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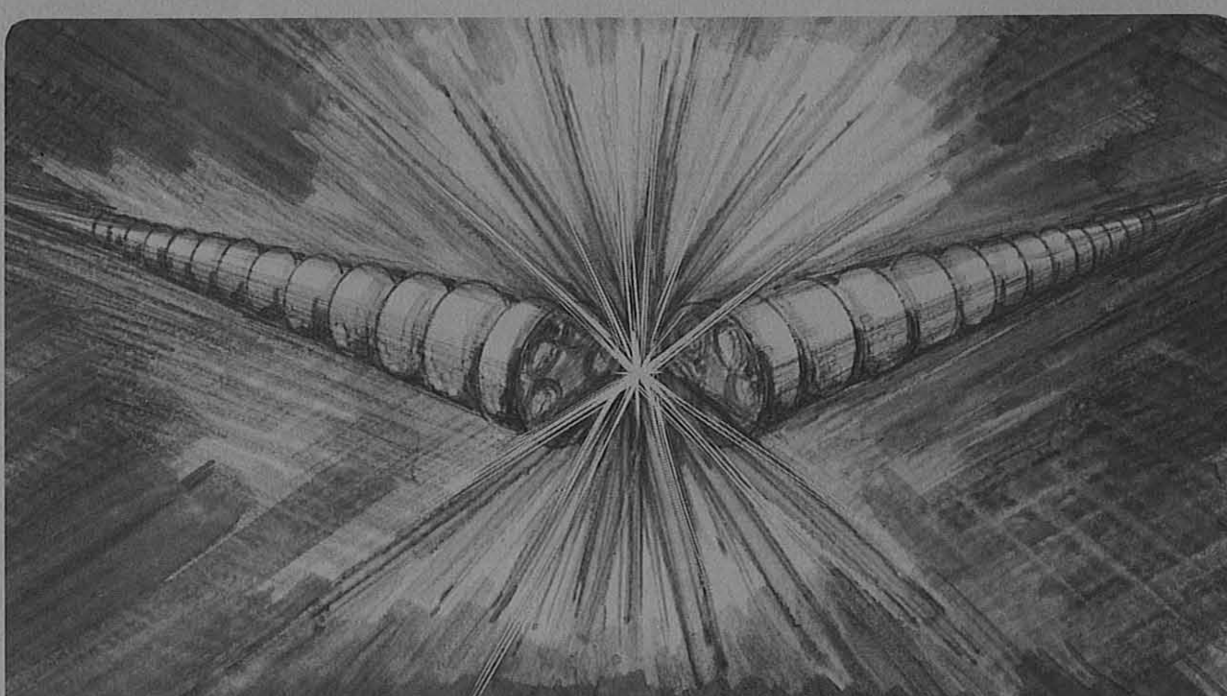

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ABSTRACT

The correction of the chromaticity of low-beta insertions in storage rings is usually made with sextupole lenses in the ring arcs. When decreasing the beta functions at the interaction point (IP), this technique becomes fairly ineffective, since it fails to properly correct the higher-order chromatic aberrations. Here we consider the approach for the PEP-II *B* Factory low energy ring (LER) where the chromatic effects of the quadrupole lenses generating low beta functions at the IP are corrected locally with two families of sextupoles, one family for each plane. For the IP straight section the lattice is designed in such a way that the chromatic aberrations are made small and sextupole-like aberrations are eliminated. The results of 6-dimensional tracking simulations are presented.

1. INTRODUCTION

In order to insure a good injection efficiency, a large quantum and Touschek lifetimes, and no lifetime degradation due to beam-beam effects, it is necessary that the ring have a sufficiently large dynamic aperture. In terms of injection the requirements are that most of the injected beam be inside of this aperture. In terms of quantum lifetime the requirements are that the aperture be at least a factor of 10 larger then the rms value of the beam in the horizontal (x), vertical (y) and longitudinal (s) planes.

In the case of the PEP-II LER, the limits of the lifetime come from injection in the vertical plane and from quantum lifetime in the horizontal and longitudinal planes.

For interaction point, vertical beta functions of about 1 cm, the amount of chromaticity generated in the interaction region is large enough to necessitate the use of a "nonconventional" chromaticity correction scheme, which shows benefits over a more traditional chromaticity correction scheme.

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2. PARAMETER REGIME

Providing a large dynamic aperture in the LER is difficult because of the parameter choices for the ring. We would like to motivate the reasoning behind the choices of parameters which are relevant to this discussion.

First, all the parameters are chosen to meet the luminosity goals of the machine. For equal beam sizes at the IP and equal beam-beam tune shift parameters for both beams in both transverse planes, the luminosity can be written as[1]

$$L = 2.17\times\ 10^{34}\xi\,(1+r)\left(\frac{I\cdot E}{\beta_y^*}\right)_{+/-}\ [\mathrm{cm^{-2}s^{-1}}] \qquad (1)$$

where $r = \sigma_y^* / \sigma_x^*$ is the beam aspect ratio, I is the total beam current, E is the beam energy in GeV, β_y^* is the vertical beta function at the IP in cm and ξ is the beam-beam tune shift parameter. With +/– we indicate that the ratio of $I\cdot E/\beta_y^*$ is to be equal for both the LER (designated by +) and the high energy ring (designated by –).

Having chosen beam energies of 3.1 GeV for the LER and 9.0 GeV for the HER we are then left with four parameters, ξ, β_y^*, r, and I. We will discuss each of these parameters and show how they influence the design of the lattice and the subsequent implications about the dynamic aperture.

It is generally considered bad for the beam-beam parameter, ξ, if there is a large discrepancy in the damping times of the two rings. We therefore employ wigglers to decrease the damping time of the LER. In addition to decreasing the damping times, wigglers also increase the relative energy spread, δ_{rms}. Without the wigglers δ_{rms} is 0.00067, which is comparable to that of the HER. With wigglers δ_{rms} is 0.00095 for the LER, an increase of 30%.

The second parameter is the interaction point vertical beta function, β_y^*. In order to achieve the required luminosity it is desirable to make β_y^* as small as possible in each ring. However it is difficult to focus both beams down to small values β_y^* simultaneously because of the energy asymmetry of the beams. We have chosen the β_y^* for the HER to be twice as large as that for the LER.

$$\beta_y^{+*} = 1.5 \text{ cm} \qquad \beta_y^{-*} = 3.0 \text{ cm} \qquad (2)$$

Because of this asymmetry in the IP beta functions the emittance of the LER must be twice as large as the emittance of the HER.

A consequence of having the small IP beta functions is that the beam bunch length needs to be small, smaller than β_y^* in order to avoid degradation of the luminosity due to the "hourglass effect." Due to the large energy spread it is necessary to decrease the momentum compaction in order to keep the bunch length small (1 cm) while simultaneously maintaining reasonable rf cavity voltages. In order to decrease the momentum compaction without using any exotic schemes (regions of inverted bending, negative dispersion, ...) it is necessary to increase the phase advance per arc cell. We choose 90° as a cell phase advance for the LER.

The beam's aspect ratio, r, was chosen to be 0.04. This value for r is rather conservative because coupling is more easily maintained if the r is large. However if r is large then the final doublet has to focus strongly in both planes. This has the effect of increasing the chromaticity in both planes.

With all these parameter choices, the total beam current I is then determined by the beam luminosity requirement. What is not determined is the number of bunches in the ring. From beam-beam simulations it seems desirable to have fewer bunches in the ring in order to obtain a larger beam separation at the parasitic crossings. Larger bunch separation implies a larger number of particles per bunch. In order to have the same beam-beam tune shift it is necessary to increase the emittance in proportion to the bunch spacing. In the LER the choice of the bunch spacing is 1.26 m. The horizontal emittance is 96.4 nm•rad.

However the LER has a naturally small emittance because of its energy and because of its large phase advance per cell. Therefore it is necessary to use the wigglers not only to reduce the damping time but also to increase the emittance.

Collecting all the effects of our parameter choices we see that the LER has

(1) large energy spread	9.5×10^{-4}
(2) large hor. emittance	96.4 nm•rad
(3) large tune per cell	90°
(4) large aspect ratio	0.04

Because the wigglers increase both the transverse and longitudinal emittance of the ring to an artificially large value one must be able to provide a larger dynamic aperture. The increased cell tune and the large aspect ratio increase the natural chromaticity of the ring. This, combined with small values of dispersion and beta functions at the position of arc sextupoles (resulting from the 90° cell) means that the ring have stronger sextupoles. Stronger sextupoles tend to decrease the dynamic aperture.

3. LOCAL CHROMATICITY COMPENSATION SCHEME

The motivation behind the local chromaticity compensation (LCC) scheme came from work which was done at SLAC on the Stanford Linear Collider (SLC) and in particular the Final Focus Test Beam (FFTB). The design is an adaptation of the design of the FFTB by Oide[2].

At first glance it might seem strange that a scheme designed for a linear collider might be useful for a storage ring. In a linear collider there is no concern about lifetime. But there is concern about producing small spot sizes at the collision point. In order to provide small spot sizes, the geometric and chromatic aberrations of the machine must be minimized. This is precisely what is necessary in order increase the dynamic aperture. So adopting a scheme which successfully generates small spot sizes in linear colliders can also be useful in producing a large dynamic aperture for storage rings.

3.1 Isolating the Problem

When examining the LER we see that 33% of the natural horizontal chromaticity and 43% of the natural vertical chromaticity come from 17% of the ring, the IP sextant. A large proportion of that comes from the strong focussing of the final doublet, a single point in terms of betatron phase advance. The problem with correcting this chromaticity in the arcs is twofold. By placing the burden of the chromaticity correction solely on the arcs one needs large arc sextupole strengths which tend to increase the geometric aberrations. The second problem, which we find to be more severe, is that even if one corrects the linear chromaticity, the nonlinear chromaticity may still be large. If the nonlinear chromaticity is large then the tune shift with energy will be large at large values of δ.

It is extremely hard to correct the nonlinear chromaticity with distributed arc sextupoles. A much more effective technique is to correct the chromaticity at the place where it is created. This is the idea behind the local chromaticity compensation scheme: Correct the chromaticity coming from the IP doublet as locally as possible and in such a way that the IP straight is nonlinearly transparent to the rest of the ring.

3.2 Nonlinear Chromaticity

As mentioned earlier the most severe problem which we found with regard to the dynamic aperture was the nonlinear tune shift with energy. This problem arises from letting the chromatic beta function get very large. By the chromatic beta function we mean the relative change in the beta function with δ,

$$\frac{\beta(s,\delta) - \beta(s,0)}{\beta(s,0)} \quad . \qquad (3)$$

The effect of the final doublet is to generate a large amplitude of oscillation of the chromatic beta function. This oscillation, if left uncorrected, propagates around the ring with large amplitude. The size of the higher order chromaticities (i.e. $\partial^2\nu/\partial\delta^2$, $\partial^3\nu/\partial\delta^3$, ...) are related to the amplitude of this oscillation. By placing sextupoles near the final doublet it is possible to minimize the amplitude of the oscillation which "leaks" into the ring arcs and then propagates around the rest of the ring. Once in the arcs the amplitude of the oscillation tends to stay small around the rest of the ring. It is important to choose the proper phase between the IP and the sextupole pair in order to minimize the amplitude of the chromatic beta function which "leaks" into the arcs.

The lattice (see figure 1) is set up such that the vertical correction is done first followed by the horizontal. This is due to the fact that the final doublet creates more vertical chromaticity than horizontal and we would thus like to correct it first. The correction in each plane is made with sextupole pairs placed symmetrically on each side of the IP. A $-I$ transformer in both planes connects each sextupole in the pair. By doing this we minimize the geometric nonlinearities of the sextupoles. The phase advance between the IP and the first vertical sextupole is chosen to be $0.75*2\pi$ and the phase advance between the IP and the first horizontal sextupole is chosen to be $1.75*2\pi$ in order to minimize chromatic aberrations.

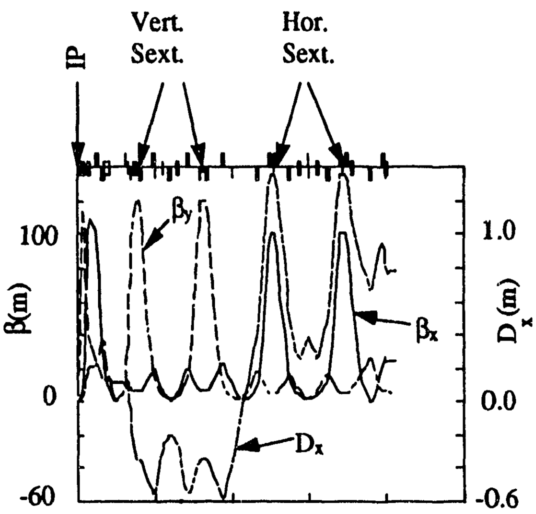

Figure 1. Lattice functions (right hand side of the IP straight) of the "test" lattice. The vertical sextupole pair and the horizontal sextupole pair follow the IP and the final doublet.

4. Testing the Idea of Local Correction

In order to test the LCC scheme approach we designed a test lattice. The performance of this ring was compared with a reference ring which did not have the LCC scheme implemented and used two families of interleaved sextupoles in the arcs to correct the chromaticity. The requirement on the LCC ring was that it was to have the same final doublet and the same noninteger tunes (0.57 horizontally and 0.64 vertically) as the reference ring. In fact the lattice of the test LCC ring was almost identical with the reference ring except for the straight section around the IP where the LCC scheme was implemented.

After setting the linear chromaticity to zero in both rings we calculated the tune shift with energy. The results can be seen in figures 2 and 3.

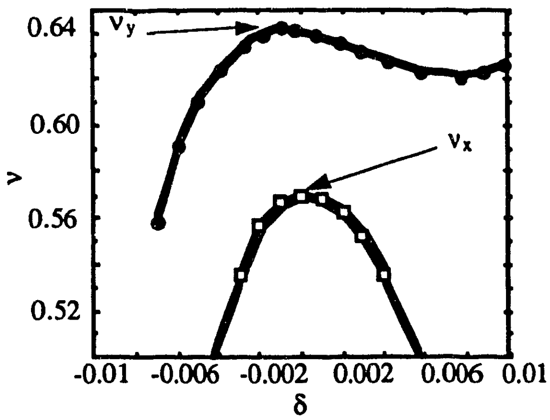

Figure 2. Tune versus energy for the reference lattice which has only 2 families of sextupoles in the arcs to correct the linear chromaticity.

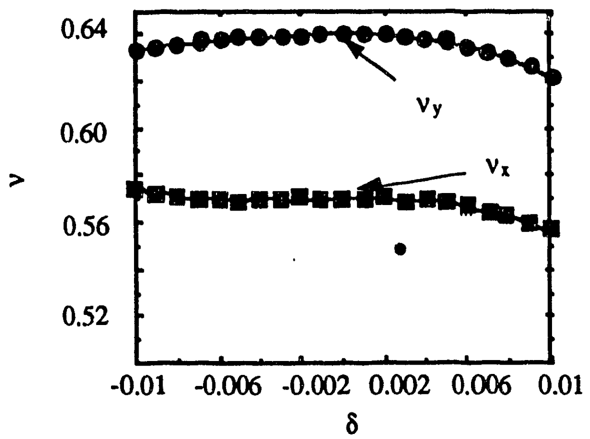

Figure 3. Tune versus energy for the test lattice which has 4 families of sextupoles, 2 in the arcs and 2 for the LCC section.

As can be seen from figures 2 and 3 there is a dramatic improvement in the behavior of the tune versus energy of the test lattice compared with the reference lattice. In fact the reference lattice is unstable at about ±0.005 in δ (or 5 δ_{rms}) because at those values the horizontal tune crosses over the half integer. In the case of the test lattice the variation in tune in both planes is less than ±0.01 over the range of ±0.01 in δ. Therefore the nonlinear tune shift is well under control over the necessary range in the test lattice.

5. FURTHER LATTICE DEVELOPMENTS

In order to have room for a lattice in which the LCC is contained entirely within the IP straight section we needed to make the LCC more compact. We have designed such a lattice and find that it also has very good tune versus energy behavior, comparable with that of the test lattice.

5.1 Dynamic Aperture Results

The particle tracking was done with an explicit simplectic integrator[3] where the cavity was represented as a thin lens. We took the IP to be the tracking point. At the IP the beam sizes are 0.2 mm horizontally and 0.03 mm vertically assuming an uncoupled beam horizontally ($\varepsilon_x = \varepsilon_0$) a fully coupled beam vertically ($\varepsilon_y = \varepsilon_0/2$) which gives us the largest possible beam sizes in either direction. Particles were launched with initial values of x, y and δ and were tracked for 1000 turns with synchrotron oscillations. The results can be seen in figures 4 and 5.

The tracking results indicate that without the introduction of errors this lattice provides an aperture which is large enough for good injection efficiency and good quantum lifetime. It remains to be seen how the aperture degrades with errors.

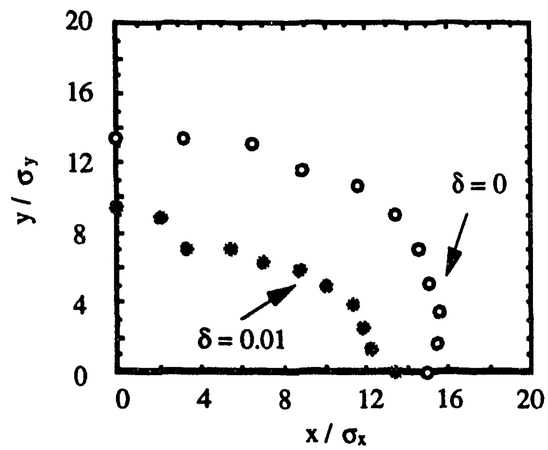

Figure 4. Initial values of particles which survived 1000 turn tracking. The open circles represent particles which were launched with zero initial energy deviation and the closed circles represent particles which had an initial energy deviation of 1%. The horizontal rms beam size, σ_x, was calculated assuming an uncoupled beam ($\varepsilon_x = \varepsilon_0$) and the vertical rms beam size, σ_y, was calculated assuming a fully coupled beam ($\varepsilon_y = \varepsilon_0/2$).

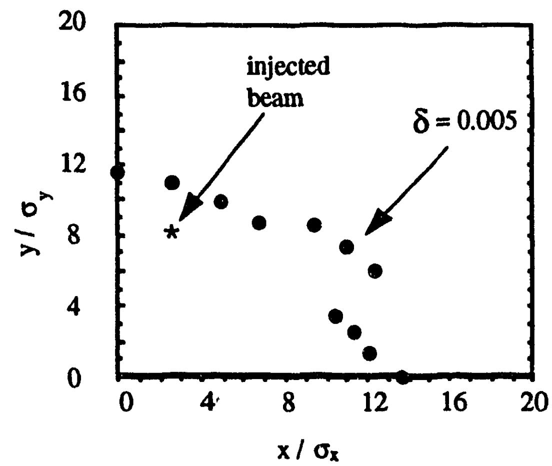

Figure 5. Particles were launched with an initial energy deviation of 0.5%. The asterisk represents the acceptance necessary for injection.

6. Limits to the Dynamic Aperture

We have found that the main limit to the dynamic aperture comes from the LCC sextupoles. In order to make the LCC section more compact it was necessary to increase the strength of the sextupoles almost by a factor of two from the test lattice. The resulting dynamic aperture is a factor of 1.5 smaller than that of the test lattice.

We are now in the process of designing a LCC which extends into the arcs which should enable us to keep the strengths of the sextupoles down.

7. Summary

The task of supplying sufficiently large dynamic apertures for *B* factory storage rings is challenging. The small beta functions and large currents necessary to increase the luminosity lead to large chromaticity and emittances in the rings, especially the LER.

Our study demonstrates that it is an attractive option to employ local chromaticity compensation for the interaction region for several reasons. First it helps to control the tune shift with energy. Second, it permits decoupling the correction of the interaction region from the rest of the ring, making the ring more robust.

Using this technique we have been able to design an interaction region that provides the LER (bare lattice) with a reasonably large aperture.

8. Acknowledgments

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