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PRESENT AND FUTURE COLLIDING BEAM FACILITIES AT SLAC*

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Introduction

In April, 1972, the 3-GeV electron positron storage ring, SPEAR,[1] was put into operation at the end of the linear accelerator at Stanford. By the recent discoveries in high energy physics the value of electron-positron storage rings for high energy physics has been clearly demonstrated. This development certainly encouraged the relatively early funding of the new electron-positron storage ring, PEP,[2] at SLAC (Fig. 1). The

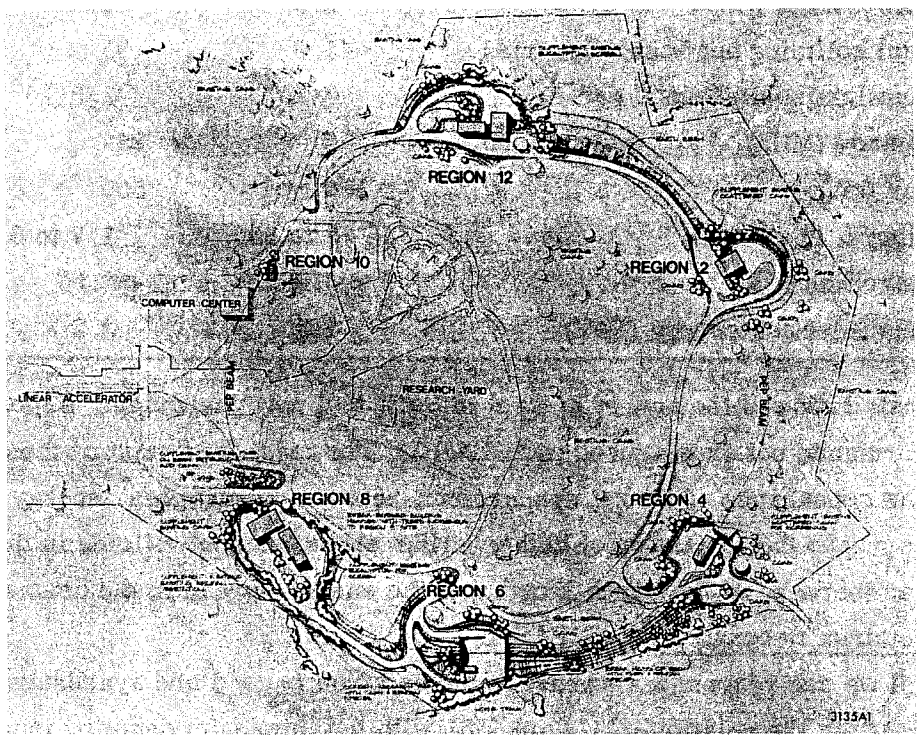

Fig. 1. Storage ring facilities at SLAC.

maximum energy per beam in PEP will be 18 GeV in the initial stage and provisions are made to increase that energy at a later time to 24 GeV.

In addition to its role as a particle physics research tool, SPEAR has been and remains a priceless model or prototype for larger storage rings like PEP. Numerous accelerator physics observations and measurements at SPEAR have made us more knowledgeable about the behavior of two strong colliding beams and their interaction with their environment. Many of the technical components used and proven reliable in SPEAR will also be used in PEP. SPEAR has also clearly demonstrated that the concept of one ring with only half as many bunches per beam as there are interaction points is as successful as it is simple.

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In the following sections a few of the recent observations in SPEAR which have important implications to the design of PEP will be described. Although the PEP design follows closely the SPEAR concept in many respects it has its own distinctive and important features which will be discussed in more detail in the latter part of this report.

SPEAR Parameters

Initially, the SPEAR energy was limited to about 2.6 GeV. In 1974 a new and more powerful rf system as well as larger power supplies for the magnets were installed which increased the maximum SPEAR energy to 4.1 GeV per beam. In Table 1 some of the parameters for both stages are compiled.

Table 1

	SPEAR I	SPEAR II
Maximum energy (GeV)	2.6	4.1
Maximum colliding beam current (mA)	~45	35
Maximum luminosity (cm^{-2} sec^{-1})	$7 \cdot 10^{30}$	$1.3 \cdot 10^{31}$
Rf frequency (MHz)	50	358
Rf power (kW)	160	500
Bunch length ($2\sigma_z$) (cm)	5 to 20	1.7 to 6
Synchrotron tune ν_s	$\lesssim 0.005$	$\lesssim .06$
Maximum injection energy (GeV)	1.5	2.2

With the installation of the new rf system in SPEAR II new phenomena imposed limitations on performance not experienced in SPEAR I. The most important of these phenomena were the appearance of strong synchrotron-betatron resonances, energy losses from the beams due to the excitation of higher-order electromagnetic fields in the vacuum chamber, and an increase of the bunch length and the energy spread in the beams.

Synchrotron-Betatron Resonances in SPEAR II[3]

In SPEAR II we see resonances whenever the betatron (ν_x, ν_y) and synchrotron (ν_s) wave numbers satisfy the relation $\nu_{x,y} - m\nu_s = 5$, with the integer m denoting the m-th satellite. Observations of the beam size at these resonances show that the vertical beam size is blown up for m as large as 10. The horizontal beam size however, is affected very little. Moreover these resonances result in a loss in luminosity even when the tunes do not exactly satisfy the resonance condition. The loss in luminosity at 1.5 GeV in SPEAR II is of the order of a factor of three with respect to the luminosity in SPEAR I and the loss increases with decreasing order of the closest satellite. We therefore run SPEAR II at any energy with the lowest possible rf-voltage, i.e., the lowest possible synchrotron oscillation frequency. We have done many experiments at SPEAR to identify the nature and cause of the observed synchrotron-betatron resonances. The observations show that the resonances are spaced by ν_s and not $\frac{1}{2}\nu_s$. Their strength decreases with energy and increases with current, is strongly dependent on the vertical orbit distortion, and is insensitive to

changes in the chromaticity or the harmonics of the chromaticity function. Synchrotron-betatron resonances had been observed already 20 years ago and were analyzed by Hammer et al. and Orlov[4] as being caused by the frequency modulation of the betatron motion due to energy oscillations. The observations in SPEAR clearly rule out this mechanism and they also rule out the possibility that a periodic variation in the chromaticity function causes the excitations of half-integer resonances. A systematic study of the effect of orbit distortions on the resonances, however, has led us to an explanation which we now believe is the real cause for the synchrotron-betatron resonances observed in SPEAR. Errors in the vertical equilibrium orbit cause a vertical dispersion function η_y. A change in a particle's energy at a point where this dispersion function is nonzero causes a sudden change of the equilibrium orbit for this particle and, consequently, also a sudden change in its betatron oscillation amplitude given by:

$$\Delta y_\beta = \eta_y \, \Delta\epsilon , \qquad \Delta y'_\beta = \eta'_y \, \Delta\epsilon \quad . \tag{1}$$

Another important ingredient necessary to explain all of the observed resonances in SPEAR is the assumption that the synchrotron motion be nonlinear. For a short bunch the rf restoring field in the main accelerating cavities is nearly linear and, therefore, we conclude that the fields that produce nonlinear energy oscillations must come from higher-order modes in cavities, vacuum chamber discontinuities, etc. Since these elements are rather uniformly distributed around the ring the resonance $(\nu_y - m \cdot \nu_s) = p$ is driven by that part of the energy change that oscillates with $m\nu_s$ together with the p-th harmonic of η_y and η'_y. In SPEAR the dominant harmonic in ν_y occurs for p=5 and is entirely due to orbit distortions. A convenient measure of the resonance effect is the blowup factor B of the vertical beam size which according to our model is supposed to be given by $B=1+K|F_p(Y_0)|^2$ where K is a constant and $F_p(Y_0)$ a function of the p-th harmonic of the orbit distortion. In SPEAR it could be arranged that $F_5(Y_0) \sim Y'^*_0$ the slope of the orbit distortion at the interaction point. The measured blowup factor as a function of Y'^*_0 is shown in Fig. 2 and appears to be consistent with our model. In view of these observations we plan to minimize the discontinuities of the vacuum chamber in PEP and to correct the orbit as well as possible. In order to accomplish this we will install in PEP as many as 156 beam position monitors which is about eight per betatron wave length.

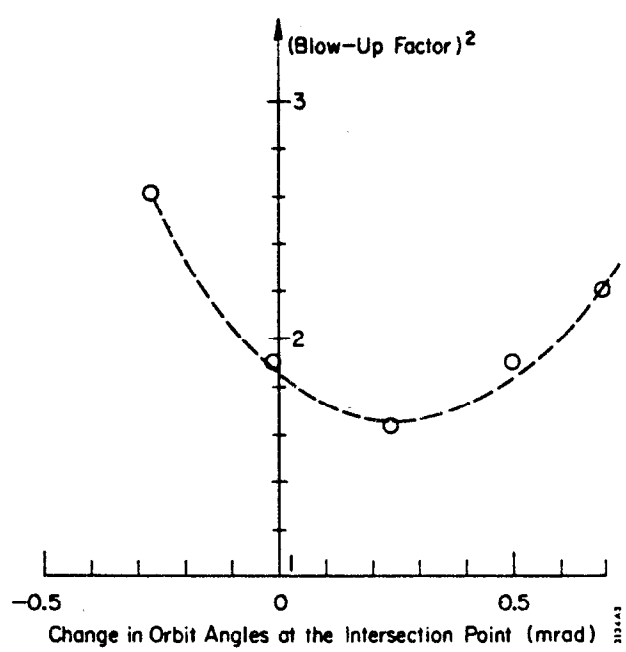

Fig. 2. Blowup factor due to synchrotron-betatron resonances.

Higher-Order Mode Losses[5]

For a long time it has been known that the short bunches in electron-positron storage rings strongly interact with accidental cavities in the ring-like vacuum chamber discontinuities. These losses are estimated to amount in PEP, for example, to 700 kW total and the total installed rf power has to provide for these additional losses. Furthermore operation at high currents in SPEAR has revealed that the local higher-order mode losses in particular vacuum-chamber components can cause severe heating problems which limit the permissible beam current. In one attempt to collide two beams of 50 mA each in SPEAR a bellows burned through due to higher-order mode losses and caused a complete loss of the vacuum. Therefore, the current and the luminosity at high energies in SPEAR is limited well below the rf power and beam-beam limitations. Many measurements at SPEAR as well as laboratory bench measurements have been performed together with theoretical work to determine the parameters of the higher-order mode losses. Agreement between all three procedures has been achieved and for bunch lengths of a few centimeters the higher-order mode losses per beam into a particular component is given by:

$$P_{HM} \simeq K(\sigma_z) \cdot q \cdot I \quad , \qquad (2)$$

where $K(\sigma_z)$ is the loss parameter dependent on the bunch length σ_z and the resonator geometry, q is the charge per bunch and I the average circulating beam current. The loss parameter has been measured in SPEAR as a function of bunch length (Fig. 3). It turns out that the loss parameter for the total SPEAR vacuum system has the proportionality $K \sim \sigma_z^{-1.21}$. The exponent, however, is not the same for different vacuum components but depends strongly on the geometry and can be determined by bench measurements. Since in PEP the bunch charge q is much larger and σ_z is smaller than in SPEAR the higher-order mode losses would constitute a severe problem in PEP if we were to use exactly the same vacuum components as in SPEAR. The remedy to avoid overheating is to minimize as much as possible any discontinuities in the vacuum chamber. We build a model of every PEP vacuum chamber component and measure in the laboratory its higher-order mode losses. By modifying the design where necessary we assure that the heating in no component exceeds a tolerable level.

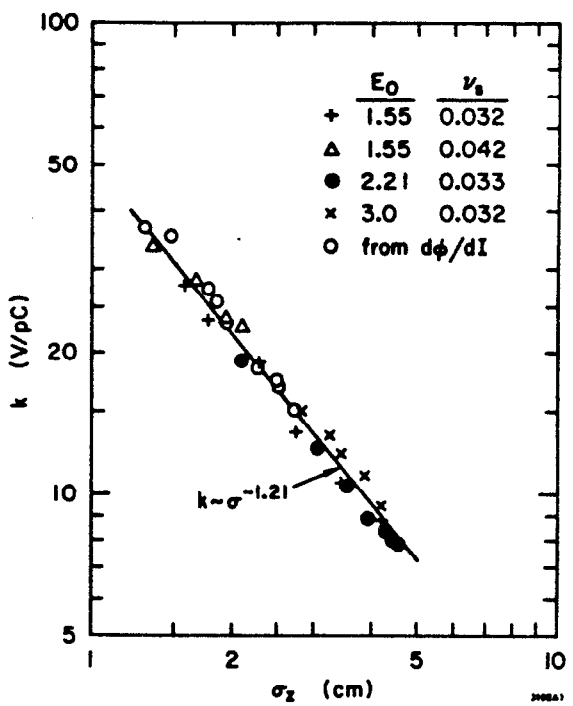

Fig. 3. Higher-order mode loss parameter in SPEAR

Active Bunch Lengthener in SPEAR[6]

The power dependence of the higher-order mode losses on the bunch length makes it possible to reduce these losses by a relatively small increase of the bunch length. It has been proposed to lengthen the beam bunch with the help of an additional rf system working near the third harmonic of 358 MHz. Such a system would reduce the slope of the rf wave in the neighborhood of the synchronous phase angle and, thereby, lengthen the bunch without increasing the energy spread at the same time. To check the feasibility of such a system for PEP a third harmonic cavity has been built and will be installed in SPEAR this summer.

Experiments on Bunch Lengthening[7]

Bunch lengthening in SPEAR as well as in other storage rings has been observed for a long time. The cause of the observed bunch lengthening, however, was not uniquely determined nor did we have a scaling law to extrapolate from SPEAR to PEP. Last year extensive experiments were performed at SPEAR to unravel the mechanism of the bunch lengthening.

The bunch lengthening observed in SPEAR is coupled with a proportional widening of the energy spread. This increased energy spread can cause beam loss due to the limited acceptance of the beam dynamics configuration. It is therefore of great importance for PEP to know the cause and the scaling laws for bunch lengthening so countermeasures can be taken. The bunch length was measured by a fast photodiode viewing the synchrotron light. The energy spread of the beam core was derived from an optical scanning system and the energy spread of the beam tail was determined from beam width measurements with beam scrapers at points where the dispersion function is large and at others where it is zero. Since we suspected the bunch lengthening to be caused by internal bunch instabilities we fed the signal from an electrode in the vacuum chamber to a microwave diode and analyzed the output signal with a frequency analyzer. Finally the energy loss to parasitic modes was measured by monitoring the change of the synchronous phase angle with current. The results of these measurements are shown in Fig. 4. It appears clearly that the bunch lengthening has a threshold behavior and that the onset of the bunch lengthening coincides with the widening of the energy spread and the start of quadrupole mode oscillations within the bunch. The data strongly suggests that the dominant lengthening mechanism in SPEAR II results from bunch instabilities due to the bunch interaction with the environment. These bunch instabilities appear to be bounded by growth in bunch length. A general scaling law for bunch lengthening can be derived[8]:

$$\sigma_z = F(\zeta) \qquad \text{where} \quad \zeta = \frac{I\alpha}{\nu_s^2 E} \quad . \tag{3}$$

Here, I is the beam intensity, α the momentum compaction factor, ν_s the synchrotron wave number and E the energy. Using a power law for the coupling impedance responsible

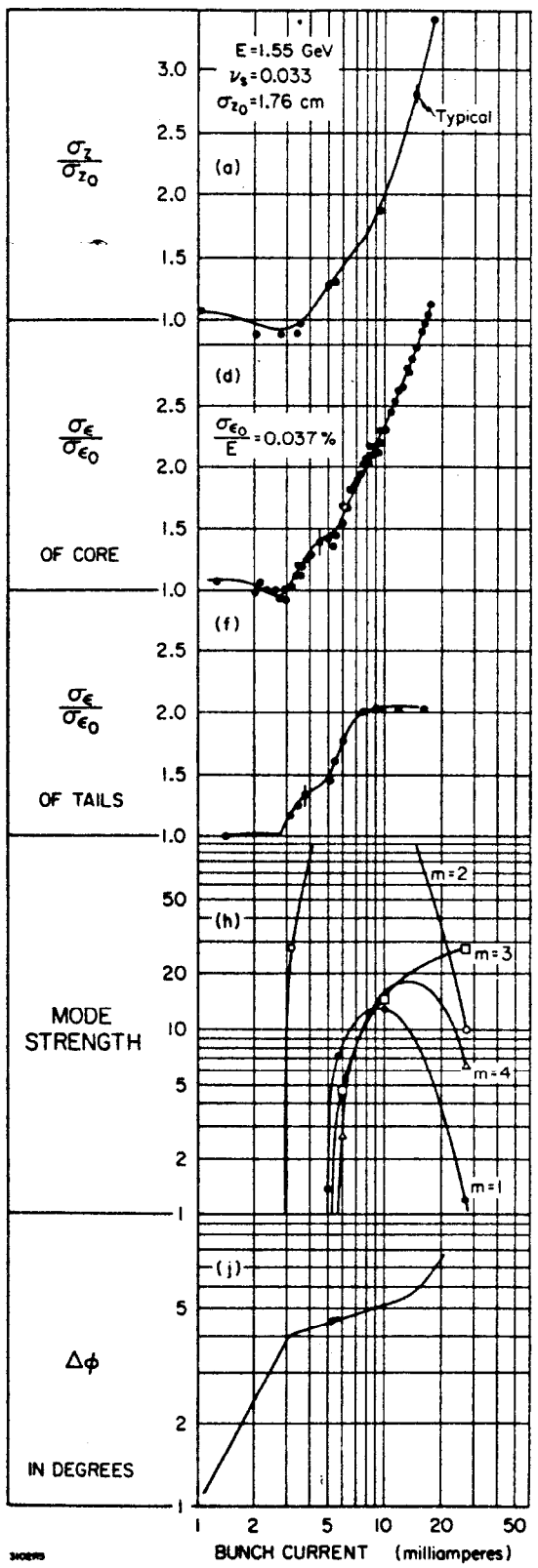

Fig. 4. Experiments on bunch lengthening in SPEAR.

for the instability $Z(\omega) = Z_0 R \omega^a$ we get

$$\sigma_z \sim (\zeta Z_0 R^3)^{1/(2+a)} \qquad (4)$$

(R is the average ring radius.) This scaling agrees very well with the observations at SPEAR II. If we equate the bunch length from Eq. (3) with the natural unperturbed bunch length we get the threshold of the bunch lengthening again in good agreement with the data. The measurements of the shift of the synchronous phase permits the calculation of the SPEAR II parasitic-loss parameter K which turns out to be proportional to $\sigma_z^{-1.21}$ for bunch lengths of 1.5 cm to 5 cm (Fig. 3). It also follows from the loss parameter measurements that in SPEAR II the impedance parameter $Z_0 = 9000\ \Omega$ which is the equivalent to the total theoretical loss in 100 rf cells. Since there are only 20 rf cells in SPEAR II we deduce that most of the losses occur in the vacuum components. This again emphasizes the importance in PEP of reducing the vacuum chamber impedance to a minimum.

The PEP Storage Ring Facility

PEP is an 18-GeV positron-electron storage ring facility presently under construction at the site of the Stanford Linear Accelerator Center. This project has been designed by a team from the Lawrence Berkeley Laboratory and the Stanford Linear Accelerator Center under the leadership of John Rees.

The facility is shown in Fig. 1. There are six interaction areas evenly distributed around the 2200 m circumference, five of which are designed for full-size experiments. The sixth interaction area is deep underground and is used for machine physics experiments or small-scale high-energy physics experiments. PEP in its initial stage is designed to run between a beam energy as low as 4 GeV, which coincides with the maximum SPEAR energy, and as high as 18 GeV. Within this energy range the

luminosity is designed to be between 10^{31} cm^{-2} sec^{-1} and 10^{32} cm^{-2} sec^{-1}. A few of the main PEP parameters are shown in Table 2.

Table 2. PEP Storage Ring Parameters

Maximum energy	18 (24) GeV
Maximum beam current (3 bunches)	55 mA
Maximum luminosity at 15 GeV	1×10^{32} cm^{-2} sec^{-1}
Luminosity between 4 GeV and 18 (24) GeV	$\geq 1 \times 10^{31}$ cm^{-2} sec^{-1}
Number of interaction regions	6
Circumference	2200 m
Bending radius	165.5 m
Minimum betafunction at IP (β_y^*)	11 cm
Maximum betafunction (β_y)	910 m
Natural chromaticity ξ_x/ξ_y	-41.7/-158.3
Rf frequency	353.21 MHz
Rf power (total)	6 (12) MW
Total active length of accelerator cavities	51 (204) m
Injection energy	4 to 18 GeV
Filling time (30% efficiency)	4 to 10 min
First beam	October 1979

PEP Design Luminosity and Energy

The primary considerations in designing a storage ring are to maximize the luminosity and the energy of the ring. Figure 5 shows the design luminosity for PEP. The maximum luminosity of $1 \cdot 10^{32}$ cm^{-2} sec^{-1} at 15 GeV as well as the luminosity scaling below

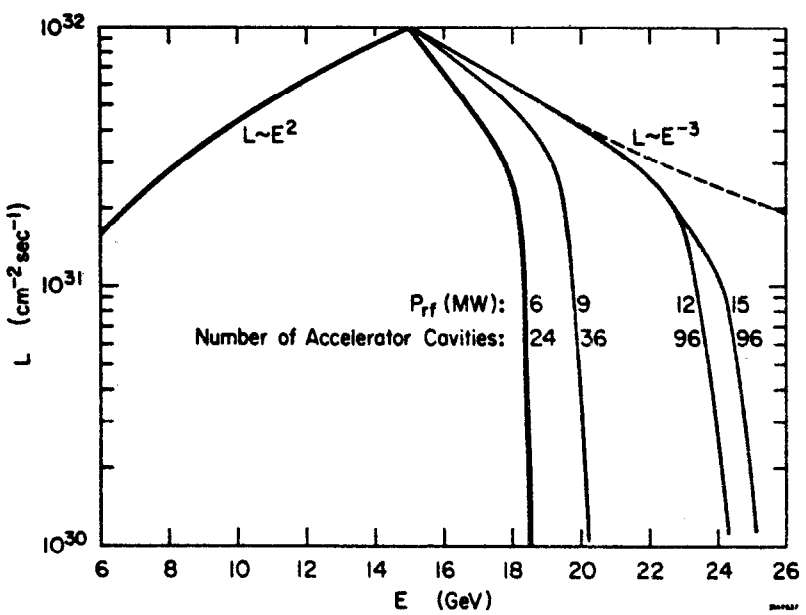

Fig. 5. Design Luminosity for PEP.

and above 15 GeV imply special design considerations which I shall address in more detail.

The luminosity of a storage ring is defined as the product of the target density times the number of particles that collide per unit time with this target. Since each beam is the target for the other beam we have:

$$\mathscr{L} = \frac{N}{A \cdot B} N \cdot f \quad , \tag{5}$$

where A is the effective beam cross section at the interaction point, B the number of bunches per beam, f the revolution frequency of the particles and N the number of particles per beam assumed to be the same for both beams. At 15 GeV the PEP luminosity is limited by the available rf power to compensate the energy loss of the particles due to synchrotron radiation and by the so-called beam-beam interaction which is the destructive effect of the electromagnetic field of one beam upon the particles of the other when they collide. The luminosity at 15 GeV, therefore, is proportional to

$$\mathscr{L} \sim P_B/\beta_y^* \quad . \tag{6}$$

Here, P_B is the synchrotron radiation power per beam and β_y^* is the vertical betatron function at the interaction point.

Chromaticity Correction in PEP[9]

To maximize the luminosity one tries to make β_y^* at the interaction point as small as possible (Eq. (6)). Although it is easy in principle to do so there is a very serious adverse effect. The betatron function increases with the square of the distance from the interaction point and gets very large at the first quadrupoles which are located ±10 m away from the interaction point to allow space for the experimental detectors. The stability of the beam, therefore, is very sensitive to any perturbation within these high-beta regions. The most serious effect is the perturbation of the focussing structure due to momentum errors of the particles. These chromatic aberrations must be compensated by a strong sextupole system. In any storage ring like PEP a luminosity of $1 \cdot 10^{32}$ cm^{-2} sec^{-1} at 15 GeV can be obtained only if one allows chromatic aberrations which are an order of magnitude more severe than in present storage rings like SPEAR and then if methods are found to correct these aberrations. In the last two years we have expended a great deal of effort to develop theories which explain these chromatic aberrations in more detail so that we can design a proper correcting scheme for them. This we have accomplished and now we have arrived at a consistent design of the storage ring that allows us to reach a luminosity of $1 \cdot 10^{32}$ cm^{-2} sec^{-1} at 15 GeV.

In determining the chromaticity correction in PEP it was found that further sophistication of the correction was needed over that required for SPEAR. In SPEAR only two families of sextupoles are required to give the vertical and horizontal chromaticity the desired values. While this can be accomplished in principle by as few as two sextupoles, in practice, the linear beam dynamics would be perturbed too much by the strong nonlinear fields required. Tracking studies for SPEAR have shown that distribution of the sextupoles

around the ring is necessary to ensure stable particle trajectories within the beam-stay-clear region and apart from that, no further sophistication of the sextupole correction was found to be necessary.

The very large chromaticities encountered in storage rings like PEP, PETRA and the "Very Big Storage Rings" produce a new set of undesirable characteristics in the beam dynamics which require a more complicated means of correction. The method of attack used at PEP to solve the problem of both satisfactory chromaticity correction and stable nonlinear motion is to determine analytically the effect of the sextupoles on the distorted equilibrium orbit x_e through second order in $\delta = \Delta p/p$ and the tune variation through both third order in δ and second order in the transverse betatron amplitude x_β.

The need for this higher approximation can clearly be seen in Fig. 6. With two families of sextupoles only the linear chromaticity can be corrected. Strong quadratic

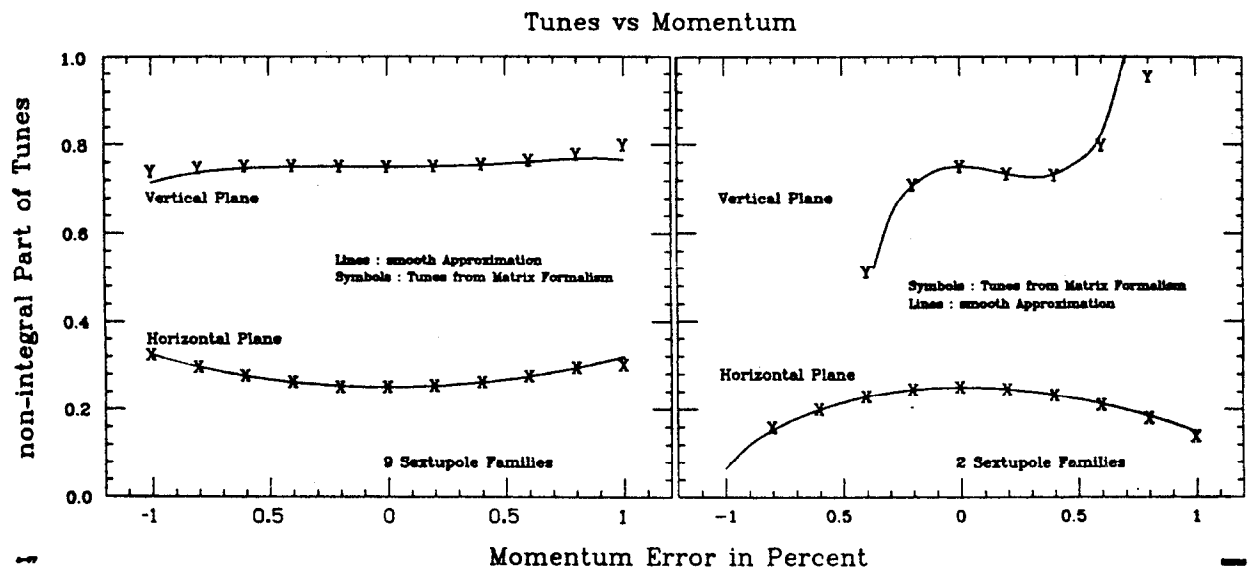

Fig. 6. Correction of the chromaticity in PEP.

and even cubic terms appear in large storage rings and cause instability of the beam. The source for these higher-order terms can be evaluated analytically and are dependent upon the harmonic content of the chromaticity function $\nu_0^2 \beta^2 (k - m\eta_x)$ where ν_0 is the linear betatron wave number, β the betatron function, k and m the quadrupole and sextupole strength, respectively, and η_x the dispersion function. Introducing more sextupole families allows us to minimize the higher-order perturbations. In PEP we employ 9 different sextupole families and with these we can minimize the energy dependence of the betatron wave numbers below tolerable values. We have developed a tracking program which follows particle trajectories many times around the ring while they perform both betatron oscillations and synchrotron oscillations. With this program we have established a sextupole system which gives stable trajectories with amplitudes in excess of 10σ in any of the three degrees of freedom.

Beam Size Control in PEP

If PEP were operated with the same focusing configuration for all energies below 15 GeV as is the case in SPEAR, the luminosity would scale like $\mathscr{L} \sim E^4$, resulting in a very low luminosity at 4 GeV. This happens because the beam size diminishes at lower energies; therefore, the beam density or the beam-beam effect increases. To avoid the loss of the beams, the beam current must be reduced in order to avoid the beam-beam limit. This causes the significant loss in luminosity. Remaining at the beam-beam limit, the beam current could be increased if the beam cross section could be increased at the same time. Many methods have been invented and tried in the past to increase the beam size artificially, but all attempts to do so have failed to date, probably because none of them could increase the beam size in a purely incoherent way. If it were possible to increase the beam size incoherently up to the aperture limit at all energies below 15 GeV the luminosity would scale as $\mathscr{L} \sim E^2$, a gain in luminosity of up to a factor of 10. In order to achieve this leap in luminosity we developed the idea of increasing the beam size with so-called "wiggler" magnets.[10] At three places in PEP we shall have symmetric triplets of bending magnets which deflect the beam back and forth with a zero net deflection and displacement of the beams. These devices cause the particles to radiate additional and higher-energy synchrotron radiation photons. Since each emission of a photon constitutes a perturbation of the particle's trajectory, the beam size is increased in a purely random way. The beauty of this system is that it does not interfere with the focussing configuration of the ring and the beam size can be adjusted simply by changing the strength of the wiggler magnets. This solution is operationally much simpler than any other method proposed so far.

High Energy Capability of PEP[11]

A great deal of thought has been given to improving the high energy potential in PEP above 18 GeV. If we tried to use the 15-GeV focussing configuration for higher energies the luminosity would fall off like $\mathscr{L} \sim 10^{-10}$ assuming a constant rf power available for the beams. This sharp loss in luminosity in practice is enhanced due to the rapid increase of the rf power losses in the accelerating cavities which means that little power remains for the beams. In the past two years the PEP magnet structure has been modified to improve greatly the high energy capabilities of PEP. Above 15 GeV the available rf power cannot support enough current to stay at the beam-beam limit or, in other words to reach the maximum allowable beam density at the interaction point unless the operating mode is changed. This can be done by reducing either the number of bunches or the beam emittance. Reduction of the number of bunches is not feasible at PEP since it would reduce the number of interaction points. The PEP focussing structure, therefore, will be changed at high energies to allow much stronger focussing of the beam which is necessary to keep the beam density at the interaction point as high as the beam-beam interaction permits. Disregarding rf power limitations for a moment, this feature causes the luminosity above 15 GeV to drop off only as $\mathscr{L} \sim E^{-3}$ instead of $\mathscr{L} \sim E^{-10}$. For the present design of the PEP

rf system, which provides 6 MW of rf power and 51 m of accelerating structure, the maximum energy where a luminosity of $1 \cdot 10^{31}$ cm^{-2} sec^{-1} can be achieved is extended to 18 GeV. All the provisions have been made to allow us to add 3 MW of rf power and 25 m of accelerating structure which would increase this maximum energy to 20.2 GeV. In a separate study we have also demonstrated the feasibility of expanding the total rf power from 6 MW to 15 MW and the total accelerating structure from 51 m to 204 m. This would boost the maximum energy to 24 GeV at a luminosity of $1 \cdot 10^{31}$ cm^{-2} sec^{-1}. This is the maximum energy we believe we can achieve with conventional design of the quadrupoles, sextupoles and accelerating cavities. For significantly higher energies, of course, these components could be superconductive.

Background into the Experimental Apparatus

Another important design feature in PEP is expected to reduce greatly the background problems for the experiments. Here again, SPEAR provides us with a valuable and effective prototype for directing the design of PEP. Above 2.8 GeV the background in the experimental apparatus in SPEAR increased dramatically because the energy of the bulk of synchrotron radiation photons, which is near the so-called critical energy, was high enough to permit a significant fraction of the photons to be transmitted through the vacuum chamber. In PEP both the critical energy and the power of the synchrotron radiation is much higher. We were compelled to incorporate components for reducing the background radiation into the design of PEP.[12] As demonstrated in SPEAR, this can only be done by using a combination of weak bending magnets at the end of the arcs and a set of masks around the beam. The weak bending magnets reduce the photon energies by a factor of 15 and diminish the number of photons radiated into the experimental area. Hard radiation from the main bending magnets is absorbed by masks around the beam some 10 m and 40 m away from the interaction point.

Another serious source of radiation are the quadrupoles next to the interaction point. The bulk of this radiation however passes through the interaction area without striking the vacuum chamber. For the absorption of the remaining photon flux which could enter the experimental apparatus a set of masks individually designed for each experiment will be installed.

Status of the Project

Construction of the injection tunnels between the linac and the PEP storage ring started in May 1977. The beginning of the construction of the storage ring tunnel is scheduled for this fall and will be finished by January 1979. Procurements and construction of the machine components are in full swing and we plan to start installation by mid-1978. The first beam is expected to go around in the storage ring by October 1979.

Acknowledgments

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