THE PEP ELECTRON-POSITRON RING[†]

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Abstract

The first stage of the positron-electron-proton (PEP) colliding-beam system which has been under joint study by a Lawrence Berkeley Laboratory-Stanford Linear Accelerator Center team for the past two years, will be the electron-positron storage ring. The physics justification for the e^+e^- ring is summarized briefly and the proposed facility is described. The ring will have six arcs having gross radii of about 220 m and six interaction regions located at the centers of straight sections about 130 m long. The longitudinal distance left free for experimental apparatus at the interaction regions will be 20 m. The range of operating beam energies will be from 5 GeV to 15 GeV. The design luminosity at 15 GeV will be $10^{32}\text{cm}^{-2}\text{s}^{-1}$, and the luminosity will vary approximately as the square of the beam energy. Alternative methods under consideration for adjusting the beam cross-section are discussed. The designs of the storage ring subsystems and of the conventional facilities including the experimental halls at the interaction regions are described.

[†] This report is based upon a paper presented at the IXth International Conference on High-Energy Accelerators, May 1974, held at SLAC, and is somewhat abbreviated from the complete paper which can be found in the proceedings of that Conference. Some design parameters, especially in experimental areas, may have changed since the date of the paper.

1. Introduction

In the autumn of 1973, following the 1973 PEP Summer Study, the two cooperating laboratories, LBL and SLAC, reached the conclusion that the electron-positron storage ring component of the system, operated at beam energies up to 15 to 20 GeV and capable of yielding high luminosity in electron-positron collisions, was a straightforward extension of techniques already successfully used in several laboratories and that such a ring could be designed and built immediately with confidence. For the proton ring, superconducting-magnet technology offered the promise of achieving high beam energy with economical size and with low power consumption; however, there appeared to be some technical uncertainties yet to be resolved. In the meantime electron-positron rings operating in Europe and the U. S. had revealed that a wealth of new and previously unexpected high-energy physics information concerning the structure of elementary particles, both leptons and hadrons, was forthcoming from electron-positron collisions. These experiments suggested that it was urgent to move to higher energies than those available from existing machines.

With these facts in mind, LBL and SLAC jointly decided to propose the immediate design and construction of the 15-GeV electron-positron storage ring, PEP Stage I, and to defer the proposal of the proton storage ring until further development of superconducting technology had taken place. The two laboratories agreed to locate PEP at SLAC and to design the electron-positron ring and its housing to be compatible with the future addition of a 200-GeV proton ring such as that described in the preceding paper.[1] The two universities signed an agreement in February, 1974, outlining joint financial and management arrangements for the project.

The main component of the proposed facility is an electron-positron storage ring having six bending arcs and six long straight sections. The major diameter of the ring is about 700 m and the radius of the arcs is about 220 m. The facility is shown in Fig. 1. The electrons and positrons are produced in the SLAC linac and introduced into the storage ring via two beam transport paths emanating from the end of the two-mile accelerator and joining the storage ring in the northwest and southwest straight sections. Beams of energies up to 15 GeV can be injected and stored, and, at a future date, components could be added to permit stored-beam energies as high as 20 GeV. Also

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[*] Work supported by the U. S. Atomic Energy Commission.

provisions are made in the design of the ring housing so that a synchrotron-radiation research facility could be added in the future.

The energy lost from the beams by synchrotron radiation is restored by a high-power radiofrequency accelerating system which employs klystrons to drive the accelerating structure at a frequency of about 360 MHz and which is capable of delivering several megawatts of power to the beams. Since this power appears as synchrotron radiation which strikes the outer wall of the (mostly aluminum) vacuum chamber, that wall will be water-cooled. The radiation-desorbed gases will be pumped away very rapidly by means of long, narrow sputter-ion pumps located in the vacuum chamber in the bending magnets directly alongside the beams to sustain pressures of about 10^{-8} torr which must be maintained in the vacuum chamber to achieve adequate beam lifetimes (several hours) and low experimental background counting rates.

The proposed storage ring is designed to generate a luminosity of $10^{32} cm^{-2} s^{-1}$ per interaction region at a beam energy of 15 GeV. This luminosity appears adequate to support a vigorous experimental program. To achieve this performance, it is necessary to store a current of about 100 mA in each beam. Based on the expected performance of the SLAC two-mile accelerator in filling SPEAR II,[2] the filling time for PEP will be ten to fifteen minutes, which is a comfortably short period compared to the storage time of several hours, and ensures that storage ring operations will consume only a small fraction of the linear accelerator beam time.

The fundamental limitation on the performance of existing electron-positron storage rings is the transverse beam-beam limit which imposes an upper limit on the current density of the beams where they collide.[3] The magnetic guide field of PEP is designed to attain the specified performance, as described in Section 3, within the limitations established by this instability.

Each counter-rotating beam will be concentrated into three bunches, each a few centimeters long, equally spaced around the ring, and the bunches will collide only at the centers of the six long straight sections. Five of these interaction regions will be housed in experimental halls of various designs for high-energy physics experiments. These designs are discussed in Section 4. The sixth interaction region (northwest) will be reserved for accelerator physics measurements and experiments.

The construction schedule calls for completion of the facility four years after full authorization so that experimental physics could begin in 1980 if full authorization occurs in 1976. The total cost is estimated to be $ 53.3 million plus escalation.

2. High-Energy Physics with Electron-Positron Colliding Beams

High-energy electron-positron colliding-beam storage rings have opened up a new physical region for the study of elementary particles and their interactions, the region in which a state of pure energy is produced by the annihilation of the colliding electron and positron. This state comes into being only when a particle strikes its anti-particle and therefore does not occur when primary beams from conventional accelerators strike material targets or when protons collide with protons in a proton-proton storage ring system. The energy can rematerialize into combinations of all of the presently known elementary particles. Thus data can be obtained about the structure and interactions of these particles in a new experimental regime.

The results from entering this new region have been surprising and profound. As the energies of the colliding beams have been increased, the results of experiments done with them have become more and more difficult to understand in terms of present models of elementary-particle structure and interactions. Most recently, new experiments from the SPEAR facility at SLAC and the CEA facility in Cambridge have given results which flatly contradict the predictions of the theoretical ideas involving substructure within the nucleon which had been so successful in explaining a host of experiments done with conventional accelerators, and the resolution of this contradiction seems certain to lead to a far deeper understanding of elementary-particle physics. With the PEP storage ring we shall extend the available reaction energy in electron-positron collisions to 30 GeV, thus greatly expanding our reach into the annihilation region.

The range of experimental studies opened up by PEP is extremely rich and varied, spanning the entire field of elementary-particle physics including the strong interactions, the electromagnetic interactions and the weak interactions. In the field of strong interactions, reactions leading to mesons and nucleons in the final state will reveal new and vital information about the structure and sub-structure of the elementary particles. For example, a conceptually simple experiment, the measurement of the total reaction cross section for producing strongly interaction particles by electron-positron collisions, tests some very basic hypotheses about the structure of the particles produced. These hypotheses have failed the tests of experiments with the present generation of electron-positron rings, and experiments at higher energy may demand entirely new theoretical constructs.

In the field of pure electromagnetism, processes with only electrons, mu-mesons and gamma rays as reaction products can be studied. The theory of the electromagnetic interaction, quantum electrodynamics, is the only successful field theory in particle physics in the sense that all experimental tests to date agree with its predictions. PEP will greatly increase the energy limits to which this theory can be tested. Particularly exciting is the fact that, if present trends in the hadron production observed in e^+e^- colliding beams continue to the maximum PEP energy, and if our present concepts of the way these reactions take place have any validity, then quantum electrodynamics must break down in the PEP energy region.

In the study of the weak interaction, PEP will open new vistas. For example, the colliding electron-positron pair can transform itself into a mu-meson pair either by the weak or by the electromagnetic interaction, and the energy-dependences of these two processes are such that the weak interaction amplitude becomes more and more competitive with the electromagnetic amplitude the higher the energy. At PEP energies, the interference between the two should become observable. Particle physicists are now seeking a unified picture of the weak and electromagnetic interactions and PEP offers the possibility of testing various unifying concepts from a new experimental vantage point.

Theoretical calculations based on current ideas and models indicate that luminosities in the range $10^{31}\text{cm}^{-2}\text{s}^{-1}$ to $10^{32}\text{cm}^{-2}\text{s}^{-1}$ are required to carry out a comprehensive program of studies in weak, strong and electromagnetic interactions.

In summary, PEP offers the possibility of the study of a very broad range of fundamental questions in particle physics in a new and presently inaccessible energy region. The mysteries unveiled in the present generation of electron-positron colliding-beam facilities lead us to expect new phenomena to be uncovered with this device. These experiments, together with the complementary experiments with protons, neutrinos and mesons at the highest-energy proton accelerators, offer great promise of leading to a new depth of understanding of elementary particles and the fundamental laws of physics.

3. Description of the Electron-Positron Storage Ring Magnetic Focusing System for the Storage Ring

Tables of Parameters. Table 1 presents a summary of general parameters and lattice parameters of the PEP e^+e^- storage ring, and Table 2 gives typical beam parameters for 15-GeV operation. Emittances are defined as (σ_β^2/β).

Choice of General Parameters. The primary design goals set for the PEP storage ring were: (1) to cover the range of beam energies from 5 GeV up to 15 GeV in order to provide a range of center-of-mass energies extending approximately from those expected to be available at other smaller e^+e^- colliding-beam machines up to those available at the largest proton accelerators; (2) to maintain luminosities around $10^{32}\text{cm}^{-2}\text{s}^{-1}$ over this range in order to provide experimentally useful reaction rates with the expected cross sections; (3) to furnish an adequate number and variety of experimental halls (interaction regions) to permit a vigorous and varied national program of experimentation and (4) to ensure compatibility of the housings and experimental halls with the possible future addition of a superconducting 200-GeV proton storage ring for e-p collisions, another 15-GeV electron ring for e^-e^- or e^+e^+ collisions, or both additional rings. These goals together with the size, shape and geophysical characteristics of potential locations at SLAC led us to the choice of the six-sided storage ring shown in Fig. 1. With a radiofrequency power of about 5 MW available to the beams and with the arrangements for controlling the cross-sectional area of the beams described below, the storage ring should achieve a peak luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$ at a beam energy E of 15 GeV, and a variation of luminosity approximately proportional to E^2 below that energy. It may also be possible to operate the storage ring at energies somewhat higher than 15 GeV with reduced luminosity. The design-luminosity curve is shown in Fig. 2.

The arc radius and the straight-section length are the two most influential parameters in determining the performance of the storage ring. The arc radius should be as large as possible to minimize synchrotron radiation power. Component-free drift spaces 20 m long centered at the interaction regions have been reserved for experimental purposes. The rest of the space in the straight section is used for injection systems, rf cavities and various beam-control elements.

TABLE 1

General Parameters

Beam Energy, E	
Nominal Maximum	15 GeV
Minimum	5 GeV
Design Luminosity per Interaction Region, $\mathscr{L}_{max}$	
At 15 GeV	$10^{32}cm^{-2}s^{-1}$
Below 15 GeV	$10^{32}(E/15)^{2}cm^{-2}s^{-1}$
Nominal Crossing Angle, 2δ	0 radians
Number of Interaction Regions	
Total	6
Available for High-Energy Physics	5
Reserved for Machine Physics Studies	1
Number of Stored Bunches, N_b	3
Available Length at Each Interaction Region	20 m

Lattice Parameters

Straight Section Length	130.416 m
Gross Radius of Arcs	220.337 m
Magnetic Bending Radius	169.916 m
Maximum Diameter of Ring	701.505
Circumference of Ring	2166.912 m
Cell Length	28.842 m
Total Number of Cells	48
Number of Standard Cells	36
Effective Length of Bending Magnets	5.561 m
Effective Length of Cell Quadrupoles	0.780 m
Bending Field at 15 GeV	2.9447 kG
Maximum Quadrupole Field at Bore Radius	< 7.5 kG

TABLE 2

Typical Beam Parameters at 15 GeV

Total Betatron Tunes	
Horizontal	18.75
Vertical	18.75
Horizontal Emittance	2.3×10^{-5} cm-rad
Vertical Emittance	1.8×10^{-5} cm-rad
Number of Stored Particles (each beam)	4.44×10^{12}
Synchrotron Radiation Power (each beam)	2.6 MW
Linear Tune Shifts per Interaction Region	
Horizontal, $\Delta\nu_x$	0.06
Vertical, $\Delta\nu_y$	0.06
Luminosity (each interaction region), $\mathscr{L}$	1.0×10^{32} cm^{-2}s^{-1}
Interaction Region Parameters	
Horizontal Beta, β_x^*	4.0 m
Vertical Beta, β_y^*	0.20 m
Momentum Dispersion, η^*	-0.73 m
Beam Size (r.m.s.)	
Horizontal Betatron, σ_x^*	0.096 cm
Horizontal Dispersion, σ_{xE}^*	0.072 cm
Total Horizontal, σ_x^*	0.12 cm
Total Vertical, σ_y^*	0.006 cm

In order to attain high luminosity, it is necessary to collide intense beams within a small cross-sectional area. However, the number of particles which can be collided within a given area is limited by the incoherent beam-beam interaction;[3] this limit is usually characterized by the small-amplitude vertical and horizontal tune shifts $\Delta\nu_y$ and $\Delta\nu_x$. It is well known that, when beam currents are limited by the beam-beam interaction, the maximum theoretical luminosity $\mathscr{L}_{max}$ may be increased if the beam size is enlarged. If one operates a storage ring at different energies under the same focusing configuration, the transverse beam dimensions vary directly as energy E, the maximum (tune-shift-limited) number of storage particles as E^3; thus the luminosity varies as E^4 and drops off very rapidly at lower energies. If, however, the focusing configuration is changed as the energy is lowered in such a way that beam size remains essentially constant, approximately filling the aperture, then the maximum number of stored particles varies as E and luminosity as E^2. This E^2 luminosity is quite acceptable, because most reaction cross sections increase at lower energies. Above the design energy, luminosity will be rf-power-limited, and will drop precipitously, cutting off at an energy of around 18 GeV.

Several different methods for beam size control will be provided. These include varying the momentum dispersion function at the interaction point as in SPEAR,[2] unmatching the momentum dispersion function so that it does not repeat periodically from cell to cell and varying the betatron tune.[4] Vertical size will be adjusted by means of variable horizontal-vertical betatron-oscillation coupling. Using combinations of these techniques, it should be possible to reach, or at least approach, the luminosity shown in Fig. 2 at all operating energies.

Variation of the betatron tune gives a contribution to $\mathscr{L}_{max}$ which varies as ν_{xA}^{-3}, where ν_{xA}^{-3} is that part of the radial tune which comes from the bending arcs. Momentum dispersion at the interaction region gives a contribution proportional to η^{*2}/β_x^*, where η^* and β_x^* are respectively the momentum dispersion function and the betatron amplitude function at the interaction point. An unmatched dispersion function η gives a luminosity increment proportional to η_1^2/β_x^* where η_1 is a measure of the mismatch in the bending cells.

A lattice in which the arcs consist of doublet cells and are joined by comparatively simple insertions was chosen.[5] Preliminary studies showed that the natural beam size would be about right to give the peak design luminosity if the bending part of the lattice contained between 40 and 50 cells operating with a betatron phase advance per cell of around 90° in both the horizontal and vertical planes. For convenience, the number of cells was chosen to be 48, or eight cells per 60-degree arc. The nominal phase advance of 90° per cell allows considerable latitude in varying the tune, since doublet cells work reasonably well at phase advances from below 45° to above 135°. A conventional separated-function bending cell, shown in Fig. 3, provides independent control of the total betatron tunes ν_x and ν_y by means of the independently controllable focusing and defocusing quadrupoles. The spaces between the quadrupoles and bending magnets provide room for various devices including the sextupoles, which are necessary to control chromaticity.

Each insertion consists of a straight section, shown in Fig. 4, of approximately 130 m in length, and two modified bending cells which have standard dimensions but independently-powered quadrupoles. Suitable configurations have been found over a considerable range of values of tunes, β_x^*, β_y^*, η^* and η_1 (the η-mismatch amplitude). These configurations include ranges for the various beam-enlargement schemes which are adequate to produce the design luminosity over the designated operating range of 5 to 15 GeV. Solutions which are favorable for injection also have been found.

4. Physical Plant*

Ring Housing and Shielding

The ring will be located symmetrically about the axis of the SLAC two-mile accelerator with the western-most point approximately 100 m downstream from the end of the accelerator. The terrain slopes downward from the accelerator axis in both north and south directions so that the interaction regions, which are off the axis, will generally lie in areas of lower elevation. Some segments of the ring will be in areas low enough to permit cut-and-cover construction. Those parts deeper underground will require bored tunnels.

The ring, which is horizontal, will be housed in a tunnel at an elevation of approximately 65 m above mean sea level. It crosses under the SLAC beam switchyard about 11 m below the accelerator beam. As shown in Fig. 1, the ring will circumscribe the present research yard. The beam transport tunnels, through which electrons and positrons are brought into the ring, will

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*May be modified as result of PEP Summer Study recommendations in this proceedings.

start at the end of the linear accelerator and branch away and downward, crossing over the ring to insertion points from the inside of the ring, as shown in Fig. 1.

The electron-positron storage ring will be positioned high in the tunnel and suspended from the concrete lining. The tunnel design provides for eventual inclusion of a proton ring. The proton storage ring would occupy a middle height and the electron-positron storage ring would be remounted to alternate above and below it, crossing it in a vertical plane at the interaction points. In the bored tunnel areas a circular housing will be constructed 3.3 m in diameter, as shown in Fig. 5. A rectangular section 3.3 m wide by 2.7 m high is planned in the cut-and-cover areas. The access aisle will be on the outside of the ring. Because the production of neutrons by proton interactions is some three orders of magnitude greater than that due to electron interactions, and, in addition, because the energy of stored protons will be about 200 GeV as compared to 15 GeV for the stored electrons and positrons, the total shielding requirements will be determined by beam losses from the future proton storage ring.

Experimental Areas

The planned site for PEP offers convenient access to five of the six interaction regions. Thus, it is proposed that five experimental areas be developed in a manner suitable for experiments in the first stage of PEP. The sixth one will have access for only relatively small experimental setups such as those needed for accelerator physics and luminosity monitoring.

The complement of experimental areas is regarded as typical; however, a Summer Study will be held in 1974 on the subject of PEP experimentation, and the details of the experimental areas may change.

The primary constraint on the experimental areas, imposed by the magnet configuration, is the length of the interaction region drift section, which will be 20 m. This is the distance between the final focusing elements of the storage ring and is the space in which most experimental equipment will be mounted.

It is proposed that two of the experimental areas be of the basic design shown in Fig. 6. These so-called "Standard" areas are seen as general purpose facilities which will accommodate many of the experiments planned for PEP, including those involving a future proton ring. The basic design consists of an 8-meter-by-20-meter pit with 4 m of clearance above and below the beam line. On either side of the pit is a platform 4 m wide and 3 m below beam elevation and extending along the beam line are 20-meter alcoves 6 m wide. These dimensions are determined by examining some of the experiments envisaged for standard areas, such as tests of quantum electrodynamics, various studies of hadron production and searches for weak interaction effects.

The third area will have the same transverse dimensions as that described above, but the pit will be extended along the beam direction to a total length of 30 m and the forward-angle alcoves will be omitted. This extension is provided mainly for weak interaction experiments where there may be significant interference between the single-photon exchange amplitude and weak amplitude in the forward direction for processes such as muon pair production. Rather involved forward-angle experiments providing for ranging out muons (using 10-15 m of iron) to measure their polarization are accommodated by this area.

The fourth experimental area is the largest and could be dedicated to a large 4π-steradian magnetic detector or some other large device as yet unconceived. The layout of the experimental pit area at the interaction region is largely determined by the geometry of a large cylindrical magnetic detector similar to the one in current use at SPEAR, except with a superconducting coil and possibly also provisions for calorimetry to give additional information on energetic hadrons. The pit region has clearance of ±6 m vertically, and horizontally 8 m and 12 m on either side of the center line.

The fifth area is designated with an eye to future potential expansion. Initially, it will have the same dimensions as the Standard experimental area except that the alcoves will be omitted. In addition, the ends of the pits will be made in such a manner that either one or both can later be easily extended to provide additional experimental space downstream of the proton beam for various possible e-p devices.

Power and Cooling

The maximum power demand of the electron-positron storage ring and experimental apparatus is estimated to be 26 MW. The installed capacity will be 36 MW. While the distribution system can provide 3 MW to each of the five experimental areas, it is expected that the total experimental-equipment load will not exceed 5 MW at any time.

Except for experimental areas, low-conductivity water (LCW) will be provided for the installed power capacity. One megawatt of cooling capacity will be installed at each experimental area. Cooling will be done by relatively small local LCW systems exchanging heat with cooling tower water which will be distributed around the ring to cool the closed-loop LCW systems.

Acknowledgements

The work reported in this paper is that of the members of the LBL-SLAC Joint Study Group; the author is only their spokesman. Special thanks, however, are due W. B Herrmannsfeldt and C. S. Nissen.

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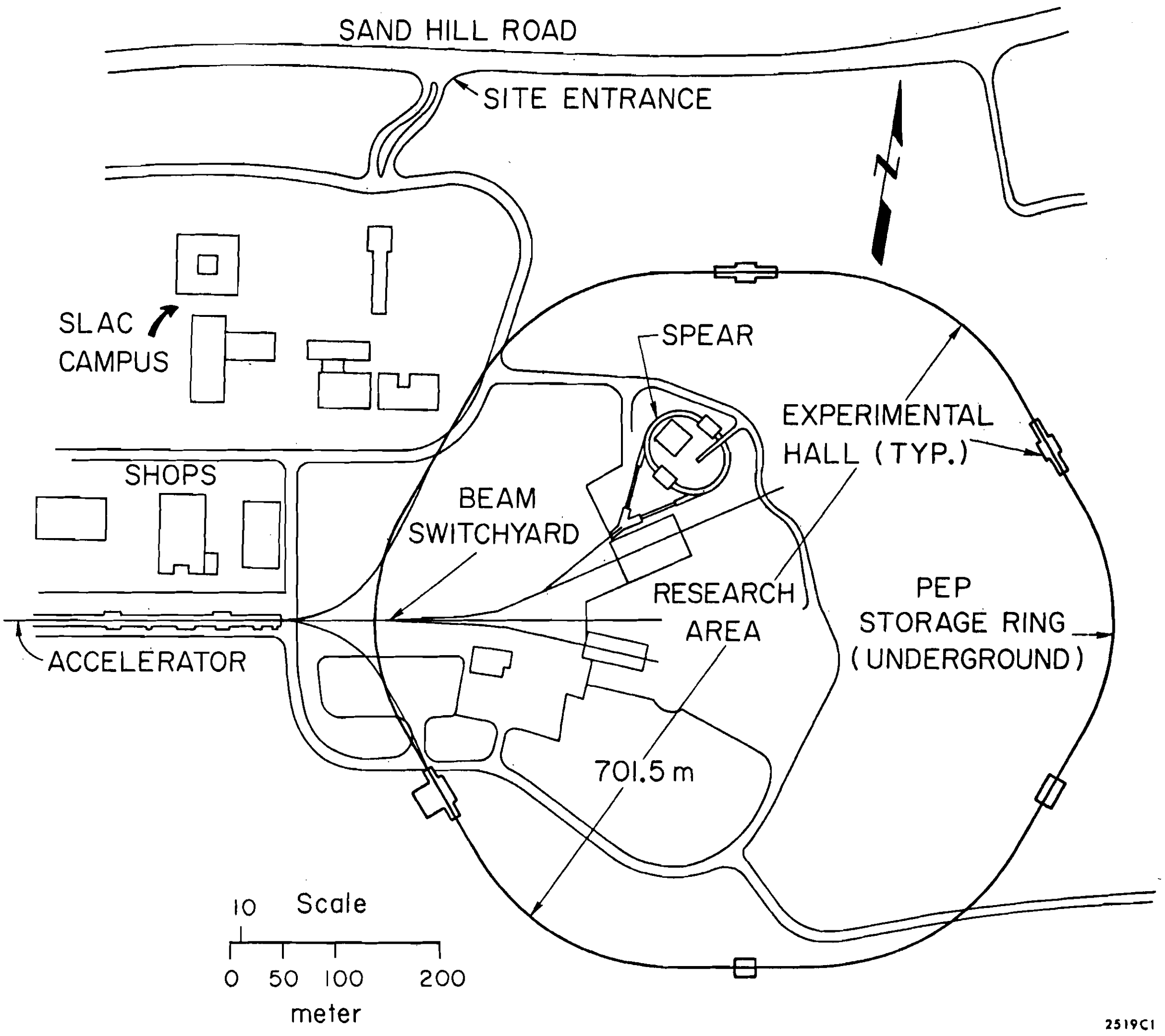

Fig. 1. Layout of the PEP ring superimposed on an aerial view of the SLAC site.

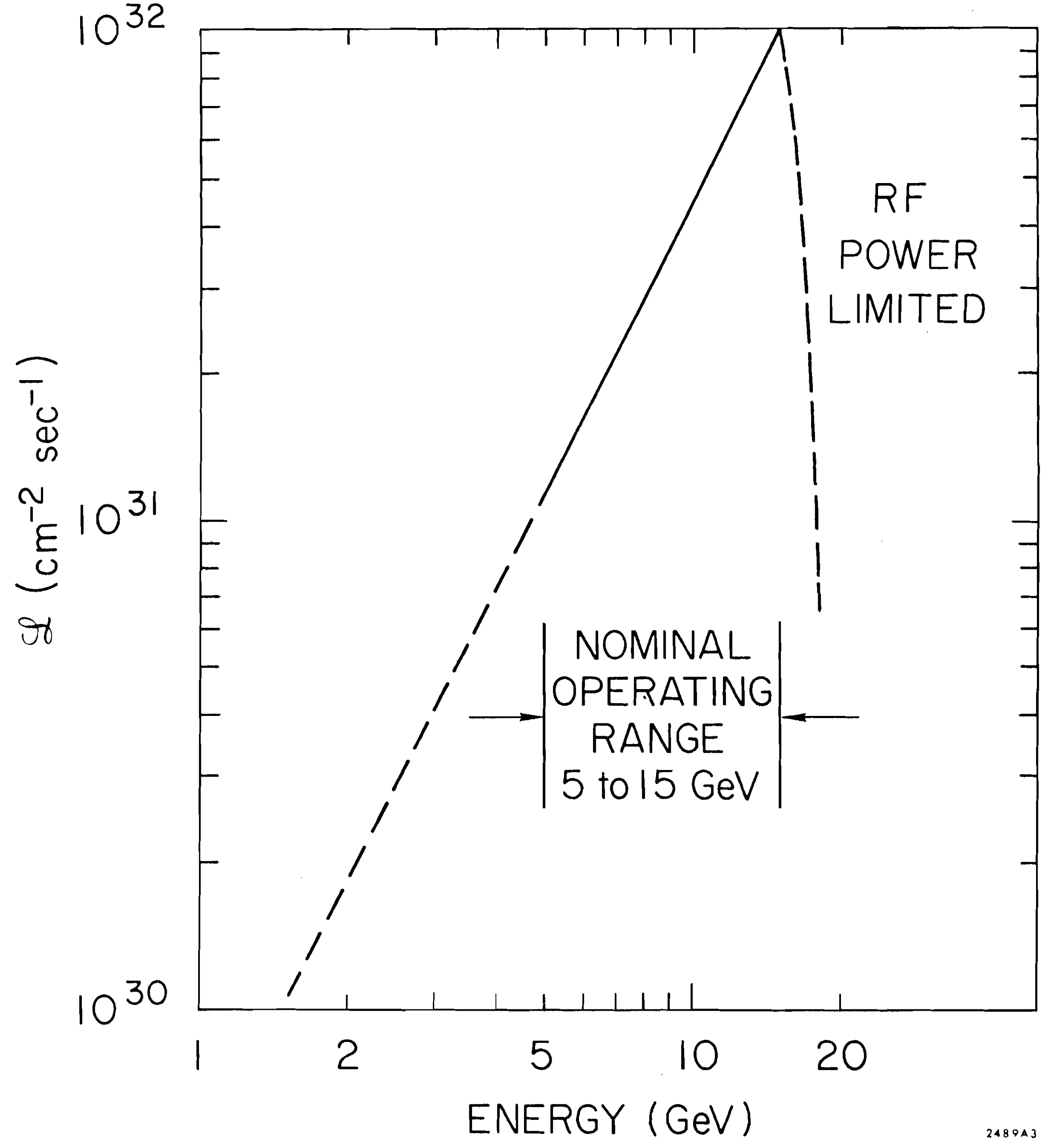

Fig. 2. Design luminosity as a function of beam energy showing the nominal operating range and the upper limit imposed by the available rf power.

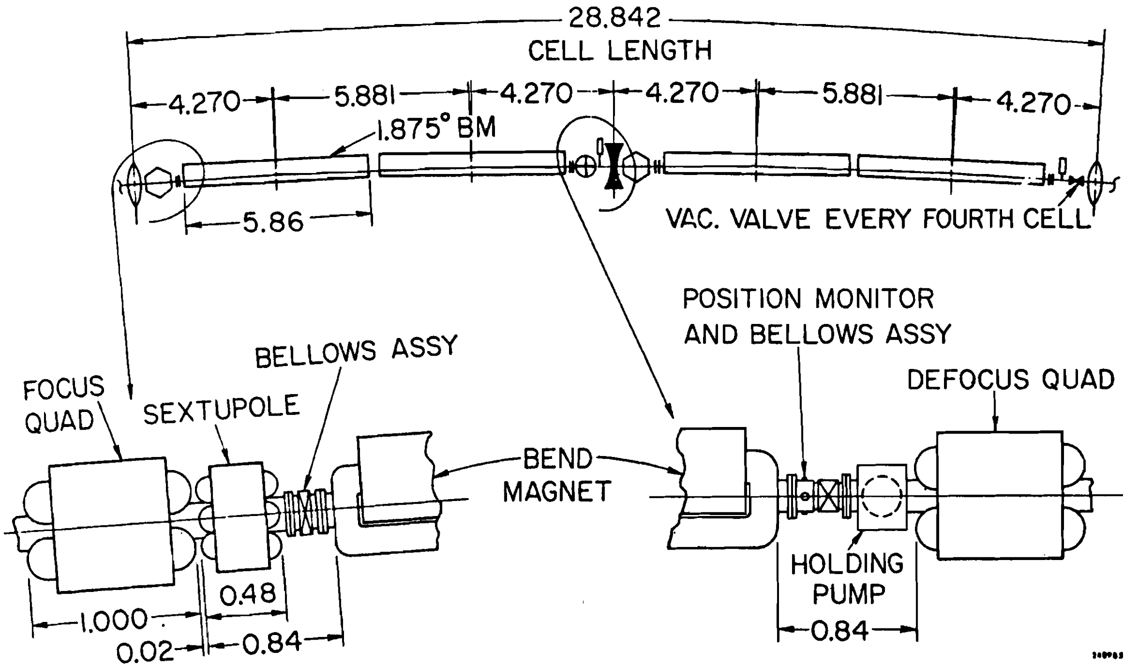

Fig. 3. A standard cell is shown between the quadrupole centerlines. Dimensions are in meters.

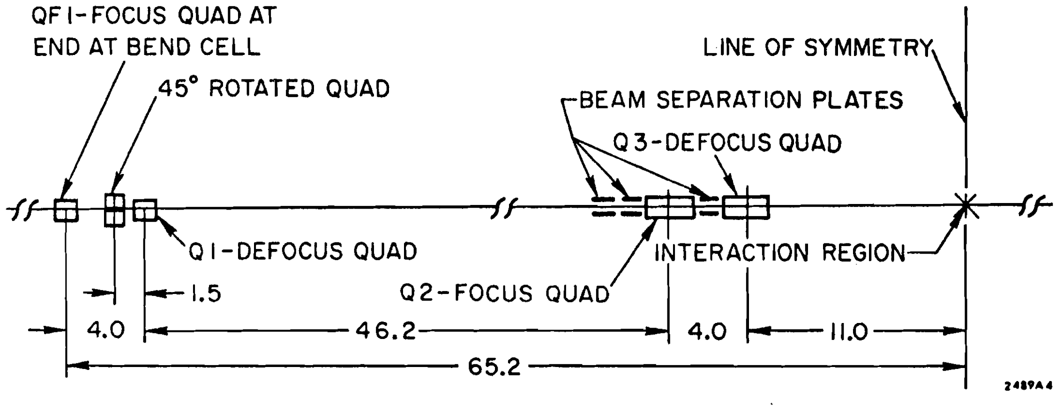

Fig. 4. The straight insertion, which is symmetric about the interaction point, is shown from the centerline of the cell quadrupole to the interaction point. Dimensions are in meters.

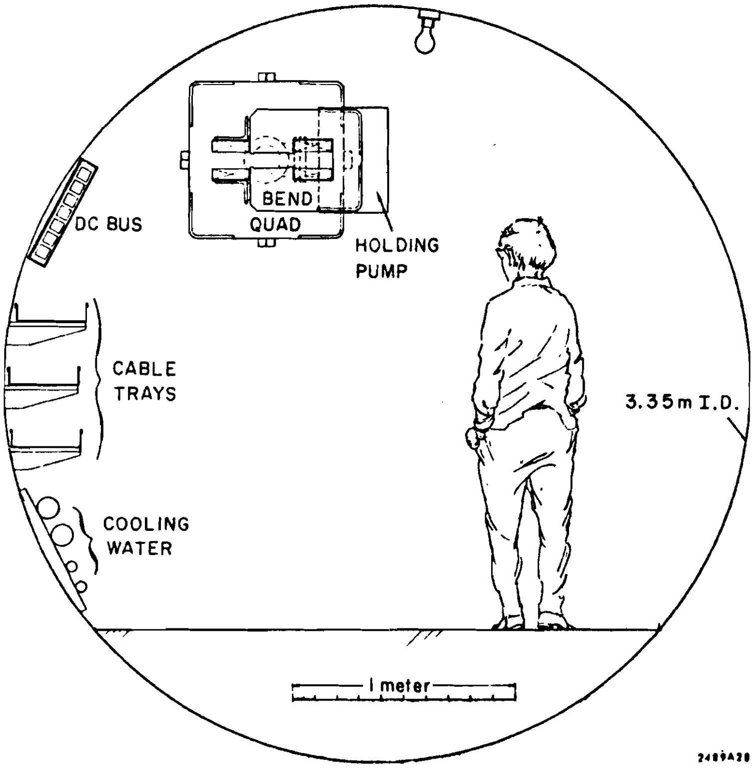

Fig. 5. Cross section of the PEP housing.

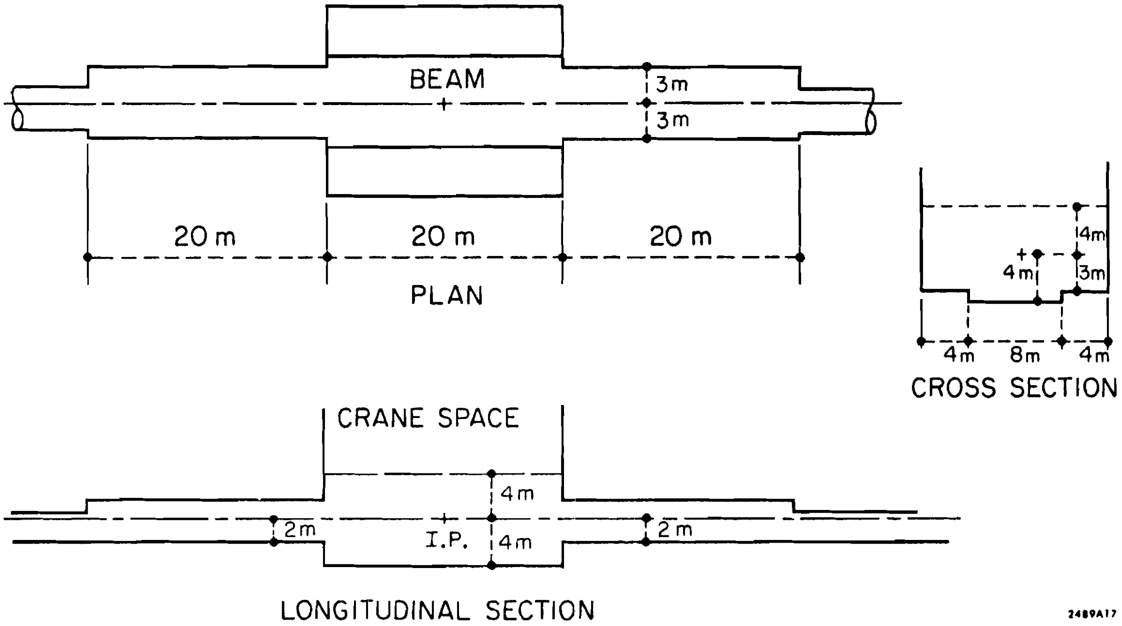

Fig. 6. "Standard" interaction area with alcove.