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LBL-3032
PEP Note 86

THE PROTON-ELECTRON-POSITRON PROJECT-PEP

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L. Smith

May 17, 1974

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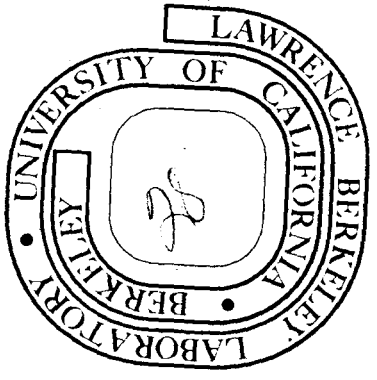

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LBL-3032
PEP Note-86

THE PROTON-ELECTRON-POSITRON PROJECT - PEP*

L. Smith

LBL-SLAC Joint Study Group
Berkeley and Stanford, California

May 17, 1974

ABSTRACT

The LBL-SLAC Joint Study Group has produced a design for an electron-positron and proton-electron or positron colliding beam facility (PEP) which will provide for electrons up to 15 GeV and protons up to 200 GeV with a luminosity of 10^{32} $cm^{-2}sec^{-1}$ for the peak energies at six collision points. The physics justification for the electron-proton rings will be summarized briefly and the proposed facility will be described. The rings will have six arcs having gross radii of about 220 meters, with the electron ring sextants alternately above and below the plane of the proton ring. Five of the interaction regions will be developed for experimental use, providing 20 meters of free space for experimental equipment about the interaction points, which are at the center of insertions about 130 meters long. The design of the total facility has been considered in sufficient detail to provide a basis for, and to insure compatibility with, a first-stage facility consisting of the $e^{\pm}$ ring alone. A proposal for construction of this first stage has been submitted to the Atomic Energy Commission. This report will describe the total concept of the project, with particular emphasis on our current ideas concerning the proton ring, which involves the new features of using superconducting magnets and maintaining a tightly bunched proton beam of high intensity.

INTRODUCTION

In the summer of 1971, a group of physicists at LBL and SLAC, including visitors from CERN and Frascati, made an inquiry into the feasibility of a new colliding beam complex capable of producing collisions at higher energies than hitherto envisaged between electrons and positrons and also between electrons and protons and positrons and protons. They concluded that such a facility, which would consist of an electron storage ring and a proton storage ring, was quite possible and that no known physical limitation of the behavior of stored beams would prevent the achievement of luminosities sufficient to yield useful reaction rates for many important high-energy interactions. To illustrate these conclusions, a conceptual design was described and analyzed.[1] The physics importance was later forcefully emphasized by an LBL-SLAC Physics Study Group.[2]

Subsequently, the collaborative study between LBL and SLAC grew, involving more people as the concepts and designs became more refined. A combination of a 15 GeV electron-positron ring and a 200 GeV superconducting proton ring, referred to as PEP, emerged as the preferred design. In the meantime, other laboratories began studying similar or related ideas in both the U.S. and Europe and their representatives came together at SLAC and LBL in the summer of 1973 to exchange ideas and work on common problems. By the end of 1973, a version of PEP suitable for location on the SLAC site had been developed and the two laboratories entered into a formal agreement to jointly propose and construct the electron-positron portion of the system, in a manner compatible with the subsequent addition of the proton ring to achieve the full PEP capability. This paper will describe the full PEP complex

as presently visualized; the accompanying paper by John Rees[3] will describe the specific electron-positron system for which a formal proposal for construction is presently being submitted.

PHYSICS POTENTIAL

For electron-proton collisions with the maximum energies of the preferred design, the center-of-mass energy is 110 GeV which is the same as that which would be available with a 6000 GeV beam from a conventional accelerator incident on a stationary hydrogen target (there is no economically feasible way of reaching these energies with a conventional accelerator). The facilities of the present proposal are designed to be compatible with this addition. The future electron-proton system, together with the presently proposed electron-positron system, would comprise a total facility of unique capability for particle physics research which is briefly outlined below.

(a) Deep Inelastic Lepton Scattering ($e^-(e^+)p \rightarrow e^-(e^+)$ + hadrons)

Inelastic electron-proton scattering plays an essential and unique role in the investigation of the structure of the hadrons. The known electromagnetic field generated by the scattered electron interacts with the local electromagnetic current of the proton and thus can probe the structure of the nucleon at arbitrarily small distances. This local interaction is in sharp contrast to hadron-hadron scattering in which the basic interaction between the particles is more complex. By varying the energy and angle of the scattered electron it is possible to "tune" or vary the virtual photon's mass Q^2 over a large range. In particular, it is possible to achieve virtual photon masses whose square is negative and whose magnitude is

much greater than the proton mass and therefore allows for collisions in an asymptotic region not available in accelerators using a fixed mass projectile.

Experiments on inelastic scattering at SLAC, where both the mass and energy of the virtual photon are large, have yielded profound and unexpected results. These results show that the cross sections do not depend independently on both the mass and energy of the photon, but instead on their ratio. This "scaling" behavior has led to major new concepts in our understanding of hadronic structure in terms of a possible substructure within the hadron that is composed of point-like constituents (partons). The greatly enhanced center-of-mass energy of a PEP facility would extend the measurements of deep inelastic scattering far into the unknown region. With the example parameters used here the virtual photon energy would reach to 600 GeV and its mass to 110 GeV compared to any energy of 20 GeV and a mass of 5 GeV at the present SLAC frontier.

Confirmation of the scaling behavior at these larger values of energy and mass would give support to these new ideas while observation of violations of scaling would indicate a new energy scale for hadronic phenomena perhaps associated with the production of new particles and of a "size" for the constituents themselves. This point is emphasized by the surprising results of the recent SPEAR experiments in the time-like region which do not support these ideas of the quark-parton model, and in this respect make the further study of the inelastic electron reactions even more intriguing. Other general and fundamental features to be studied for large photon masses include the applicability of Regge theory analyses, the validity of sum rules based on current

algebra, and the "fragmentation" of very massive virtual photons into jets of secondary hadrons.

Besides the electromagnetic inelastic electron scattering, it will be possible to observe the effects caused by weak neutral current of the type discovered in the recent CERN and NAL neutrino experiments. The effects of the neutral current would be observable as parity violations, charge conjugation violation, and possibly electromagnetic scaling violations. Since both energy and momentum transfer are easily determined, detailed knowledge as to the nature of these neutral current effects will be possible.

Thus, this unique feature of a PEP facility, the study of deep inelastic scattering, will yield results on one of the most significant problems in particle physics.

(b) Weak Interactions ($ep \rightarrow \nu_e$ + hadrons)

If the scaling phenomena observed in deep inelastic scattering is assumed to hold also for the weak interactions, as would be implied at least in part by the conserved vector current (CVC) idea, then with the Fermi theory one is led to the conjecture that the total weak interaction cross section will continue to grow quadratically with the center-of-mass energy. This has the startling consequence that at energies in the PEP region the weak interactions with their inherent violation of parity and strangeness would have grown in strength to be comparable to the electromagnetic interactions. In fact in the region of the largest momentum transfer accessible for the particular example of PEP parameters used in this study, the scaling hypothesis indicates that the deep inelastic electromagnetic cross section is smaller than the weak process.

Experiments with PEP will show either that the weak interaction is no longer "weak" or that the Fermi theory in its simple form breaks down. The discovery of a failure in the Fermi theory would in itself be of the first magnitude in importance; additionally one could then entertain hopes of discovering the mechanism of breakdown. If a W boson, for example, were the source of a major failure of Fermi theory, its mass might be sufficiently low ($\approx$ 30 GeV) that W particles could be produced by PEP.

Thus, the exploration of weak interactions at PEP energies will present some of the most exciting possibilities for new discoveries. Information from experiments in this area could lead also to unifying principles for the basic forms of elementary particle interactions.

GENERAL DESCRIPTION

The goal of PEP is to provide collisions at energies ranging from 30 to 110 GeV in center-of-mass energy for electrons and protons, and from 10 to 30 GeV for electrons and positrons. A luminosity of 10^{32} cm^{-2}sec^{-1} at the top energies, to be achieved simultaneously at a number of interaction points, is deemed adequate to support a vigorous and varied experimental program in both $e^{\pm}p$ and $e^{+}e^{-}$ physics. In order to achieve that luminosity with a relatively modest number of stored particles, we have chosen to use bunched beams in head-on collision. The head-on collision scheme appears also to be more advantageous for experimental detectors as well as affording a greater simplicity in the insertion structure. We have furthermore adopted a six sided configuration, which provides five areas for physics experiments and one for accelerator physics investigations and monitoring.

The geometrical configuration of the two rings is shown schematically in Fig. 1. The six collision points are at the centers of 20 meter long straight sections at each crossing of the rings. The electron ring is placed alternately above and below the plane of the proton ring; this pattern eliminates vertical dispersion in the circular portions of the electron ring, and the attendant and undesirable quantum-excitation contribution to vertical emittance, and eliminates the need for a series of quadrupoles in the sloping sections (see Fig. 2) of the electron ring. As a result, the required insertions are shortened, overcrowding of magnet elements is avoided, and the electron path length can be varied in these sections to provide synchronization with the protons over the projected range of proton energies (50 to 200 GeV).

The circular arcs of both rings are made up of 48 conventional FODO cells (8 per sextant) operating at a nominal phase advance of about 90° per cell at maximum beam energies. In addition to insuring positive damping for the electrons, the separated function scheme simplifies the design of the super-conducting magnets in the proton ring and, in both rings, permits a wide range of focusing conditions useful for controlling beam size. To achieve matching between cells and insertions for the variety of conditions required in the interaction region, the quadrupoles in the insertions, the normal cells, and in the two cells on each side of each insertion are independently controlled.

The insertions, as presently conceived, are shown in Fig. 2, along with the adjacent cells. Starting from the interaction point, both beams go through the doublet, $Q_{1,2}$, which consists of conventional steel quadrupoles and which is strong enough to focus the

electrons and/or positrons, but has little effect on the protons. The bending magnet, B_1, also conventional, serves to separate the two beams, deflecting the light particles toward the elevation of their next sextant. The small deflection given to the protons is compensated by three vertical bending magnets ($B_{2,3,4}$), which restore the protons to the median plane. The angle of deflection provided by B_1 is adjustable to permit the variation in total circumference of the electron ring needed for synchronization at different proton energies. On the basis of single particle beam dynamics, the subsequent bending magnets in the electron line could be wide aperture magnets fixed permanently in position. However, the electromagnetic fields generated by a high-intensity beam in such a vacuum chamber configuration might make that scheme infeasible, in which case it would be necessary to move magnets or the vacuum chamber in this region when the proton energy is to be changed.

In the proton line, the doublet, $Q_{3,4}$, consists of super-conducting quadrupoles which focus the protons. Beyond $Q_{3,4}$ is a 28 meter long straight section; these straight sections, twelve in all will be used to accommodate rf systems, injection hardware and other beam components. The twelve 20 meter long straight sections directly above or below in the electron ring will serve the same purposes for the light particles.

The choice of 20 meters free space around the interaction point represents a compromise between the desire for as much room as possible for experimental equipment and the machine physics requirement that β_{max} should be as small as possible because of aperture, chromaticity, and tolerance considerations. It appears that the straight section

space assigned to major accelerator hardware is more than adequate; if this is really the case, one or more of the insertions could be modified to meet particular experimental requirements by extending the interaction region at the expense of the adjoining 28 and 20 meter straight section. The vertical separation of 80 centimeters between the two rings appears to be adequate to accommodate the necessary equipment in both rings. The tunnel size adopted for the Stage I proposal[4] would permit the further addition of another electron ring, a feature which might prove to be extremely valuable in light of the fact that current experimental results are indicating that electron-electron collisions at high energy would yield significant additional information. A second electron ring would also make it possible to achieve higher luminosities for the e^+-e^- system at lower energies by permitting an increased number of bunches.

Figure 3 shows an overall view of the rings on the SLAC site. We include it here only to give a general impression, since it is, of course, identical to the layout proposed for Stage I and will be discussed in detail in the following paper. Figure 4 shows tunnel cross sections in alternate sextants of the ring.

OPERATING PARAMETERS

Tables I and II give the lattice parameters and typical operating parameters. Figures 5 and 6 show the betatron and off-momentum functions for the high energy mode of Table II. In contrast to an electron-positron system, in which emittances are determined by the lattice configuration and particle energy (and the limitations on performance imposed by the beam-beam interaction are known empirically,

if not understood theoretically), one must make assumptions concerning the behavior of protons in order to arrive at a set of operating parameters for an electron-proton system. Regarding emittances, there is sufficient experience with high energy accelerators to provide reasonable figures, but regarding the beam-beam effect, there is as yet no indication of the ultimate limitations. We must assume, however, that protons are subject to the same harmful effect, and, in the absence of radiation damping, are probably more sensitive than are electrons. We have therefore taken as design criteria that the linear beam-beam tune shift should not exceed 0.05 for the electrons (based on actual experience) or 0.005 for protons, the latter figure having also some justification on theoretical grounds.

The performance is then limited by this criterion, as in well-designed electron rings, and the interaction point parameters are determined by maximizing luminosity consistent with the above tune shifts while minimizing β_{max}, chromaticity, and restricting the total number of particles used. The number of protons required (3.6×10^{13}) is small compared to the number stored in the ISR (6×10^{14}), but it should be remembered that in our case they must be accelerated from a low energy and collected into short bunches. Thus, the intensity achieved at Brookhaven (10^{13}) and the design goal at Batavia (5×10^{13}) are better standards for comparison.

The assumed transverse emittances are somewhat larger than those achieved in existing synchrotrons, but here again the beam-beam limit precludes any advantage in striving for greater brightness.

The chromaticity is sufficiently low that it can be controlled by using two sextupoles in each of the FODO cells in both rings. This

distribution is smooth enough to eliminate serious nonlinear resonances near the chosen working points while providing necessary control over head-tail instabilities.

INJECTION, ACCELERATION, AND BUNCHING

The electrons or positrons would be handled in the same way as in Stage I, as described in the next paper. It should be noted that the vertical bends required to separate the rings in the full PEP configuration cause an increase in synchrotron radiation, so that, for the full configuration more rf power will be required.

For the protons, the procedure is more complicated. Referring to Table II, 24 bunches, each with 1.5×10^{12} protons, are required. The present concept is to accelerate 1.5×10^{12} protons first to about 5 GeV in a small proton synchrotron located, possibly, at the present SPEAR site, and then transfer them by single turn extraction to an existing bucket at the 96th harmonic in the PEP proton ring. This process would be repeated 24 times, filling every fourth bucket in the main ring. The protons would then be accelerated to the appropriate energy and the rf voltage increased until the bunches are short enough to fit into buckets at four times higher frequency ($h = 384$, $f = 53$MHz). At this frequency, the voltage would be raised to compress the bunches to the desired length. Assuming a longitudinal emittance of 10π cm in $(\Delta\beta\gamma,\ \Delta z)$ units, the final voltage would be about 6 MeV/turn for $\sigma_\ell = 25$ cm.

Since this value of σ_ℓ is much less than the minimum-β values for the protons, the luminosity is not sensitive to proton bunch length but, unfortunately, the beam-beam tune shifts are sensitive since the electrons or positrons may encounter protons in regions of higher

electron-ring-β if the proton bunches are longer. The voltage needed in the proton ring depends strongly on both longitudinal emittance and required bunch length; a final choice of voltage will require careful consideration of achievable emittance and the parametric dependence of the beam-beam effect.

After the proton bunches are formed, the electrons would be introduced into their ring already synchronized in azimuth and perhaps separated laterally in order to prevent particles from meeting each other except at low-β points. How long this situation can be maintained for experiments is difficult to predict for the electron-proton system, but judging from electron ring experience, we anticipate a need to re-fill every few hours. The remaining protons would be decelerated as far as possible and then dumped.

MACHINE COMPONENTS

The electron-ring system would differ very little from that described in the next paper. The proton ring would have a number of unique features, some of which are described below.

(a) Superconducting Magnet System

The magnet design incorporates intrinsically stable, fine filament, NbTi super-conductor. Cross sections of the magnets are shown in Fig. 7. The ultra-high vacuum region is enclosed by a non-magnetic beam tube, upon which the multi-layered coil is wound. Circular symmetry is used in all inner regions to yield the best structural and magnetic properties.

The cryostat is continuous through a half-sextant of the ring with surrounding evacuated thermal insulation, an 80° temperature shield, and finally a room-temperature vessel. Helium at 4.4°K is

introduced at the center of a sextant and forced in both directions to the ends, from whence it flows back at reduced temperature and pressure in the outer annular region of the cryostat, acing as a counter-flow heat exchanger.[5] The only additional element in the tunnel is the transfer line from the surface, where the rest of the refrigeration equipment is housed. This scheme minimizes interference between refrigeration components and tunnel hardware, particularly with experimental apparatus near the interaction region.

The heat leak at 4.4°K is assumed to be 1.2W/meter, and that from room temperature to 80°K is taken to be 2.5W/meter. Allowance is made for two pairs of electrical leads for the dipoles, six for the quadrupoles and, in addition, for quench leads and auxiliary beam equipment. The additional heat load due to eddy current heating and beam induced currents appears to be much less. The total load at 4.4°K is about 1500W per sextant, requiring some 600kW of installed power capacity at each of the six stations. The magnet power supply circuit would parallel the refrigeration system.

(b) Vacuum System in the Proton Ring

Much attention has been given in the recent past to the question of warm-bore versus cold-bore vacuum systems. A cold-bore system has many attractive features--continuous cryo-pumping surfaces, no need for baking, simple design and minimal running cost, for example. On the other hand, desorption coefficients as high as 10^5 from cold surfaces have been reported, which raises the possibility of a run-away phenomenon similar to that which has affected operation of the ISR. Analyses of cryo-systems carried out independently at LBL and Rutherford indicate that pumping speed is probably adequate to maintain good vacuum

and so we have tentatively chosen to follow the cold-bore route for the proton ring. In the neighborhood of the interaction regions the pumping capacity would probably have to be increased, perhaps by a permanent electro-deposit of porous silver or by a replaceable condensation of CO_2. Gas loads that could enter from the electron ring or pass from the straight sections into magnet sections can be intercepted by short lengths of tubular cryo-pumps that are easily cycled.

(c) Radio-Frequency Systems

Because of the limited vertical clearance, special problems arise in designing the rf systems. In the electron ring, fortunately, a cost optimization study leads to a choice of about 350 MHz for the frequency, and, as a result, the cavities are small enough to clear the proton ring. In the proton ring, the frequencies of the accelerating and bunching systems are 13 and 53 MHz, respectively, the bunching frequency being determined by requiring that the final desired bunch length should occupy about one-fourth of the bucket length. It is visualized to use a single set of structures in the proton ring for both modes; it would consist of a number of tubes which would act as frequency modulated drift tubes during acceleration and initial bunching and as half wave transmission lines at the higher frequency. The requirement of 6 MeV/turn could be met by using 17 tubes, occupying a total length of 50 meters and consuming about 2 MW of power in the CW mode. They would be located in two of the 28 meter straight sections, separated in azimuth from the electron rf straight sections.

CONCLUSION

The design presented in this paper is subject to further modification and optimization. The procedure has been to evolve a conceptual design on which to base the Stage I proposal, and to consider detailed design of the final PEP complex only to the point of satisfaction that the two are indeed compatible. An obvious next step is to demonstrate the feasibility of a superconducting accelerator and storage ring; the LBL project, ESCAR,[6] is directed toward that end, including also the development of a suitable vacuum system. There are numerous questions in beam dynamics, particularly in the area of collective effects, which require additional study before we can feel confident that the operating specifications can be realized. This work will continue in parallel with the detailed work required for the construction of Stage I.

It is believed that the total PEP complex will provide one of the most important facilities for future research in high energy particle physics. In addition to the extremely important physics results[3] expected from the electron-positron collisions, the provision for electron (or positron) collisions with protons, outlined here, will permit an enormous extension of parameters in traditional electron machine experiments (inelastic electron scattering, photoproduction, ect.), and in addition will open the field of weak interactions to practical experimentation with a well-understood, well-controlled probe --the electron.

ACKNOWLEDGMENT

The work reported here is that of the members of the LBL-SLAC Joint Study Group. The author is their spokesman. Special mention should be made of the contribution of A. Garren, who is primarily responsible for developing the basic configuration and the associated lattice.

FOOTNOTES AND REFERENCES

* The work was supported by the U. S. Atomic Energy Commission.

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2. Particle Physics with Positron-Electron-Proton Colliding Beams, LBL-SLAC Study Group, LBL-750 or SLAC-146, April 1972.

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TABLE I

Lattice Parameters

Average Radius	R	345	m.
Number of Interaction Points	N_I	6	
Radius of Circular Sextant	R_n	220	m.
Straight Insertion Length	L_s	130.5	m.
Interaction Region Free Space	L_I	20	m.
Vertical Separation of Rings	h	0.8	m.
Number of Cells	N_c	48	
Cell Length	L_c	28.8	m.

		Proton Ring	Electron Ring	
Dipole Length	ℓ_d	4.96	5.56	m.
Quadrupole Length	ℓ_q	1.20	0.78	m.
Dipole Peak Field	B_o	44	2.94	kG
Quadrupole Peak Gradient	$\lvert B'_o \rvert$	560	55.4	kG/m.

TABLE II

Operating Parameters

		High-Energy Mode		Low-Energy Mode		
		Proton	Electron	Proton	Electron	
Momentum	P	200	15	50	5	GeV/C
Number of Particles	$10^{-13}N$	3.6	0.7	3.6	1.06	
Number of Bunches	n_B	24	24	48	48	
Beam Power Radiated	P_B	--	4.9	--	2	MW
Luminosity/crossing	$\mathcal{L}$	10^{32}		2.1×10^{31}		$cm^{-2}s^{-1}$
Momentum Width - $\left(\frac{\Delta p}{p}\right)_{rms}$	σ_p	.047	.094	.188	.031	%
Bunch Length (rms)	σ_ℓ	25	2.6	25	2.6	cm
Interaction Point:						
rms beam width	σ_x^*	.064	.067	.128	.117	cm
rms beam height	σ_y^*	.021	.012	.043	.021	cm
β-function horizontal	β_x^*	3.25	1.05	3.3	3.2	m
β-function vertical	β_y^*	1.42	0.34	1.45	1.05	m
Dispersion	$\eta_x^* = \eta_y^*$	0	0	0	0	
Normalized Emittance (95% beam)						
Horizontal	$\beta\gamma\epsilon_x/\pi$	.016	7.52	.016	2.51	cm-rad
Vertical	$\beta\gamma\epsilon_y/\pi$	.004	.752	.004	.251	cm-rad
Beam-Beam Tune Shift						
Horizontal	$\Delta\nu_x$	.002	.045	.002	.050	
Vertical	$\Delta\nu_y$	.005	.049	.005	.050	
Betratron Function (Max)	β_{max}	771	352	750	100	m
Chromaticity	$\xi = -\left(\frac{P}{\nu}\right)\left(\frac{d\nu}{dp}\right)$					
Horizontal	ξ_x	4.1	3.8	4	4	
Vertical	ξ_y	3.7	5.0	4	4	
Betatron Tune	$\nu_x = \nu_y$	15.75	15.75	15.75	12.75	
Dipole Field (Cells)	B_0	44.0	2.94	11.0	.98	kG
Quadrupole Gradient (Cells)	$\lvert B'_0 \rvert$	560	55.4	140	15.0	kG/m
Transition Energy	γ_τ	14.5	13.2	14.5	10	

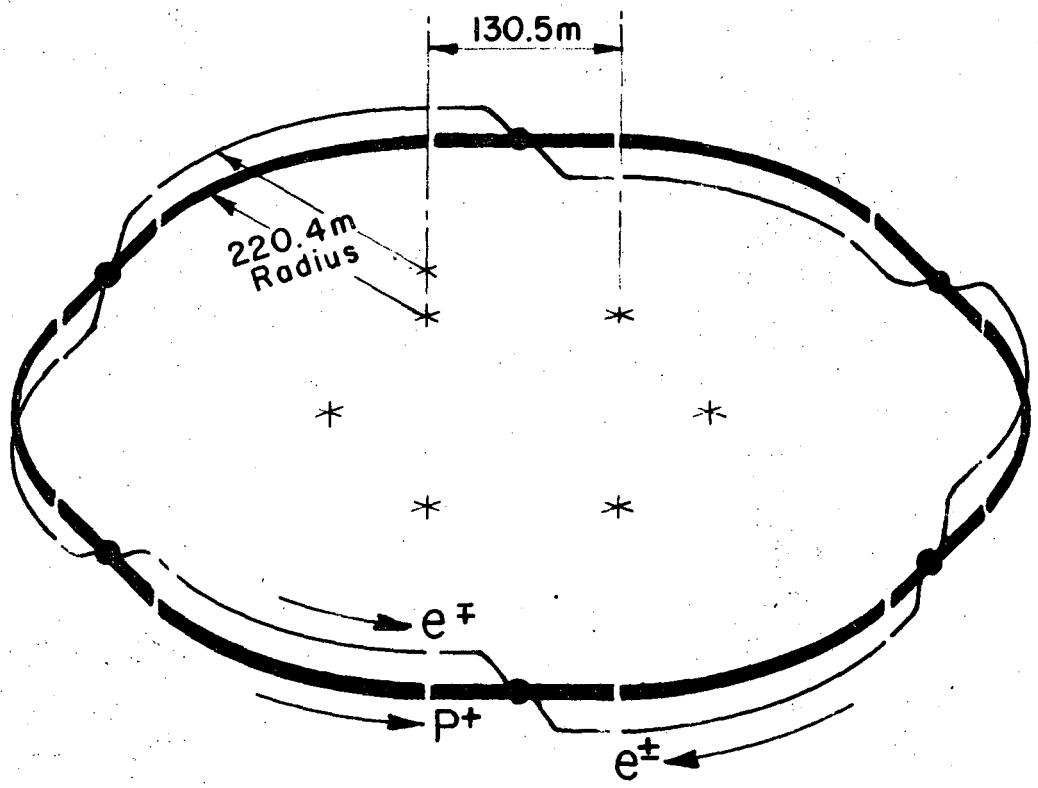

Fig. 1 PEP SCHEMATIC

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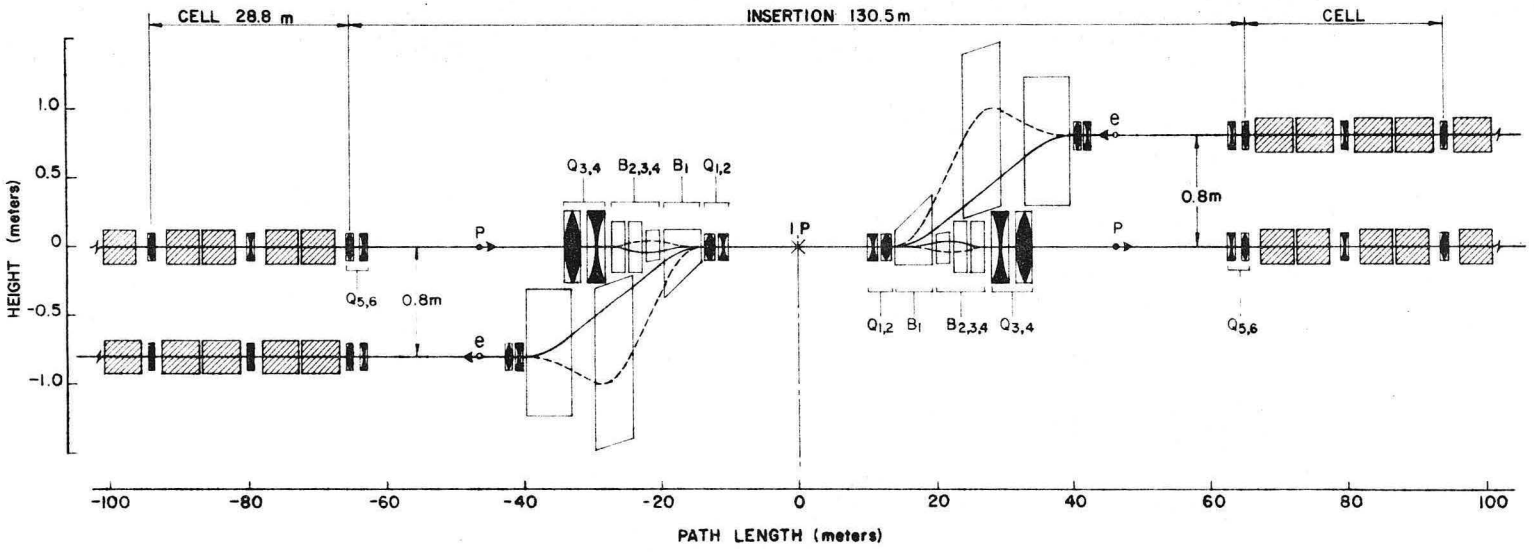

Fig. 2

SCHEMATIC SIDE VIEW OF INSERTION AND CELL STRUCTURE FOR PROTON ELECTRON SYSTEM.

B_H B_V QD QF

XBL 743-522

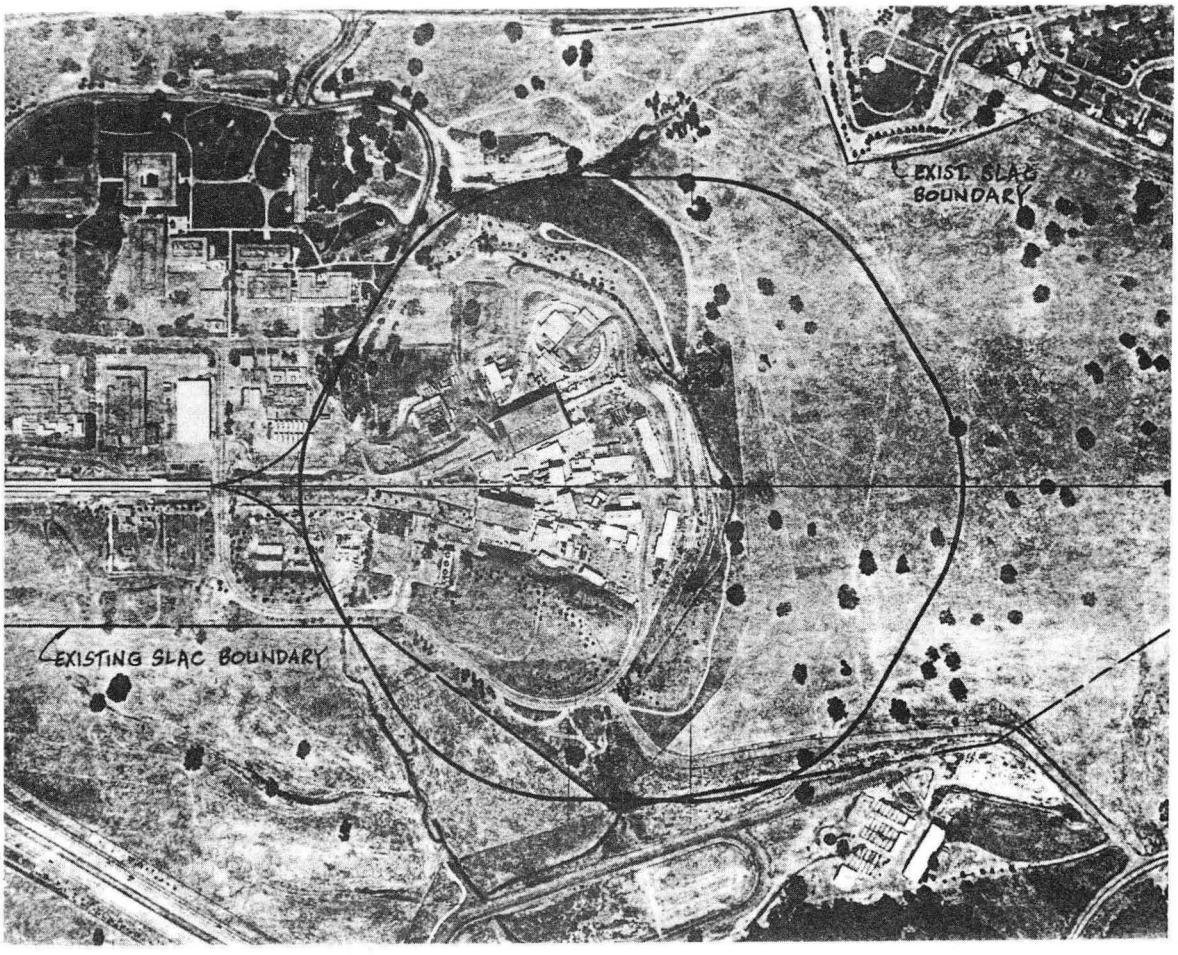

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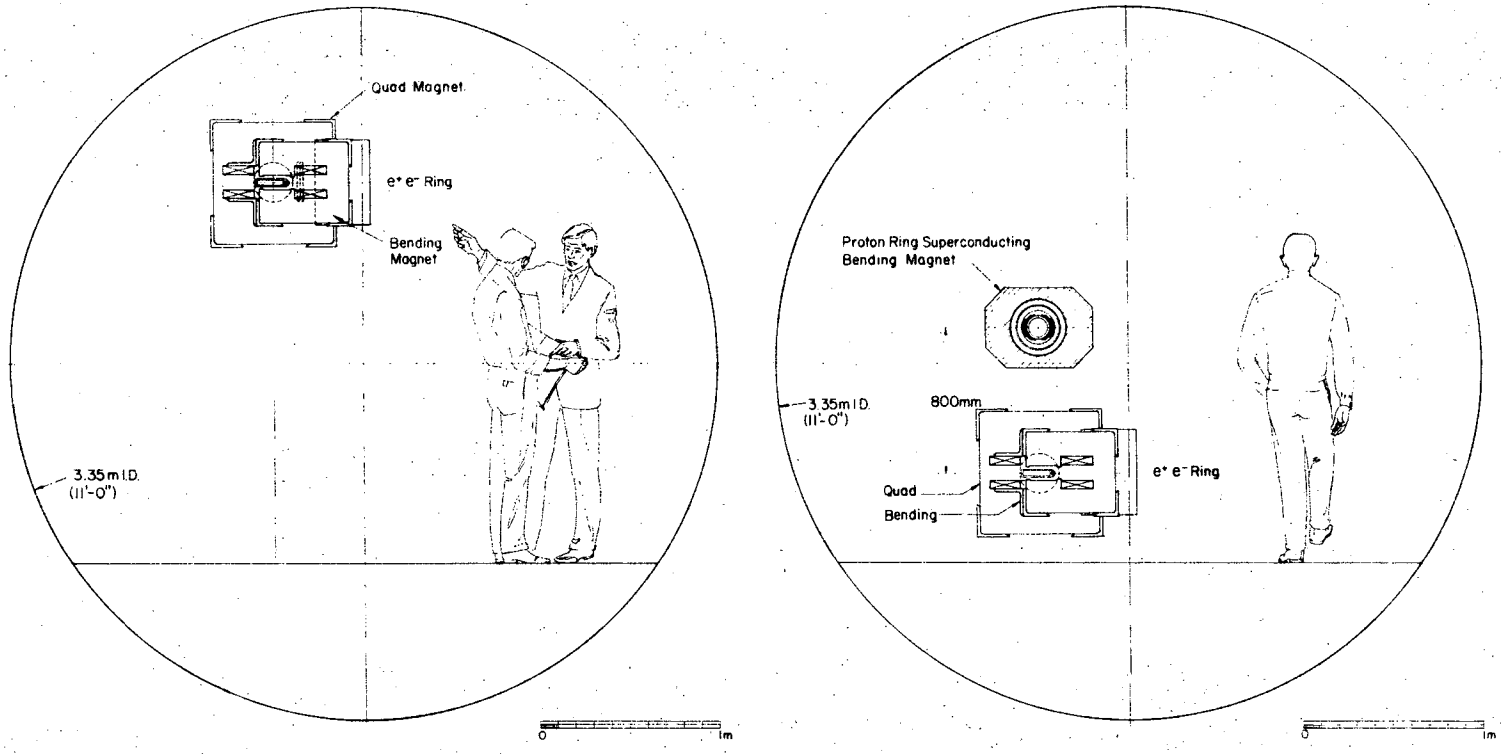
Fig. 3 General layout at SLAC site



ELECTRON MAGNETS BELOW PROTON RING

Fig. 4b

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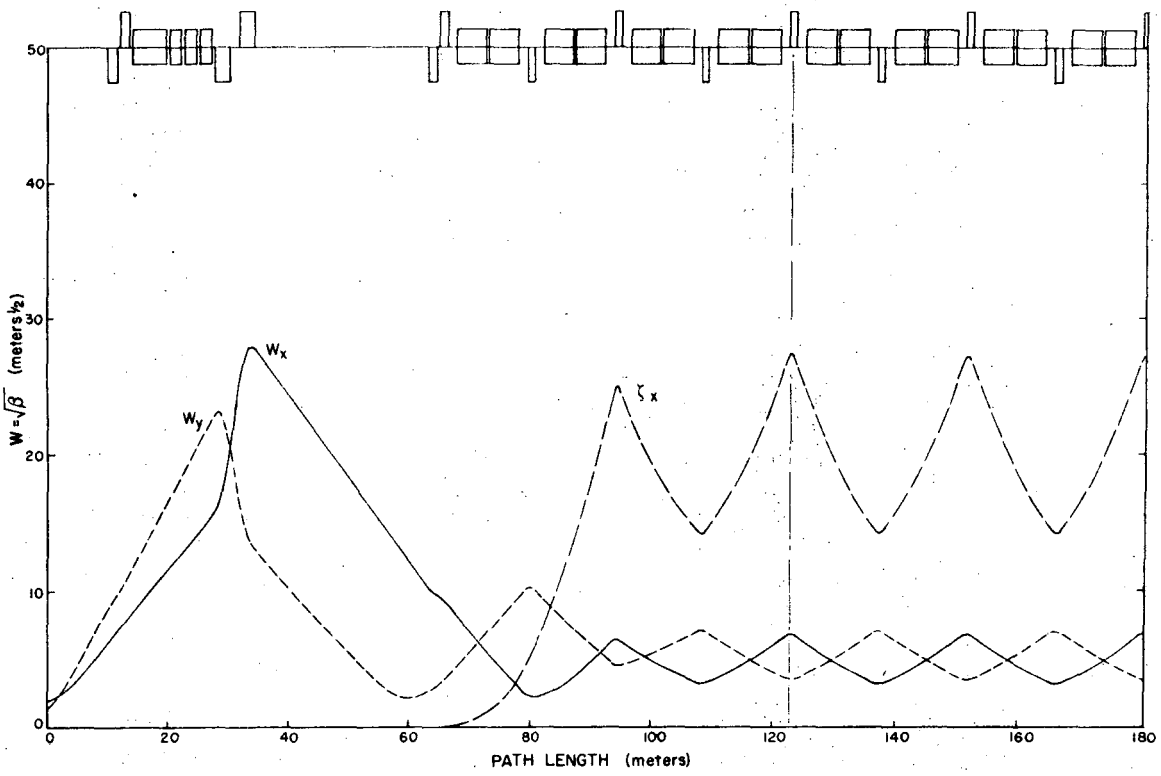

PEP STAGE II

Fig. 5 PROTON BETATRON FUNCTIONS THROUGH HALF SEXTANT

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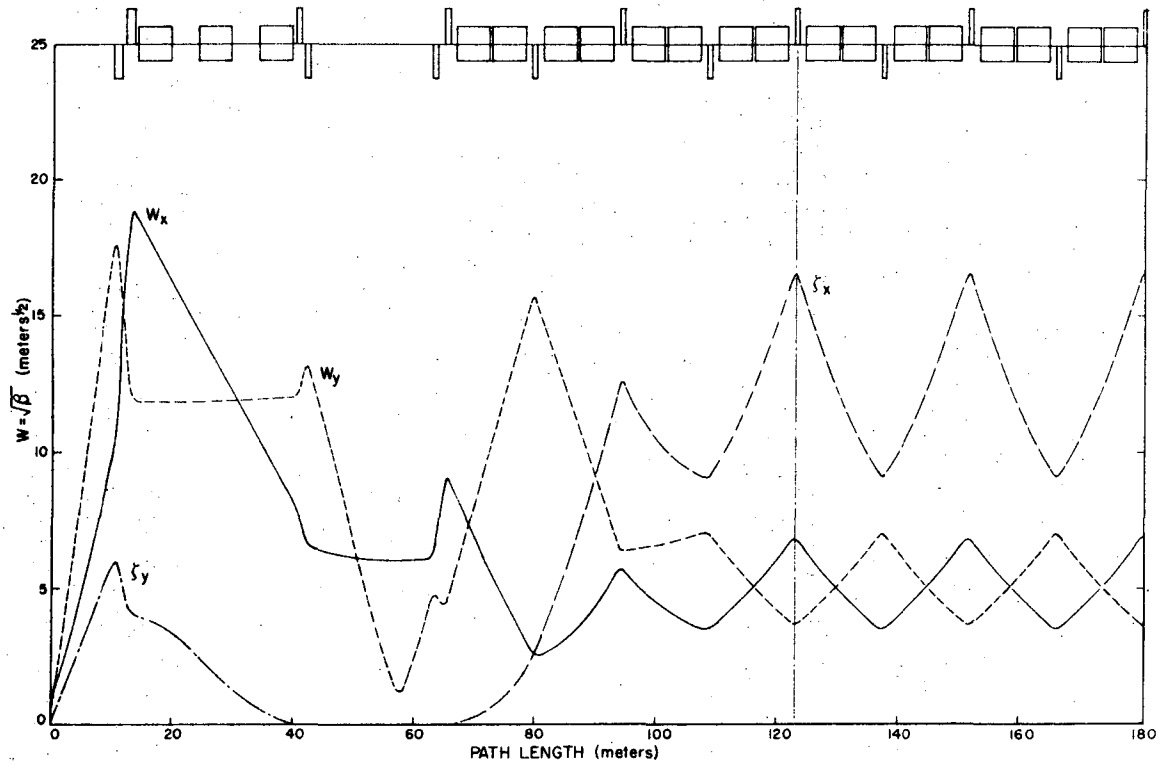
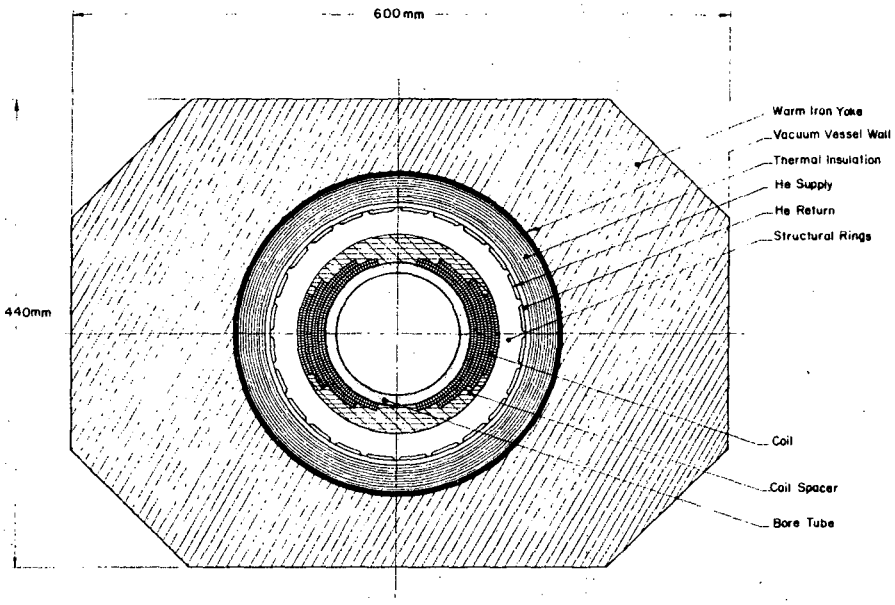


PEP STAGE II

Fig.6 ELECTRON BETATRON FUNCTIONS THROUGH HALF SEXTANT

XBL 743-519



PEP SUPERCONDUCTING PROTON RING BENDING MAGNET

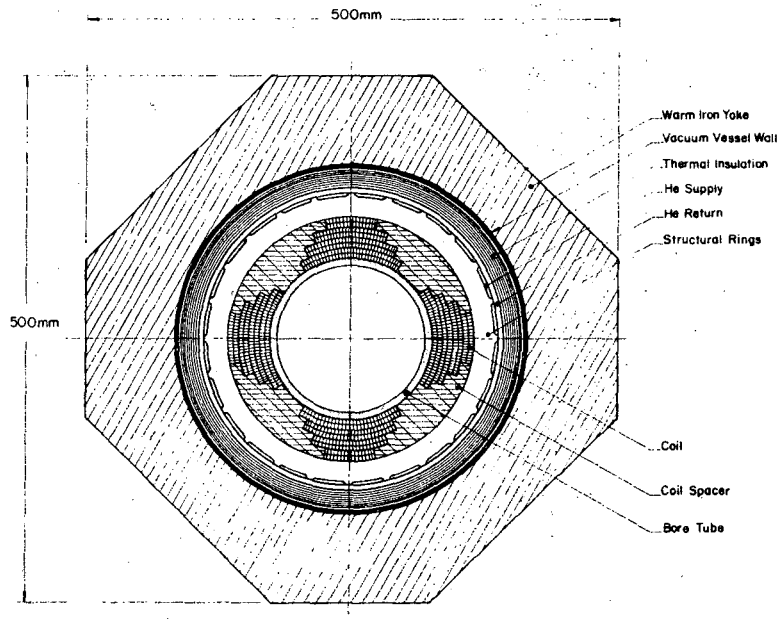


Fig. 7 PEP SUPERCONDUCTING PROTON RING QUADRUPOLE

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