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Energy transparency and symmetries in the beam-beam interaction

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We have modified the beam-beam simulation code CBI to handle asymmetric beams and used it to look at energy transparency and symmetries in the beam-beam interaction. We find that even a small violation of energy transparency, or of the symmetry between the two beams, changes the character of the collective (coherent) motion; in particular, period-*n* oscillations are no longer seen. We speculate that the one-time observation of these oscillations at LEP, and the more ubiquitous observation of the flip-flop instability in colliders around the world, may be a consequence of breaking the symmetry between the electron and positron beams. We also apply this code to the asymmetric collider PEP-II, and find that for the nominal parameters of PEP-II, in particular, the nominal tune-shift parameter of $\xi_0 = 0.03$, there are no collective beam-beam issues. Collective quadrupole motion sets in only at $\xi_0 = 0.06$ and above, consistent with earlier observations for symmetric beams.

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I. INTRODUCTION

The code CBI (collective beam-beam interactions) is a self-consistent beam-beam code that models the transverse beam-beam dynamics of beams with arbitrary distribution and ellipticity. It is a particle-in-cell (PIC) code that calculates the beam-beam force on a two-dimensional (transverse) Cartesian grid. The code is evolving and, until recently, had the following features: (a) there is only one bunch per beam and there is only one collision point; (b) the beams are ultrarelativistic; (c) longitudinal dynamics is not modeled; (d) arc transport is linear; (e) radiation damping and fluctuations are put in once a turn and at one point in the ring; (f) there is no crossing angle; (g) transverse dimensions and distributions of the beams can be completely arbitrary. Details of the symmetric code can be found in Refs. [1,2].

The code as described above modeled only symmetric colliders. In order to model asymmetric colliders such as PEP-II it was necessary to generalize the code and allow for independent parameters for the two beams. This includes the energies, revolution frequencies, currents, emittances, beta functions, and damping rates, as well as simulation parameters such as the grid spacing and the number of grid points. At present, the number of simulation particles is constrained to be the same as in the two beams. The modified code was benchmarked in the symmetric limit by reproducing some of the results in Ref. [1].

II. NOMINAL PEP-II PARAMETERS

Design parameters for PEP-II are given in the second column of Table I. In the code, PEP-II was simulated with parameters close to, but not all identical with, the design parameters; these are given in the third column of Table I. There were two main deviations. One was that the "PEP-II" simulated in the code has an aspect ratio of 8:1 (instead of 33:1); as a consequence, the vertical emittance and horizontal beta function are different from that of the actual machine. The second deviation was that a damping time of 1000 turns was assumed, for both rings, even though the real damping times are almost an order of magnitude higher. Both were done to reduce the computational time. In both cases, the deviations make the beam-beam dynamics more benign, so that the simulations should give an upper bound on the allowable tune shift for PEP-II.

TABLE I. Parameters for PEP-II: design parameters (column 2) as well as those used in the simulations (column 3).

	Actual PEP-II value		Nominal "PEP-II" value	
Parameter	LER	HER	LER	HER
Energy (GeV)	3.1	9.0	3.1	9.0
Damping time (turns)	8000	5000	1000	1000
Horz. emittance (nm rad)	49.18	49.18	50.0	50.0
Vert. emittance (nm rad)	1.48	1.48	6.25	6.25
Horz. beta (cm)	50	50	12	12
Vert. beta (cm)	1.5	1.5	1.5	1.5
Horz. tune	0.57	0.57	0.57	0.57
Vert. tune	0.64	0.64	0.64	0.64
Nominal bunch current (mA)	1.3	0.45	1.3	0.40

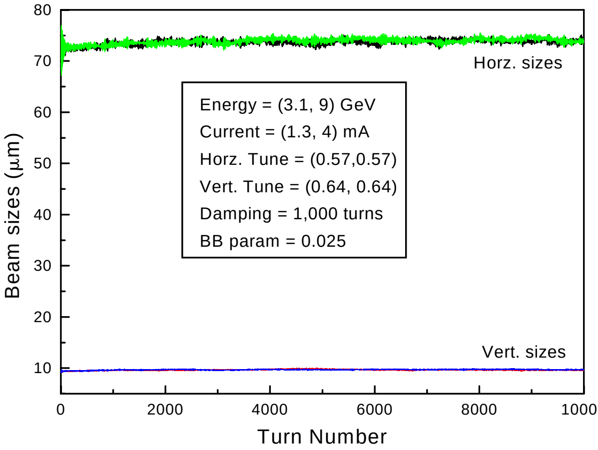

FIG. 1. (Color) Beam sizes as a function of turn number for "nominal" PEP-II parameters.

It is relevant to note here that PEP-II is supposed to operate under *energy transparent* conditions. Energy transparency is the condition that the beam-beam interaction in an asymmetric collider should be identical to that in a symmetric collider. Energy transparency conditions have been derived within the framework of single particle, i.e., incoherent, dynamics [3], and, in essence, demand that the energy asymmetry be compensated for by an equal and opposite asymmetry in the beam currents. Simulations of PEP-II have generally been under these conditions of energy transparency, and the consequences of violating these conditions have been only briefly explored before [4].

Figure 1 shows the beam size as a function of time for the nominal PEP-II simulation parameters (column 3 of Table I). It can be seen that for these parameters there are no collective effects, and there is only a slight incoherent blowup of the beam.

III. COLLECTIVE EFFECTS IN PEP-II

Next, an attempt was made to seek out the threshold for collective effects in PEP-II. In an earlier work [1] we have seen that collective effects (for a symmetric collider modeled on CESR) are seen at a tune of 0.79, at ξ_0 of around 0.06 and above. Two kinds of collective effects are seen: (a) *period-n oscillations*, in which the beam sizes of the two beams vary rapidly turn-by-turn in a fixed n-fold pattern, and (b) *flip-flop solutions*, in which the beams maintain steady but unequal sizes; one beam gets blown up to a very large size, while the other remains small. Which of the two dominates, and is the equilibrium solution, depends on the current and the tune.

For the present work, therefore, we chose to investigate the beam-beam dynamics with PEP-II parameters, at a tune of 0.79. The results are shown in Table II. It can be seen from the table that collective motion is seen only at a tune shift of 0.06 and above, consistent with the results for symmetric beams. It is interesting to note, however, that there is no sign of the period-n behavior that is seen in the symmetric case. The threshold for the onset of collective oscillations is around the same, $\xi_0 = 0.06$.

TABLE II. Equilibrium configuration after 10 000 turns (10 damping times). Energies are 3.1 and 9 GeV.

Nominal beam-beam parameter	Current (mA) [LEB, HEB]	Equilibrium collective behavior
0.024	[1.2, 0.4]	none
0.050	[2.4, 0.8]	none
0.060	[3, 1]	slight flip-flop
0.075	[3.6, 1.2]	flip-flop
0.078	[3.9, 1.3]	flip-flop
0.080	[4.2, 1.4]	flip-flop
0.090	[4.5, 1.5]	flip-flop
0.100	[4.8, 1.6]	flip-flop
0.105	[5.1, 1.7]	flip-flop
0.110	[5.4, 1.8]	flip-flop
0.124	[6, 2]	flip-flop
0.135	[6.6, 2.2]	flip-flop

IV. ENERGY TRANSPARENCY AND COLLECTIVE EFFECTS

In the data in Table II, the careful reader would have noticed that energy transparency is not strictly maintained; the ratio of the currents is exactly 3, whereas the ratio of the energies is around 2.9. The violation of energy transparency is slight, but, keeping in mind the fact that Table II does not show any period-n behavior, we decided to investigate this issue in greater depth. The particular question in mind was as follows: *Are period-n oscillations a consequence of having symmetric beams?*

To study this aspect, we repeated the runs of Table II, but with a LEB energy of 3 GeV, so that the ratio of the energies was also exactly 3. Results are shown in Table III. Except for the energy, all other parameters were identical for the data in Tables II and III.

TABLE III. Equilibrium configuration after 10 000 turns (10 damping times). Energies are 3 and 9 GeV, so that energy transparency is exactly maintained.

Nominal beam-beam parameter	Current (mA) [LEB, HEB]	Equilibrium collective behavior
0.062	[3, 1]	none
0.075	[3.6, 1.2]	flip-flop
0.090	[4.2, 1.4]	flip-flop
0.100	[4.8, 1.6]	flip-flop
0.106	[5.1, 1.7]	flip-flop
0.112	[5.4, 1.8]	flip-flop
0.118	[5.7, 1.9]	flip-flop
0.124	[6, 2]	period-n
0.127	[6.15, 2.05]	period-n
0.130	[6.3, 2.1]	flip-flop
0.137	[6.6, 2.2]	flip-flop

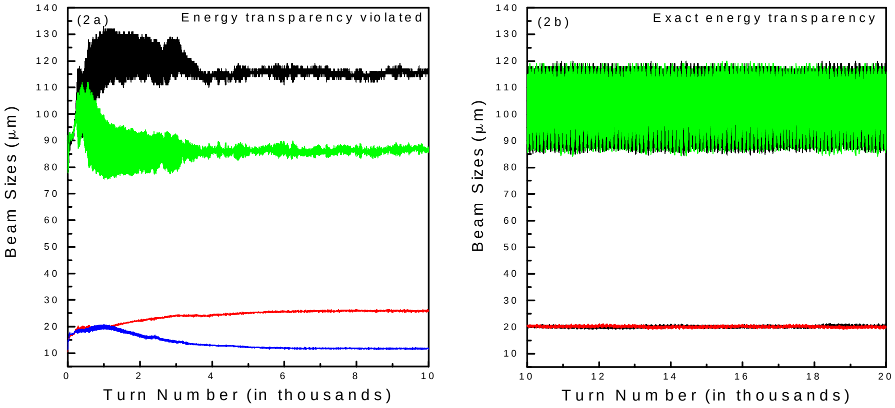

FIG. 2. (Color) Plots of beam size vs turn number for (a) energy $= (3.1, 9)$ GeV and (b) energy $= (3, 9)$ GeV. All other parameters identical. $\xi_0 = 0.124$.

It can be seen from Table III that for the case when exact energy transparency is maintained, period-n behavior *is* seen over a small range of ξ_0, after which the flip-flop again takes over as the equilibrium solution. The behavior, at least qualitatively, is exactly like that for symmetric beams [1].

Figure 2 shows a plot of beam size as a function of turn number, at the tune of 0.79 and $\xi_0 = 0.124$, for the case of exact energy transparency and when energy transparency is slightly violated (by around 3%). The difference in the equilibrium solution is evident. We have checked that in both cases the observed behavior remains for at least 40 000 turns (40 damping times).

V. BEAM SYMMETRY AND COLLECTIVE EFFECTS

The results of the previous section are interesting, and immediately bring to mind one question: Are such effects seen in symmetric colliders too? In an ideal symmetric collider, the two beams are exactly symmetric, but in an operational collider many small effects can break that symmetry. Besides, it is sometimes found, empirically, in the control room, that the best tuned up conditions for optimizing luminosity involve unequal currents in the two beams. The question then is as follows: *In symmetric colliders, does the breaking of the symmetry between the two beams affect the collective beam-beam dynamics?*

The present, asymmetric, version of CBI allows us to investigate the consequences of having slightly asymmetric parameters for the two beams, even in a collider that is nominally symmetric. We therefore investigated this issue for the symmetric collider with CESR-like parameters referred to earlier. We chose conditions of tune and current for which the equilibrium condition is a period-n solution [Fig. 3(a)]. We then broke the symmetry by making the currents very slightly asymmetric (by around 3%). As Fig. 3(b) shows, the equilibrium solution changes and is now a flip-flop.

VI. DISCUSSION

Our results here show that the character of collective beam-beam effects, in symmetric as well as asymmetric

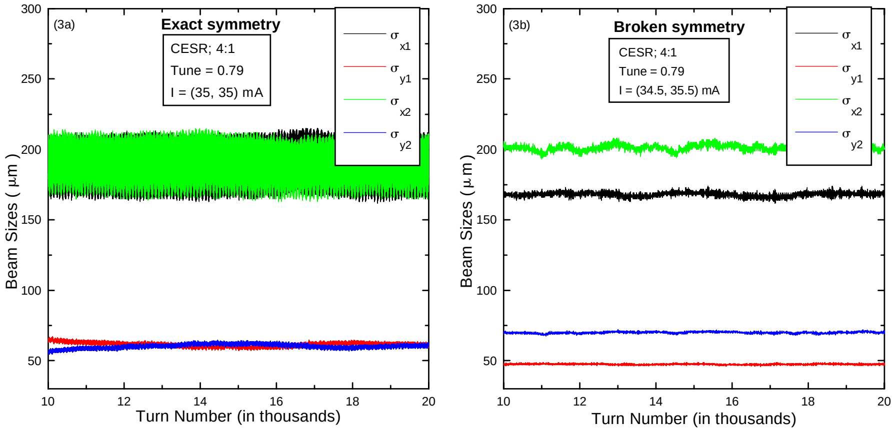

FIG. 3. (Color) For a symmetric collider with CESR-like parameters, plots of beam size vs turn number for (a) exact symmetry with a current of 35 mA in both beams and (b) broken symmetry, with unequal beam currents of 34.5 and 35.5 mA. Note that once the symmetry is broken the equilibrium solution changes from a period-n solution to the more ubiquitous flip-flop solution.

colliders, is strongly influenced by the symmetries in the problem. In particular, we find that if energy transparency, or the symmetry between the electron and positron beams, is violated even slightly, then the period-n oscillations disappear. This is true for both asymmetric as well as nominally symmetric colliders. The immediate question is whether this dependence on the symmetry is an artifact of the simulations or whether these results correctly represent the underlying dynamics. Certainly, flip-flop is widely seen in lepton colliders around the world, while period-n oscillations have been seen only once at LEP [5], and that observation has never been reproduced. However, our results would have to be confirmed by further simulations, preferably using a code that uses a different calculational algorithm, in order to rule out spurious simulation effects.

We would like to point out that experimental data for collective beam-beam effects are scant. In order to see period-n oscillations, or to authoritatively rule them out, one needs fast beam diagnostics that can image both beams turn-by-turn. To our knowledge that has been done only at LEP, where period-n oscillations were seen once. It may be that this data was taken at a time when, by design or accident, the collider was run with exact symmetry, and these observations were never reproduced because the collider was never run again in that mode. We very strongly urge a repetition of that experiment, with a careful attempt to run under conditions of exact and broken symmetry, before LEP shuts down later this year.

An important conclusion from these simulations, that is of direct relevance to PEP-II, is that there seem to be no surprises in the collective beam-beam dynamics as one goes from symmetric to asymmetric colliders. Collective effects are seen at around the same values of ξ_0 as for symmetric beams (above 0.06) and are of the same nature (flip-flop and period-n). For nominal PEP-II parameters, particularly $\xi_0 = 0.03$, these simulations suggest that the beam-beam dynamics is expected to be benign, and, in particular, collective beam-beam effects are not expected to play a role in limiting the luminosity.

The results obtained here raise the interesting question of whether better performance (larger ξ_0) can be obtained in asymmetric colliders by breaking energy transparency. This was also suggested in earlier work [6], though not in the context of *collective* beam-beam effects. Certainly, operating experience with PEP-II seems to indicate that there are no dangers in violating energy transparency, and our results here are consistent with that observation. This provides impetus for detailed simulations to explore "energy opaque" parameter space to look for conditions and operating points that could yield higher luminosity.

VII. CONCLUSIONS

In conclusion, we have extended our simulation code CBI to handle asymmetric beams. We find that there are no surprises in the collective (coherent) beam-beam dynamics as one goes from symmetric to asymmetric colliders. For nominal PEP-II parameters, particularly the nominal beam-beam parameter of $\xi_0 = 0.03$, we find no collective beam-beam effects. Collective effects are seen at ξ_0 of 0.06 and higher, in agreement with earlier results for symmetric beams. However, we find that collective beam-beam dynamics depends crucially on the symmetry in the machine. In particular, period-n oscillations are seen *only* for beams that are energy transparent. If energy transparency or beam symmetry is violated by even a small amount (3% in these simulations) then period-n oscillations disappear. We strongly urge an experimental study of this aspect at LEP. In future work we plan to study in greater detail the role of symmetries in collective beam-beam dynamics.

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