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A SUPERCONDUCTING PROTON STORAGE RING FOR PEP*

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Summary

In order to provide for electron-proton collisions in the PEP system, plans for a high-energy superconducting proton storage ring are being explored. The energy is constrained to 300 GeV by the radius of the PEP tunnel (350 meters) and the field strength (7 tesla) expected to be available in practical superconducting magnets. A new configuration has been developed in which the proton ring vertically crosses the horizontal electron ring in 4 of the 6 straight-sections. Synchronization of the two beams is provided by means of bypasses in the two non-crossing straight sections in the electron ring. The proton injector is a 5 GeV/c synchrotron 1/18 as large as the main ring.

Geometry and Lattice

The space needed for RF, injection, and other purposes, requires that orbits cross only in four of the six long straight sections. One must then choose whether the rings are to be separated horizontally or vertically. The latter is preferable because it facilitates path-length equilization between crossings and conserves tunnel space.

A fundamental question concerns which ring should be flat, and which one should have vertical displacements. The momentum of the electrons makes them easier to bend to cross a planar proton ring than the opposite. However, if this is done, strong electron dipoles needed near the interaction region will make copious synchrotron radiation, difficult to shield from the detectors. Therefore, we have chosen to investigate a scheme in which the electron path is entirely straight through the insertion, and the proton beam is bent vertically.

To avoid bending the electrons near the crossings, the beams must be separated through the use of a crossing angle and a proton septum-magnet system. Unfortunately, a large angle which makes the proton septum magnets easier, also reudces luminosity. Therefore, the crossing angle should be made as small as reasonable magnet construction and power considerations permit. We have provisionally chosen this angle to be 2 mrad.

We have thus arrived at an overall design that leaves the e-ring in the mid-plane, with the p-ring crossing it at four interaction points, (I.P.) and passing parallel at the other two. The p-ring between crossings is alternately above and below the e-ring separated vertically by 0.75 meters.

Crossing Region

For the design of the crossing regions a proper order of proton and electron quadrupoles and dipoles is essential. There are numerous possibilities; at present we favor the scheme shown in Fig. 1, which gives a vertical view of one side of an experimental crossing insertion. The beams cross at the I.P. on the left of the figure and traverse the electron quadrupoles 1Q and 2Q. The electrons then drift 42 meters to the doublet 3Q and 4Q, which precede the bending arc of the sextant. The protons then traverse the (conventional) septum quadrupoles Q1 and Q2. Thus low-beta quadrupoles are placed on each beam as close as possible to the I.P. This minimizes the beta-functions at the I.P., and increases the luminosity.

After Q1 and Q2 the p-beam traverses the vertical septum dipoles BV1-BV4, of which BV1 is a 1.2 tesla conventional magnet, while the others are superconducting, the quadrupole doublet Q3, Q4, the final vertical dipole BV5, quadrupole Q5, and then the regular lattice.

Beam Matching.

Quadrupoles Q1-Q5 produce a beam waste of the protons at the I.P. with the desired β-values and zero vertical dispersion. Suppression of the horizontal dispersion η and matching to the normal cells is done with the quadrupoles in the ends of the arcs. The situation with the electrons is similar, but since there is no vertical dispersion, one less quadrupole is needed. Orbit functions of the two rings are shown in Figs. 2 and 3.

Arcs.

The arcs of both rings are made up of separated function FODO cells. The proton arc does not have a short drift at the arc center as in the e-ring. It contains 16 cells, identical geometrically but with special gradients in the first 5 quadrupoles, leaving 12 normal 60° cells. This arrangement facilitates chromaticity correction. For 300 GeV operation, the 4.5 m dipoles and 2.5 m quadrupoles require 7.3 T and 60 T/m respectively. The required good-field aperture is 2 cm radius.

Operating Parameters

In order to arrive at an economical design we have aimed for simplicity and moderate intensities. Thus we restrict the number of electrons to 8×10^{12}, requiring 12 MW power at 15 GeV, which can be provided by the present 24 cavities and 12 additional klystrons (24 total). Provision of the required 1.5×10^{13} protons, with a normalized emittance of 5π mm-mrad in both planes is straight-forward, as described in the section on injection.

The proton Q1, Q2 quadrupoles are about 50% further from the I.P. than the electron 1Q, 2Q. In order to equalize the maximum β-values in these quadrupoles, the proton betas at the I.P. should be about twice as large as those of the electrons. To match beam sizes the electron emittance is made twice the proton value, with full coupling assumed.

As luminosity varies inversely with number of bunches, this number is chosen as small as possible consistent with limits on the allowable beam-beam tune shifts, which are taken to be .06 for electrons and .005 for protons.

The principal operating parameters affecting experimental performance are shown in Table I.

Space Requirements and Energy Variations

Many accelerator components in the electron and proton rings, apart from the magnets, must be installed in the straight sections where free space is available. A preliminary examination of space requirements has led to the following conclusions. First, the electron beam RF system and the electron injection system will make major demands on space around the electron ring, as is true in the present PEP design. Second, by-passes for varying beam pathlength will be required in the electron ring, in order to synchronize electron and proton bunches at different proton energies. Third, the injection system and two RF systems, for acceleration and final bunching, will require considerable room in the proton ring. At present, it appears that there is sufficient space in the two rings to accommodate all of these components.

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Table I - Operating Parameters of the PEP Proton-Electron System

		Proton	Electron	
Momentum - Peak	P	300	15	GeV/c
Injection	P_i	5	15	GeV/C
Number Particles	N	1.5×10^{13}	$.8 \times 10^{13}$	
Number Bunches	N_b	36	36	
Crossing Angle	2δ	2×1		mrad
Emittances at Peak Energy ($\varepsilon = \sigma^2/\beta$)	$\varepsilon_x = \varepsilon_y$	$.0156\,\pi$	$.0313\,\pi$	mm-mrad
	ε_ℓ	.025	.340	m
Bunch Length	σ_ℓ	.3	.012	m
Momentum Width	$\sigma(\Delta p/p)$	.001	.001	
Interaction Point Orbit Functions	β_x/β_y	1.0/1.9	.50/1.25	m
	η_x/η_y	0/0	0/0	m
	η_y'	.016	0	
Beam-Beam Tune Shifts	$\Delta\nu_x/\Delta\nu_y$	.004/.005	.054/.049	
Luminosity	L	1.0×10^{32}		$cm^{-2}s^{-1}$
Aperture Radius	a	25	30	mm
Beta-function Maxima	$\hat{\beta}_x/\hat{\beta}_y$	1114/778	884/370	m
Chromaticity-uncorrected	ξ_x/ξ_y	-121/-91	115/-54	
Betatron Tunes	ν_x/ν_y	25.85/22.65	25.67/16.77	
Cells - Maximum Beta	$\hat{\beta}_c$	25.35	24.10	m
- Maximum Dispersion	$\hat{\eta}_c$	.7560	.9272	m
- Phase Advance	μ_c	60	69	deg

Energy Variations.

It is desirable to span a considerable range in center mass energy E_{cm} in the e-p physics to be done at PEP. The highest accessible value of $S = E_{cm}^2$, at the maximum electron and proton energies of 15 GeV and 300 GeV, respectively, is $S_{max} = 4E_eE_p = 18000\ GeV^2$. On the other hand, it would be highly desirable to study e-p physics down to the energy accessible from μ-p scattering on fixed targets. If we assume that 800 GeV muons will be available, we get $S_{min} = 2m_pE_\mu = 1600\ GeV^2$.

Figure 4 shows that this energy range can be spanned by many combinations of electron and proton energies. However, several constraints apply. First, it is desirable to minimize the pathlength variations and the difficulties in bunch synchronization. Second, minimizing the number of discrete proton energies would simplify the operation of the pathlength variation bypass in the electron ring. Third, the electron ring must be operated above some minimum energy, possibly 3 GeV or 4 GeV because of the intra-beam scattering. Fig. 4 shows that the entire desired energy range can be spanned by the following strategy: values of S above 4800 GeV^2 can be reached while keeping E_p constant at 300 GeV, and values of S below 4800 GeV^2 can be reached with E_p equal to 100 GeV. For the most part, the energy variations will be achieved by variations of the electron beam energy.

Injection System.

For the injection system to the proton storage ring a slowly-cycling 5-GeV/c booster synchrotron fed by a 50-MeV linear accelerator is envisaged. With a booster radius equal to 1/18 that of the storage ring, the storage ring can be filled in 1 minute with 18 pulses from the booster cycling with a 5-second period and with 0.83×10^{12} protons per pulse. This intensity can be provided by a 100-mA beam from the 50-MeV linac with single-turn injection and adiabatic pick-up in the booster and bucket-to-bucket transfer to the storage ring. Because of the single-turn injection and synchronized transfer, phase-space dilution can be minimized throughout the system. Parameters of the booster synchrotron are:

Momentum	5 GeV/c
Energy	4.15 GeV
Intensity	0.83×10^{12} protons per pulse
Circumference	$122.2 = 2\pi \times 19.45$ meters
Magnetic Field, approx.	13 kilogauss
Harmonic	2
Radiofrequency	1.54 to 4.82 MHz
Injection Energy	50 MeV
Injection Field	800 gauss

The injection system described is considered a practical example. but not a final choice. Several other injection systems have been examined. For example, the electron storage ring could be used as a second booster synchrotron with an output energy of 20 GeV. The proton beam size would be halved and transition energy avoided in this way. However, with present parameters the beam radius is only 15mm at 5 GeV, so this complication seems unnecessary. Nonetheless, this option will be kept in mind as we seek means to increase the luminosity further.

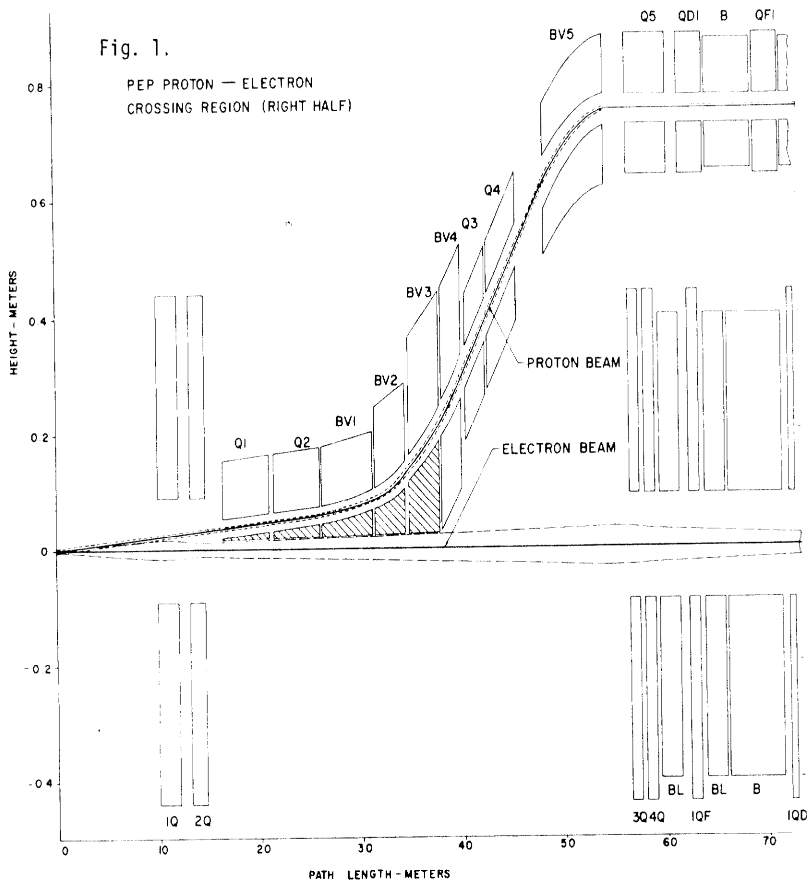

Fig. 1.

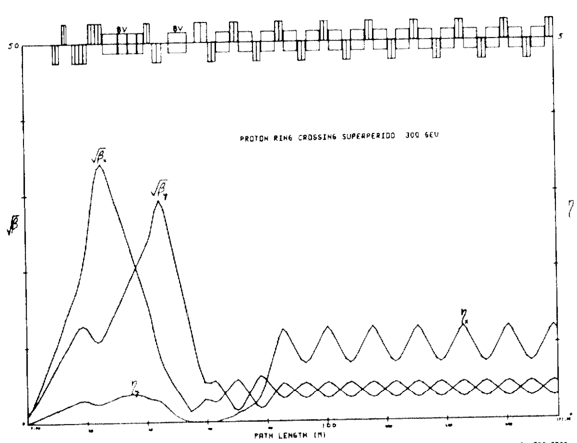

Fig. 2. Proton Ring Crossing Superperiod 300 GeV

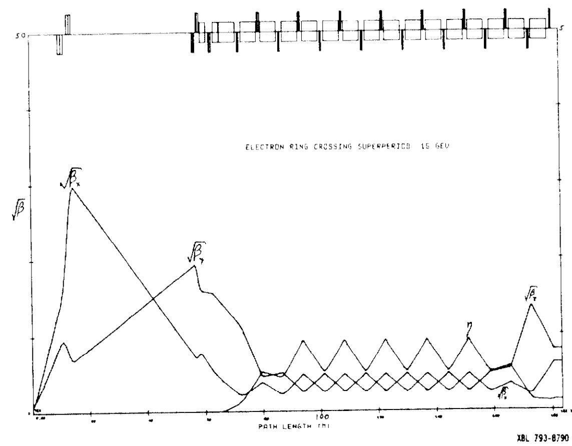

Fig. 3. Electron Ring Crossing Superperiod 15 GeV

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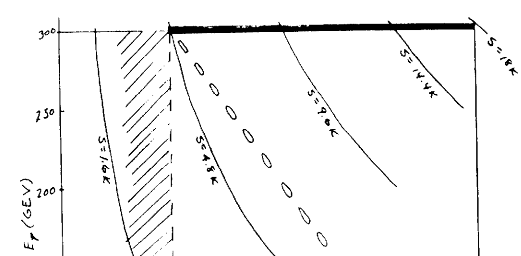

Fig. 4. Energy Variations of beams.