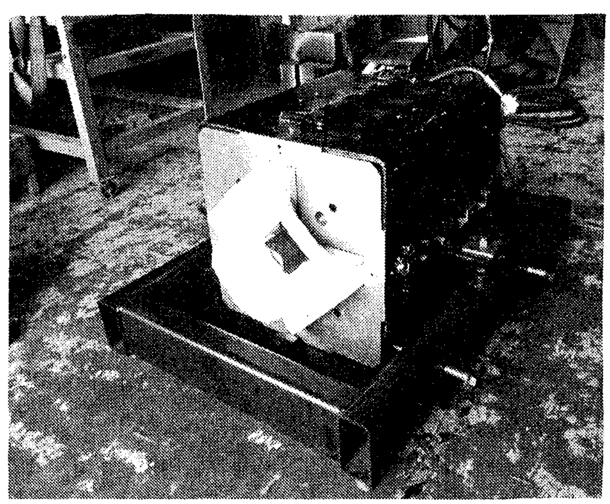
As noted in the caption, a quadrupole differs from an optical focusing lens in that it can focus a beam in only the vertical or the horizontal direction, with defocusing in the other direction. It turns out, however, that there is a simple solution to this apparent problem. The solution is to use *two* 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 Zawojski.)*

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 accomodate 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.

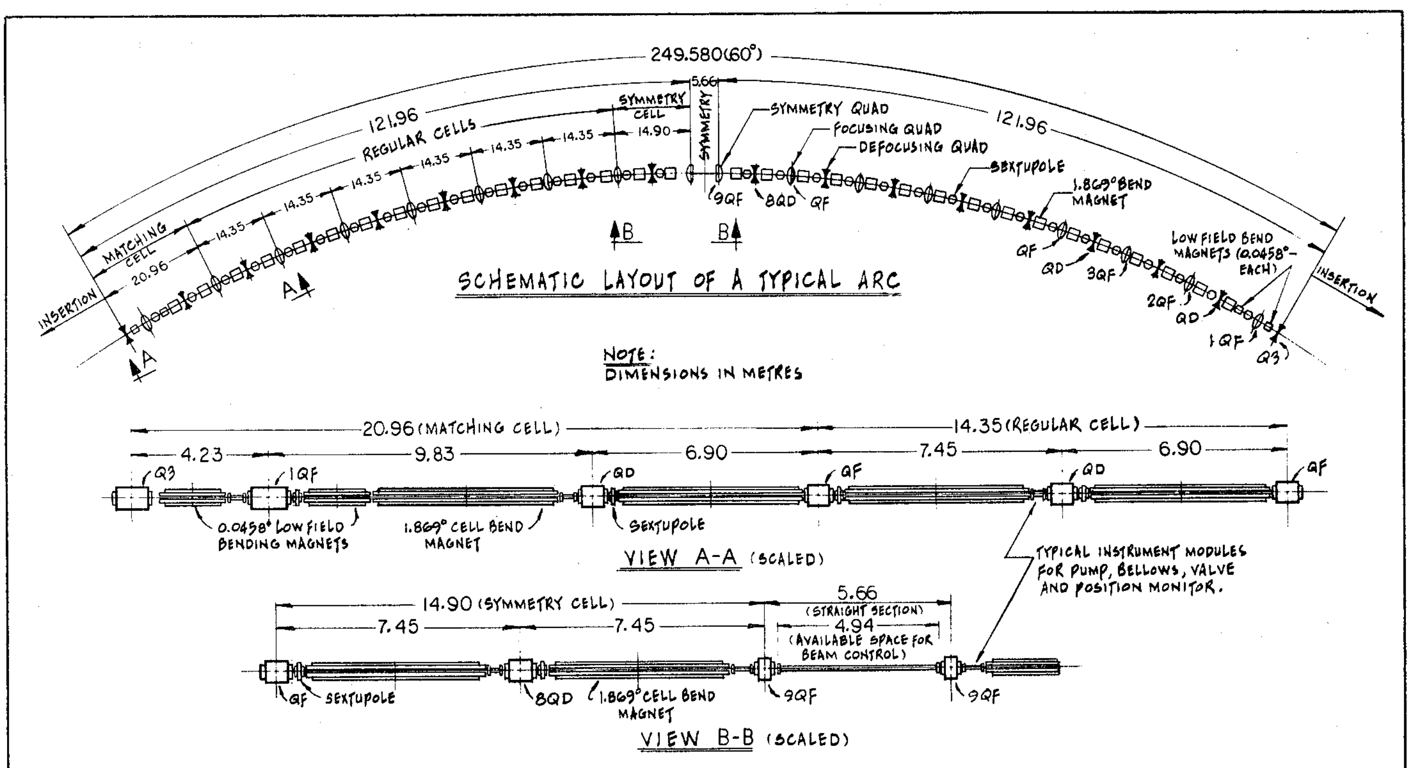
Sextupole Magnets

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 "regular" cells, 2 "symmetry" cells (on either side of the midpoint), and 2 "matching" cells (at the ends). The regular 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 quad pairs 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)
Bending magnets				
Standard	70C5400	192	5.40	8580
Low-field	70C2000	24	2.00	
Quadrupoles				
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
Sextupoles	140S250	204	0.25	
Wigglers	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 collisons 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

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

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

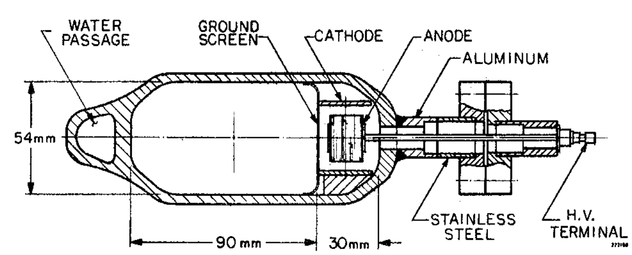
To attain and hold this level of ultrahigh vacuum is a tough business. The first step is to carry out a thorough chemical cleaning of the inner surface of the aluminum beam pipe, after which the pipe is then heated and baked for a time at a temperature of 180°C. These treatments will remove nearly all 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 accomodate 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 remark 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 enthusiatic 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.)

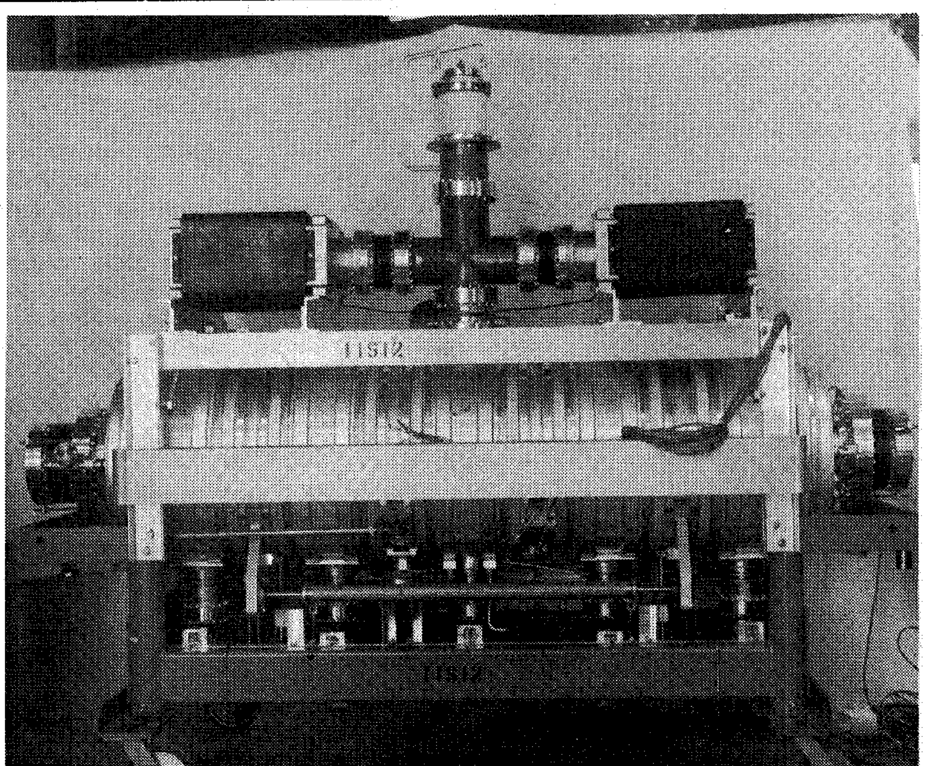
Sizing Up The Need

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 perhaps 23-24 GeV at some future time.) The 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

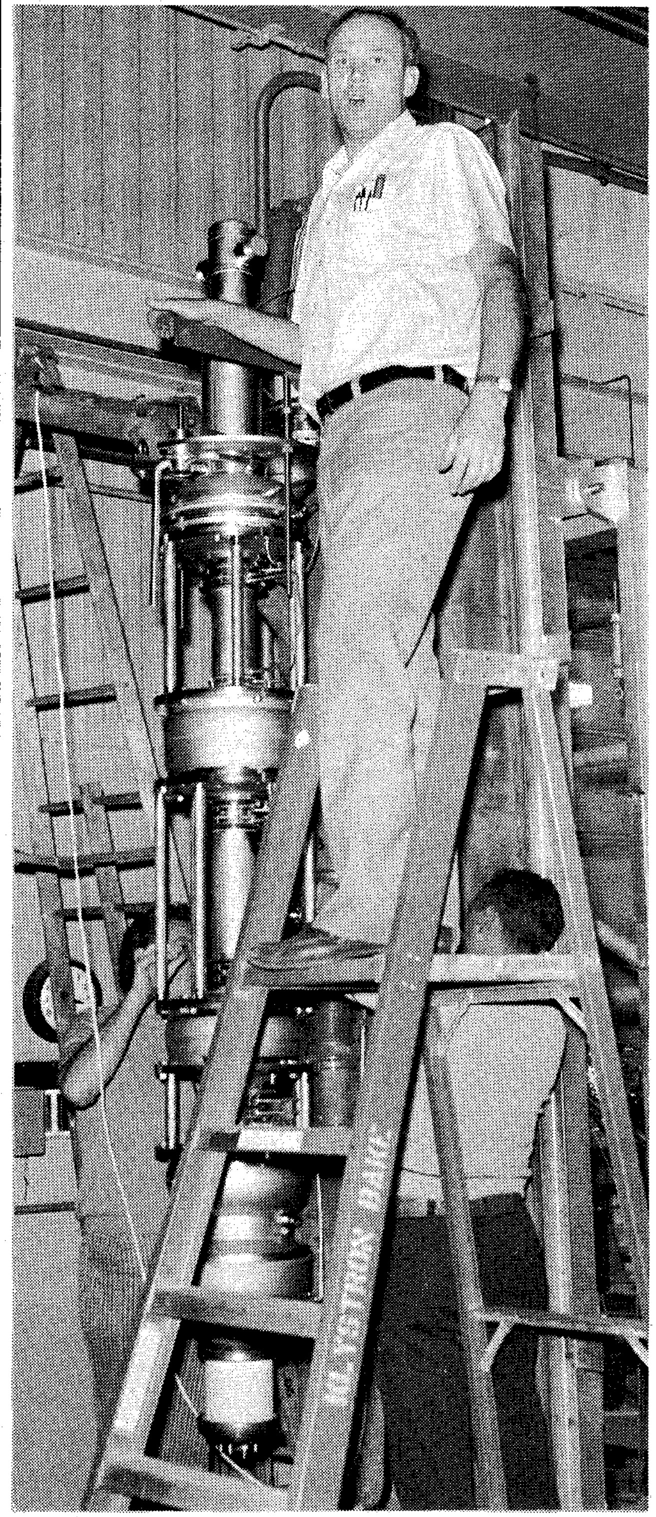
To sustain the maximum circulating beam current of 54 milliamps in each beam at an energy of 15 GeV, a total of about 6 million watts (6 MW) of radiofrequency power will be required. 3 MW will be needed to compensate for the synchrotron radiation losses suffered by the circulating beams, about 0.5 MW 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.

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
Operating at 15 GeV:	
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	$\sim$4 cm

5. BEAM INJECTION SYSTEM

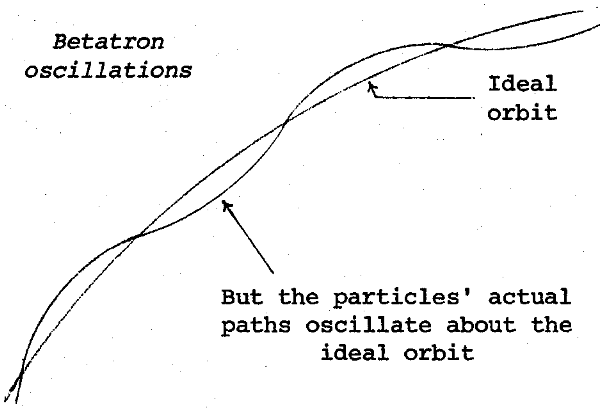
So far we've described many of the good and bad things that happen to the particles as they go round in the storage ring, but we haven't yet talked about how the particles get into the ring (beam injection), nor where the particles come from in the first place (the injector). We'll begin by discussing 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 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):



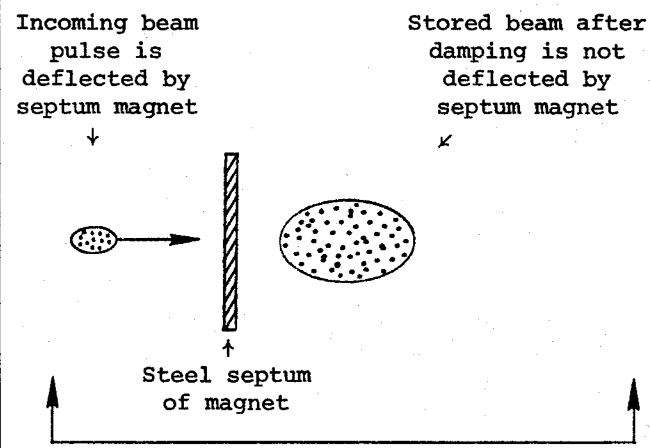
This oscillatory motion is largest (moves farthest from the ideal orbit) for those particles that have just entered the ring, and its amplitude gradually decreases with time as a result of the emission of synchrotron radiation by the particles. This is described by saying that the betatron oscillations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



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.

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 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 $\sim$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
No. particles/pulse		
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 monitors 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 that lies along the vacuum chamber's central axis. In order to detect 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.

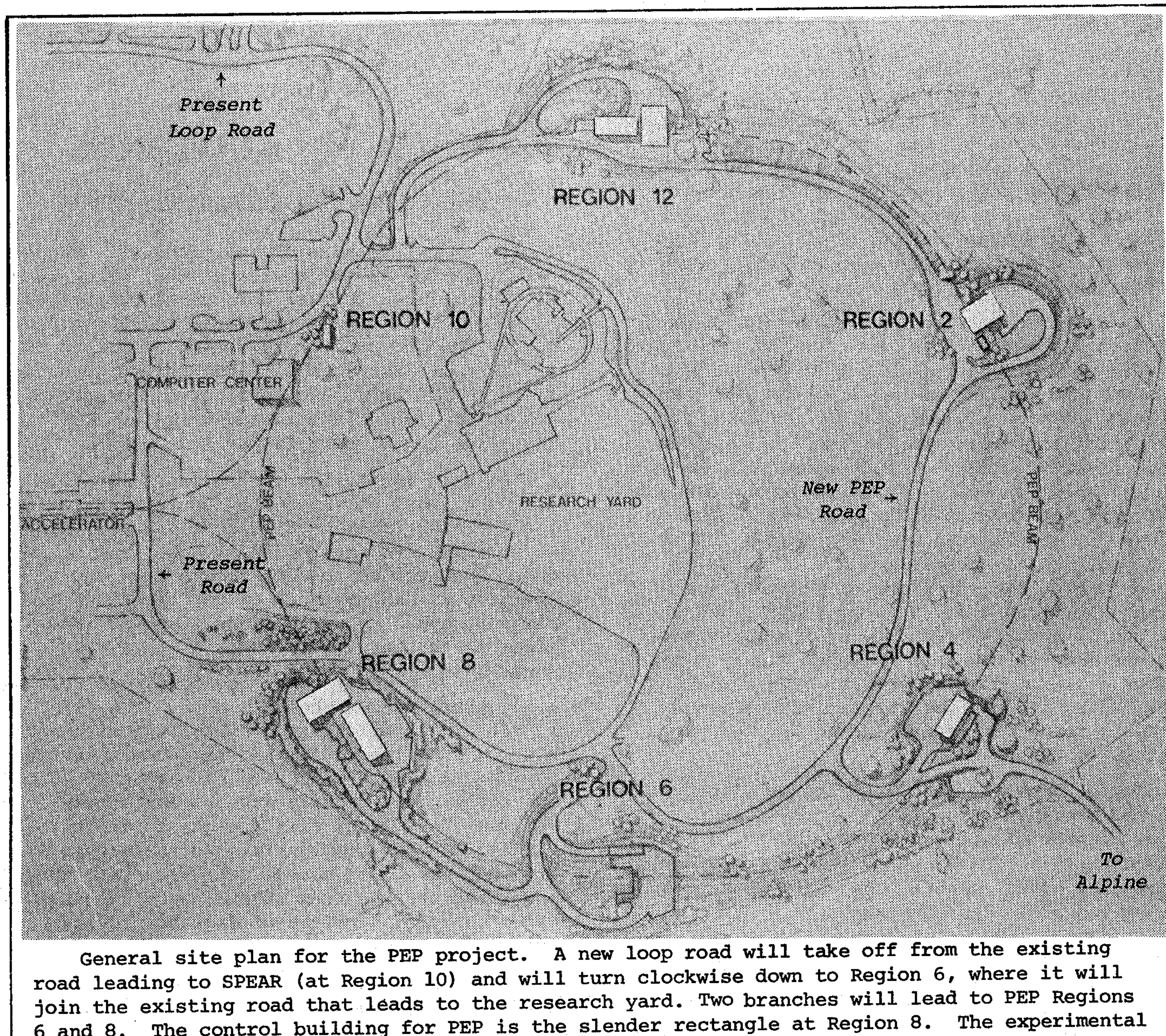
The optimization of these several points resulted in the choice of location that is shown on the next page. Several compromises had to be made. One of the interaction regions (Region 10) ended up so deep underground that plans to develop it for physics experiments were abandoned, and it has since been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

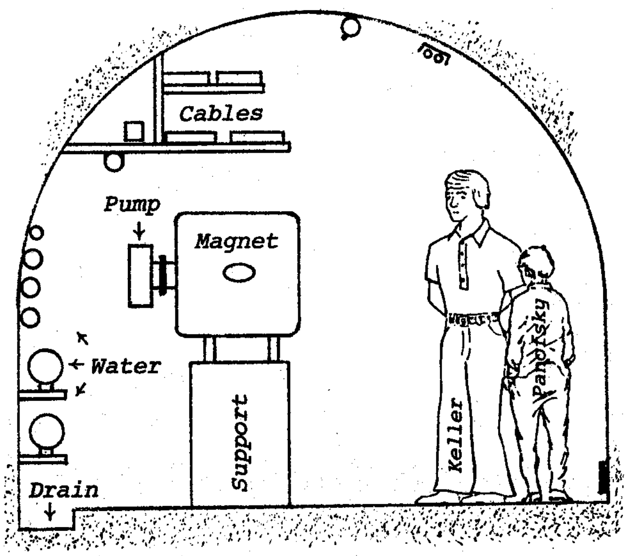
The purpose of the PEP storage ring is, of course, to do physics. Consequently, the design of the interaction-region buildings, where the physics will be done, is an important matter. Choices made now on the size and shape of these buildings may place constraints on the kinds of physics apparatus that 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.

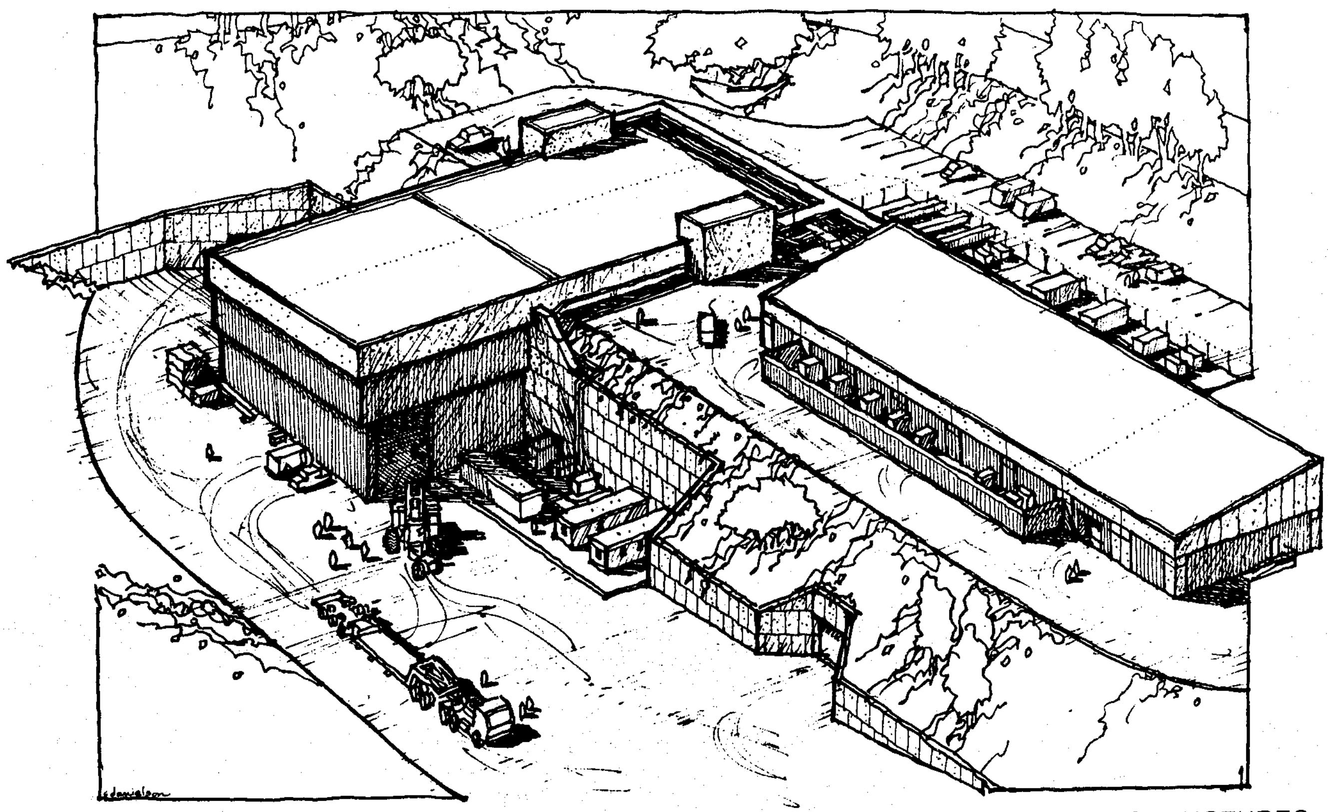
The PEP control building will also house the power supplies for some of the magnet systems, as well as the klystrons and their associated power supplies which feed the RF cavities in Region 8. The klystrons and power supplies for the RF cavities in Regions 4 and 12 will be housed in other, smaller surface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



SKETCH OF REGION 8 STRUCTURES

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 design.

PEP: PART II

In Part I of this article we were concerned mainly with the PEP storage ring itself as a technical system, and with the site that it will occupy at SLAC. In Part II our attention will turn to the characteristics of the ring as a research instrument, the physics it will do, and the large experimental detectors being planned.

D. PEP AS A RESEARCH INSTRUMENT

In the next three pages we plan to give a brief description of how PEP's characteristics as a research instrument compare with those of conventional accelerators and other storage rings. In doing so, we will give only a compressed version of the physics background information on which the comparison is actually based. Those who wish to explore the subject in more detail may find some of the earlier *Beam Line* articles listed on page *40* to be useful.

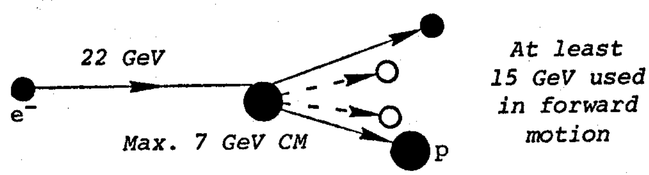
1. ACCELERATORS & STORAGE RINGS

The two most important characteristics of a conventional accelerator are its *beam energy* and its *beam intensity*. For a storage ring, the analagous characteristics are *center-of-mass energy* and *luminosity*. In the following paragraphs we discuss how these accelerator and storage ring properties differ from each other, and why the differences are important.

Beam Energy vs. Center-Of-Mass Energy

When the beam from a conventional accelerator strikes a target particle, the amount of energy that is "useful" in making something actually happen in the collision is always less than the total energy carried by the beam particles. This useful part of the total energy is most often called the *center-of-mass* (CM) *energy*, but several other names such as *effective collision energy* or *available reaction energy* mean exactly the same thing. As an example, a 22 GeV electron from the SLAC accelerator striking a proton target (a bottle of liquid hydrogen) will produce a maximum useful or CM energy of about 7 GeV.

Why is this so? What happens to the other 15 GeV of beam energy? The answer is that all of the remaining 15 GeV is used up in giving a strong forward push to the target particle and to any new particles that happen to be created in the collision--something like this:



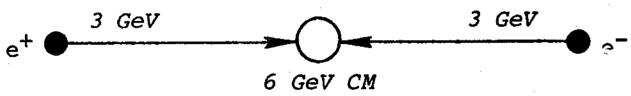
Now let's suppose that we want to have more than 7 GeV of CM energy available from the SLAC accelerator (or more CM energy from any conventional accelerator). The most obvious way to get this extra CM energy is simply to increase the total energy carried by the incoming beam. This solution will work, all right, but it has a serious snag that is illustrated in the following table:

Conven. Accel.	*Beam**	*Beam Energy (GeV)*	*CM Energy (GeV)*	*% of Beam Energy Avail. as CM Energy*
DESY	e^-	6	3	50%
SLAC	e^-	22	7	30%
BNL AGS	p	32	8	25%
Serpukhov	p	76	11	15%
FNAL/CERN	p	400	28	7%
FNAL plan	p	1000	40	4%

*e^- = electron; p = proton.

What happens, then, is that going to higher and higher beam energies results in a smaller and smaller fraction of that energy being available as useful CM energy. (The CM energy increases only as the square root of the beam energy.) And because of this, there has been a strong incentive to find some other, less expensive way to achieve very high CM energies--which is where colliding-beam storage rings come in.

The problem with conventional accelerators is that the stationary target that is used is too easily pushed around the the high-energy beam. (It's like punching a balloon--the impact is not very forceful no matter how hard the blow.) In a storage ring, the stationary target is replaced by a *second* high-energy beam traveling in the opposite direction. Then, with two beams of equal energy colliding head-on, there is no "forward" or "backward" direction in the collision, and the result is that *all* of the energy carried by *both* of the beams in available as useful center-of-mass energy. For example:



The next table shows the CM energies of several different storage rings (existing, in construction, or proposed), and in the last column the beam energies that a conventional accelerator would have to have in order to achieve equal values of CM energy.

Storage Rings	*Beams**	*Single Beam Energy (GeV)*	*CM Energy (GeV)*	*Conv. Accel. Energy Req. To Equal CM Energy†*
ADONE	e^+e^-	1.5	3	6 GeV
SPEAR	e^+e^-	4	8	36 GeV
PEP	e^+e^-	18	36	690 GeV
CERN ISR	p p	30	60	2000 GeV
ISABELLE (proposed)	p p	200	400	85,000 GeV

*e^+ = positron; e^- = electron; p = proton.

† These figures assume that a stationary proton target is used, which is somewhat confusing for the e^+e^- rings. But electrons in a stationary target have so little mass that to achieve large CM energies would require impossible beam energies. To equal PEP's 36 GeV CM energy, for example, using an electron target, a conventional accelerator would have to produce a positron beam of about 1,250,000 GeV (about 50,000 SLAC machines end-to-end).

The good news, then, is that colliding beam storage rings are a first-class solution to the problem of how to get very high center-of-mass energies--and thus very important physics possibilities--without going bankrupt in the process. Next comes the bad news.

Beam Intensity vs. Luminosity

If the high CM energies that storage rings can produce are such a big deal, then why haven't they made conventional accelerators obsolete? This question has several different answers, but here we'll discuss only two of these answers (and the first only briefly):

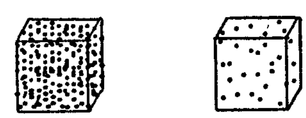
1. Versatility. Conventional accelerators are much more versatile research devices than storage rings because they can produce a variety of different kinds of particle beams, and also because these beams can be directed to several different experimental areas away from the accelerator itself. This makes possible a broadly diversified program of experiments. In contrast, the experiments at storage rings are necessarily based on electron-positron or proton-proton collisions, and they must be located directly in the few regions around the ring where the stored beams interact with each other.

2. Interaction rate. The beam intensity of a conventional accelerator is simply the number of beam particles it can deliver to a target during a certain period of time, and it is usually expressed, for example, as "10^{12} protons per pulse" or "30 microamps of average current." In the case of storage rings, the analagous factor is called the *luminosity*, which we'll define in the following somewhat simplified way:

> Luminosity is a measure of the rate at which the beam particles in a storage ring collide with each other.

The key point here is that the "target" for each of the two beams in a storage ring is the other beam, and these beams contain so little actual "stuff" that there's almost nothing there to hit. For comparison, let's cut out a little cube of material from a typical accelerator target and also a cube of the same size (one cubic millimeter) from a typical electron beam in an e^+e^- storage ring:

1 mm^3 of "target" →



Machine	Accelerator	Storage ring
Target mtl.	Liq. hydrogen	Electrons
No. particles	10^{20} (atoms)	10^8
Rel. density	1,000,000,000,000	1

So a real target is about 10^{12} or one trillion times more packed full of things to hit than a storage ring beam. In fact, storage ring beams have just about the same density of electrons or positrons in them as the density of gas molecules in an ultrahigh vacuum system.

So where does that leave us? Well, the designers of storage rings go to a great deal of trouble to try to pack as many particles as possible into the beams. The limits on this beam-packing are sometimes set by the amount of RF power you can afford to pay for to keep the beams circulating, and more fundamentally by the onset of what are called "instabilities," which cause the beams to drive themselves or each other out of stable orbits and thus be lost. As was discussed back on pages *6* and *9*, the luminosity can also be increased to some extent by squeezing the beams down to narrow ribbons at the interaction points. But this and certain other technical tricks that are possible are beyond the scope of this article, so we'll just settle here for the following summary: The luminosity of the SPEAR and DORIS (DESY) storage rings has been good enough to produce a small revolution in physics during recent years, and PEP's luminosity is expected to be higher than SPEAR's.

2. THE ANNIHILATION PROCESS

For more than 40 years it has been realized that each basic form of matter (particles) has an "antimatter" equivalent (antiparticles). The difference between particle and antiparticle is that they possess properties that are either opposite or complementary to each other. The electron, for example, carries one unit of negative electric charge, while the "anti-electron" carries one unit of positive electric charge (which is why it was given the special name *positron*). Because of this oppositeness or complementarity, a collision between an electron and a positron can result in a particular kind of interaction called *annihilation*, which occurs as a two-step process. In the first step, the two particles disappear and a state of pure electromagnetic energy is formed--a *virtual photon* or *virtual gamma ray* (its symbol is γ_V). Then, after an unimaginably brief period of time (about 10^{-25} second), the virtual photon "materializes" into one or more newly created particles. This two-step process can be expressed in the following symbolic form (in which the newly created particles $\pi^+\pi^-\pi^o$ are pi-mesons or pions):

EM: $$e^+e^- \rightarrow \gamma_V \rightarrow \pi^+\pi^-\pi^o$$

We've drawn a circle around the virtual photon intermediate state and added the letters "*EM*" to emphasize the fact that this is an *electromagnetic* process for creating new particles. Now we want to compare this process with what happens at proton accelerators when the high-energy proton beam strikes a stationary proton target and creates new particles:

Strong: $$pp \rightarrow ? \rightarrow \pi^+\pi^-\pi^o pp$$

In this case the same new particles are created ($\pi^+\pi^-\pi^o$), but the creation process is different from that shown above in the following two ways:

1. The more obvious but less important difference is that the two protons (pp) that created the new particles are still left hanging around afterward, whereas the e^+e^- pair has disappeared (been annihilated). If our purpose is to study the pions that are created, then the remaining "spectator" protons serve only to complicate the analysis of what is happening. This is a moderate disadvantage when compared with the "clean slate" left by the e^+e^- annihilation process.

2. The critically important difference occurs in the middle of these processes where the circles are drawn. In the second process, new particles are created through the *strong* or *nuclear* force, and the circled ? expresses the very limited understanding we have of how such strong interactions actually happen. In contrast, the electromagnetic force which governs the first process is by all odds the most completely understood of the fundamental forces in nature. The theory that describes the workings of electromagnetism in the microscopic world of the elementary particles is called *quantum electrodynamics*, or "QED" for short, and it is not an exaggeration to say that QED has been found to be almost perfectly accurate over an enormous range of physical phenomena. So the message here is this:

> The ideal way to explore the *unknown* structure and properties of particles is with the *known* electromagnetic force.

3. WHERE PEP FITS IN

Although there is more that might be said in comparing PEP with conventional accelerators and other storage rings, the foregoing discussion should make it evident that the research carried out with accelerators and storage rings tends to be complementary, with each focusing on what it does best. To end this section, we list below the world's past, present and future collection of large electron-positron storage rings.

ELECTRON-POSITRON STORAGE RINGS

Machine	*Location*	*First Oper.*	*Max. CM Energy (GeV)*	*Note*
ACO	Orsay, France	1966	1.0	syn*
ADONE	Frascati, Italy	1969	3.1	
CEA	Cambridge, Mass.	1971	5.0	gone
SPEAR	Stanford	1972	8	
DORIS	Hamburg, Germany	1974	9	
VEPP-2M	Novosibirsk, USSR	1975	1.3	
DCI	Orsay, France	1976	3.4	
VEPP-4	Novosibirsk, USSR	1978	15	const
PETRA	Hamburg, Germany	1979	38	const
PEP	Stanford	1980	36	const
CORNELL	Ithaca, New York	1980	16	const
CERN LEP	Geneva, Switz.	?	200	study

*Now used as a synchrotron radiation source.

E. EXPERIMENTS AT PEP

As is the case with the present SLAC linear accelerator and research facilities, PEP will be a national facility, available to any qualified scientist or group of scientists on the basis of the scientific merit of the proposed experiment. For some years now, there had been a gradual reduction in the number of accelerator laboratories at which "forefront" high-energy physics research could be done. Most of the important new results in this field have recently come from about five such labs in the US, and perhaps another half-dozen or so in the rest of the world. And the prospect is that even this small number will eventually be reduced even further. This places a strong responsibility upon the remaining labs --the "survivors"--to work not only for the most productive local research program but also for the most productive national and even international program. It's nice to be among the chosen few. Our task at SLAC is to see to it that the choice was a good one.

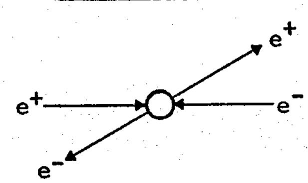
In this section we'll begin by describing in some detail the basic physics of electron-positron collisions at the energies expected for PEP. With this background, we'll then move on to a description of the plans that are now being made for the first round of PEP experiments, including the large new detection devices that are being built for this work.

1. THE BASIC PHYSICS

Lepton Production: Two In/Two Out

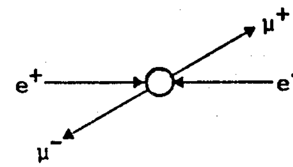
The simplest physical processes that occur in electron-positron annihilation are those in which lepton pairs are created. In the first example, an electron (e^-) and a positron (e^+) collide, and after the collision an electron and a positron emerge. This kind of reaction is called "Bhabha scattering"--named after the Indian physicist who calculated the rate at which it should (and does) happen. Because this reaction is well-understood, it does not have a great deal of physics interest in itself, but for that very reason it is used for calibrating the detection efficiencies of experimental equipment and also for determining the luminosity of the storage ring. The characteristic pattern, or "signature," for Bhabha scattering is e^+ and e^- emerging from the interaction region back-to-back, each particle having the same energy as that of the incoming beam particles.

$$\boxed{e^+e^- \rightarrow e^+e^-}$$



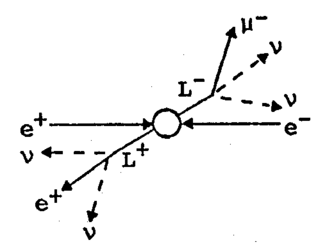
The second example of lepton-pair production is one in which e^+e^- annihilation leads to the creation of two mu-mesons or muons ($\mu^+\mu^-$). In all of their properties except mass, muons appear to be identical to electrons, and it has long been an intriguing question why nature has provided the electron with a big brother some 200 times as massive as itself. The signature for muon-pair production is the same as that for Bhabha scattering, except that we have to distinguish between outgoing electrons and muons. That is, we need to have *particle identification* as well as measurement of the paths following by the outgoing particles.

$$\boxed{e^+e^- \rightarrow \mu^+\mu^-}$$



The mystery of the muon's role in nature may be connected with the third possible example of lepton production. During the last several years, the SLAC-LBL experimental group working at SPEAR has observed a number of so-called "e-μ" events that are difficult to explain in any conventional way. Over time the evidence had gradually grown stronger that these events result from the production and subsequent decay of a pair of "heavy leptons" not previously known. The symbol τ (tau) has recently come into use as a designation for the SPEAR heavy lepton, but we use "L^+L^-" here in order to include any new lepton more massive than the muon that may exist.

$$\boxed{e^+e^- \rightarrow L^+L^-}$$



The experimental signature of heavy lepton production is a complex problem. Such particles will not be directly detectable because they will have lifetimes that are too short--on the order of 10^{-14} second. So their existence will have to be inferred by analyzing the patterns of the particles into which they decay. In the case of the SPEAR events, the observed $e^\pm$ and $\mu^\mp$ are assumed to appear from the decays

$$\tau^\pm \rightarrow e^\pm\nu\nu \quad \text{and} \quad \tau^\mp \rightarrow \mu^\mp\nu\nu,$$

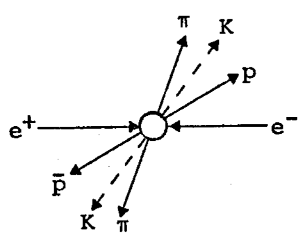
so we've shown these same decay modes for the general heavy-lepton pair $L^\pm$ in the sketch above. A good deal of the difficulty in trying to identify any new heavy leptons unambiguously results from the neutrinos (ν) that appear in the decay products. (There are actually two kinds of neutrinos and two kinds of antineutrinos: ν_e and $\bar{\nu}_e$ go with e^+ and e^-, and ν_μ and $\bar{\nu}_\mu$ go with μ^+ and μ^-. But mostly we just use ν for any or all of them.) These particles have no electric charge, no mass, and nearly no nothing, and for this reason are almost impossible to detect.

Hadron Production: Two In/Many Out

"Hadron" is the name given to any of the large family of particles that are affected by the strong or nuclear force (leptons are those which are not so affected). The best-known members of this family are the proton and neutron that together make up the nuclei of atoms, and the pions (π) and K-mesons (K) that play a role in binding the protons (p) and neutrons (n) together. The hadron family consists of well over a hundred particles or "states," and the search for a simple pattern that may underlie this apparent complexity continues to be one of the central themes in particle-physics research.

In comparison with the two-in/two-out lepton production processes, the creation of hadrons in e^+e^- collisions most often occurs in *multiparticle* or *multibody* reactions. At PEP, it will not be uncommon for a single collision to yield 10 to 20 newly created particles, most of them unstable, and about half of them having no electric charge that can be used as a handle for tracking or particle identification. (The sketch at the right shows a simpler example of the many different possible combinations that can be produced. The dashed line is meant to indicate electrically neutral particles.) Thus hadron-production is too multiple and too various a collection of different processes to have any single experimental signature, and as we'll see later, much of the effort and ingenuity that is going into the new detectors for PEP is directed toward combining several different detection techniques into overall systems of broad versatility.

$e^+e^- \rightarrow 2\pi 2Kp\bar{p}$

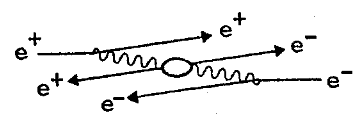


A point of interest in this connection is the fact that multiparticle hadron production at PEP is expected to have a very strong tendency to occur in the form of two oppositely directed clusters of particles called "jets"--as is suggested by the back-to-back pattern of the two groups of particles in the sketch above. The specific directions in which the jet sprays of particles are emitted will vary randomly from event to event, with no one direction preferred over any other. This means that the big PEP detectors must be designed to cover as much of the "solid angle" (the spherical volume surrounding the interaction point) as possible. However, since the bulk of the emitted particles in any particular event will be concentrated in the narrow cone-shaped jets, the detectors must also be designed with enough segmentation or separate little pieces to respond to the individual closely spaced particles within each jet. Thus the problem is not only to cover the whole volume but also to cover each little piece of the volume in detail.

Two-Photon Annihilation: Something New

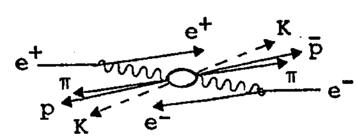
In all of our earlier discussions, both in this and previous articles, we've said that the electron-positron annihilation process proceeds in two steps, with the first step being the creation of a short-lived intermediate state called a "virtual photon" or "virtual gamma ray," which in the second step then materializes into newly created particles. We'd better now give this process a name, *one-photon annihilation* (1γ), because at the higher PEP energies we have to start worrying about an alternate process called *two-photon annihilation* (2γ). Although this 2γ process does occur at SPEAR, it is relatively much less important there than it will be at PEP. The difference between 1γ and 2γ annihilation can be illustrated by comparing the processes in which an e^+e^- pair is created in the two cases. In the 2γ case, the incoming e^+ and e^- are not themselves annihilated. Instead, each emits a photon or gamma ray (∿∿∿), and it is these photons that annihilate, with subsequent production of a new e^+e^- pair. Thus the final state consists of four particles ($e^+e^-e^+e^-$): the incoming e^+e^- which are scattered but not annihilated, and the newly created e^+e^- which emerge from the annihilation of two photons.

$e^+e^- \rightarrow e^+e^-e^+e^-$



Two-photon annihilation can also result in the production of hadrons in a way that may, within certain limits, mimic their production by the 1γ process previously described. At the right we show a 2γ event that is similar to that on the left. An event of this kind is possible but very unlikely, because only rarely will the two photons radiated by the beam e^+ and e^- have enough energy to create as many, and as massive, new particles.

$e^+e^- \rightarrow e^+e^-2\pi 2Kp\bar{p}$



It will be important at PEP to understand the 2γ process for two reasons: (1) The physics is quite different from that of 1γ annihilation, is largely unexplored, and for these reasons may be intrinsically important of itself. (2) As a practical matter, 2γ events at PEP will constitute a large "background" that is mixed in with the usual 1γ physics, and which therefore must be separated out in a known way before the 1γ physics itself can be confidently interpreted.

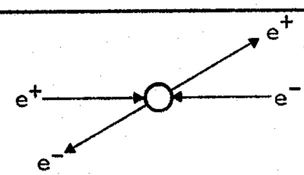
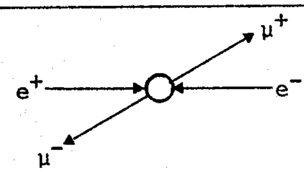
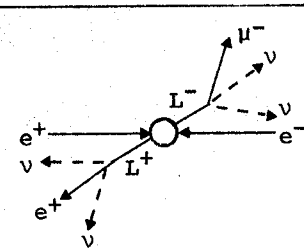
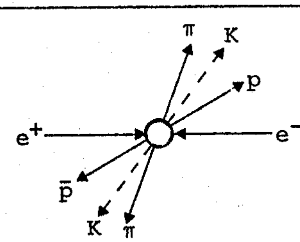
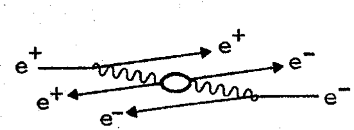
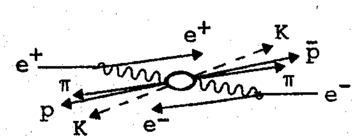
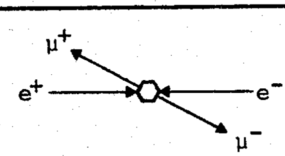
In this connection, the 2γ events will have a characteristic experimental signature that can be used to good advantage: the final particles will be directed preponderantly within narrow cones along the line of the beams. Thus these limited regions can be specially instrumented to assure adequate detection.

Weak-Interaction Effects

The process $e^+e^- \rightarrow \mu^+\mu^-$ (and others) can occur not only through the electromagnetic force, as we've already seen, but also through the *weak* force. At present storage ring energies, such weak-force events are swamped by the much stronger electromagnetic interactions, but at PEP energies the relative strengths will be much closer together. Because of this, it will be very important to try to observe the effects

(The chart below summarizes the basic physics processes we've been describing here.)

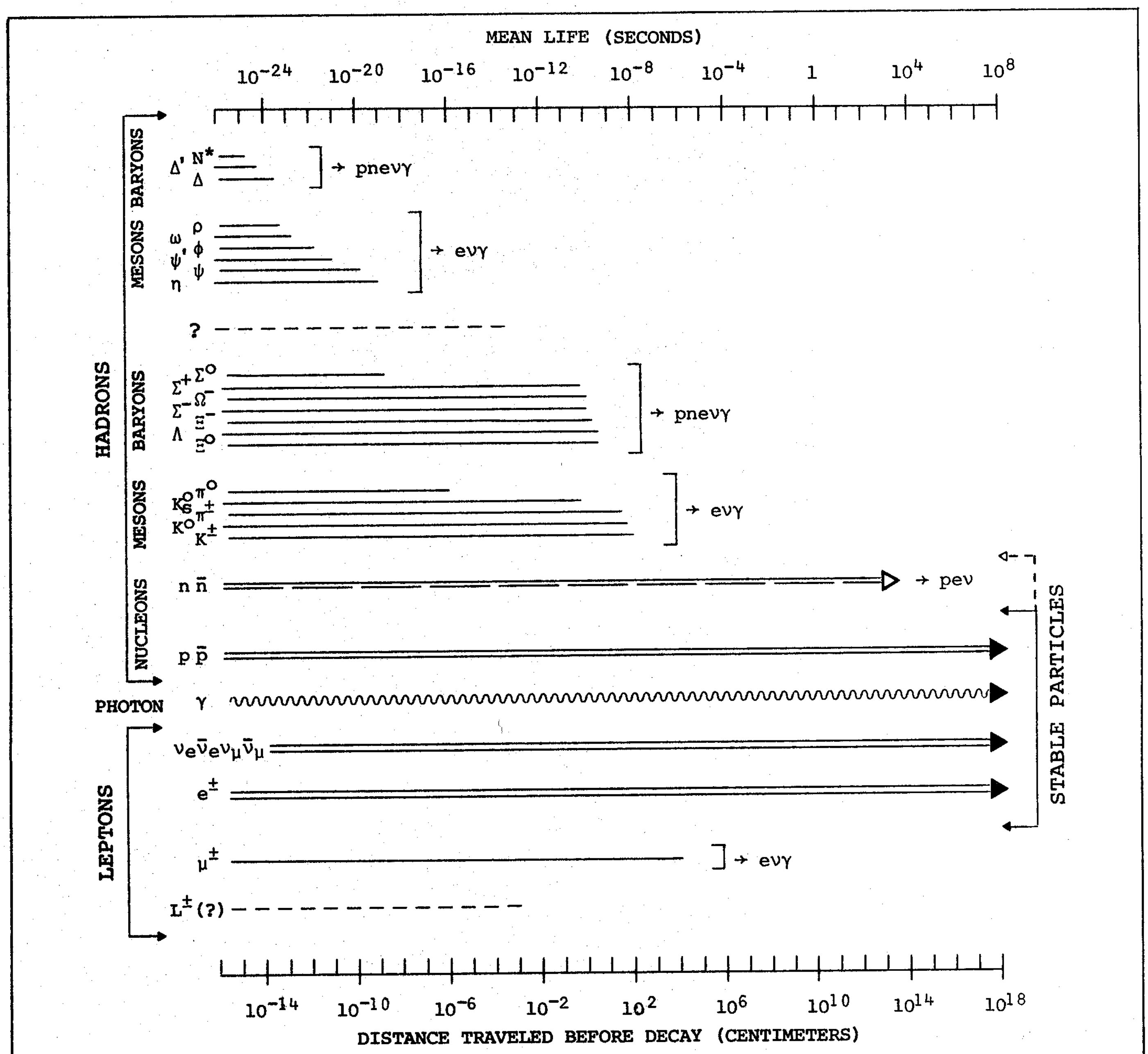
THE BASIC PHYSICS AT PEP

PROCESS	REACTION	DIAGRAM	EXPER. "SIGNATURE" (PATTERN) / NOTES & COMMENTS
ONE-PHOTON ANNIHILATION — LEPTON PRODUCTION — ELECTRONS	$e^+e^- \rightarrow e^+e^-$		e^+e^- emerge back-to-back, each with 1/2 total CM energy. Identified through "showers" of gamma rays and e^+e^- pairs created. Used to calibrate ring luminosity and detector efficiencies.
ONE-PHOTON ANNIHILATION — LEPTON PRODUCTION — MUONS	$e^+e^- \rightarrow \mu^+\mu^-$		Same signature as above, except muons identified by measuring deep penetration through matter. Search for weak-force effects at PEP (see below). Used as a comparison standard in hadron prod.
ONE-PHOTON ANNIHILATION — LEPTON PRODUCTION — HEAVY LEPTONS	$e^+e^- \rightarrow L^+L^-$ $L^+ \rightarrow e^+\nu\nu$ $L^- \rightarrow \mu^-\nu\nu$		Lifetime too short for direct identification; inferred from e-μ events at SPEAR, which are thought to result from the leptonic decay modes shown at left. Is there a sequence of leptons: e, μ, L . . . ? Fundamental issue. SPEAR search for L . . . will continue at PEP.
ONE-PHOTON ANNIHILATION — HADRON PRODUCTION	$e^+e^- \rightarrow 2\pi 2Kp\bar{p}$ (+ many others)		At PEP, often 10-20 particles per event. All particle types possible. Strong tendency for particles to cluster around two back-to-back "jet" axes. Need maximum detection power to track and identify multiparticles. Backbone of SPEAR program and probably also PEP program.
TWO-PHOTON ANNIHILATION — LEPTON PRODUCTION	$e^+e^- \rightarrow e^+e^-e^+e^-$		Most particles emerge at small angles centered around the beam axis. (In contrast, one-photon events have no preferred angular distribution). Important to measure two-photon events because: (1) the physics is quite different and may produce some surprises; (2) must be able to subtract the 2γ "background" in order to understand the 1γ physics.
TWO-PHOTON ANNIHILATION — HADRON PRODUCTION	$e^+e^- \rightarrow e^+e^-2\pi 2Kp\bar{p}$ (+ many others)		
WEAK FORCE — LEPTON PRODUCTION	$e^+e^- \rightarrow \mu^+\mu^-$		Interference between weak & electromagnetic production of $\mu^+\mu^-$ may be seen at PEP as asymmetry in angular distribution. Search for weak-force effects is vital ("carried" by W particles).

of the weak interaction at PEP, and muon-pair production is an experiment that would be well-suited to this purpose. The reason is that weak-force production of muon pairs is expected to interfere with electromagnetic production in a way that will distort the symmetric angular distribution of the latter process. Such an asymmetry would show up, for example, as an excess of positive over negative muons observed at certain production angles. This interference asymmetry is expected to grow with increasing energies, but may still be only marginally detectable even at 18 GeV. This is one of the main reasons for planning an eventual expansion of PEP's beam energy to 23-24 GeV. We'll describe this possible energy-increase program in the last section of this article.

The Particles To Be Detected

We conclude this section by listing, in the following chart, the more common of the hadrons, the photon, and all of the leptons, together with their lifetimes and decay distances (at speeds near that of light). We judge the 938-second life of the neutron to qualify it as "stable." Although the various complex decay modes for the unstable particles are not shown, the end result is that all of them decay into stable particles within about one-millionth of a second. The big detectors are designed to cope directly with these stable particles, and directly or indirectly with the most frequently produced unstable particles: muons, pions and K mesons.



2. DECISIONS, DECISIONS

All going well, the PEP storage ring will begin to operate early in 1980, or perhaps late 1979. To do physics at a machine like PEP will require several large new pieces of experimental equipment similar in scope to such present detectors as the LASS spectrometer, the Mark I magnetic detector at SPEAR, and the Streamer Chamber. The costs of these new detectors for PEP will easily run into the millions, and the time required to design, build and test them will be on the order of 2 to 3 years. A little arithmetic leads to the conclusion that work on these major new detectors should already have started if they are to be ready when PEP is. And in fact the work has already started.

Back in mid-1976, the Directors of SLAC and the Lawrence Berkeley Laboratory (LBL) sent out an invitation to the 1000 or so high-energy experimentalists in the US to prepare and submit proposals for new experimental facilities to be used in the first round of PEP experiments. By the specified submission deadline of December 30, 1976, a total of 9 such proposals had been submitted, representing the work of about 180 physicists from 25 different institutions. These proposals are listed in summary form on the next page.

How to decide? Concurrent with this proposal period, a special advisory group called the PEP Experimental Program Committee (EPC) had been established. The EPC consists of 15 senior physicists from many different institutions, and its first task was to assess the relative scientific merit of the 9 proposals and then to advise the SLAC and LBL Directors on which of the proposals should be chosen. As a part of this evaluation process, a couple of open general meetings were convened at SLAC during the first three months of 1977 to present, discuss and criticize each proposal; to coordinate the planning of cryogenic facilities; and so on. In addition, various sub-committees of the EPC sought out more detailed information from the individual proposing groups, sent out questionnaires to be answered, and invited the groups to submit any additional material they wished as supplements to the original proposals.

D-day arrived when the EPC met at SLAC on April 14 and 15. Tentative recommendations were reached, slept on, rehashed, and finally made firm. The recommendations of the EPC were accepted by the two Directors, and in short order a series of phone calls and formal letters were sent out to each of the Spokesmen for the 9 proposals--winners and losers alike.

The Winners

The proposals that were approved for this first round of PEP experiments were the following:

PEP-5
PEP-6
PEP-4 + PEP-9

(PEP-2 is a much more modest proposal than the others, and it will not be acted upon until a later time.) Although four proposals were approved, PEP-4 and PEP-9 will be combined into a single large detection system (as PEP-9's proponents had proposed) for use in one of the interaction regions. Thus 3 of the 6 PEP interaction regions were committed by these decisions, as had been intended. This leaves 2 interaction regions still available for experiments that are yet to be chosen, while the 6th is being reserved for studies of the PEP storage ring itself.

A call for the second round of PEP proposals has recently gone out to the experimental community, with the deadline for submission set for October 30, 1977, and with decisions on this second round to be reached no later than February 1, 1978.

3. THE FIRST-ROUND DETECTORS

An ideal experimental detection system for PEP would be able to measure with high precision both the energies of and the paths followed by all of the particles that emerge from the beam-interaction regions. This would include both charged and neutral particles, and it would also be able to identify unambiguously each particle by type. In addition, the ideal system should be able to collect data at a very rapid rate, carry out some rough analysis of the data with a local computer as it comes in, and and perhaps also pass on the data for permanent recording to the SLAC central computer facility. The system to accomplish all this should be designed, built, tested, debugged and christened in time to receive the first PEP beams some 30 months from now, and the whole project from soup to nuts should preferably cost something less than Disneyland.

Although there ain't no such thing, there have been some ingenious compromises worked out by the proponents of PEP-4,5,6 and 9, and the instruments they have imagined seem likely to milk a great deal of interesting physics out of PEP. Here they are.

PEP-6: MAC

"MAC" or "Big MAC" is the unregistered trademark of the physics group from five different universities that plans to build a magnetic calorimeter for use in muon physics, new particle searches, and total cross section measurements. We consider first their general approach to the problem of identifying muons. Muons are distinguishable from other particles by their ability to penetrate deeply into matter with

PEP EXPERIMENTAL PROPOSALS - FIRST ROUND

PEP-1: A GENERAL MUON DETECTOR FOR PEP	U. Washington	Cook, Mockett, Rothberg
	U. Wisconsin	<u>Williams</u>, Young, Benvenuti, Camerini, Cline, Learned, March, Morse, Reeder, Resvanis, Rhoades
PEP-2: SEARCH FOR HIGHLY IONIZING PARTICLES	SLAC	Fryberger
	UC-Berkeley	Price
PEP-3: PEP SPECTROMETER FACILITY	Argonne Nat. Lab.	Cho, Derrick, Jaeger, Singer, Schreiner, Ward
	Indiana U.	Brabson, Gray, Neal, <u>Ogren</u>, Rust
	U. Michigan	Akerlof, Meyer, <u>Thun</u>
	Northwestern U.	Buchholz, Gobbi, Miller
	Purdue U.	McIlwain, Loeffler, Miller, Shibata
PEP-4: TIME PROJECTION CHAMBER FACILITY	LBL	Clark, Dahl, Eberhard, Fancher, Galtieri, Garnjost, Kenney, Loken, Kerth, Madaras, <u>Nygren</u>, Oddone, Pripstein, Robrish, Ronan, Shapiro, Strovink, Wenzel, Urban
	UC-Los Angeles	Buchanan, Hauptman, Slater, Stork, Ticho
	Yale U.	<u>Marx</u>, Nemethy, Zeller
	UC-Riverside	Gorn, Kernan, Layter, Shen
	Johns-Hopkins	Barnett, Chien, Madansky, Matthews, Pevsner
PEP-5: GENERAL SURVEY OF PARTICLE PRODUCTION	SLAC	Alam, Boyarski, Breidenbach, Dorfan, Feldman, Fischer, Hanson, Hitlin, Jaros, <u>Larsen</u>, Luke, Martin, Paterson, Perl, Richter, Schwitters, Tanenbaum, Taureg, Weiss
	LBL	Abrams, Broll, Carithers, Chinowsky, DeVoe, Goldhaber, Johnson, <u>Kadyk</u>, Pang, Shannon, Trilling
PEP-6: LEPTON/TOTAL-ENERGY DETECTOR	U. Colorado	Bartlett, Ford, Nauenberg, Smith
	Northeastern U.	Faissler, Gauthier, Gettner, Gottschalk, Mallary, Moromisato, Pothier, Potter, von Goeler, Weinstein
	Stanford/SLAC	Ash, Gustavson, Rich, Ritson
	U. Wisconsin	Aronson, Johnson, Morse, <u>Prepost</u>, Wiser
	U. Utah	Groom, Loh
PEP-7: A PEP STREAMER CHAMBER FACILITY	UC-Santa Cruz	Dorfan, Flatte, <u>Heusch</u>, Schalk, Seiden, Smith
	LBL	Ely, Gidal
	U. Michigan	Chapman, Seidl
	SLAC	Bunnell, Mozley, Odian, Wang
PEP-8: A MAGNETIC DETECTOR FOR PEP	Brown U.	Cutts, Lanou, Massimo, Dulude
	CalTech	<u>Barish</u>, Bartlett, Gomez, Pine, Linsay
	MIT	Brandenburg, Busza, Friedman, Halliwell, Kendall, Nelson, Osborne, Rosenson
	SLAC	Atwood, Carroll, Chadwick, Cottrell, DeStaebler, Moffeit, Prescott, Rochester, Sherden, Sinclair, Taylor, Kirkby, Wojcicki
PEP-9: PEP FORWARD DETECTOR FACILITY	UC-Davis	Klems, Ko, Lander, Pellett, Lander
	UC-San Diego	Lyon, <u>Masek</u>, Miller, Vernon, Wallace
	UC-Santa Barbara	Caldwell, Eisner, Morrison, Yellin

Underline indicates spokesmen.

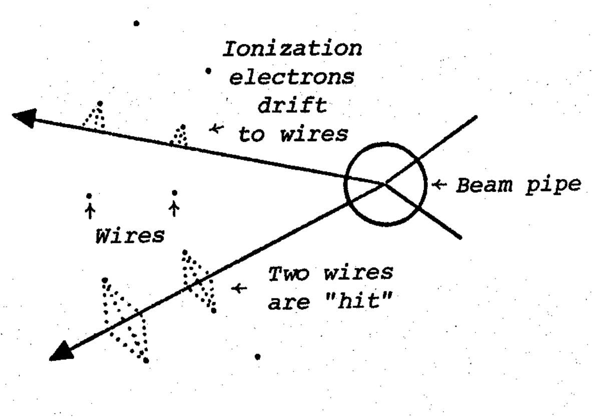
comparatively little loss of energy. So the obvious solution is simply to surround the interaction region with a shell of material that is thick enough to stop everything but the muons, and then to count the muons that actually come through with a suitable array of detectors.

But there are some problems. One is the fact that the region immediately surrounding the interaction point has to be used for finding the tracks of the particles, rather than for absorbing them, and so the shell of material needs a fairly large hollow core. And at PEP energies the shell thickness needed to discourage everything but muons is about 3 feet if the shell is made out of the customary iron. After making some other allowances for various odds and ends, the end result of a simple idea turns out to be the ≈ 500-ton iron barrel that is shown in the MAC layout sketches on the next page.

Referring to this figure, let's now look briefly at the functions that are served by each of the main sub-systems in MAC, starting at the beam and working our way radially outward.

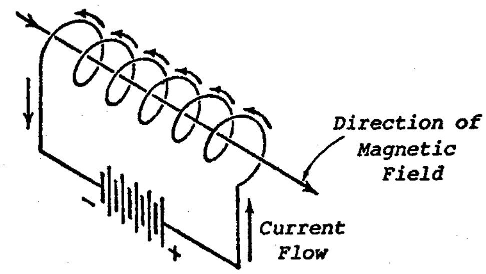
Core Drift Chamber: Tracking & Momentum Analysis

Surrounding the beam pipe is a cylindrical chamber about 2.3 meters (m) long and 1 m in diameter. Inside this chamber are four concentric layers of fine wires that are stretched along the length of the cylinder to form a drift chamber. The purpose of this drift chamber is to measure the paths or tracks followed by the charged (and thus ionizing) particles that emerge from the beam pipe. Schematically, what happens is the following:



In an actual wire drift chamber of this kind, the wires are spaced much closer together (typically 1 cm) than the sketch implies. In addition, the electronics measures the time required for the electrons produced by ionization to drift to each of the wires that is "hit," so the actual particle trajectories can be determined more accurately than the spacing between adjacent wires.

The drift chamber has wrapped around it a coil of heavy alumininum conductor that is used to produce a magnetic field up to about 5 kilogauss throughout the volume of the chamber. A magnetic configuration of this kind is called a "solenoid," and it produces a magnetic field whose direction is parallel to the axis of the coil and thus of the beam path:

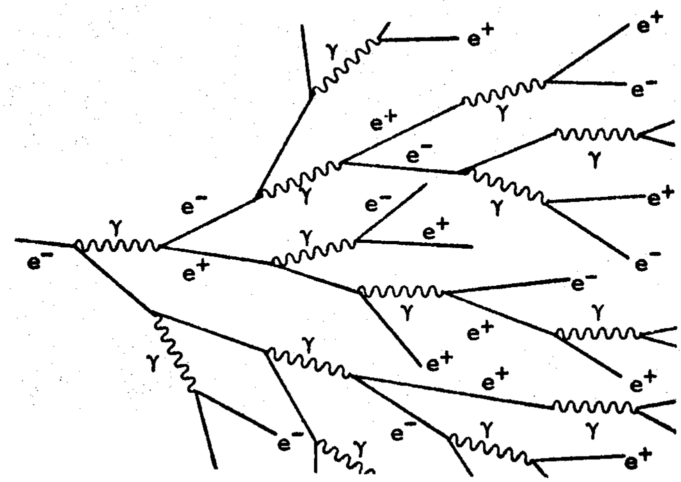


This solenoidal magnetic field causes the charged particles passing through the chamber to be deflected and thus to follow curved rather than straight trajectories. It is difficult to draw a two-dimensional picture of the tracks because they have a complicated helical form, but what happens can be summarized in the following way: (1) Positive and negative particles are deflected in opposite directions. (2) Particles with high momentum are deflected less than those of low momentum. (3) Particles emerging at 90° with respect to the beam direction are deflected more than those emerging at smaller angles.

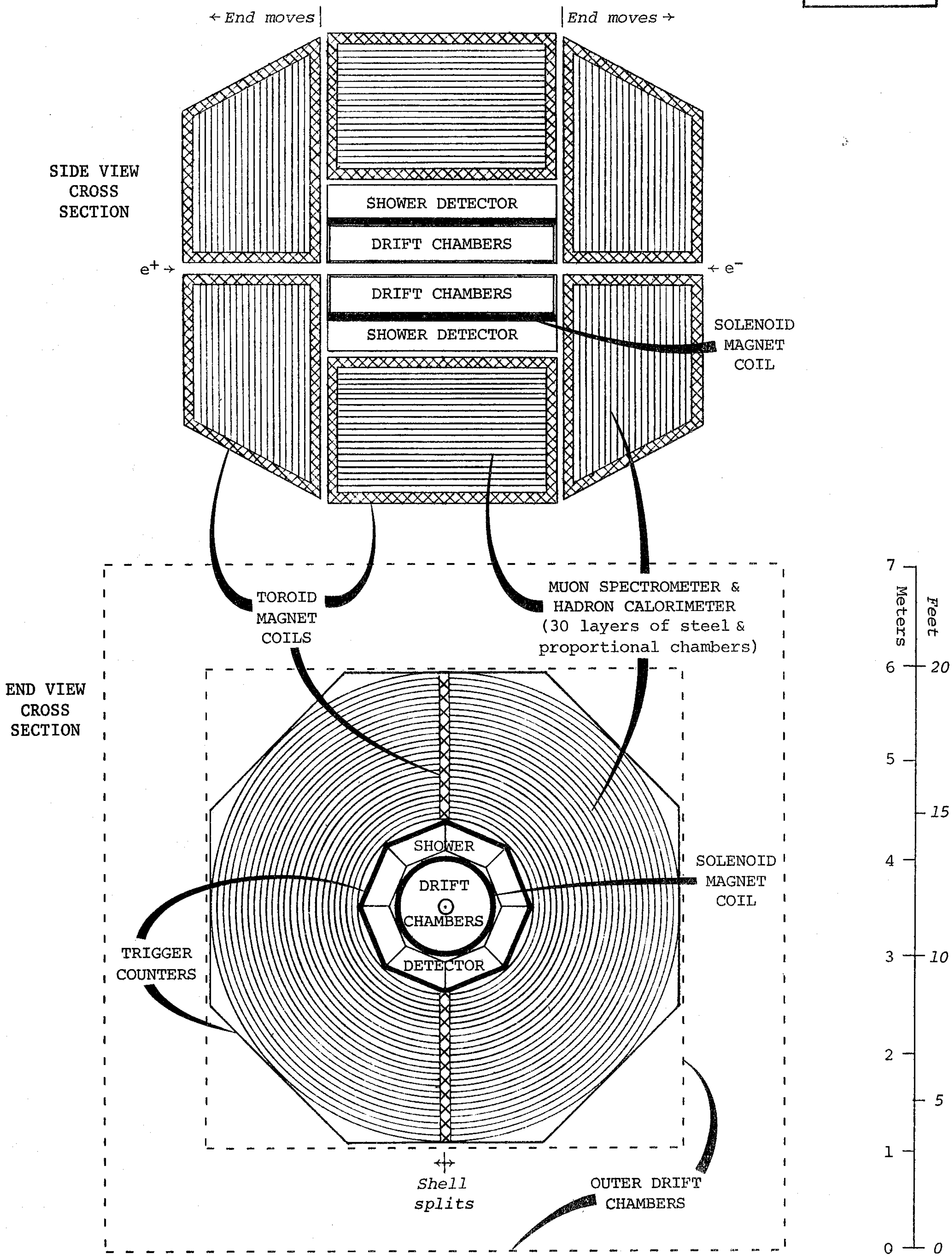
The curvature of the particle trajectories, as determined by the succession of hits on the drift chamber wires, thus provides information that can be used to deduce the momentum of each of the observed particles.

Shower Detector

Moving outward from the drift chamber and solenoid magnet coils, we come next to the system that is designed to identify electrons (e^-), positrons (e^+) and gamma rays, and also to measure their energies. The experimental signature for these particles is an *electromagnetic shower*, and what is meant by "shower" is the following:



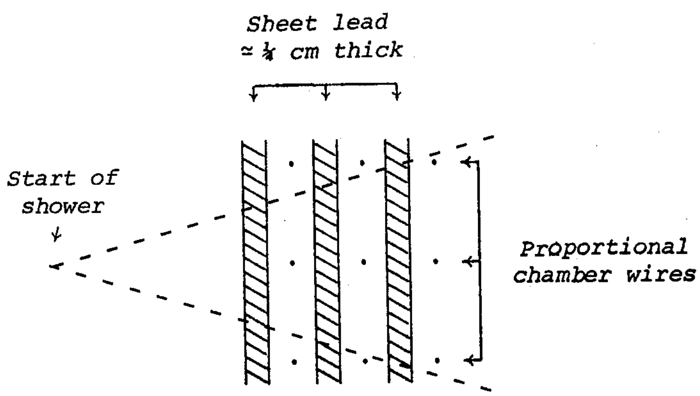
PEP-6: MAC



← End moves
End moves →
SIDE VIEW CROSS SECTION
SHOWER DETECTOR
DRIFT CHAMBERS
e+ →
← e−
DRIFT CHAMBERS
SHOWER DETECTOR
SOLENOID MAGNET COIL
TOROID MAGNET COILS
MUON SPECTROMETER & HADRON CALORIMETER (30 layers of steel & proportional chambers)
END VIEW CROSS SECTION
SHOWER
DRIFT
CHAMBERS
DETECTOR
SOLENOID MAGNET COIL
TRIGGER COUNTERS
Shell splits
OUTER DRIFT CHAMBERS
Meters
Feet
0
1
2
3
4
5
6
7
0
5
10
15
20

This multiplying cascade can be initiated by e^-, e^+ or γ. The higher the energy of the initiating particle, the larger the shower will be in both the number of particles created and the depth to which they penetrate.

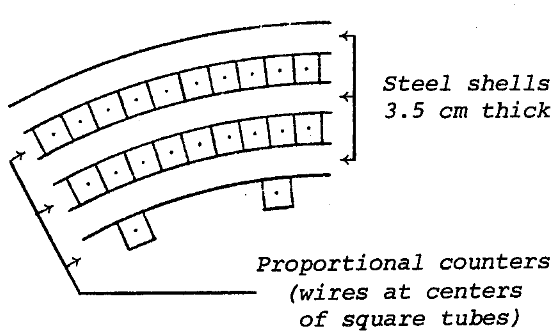
In MAC these electromagnetic showers will be detected in an eight-sided structure that consists of 30 alternating layers of dense material (lead) and electronic counters (proportional wire chambers). A small section of this 30-layer sandwich will look something like this.



Proportional wire chambers work in about the same way as drift chambers do--that is, by collecting the ionization electrons that are knocked loose by the charged particles in the shower. What is "proportional" about these chambers is the fact that the magnitude of the output signal from each wire depends upon how many electrons it collected. (Some wire chambers simply scream "I've been hit!" rather than calmly stating "I have received a hit of the following size.") Thus by adding up the signals from each of the wires that responded to a shower, a reasonably accurate indication of the energy of the initiating particle can be obtained.

Muon Spectrometer & Hadron Calorimeter

The bulk of Big MAC consists of a massive laminated iron-and-detector barrel that surrounds the central core region of the device. As before, there will be 30 interleaved layers of dense material and electronic counters, with the structure shown in the following partial cross section:



The total thickness of the 30 layers will be about 150 cm, with the iron (steel) shells making up about 2/3 of this thickness. Detection of charged particles is again done with proportional counters, but this time each wire is enclosed within its own section of square tubing.

Muons. The first of the two functions served by the big barrel is to identify muons and to measure their momentum. Muons will be distinguished from other charged particles by the fact that they lose energy less rapidly than the others--and thus produce smaller signals in the proportional tubes--as they pass through the successive layers of the barrel. The magnetic field needed to provide momentum information (by deflecting the particles) is provided by the set of "toroid magnet coils" shown on page *31*. The direction of the magnetic field produced by these coils is not parallel to the beam axis, but its overall form is something like that of a doughnut (toroid). At any rate, by following the curved trajectories of the muons through the barrel, their momenta can be determined to an accuracy of about 20%.

Hadrons. The second of the barrel's two functions is to measure the total energy that is carried by hadrons in each event. In contrast to muons, many of which will penetrate completely through the barrel's 30 layers, all of the hadrons will be stopped sooner or later within the iron (including the neutral ones). What happens is that the hadrons undergo a series of collisions with both the nuclei and the electrons of the iron atoms, and these collisions eventually result in the initial energy being spread over a large number of low-energy charged particles or ions. Although different in character from an electromagnetic shower, this hadron-induced spray of secondary particles can be measured in a similar way by the proportional counters interleaved between the steel sheels.

(Total absorption of the hadron energy within the laminated barrel structure has led to the name *Hadron Calorimeter*, which literally means "calorie measurer." The analogy is with an old tried-and-true technique for measuring difficult forms of energy--light, mechanical, chemical--by absorbing it totally in some heavy body and measuring the resulting rise in temperature. This is not exactly what MAC will do, but the idea seems close enough to permit the use of a good name.)

The calorimeter should respond to almost all of the events in which hadrons are created, but not to the usual background events because they will not in general produce a large enough signal. This characteristic will provide a useful technique for measuring the total cross-section (probability) for electron-positron annihilation, and it will do so in a way that is different from (and thus complementary to) that of any of the other detectors at PEP or at PETRA.

PEP-5: MARK II

The Mark II magnetic detector, shown below, is the same device that is now being readied for installation at SPEAR during the next few months. In the discussions leading to the selections of the first-round detectors for PEP, it was perhaps natural that Mark II got special consideration. Apart from its inherent abilities, which are substantial, the Mark II will have two unique advantages going for it: (1) it is certain to be ready on time, and (2) it will have accumulated about 18 months of operating experience by the time it moves to PEP. (During the meetings it was a little odd to hear this experience factor alluded to by describing the still-unfinished Mark II as "the old warhorse.")

The Mark II detector was described at some length in an article in the June 1976 issue of the *Beam Line*, so in the following we'll give only a brief description by using some of the information from this earlier article.

Tracking and *momentum measurement* of charged particles in Mark II is handled by a cylindrical drift chamber immersed in a solenoidal magnetic field in a system much like that of Big MAC.

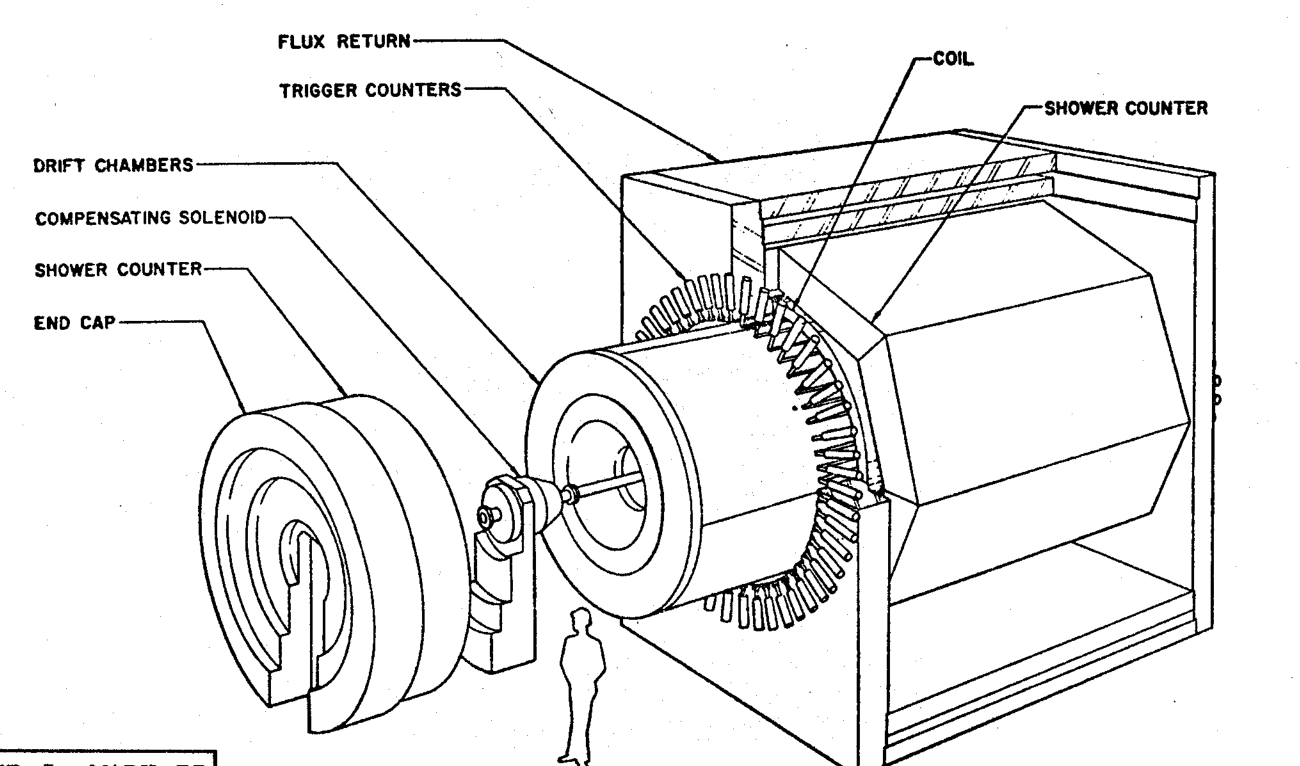
Shower Counter

The method for identifying electrons, positrons and gamma rays in Mark II is distinctive enough to merit separate attention. As with MAC, Mark II's shower counter will be contained within an eight-sided structure (plus two end-cap sections), but the shower will develop in a series of lead sheets alternating with lead collection strips (rather than sensing wires), and the ionizing medium will consist of a liquid-argon bath rather than the more common mixture of gasses. The ionization electrons produced in the argon will generate proportional signals in the strip sensing elements, and these signals can be analyzed to give an accurate measurement of both the direction and the energy of the initiating particle.

The energy resolution that can be obtained with this lead/liquid argon shower detection system is not as good as that of such special materials as sodium iodide crystals or lead-loaded glass, but the cost of these materials becomes prohibitively high when the whole region around the interaction point has to be covered. An important virtue of the lead/liquid argon technique is that it provides a very accurate picture of the spatial development of the shower as it spreads through the layered structure of the counters.

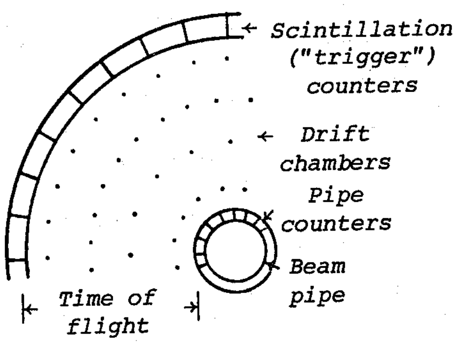
Hadron Identification

The lead/liquid argon counters just described will be useful within certain limits in distinguishing between electromagnetic showers and the "hadronic showers" we talked about in con-



PEP-5: MARK II

nection with MAC's hadron calorimeter. But the chief method for identifying charged hadrons in Mark II will be the technique known as "time-of flight." The general idea is the following:



We've already seen how track curvature can be used to determine a particle's momentum. The time-of-flight system provides an accurate measurement of the time required for a particle to travel from the inner pipe counter to any of the 48 "trigger" counters that form a cylindrical array around the drift chambers. Knowing time and distance, this measurement thus determines the particle's velocity, and the combination of velocity and momentum uniquely determines the mass of the particle and thus its identity:

$$\text{mass} = \text{momentum} \div \text{velocity}$$

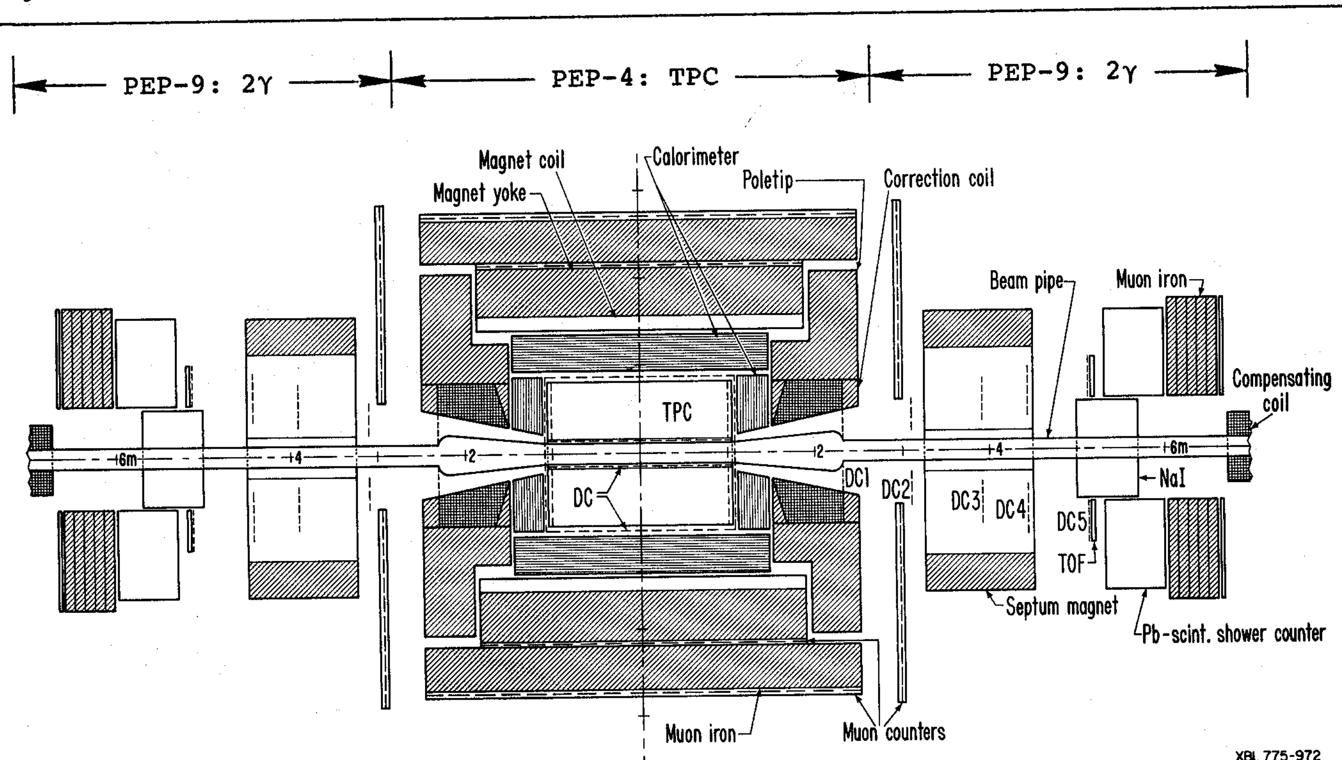
The trigger counters are actually long slabs of a special plastic material that emits flashes of light or *scintillates* when struck by a charged particle. Such scintillators are well suited to the fast timing needed in this system.

PEP-4: TPC + PEP-9: 2γ

We come last to the combined PEP-4/PEP-9 experimental facility for PEP. The designation "2γ" for PEP-9 expresses the fact that this facility is intended to handle the *two-photon annihilation* physics that we talked about back on page *25*. The PEP-9 proponents specifically intended that their facility should form the 2γ "bookends" on either side of a large central detector designed mainly for 1γ physics, and PEP-4 was chosen as that central detector. A general layout of the combined facility is shown below. We'll discuss PEP-4 first, then take up PEP-9.

TPC

"TPC" stands for "time projection chamber," which is the heart of the PEP-4 facility. In the drawing below, note that several sub-systems within the complete PEP-4 package are similar to those we've already described: muon counters located behind thick sections of iron absorber, a calorimeter, and a number of drift chambers (labelled "DC" in the drawing). The central chamber is also immersed in a solenoidal magnetic field, as before, but in this case the magnet is superconducting. What is new about PEP-4,

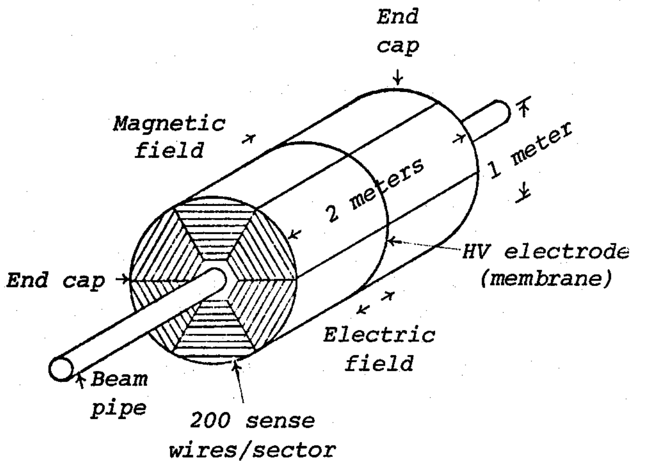


DC = Drift chambers

essentially, is the time projection chamber itself, and it is this remarkable device that we will focus on.

Time Projection Chamber

The TPC is an imaginative variation on the theme of drift and proportional wire chambers in which charged particles pass through a large volume of high-pressure gas, leaving an ionized trail. The chamber is divided in the center by a thin membrane which is used as a negative high-voltage electrode and thus creates an electric field within the volume of the chamber, with the field direction being opposite on the two sides that are separated by the membrane. Here's the general idea:



Each of the six sectors of the end caps contains about 200 sense wires, rather than the few shown in the sketch.

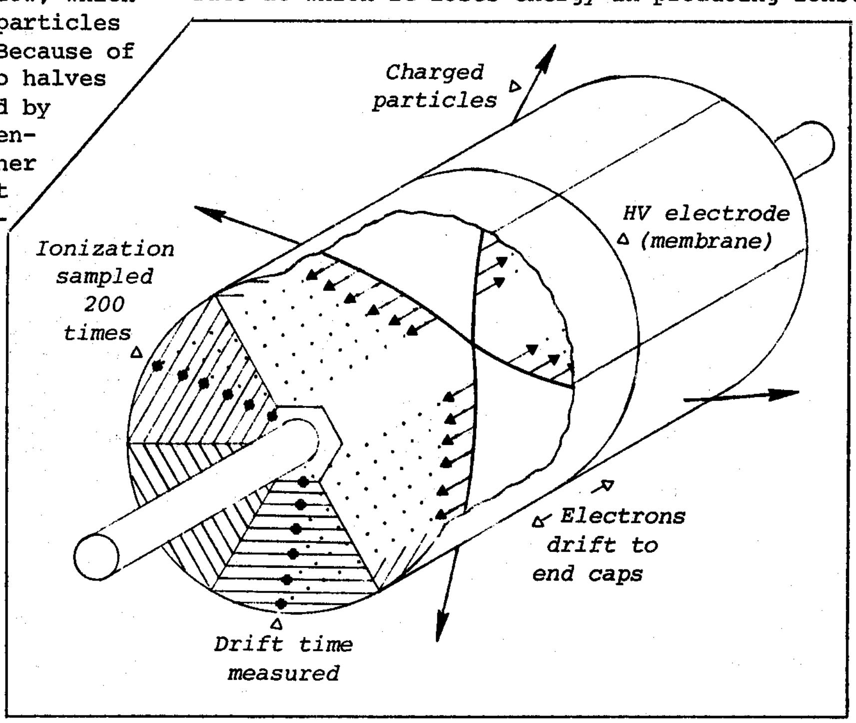
We can get a picture of what happens inside the TPC by using the larger sketch below, which shows an event in which four charged particles emerge from the interaction region. Because of the reversed electric field in the two halves of the chamber, the electrons produced by ionization will drift away from the center membrane and toward one or the other of the end caps. With such long drift distances (as much as 1 meter in either direction), it might be expected that the drifting electrons would disperse, but the parallel magnetic and electric fields constrain the electrons to travel toward the endcap wires in fairly straight trajectories. At the end of the drift, the ions are collected by the wires and thus produce an output signal. (Note in the sketch that "hits" are shown only on alternate wires for clarity. In fact the hits would occur on each of the ≈ 200 sense wires in a sector for the particle trajectories shown here.)

We can now summarize the kinds of information that result from the TPC system in the following way:

Three-dimensional tracking. The path followed by the particle through the chamber is immediately given in two dimensions by the sequence of hit-locations along the wires. (The location on each wire is actually determined by signals induced in a series of ground-plane pads that are not shown in the sketches.) The third dimension is added by measuring how long it takes the electrons from the different parts of the particle track to arrive at the the respective wires that record them.

Momentum measurement. As with the other detectors we've discussed, the TPC uses a solenoidal magnetic field to deflect charged particles into curved trajectories, and the degree of curvature and thus the particle's momentum is given automatically by the three-dimensional reconstruction of its track.

Particle identification. The time projection chamber would be an impressive device if it did no more than provide tracking and momentum measurement in the novel way described above, but it actually has yet another very important feature. It turns out that the end-cap wire arrays can also measure the amount of ionization that occurs at each of ≈ 200 different points along the track, and this information can be used in the following way. The amount of ionization produced by a particle in a certain distance of travel depends not only upon its momentum but also its mass. If we take as an example the particles e^+, π^+, K^+ and p, with each having exactly the same momentum, then it will generally be easy to distinguish the e^+ from the three hadrons by the significantly different rate at which it loses energy in producing ions.



The differences among π^+, K^+ and p are much smaller, and they also change in a complex way at different values of momentum. The great advantage of the TPC in this regard is that it will sample the ionization many times along each track, and by averaging all these samples together even very small differences can be pinned down as statistically significant. Thus by relating ionization to mass, the TPC will accomplish particle identification within the same system that also gives three-dimensional tracking and momentum measurement. Wow.

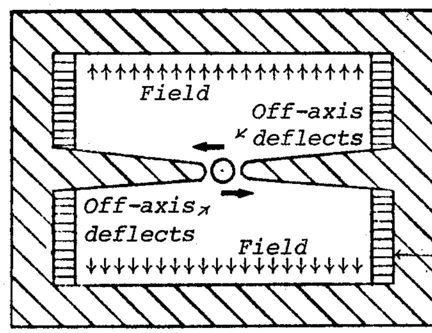
$\boxed{2\gamma}$

The drawing at the lower right shows a cross section view, in perspective, of one of the two identical detection systems that will be provided by PEP-9 for coverage of events in which the particles emerge at small angles with respect to the beam direction. Working from the left in toward the interaction region (I.R.), muons will be identified with a conventional system consisting of several layers of counters and iron absorbers. Then comes a composite shower-counter system, the septum magnet, and a series of drift chambers (DC-1, etc.) placed between successive elements in the system. We single out for special attention the septum magnet and the shower counter systems.

Septum Magnet

As we noted earlier, the usual experimental signature for the events resulting from two-photon annihilation is that the beam electrons and positrons that emit the two photons are themselves deflected only slightly as a result. This means that in many cases the scattered e^+ and e^- will emerge along trajectories so close to that of the beams that it will be difficult or impossible to detect them. But such detection (called "tagging") is important if 2γ processes are to be recognized, and the purpose of the septum magnet is to reach in close to the beam and pull the particles out to a position in which they can be detected.

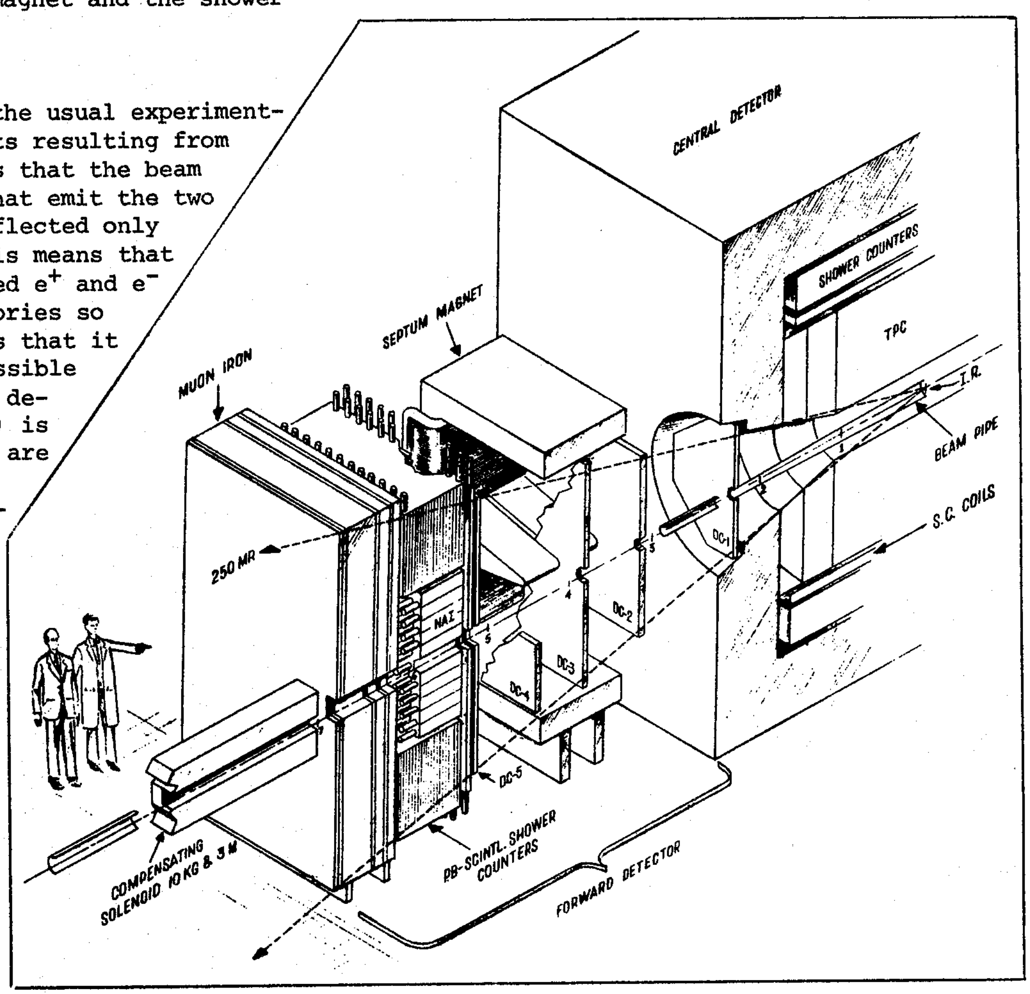
The sketch at the top of the next column shows how this is accomplished. In full cross section, the septum is a modified form of "H" magnet (this one is often called the "beltbuckle") in which one of the two coils is wired backwards. This has the necessary result that the



magnetic field along the axis is zero, so the stored beams themselves are not affected. But particles that are off-axis, either above or below the center, will be deflected sideways farther away from the axis, and will thus move out to where the following devices can see them.

Shower Counters

This composite system consists of a core section of sodium iodide (NaI) crystals, and an outer section of scintillation counters loaded with lead (Pb). These are the best and most expensive materials for the purpose, as we noted earlier, and their use in this application is affordable because only reasonable quantities are needed for the small-angle coverage.

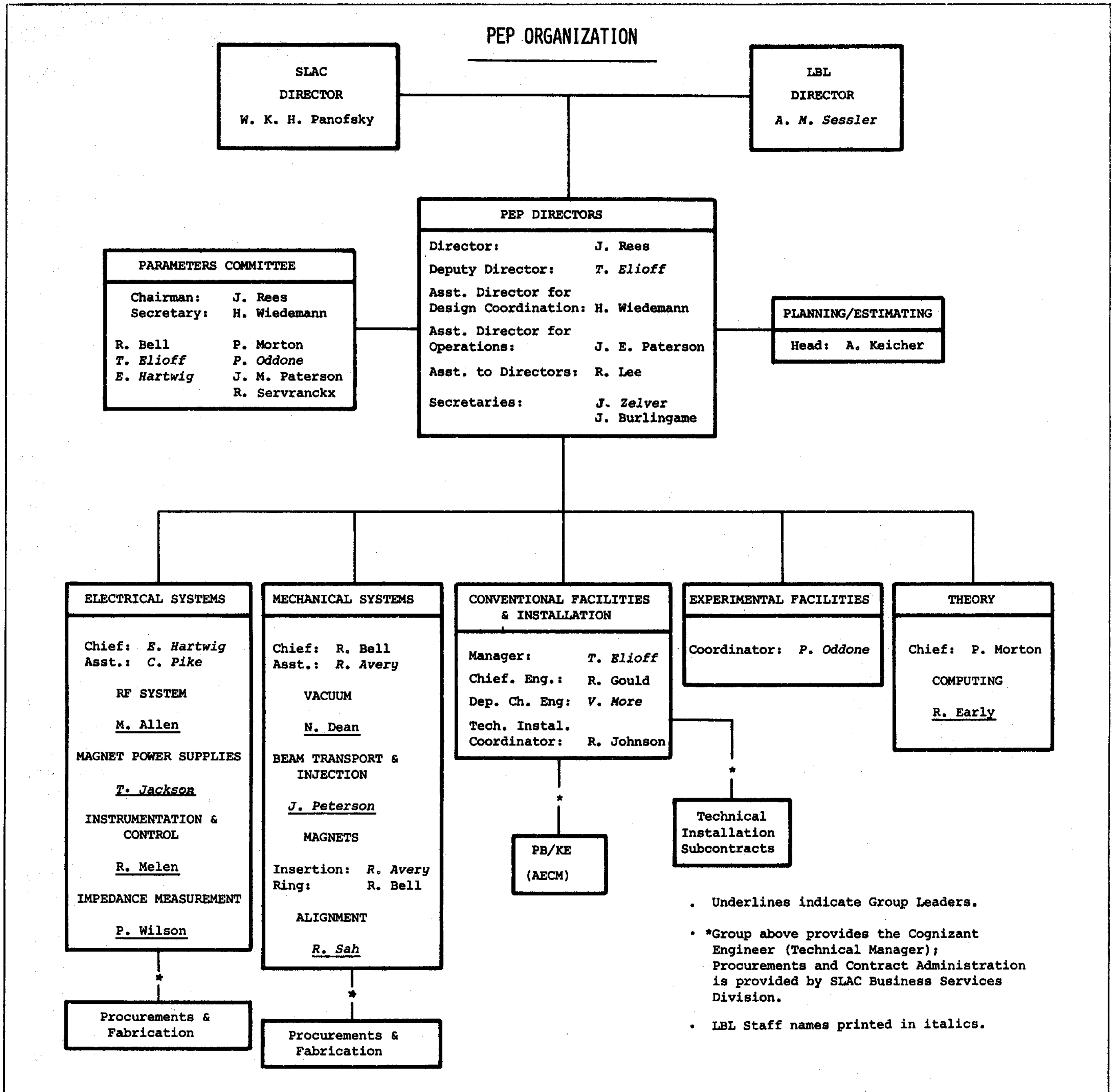


F. ADMINISTRATIVE & MISC.

In this concluding section, we give some information about the PEP organization, and about project management and costs. Then we'll also give a brief description of the possible future options that exist for expanding the research potential of PEP.

1. PEP ORGANIZATION

PEP is a joint undertaking of SLAC and of the Lawrence Berkeley Laboratory (LBL). The chart below shows the individuals from SLAC and from LBL (names in *italics*) who form the core of the PEP organization. There are other persons who work in the groups that are shown, and at any given time PEP work is also being done in the shops, drafting rooms, engineering departments, etc., of the two laboratories. Some of the reasons for this method of organizing the project--in which a relatively small central group draws upon the services of the other parts of the two labs as needed--are discussed in the fol-



NOTE: This chart shows structure to the level of the system group. For a list of personnel working in the groups, and for any organizational structure internal to the groups, a separate listing is maintained in the PEP Director's Office.

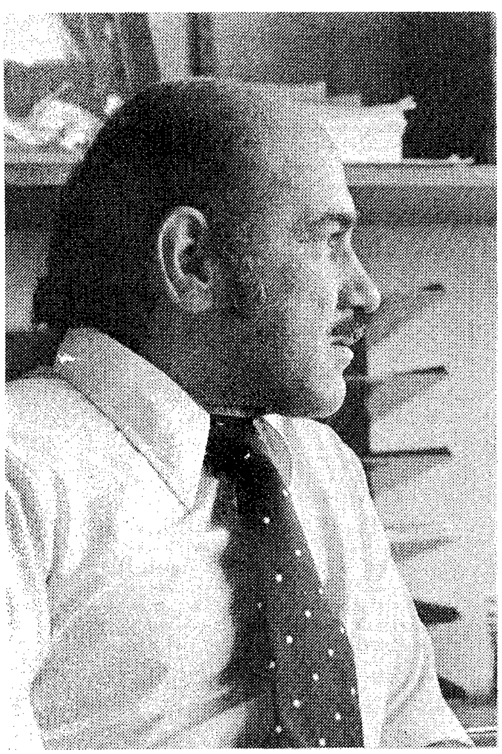
lowing section.

2. PROJECT MANAGEMENT & COSTS

Building a big machine like PEP presents management problems as well as technical problems. The particularly rigorous dimension of the management problem is control of the budget. Consider the case of PEP: a $78 million construction program spanning four years. Unlike many other expenditures of public funds, it is the tradition in high-energy physics that big machines get built "on budget." That is, you don't go back and ask for more money to finish the project. And this is true despite the fact that each large new machine is a unique device, with many innovative technical systems, and also despite the fact that the money to build the machine has to be asked for before the machine itself has been designed.

In addition to the technical uncertainties, there are also market uncertainties--the construction industry in particular has recently been experiencing rapid cost inflation. On the other hand, some parts of the construction industry may be temporarily depressed, and a contractor may choose to bid low just to keep his organization afloat until business picks up. In short, when the construction bids come in, there may be some surprises, both good and bad.

A third cost-management problem comes from the sheer rate of spending that is necessary to get the work done. In the peak spending year



PEP Deputy Director Tom Elioff of LBL.
(Photo by Joe Faust.)

PEP Director John Rees of SLAC.
(Photo by Joe Faust.)

for PEP, Fiscal Year 1978 (which starts in October 1977), the project will be committing money at the rate of about $120,000 *every working day*. At that rate, even the most accurate and prompt accounting system may not pick up potential problems before things go seriously awry.

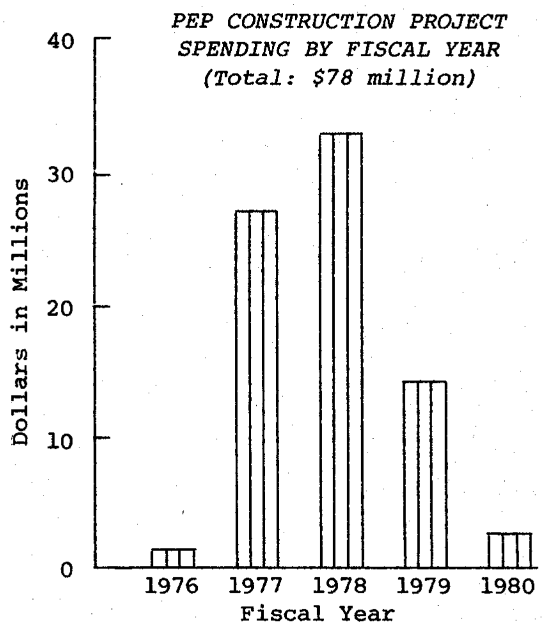
What to do about all these problems and uncertainties? One approach is to form a vast bureaucracy to keep track of everything, right down to the last nut and bolt. There are plenty of examples, often in military projects, which show that the bureaucratic approach doesn't work very well. And even worse is the fact that, at the end of it all, you are still stuck with the bureaucracy that you created to keep control of things. Then pretty soon it becomes evident that the bureaucracy is eating up all the money that might have been spent on hardware.

The alternative to the bureaucratic approach is one of keeping your options open.

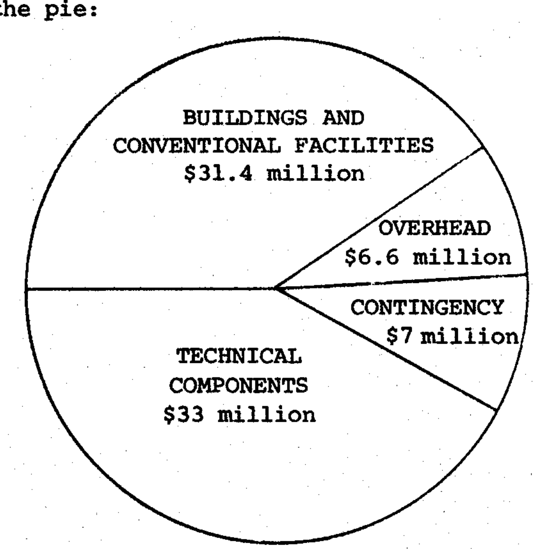
In the case of PEP, this is being done in two ways. The first is the conventional way of setting aside a certain fraction of the total funds as contingency, to be used as late in the game as possible and only to cover emergencies. For PEP, this contingency amounts to about $7 million, or about 9% of the total cost.

The second approach is to be willing to forego certain conveniences or operational possibilities that do not affect the essential scope of the project. As an example, the experimental area in Region 6 at PEP is presently planned for only partial development, with additional facilities to be added only as the funding picture and the program needs become clearer. If the cost experience looks good, it may be possible to move ahead with some additions of this kind.

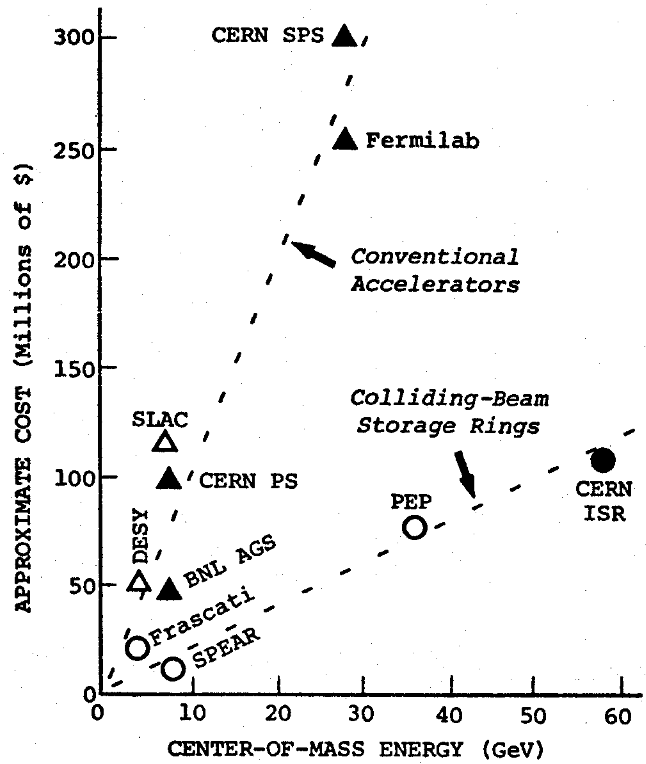
The total cost of PEP, as noted, is estimated to be $78 million. The heaviest spending years will be this year and the year following. This spending schedule is shown in the following figure:



The way in which the money will be spent can be divided into two large pots and two small pots. The two large pots of almost equal size are the "conventional facilities" (tunnels, buildings, roads, utilities) at $31.4 million; and the magnets, electronics, vacuum and RF components, etc., at $33 million. The two smaller pots are also of almost equal size: the overhead costs of administrative services, fringe benefits and other indirect costs at $6.6 million; and the contingency fund of $7 million. All of which looks like this in terms of slices of the pie:



In a more general vein of cost comparison, it may be of interest to amplify our earlier remarks about storage rings being a relatively economical way to achieve high center-of-mass energies in relation to conventional accelerators. In the following figure we show a number of large accelerators and storage rings plotted according to their CM energies and approximate costs.



Conv. accel: ▲ proton beam; △ electron beam
Collid. beam storage ring: ● pp; ○ e^+e^-

The relative costs given in this figure may be inaccurate to a certain extent, since it is sometimes difficult to translate different currencies and different accounting practices. But this should not significantly alter the clear trend: storage rings really are a good way to get more bang for a buck.

3. FUTURE PEP OPTIONS

Although high-energy physics research has a way of making predictions about the future eventually look silly, we'll risk taking a flyer here on the two main possibilities for expanding PEP's research potential that now appear most promising:

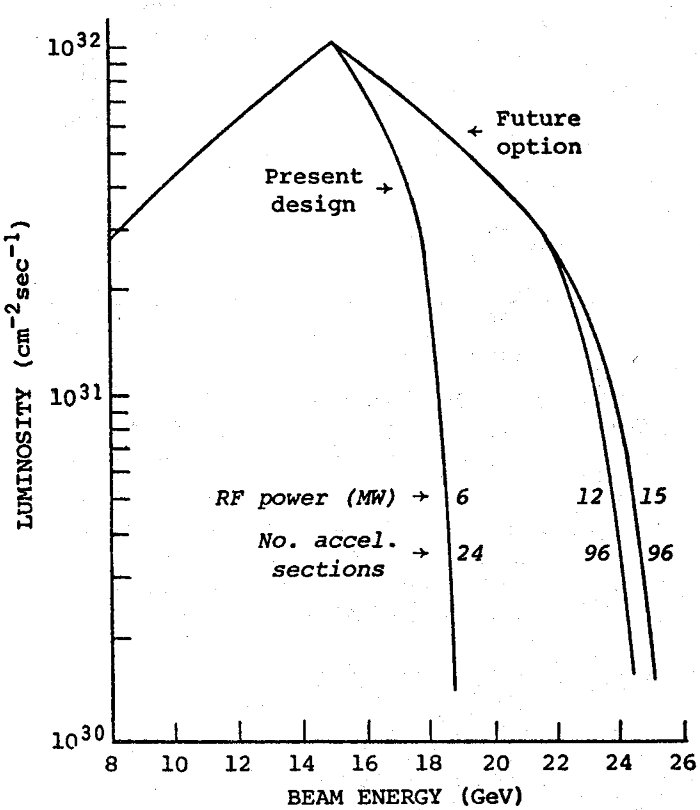
(1) Increasing the maximum single-beam energy from the present design goal of 18 GeV to 23-24 GeV.

(2) In the longer term, adding a separate storage ring for 200 GeV protons in the same tunnel structure, thus allowing electron-proton collisions.

In the space remaining, we shall pass up any discussion of the physics motivation for these two future possibilities in favor of a brief summary of the main technical matters.

23-24 GeV Beam Energy

The main cost in increasing the maximum beam energy of PEP would be that associated with RF power. The present design makes use of 24 accelerating sections to which power is fed from 12 500-kW klystrons for a total RF power of 6 MW--about 1/2 of which is used by the circulating beams. By increasing the number of accelerating sections to 96 and the number of klystrons to 24, the resulting total RF power of 12 MW would provide a maximum beam energy of about 23 GeV at a luminosity of $10^{31}cm^{-2}sec^{-1}$. If klystrons capable of 625 kW per tube can be developed, the maximum beam energy would be about 24 GeV at the same luminosity. The RF situation is summarized in the following figure.



At the present time there are two different, self-consistent designs for the magnetic guide field of PEP, one limited to beam energies of 18 GeV, and the other able to sustain ≃ 24 GeV. The construction schedule permits deferring the decision between these two alternates until the Fall of this year, when the accumulating cost experience with PEP will make the choice clearer. It may thus be possible eventually to go to the higher beam energies without replacing any of the ring guide-field magnets.

Some relatively minor additions to power-supply capacity and utility systems would be the only other requirements of this program.

200 GeV Proton Ring

The eventual addition of a separate storage ring for protons to the PEP facility would be a major program, comparable in construction cost to that of PEP itself. The technical feasibility of such a project depends strongly upon the successful development of superconducting magnets that can be fabricated in quantity with reliable results. It now appears that this difficult technology will have matured sufficiently within the next several years to make the proton-ring option for PEP a realistic possibility.

The proton-ring guide-field magnets would be installed in an alternating over-and-under arrangement within the existing tunnel, with the proton and electron (or positron) beams crossing through each other at the six present interaction regions. The collision of 200 GeV protons with ≃ 24 GeV e^+ or e^- would produce center-of-mass energies up to about 140 GeV--far beyond anything that is imaginable from a conventional accelerator.

3. SOME RELATED READING

To conclude, we list below some articles from earlier *Beam Line* issues that are related in one way or another to PEP. Copies of these articles (in small quantities) can be obtained from Bill Kirk or Roslind Pennachhe (ext. 2605, Bin 80), or from Herb Weidner (ext. 2521, Bin 20).

1. "An introduction to colliding-beam storage rings," Aug & Sep 1974.

2. "We have observed a very sharp peak...," Dec 5, 1974. [*Discovery of the psi particles.*]

3. "More new particles," Oct & Nov 1975. [*More psions; jets; heavy leptons; quarks.*]

4. "Charmed particles," July 1976. [*The charmed D mesons; the charmed quark.*]

5. "SPEAR: A review of the facility and the SLAC-LBL experiments," Nov 1976. [1-4 *summary.*]

6. "SPEAR Mark II magnetic detector," June 1976.

7. "The hunting of the quark," by Sheldon Lee Glashow, Sep 1976. [*NYTimes reprint.*]

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