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Beam-Beam Issues for High-Luminosity e^+e^- Colliders*

Miguel A. Furman†
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

ABSTRACT

We present a primarily non-technical review of beam-beam issues that are particularly relevant for the new generation of e^+e^- "factory" colliders.

1 Introduction

The new "factory" colliders DAΦNE [1)], KEKB [2)] and PEP-II [3)] are now being completed and will be commissioned during the course of 1998. These machines are optimized to explore in detail the physics of the decay products of one (or a few) hadronic resonances available through e^+e^- annihilation. The success of such an exploration demands a large number of events, which in turn demands high average luminosity and reliability of operation. The word "factory" is meant to emphasize these two requirements. The peak luminosity that these machines aim to achieve is on the scale 10^{33-34} cm^{-2}s^{-1}, more than an order of magnitude higher than in existing colliders. Thus, assuming an "experimental year" of 10^7 s, these machines are expected to deliver an integrated luminosity of 10–100 fb^{-1} per year.

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†MAFurman@lbl.gov

Factory collider designs call for beams with large number of closely-spaced bunches whose bunch current, emittances and beam-beam parameters are not qualitatively different from those of previous machines. Thus, while the luminosity per collision is comparable to that of first generation colliders, a high overall luminosity is achieved from the high repetition rate of the collisions.

In this article we will provide a broad, primarily non-technical, overview of the beam-beam issues facing the new factories. We shall draw upon the experience of existing or defunct machines, particularly CESR, LEP, DORIS-I, SPS, HERA and DCI, and on theoretical and simulation results.

2 Beam-beam parameters and luminosity

2.1 Basic definitions

For beams in separate rings, there are, in principle, four different beam-beam parameters: horizontal and vertical, one for each beam. If, say, a positron close to the center of its own bunch is displaced vertically by a small distance y, its vertical beam-beam parameter $\xi_{y,+}$ is defined by

$$\Delta y'_+ = -4\pi\xi_{y,+}\frac{y}{\beta^*_{y,+}} \tag{1}$$

where $\Delta y'_+$ is the deflection it experiences in the collision and $\beta^*_{y,+}$ is the optics function at the interaction point (IP). For bunches with gaussian transverse profiles having rms sizes $\sigma^*_\pm$ and bunch length σ_z small compared with β^*_y, $\xi_{y,+}$ is given by

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

where N is the number of particles per bunch, $r_e = e^2/mc^2 \simeq 2.82\times10^{-15}$ m is the classical radius of the electron, γ is the usual relativistic factor, and the subscripts $+$ and $-$ refer to the e^+ and e^- beams, resp. The three other beam-beam parameters are obtained from (2) by the substitutions $+\leftrightarrow-$ and/or $x\leftrightarrow y$.

If the bunches collide with a frequency f_c, the luminosity is

$$\mathcal{L} = f_c\frac{N_+N_-}{4\pi\sigma^*_x\sigma^*_y} \tag{3}$$

where, for simplicity, the conditions $\sigma^*_{x,+} = \sigma^*_{x,-} = \sigma^*_x$ and $\sigma^*_{y,+} = \sigma^*_{y,-} = \sigma^*_y$ are assumed to hold. If, in addition, the beam-beam parameters are pairwise equal, *i.e.*

$\xi_{x,+} = \xi_{x,-} = \xi_x$ and $\xi_{y,+} = \xi_{y,-} = \xi_y$, then the luminosity is conveniently written in the form

$$\mathcal{L}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}] = 2.167 \times 10^{34}(1+r)\xi_y \left(\frac{EI}{\beta_y^*}\right)_{+,-} \tag{4}$$

where β_y^* is in cm, E is the beam energy in Gev, I is the total beam current in A and $r = \sigma_y^*/\sigma_x^*$. The pairwise equality of the beam sizes and beam-beam parameters at the IP are part of the so-called "transparency symmetry," discussed in Sec. 4. The symbol $(\ )_{+,-}$ in Eq. (4) means that the enclosed parameters may be taken from either beam, on account of the transparency symmetry. It is important to note that ξ has an implicit dependence on I, E and other machine parameters.

2.2 Beam-beam limits

The beam-beam parameter and the luminosity pertain to the core of the particle distribution. The basic phenomenology of ξ, which has been observed in essentially all e^+e^- colliders [4, 5], can be stated as follows: as N increases starting from low values, the beam sizes σ at first remain constant. Formulas (2-4) then imply that ξ and $\mathcal{L}$ scale as N and N^2, resp. Beyond a threshold value of N, the σ's blow up linearly with N, hence ξ saturates at some value ξ_{lim} and $\mathcal{L}$ scales like N rather than N^2. This change in behavior has been called the "first beam-beam limit" [6], to distinguish it from the "second beam-beam limit," associated with poor beam lifetime, which is determined, in turn, by the large-amplitude tails of the particle distribution.[1]

The value of ξ_{lim} is in the range $\sim 0.03 - 0.06$ for all colliders. The precise value is machine dependent, and it typically increases in time as the machine matures and becomes better understood. In order to extract as much luminosity as possible, colliders are typically operated with N beyond the value where ξ first saturates to ξ_{lim}. Problems arising at larger N, such as excessive particle backgrounds due to increased beam blowup, poor lifetime, or instabilities, place a practical limit on the maximum achievable average luminosity. [7]

2.3 Some aspects of the beam-beam limit

It is probably fair to say that the first beam-beam limit is not well understood theoretically even within a given machine. [8] However, experimental and theoretical work indicates that several ingredients affect the beam-beam performance such as:

[1] Neither of which is a true limit in the mathematical sense.

incoherent and coherent resonances, bunch length effects, transverse and longitudinal bunch shape, radiation damping, beam energy, etc. [9, 10] The primary effect of the beam-beam interaction is a tune shift $\Delta\nu$ given by

$$\cos 2\pi(\nu + \Delta\nu) = \cos 2\pi\nu - 2\pi\xi \sin 2\pi\nu \qquad (5)$$

which shows that $\Delta\nu \simeq \xi$ unless the tune ν is very close to an integer or half-integer. The tune shift $\Delta\nu$ given by (5) pertains to a particle close to the bunch center. At large amplitudes the beam-beam force vanishes, hence these particles experience a vanishing tune shift. This implies that the beam-beam force leads to a tune *spread* of size $\sim \Delta\nu$ in addition to a tune shift. It is this tune spread that leads to a limitation in performance rather than the tune shift, since the spread cannot be compensated by (traditional) means.

2.4 Road to high luminosity

The fundamental objective of all e^+e^- colliders is to yield as many e^+e^- annihilation events as possible in a given period of time, subject to the constraint that the average number of such events per bunch crossing should not exceed a number of order unity. The figure of merit for this "incoherent quantum effect" is, of course, $\mathcal{L}$. However, when positron and electron bunches pass each other, the particles suffer deflections from the collective electromagnetic fields of the opposing bunch, which are characterized by ξ. Such "classical coherent effects" have a detrimental effect on the luminosity at high ξ. Ideally, one would like to have quantum effects without classical effects; unfortunately, nature does not easily allow achieving such an ideal. Indeed, Eq. (4) shows that $\mathcal{L} \propto \xi$, at least for gaussian beams.

Since E is fixed by the physics the machine is meant to explore, one is left with the parameters β_y^*, ξ, I, and r in Eq. (4) to try to obtain high $\mathcal{L}$. The parameter β_y^* is chosen as small as possible consistent with the requirement that $\sigma_z < \beta_y^*$ in order to avoid serious hourglass effects [12]. β_y^* is also constrained by magnet aperture requirements near the IP, and by chromaticity correction needs. [13] Since ξ is limited to $\xi_{\rm lim}$, schemes have been proposed to decouple, at least partially, $\mathcal{L}$ from ξ. One such scheme is the "compensation scheme," in which four bunches (two e^+ and two e^-) collide simultaneously at the IP. In this case the net transverse electromagnetic field seen by any given particle vanishes, hence $\xi = 0$. A related compensation scheme has been proposed for the Tevatron, [14] in which a counter-circulating electron beam would neutralize the proton beam. The four-beam scheme was tried at the collider DCI; [15] the beam-beam performance, however, turned out to be comparable to that of a conventional two-beam collider. The explanation for this disappointing performance seems to be that *coherent* beam-beam effects become more severe than in the conventional case owing to the absence of Landau damping provided by the incoherent tune spread. [16, 17]

It has been proposed to increase both ξ and r by using round beams, as discussed in Sec. 7 below. All three factories now being built, however, resort to increasing I by using beams with many closely-spaced bunches, each of which has rather conventional values for N, ξ and emittances. High $\mathcal{L}$ results from the high value of the collision frequency.

2.5 First and second generation factories

It may be of interest to compare the parameters for the new factories with those of the two most mature e^+e^- colliders, namely CESR and LEP. Table 1 shows the parameter values for these "first generation" factories. [18] Both machines have a common vacuum chamber for the e^+ and e^- beams, a relatively low number of bunches per beam k_B, and relatively low I. These values can be contrasted with those in Table 2, which shows parameters for the new factory colliders. It can be seen that N is lower in the new machines by a factor 2–4, but k_B and I are much higher than in the first generation.

Other second generation factories actively being investigated at Beijing [19], Novosibirsk [20] and Dubna [21] are e^+e^- colliders optimized for the study of τ leptons and charmed mesons (τ-charm factory, or "τcF") in the center-of-mass energy range 3–5 GeV. These machines have equal beam energies, separate chambers for the two beams, and also promise a luminosity in the 10^{33-34} cm^{-2}s^{-1} range. In order to study the J/ψ resonance in detail, these factories allow a monochromatization option (see Sec. 6) which leads to a much improved energy resolution over the conventional design. Table 3 lists selected parameters.

The combined features of large I and small bunch spacing s_B force the two beams to be contained in separate vacuum chambers in order to avoid excessive parasitic collisions, and present new demands for machine physics and technology such as: (a) Powerful feedback systems are required in order to control multibunch instabilities and to keep the beams in collision (single-ring constraints, which traditionally help keep the beams in collision, are absent in two-ring colliders). [23] (b) The interaction region (IR) design is more complicated than in first generation machines on account of the need for synchrotron radiation masking, prompt beam separation, avoiding trapped mode heating, etc. [13] In addition, B factories have unequal beam energies, which entail other issues, as discussed in Sec. 4.

The need for prompt separation of the two beams near the IP leads naturally to the desirability of a crossing angle. In Sec. 3 we discuss the possible effects from synchrobetatron resonances (SBRs) that arise from such a crossing angle. In the case of PEP-II, the present design corresponds to a first phase of operation, in which beams collide head-on and are separated magnetically in the horizontal plane, and the bunches fill every other bucket. In Sec. 5 we discuss issues related to the parasitic collisions experienced by the beams that arise from such a separation scheme. The PEP-II design allows for a future upgrade with nonzero crossing angle in which all buckets will be filled.

3 Crossing angle

In a configuration with horizontal beam crossing, the horizontal beam-beam kick experienced by a particle is of the form

$$\Delta x' = f(x + s\phi) \tag{6}$$

where x and s are the transverse and longitudinal displacements of the particle relative to its own bunch center, resp., and ϕ is the crossing half-angle. This formula shows that a crossing angle couples the transverse and longitudinal motions of the particle, potentially leading to detrimental SBRs. More precisely, when $\phi \neq 0$, resonances of the form $m\nu_x + n\nu_y = p$ acquire synchrotron sidebands, $m\nu_x + n\nu_y + k\nu_s = p$. As a result, there is less space in the tune plane in which to choose a good working point.

The figure of merit for SBRs that follows from the analysis of the kick (6) is not ϕ but rather the "normalized crossing angle," $\Phi = \phi\sigma_z/\sigma_x^*$. The value of Φ for first and second generation factories is listed in Tables 1, 2 and 3. Notable among these is the large value for KEK-B, $\Phi = 0.57$. SBRs were first identified at DORIS-I as the cause for poor lifetime [25]. In that case, the crossing was in the vertical plane, with $\Phi = 0.6$, $\nu_s = 0.034$ and $\xi = 0.01$. A rule of thumb was apparently set forth stating that good performance requires $\Phi \ll 1$. In fact, this rule of thumb now appears to be incomplete and overly pessimistic. At DORIS-I it was not the SBRs *per se* that led to the problem but rather a combination of SBRs plus a lack of a feedback system. This machine used a deliberate modulation of ν_y and ν_s to Landau-damp multibunch instabilities, and this modulation reduced the available space in the tune plane to the point that there was always one or two bunches straddling a resonance at any given time, hence the poor lifetime. [24]

More recent experience and simulation studies support the conclusion that a crossing angle is not necessarily detrimental. Operation of CESR with a crossing angle shows no significant degradation of lifetime. [26, 27] In this case, however, $\Phi = 0.085$ is rather small, so perhaps this is not a reliable indicator for larger Φ. Similar conclusions about the harmlessness of the SBRs were reached at the SPS. [28, 29] In this case, although $\Phi = 0.45$ was substantial, ν_s and ξ were small compared to typical values for e^+e^- colliders. Simulations for the LHC [30] show that SBRs are not expected to be a problem for $\Phi = 0.5$ but, as in the case of the SPS, ν_s and ξ are small.

Although at present there is no experimental confirmation that an e^+e^- factory can operate reliably with Φ, ξ and ν_s simultaneously large, recent simulations do support this conclusion. A computer code [31] based on the "strong-strong" simulation scheme, with a 6D symplectic beam-beam map [32] and a Lorentz boost to the frame where the beams collide head-on has been applied to carry out tune scans for KEK-B [33], DAΦNE [34] and BTCF [35]. The conclusion is that good performance can be achieved for these machines.

4 Transparency symmetry

In a two-ring collider, beam and optics parameters need not be identical in both rings. In particular, the e^+ and e^- beams in PEP-II and KEK-B have unequal energies. The purpose of this inequality is to impart a net velocity $v \simeq c/2$ to the center-of-mass system in order to improve the detection efficiency of certain B-meson decays. To restrict the available parameter space, it has been suggested [36, 37, 38] that parameters be chosen to mimic the situation in a symmetric collider. The "energy transparency" conditions adopted by designers of these colliders include: (i) pairwise equality of beam-beam parameters ($\xi_{x,+} = \xi_{x,-}$; $\xi_{y,+} = \xi_{y,-}$); (ii) pairwise equality of beam sizes ($\sigma^*_{x,+} = \sigma^*_{x,-}$; $\sigma^*_{y,+} = \sigma^*_{y,-}$); (iii) equality of tune modulation amplitudes associated with synchrotron oscillations ($(\sigma_z\nu_s/\beta^*_{x,y})_+ = (\sigma_z\nu_s/\beta^*_{x,y})_-$, where σ_z and ν_s are the rms bunch length and synchrotron tune, respectively); and sometimes (iv) the equality of radiation damping decrements for the two rings.

A more stringent set of conditions requires the pairwise equalities of the σ's, the ξ's, the three tunes and the β^*'s. [38] The only freedom left in this scheme is the trading off of E with N according to $(NE)_+ = (NE)_-$. This set of conditions was reached by requiring the same sets of single-particle beam-beam resonances for both beams.

There is no fundamental reason why transparency symmetry should lead to optimal performance. In fact, it has been argued that optimal performance requires a (weak) departure from transparency [11]. Issues outside the scope of the beam-beam interaction also have an impact on which transparency conditions should be adopted. The actual PEP-II and KEK-B designs only implement conditions (i) and (ii); the other two are only approximately satisfied. Simulations [2, 3] show that the beam-beam performance of asymmetric colliders with transparency symmetry is not different from that of a symmetric collider, and that luminosity performance varies smoothly as the parameters depart from exact transparency. A living proof of a successful asymmetric collider is provided by HERA, [39] which arguably embodies a more extreme case of asymmetry than the B factories mentioned here.

5 Parasitic collisions

In a single-ring collider collisions would occur in mid-arc, in addition to the IP, if the number of bunches is sufficiently large (typically more than a few). These unwanted parasitic collisions (PCs) are avoided by means of an orbit separation at the collision points. The rule of thumb from CESR and LEP is that the beam lifetime is adequately long if the minimum orbit separation d at the PCs is $> 10\sigma$ or so, where σ is here the local beam size.

Parasitic collisions also lead to a "long-range" tune shift. If the orbit separation is larger than a few σ's, this tune shift is $\Delta\nu_{PC} \propto \beta/d^2$, where β is the local optics function. Studies at CESR [27] for horizontally-separated beams at the PCs show that the beam lifetime does not correlate well with $\Delta\nu_{PC}$, but correlates well with the parameter

$$B = 10 I_b \sqrt{\sum_{\text{PCs}} \left(\frac{\beta_y \sigma_x^2}{d^2} \right)^2} \tag{7}$$

where I_b is the bunch current in mA, β_y is in m, and σ_x and d are in mm. The operational criterion for a minimum acceptable pretzel amplitude is that B should not exceed ~ 1. However, since B is not dimensionless, its physical interpretation is unclear, and so is its usefulness in extrapolating to other machines.

For closely-spaced bunches, there are unavoidable PCs in the new factory colliders near the IP, where the two beams share a common vacuum chamber. In the case of PEP-II, the IR design pays particular attention to the PCs since the beams collide head-on. [3] Each bunch experiences four PCs on either side of the IP. The strongest one is the one closest one to the IP, which contributes a vertical tune shift for the positron beam $\Delta\nu_{PC} = 0.004$ (the remaining tune shifts are much smaller). At this first PC the orbit separation is $\sim 12\sigma_x$, and simulations show that this separation is more than adequate to avoid significant beam blowup. Other issues arising from the PCs in PEP-II have been shown to be very mild. [40]

6 Monochromatization

The τcF's call for a "monochromatization option" in which the effective energy spread of the beams is substantially reduced, allowing the study of narrow resonances in much more detail than in the conventional case. Monochromatization is achieved with large vertical dispersion at the IP such that $D^*_{y,+} = -D^*_{y,-}$. The effective energy spread of the center of mass of any given colliding e^+e^- pair is reduced relative to the standard (zero dispersion) case [41, 42] by the "monochromatization factor"

$$\lambda = \sqrt{1 + (D^*_y \sigma_\epsilon)^2 / \beta^*_y \epsilon_y} \tag{8}$$

where $\sigma_\epsilon = \sigma_E/E$ is the relative energy spread of either beam. The dispersion is typically chosen in the range $D^*_y = 0.3 - 0.5$ m and $\lambda \sim 10$. The lattice designs of the τcF's are flexible in order to accommodate the standard as well as the monochromatization configurations. The factory-like constraints arising from multibunch operation, mentioned in Sec. 2.5, must be met.

For large D^*_y the particle dynamics must be re-examined even at the linear level in order to ensure 6D symplecticity, since the usual approximation of treating the synchrotron motion as a parametric rotation in longitudinal phase space is no longer adequate. Such an analysis has been carried out, [43] and its effect on beam-beam simulations investigated. As with a crossing angle, a nonzero dispersion at the IP implies the potential for SBRs. [24] The combination of the factory constraints and the beam-beam effect [44] strongly suggest that the beta-functions at the IP must satisfy $\beta^*_x \ll \beta^*_y$, *i.e.*, the opposite of the conventional case.

7 Round beams

Eq. (4) indicates that the factor $(1 + r)$ would yield a factor of ~ 2 increase in $\mathcal{L}$ for round relative to flat beams, assuming that β^*_y and ξ_y are the same in both cases. In addition, round-beam simulations suggest that the value of $\xi_{\rm lim}$ can reach ~ 0.1, roughly twice the value for flat beams. [45] A simple plausibility argument why this might be so is that, for round beams, the beam-beam force has a cylindrical symmetry and hence an additional conserved quantity [46] closely related to the angular momentum along the beam axis. This symmetry implies that the dynamics is effectively one-dimensional, which is inherently more stable than its two-dimensional counterpart. [47, 48] A scheme to decouple $\mathcal{L}$ from ξ is to use round hollow beams. [49] Implementing this scheme would be challenging for hadron beams, and probably impossible for e^+e^- colliders.

If, indeed, $\xi_{\rm lim,round} = 2\xi_{\rm lim,flat}$, Eq. (4) implies that round-beam optics becomes competitive with a flat-beam optics when $\beta^*_{\rm round} \leq 4\beta^*_{y,\rm flat}$. The challenge in this case is to produce small β^* in *both planes*, which brings up issues of chromaticity correction and synchrotron radiation masking in the IR. An example of round-beam optics is the NTCF design, [20] which calls for $\beta^* = 1$ cm and $\xi = 0.1$. One way to achieve round beams with conventional optics is to run the machine on the coupling resonance, $\nu_x = \nu_y$. A more robust mechanism calls for a "Möbius insertion" based on skew-quads. These magnets are positioned and powered such that they interchange β_x with β_y, thereby guaranteeing beam roundness. In this case, there is only one beta function and one chromaticity rather than two. A specific proposal for CESR is the subject of active research. [50]

An experiment at CESR with round beams (but not with the Möbius insertion) was carried out recently, achieving $\xi \simeq 0.09$ without significant degradation of lifetime. [51, 52] While this result is promising, it should be kept in mind that it was achieved with $\beta^*_x = \beta^*_y = 30$ cm, which was too large to yield substantial luminosity. Current plans call for installation of superconducting quads within a year in order to achieve smaller β^*.

8 Conclusions

Space limitations have prevented us from addressing recent progress in other issues related to the beam-beam interaction, such as observations of the dynamical beta function effect, [53, 54] new calculations of the renormalization of the $\sigma - \pi$ tune shift factor, [55] new simulation tools both for the beam core [56] and beam tails, [57], observations of beam tails, [58] etc. While these topics are not specifically related to the new generation of e^+e^- factories, it is probably true that much of the progress in these areas has been fueled by the current drive towards factory colliders.

Although beam-beam simulations have advanced significantly in the past 5 years or so, more ingredients need to be incorporated to make them more realistic, such as nonlinear lattice maps, PIC calculations with bunch length effects, current-dependent effects (which may lead to a distortion of the bunch shape due to wake fields), and errors such as jitter and off-center collisions. Ideally, beam-beam simulations should reach the point where they can actually *predict* the behavior of a collider, and eventually do better at optimizing its performance than an experienced operator.

A big push seems afoot for round beams. While the CESR experiment is encouraging, it remains to be proven that, all things considered, round beams represent a significant advantage over flat beams. If so, machine design optimization for round beams will certainly be the subject of future workshops such as this one.

The three premier second-generation factory colliders, DAΦNE, KEK-B and PEP-II, will be completed and commissioned during the course of 1998. Expectations are that beam-beam issues will not be particularly severe. If these machines prove that they can operate reliably at high luminosity as designed, they will set the stage for further developments on the luminosity frontier, such as τ-charm factories with new options such as monochromatization and polarized beams. A successful portfolio of such factories will enable a detailed exploration of a vital part of the standard model well into the next century, and perhaps lead to unexpected discoveries in so doing.

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Table 1: First generation factories parameters.

	CESR (present)	LEP94 (Z^0) [f]	LEP97 (W^+W^-) [i]
E [GeV]	5.3	45.6	91.5
C [m]	768.43	26658.87	26658.87
k_B	18 (9 trains of 2) [b]	8 [b]	4
N_{IP}	1	4 [a]	4 [a]
$\mathcal{L}$ [cm^{-2}s^{-1}]	4×10^{32}	2×10^{31} [h]	4.1×10^{31} [h]
ϕ [mrad] [j]	2.3	0	0
$\Phi(= \phi\sigma_z/\sigma_x^*)$	0.085	0	0
N [10^{10}]	15	16.7	27.8
I [mA]	170	2.4	2
ϵ_x [m–rad]	2.1×10^{-7} [c]	2.22×10^{-8} [c,d,g]	2.96×10^{-8} [c,d]
ϵ_y [m–rad]	6.1×10^{-9} [c]	2.94×10^{-10} [c,d]	2.32×10^{-10} [c,d]
β_x^* [cm]	125	200	200
β_y^* [cm]	1.89	5	5
σ_x^* [μm]	512	210	240
σ_y^* [μm]	10.7	3.8	3.1
ξ_x	0.029 [k]	0.037 [d]	0.023 [d]
ξ_y	0.04 [k]	0.051 [d]	0.058 [d]
h	1281	31320	31320
s_B [m]	$\sim 12.6 \times 84$ [ℓ]	3332.36	3332.36
σ_z [cm]	1.9	0.88	1.05
ν_x	10.53	90.28	90.28
ν_y	9.57	76.19	76.19
ν_s	0.054	0.085	0.107
τ_x [turns]	9125	680	56 ($J_x = 1.6$)
τ_y [turns]	9125	680	89 ($J_y = 1$)
τ_E [turns]	4563	340	64 ($J_E = 1.4$)

(a) beams vertically separated at the odd IPs (LEP has 8 possible IPs)
(b) pretzel separation in the arcs
(c) coupled
(d) unperturbed
(e) note that the $W^{\pm}$ mass is 80.33 GeV/c^2
(f) typical numbers for a good (not record-breaking) fill at time of maximum $\mathcal{L}$ at the Z^0
(g) emittance control wigglers on
(h) per IP
(i) best conditions achieved several times after tuning
(j) ϕ = half-crossing angle
(k) observed
(ℓ) 12.6 m within a train, 84 m between trains; pattern not uniform

Table 2: Second generation factories parameters.*

	DAΦNE	KEK-B	PEP-II
E [GeV]	0.51	3.5/8.0	3.1/9.0
C [m]	97.69	3016.26	2199.32
k_B	120 $^{(f)}$	5120 $^{(f)}$	1746 $^{(g)}$
N_{IP}	2	1	1
$\mathcal{L}$ [cm^{-2}s^{-1}]	5.3×10^{32} $^{(a)}$	1×10^{34}	3×10^{33} $^{(h)}$
ϕ [mrad] $^{(b)}$	10–15	11	0
$\Phi(= \phi\sigma_z/\sigma_x^*)$	0.15–0.23	0.57	0
N [10^{10}]	8.9	3.3/1.4	5.6/2.6
I [A]	5.2	2.6/1.1	2.1/1
ϵ_x [m–rad]	1×10^{-6}	1.8×10^{-8}	$6.1 \times 10^{-8}/4.6 \times 10^{-8}$
ϵ_y [m–rad] $^{(c)}$	1×10^{-8}	3.6×10^{-10}	$2.5 \times 10^{-9}/1.8 \times 10^{-9}$
β_x^* [cm]	450	33	37.5/50
β_y^* [cm]	4.5	1	1.5/2
σ_x^* [μm]	2000 $^{(d)}$	77	150
σ_y^* [μm]	20 $^{(d)}$	1.9	6
ξ_x	0.04	0.039	0.03
ξ_y	0.04	0.052	0.03
h	120	5120	3492
s_B [m]	0.814	0.59	1.26
σ_z [cm]	3	0.4	1
ν_x	5.09 or 4.53	45.52/45.08	38.57/24.62
ν_y	6.07 or 6.06	47.52/43.08	36.34/23.64
ν_s	0.012	0.01–0.02	0.037/0.052
τ_x [turns]	1.1×10^5	4572 $^{(e)}$/4572	7500/5000
τ_y [turns]	1.1×10^5	4572 $^{(e)}$/4572	7500/5000
τ_E [turns]	5.5×10^4	2286 $^{(e)}$/2286	3750/2500

* Parameters taken from various sources; some may not be current. There is no guarantee of consistency or performance. For KEK-B and PEP-II, the first number corresponds to the e^+ beam, the second to e^-; a single entry means a common value for both beams.

(a) per IP

(b) ϕ = half-crossing angle

(c) coupled

(d) unperturbed

(e) with LER wigglers turned on

(f) if all buckets filled

(g) every other bucket filled

(h) $\mathcal{L}$ will be higher in the ultimate configuration with all buckets filled and $\phi \neq 0$

Table 3: τ-charm factories parameters.*

	Beijing [(a)]	Novosibirsk	JINR [(e)]
E [GeV]	2	2.1	2
C [m]	385.447	773.036	377.8
k_B	86	95	30
N_{IP}	1	1	1
$\mathcal{L}$ [10^{33} cm^{-2}s^{-1}]	1 [(a)]	10	1
ϕ [mrad] [(b)]	5.2	0	0
$\Phi(=\phi\sigma_z/\sigma_x^*)$	0.13	0	0
N [10^{10}]	5.4	20	14.9
I [A]	0.57	1.12	0.57
ϵ_x [m–rad]	1.5×10^{-7}	1×10^{-7}	4.26×10^{-7}
ϵ_y [m–rad] [(c)]	2.3×10^{-9}	1×10^{-7}	
β_x^* [cm]	65	1	20
β_y^* [cm]	1	1	1
σ_x^* [μm]	315 [(d)]	32	290
σ_y^* [μm]	4.8 [(d)]	32	
ξ_x	0.04	0.1	0.04
ξ_y	0.04	0.1	0.04
h	612	1805	600
s_B [m]	4.48	8.14	12.6
σ_z [cm]	0.76	0.8	0.8
ν_x	11.8	29.077	
ν_y	12.6	31.077	
ν_s	0.068	0.012	0.077
τ_x [turns]	2.3×10^4	4.3×10^4	2.9×10^4
τ_y [turns]	2.3×10^4	4.3×10^4	1.7×10^4
τ_E [turns]	1.2×10^4	2.1×10^4	7.14×10^3

* Parameters taken from various sources; some may not be current. There is no guarantee of consistency or performance.

(a) "high luminosity mode"

(b) ϕ = half-crossing angle

(c) coupled

(d) unperturbed

(e) "standard scheme"