PARASITIC COLLISIONS IN PEP-II†

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Abstract

The PEP-II collider design calls for large numbers of closely-spaced bunches and head-on collisions. These two features, taken together, imply that there are parasitic collisions in the neighborhood of the interaction point. Since the bunch populations of the beams are not uniform due to the ion-clearing gaps, the bunches at the head or tail of the train ("pacman bunches") experience different effects from those away from the edges ("typical bunches"). In this article we summarize the effects arising from the parasitic collisions on luminosity, tune shifts and closed orbit distortion both for typical bunches and for pacman bunches.

1. Introduction

The SLAC/LBNL/LLNL B Factory [1] is an asymmetric e^+-e^- collider with a design luminosity of 3×10^{33} cm^{-2} s^{-1} whose primary purpose is the detailed study of the B meson system. The energy asymmetry is intended to enhance the detection efficiency of certain decay modes that are of particular interest for the study of CP violation. The value chosen for the luminosity will lead to a productive program of studies of the B meson. The low-energy beam (LEB) is positrons, with an energy of 3.1 GeV, while the high-energy ring (HEB) is electrons, with an energy of 9 GeV. The center-of-mass energy is 10.6 GeV, corresponding to the Υ(4S) resonance. The machine is being built in the PEP tunnel and uses the SLAC linac as its injector. Construction started in 1993 and will be completed in 1998.

The two rings intersect at only one interaction point (IP). Although the interaction region (IR) design allows for the possibility of crossing with a finite angle, in the current design the beams collide head-on and are magnetically separated in the horizontal plane. This separation scheme entails parasitic collisions (PCs) near the IP whose effects on the beam-beam dynamics have been studied quite extensively [1,2]. The design also calls for an ion-clearing gap equivalent to ~5% of the total beam length. The gaps in the two beams have the same length and are positioned such that head bunch in one beam collides at the IP with the head bunch of the other beam (the two beams have the same bunch spacing and overall length).

In this article we summarize effects arising from the PCs from the perspective of the beam-beam interaction. Anticipating our conclusion, we can state that the PEP-II IR design solves or avoids all issues that were initially identified as potential difficulties.

2. IR Parameters

The IR is such that a typical bunch experiences four PCs on either side of the IP, for a total of 9 collisions. In contrast, pacman bunches experience only a subset of these. For example, the first bunch and the last bunch in the train experience only 5 (the main collision at the IP plus 4 PCs on

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one side only). Figure 1 shows a plan sketch of the IR with typical bunches in collision; for the nominal bunch spacing of 1.26 m, the PCs occur every 0.63 m.

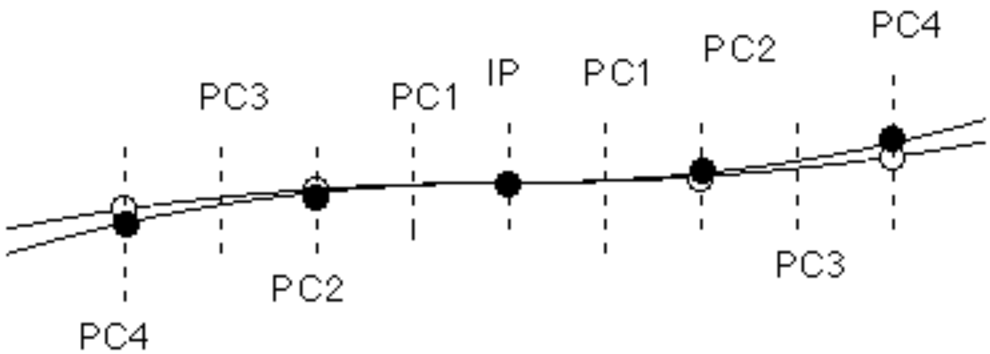

Fig. 1 Plan sketch of the IR showing the parasitic collisions.

It turns out that the first PC (labelled PC1 in Fig. 1) is much stronger than the others. For this reason we neglect PCs #2, 3 and 4 in some of our calculations. At the PC1 location, the center-to-center beam separation is d=3.5 mm, corresponding to 11.8σ_{0x+}. Table 1 shows a selection of parameters including those of PC1 (the IR optics is symmetrical about the IP in this region).

Table 1: Nominal PEP-II parameters (CDR, June 1993)

	LEB (e^+)		HEB (e^-)	
$\mathscr{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}			
N	5.63×10^{10}		2.57×10^{10}	
ε_{0x} [nm-rad]	61.3		45.9	
ε_{0y} [nm-rad]	2.45		1.84	
σ_z [cm]	1.0		1.0	
s_B [m]	1.26		1.26	
	IP	1st PC	IP	1st PC
β_x [m]	0.375	1.43	0.500	1.29
β_y [m]	0.015	26.46	0.020	19.85
α_x	0	–1.68	0	–1.26
α_y	0	–41.99	0	–31.49
σ_{0x} [μm]	151.6	296.3	151.6	243.8
σ_{0y} [μm]	6.063	254.6	6.063	191.0
d [mm]	0	3.5	0	3.5
d/σ_{0x}	0	11.8	0	14.3
ξ_{0x}	0.03	–0.000224	0.03	–0.000152
ξ_{0y}	0.03	+0.004133	0.03	+0.002326

In this table the subscript “0” attached to the luminosity ($\mathscr{L}$), rms beam sizes (σ’s), emittances (ε’s) and beam-beam parameters (ξ’s) is meant to emphasize that these are nominal quantities, *i.e.*, neglecting the effects from the beam-beam collisions. As it will be explained below, simulations show that the actual vertical beam sizes are a bit larger than nominal when the beams are in collision.

3. Beam Footprint and Long-Range Tune Shift Parameter.

3.1. Footprints with and without PCs.

If one neglects the effects from the PCs altogether, the beam footprint has a characteristic "necktie" shape that extends to the right and above the working point by about 0.03, corresponding to the value of the beam-beam parameters. Figure 2 shows such a footprint, obtained by computing the actual tunes of a single particle that is launched with various horizontal and vertical amplitudes.

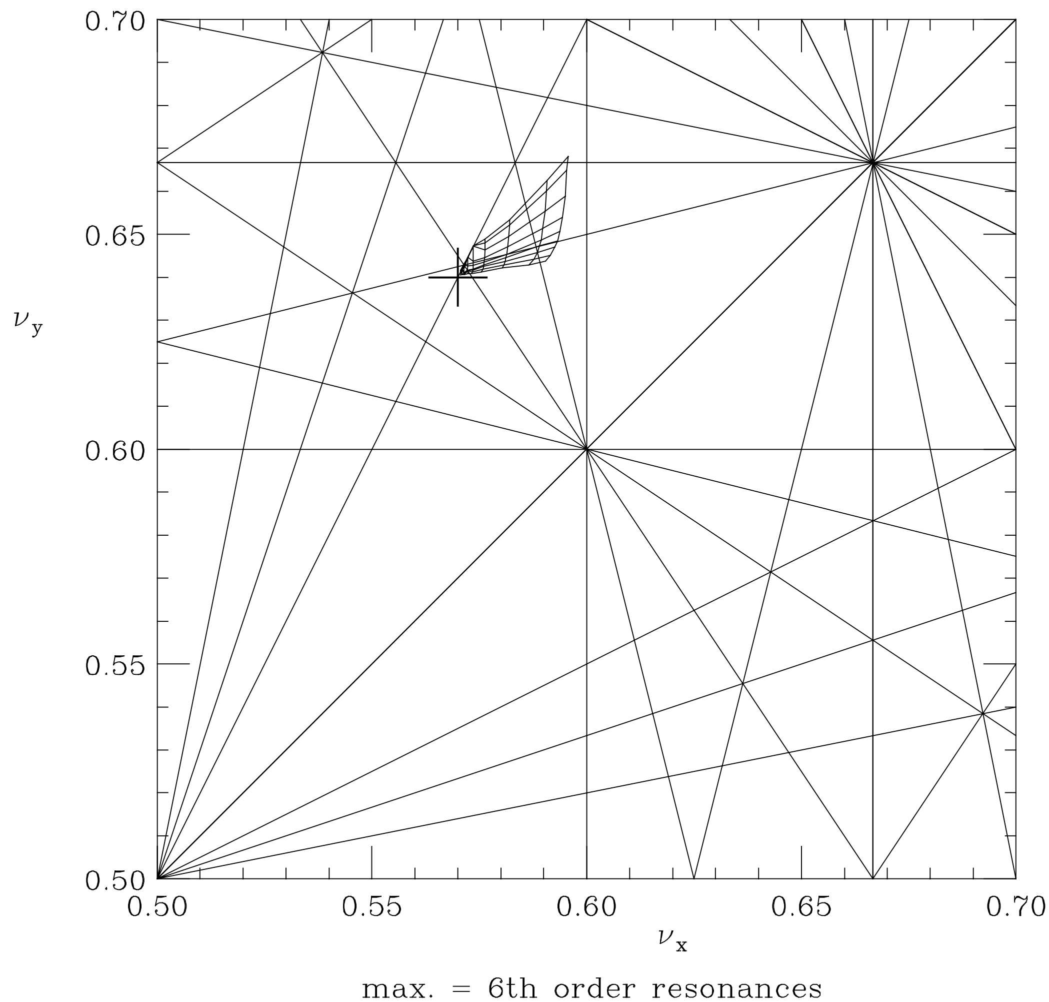

Fig. 2 Footprint of the LEB in the absence of PCs for a working point (0.57,0.64) (cross) obtained from particles launched at 0, 1, 2, 3, 4, 5, 6, 8 and 10σ_0. Resonance lines up to a maximum of sixth order are shown.

In this plot the particle at the center of the bunch is at the top right corner of the footprint. The beam-beam kick it receives is characterized by the beam-beam parameter at the IP. For a positron, the vertical parameter is

$$\xi_{0y+} = \frac{r_e N_- \beta_{y+}}{2\pi\gamma_+ \sigma_{0y-}(\sigma_{0x-} + \sigma_{0y-})} \qquad (1)$$

where r_e is the classical electron radius and γ is the usual relativistic factor. The expression for the horizontal parameter is obtained by exchanging x $\leftrightarrow$ y, and those for an electron by exchanging + $\leftrightarrow$ –. By design, all four ξ_0's have the numerical value 0.03, as listed in Table 1. In Fig. 2, the tune of the central positron is shifted approximately by 0.03 in both planes (it is not exactly 0.03 on account of the so-called "dynamical effect" [5], as discussed below).

The large-amplitude particles experience a weaker beam-beam interaction and hence they tend to be at the lower left corner of the necktie, close to the lattice working point.

If one now adds the effect of the two PC1's, the footprint is substantially changed. Figure 3 shows the corresponding results, obtained under identical conditions as in Fig. 2, except that the PC1's have been included.

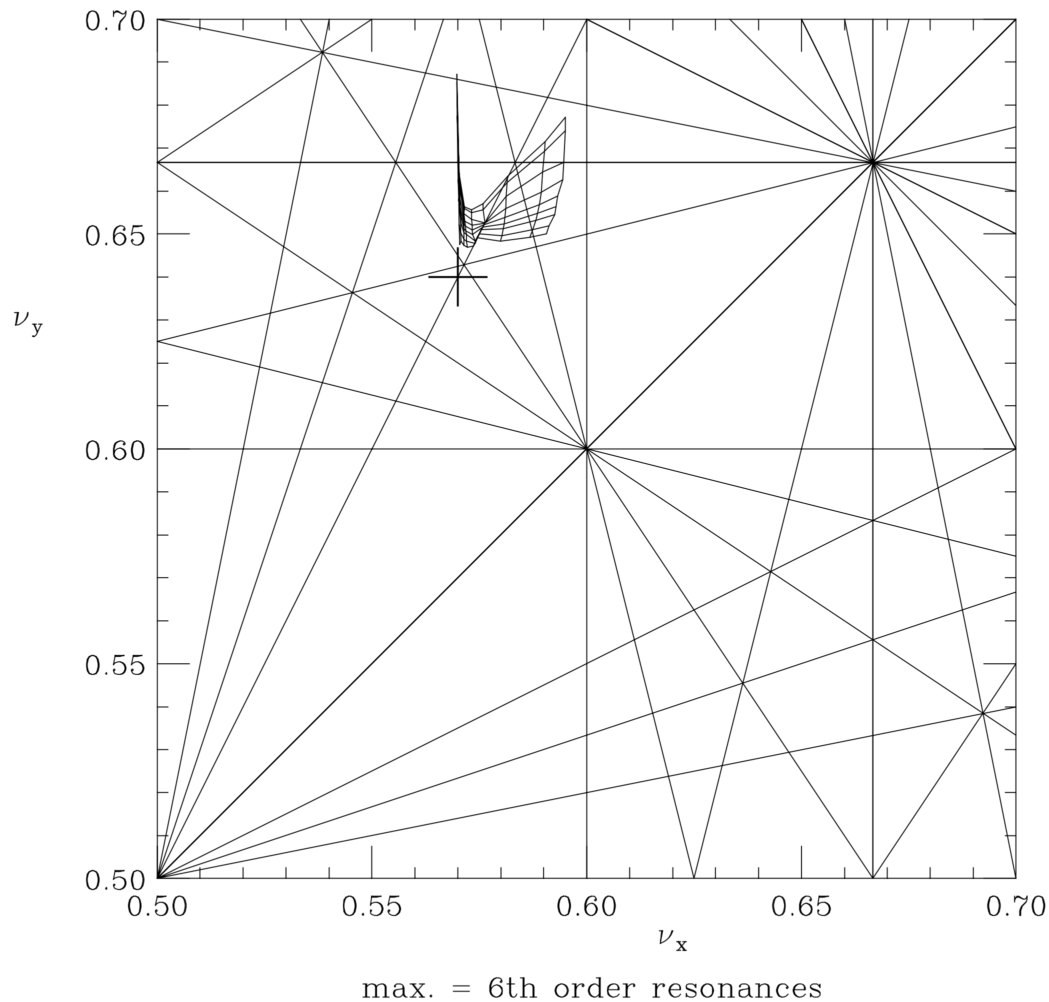

Fig. 3 Footprint of the LEB including the effect of the PC1s. The conditions are exactly the same as those in Fig. 2 except for the addition of the PCs.

One can see from this that the PCs have two distinct effects: (1) the tunes of the particle at the bunch center are shifted relative to the IP-only case; and (2) the tunes of the particles at large horizontal amplitude (those that typically get close to the center of the opposing bunch at the PC location) are shifted vertically by a substantial amount.

In the calculation of the tune footprint we have neglected all lattice nonlinearities. This approximation is only justified for particles close to the beam center, where the nonlinear effects from the lattice are weak compared to those arising from the beam-beam collision. One should therefore be cautious when interpreting these footprints at large amplitudes in this approximation.

3.2. The long-range beam-beam parameter.

The beam-beam parameters for the central particle induced by the PCs (usually referred to as the "long-range beam-beam parameters") can be computed in perturbation theory in the usual fashion. The result for a positron is

$$\xi_{x+}^{PC} = -\frac{r_e N_- \beta_{x+}^{PC}}{2\pi d^2}, \qquad \xi_{y+}^{PC} = +\frac{r_e N_- \beta_{y+}^{PC}}{2\pi d^2} \tag{2}$$

with corresponding expressions for an electron, obtained from the above by replacing $+ \leftrightarrow -$. The numerical values for the case of PEP-II are listed in Table 1.

It should be noted that the vertical and horizontal long-range beam-beam parameters are of opposite signs. If the beams were to cross in the vertical plane, the signs would be reversed relative to those in Eq. (2). It is easy to see that Maxwell's equations imply in a very straightforward manner that the signs should always be opposite: consider a positron with coordinates (x,y) close to the center of its own bunch center as it experiences a parasitic collision with an electron bunch, as sketched in Fig. 4.

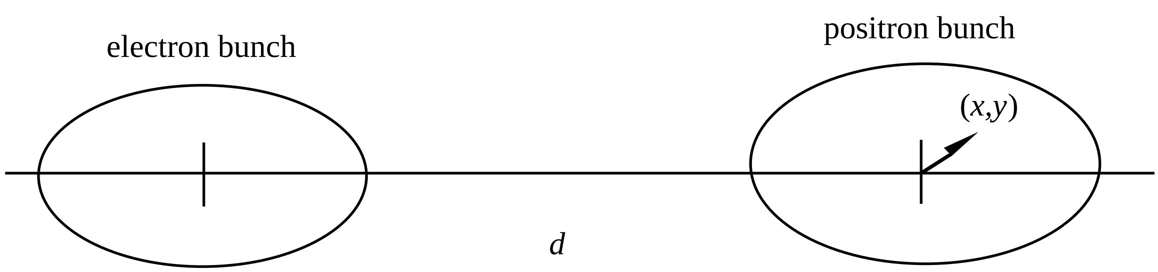

Fig. 4 Sketch of a parasitic collision in which the bunch centers are separated by a distance d. The positron, with coordinates (x,y), is very close to its own bunch center.

The ξ-parameters are, in general, defined by

$$\Delta x' = -4\pi \xi_{x+}^{PC} \frac{x}{\beta_{x+}^{PC}}, \qquad \Delta y' = -4\pi \xi_{y+}^{PC} \frac{y}{\beta_{y+}^{PC}} \tag{3}$$

where $\Delta x'$ and $\Delta y'$ are the angular deflections suffered by the positron in the collision. These deflections are given by

$$\left(\Delta x', \Delta y'\right) = -\frac{r_e N_-}{\gamma_+} \mathbf{E}(x,y) \tag{4}$$

where $\mathbf{E}(x,y)$ is the electric field per unit charge produced by the electron beam. This electric field satisfies the equation

$$\nabla \cdot \mathbf{E}(x,y) = 4\pi \frac{\rho_-(x,y)}{Q_-} = 0 \tag{5}$$

where $Q_- = N_- e$ is the charge of the electron bunch. The right side is 0 because the beams are well separated ($d \gg \sigma_x, \sigma_y$) and hence there is a vanishingly small electron charge density at the location of the positron. Thus by combining Eqs. (3–5) we obtain

$$\frac{\xi_{x+}^{PC}}{\beta_{x+}^{PC}} + \frac{\xi_{y+}^{PC}}{\beta_{y+}^{PC}} = 0 \tag{6}$$

which immediately implies that the ξ's have opposite signs. Obviously, the expressions in Eq. (2) satisfy Eq. (6), but Eq. (6) is more generally valid because it holds regardless of the orientation of the beam separation as long as $d \gg \sigma_x, \sigma_y$.

4. Closed-Orbit Distortion Due to the PCs.

As a result of the PCs there is a net attractive force between the beams that distorts their closed orbits [3]. There are two main manifestations of this closed-orbit distortion: an induced horizontal crossing angle, and a horizontal displacement of the pacman bunches at the IP. These effects depend on the horizontal tune of both beams. If the beams were uniformly populated, the crossing angle would be the same for all bunches. However, the existence of the ion-clearing gap implies that pacman bunches experience crossing angles different from typical bunches, and collide off-center due to the imbalance of the net forces to the right and to the left of the IP. Typical bunches experience only a crossing angle without orbit separation. Because the orbit distortion is a periodic function of the horizontal tune with period 1, only the fractional part of the tune matters. Since the tunes of the beams can, in principle, be chosen independently of each other, these closed orbit effects can be largely compensated if necessary. For the purposes of the calculation in this section, *we take into account all the PCs*, not just the first one.

4.1. Induced crossing angle at the IP.

Figure 5 shows the orbit slopes at a point immediately upstream (seen from the perspective of the LEB) of the IP, and the full crossing angle, $\phi \equiv X'_+ – X'_-$ (the crossing angle curve assumes the same fractional tune for both beams). It should be noted that the crossing angle is quite small: for a fractional tune of 0.64, a value that has been used in many simulation studies [1,2], the crossing angle is 34 μrad, which is much smaller than $\sigma_x/\sigma_z = 15.6 \times 10^{-3}$. Even for a fractional tune as high as 0.9, the crossing angle is only 0.13 mrad. Therefore the effect on the beam-beam dynamics from this crossing angle is expected to be negligible [4].

The corresponding results for the first pacman bunch (*i.e.*, the bunch at the head or at the tail of the train) show that the magnitude of the effect is about half of that for typical bunches. The simple explanation for this is that the first pacman bunch suffers only half of the PCs, and hence its orbit distortion is roughly half of that for a typical bunch.

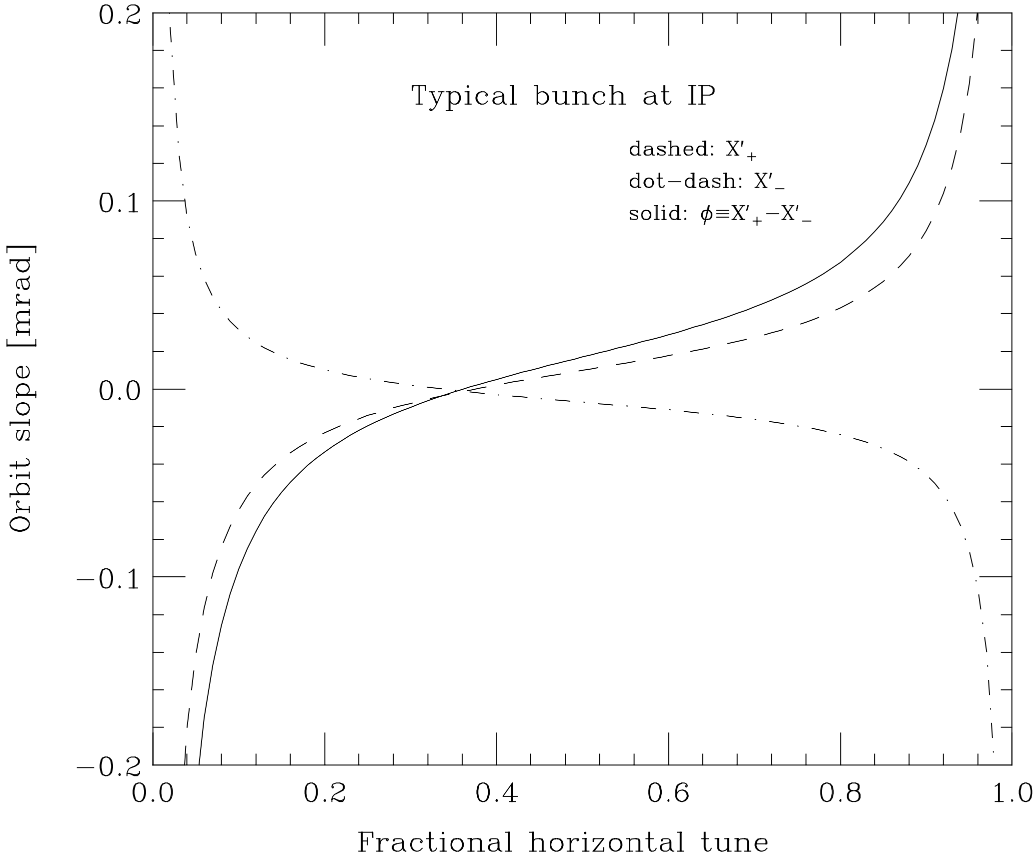

Fig. 5 Horizontal orbit slopes and full crossing angle of typical bunches. The crossing angle is computed assuming the same fractional tunes in both beams.

4.2. Induced orbit separation for pacman bunches at the IP.

Figure 6 shows the absolute and relative displacements of the orbits of the first pacman bunch at the IP. It should be noted that, for most values of the fractional tune, both bunches are displaced to the *same side* of the nominal orbit (X_+ and X_- are of the same sign). This makes physical sense: there is a net imbalance of the forces from the PCs such that the head bunches of *both* beams are pulled to the same side. The magnitude of the displacement of the first pacman bunch from its nominal orbit is $\lesssim 10$ μm for most values of the tune. More interestingly, the displacement of one bunch *relative to the other*, which is what matters for the beam-beam dynamics, is even smaller, $\Delta X < 2$ μm. These numbers are small compared to the rms bunch width of 152 μm and therefore the effects from these displacements are not expected to be important.

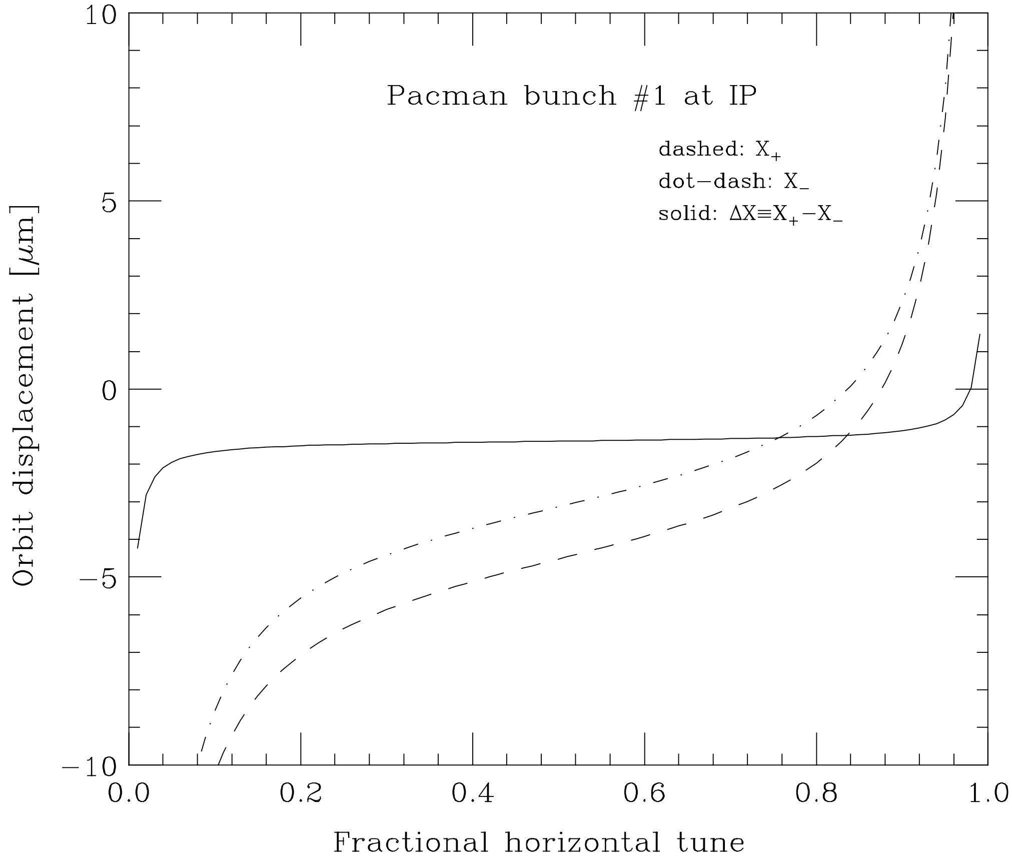

Fig. 6 Orbit distortions of the head pacman bunches at the IP. The change in orbit separation ΔX is computed assuming that the two beams have the same fractional tune.

5. Dynamical Effects for Typical and for Pacman Bunches.

As mentioned above, the tune shift is not equal to the beam-beam parameter on account of the so-called dynamical effect: the tune shift is a function of the tune as well as the beam-beam parameter. By representing the beam-beam collisions as thin-lens kicks located at the IP and the PCs, one can compute the dynamical effects in standard linear approximation for the particles near the bunch center. The actual, or dynamical, beta function experienced by these particles is computed in a similar fashion [5]. This linear analysis of the beam-beam interaction exhibits constraints that are absolutely necessary, although far from sufficient, for acceptable luminosity performance. As in the previous section, here we *take into account all PCs*.

Figure 7 shows the tune shifts for a typical bunch as a function of the lattice (or "bare") tune. In this case, the curves repeat with a periodicity of half a unit in tune. If the PCs were neglected, all four curves would coincide (they would be very close to the solid line, corresponding to the horizontal tune shift of the LEB).

One can see that the tune shifts have a nontrivial dependence on the tune. In particular, stopbands appear just below the half-integer and the integer. The stopband width can be calculated in first order in terms of the beam-beam parameters with the result

$$\delta\nu = 2\xi_0 + 4\sum_{n\geq 1}\xi_n \cos 2\phi_n + O(\xi^2) \tag{7}$$

where ξ_0 is here the beam-beam parameter at the IP, the summation is over the beam-beam parameters of the PCs to one side of the IP only, and the ϕ_n's are the betatron phases of the PCs (this formula is valid only for left-right symmetric optics). It is interesting to note that the PCs tend to make the *vertical stopbands narrower* than in the IP-only case. This can be seen from Eq. (7) by taking into account only the first PC (which is a good approximation) as follows: there are no intervening focusing elements between the IP and PC1, and the vertical β-function at the IP (1.5 or 2 cm) is small compared to the distance to the PC1 location (0.63 cm); therefore the phase ϕ_1 is close to $\pi/2$, hence $\cos 2\phi_1 \approx -1$. Now since, according to Eq. (3), $\xi_1 > 0$, we conclude that $\delta\nu$ is smaller than what it would be in the absence of PC1. This can be seen in Fig. 7, which shows that the right edges of the vertical stopbands are shifted downward from the half-integer relative to the IP-only case.

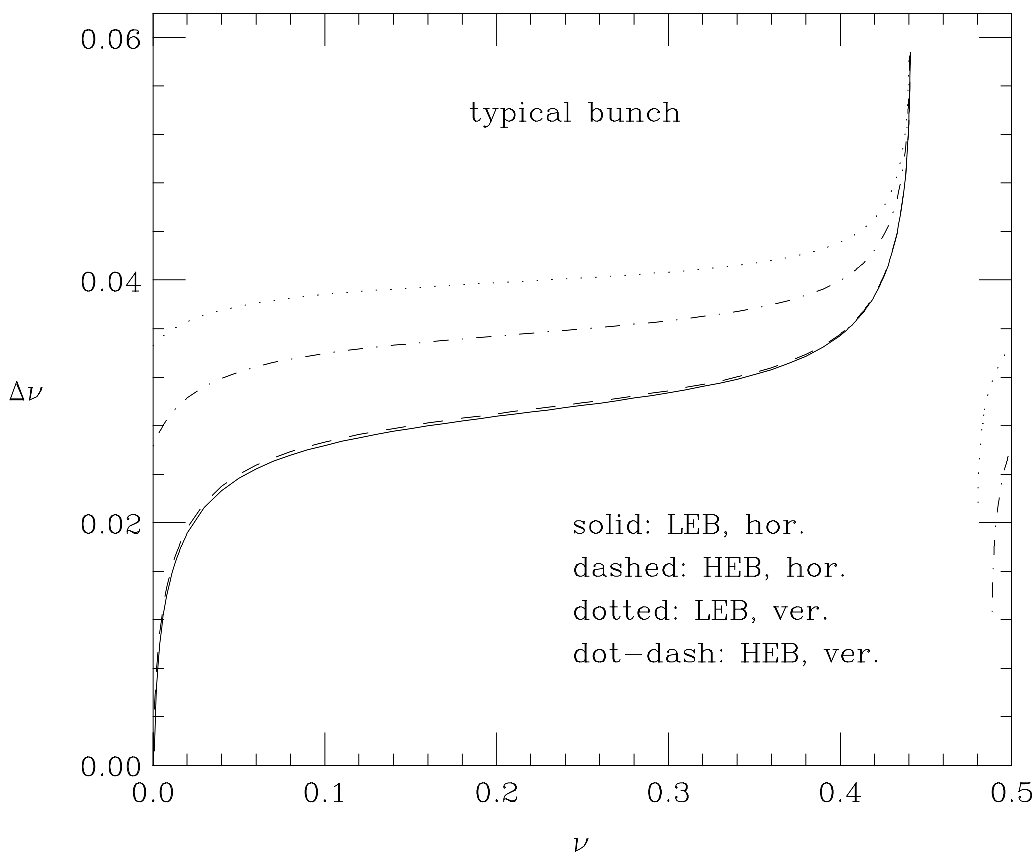

Fig. 7 The beam-beam tune shift for a typical bunch as a function of the corresponding tune for nominal PEP-II parameters. The figure is periodic in ν with a period of 0.5. If the PCs were neglected, all four curves would coincide.

For most values of the tune, the vertical tune shifts are larger than the horizontal on account of the fact that the vertical long-range beam-beam parameters are positive and larger in absolute value than the horizontal counterparts (Eq. (3) and Table 1). However, the tune shifts become relatively small just above the integer (and half-integer), which suggests that these values of the tune are desirable choices as a working point (actually, the vertical tune shifts are even smaller just *below* the half-integer, as discussed above; however, it's probably dangerous to choose a working point in this region!).

The corresponding results for the pacman bunches are qualitatively similar, except that the effects on the tune shifts are smaller in magnitude. The reason is the same as for the closed-orbit distortion: the pacman bunches experience fewer collisions which results in smaller tune shifts.

6. The Pacman Tune Spread and a Possible Compensation Method.

The difference in beam-beam tune shifts between the pacman and typical bunches is the "pacman tune spread." This spread implies that a working point that may be appropriate for typical bunches might not be good for the pacman bunches and vice versa. It may be desirable, therefore, to cancel this spread.

We consider a positron at the bunch center and take only PC1 into account. Neglecting the dynamical beta function effect, the vertical pacman tune spread is given by the difference between a typical bunch and the first pacman bunch,

$$\Delta\nu_{y+} \approx \xi_{0y+}^{PC1} \tag{8}$$

with a corresponding expression for the other beam. This vertical tune spread can be compensated simultaneously in both beams in first order approximation by tailoring the bunch currents [6]. The results of the compensation method are shown schematically in Fig. 8, which sketches the currents in all bunches of both beams. The first and last bunches of the train have a current slightly higher than the typical bunches, while the second and next-to-last bunches have slightly lower current. The rule of thumb is that the extra current in the first and last bunch of the HEB necessary to compensate the vertical LEB tune spread is given by

$$\frac{\Delta N_-}{N_-} \approx \frac{\xi_{y+}^{PC1}}{\xi_{y+}^{IP}} \approx 0.14 \tag{9}$$

while the second and next-to-last bunches must have currents *lower* than nominal by 0.14^2=0.02. A similar analysis applies to the other beam, obtained by replacing $+ \leftrightarrow -$ in the above.

The differences in sign and magnitude between the vertical and horizontal beam-beam parameters at the PCs, however, make it impossible to compensate vertical and horizontal tune spreads simultaneously. In fact, a generic feature of the method is the trade-off between the vertical tune spread and the horizontal: if the vertical tune spread is compensated, the horizontal tune spread becomes roughly equal to the uncompensated vertical tune spread, which is typically larger than the nominal value of the horizontal spread. However, the horizontal beam dynamics is much more tolerant than the vertical, so horizontal tune spreads of this magnitude should not cause any problems, and the method therefore implies a net advantage. We believe that this beneficial trade-off is a generic feature of flat beams, such as in the case of PEP-II. By the same token, this technique seems unlikely to be applicable to round beams, such as those encountered in multibunch proton colliders. Tailoring $N_\pm$ of the first and last bunches to the level required by this method is well within the capabilities of the PEP-II injection system. Tailoring $N_\pm$ of the second and next-to last bunches to the level required is more difficult, but probably much less important.

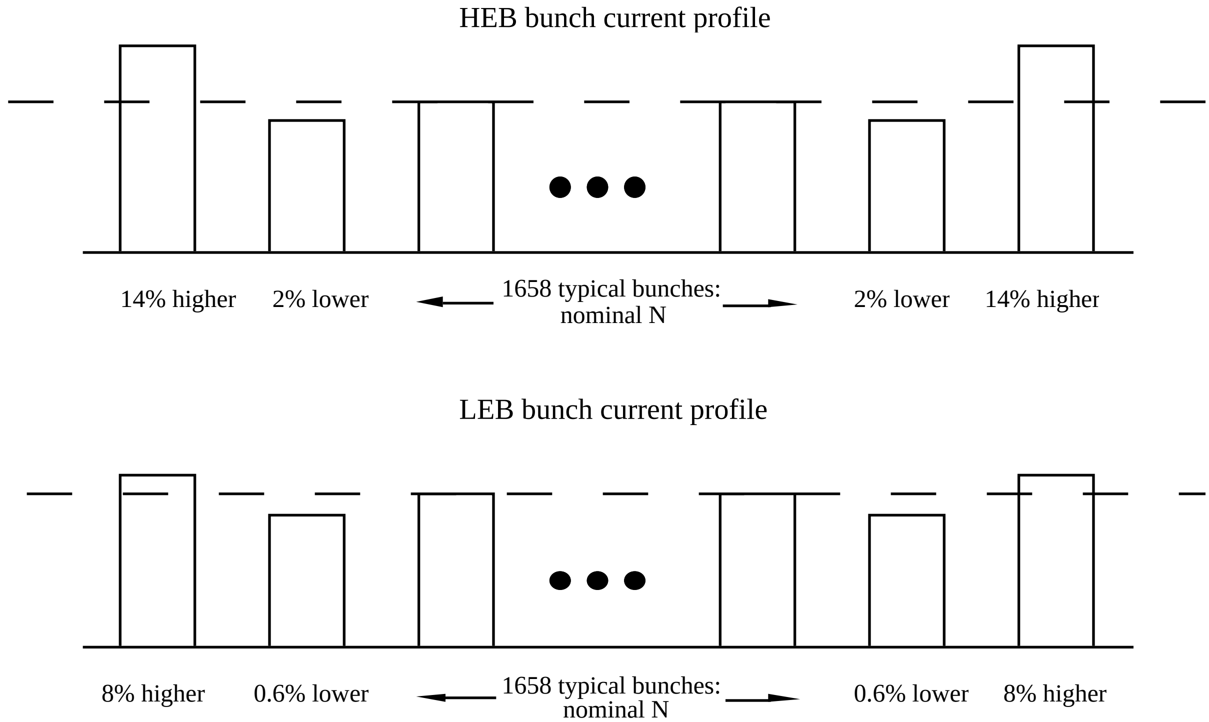

Fig. 8 The number of particles per bunch (N) necessary to compensate the vertical tune spreads in both beams. The first and last pacman bunches in the HEB and LEB have bunch currents 14% and 8% higher, respectively, than the nominal value, indicated by the dashed lines.

7. Beam Blowup Due to the PCs.

The PCs also cause blowup of the beam core. Figure 9 shows the results of a "strong-strong" simulation with the code TRS [7] in which we plot the relative beam blowup as a function of the beam separation at PC1 normalized to the local beam size of the LEB (the other PCs are neglected). In this case the beams were represented by 1024 particles and the tracking was carried out for five damping times (approximately 27000 turns) for each value of the beam separation. All parameters were fixed except for the beam separation at PC1 (the nominal design value is listed in Table 1).

It can be seen that there is substantial vertical beam blowup when the separation falls below $6\sigma_{0x+}$ or so. For the nominal separation of $11.8\sigma_{0x+}$ there is some 10-15% blowup relative to the nominal value. This blowup has the effect of reducing the nominal value of the luminosity, but this reduction can be easily compensated by a small increase in the bunch current. As the separation decreases, the onset of substantial beam blowup happens sufficiently below the nominal value of the separation that we can say that the design is quite safe, since it is not "close to an edge".

8. Conclusions.

We have summarized some of the beam dynamics effects in PEP-II arising from the PCs. Other issues, such as dynamics during injection and beam lifetime are discussed in the CDR [1]. In general, all studies to date show that there are no unusual problems relative to those that arise in symmetric colliders and that the PEP-II IR design is conservative from the perspective of the beam-beam interaction. Thus the head-on collision scheme is comfortable and it allows room for upgrading if necessary.

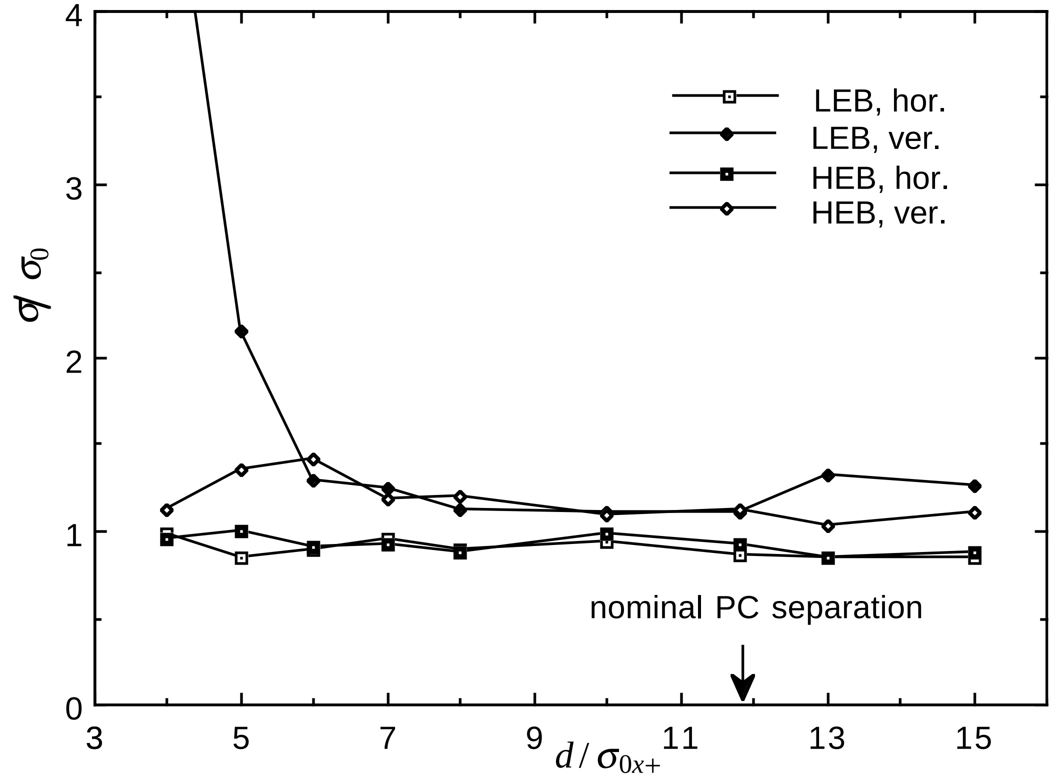

Fig. 9 Beam blowup as a function of the beam separation at the first PC (strong-strong simulation with TRS). The working point is: LEB: (0.580, 0.622); HEB: (0.580, 0.625).

9. Acknowledgments.

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