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PEP LATTICE DESIGN

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Summary

Details of the current lattice design for PEP, the proton-electron-positron colliding beam system[1] will be described. This system allows collisions of protons up to 150 GeV with electrons or positrons up to 15 GeV, by storing the proton beams in a superconducting storage ring and the electrons or positrons in a concentric conventional ring, and allows collisions between electrons and positrons in the same ring up to 15 GeV.

Introduction

This design evolved from the concept put forward by Pellegrini et al.[2] which proposes the achievement of high luminosities by use of single short bunches of a relatively modest number of particles in each of the colliding beams. The performance goal of the present design is the attainment of a luminosity of about 10^{32} cm^{-2} sec^{-1} for center-of-mass energies up to about 100 GeV in proton-electron collisions.

The machine consists of two concentric rings, separated vertically except in four interaction regions designed with zero, or perhaps small, crossing angles. See Fig. 1. In plan view the two rings look nearly identical, each consisting of four 200-meter-radius arcs separated by four 200-meter-long straight sections. For electron-positron experiments both bunches would counter-circulate in the e-ring, while for proton-electron or proton-positron experiments protons would be stored in the p-ring and either electrons or positrons in the e-ring, with suitable choice of polarities in the magnets.

In the normal single-bunch mode envisioned, two opposite interaction regions would be used simultaneously; in a two-bunch mode all four could operate at once with the same total luminosity and RF power, provided that twice the total number of protons and the same total number of electrons were stored.

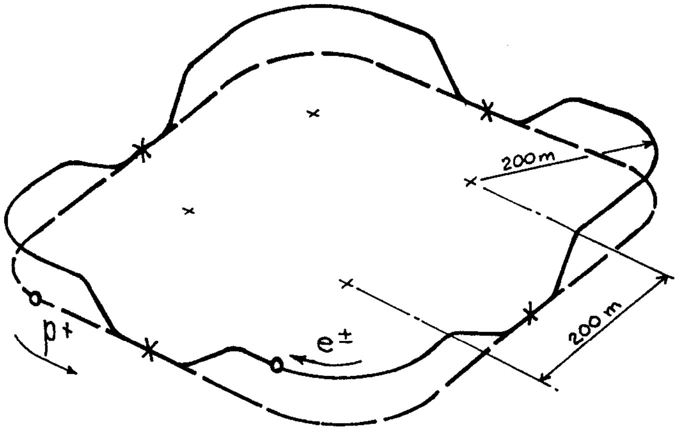

Fig. 1. Schematic diagram of PEP ring configuration.

For protons with energies between 70 and 150 GeV interacting with 15-GeV electrons, we expect a luminosity of 10^{32} cm^{-2} sec^{-1} at each of the two collision points, and a decline at lower proton or electron energies. A luminosity of 0.6×10^{32} cm^{-2} sec^{-1} is predicted for electron-positron collisions at 15 GeV.

Design Considerations

The principal parameters affecting performance in the proton-electron mode at peak energies are listed in Table I, the beam dimensions being determined by the emittances given in Table II. The number of protons used is in the range of existing synchrotrons, and the number of electrons corresponds to a reasonable level of radiated power. Of course the short bunch lengths required imply high peak currents, which fact makes imperative a careful theoretical and experimental study of collective phenomena.

It has become apparent to us that the performance of a PEP-type device will probably be limited by the beam-beam interaction rather than by practical limitations on particle phase-space density. This interaction sets a limit to the allowable transverse particle density, so the interaction cross section must be carefully adjusted. To obtain a suitable area we have used normalized proton emittances much larger than those available from AG synchrotrons, and in fact comparable to those measured in the Bevatron. The electron horizontal emittance is determined by lattice properties and energy, and the vertical emittance by horizontal-vertical betatron coupling. Even though we have employed maximum coupling, the electron area is uncomfortably small.

A finite crossing angle increases effective cross-sectional area, but this approach was discarded for the basic configuration since more stored particles

Table I. Peak Energy p-e Operating Parameters

		p	$e^{\pm}$	
Momentum (maximum)	P	150	15	GeV/c
Number of Particles	N	5×10^{12}	5×10^{12}	
Luminosity (each int. point)	$\mathcal{L}$	10^{32}		cm^{-2}s^{-1}
Number of RF Bunches	n_B	1		
Length of Each Interaction Region	L_I	20		m
Crossing Angle	2δ	0		deg
Interaction Point Parameters:				
beta-function - horizontal	β_x^*	4.19	0.6	m
- vertical	β_z^*	0.45	0.11	m
dispersion - horizontal	η_x^*	-0.20	-0.96	m
- vertical	η_z^*	0	0	m
Interaction Point Amplitudes:				
bunch length	σ_ℓ	13	1.6	cm
momentum spread	$\sigma_{\Delta p/p}$	1.2×10^{-3}	1.15×10^{-3}	
dispersion width	σ_{xp}^*	0.024	0.11	cm
betatron width	σ_{xb}^*	0.140	0.026	cm
total width	σ_x^*	0.142	0.113	cm
total height	σ_z^*	0.026	0.011	cm
Beam-Beam Tune Shifts:				
horizontal	$\Delta\nu_x$	0.023	0.019	
vertical	$\Delta\nu_z$	0.024	0.025	

Table II. Orbit Parameters

		p-ring	e-ring	
Betatron frequencies - horizontal	ν_x	23.25	31.25	
- vertical	ν_z	15.25	27.25	
Phase advance-normal cells	$\mu_x/2\pi$	80.2	79.7	deg
	$\mu_z/2\pi$	75.8	77.5	deg
Transition energy	γ_t	20.7	28.3	
Beta-function max. -cells	β_{max}	28.5	28.5	m
Dispersion maximum-cells	η_{max}	1.20	1.22	m
Beta-function max. -straight	$\bar{\beta}_x$	1047	2110	m
	$\bar{\beta}_z$	3417	1879	m
Dispersion maximum-straight	$\bar{\eta}_x$	-0.31	-6.94	m
Normalized Emittances/π				
$\epsilon_x = 6\sigma_{xb}\,\sigma_{x'b}\,\beta\gamma$ (95% of beam)	ϵ_x	0.045	2.033	cm-rad
σ_{xb}= rms betatron ampl.	ϵ_z	0.015	2.033	cm-rad
$\epsilon_\ell = 6\sigma_\ell\,\sigma_{\beta\gamma}$	ϵ_ℓ	15.	386	cm
Injection				
Assumed injection energy	E_i	5	15	GeV
Momentum spread	$\pm\Delta p/p$	10^{-3}	0.75×10^{-3}	
Betatron amplitudes*-horiz.	a_{bet}	4.13	1.18	cm
vert.	b_{bet}	2.69	1.19	cm
Synchrotron amplitude	a_s	0.12	0.12	cm
Proposed apertures - horiz.	a	5.5	2.5	cm
- vert.	b	4.0	2.5	cm
Maximum apertures in insertions at 70 GeV, 15 GeV:	$\bar{a}$	12.	12.	cm
	$\bar{b}$	14.	12.	cm

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*For protons the beam radii used for aperture are $\sqrt{6}\sigma$, for electrons 6.5σ is used, for a quantum lifetime of 10^5 sec at 15 GeV.

are required for the same luminosity--too much more, in our opinion, if common quadrupoles are to be avoided--and the experimental configuration becomes more complicated. Instead, the minimum β-values have been increased substantially from the 15 cm suggested in Ref. 2 for protons and the 5 cm suggested for electrons, and in addition horizontal dispersion has been introduced. With this combination of measures we have limited the linear tune shifts $\Delta\nu_x$ and $\Delta\nu_z$, which measure the strength of the beam-beam interactions, to values below 0.025, a number found to be sufficiently small in electron storage rings. However, it should be noted that recent results suggest that this value may be pessimistic for electrons, and there are theoretical grounds to suspect it may be optimistic for protons. We thus obtain the operating parameters of Table I which give the desired luminosity of 10^{32} cm^{-2} sec^{-1}, with reasonable apertures and RF requirements.

In the lattice as presented, large β-values in some quadrupoles lead to high natural chromaticity ($pd\nu/dp$). The presence of dispersion in these quadrupoles makes it possible to remove the chromaticity with nearby sextupoles, but the sextupoles cause serious nonlinear effects. Modifications will be made to correct this condition.

For electron-positron experiments at 15 GeV, we contemplate operating with electron parameters similar to those of Table I, except that there would be 2.5×10^{12} particles in such beam, the same total radiated power, and a luminosity of 0.6×10^{32} cm^{-2}sec^{-1}.

The range of accessible operating energies and the corresponding luminosities has not yet been completely mapped out. However, we plan to cover the proton energy range from about 70 to 150 GeV with 15-GeV electrons or positrons at full luminosity, and complete parameter sets are now in hand for both ends of this range. (We have also calculated quadrupole settings for proton injection and acceleration.) The procedure proposed is to assume that proton emittance varies inversely with momentum, and to let the proton β_x^* and β_z^* vary directly. In this way the beam sizes, tune shifts, and luminosity remain constant. Below 70 GeV one can no longer decrease β^* without increasing quadrupole apertures in the nearest doublet, above those proposed here, since these vary as $(\beta^*)^{-1}$.

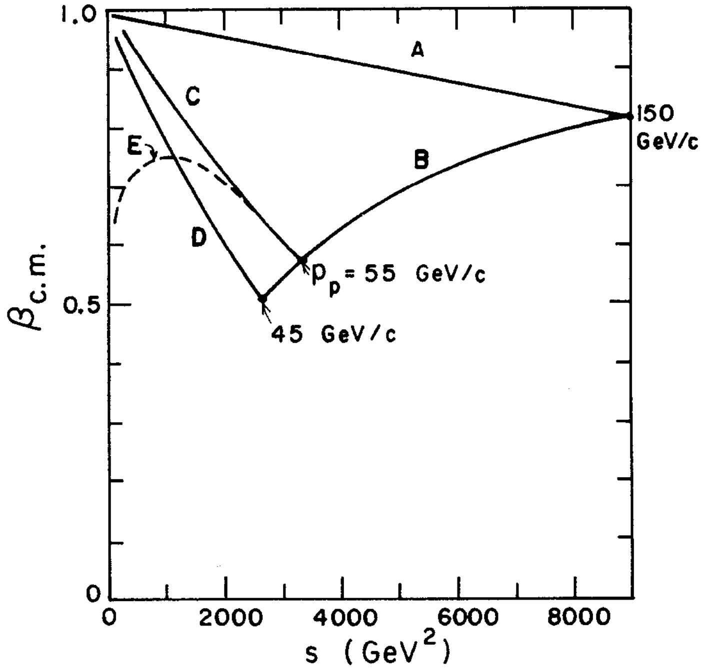

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Fig. 2. Values of Center-of-mass energy squared (s) and velocity ($\beta_{c.m.}$) accessible with synchronism of bunches.

Curves A: E_e varied.

B: E_p varied.

C: s_{min} determined by aperture needed for injection.

D: s_{min} with 2-cm extra aperture width.

E: adjustable dog-leg in p-ring.

For different proton energies it is necessary to change the closed-orbit path length to maintain synchronism between the two colliding bunches. This will be done by varying the ratio of magnetic field to momentum to change the radial position of the proton bunch. Because the proton beam width at injection is larger than it is at the experimental operating energies, there will be sufficient aperture available to maintain synchronism between 55 and 150 GeV. (See Fig. 2). A further decrease would require provision of extra aperture or lattice changes. Changes of electron energy can also be made in order to alter the center-of-mass energy; these do not entail synchronism problems, but will require selection of other interaction point parameters.

Description of the Lattice

In order to simplify the description we shall treat separately the periodic structure of normal cells that comprises most of the circular arcs, and the matched insertions that are composed of the (horizontally) straight sections and adjacent portions of the arcs. The orbit lattice and parameters are summarized in Tables II and III.

A. Normal Cells

The central portion of each arc is made up of 14 identical separated function FODO cells, with the

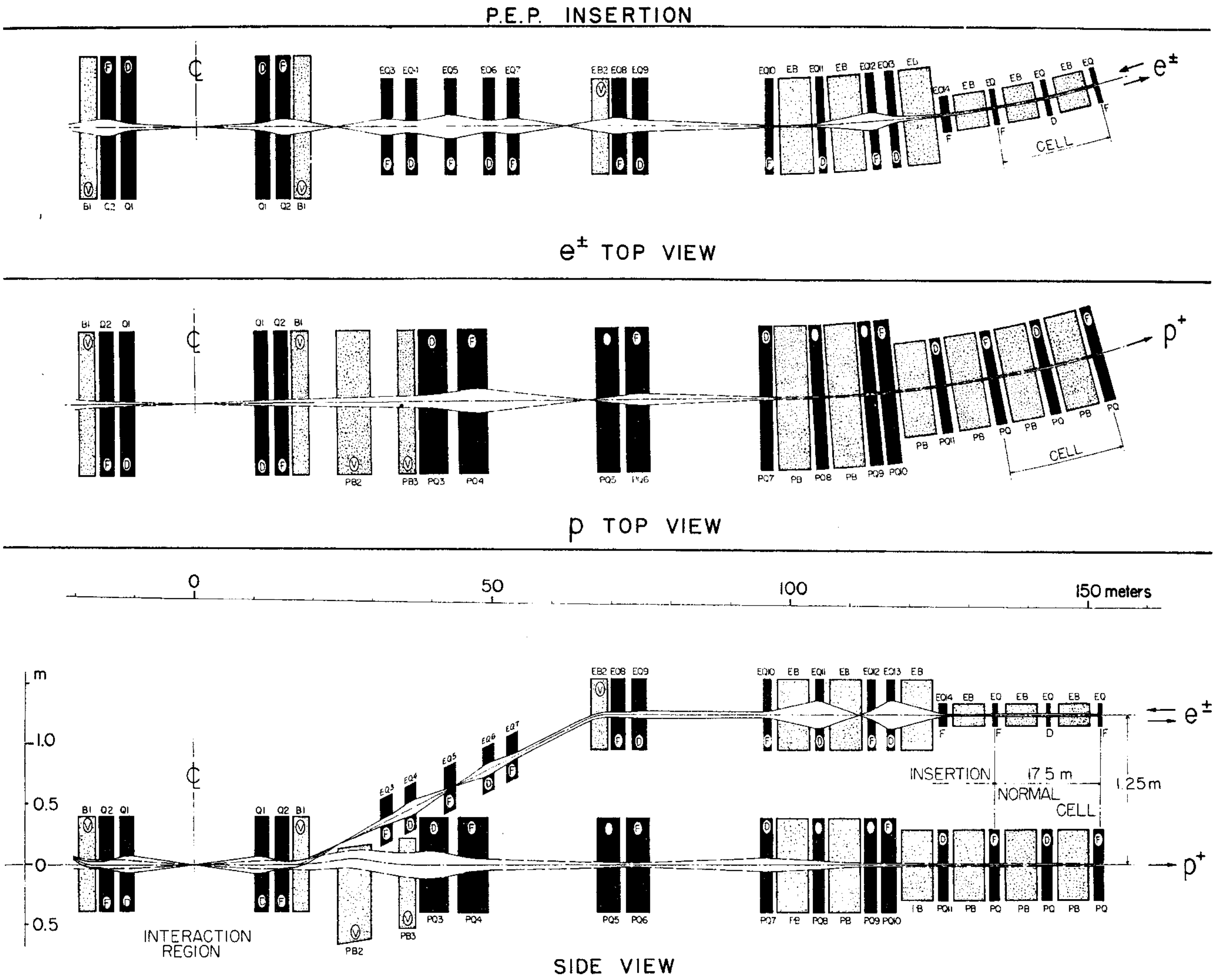

Fig. 3. Diagrams of insertion structure. Quadrupoles are dark, dipoles shaded. Beam profiles represent 70-GeV protons and 15-GeV electrons.

Table III. Lattice Parameters

		p-ring	e-ring	
Total Radius	R	327	327	m
Gross Radius Circular Arcs	R_n	200	200	m
Straight Section Length	L_S	200	200	m
Bending Radius	ρ	125	125	m
Magnetic, Field, Peak	B_o	40	4	kg
Gradient in Cell Quadrupoles	G	450	106	kg/m
Number of Superperiods	N_p	4	4	
Total Number of Cells	N_{CT}	72	72	
Number of Normal Cells	N_C	56	56	
Cell Length	L_C	17.5	17.5	m
Dipole Length		5.45	5.45	m
Quadrupole Length		1.70	0.70	m
Length of Cell Drifts		0.80	1.30	m
Vertical Separation of Rings		1.25		m

elements of the electron arc directly above the corresponding elements of the proton arc. One normal cell is shown in Fig. 3, to the right of the insertion structure.

The separated function configuration was chosen to insure positive damping in all three modes of oscillation for the electrons, to simplify construction of the superconducting magnets, and to insure flexibility in manipulation of the operating point. The last feature is particularly important because of the need to conserve aperture by moving into the low-β configuration only after the protons have been accelerated and their amplitudes decreased.

Having decided on a separated function lattice, a FODO focusing structure was chosen for the normal cells, since this provides the most efficient use of azimuthal space for bending and focusing.

The cell length results from a compromise between a desire for high proton energy, high electron emittance (to moderate the beam-beam effect), and low electron radiated power on the one hand and for small aperture and low RF overvoltage requirements in both rings on the other hand. The former considerations call for long cells and the latter for short cells.

B. Insertions

Figure 3 shows the right half of the symmetric insertion structure and Table I gives beam properties at the interaction region center point proposed for p-e collisions at 150 and 15 GeV respectively, with zero crossing angle. The beam envelopes shown in Fig. 3 correspond to 15-GeV electrons and 70-GeV protons, the lowest energies contemplated for experiments at full luminosity. This combination sets the aperture requirements in most of the insertion magnets since,

Table IV. Radiofrequency Systems[*]

		p-ring	e-ring	
Radiofrequency	f	146	350	MHz
Harmonic Number	h	1000	2400	
Power Dissipated in Cavities		5	1	MW
Power Radiated by Beam			4.2	MW
Peak RF Voltage	$\hat{V}$	93	51	MV
Quantum Lifetime			1	day
Total Shunt Impedance		2000	2500	MΩ
Total Accelerating Cavity Length[†]		150	100	m

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[*] For p-ring, only the 3rd stage system, used during p-e experimentation, is tabulated.

[†] Includes all three proton RF systems.

as mentioned above, injection and acceleration would be carried out without the sharp focus at the interaction point.

There is a clear region (free of magnets) of ±10 meters for experimental apparatus at the interaction regions. The two beam lines are separated by the vertical bending magnet B1, the electrons rising to their ring 1.25 meters above, and the protons returning to the elevation of the interaction point under the action of PB2 and PB3 to reenter their ring.

The focusing characteristics of the insertions are dominated by the sharp focus at the low-β interaction point and the first doublet to which the beam freely expands. For the electrons the first doublet is Q1, Q2, but for the protons the first effective doublet is PQ3, PQ4, since the electron doublet has little effect on the relatively high-momentum protons. The first doublet arrests the beam-widening, and together with the succeeding quadrupoles to the right it provides an exact match to the proper beta-function and dispersion values of the normal cells. A small vertical crossing angle may be produced by adding a vertical dipole to the electron insertion above PB2.

The first electron doublet Q1, Q2 produces a focus in the electron beam at the position of the proton vertical septum magnet PB2. The vertical dispersion η_z introduced by the vertical bends is removed in the electron insertion by adjusting EQ3, EQ4 so that η_z is zero in the center of EQ5 and by making the segment between B1 and EB2 symmetric about EQ5 in its focusing pattern. In the proton beam, η_z is equal to the vertical beam displacement from the interaction region level through the dog leg between B1 and PB3, and hence returns to zero after PB3.

For p-e^+ collisions the polarities of the vertical bending magnets and of all e-ring quadrupoles are reversed so that the e^+ and e^- beams are identical; the proton beam bends downward in the dog leg but is otherwise unchanged, although slight tuning changes must be made due to the reversal of polarities in Q1 and Q2.

The portion of the insertion structure immediately to the left of the first normal cell resembles two normal cells, at least with respect to the horizontal bending. However, the quadrupoles differ in length and gradient, since they function as part of the matching structure of the insertion, and one of them has been replaced by a doublet (PQ9, 10 and EQ12, 13).

Adequate space for RF and injection systems is provided to the right of PQ4 and PQ6 in the p-ring, and to the right of EQ7 and EQ9 in the e-ring.

Computations

Choice of the interaction point parameters was aided by the interactive computer program SHINE. The lattice design was carried out in a manner similar to that used for SPEAR.[3] We first designed the cells using program SYNCH,[4] then the insertions using an interactive version of TRANSPORT,[5] and again SYNCH to obtain orbit functions through the complete ring. This procedure is iterated to obtain reasonable ν-values. The insertion was designed by starting at the interaction point with the desired orbit parameters, and ending at the center of the first F-quadrupole of the normal cells. At that point six conditions are imposed to match the orbit functions to the cells.

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