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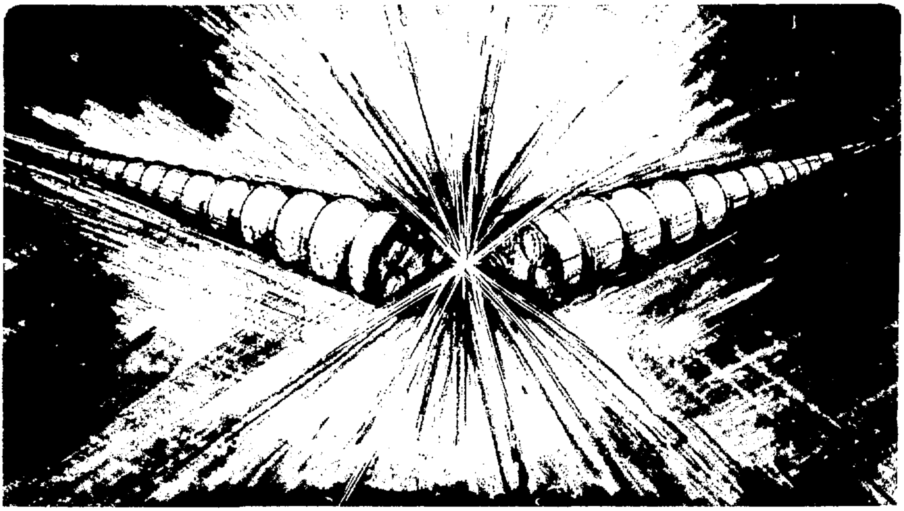

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BEAM-BEAM STUDIES FOR THE PROPOSED SLAC/LBL/LLNL B FACTORY*

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ABSTRACT

We present a summary of beam-beam dynamics studies that have been carried out to date for the proposed SLAC/LBL/LLNL B Factory. Most of the material presented here is contained in the proposal's Conceptual Design Report, although post-CDR studies are also presented.

1. A Basic Description of the B Factory

The proposed SLAC/LBL/LLNL B Factory 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 machine would be built in the existing PEP tunnel at SLAC.

The two rings are designed in an over-under configuration such that the low-energy ring (LER) lies above the high-energy ring (HER). The rings have the same circumference, C =2,200 m, and intersect at only one interaction point (IP). In its present conception the LER contains the positrons, with an energy of 3.1 GeV, and the HER contains the electrons, with an energy of 9 GeV. These values imply a center-of-mass energy of 10.56 GeV, corresponding to the Υ(4S) resonance. The bunch spacing is 1.26 m. Although the interaction region (IR) design allows for the possibility of crab crossing with a finite angle, in the current design the beams collide head-on and are magnetically separated in the horizontal plane. Full details of the design are contained in the Conceptual Design Report (CDR).[1] This article summarizes the results contained in Section 4.4 of the CDR, and also presents some new results.

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2. Beam-Beam Issues

2.1 Peak and Average Luminosity

Since the primary mission of the B Factory is the high-precision study of the B meson system, its key figure of merit is integrated luminosity. The word "factory" is meant to emphasize this figure of merit; a good design, therefore, requires good operational reliability and high average luminosity. This last requirement implies high peak luminosity and long beam lifetime, two requirements that are almost always in conflict.

The bulk of the beam-beam studies carried out to date, which are summarized here, have set a priority on demonstrating the feasibility of attaining or exceeding a short-time-average luminosity of 3×10^{33} cm^{-2} s^{-1}. We have done this by choosing a conservative design specification, with a reasonably weak beam-beam interaction that implies dynamical behavior close to nominal. We are now confident that we have a comfortable solution that meets the goal, and that there is plenty of room for improved variants, as explained below.

The short-time-average luminosity is determined by the dynamics of the beam core, while the beam lifetime is determined by the long-time dynamics of the tails of the beam. The beam core is studied quite effectively and, we believe, reliably, with "strong-strong" simulations involving a few hundred macroparticles per bunch tracked for several damping times. This type of simulation is relatively fast and inexpensive. On the other hand, a study of the beam lifetime with comparable reliability is almost certainly far more time consuming and expensive. For this reason, and because it is impossible to have good average luminosity with poor peak luminosity, we have deferred the study of the important issue of the beam lifetime until the present or the very near future. Although we have good reason to believe that our solution, or a close variant, will have good lifetime, a detailed confirmation is not yet available.

2.2 Nominal and Dynamical Beam Quantities

In accordance with our cautious approach at the present design stage, we have adopted the relatively low value for the beam-beam parameter of 0.03. When the beam-beam interaction is sufficiently weak the beams behave as if the collisions had no effect, so that the performance is controlled by the single-beam parameters of the two rings. We refer to this as "nominal behavior," and we label the corresponding quantities with a subscript 0. This condition implies a relative simplicity in the operation of the collider, because the two beams are effectively decoupled. The present design has devices such as wigglers to control the single-beam vertical emittances. Once the beams are brought into collision, the emittances deviate from their nominal values and, as a result, so do all quantities involving the beam sizes, including the beam-beam tune shifts and the luminosity. These are the "dynamical" quantities, which we denote without the subscript 0. As an example of our notation, the nominal vertical beam size at the IP $\sigma^*_{0y,+}$ and beam-beam parameter $\xi_{0y,+}$ of the e$^+$ beam, and the nominal luminosity $\mathscr{L}_0$, are given by

$$\sigma^*_{0y,+} = \sqrt{\varepsilon_{0y,+}\,\beta^*_{y,+}} \tag{1}$$

$$\xi_{0y,+} = \frac{r_0 N_- \beta^*_{y,+}}{2\pi\gamma_+ \sigma^*_{0y,-}\left(\sigma^*_{0x,-} + \sigma^*_{0y,-}\right)} \tag{2}$$

$$\mathcal{L}_0 = \frac{N_+ N_- f_c}{2\pi\sqrt{\left(\sigma^{*2}_{0x,+}+\sigma^{*2}_{0x,-}\right)\left(\sigma^{*2}_{0y,+}+\sigma^{*2}_{0y,-}\right)}} \tag{3}$$

where $\beta^*_{y,+}$ and $\varepsilon_{0y,+}$ are the vertical beta function at the IP and nominal emittance of the e^+ beam, the $N_\pm$ are the number of particles per bunch, $r_0 \equiv e^2/mc^2 = 2.815 \times 10^{-15}$ m is the classical electron radius, and f_c is the bunch collision frequency. We assume here that the bunches collide head-on, and that they have elliptical Gaussian transverse profiles with common axes. The remaining three beam sizes and beam-beam parameters can be obtained by the substitutions $x \leftrightarrow y$ and/or $+ \leftrightarrow -$ on both sides of the above expressions.

The basic strategy adopted for the beam-beam studies is to choose values for the nominal quantities in order to achieve a certain nominal value for the luminosity, and then to verify by simulations that the dynamical behavior is close to nominal, *i.e.*, that the beam size (or emittance) blowup is relatively small. Ideally, we wish to obtain the highest luminosity, with acceptable beam lifetime, at the lowest cost, and also with the highest reliability and flexibility of operation. We will present below one set of parameters, summarized in Tables 1 and 2, that strikes a balance between these conflicting requirements. We do not claim this solution to be unique or optimal; it is simply an existence proof that a luminosity of 3×10^{33} cm^{-2} s^{-1} is an achievable goal. Variants of this solution with improved performance will be presented for comparison.

2.3 Transparency Symmetry

Because no asymmetric colliders exist at present, and because the consequences of the beam-beam interaction are not completely understood for intense beams, it has been argued[2] that a cautious approach might be to force the beam dynamics of an asymmetric collider to resemble as closely as possible that of a symmetric one. In this way the design can draw upon the experience gained from single-ring colliders. This is the so-called "transparency symmetry" condition; it is reached by imposing constraints on the parameters of the two rings according to the following:

(i) pairwise equality of nominal beam-beam parameters: $\xi^*_{0x,+} = \xi^*_{0x-}$ and $\xi^*_{0y,+} = \xi^*_{0y,-}$;

(ii) pairwise equality of nominal beam sizes: $\sigma^*_{0x,+} = \sigma^*_{0x,-}$ and $\sigma^*_{0y,+} = \sigma^*_{0y,-}$;

(iii) equality of damping decrements of the two rings;

(iv) equality of the tune modulation amplitudes due to synchrotron oscillations: $(\sigma_\ell \nu_s/\beta^*_{x,y})_+ = (\sigma_\ell \nu_s/\beta^*_{x,y})_-$, where σ_ℓ =bunch length and ν_s =synchrotron tune.

An immediate consequence of the transparency symmetry is a significant reduction in the number of free parameters, which is certainly a practical advantage for beam-beam studies. On the other hand, it has been argued on general grounds[3] that, given an asymmetric machine design, the beam-beam limit (maximum luminosity with acceptable beam lifetime) subject to certain constraints can only be achieved with asymmetric beam parameters. Thus the transparency symmetry might preclude reaching the actual beam-beam limit. It is possible, however, that the ultimate beam-beam limit can be achieved only at the price of relinquishing too much flexibility and therefore operational reliability, or of undesirably tight tolerances. Furthermore, it is not known at present how different the luminosity at the beam-beam limit would be compared with what could be achieved in a given transparent case. These are matters that are now being investigated; in the meantime, however, we have adopted an approximate transparency symmetry as a prudent starting point, even though this symmetry is broken by the dynamics once all the ingredients of the simulation are included, as it will be seen in the results shown below.

Transparency symmetry implies certain equalities among the beta-functions and emittances.[2,4] In particular, the expression for the nominal luminosity becomes

$$\mathcal{L}_0 = 2.17\times10^{34}(1+r)\xi_{0y}\left(\frac{EI}{\beta_y^*}\right)_{+,-} \quad [\mathrm{cm^{-2}s^{-1}}] \tag{4}$$

where the energy E is expressed in GeV, the total beam current I in A and the beta-function in cm. The subscript +,– means that the expression in parentheses can be taken from either beam, and $r = \sigma^*_{0y}/\sigma^*_{0x}$ is the beam aspect ratio.

2.4 Details of the Simulations

We have used two simulation codes (by K. Yokoya* and J. Tennyson) that are similar but not identical. These codes represent each bunch by a collection of many (we have used up to 300) "superparticles." Initially these superparticles have a Gaussian distribution in phase space. The rms beam sizes at the IP σ_x and σ_y are calculated from the superparticle distribution at every turn. Although the shape of the distribution deviates from Gaussian as time progresses, for the purposes of computing the beam-beam kick it is a good approximation to assume the Gaussian shape, albeit with time-dependent σ_x and σ_y. From this distribution the beam-beam force on each superparticle of the opposing bunch is computed by means of the well-known expression of the transverse electric field in terms of the complex error function.[5] Deviations from the Gaussian shape are monitored; if the dynamic distribution differs substantially from Gaussian, one has reason to suspect the results due to the lack of self-consistency.

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* Yokoya's code has been appropriately augmented to describe asymmetric two-ring colliders by Yong Ho Chin, who has also performed all the simulations with this code presented here.

Each beam is transported through the rest of the machine by a linear matrix; thus no lattice nonlinearities of any kind have yet been included in these simulations. Damping and noise due to synchrotron radiation are included, and are represented by localized kicks. The RF system is also represented by a localized kick. The beams are tracked until an equilibrium situation has been reached; for the specific set of parameters presented below, we have verified that five damping times is long enough to yield stable results, and three damping times is often adequate.

Near the IP the vertical beta function is small and therefore the betatron phase of a particle changes rapidly. Consequently the beam-beam interaction is distributed over a wide range of betatron phase. This important feature[6] is incorporated in the codes by dividing the bunch longitudinally into several slices. As the bunches pass through each other during the collision, the beta functions seen by the different slices are different because the slices collide at points away from the IP. We assume that the s-dependence of the beta functions is that of a drift. Typically we have used five slices, although we have carried out spot-checks with up to nine slices.

The codes distribute the slices evenly along the length of the bunch and symmetrically about its center. However, when the number of slices is less than 15, Tennyson's code concentrates them closer to the center of the bunch than does Yokoya's code. The codes also differ in details having to do with the way certain quantities are averaged from turn to turn in order to smooth out statistical fluctuations associated with the relatively small number of superparticles. The two codes have been tested by carrying out simulations for PEP, and reasonable agreement with experimental results has been found.[1]

As mentioned above, the beams collide head-on at the IP and are then magnetically separated in the horizontal plane. The bunches go into their separate vacuum pipes only after traveling about 4 m away from the IP; as a result, they experience several grazing collisions on their way into and out of the IP. There are six such "parasitic crossings" (PCs) on either side of the IP in the present design. These PCs couple the dynamics of all bunches, so that a completely faithful simulation of the B Factory beam-beam dynamics would require 1658 bunches per ring, along with a gap equivalent to 88 bunches. Since this is an impractical requirement for any present-day simulation, we have made two simplifying approximations: (i) we consider only the first PC on either side of the IP, and (ii) we use only one bunch per ring, which is "re-used" so that this bunch collides three times per turn – two PCs plus the the main collision at IP – with the same partner in the other beam. The first approximation is quite reasonable because the first PC overwhelms all the others[1] (the first PC is separated form the IP by the beam separator dipole magnet; the remaining PCs are separated from the first one by quadrupole magnets). The second approximation rests on the sensible assumption that, in reality (or in a faithful simulation), the particle distributions will not differ much from bunch to bunch, especially when seen at a distance, as is the case at the PCs.

3. Beam Dynamics Studies

3.1 Strategy

Our strategy, explained in more detail below, is an iterative procedure divided into five steps:

(i) choose nominal parameters;

(ii) choose a working point;

(iii) study the dynamics with IP collisions only;

(iv) study the dynamics including parasitic crossings;

(v) study the beam lifetime.

If the dynamical behavior is not acceptable (for example, if the beam blowup is too large or the lifetime too short), the iteration is repeated until an acceptable solution is found. So far we have only iterated the first four steps, and we are confident that we have found a comfortable solution, as described below. We are only beginning the study of the beam lifetime of this solution.

3.2 Choice of Nominal Parameters

The primary parameters that determine the strength of the beam-beam interaction are the four nominal beam-beam parameters $\xi_{0x,\pm}$ and $\xi_{0y,\pm}$. If these are small enough, and if the working point is not too close to integer tunes, ξ_0 is equal to the nominal tune spread induced by the beam-beam interaction. We specify

$$\mathcal{L}_0 = 3\times10^{33} \quad \left[\mathrm{cm}^{-2}\mathrm{s}^{-1}\right] \tag{5}$$

and we adopt as a starting point the fully symmetric condition

$$\xi_{0x,+} = \xi_{0y,+} = \xi_{0x,-} = \xi_{0y,-} = 0.03 \tag{6}$$

which is intended to be conservative insofar as existing machines have already achieved substantially higher values.[7] From this requirement and other considerations a complete set of parameters for both rings can be reached; an abbreviated list is shown in Table 1, in which C =circumference, E =beam energy, s_B =bunch spacing, $f_c = c/s_B$= bunch collision frequency at the IP, V_{RF} =RF voltage, f_{RF} =RF frequency, ϕ_s = synchronous phase, α =momentum compaction factor, ν_s =synchrotron tune, σ_ℓ =rms bunch length, N =number of particles per bunch, τ_x and τ_y =horizontal and vertical damping times, respectively. The other parameters are the nominal emittances ε_0, beta functions β^*, and nominal rms beam sizes σ^*_0 at the IP.

Table 1. Main B factory parameters used in beam-beam studies.

	LER (e^+)	HER (e^-)
C [m]	2,200	2,200
E [GeV]	3.1	9
s_B [m]	1.26	1.26
f_c [MHz]	238	238
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.0	476.0
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
v_s	0.0403	0.0520
σ_ℓ [cm]	1	1
N	5.61×10^{10}	3.88×10^{10}
ε_{0x} [nm-rad]	92	46
ε_{0y} [nm-rad]	3.6	1.8
β^*_x [cm]	37.5	75.0
β^*_y [cm]	1.5	3.0
σ^*_{0x} [μm]	186	186
σ^*_{0y} [μm]	7.35	7.35
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

The values in Table 1 are consistent with Eqs. 5 and 6 but do not correspond exactly to the requirements of transparency symmetry because of the difference in the damping times between the two rings, and also because of the difference in the amplitudes of the tune modulation,

$$\left(\frac{\sigma_\ell\, v_s}{\beta_x^*}\right)_+ = 1.07\times10^{-3}, \quad \left(\frac{\sigma_\ell\, v_s}{\beta_x^*}\right)_- = 6.93\times10^{-4} \tag{7}$$

$$\left(\frac{\sigma_\ell\, v_s}{\beta_y^*}\right)_+ = 2.69\times10^{-2}, \quad \left(\frac{\sigma_\ell\, v_s}{\beta_y^*}\right)_- = 1.73\times10^{-2} \tag{8}$$

3.3 Choice of Working Point

Only the primary collisions at the IP are considered in this step. The choice of tunes is made quite effectively with "weak-strong" simulations, in which the high-energy beam is forced to remain undisturbed while the low-energy beam is studied dynamically. The weak-strong simulation has the advantages that it is relatively fast and that the effects of resonances, such as synchrotron sidebands, are clearly seen (thus allowing, in principle, a theoretical understanding of the underlying beam dynamics). The main figure of merit we use in this study is beam blowup factor of the low-energy beam. We have performed a limited tune scan; for the present limited purpose of studying the beam-beam dynamics, we have selected the fractional tunes to be $\nu_x = 0.09$ and $\nu_y = 0.05$ (both beams), for which the LER beam blowup factor is 10% or less.[8] We have checked that the weak-strong approximation is reasonable because the more realistic "strong-strong" simulations show that there is little or no beam blow up for the high-energy beam for the above choice of nominal parameters. Other considerations, such as dipole error sensitivity, will likely dictate working points further away from the integer. Nevertheless, at least some existing machines[7] have chosen to operate in this general area of the tune plane (in post-CDR simulations, briefly discussed below, we have chosen $\nu_x = 0.64$ and $\nu_y = 0.57$).

3.4 Dynamics With IP Collisions Only

Here we use "strong-strong" simulations, in which both beams are allowed to vary dynamically according to their mutual beam-beam interaction; however, only the primary collisions at the IP are considered. As a check on the robustness of our chosen parameters and working point, we have gone to values of ξ_0 much higher than the nominal value of 0.03 in the simulations (we increase ξ_0 by increasing the bunch currents and keeping the nominal emittances and beta-functions constant; in doing this we maintain the equality of all four ξ_0 parameters). The resulting dynamical luminosity $\mathcal{L}$ is plotted in Fig. 1. One can see that the two codes predict reasonably similar dynamical behavior; the disagreement at large ξ_0 is due to the onset of strong coherent oscillations that were artificially suppressed in Tennyson's code. If the behavior were strictly nominal, $\mathcal{L}$ would increase quadratically with ξ_0; the approximately linear behavior for $\xi_0 \geq 0.05$ is due to beam blowup.

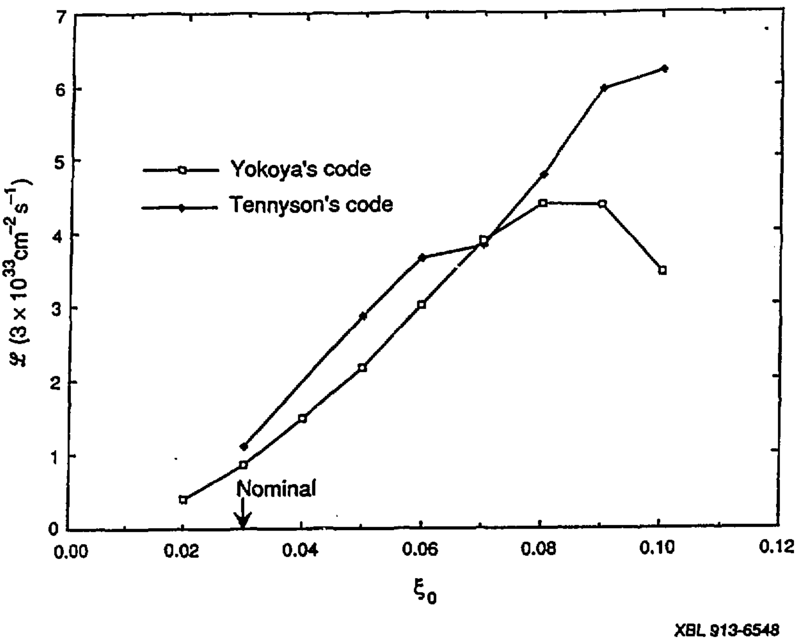

Fig. 1. Luminosity vs. ξ_0 (IP collisions only).

3.5 Effect of Parasitic Crossings

Parasitic crossings have a potentially detrimental effect on beam blowup because they induce odd-order resonances and because the vertical beta function is sufficiently high at the crossing point locations that the long-range tune shift is comparable to the head-on tune spread at the IP. This also means that the PCs induce significant horizontal-vertical coupling. Taken together these effects make it harder to find an optimum working point in the tune plane.

There are six PCs symmetrically located on either side of the IP. For the purposes of studying the beam-beam dynamics, we neglect all but the first PC (*i.e.*, the one closest to the IP on either side) because it overwhelms the others on account of the small separation together with the large vertical beta function: the strength of the long-range beam-beam kick at this first PC is much larger than those of all remaining combined. Table 2 shows the relevant parameters for the IP and the first PC for the lattice APIARY 6.3D.

Table 2. Nominal parameters at the IP and first PC (APIARY 6.3D).

	LER (e^+)		HER (e^-)	
Δs [cm]		63		
d [mm]		2.82		
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1643	0	0.1111
$\Delta\nu_y$	0	0.2462	0	0.2424
β_x [cm]	37.5	151	75	130
β_y [cm]	1.5	2,523	3	1,301
α_x	0	−2.42	0	−1.06
α_y	0	−29.25	0	−18.74
σ_{0x} [μm]	186	373	186	245
σ_{0y} [μm]	7.35	302	7.35	153
d/σ_{0x}	0	7.56	0	11.5

In Table 2 Δs =distance from the IP to the first PC along the nominal trajectory, d = separation between the two closed orbits at the PC, $2\pi\Delta\nu_x$ and $2\pi\Delta\nu_y$ =phase advances from the IP to the PC. The nominal emittances and number of particles per bunch are listed in Table 1, and d/σ_{0x} is a measure of the extent of the overlap between the two bunches at the PC. The PCs induce a tune shift and an amplitude-dependent tune spread. It can be shown that the beam-beam kick strengths experienced by a particle at the center of the e+ bunch are, in lowest-order approximation, given by[9]

$$\xi^{(pc)}_{0x,+} = -\frac{r_0 N_- \beta_{x,+}}{2\pi\gamma_+ d^2}, \qquad \xi^{(pc)}_{0y,+} = +\frac{r_0 N_- \beta_{y,+}}{2\pi\gamma_+ d^2} \tag{9}$$

with corresponding expressions for the e− bunch. Here $\beta_{x,y}$ are the beta-functions at the PC location. The negative sign in $\xi^{(pc)}_{0x,+}$ arises from the fact that the horizontal force is a decreasing function of the separation at the PC (the "background" force induced by the closed-orbit separation is subtracted out). Using the numerical values from Table 2 we obtain

$$\begin{aligned} \xi^{(pc)}_{0x,+} &= -0.001, \qquad & \xi^{(pc)}_{0x,-} &= -0.0002 \\ \xi^{(pc)}_{0y,+} &= +0.009, \qquad & \xi^{(pc)}_{0x,-} &= +0.002 \end{aligned} \tag{10}$$

which shows that each of the first PCs contributes a vertical tune shift of almost one-third of the nominal IP tune shift of 0.03 in the e+ beam. The remaining PCs contribute negligibly to the tune shifts.

A tune shift by itself is not detrimental, since it can be compensated by a shift in the working point. The amplitude dependence, however, causes a more problematic tune spread. This spread can be calculated by numerical integration,[9] and causes a distortion of the beam footprint, as shown in Fig. 2. Such distortion makes it more difficult to find a good working point; for the present simulation purposes, however, we have maintained the original working point ν_x=0.09, ν_y=0.05.

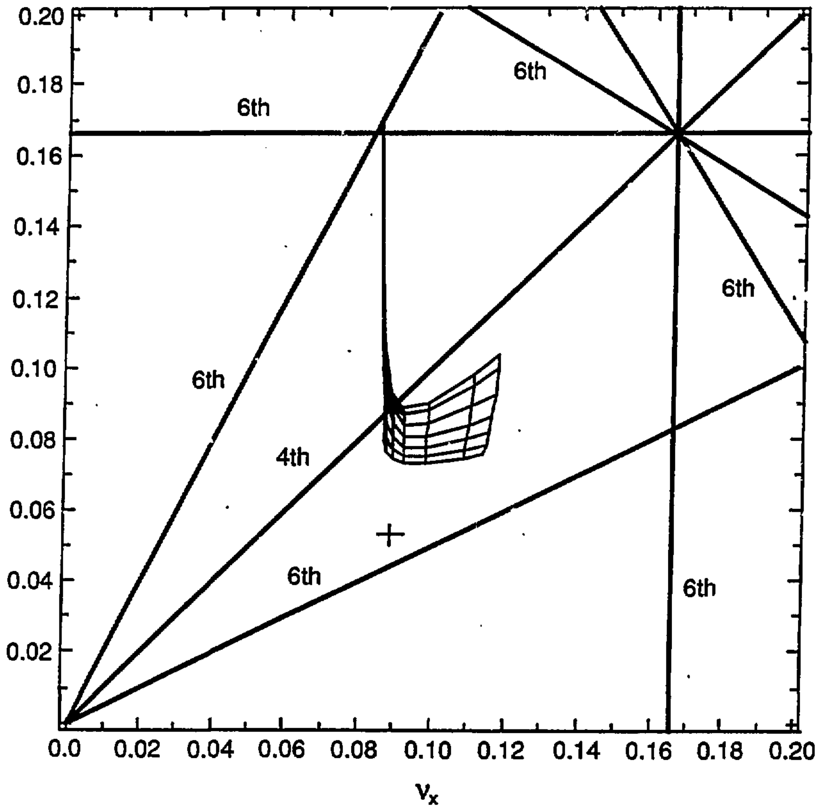

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Fig. 2. Beam footprint including the effect of the PC's. The large-amplitude distortion of the footprint produced by the long-range collision is apparent in the large vertical spike for particles at large amplitude. Even-order resonance lines through 6th order are shown.

Clearly if the separation d were large enough, all effects of the PCs would disappear altogether. In order to assess this effect, we have carried out simulations[9,10] in which we vary d and keep all other parameters fixed. Fig. 3 shows the beam blowup factors as a function of $d/\sigma_{0x,+}$, and Fig. 4 shows the corresponding luminosity ($\sigma_{0x,+}$ is here the nominal horizontal beam size at the PC). In order to get an idea of the sensitivity to ξ_0, we have carried out the simulation for ξ_0=0.05 as well; in this case ξ_0 is changed by changing the beam currents while keeping the nominal emittances fixed.

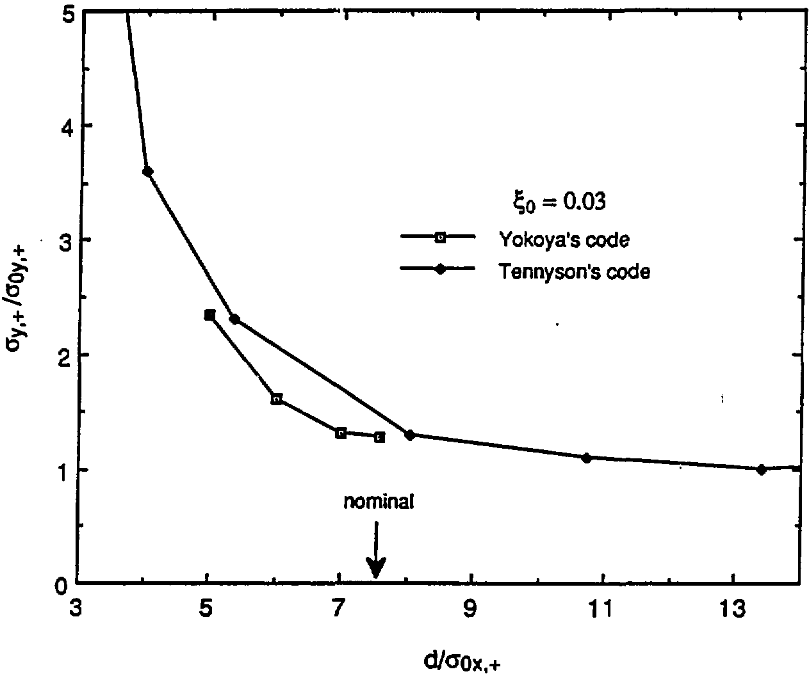

Fig. 3. Vertical beam blowup factor for the LER vs $d/\sigma_{0x,+}$. The nominal beam separation at the PC, indicated by the arrow, corresponds to $d/\sigma_{0x,+}$=7.56 (see Table 2). The remaining three beam sizes are not shown because they exhibit blowup (or contraction) factors of 10% or less in all cases except at very low values of $d/\sigma_{0x,+}$.

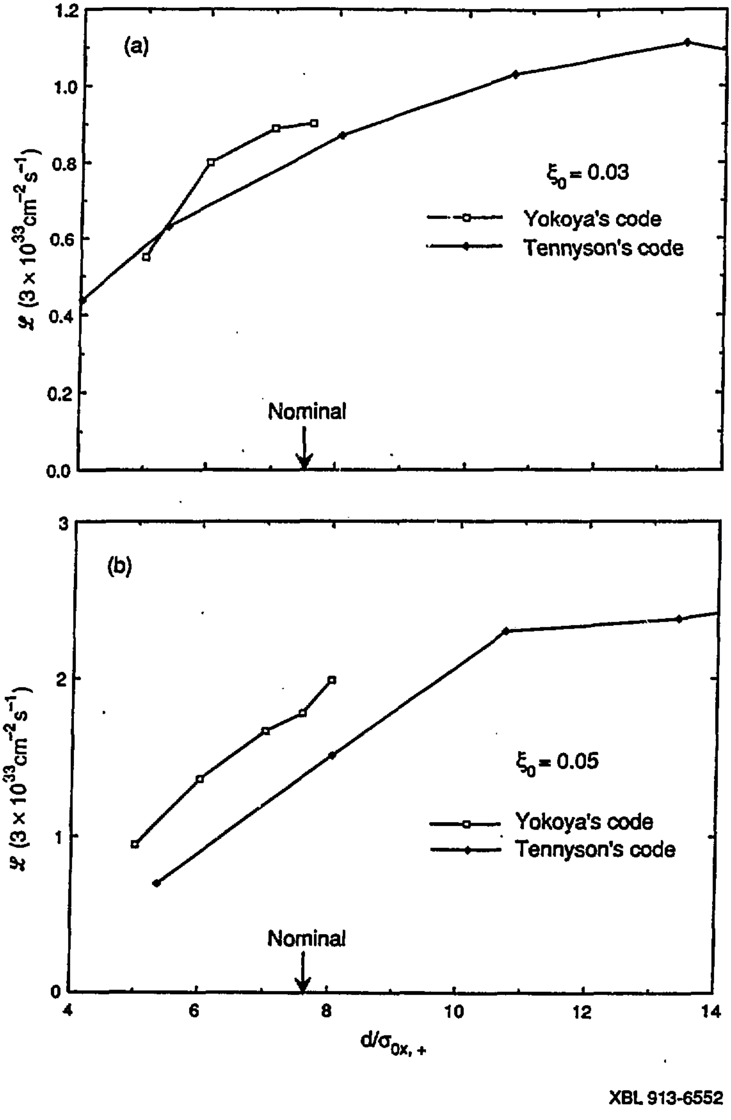

Fig. 4. Luminosity vs $d/\sigma_{0x,+}$ corresponding to the blown-up beam sizes shown in Fig. 3 (ξ_0=0.03) and also for ξ_0=0.05.

4. Discussion

Fig. 1 shows that, in the absence of the effects from PCs, nominal behavior persists up to values of ξ_0 much larger than 0.03 for the working point chosen. Unfortunately, the PCs induce significant vertical blowup in the low energy beam. Even so, Fig. 4 shows that the actual luminosity achieved is only about 10% smaller than its design value for ξ_0=0.03. For the higher value of ξ_0=0.05 the luminosity degradation from its nominal value ($\mathscr{L}_0$=8.33$\times$10^{33} cm^{-2} s^{-1}) is much more significant although its absolute value, $\mathscr{L}$~5$\times$10^{33} cm^{-2} s^{-1}, is roughly proportional to the beam current.

Although the two codes show good agreement in the absence of the effect of the PCs, the agreement is less good when the PCs are included, especially for the larger value of ξ_0. We have not yet resolved this discrepancy. It is possible that this discrepancy is simply due to the different slicing and averaging algorithms; if this is the case, then the codes' predictions should presumably be trusted to the extent that they show agreement. Qualitatively, however, both codes show the same features; for example, both indicate that it is the low-energy beam vertical blowup that is responsible for the luminosity degradation. This result means that the transparency symmetry is broken substantially by the dynamics.

We have not yet studied the beam lifetime, which is related to the long-time behavior of the tails of the particles' distribution. This investigation is much more time-consuming and difficult than the luminosity investigation presented here, which is related to the physics of the beam core. It is generally believed that, roughly speaking, good behavior in the tails is associated with good behavior in the core (it is more firmly believed that bad core behavior implies poor lifetime). We have made the implicit assumption that this is true for this asymmetric collider, hence our cautious approach at this stage. A look at Fig. 3 suggests that the onset of substantial blowup is sufficiently close to the nominal specification of $d/\sigma_{0x,+}$ to warrant the exploration of variants of this solution; some of these variants are described below.

The asymmetric behavior exhibited in the simulations suggests two approaches to try to improve the results: either make the nominal design truly conform to transparency symmetry,[2] or abandon the transparency symmetry approach altogether.[3] The fact that the low-energy beam blows up preferentially suggests that, in the latter approach, one should probably lower its specified beam-beam parameter and raise the remaining three. This approach is currently being investigated, along with a more complete exploration of the parameter space, and no results along these lines will be presented here. As mentioned at the end of Section 3.2, the transparency symmetry is broken at the nominal level and, as seen explicitly in Eqs. 7, 8, and 10, it is broken more substantially at the dynamical level. Even if the symmetry were achieved dynamically, it would not be a guarantee of improved performance; it would only mean, for example, that all four beam sizes blow up together. The hope is that such a behavior does indeed imply better performance and/or reliability.[2]

We first summarize the results of two modifiactions that bring the design closer to transparency, and then the results of other approaches that effectively decrease the effect of the PCs. In all approaches the idea is to find another specification for the set of nominal parameters (and/or another IR design) such that $\xi_0 = 0.03$ and $\mathcal{L}_0 = 3\times10^{33}$ cm^{-2} s^{-1}, and then to use simulations to assess the goodness of the solution.

4.1 Larger $\beta^*_{y,+}$ and $\beta^*_{x,+}$

The idea here is to try to make the tune modulation amplitudes, as defined in Eqs. 7 and 8, closer to the transparency condition. In order that $\mathcal{L}_0$ and the four ξ_0 parameters retain their original values, this change in $\beta^*_{y,+}$ and $\beta^*_{x,+}$ requires an increase in the emittances of the high-energy beam, $\varepsilon_{0x,-}$ and $\varepsilon_{0y,-}$, and in the number of particles per bunch of the low-energy beam, N_+, all in the same proportion as the increase in $\beta^*_{x,y,+}$ (see Eqs. 1, 2, and 3). We have chosen to compare the old case, corresponding to $\beta^*_{y,+} =$ 1.5 cm, $\beta^*_{x,+} = 37.5$ cm with a new set of values 33% larger, $\beta^*_{y,+} = 2$ cm, $\beta^*_{x,+} = 50$ cm. The simulation, which includes IP collisions only, shows lesser beam blowup than before, with a corresponding increase of ~5% in the dynamical luminosity.

The penalty in this case is a larger LER beam current, which approaches 3 A as a result of the increase in N_+. However, a beneficial effect of increasing β^* is that the beta-function at the first PC is decreased, making the bunches smaller and therefore $d/\sigma_{0x,+}$ larger, and decreasing the PC tune spread. At present, simulations including the PCs have not been carried out.

4.2 Smaller $\sigma_{\ell,+}$

Another way of making the tune-modulation-amplitude parameters closer to the transparency condition is by decreasing the bunch length $\sigma_{\ell,+}$ of the low-energy beam in such a way that the synchrotron tune ν_s remains constant (see Eqs. 7, 8). This requires changing the momentum compaction factor α and the rf voltage V_{RF}. The simulation, which again does not take into account parasitic crossings, shows lesser beam blowup and a corresponding increase in dynamical luminosity of ~10% relative to the old case.

4.3 Larger Bunch Spacing

The idea here is to effectively increase the beam separation at the first PC. One way to achieve this, which does not imply a redesign of the IR, is to increase the bunch spacing s_B by 50%, from 1.26 m to 1.89 m, by filling every third RF bucket rather than every second bucket (the RF wavelength is $\lambda_{RF} = 63$ cm). Then the first PC occurs at a distance Δs =94 cm from the IP instead of 63 cm where the beam separation is d =7.41 mm instead of 2.82 mm. Because of an intervening quadrupole magnet, the old first PC and the new first PC are not in the same drift space, and consequently the ratio $d/\sigma_{0x,+}$ is not the same as before: the new value is a more comfortable $d/\sigma_{0x,+}$=9.16 instead of 7.56 (Table 2), which implies a reduced beam overlap. In order to maintain ξ_0 and $\mathcal{L}_0$ at their original values of 0.03 and 3×10^{33} cm^{-2} s^{-1}, respectively, we require that the number of particles per bunch and nominal emittances of both beams also be increased by 50%. Simulations[1] show that beam blowup is smaller than before, as can be seen in Fig. 5, which should be compared with Fig. 3. More importantly, the onset of substantial beam blowup has now been pushed back from the new nominal specification for *d*, so that a "comfort factor" has been gained (the luminosity is quite close to nominal in both old and new cases).

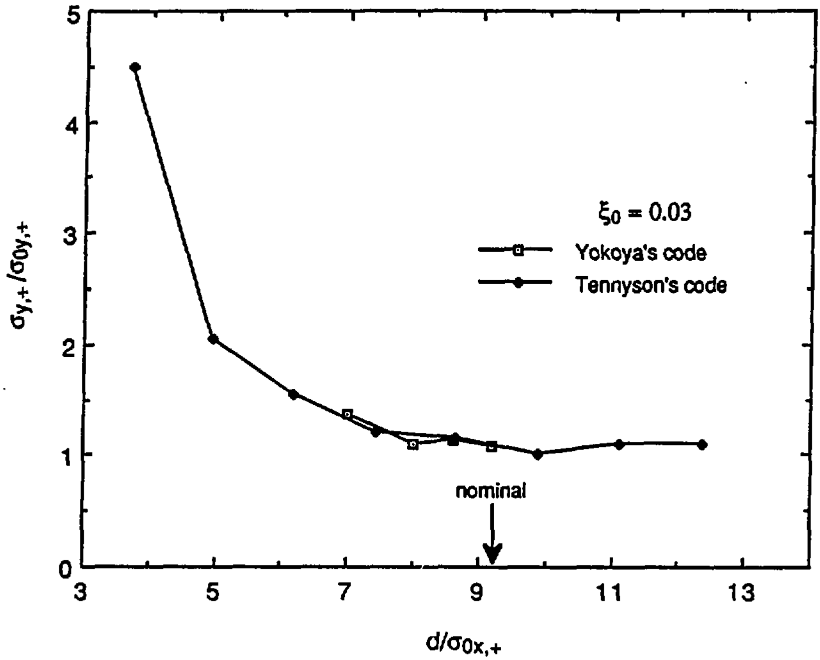

Fig. 5. Vertical beam blowup factor for the LER vs $d/\sigma_{0x,+}$ in the case where the bunches are filled every third RF bucket instead of every second bucket. The nominal beam separation at the PC, indicated by the arrow, corresponds now to $d/\sigma_{0x,+}$=9.16. The bunches have 50% more particles and 50% larger nominal emittances (both beams) than in the every-second-bucket filling scheme, so that the nominal luminosity and beam-beam parameters retain their original values. The remaining three beam sizes are not shown because they exhibit blowup (or contraction) factors of 20% or less in all cases except for very low values of $d/\sigma_{0x,+}$.

5. Post–CDR Studies

Several studies are ongoing since the printing of the CDR. Here we present a brief summary:

5.1 New Working Point

Because of sensitivity to closed orbit errors, a working point near the integer is undesirable. An expanded, but still incomplete, scan of the tune plane with weak-strong simulations has lead us to adopt a new working point for our simulations. It is $\nu_x = 0.64$, $\nu_y = 0.57$ (both beams), for which the vertical blowup of the LER is ~10% when PCs are ignored.[8] When PCs are included, simulations for the same nominal case presented above (summarized in Tables 1 and 2) show that the beam blowup behavior is better than before, as can be seen in Fig. 6 (compare with Fig. 3).

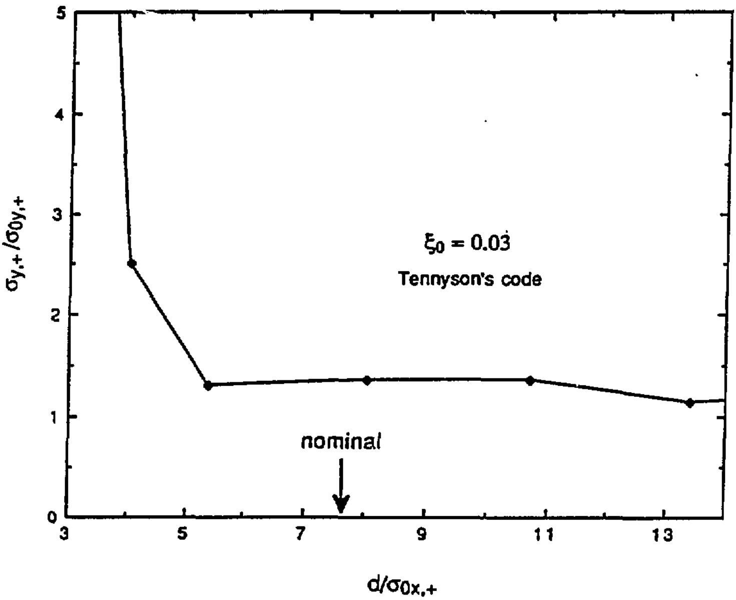

Fig. 6. Vertical beam blowup factor for the LER vs $d/\sigma_{0x,+}$ for the new working point, $\nu_x = 0.64$, $\nu_y = 0.57$ (Tennyson's code). The nominal beam separation at the PC, indicated by the arrow, corresponds to $d/\sigma_{0x,+}$=7.56 (see Table 2). The remaining three beam sizes are not shown because they exhibit blowup (or contraction) factors of 10% or less in all cases except at very low values of $d/\sigma_{0x,+}$.

5.2 Collision Tolerances

We have carried out simulations with and without PCs in which the bunches are forced to collide displaced vertically from each other.[11] For $\Delta y/\sigma^*_{0y} \leq 1$ (Δy being the vertical offset), these simulations show no significant difference in the beam blowup factors with the exactly-head-on collision case; consequently, there is no significant decrease of the luminosity beyond the expected geometrical reduction. In any case, a transverse feedback system will be available to maintain the bunch alignment at collision.

5.3 Injection Simulations

In the present conception of the B Factory, injection is in the horizontal plane with an offset of $8\sigma_{0x}$. It proceeds in five batches of 20% of full beam intensity, although the optimal sequence is as yet unspecified. The injected beam collides several times head-on with the stored beam at the parasitic crossing locations before it has had enough time to damp down to its nominal orbit. Because the beta-functions at these points are quite large, the concern is that unacceptably fast beam losses might occur. We have carried out simulations in which the HER is stored at full intensity, and we then observe the behavior of both beams following the injection of the first 20% batch of the LER (this particular sequence is probably the most detrimental from the beam-beam dynamics point of view). We have assumed that injection optics is the same as collision optics and that no beam separators of any kind are used. As expected, these simulations show substantial transient coherent oscillations and LER vertical blowup during the first damping time or so. Nevertheless, particles are seen lost only at the 1% level; this is because the beam is at all times very well contained within the allowed physical aperture in spite of the blowup.[12] A possible alternative is vertical injection; in this case the simulations show, as expected, much less blowup than in the case of horizontal injection. Although these results are very preliminary, our tentative conclusion is that the simplest injection scheme will not pose serious problems.

5.4 Hourglass Effect and Off-IP Collision Tolerances

Because the vertical beta-functions at the IP are comparable to the bunch length, there is substantial modulation of the transverse beam size and of the beam-beam parameters of individual particles. This hourglass effect is stronger on the LER because of the smaller beta-function. The simulation codes we use do incorporate this effect by way of the longitudinal bunch slicing described earlier. An analytic calculation shows that the hourglass luminosity degradation is only ~6% relative to the zero-bunch-length estimate and, in any case, it is overcompensated by the electromagnetic pinching effect, as our simulations show.[13] If the bunches collide longitudinally displaced from the IP (a situation that we have not yet simulated), the same analytic calculation shows that the luminosity degradation is no more than ~15% when the displacement is as large as 1 cm. In any case, a longitudinal feedback system will maintain the collision point within 2 mm of the IP. We conclude that the hourglass effect on the luminosity is not a concern. On the other hand, the vertical beam-beam parameter of individual particles in the LER is modulated substantially.

As a result, particles at the head or tail of the bunch have substantially larger values of ξ_y than particles at the center of the bunch. This modulation effect on the ξ-parameters is also included in the simulation codes, as explained above. However, in all simulations we have carried out so far, the particles' longitudinal positions are always within $\pm 2\sigma_\ell$ of the bunch center, where the hourglass modulation is not as important. Particles further away at the head and tail of the bunch will probably have a more significant effect on the beam lifetime than on the luminosity, and we are beginning to study this important issue.

5.5 IR Design Improvements

Redesigns of the interaction region are ongoing; one important objective is to increase the value of the parameter $d/\sigma_{0x,+}$ of the first PC in order to make the beam-beam behavior closer to nominal. One such redesign[14] has $d/\sigma_{0x,+}$=9.45 for the nominal bunch spacing s_B=1.26 m. This is more comfortable than the CDR value of 7.56 (Table 2) and than the value of 9.16 for the every-third-bucket filling scheme described earlier. Because beam blowup has an almost step-function sensitivity to $d/\sigma_{0x,+}$, even a modest increase can make a significant improvement in the performance. Simulations results are not yet available for this new IR design.

6. Conclusions

Our results show that, if it were not for the effect of the parasitic crossings, the luminosity performance of the machine is quite close to nominal up to values of ξ_0 substantially higher than the design specification of 0.03. The PCs introduce substantial horizontal-vertical coupling due to the large value of the vertical beta-function. This has the effect of blowing up the vertical size of the low-energy beam substantially. However, because the other three transverse beam sizes are not changed much, the luminosity degrades no more than ~15% from its nominal value for ξ_0=0.03. For ξ_0=0.05 the relative degradation is larger, of order 40–50% although, since the nominal luminosity is larger in this case, the *absolute value* is ~5×10^{33} cm^{-2} s^{-1}, which exceeds the nominal specification. Because we have not yet studied the beam lifetime, however, we have tried to find alternative solutions and to seek improvements in the performance by exploring alternative parameters that entail less blowup at the larger values of ξ_0. So far we have shown that:

(i) If the design is made more symmetric from the point of view of tune modulation due to synchrotron motion (*e.g.* by increasing $\beta^*_{x,y,+}$, or decreasing $\sigma_{\ell,+}$ appropriately), the beam blowup is smaller and the luminosity performance is better. However, we have not assessed the effect of the PCs in these cases.

(ii) The parameter $d/\sigma_{0x,+}$, which is a measure of the overlap of the beams at the first PC, is important in determining the luminosity performance because beam blowup has an almost step-function sensitivity to $d/\sigma_{0x,+}$. This parameter is also relevant to the lifetime performance.[15] The B Factory CDR specifications imply $d/\sigma_{0x,+}$ = 7.56. Our simulations for the working point (ν_x, ν_y) = (0.64, 0.57) show that the onset of substantial beam blowup as a function of $d/\sigma_{0x,+}$ is further away from the nominal value than for $(\nu_x, \nu_y) = (0.09, 0.05)$; therefore the working point above the half-integer is more comfortable in this respect. A more complete study is ongoing.

(iii) The luminosity performance is improved if the bunch spacing is increased from $2\lambda_{RF} = 1.26$ m to $3\lambda_{RF} = 1.89$ m with a concomitant increase in emittances and numbers of particles per bunch so that the total beam current, nominal beam parameters and nominal luminosity remain unchanged. The reason for this improvement is that, in this case, the parameter $d/\sigma_{0x,+}$ takes on the value 9.16, which is more comfortable than the CDR's 7.56.

(iv) Ongoing simulation studies show that the simplest horizontal injection scheme is probably quite acceptable. Alternatives are available should further work indicate the need to modify this simplest scheme.

(v) Simulations and analytic work show that luminosity performance requirements do not impose stringent tolerances on transverse or longitudinal collision offsets.

Other issues and approaches that are being considered now or will be in the near future include:

(i) A more complete tune scan.

(ii) Departures from transparency symmetry by introducing a slight asymmetry in the nominal beam parameters in such a way as to compensate the other asymmetries (for example, increase $\xi_{0,-}$ and decrease $\xi_{0,+}$). This approach is part of a more comprehensive study aimed at determining the beam-beam limit of the collider.

(iii) Effects of magnet nonlinearities in the simulations.

(iv) Beam lifetime studies.

(v) Effects of a slight horizontal crossing angle, so that the beams are farther apart at the first PC (this would require a more substantial IR redesign).

While many issues remain to be studied in detail, we are confident that we have a solution with good luminosity performance that meets the goal of 3×10^{33} cm^{-2} s^{-1}. This solution has acceptable behavior at injection and acceptable collision tolerances. It is likely that this solution, or a close variant, can reliably exceed the above value of the luminosity.

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8. References

1. *An Asymmetric B Factory Based on PEP: Conceptual Design Report,* LBL PUB-5303/SLAC-372/CALT-68-1715/UCRL-ID-106426/UC-IIRPA-91-01, Feb. 1991.

2. Y. H. Chin, in *Beam Dynamics Issues of High luminosity Asymmetric Collider Rings*, A. M. Sessler, ed., AIP Conf. Proc. **214**, 424 (1990); also Y. H. Chin, LBL-27665, 1989 (Proc. XIV Intl. Conf. on High Energy Accelerators, Tsukuba, Japan, August 1989).

3. J. L. Tennyson, in *Beam Dynamics Issues of High luminosity Asymmetric Collider Rings*, A. M. Sessler, ed., AIP Conf. Proc. **214**, 130 (1990).

4. M. A. Furman, ABC-25/ESG-0163, Jan. 1991.

5. M. Bassetti and G. A. Erskine, CERN-ISR-TH/80-06.

6. S. Krishnagopal and R. Siemann, in *Beam Dynamics Issues of High luminosity Asymmetric Collider Rings*, A. M. Sessler, ed., AIP Conf. Proc. **214**, 278 (1990), and *Phys. Rev.* **D41**, 2312 (1990).

7. D. Rice, in *Beam Dynamics Issues of High luminosity Asymmetric Collider Rings*, A. M. Sessler, ed., AIP Conf. Proc. **214**, 219 (1990); D. Rice, Proc. Third Advanced ICFA Beam Dynamics Workshop on Beam-Beam Effects in Circular Accelerators, Akademgorodok, Novosibirsk, USSR, 1989; J. T. Seeman, in *Nonlinear Dynamics Aspects of Particle Accelerators*, Proc. Joint US–CERN School on Particle Accelerators, Sardinia, Italy, M. Jowett, M. Month and S. Turner, eds., *Springer-Verlag Lecture Notes in Physics* **247**, 121 (1985).

8. J. L. Tennyson, ABC-29, June 1991.

9. J. L. Tennyson, ABC-28, June 1991.

10. Y. H. Chin, LBL-30701, May 1991, presented at the Particle Accelerator Conference, San Francisco, May 1991.

11. Y. H. Chin, unpublished results.

12. Y. H. Chin and J. L. Tennyson, unpublished results.

13. M. A. Furman, ABC-21/ESG-161, Jan. 1991; LBL-30833, May 1991, presented at the Particle Accelerator Conference, San Francisco, May 1991.

14. M. Sullivan, unpublished results.

15. D. Rice, Ref. 7.