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PROTON-ELECTRON-POSITRON DESIGN STUDY

The LBL-SLAC Storage Ring Study Group
(Presented by Tom Elioff)

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PROTON-ELECTRON-POSITRON DESIGN STUDY*

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Introduction

The PEP study, a joint effort by SLAC and LBL scientists, has been directed primarily toward the design of a high energy proton-electron and electron-positron colliding beam system with center-of-mass energies of $\sim$100 GeV and 30 GeV, respectively. A device with this capability would extend greatly the frontiers for the investigation of elementary particle phenomena.

High-Energy Physics has a continual appetite for experimentation at higher energies as each energy step in the past has provided new discoveries, new theories, and new puzzles in the elementary particle regime. Further steps now appear to be very difficult. It has become increasingly clear that the next large advance in experimental capability cannot be undertaken by the methods of 'conventional' accelerators from the financial viewpoint. Thus it is believed that devices such as PEP offer a way to achieve the necessary scientific advances within the present constraints.

This general outlook may appear optimistic at the present time; however, it is necessary that we strive to maintain a balance between our present needs and future programs. The AEC has stressed in its report[1] to the JCAE that new high-energy facilities are vital to the total program viability and are essential ingredients to scientific progress, to the development of new technology, and to the opening of new avenues of research. The intent of this response is at least promising.

We should not lose perspective with regard to the time element--that is--we are presently in the stage of development for the next generation of high-energy storage rings which is comparable to the early stages of the 200 BeV Design Study. In this regard, the present study is consistent with the time scale involved both for successful authorization and responsible technical development which would insure a successful operating device.

History

The idea for PEP sprang from considerations for higher energy electron-positron (e^+e^-) colliding beam devices. In the first-order optimization of an e^+e^- system[2] beyond SPEAR, the bending magnets were operating at very low fields ($\sim$4kG). Mel Schwartz pointed out that, with conventional magnets, a proton ring with nearly five times the electron energy could be placed in the same enclosure. This resulted in the original consideration for PEP[3] that was presented at the 1971 International Accelerator Conference by Pellegrini, Rees, Richter, Schwartz, Möhl, and Sessler.

Both experimentalists and theorists in particle physics at LBL and SLAC were highly enthusiastic regarding the implications of such a device and its significant potential in weak and electromagnetic interactions. The overall scale of a project of this type was appropriate such that both laboratories could contribute significantly, and an informal joint study was founded.

The first step was a physics study originally headed by G. Chew and S. Drell to clarify the physics objectives and the feasibility of experiments to obtain these objectives. The results[4] were overwhelmingly encouraging and provided added impetus to move forward with the conceptual design of the PEP storage ring system. As a result, a sub-group of accelerator physicists and engineers from both SLAC and LBL has been working toward the design goals. There are many problems yet to be resolved; however, we will try to indicate the direction we are now headed and some of the physics projections.

PEP System

The present PEP design has evolved to the two-ring configuration shown schematically in Fig. 1.

The top ring is the electron (or positron) magnetic structure that is designed for an energy capability of 15GeV. The lower ring is a superconducting system which would contain protons up to 150 GeV. The configuration has four-fold symmetry with four straight sections and hence a minimum of four interaction areas.

The electron energy of 15 GeV was determined to first order by matching the e^+e^- available energy to that which might ultimately be available in pp collisions at NAL. The size of the ring is then determined by keeping the power radiated by the electron beam to a level that is considered commensurate with a practical RF system. This leads to an overall size slightly greater than a mile in circumference, or about 1/4 of the NAL ring size. A conservative value of 40 kG for the dipoles of the proton lattice then obtains the projected proton energy of 150 GeV.

Because of the variety of experimental possibilities and the long time interval for some experiments, a minimum of four interaction areas is considered necessary. There could be multiple crossings within one or more of the insertion regions, but this will be reconsidered at a later time. In the normal mode all of the particles in each ring are concentrated in a single short bunch in order to optimize the luminosity while minimizing the number of stored particles. As illustrated in Fig. 1, the electron (or positron) bunch and the proton bunch collide every turn in each of the two opposite low β interaction points. It is also possible to operate in a two-bunch mode in which all four interaction areas could be used simultaneously with the same total luminosity and RF power, provided that twice the number of protons and the same number of electrons were stored.

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\+ M. Allen, R. Avery, J. Augustin, R. Bangerter, S. Berman, E. Close, T. Elioff, A. Garren, W. Gilbert, E. Hartwig, M. Lee, P. Morton, V. K. Neil, J. Rees, B. Richter, R. Sah, A. Sessler, L. Smith, L. Stevenson, H. Weidemann, W. Wenzel.

Protons and electrons rotate in the directions indicated for e^-p collisions. For e^+p collisions, positrons are substituted for electrons. In the case of e^+e^- reactions, the proton ring is not used (apart from common elements near the interaction point), and the electrons and positrons counter-rotate in the same ring in the same manner presently utilized at SPEAR.

A schematic of the insertion region is shown in Fig. 2 to illustrate the necessary gyrations to achieve the collision of the two bunches at the interaction point. The solid lines indicate the trajectories for e^-p collisions. For e^+p collisions, the dipoles nearest the interaction point (vertical bends) are reversed, and the protons would follow the dashed trajectory.

Zero-crossing angle is the interaction mode presently being studied as first priority. This gives a definite focus for the initial studies and eliminates complications that would arise due to the fact that the first quadrupole doublets are common to both beams. Also, the system is more suitable to solenoid fields for detectors with minimum perturbation on the circulating beams. We of course intend to be flexible and provide the capability for finite crossing-angles because it may be advantageous for increasing the luminosity and providing flexibility for overall experimental requirements. It is believed that this can be accomplished by rearrangement of magnets near the interaction point. This will be investigated in more detail.

Fig. 3 shows the detail of the lattice system along with the envelope of the beam dimensions. The elements of the interaction region mentioned above are shown more explicitly. A comprehensive report on the considerations for the lattice system has been given in a separate paper[5] by Al Garren. The first standard cell of the normal lattice structure is shown on the right. This is an FODO cell of 17.5 meters length. Next are two matching cells which together with the remaining quadrupoles shown achieve the low β interaction point and match the phase space of the normal cell. The three unmarked quadrupoles PQ5, PQ8, PQ9 are necessary to confine the proton beam at injection, when not operating in the low β mode shown here, and thus maintain minimum aperture for the elements in the insertion region. A transition to the low β mode would take place after acceleration.

An element-free region of 20 meters is provided about the interaction point. This is believed to be the minimum free space required for experimental apparatus and detectors. Some of the other relevant parameters are listed in Table I. A more complete list of parameters is given in reference 5.

A design luminosity of 10^{32} cm^{-2}sec^{-1} was considered necessary to achieve reasonable interaction rates particularly for large momentum transfer events. This is theoretically achieved with the lattice system described. The number of particles in each bunch is relatively small at 5×10^{12}. For the geometry outlined, this corresponds to 4.2 megawatts of power radiated by the electron beam. While the number of particles is modest, the beam densities are formidable at the interaction point. The number of protons and the beam sizes are chosen to maintain the tune shifts below the canonical value of .025 in order to obtain maximum luminosity consistent with the incoherent beam-beam limit. While this tune shift limit appears experimentally verified for electrons, there is no comparable information as to the appropriateness of the limit for the proton beam. Some dispersion is required at the interaction point to widen both the electron and proton beam of the present design in order not to violate this assumed limit.

TABLE I

PEP PARAMETERS

		Protons	Common	Electrons
Maximum Momentum (GeV/c)		150		15.0
Number of Particles		5×10^{12}		5×10^{12}
Luminosity (cm^{-2} sec^{-1})			1.0×10^{32}	
Average Radius (m)			327	
Vertical Separation (m)			1.25	
Total Number of Cells			72	
Length of Standard Cell (m)			17.5	
Length of Straight Section (m)			200	
Dipole Field (kG)		40		4.0
Quad. Field-F (kG/m)		460		107
Quad. Field-D (kG/m)		446		105
Dipole Length (m)		5.4		5.4
Quad. Length (m)		1.7		0.7
Interaction Point:				
Bunch Length (cm)		64		9
Total Width (cm)		.70		.55
Height (cm)		.13		.055
Half Apertures Required:				
Standard Cells	h (cm)	5.5		2.5
	v (cm)	4.0		2.5
Max. in Insertion Elements	h (cm)	12.0		12.0
	v (cm)	14.0		12.0

The limitations for minimum beam size at the interaction point result in relaxed requirements for the injected proton beam emittance. For example, with the 11 x 8 cm full aperture for the normal cells noted in Table I, the emittance and intensity assumed are consistent with that which is possible from a single turn extracted from the Bevatron at 6 GeV. Electron injection is obviously consistent with the SLAC capabilities. At this time, overall injection methods and systems remain to be optimized.

The RF systems in PEP are non-trivial as the system for the electron ring must supply ∿ 4 megawatts of power radiated by the beam. Total power of ∿ 5 megawatts is required at 350 MHz. However, elements of the system are similar to what is required by the SPEAR improvement project for energy upgrading to 4.5 GeV. Hence the operation of that system will serve as a PEP prototype.

The proton RF system is also formidable due to the requirements for an extremely short bunch length. At present, a 3-step process is visualized whereby an initial RF system operating at 1.6 MHz (10th harmonic) and ∿ 100 kV peak voltage will be used to accelerate the beam to full energy. A second system at 30 MHz and 3 MV peak will be turned on to compress the bunch from 11 meters down to ∿ 3 meters, after which the first system is turned off and a third system operating at 102 MHz (700th harmonic), and 60 MV peak voltage will be utilized for final compression to 64 cm.

While the technical aspects appear feasible in terms of hardware, the problems of maintaining the short bunch lengths over a long time period may still be troublesome. Bunch lengthening effects which are not completely understood are evident at electron storage rings. In the proton case, it is possible that RF noise could lead to loss of beam and hence loss of luminosity. Preliminary tests have been under way at the Bevatron to investigate low RF noise levels on a bunched coasting beam at the Bevatron. These have been discussed in a separate paper by Hartwig.[6] Preliminary conclusions indicate that systems can be built with the requisite noise tolerance.

The effort toward a superconducting magnet system for the protons is motivated in part by the physics; i.e., going beyond the projected energy where "weak" interactions might become comparable to "strong" interactions. Therefore, for the same amount of real estate, one would obtain the largest extension of experimental capabilities. In addition, there is the practical matter of power costs. While the electron lattice involves small low-field magnets, the proton magnets are considerably larger and, if conventional, would be operated up to ∿ 20 kG. The storage ring is essentially a d.c. device, and initial estimates for operation of a 70 GeV ring of the size noted here resulted in a power cost of ∿ \$5M/year (assuming 2/3 operation efficiency). A second proton ring would double this figure. BNL estimates[7] for a 'conventional' ISABELLE were \$16M to \$19M. These figures are already at or greater than the total power costs for all accelerators in high-energy physics. If one further speculates, backed by the trends of the last two years, that power costs will increase significantly by the time such a device is operational, one arrives at an unacceptable level of operating costs.

The success of achieving high-field, low-loss magnets[8] at LBL and Rutherford in the last year with construction methods amenable to production techniques has provided an additional degree of confidence that the superconducting system can be successfully achieved. As part of the PEP program, several magnet models are under construction to observe possible differences in two identically constructed magnets, as well as to study low-field effects and the suitability of various correction windings.

PEP Physics

Conventional electron and proton accelerators have both been successful over the years in achieving new insights toward our understanding of elementary particles. There are also numerous tie-points which promote a complimentary relationship between the results from the two classes of machines. A classic example is the early electron-scattering experiments at Stanford for which the theoretical interpretation of the nucleon charge distribution predicted the existence of the ρ and ω mesons which were later discovered with the help of proton accelerators. More recent examples of experiments from electron machines which provide new suggestions for hadron structure include the results from deep inelastic electron-scattering experiments at SLAC and hadron production from electron-positron colliding beam experiments at Adone and CEA.

One line of reasoning is that the overall complementary of the two research lines can be aided best by advancing the available interaction energy in both cases. Table II will help to show this perspective. The available energy at SLAC is near that of the AGS and the PS. Beyond this, NAL, the ISR and CERN II readily leave the electron interactions behind in terms of available energy. PEP would restore the overall balance to the total program. There is an obvious need to extend the ep interaction energy relative to SLAC. Of major importance is the unique capability of PEP to explore new features of lepton-hadron interactions in a direct manner. A few specifics of the PEP physics possibilities are mentioned below.

TABLE II

Device	Primary Energy* or (Equivalent)	$E^*_{c.m.}$	Storage Ring Energy* or (Equivalent)	
BEVATRON	6	3.8	(.9)	p x p
SLAC	22	6.1	(3.5 x 2.0)	e x p
AGS/PS	30	7.7	(2.9)	p x p
NAL	200	19.5	(8.8)	p x p
	500	31	(14.4)	p x p
ISR	(1750)	58	28	p x p
PEP	(5100)	100	15 x 150	e x p
		30	15 x 15	e x e
ISABELLE	(86,500)	402	200	p x p

* Energies in GeV

Deep Inelastic Electron Scattering. This is a class of electron-proton collisions with high momentum transfer, and hence collisions that can most effectively probe the electro-magnetic structure of the nucleon at arbitrarily small distances. This local interaction is in sharp contrast to hadron-hadron scattering in which the basic interaction is exceedingly complex. Inelastic scattering experiments at SLAC have already yielded unexpected and revealing results which show that the inelastic cross-sections do not vary independently with the mass and energy of the photon exchanged in the process, but depend instead on the ratio of these two parameters. This behavior, called "scaling" has led to new developments in the concepts of the proton structure, and indicate a possible substructure of point-like constituents.

PEP would greatly extend the inelastic scattering measurements far into unknown regions. Fig. 4 shows the range of momentum transfer squared (Q^2) and energy transfer (ν) that are available at the maximum beam energies. The numbers in each segmented region that are not in parenthesis correspond to the event rate-per-day for a luminosity of 10^{32}cm^{-2} sec^{-1}. While the event rate is not overly impressive at high-momentum transfers, the total rate is expected to be inversely proportional to the square of the center-of-mass energy, and thus increases considerably at lower beam energies. The significant point here is that the maximum momentum transfer squared and energy transfer presently available at SLAC is 25 (GeV/c)^2 and 20 GeV, respectively, which is not well-resolved from the zero of the ordinate and abscissa of the scale shown in Fig. 4. Most of the large Q^2 events occur at large scattering angles in the laboratory and are experimentally accessible. The LBL-SLAC study group[4] concluded that experimental signatures are sufficiently unique that these types of events can be readily identified with existing detectors.

The observation of the scaling behavior at PEP energies would imply that one is observing the asymtotic behavior of the proton structure, and that the carriers of the electromagnetic current in the proton are structureless and light. Observation of a scaling breakdown would indicate a new regime for hadron phenomena, for example, as might be expected from parton or quark production.

In the inelastic scattering process, $e + p \rightarrow e + X$, the details of the many possible combinations of hadronic constituents in X, such as multiplicities, momentum distributions, correlations, etc., will also be important in verifying various theoretical models. For example, final state hadrons for high Q^2 and ν values may emerge tightly in jet-like distributions according to parton models. Thus new information from PEP is expected to have an enormous impact on the understanding of nucleon structure.

For the class of experiments with low-momentum transfers if the forward scattered electron is tagged, the photon exchanged is uniquely identified, and it is possible to extend equivalent photo-production experiments such as total cross-sections, single particle inclusive results, and reactions with special final states to new energy regions.

Weak Interactions. Some of the most exciting possibilities for new discoveries are found in this area. Weak processes, such as $e + p \rightarrow \nu + X$, will be in an energy region where they may effectively become strong. Weak interactions involving neutrinos (ν) up to $\sim$ 5 GeV from present accelerators can be described by the same Fermi theory proposed for β decay processes involving extremely low energies. The total cross-section for the above process would be expected to increase as the square of the center-of-mass energy, becoming comparable to some electromagnetic processes or even to large momentum transfer components of strong interactions at $\sim$ 60 GeV center-of-mass.

In Fig. 4, the numbers in parentheses show the reaction rates/day for the neutrino production process at the highest PEP energy (Center of Mass Energy = $\sim$100 GeV). The dashed line 0-0 shows approximately where the reaction rates are comparable with the electron inelastic scattering. In the region above 0-0, the weak interaction process would be greater than the large Q^2 electron scattering rates. There would be a total of $\sim$ 300 neutrino events per day if this extrapolation is valid.

Equally important would be the discovery of the breakdown of the Fermi theory and hopefully the knowledge of the mechanism. A possibility widely predicted would be the mediation of this reaction by the intermediate vector boson (W particle) of suspected mass in the 30 GeV region which would be readily produceable with PEP. In either situation, a new list of experimental questions on the weak interaction process would be initiated and PEP should be able to provide many of the answers.

Electron-Positron Reactions. The physics of e^+e^- reactions has been reviewed at length elsewhere.[2,4] The importance is noted by the e^+e^- colliding beam facilities already in operation and under construction. The e^+e^- system allows the study of hadron final states (as well as lepton pairs) with the unique quantum numbers of the virtual photon of the annihilation process. Information on hadronic systems can thus be obtained in a clean and unique manner.

Results from Adone and the CEA which indicate much larger hadron cross-sections than anticipated have increased the motivation to achieve higher energies in order to determine the energy dependence of the cross-sections as well as the asymtotic behavior. This determination, as well as other detailed studies of the hadron systems produced, are important with regard to the predictions of the various constituent models of the nucleon.

In addition, at the higher energies, if heavy leptons (with properties similar to muons) exist, they should be produced in a simple and direct way. Also the W-particle mentioned earlier might be effectively produced by the e^+e^- process with a favorable cross-section. An additional outcome of PEP e^+e^- experiments would be a test of the validity of quantum electrodynamics to dimensions an order of magnitude smaller than presently confirmed.

SUMMARY

The LBL-SLAC joint study has made considerable progress during the past year in establishing the conceptual design for PEP. We hope to optimize more fully the various parameters associated with PEP during the coming year and work toward a comprehensive understanding of the many problems, such as the limitations imposed by various beam instabilities and field tolerances. It is also desired to achieve optimum flexibility with regard to the experimental conditions that may be required by various experiments and detection systems.

The method of colliding beams provides the most economical means of achieving significant energy gains. In particular, there are no large scale experimental areas which comprise the dominant part of the operating costs at conventional accelerators. Extensive shielding requirements are not envisioned, and there are no demands for sophisticated extraction systems, target-handling facilities, or extensive utility distribution systems. Hopefully the superconducting elements will minimize the power costs and thus, in general, PEP should not cause a significant perturbation on the total operating costs of the High-Energy Physics Program.

At this point in time it is believed that PEP will provide the most advantageous extension of parameters for the fundamental investigations of elementary particles. The physics potential already mentioned has led LBL and SLAC to consider PEP as the top priority item for future construction. We are further enticed by speculation that the expectations for the dominance of weak interaction cross-sections might even lead to unifying principles which would combine the understanding of our basic forms of interaction. In any case, new discoveries and new challenges are expected with a high degree of confidence.

Lastly, Figures 5 and 6 provide a plan view of PEP on the LBL and SLAC sites respectively, illustrating how such a device could be readily incorporated with the existing facilities.

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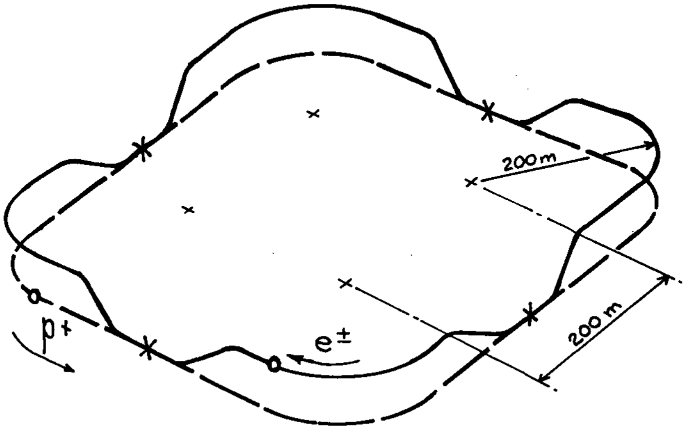

P.E.P. Configuration

Fig. 1
Schematic of PEP Configuration

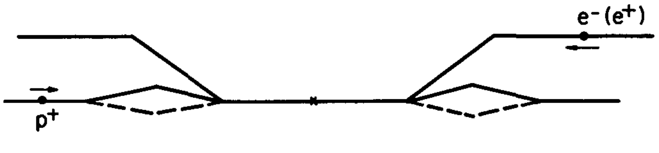

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Fig. 2
Schematic of an Insertion Region with zero-crossing angle

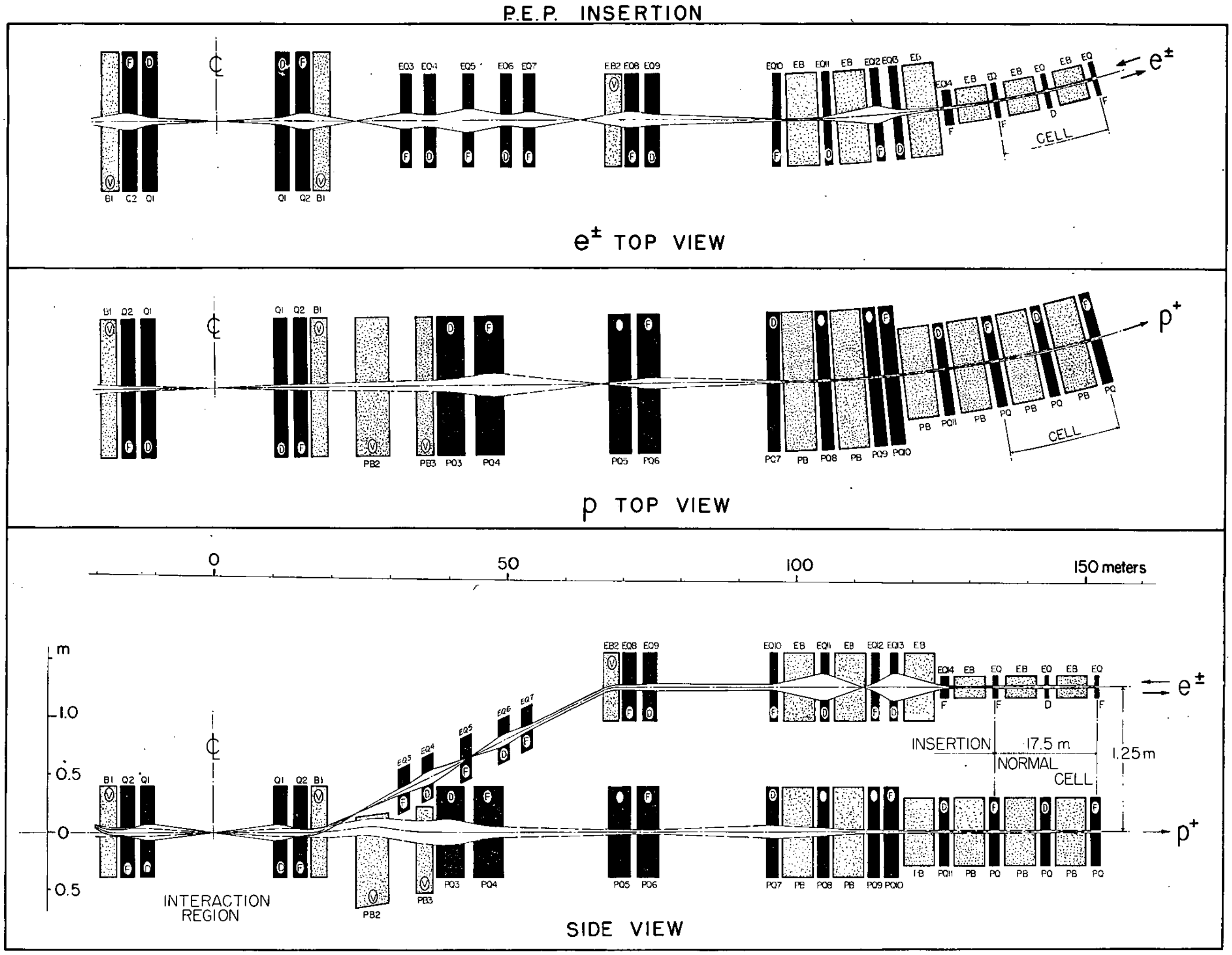

Fig. 3

Detailed Structure of the Insertion Region

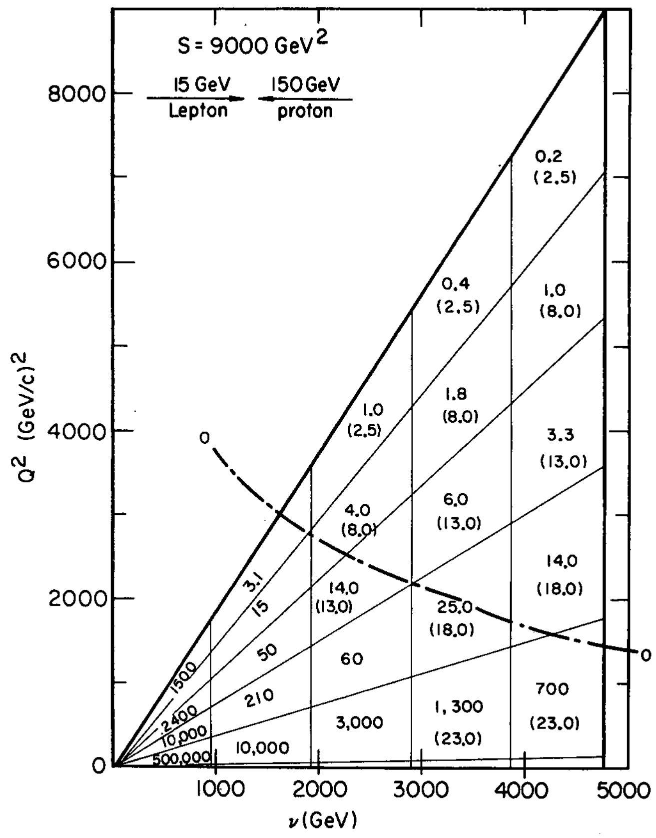

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Fig. 4

Kinematic range for inelastic lepton scattering of 15Gev leptons on .150 Gev protons. Numbers in the domains correspond to projected inelastic electron scatterings per day for $L = 10^{32}$ cm^{-2} sec^{-1}. Numbers in parentheses correspond to the events per day for the process $\ell + p \rightarrow \nu +$ (anything).

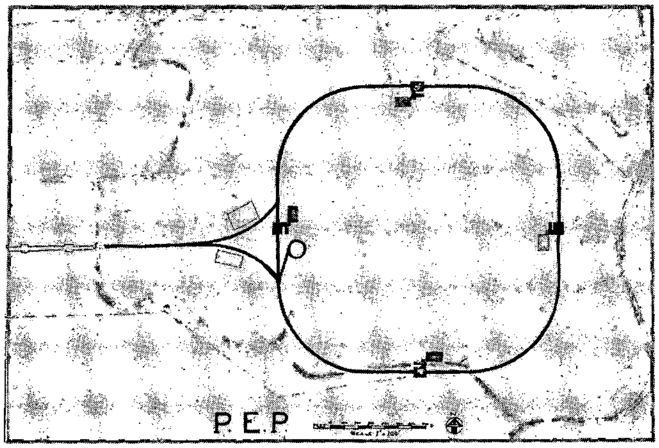

Fig. 5

Possible PEP configuration on the SLAC site. The structure at the far left is the end of the SLAC electron accelerator. The two squares outlined represent experimental end-stations A and B.

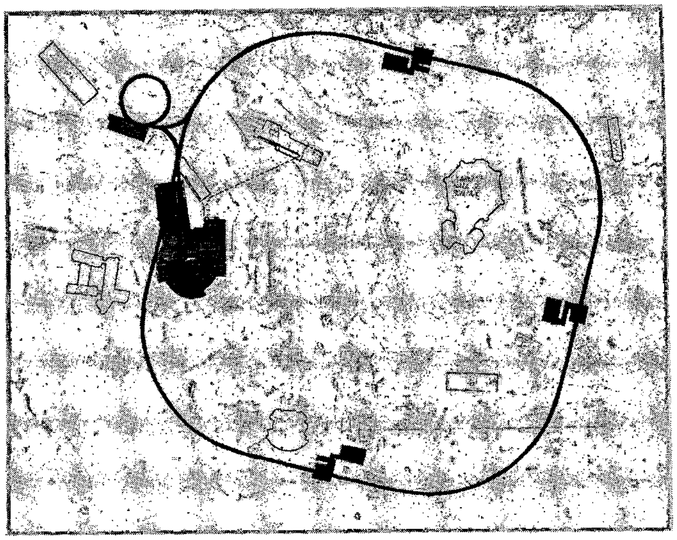

Fig. 6

Possible PEP configuration on the LBL site. The dark structure centered on the left side of the large ring is the Bevatron complex. The interaction region on the left side is shown within the existing experimental hall.

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