THE PEP ELECTRON-POSITRON RING -- PEP STAGE I*

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Summary

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 around 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 $10^{32} cm^{-2}s^{-1}$, 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.

1. Introduction

In the preceeding report presented to this Conference by L. Smith, the evolution of the PEP system was described.[1] 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 on 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

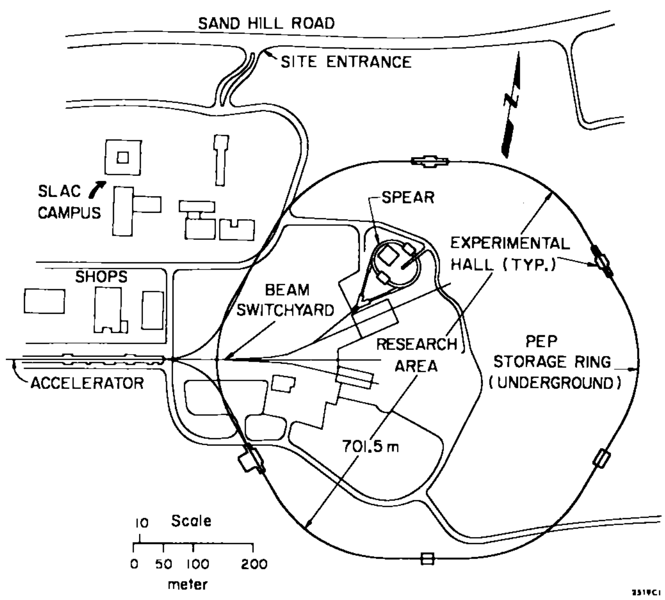

Fig. 1. Layout of the PEP ring superimposed on an aerial view of the SLAC site.

accelerator and joining the storage ring in the northwest and southwest straight sections. Beam 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 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

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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).

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	$10^{32}\text{cm}^{-2}\text{s}^{-1}$	
Below 15 GeV	$10^{32}(E/15)^2\text{cm}^{-2}\text{s}^{-1}$	
Nominal Crossing Angle, 2δ	0	radians
Number of Interaction Regions		
Total (superperiodicity)	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	m
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	
Momentum Compaction	0.00455	
Transverse Damping Time	0.00823	s
x-y Coupling Coefficient	0.280	
Horizontal Emittance	2.3×10^{-5}	cm-rad
Vertical Emittance	$1.8 \times 10^{-}$	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}	$cm^{-2}s^{-1}$
Cell Parameters		
Horizontal Phase Advance	97.0°	
Vertical Phase Advance	82.3°	
Maximum Horizontal Beta	48.2	m
Maximum Vertical Beta	50.2	m
Maximum Momentum Dispersion	2.24	m
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

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 $10^{32}cm^{-2}s^{-1}$ 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 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 $10^{32}cm^{-2}s^{-1}$ 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

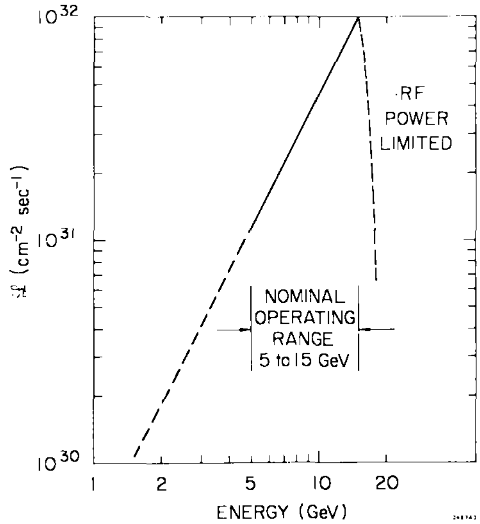

Fig. 2. Design luminosity as a function of beam energy showing the nominal operating range and the upper limit imposed by the available rf power.

cavities and various beam-control elements.

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

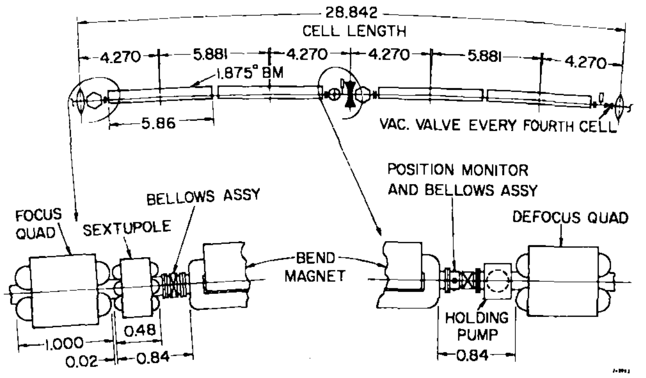

Fig. 3. A standard cell is shown between the quadrupole centerlines. Dimensions are in meters.

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

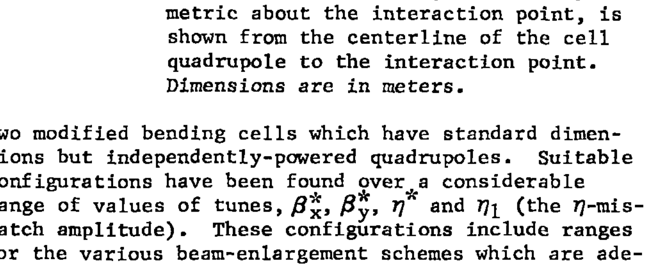

Fig. 4. The straight insertion, which is symmetric about the interaction point, is shown from the centerline of the cell quadrupole to the interaction point. Dimensions are in meters.

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.

Apertures and Magnet Design

The "beam-stay-clear", or minimum unobstructed lateral region around the design orbit, is a roughly elliptical figure with diameters

$$a_i = 20\,\sigma_i + 2 \text{ cm}$$

where a_i is the vertical or horizontal aperture diameter, σ_i is the vertical or horizontal rms beam radius and the subscript denotes the particular location on the circumference. The factor of 20 allows sufficient, but not overly conservative, clearance to give good beam lifetimes according to experience at SPEAR; the additional 2 cm is a margin for orbit distortions and misalignments. The actual bore clearance of the magnets will include an additional allowance for vacuum chamber walls, installation tolerances and for a possible bake-out mantle.

The magnet system is being designed to minimize the installed cost plus 10-years' operating cost at 15 GeV. Prudent attention was given to reducing energy consumption. The magnets themselves will be capable, nevertheless, of operation at 20 GeV. Laminated magnets were selected for the main ring elements in order to minimize capital costs and to ensure sufficient uniformity magnet-to-magnet.

Radiofrequency System

General. The energy radiated per turn by a 15-GeV electron circulating in the PEP ring is 26 MeV. In order to achieve a reasonable quantum lifetime, an overvoltage which depends on the lattice parameters and radiofrequency is required. At a frequency of 358 MHz (chosen for reasons discussed below), a peak rf voltage of 44 MV is sufficient. In order to reach the design luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$, the required circulating current is 100 mA for this same lattice. The radiated power is therefore 2.6 MW per beam, or 5.2 MW total. In addition, another 2.0 MW is dissipated in the rf structure. At lower energies, the rf power requirements are lower.

It is proposed that the required rf power of 7.2 MW be supplied by 24 klystrons, each delivering a CW output power of 300 kW to an accelerator section 2.1 m in length, comprising five cavities. The accelerator sections will be arranged in two groups of 12 sections each, located at the ends of the southern-most straight section, shown in Fig. 1. Allowing space between sections for flanges, bellows, etc., the overall length of each group will be about 30 m. Rf power will be supplied to the cavities through waveguides running down vertical penetrations from the klystrons which will be housed above ground for ease of maintenance. A list of the principal parameters for the rf system is given in Table 3.

Table 3

General Rf System Parameters

Frequency	358.6	MHz
Energy Loss per Turn	26	MeV
Peak Rf Voltage[1]	44	MV
Particles per Beam	4.4×10^{12}	
Circulating Current per Beam	100	mA
Synchrotron Radiation Power (total)	5.2	MW
Total Accelerating Structure Length	60	m
Active Accelerating Structure Length	50	m
Total Shunt Impedance (V_p^2/P_c)	950	MΩ
Total Cavity Power Dissipation	2.0	MW
Total Rf Power	7.2	MW
Conversion Efficiency at Design Current[2]	70	%
Number of 300-kW Klystrons	24	
Total Power Input to Rf Power Supplies[3]	11	MW

[1]For a quantum lifetime of 12 hours.

[2]Ratio of radiated power to total rf power.

[3]Based on klystron efficiency of 70% and a power supply efficiency of 95%

Choice of Frequency. Although operation at frequencies below 100 MHz has some advantages, the attainable shunt impedance per unit length of the cavities is low. In order to attain the high peak voltages required for PEP using such cavities, the length of the rf structure would need to be several hundred meters. By using a higher frequency, the geometric shape of the cavities can be optimized and the shunt impedance per unit length can be increased dramatically. On the other hand, as the operating frequency is increased, the overvoltage ratio (peak voltage divided by the synchrotron radiation loss per turn) required to give a reasonable quantum lifetime also increases. Taking these two competing factors into account, it can be shown that there is a rather broad optimum for PEP in the frequency region 100 to 400 MHz.

Within this frequency region, economic and engineering considerations dominate the choice of frequency. The structure diameter, weight and cost become unreasonably large below about 200 MHz. A careful study of the comparative advantages of klystrons vs gridded tubes indicated that klystrons were superior to tetrodes with respect to initial and annual operating costs, reliability and expected life. Klystron size and cost are lowest at the upper end of the 100-400 MHz frequency range. This factor, together with the decrease in structure costs with increasing frequency, led to a choice of 358 MHz for both PEP and SPEAR II.[2] Before PEP is constructed, operational experience with the new SPEAR II rf system will have served as a test of the proposed design.

System Design. Further details on the PEP rf system design are described in another report to this Conference.[6]

Vacuum System

Introduction. The vacuum system proposed for PEP will be similar in design, construction and operation to the system currently in successful use at SPEAR.[7] The vacuum chamber in the bending magnets will be an 11-m-long, 6061-T4 aluminum extrusion with an internal cross section, shown in Fig. 5, designed to accommodate

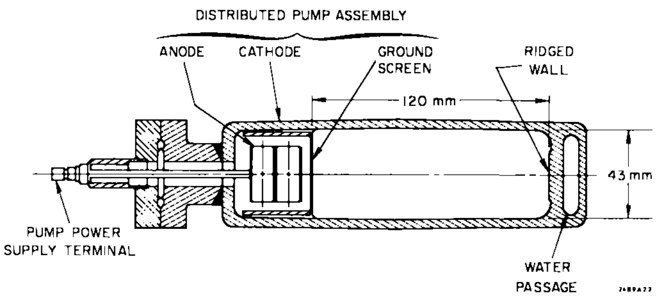

Fig. 5. Cross section of the vacuum chamber for the bending magnets. The vacuum pump which operates in the fringing-field region of the magnet is shown with one of the high-voltage terminals.

the beam-stay-clear region required by beam dynamics. The synchrotron-radiation absorbing wall will be approximately 10 mm thick. The absorbing surface will be ridged as in the SPEAR chambers in order to minimize the synchrotron-radiation-induced gas desorption. A cell vacuum chamber will consist of two bending magnet chambers and two quadrupole chambers. The quadrupole chambers will accommodate the required expansion bellows, position monitors, gauging, etc.

Synchrotron Radiation. The surfaces which are subjected to synchrotron radiation require cooling. At 15 GeV and 100 mA dc in each beam, the total power radiated per beam will be 2.6 MW. The maximum linear heat flux is 35 W/cm for a single electron or positron beam and 45 W/cm for both beams. The synchrotron radiation consists of photons with a spectral energy distribution up to well above 80 keV.

The main gas load during operation is due to synchrotron-radiation-induced desorption which is dominated by a two-step process in which a photoelectron is ejected from the vacuum chamber wall by a synchrotron-radiation photon and subsequently desorbs a gas molecule upon reentering the wall. This gas load is concentrated in the arcs where the synchrotron radiation is produced. Data from SPEAR indicate that it is conservative to extrapolate the desorption rate linearly with beam energy. The total photon desorbed gas load for the entire ring is estimated to be 10^{-5} Torr-ℓ/mA-s at 15 GeV.

Vacuum Pumps. The vacuum system is conductance-limited in the bending magnet chambers where the bulk of the outgassing occurs. Distributed sputter-ion pumps of the type which were developed and used for SPEAR will therefore be installed inside the vacuum chamber within the bending magnets. These pumps are rated at 300 ℓ/s per m of pump length. Commercially available 100-ℓ/s ion pumps will be mounted at each quadrupole and will maintain the system at a base pressure of 1×10^{-9} Torr without a stored beam. Based on the above estimate for the total gas load, the maximum pressure will be 5.0×10^{-8} Torr and the average pressure will be 2.5×10^{-8} Torr.

In the insertions, which will be fabricated of 300-series stainless steel tubing, the main gas load will be due to thermal outgassing. Initially, a system of commercially available ion pumps will be installed to maintain an average pressure of 5×10^{-9} Torr. Extra pumping ports will be provided so that added pumps could lower the average pressure in the insertions to 5×10^{-10} Torr if required by experimental conditions.

Electron and Positron Injection

The six PEP interaction regions are illuminated by three equally-spaced bunches in each beam which are filled selectively by gating the SLAC linac gun. The rf frequency of 358 MHz implies that the rf phase (time) acceptance will be of the order of nanoseconds.[2] A special new electron gun has been installed on the two-mile accelerator to provide very high peak currents in the short (~1.4 ns) pulses necessary for injection into both SPEAR II and PEP. Figure 6 is a plot showing the PEP filling time vs injection energy. The line shows the predicted injection times based on a conservative 50% injection efficiency and the expected yields of electrons and positrons with the new gun. For good operating efficiency, the filling time should not exceed ten or fifteen minutes. From Fig. 6, it can be seen that this can be achieved at energies above approximately 10 GeV up to the maximum positron energy from the two-mile accelerator, which coincidentally is 15 GeV, the design energy of the ring. The maximum injection repetition rate, which is used at the highest injection energies, is 360 pps, the full SLAC rate. At lower filling energies, the damping rates of horizontal betatron oscillations and the energy oscillations require that the filling repetition rate be reduced. The design of the injection system permits the filling of an adjacent bunch while a previously injected bunch is damping, and the curve in Fig. 6 reflects this mode of operation.

For storage ring operation at energies below reasonable injection energies, especially below 10 GeV, the beam will be stored at the injection energy and then the ring magnets will be ramped down to the operating energy.

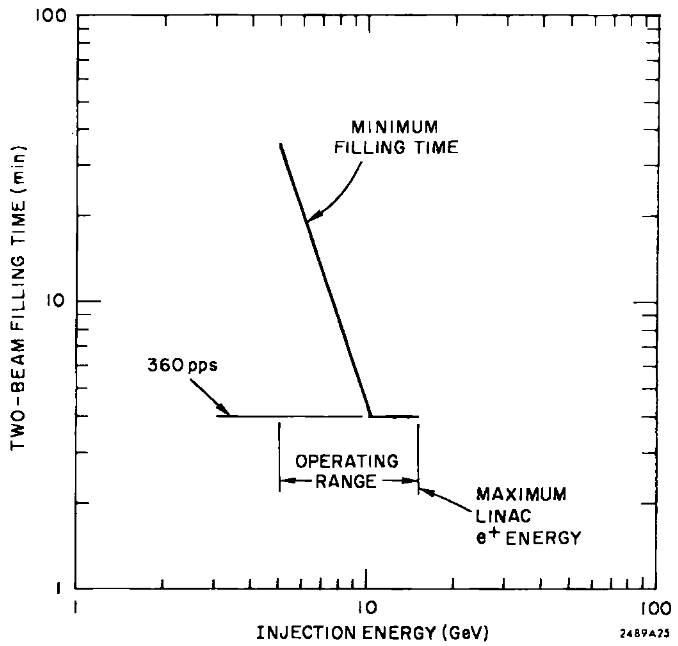

Fig. 6. Filling time vs injection energy. Filling time is the time required to fill both the electron and positron beams to a current of 100 x E(GeV)/15 mA from a beam of 20 mA e^+ and 40 mA e^- in a 1.4 ns pulse with 50% capture efficiency.

Instrumentation Monitoring and Control

The storage ring system, like the linear accelerator, is too spread out for a single data-collection point to be practical. Data will, therefore, be collected at a number of places, edited and compressed as much as possible and then transmitted to the control room. The control room will be located to permit a short path for direct transmission of fast monitoring signals from the injection lines. To reduce the amount of cabling, signals generated within the bending sextants will be wired to instrumentation racks in the nearest data center. Interlock signals will be summarized and then wired directly to the equipment they must control. The remaining signals will be edited by a small computer and sent by serial link to the control room.

The central element of the control system will be a "large mini-computer" which will provide task synchronization between the peripheral elements and manage intercommunication. It need not have elaborate computational ability. It will have three types of "peripherals". The first type is the "data-collection" computer, at least one per interaction area, which provides all connections to the real world. The second type is the console manager which provides all operator interfaces. The third peripheral will be a moderately-sized computational computer which will carry out large-scale calculations and provide file management and programming aids.

Control of Beam Instabilities

Transverse Instabilities. In the design of this storage ring it has been assumed that the maximum luminosity obtainable is determined by the beam-beam incoherent limit and that it is possible to store beams of sufficient intensity to reach this limit. The various transverse instabilities that can occur with large bunched beams and can jeopardize their storage may be categorized into three types: those that are determined by the average circulating current, those that are present because there are multiple bunches in the ring and those that depend upon the peak current in a single bunch.

The present PEP design appears to be rather conservative in requiring an average single-beam current of 100 mA in three bunches. Many electron storage rings have stored such currents at much lower energies where the transverse instabilities are generally much more troublesome. While multiple-bunch transverse instabilities have been predicted, they have not been observed in rings having only a few bunches. Also, because the bunch spacing in PEP is large and fixed, it seems feasible to build a feedback system to damp each bunch individually. The only multiple-bunch motion that has been observed in SPEAR is the coherent motion between two colliding beams. This coupled motion does not seem to be of major concern and its effect is ameliorated by use of electric quadrupoles which are planned for inclusion in the PEP lattice.

The head-tail instability has been the most important single-beam transverse instability observed in electron storage rings and it has been controlled through the chromaticities. In the PEP design it will be possible to vary the value of the chromaticity by means of the sextupole fields which are distributed throughout the lattice without producing destructive non-linear resonances.

The peak current required in PEP is not substantially different from that already attained in single beams in SPEAR.

Longitudinal Instabilities. The six circulating bunches in PEP will have six coherent normal modes. The in-phase oscillations of the bunches can be controlled by a feedback loop coupling a signal picked up from the beam back to a varactor-diode phase modulator in the input drive to one or more of the klystron groups. In order to damp the other five possible modes, a high-frequency cavity will be installed to split the synchrotron oscillation frequencies.

Three potential longitudinal instabilities which can arise out of the beam-beam interaction have been suggested and studied.[3] The first occurs only when the colliding beams cross at an angle, which is not the case in PEP. The second is due to a non-zero value of the η-function at the interaction region η^*. It places an upper limit of the value of η^* above that at which PEP will operate. The third occurs when the bunch length is large compared to the value of the β-function at the interaction region. This will not be the case in PEP.

A potential problem in the design of the PEP rf system is the additional power loss due to the excitation of higher-order cavity modes. Both theoretical and experimental approaches are planned in attacking this problem, and it is expected that by proper structure design, the enhanced power loss due to the excitation of higher-order cavity modes can be held to a tolerable level.

4. Physical Plant

Ring Housing and Shielding

The ring will be located symmetrically about the axis of the SLAC two-mile accelerator with the westernmost 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 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. 7. A rectangular section 3.3 m wide by 2.7 m

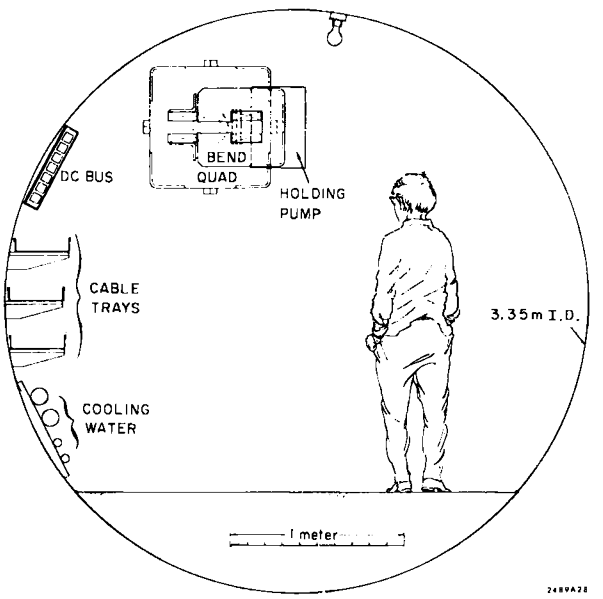

Fig. 7. Cross section of the PEP housing.

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. 8. These so-called

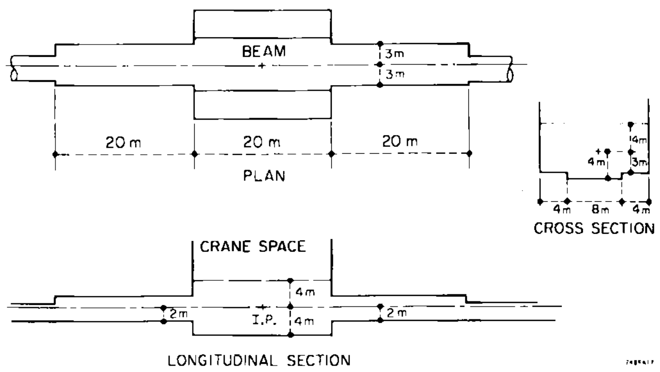

Fig. 8. "Standard" interaction area with alcove.

"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 clearances 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

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DISCUSSION

Alessandro Ruggiero (NAL): The proposed ring encircles the present research yard. Do you anticipate any interference with potential expansion of the research yard or any other conflict?

John Rees (SLAC): The answer is no, we don't expect to expand the research yard in the easterly direction because the huge backstop is required to stop the radiation from the linear accelerator and the level of the storage ring is way below ground there and does not interfere with the normal operation in any way. We even expect to be able to tunnel under the linac without disturbing it except when we have to open the enclosure to bring out the injection beams. Dr. Panofsky points out that the linac works well at a magnitude 5 earthquake and the same can be said for SPEAR. We had a stored beam and it didn't even dump.

Melvin Month (BNL): Is the luminosity quoted per interaction region and has each bunch six interactions per revolution?

Rees: Yes. The revolution is quoted per interaction region and each bunch has six interactions per revolution. Being in the same plane, they can't get by each other.