A Strong-Strong Simulation on the Beam-Beam Effect in a Linac/Ring B-Factory*

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Abstract

The beam-beam effect in a linac/ring B factory is studied here using strong-strong simulation based on a macro-particle model. Included in the ring dynamics are the linear betatron oscillation and synchrotron motion, as well as the transverse and longitudinal damping and quantum excitation. As a benchmarking test, the coherent quadruple effect in a ring/ring collider was observed by the simulation. The simulation shows that in a linac/ring collider, the stability of the storage ring bunch is strongly affected by the synchro-betatron coupling induced by the deep envelope modulation of the highly disrupted linac bunch. However, with the initial conditions for the linac bunch properly chosen, the beam-beam tune shift limit of the ring bunch can be made comparable with that for a ring/ring collider.

Introduction

The intrinsic nonlinearity in the beam-beam interaction sets a limit on the achievable beam-beam tune shift, which is typically around 0.06 for ring/ring colliders, above which the beam will start to blow up to larger equilibrium bunch sizes in a few damping times. This beam-beam effect is primarily responsible for the limitation on the observed luminosity. The idea of a linac/ring B factory is proposed[1] such that the e^+ beam is stored in a ring, and the e^- bunches in the linac are not recycled after each collision. It is expected that the limits on the beam-beam tune shifts for the e^- beam can then be loosened. However, at the required luminosity, the relatively low average-beam-current capability of linacs compared to a storage ring's implies low emittance[2] and hence leads to high disruption for the e^- beam. The beam-beam dynamics experienced by the positron bunch is therefore disparate from that in a ring/ring collider. Thus it is important to study the beam-beam tune shift limit for the e^+ beam in the linac/ring dynamical system.

Beam-Beam Interaction Model

In this study, the finite size macro-particle model[3, 4] is employed to simulate the beam-beam interaction in a strong-strong manner. This model does not impose any restriction on the charge distribution of the beams under study.

At the IR of an e^+e^- collider, the two relativistic beams exert Lorentz forces on each other only in the transverse directions. This allows us to divide each bunch longitudinally into many slices, with the width of a slice corresponding to the longitudinal step size over which the charged particles are advanced in the collisions. In the simulation, each slice is populated with macro-particles. The macro-particles in the two colliding beams experience mutual forces only when their corresponding slices overlap. For the simulation of interactions of elliptical beams, the macro-particles in a beam themselves have Gaussian charge distribution, with their aspect ratio comparable to the aspect ratio of the beam. The number and sizes of the macro-particles in each slice should be chosen to ensure sufficient overlap of the macros in order to suppress the collisional effect due to the finite number of macro-particles used in the simulation.

In the code, the force on each macro-particle is computed by direct Coulomb sum over the forces acting on the macro generated by all the macros in the overlapping slice of the approaching beam. The total luminosity is then obtained by the sum over the luminosity for each interaction pair at each time step[5]. Here, the electric fields on a two-dimensional grid, generated by a Gaussian macro-particle with given aspect ratio, are obtained in terms of the complex error functions[6] and stored in a table. The mutual force for each interaction pair of macros is then readily calculated by interpolating data from the lookup table. To properly describe the evolution of beam sizes with time, especially the pinching effect of the e^- beam from the linac, the sizes of the macros in each slice of a bunch are set to vary proportionally as the rms sizes of the slice evolve in each step of a collision. Here the ratio of the macro-particle size to the corresponding slice size is chosen to be $r = 0.5$. Smaller macro size has been used occasionally for error estimation. Simulation results are insensitive to the macro size as long as $r^2 \ll 1$.

A Benchmarking Test

The coherent quadruple beam-beam effect in a ring/ring collider is a proper candidate for the benchmarking of beam-beam simulation codes[7]. The phenomenon was predicted by Chao and Ruth using a linearized Vlasov equation, and was first observed by Krishnagopal and Siemann in beam-beam simulation. It has the remarkable feature that at tunes just below the quarter-integer, the beam distributions oscillate in an anti-correlated manner with period 2.

As a benchmarking test for our simulation, we use parameters shown in Table 1. Here the two beams are round in the transverse plane and have no longitudinal length. The anti-correlated oscillation of beam sizes with period 2 is clearly demonstrated in Fig. 1. Thses results agree well with the previous results[8] obtained using completely different simulation algorithms.

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Table 1: Parameter List in Simulation of Coherent Quadruple Effect as a Benchmarking Test

Energy (E_0)	5.3 GeV
Revolution Period (T_0)	2.56 μs
Transverse Emittances ($\epsilon_x = \epsilon_y$)	1×10^7 m
Amplitude Functions ($\beta_x^* = \beta_y^*$)	3 cm
Betatron Tunes ($Q_x = Q_y$)	0.72
Damping Decrement (δ)	1×10^{-3}
Current (I)	35 mA
Nominal Beam-Beam Parameter (ξ_0)	0.121
Number of Test Particles	300

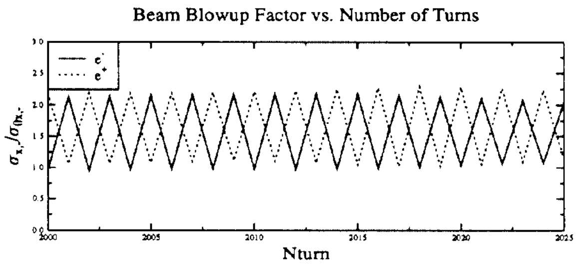

Figure 1: Results of coherent quadruple effect in a ring/ring collider with parameters given in Table 1.

Beam-Beam Effects in a Linac/Ring Scheme

The parameter list shown in Table 2 [9] is used in our simulation for the study of the beam-beam effect in a linac/ring colliding scheme. Notice that the proposed nominal luminosity is $\mathcal{L}_0 = 1 \times 10^{34}$, with the nominal vertical beam-beam tune shift for the e^+ beam being $\xi_{y+,0} = 0.056$ and the nominal vertical disruption parameter for the e^- beam being $D_{y-,0} = 273.7$. The simulation-related parameters are listed in Table 3.

In the simulation, the e^+ beam is circulated in the storage ring, experiencing beam-beam collisions at IP once a turn with a new e^- bunch. The ring dynamics includes linear betatron oscillations, synchrotron oscillations, as well as damping and diffusion in all three dimensions [10]. The initial distribution of macro-particles in the e^+ bunches is 3-D Gaussian with the nominal beam sizes. The precollision charge distributions for the e^- bunches are transversely Gaussian and longitudinally parabolic. In Fig. 2 we show the variation of the vertical rms size for each e^- slice through the e^+ bunch during the first collision. The formation of pinches when the e^- macros oscillate through the e^+ bunch can be clearly seen as the effect of the high disruption of the e^- beam. This will induce (1) stronger nonlinearity and (2) stronger synchro-betatron coupling compared to the case of a ring/ring collider. The consequent blowup of the vertical bunch size for the e^+ beam is shown in Fig. 3, which reaches an equilibrium value in about three damping times.

Table 2: Linac/Ring B-Factory Parameter List

Linac(e^-)	Storage Ring(e^+)
$E_- = 3.5$ GeV	$E_+ = 8.0$ GeV
$N_- = 0.544 \times 10^9$	$N_+ = 6.1 \times 10^{11}$
$f_c = 20.0$ MHz	$n_B = 30$
$\epsilon_{x-,0} = 5.75$ nm	$\epsilon_{x+,0} = 5.75$ nm
$\epsilon_{y-,0} = 0.37$ nm	$\epsilon_{y+,0} = 0.057$ nm
$\beta^*_{x-,0} = 3.32$ mm	$\beta^*_{x+,0} = 3.33$ mm
$\beta^*_{y-,0} = 3.33$ mm	$\beta^*_{y+,0} = 21.55$ mm
$\sigma^*_{x-,0} = 4.37\mu$m	$\sigma^*_{x+,0} = 4.37\mu$m
$\sigma^*_{y-,0} = 1.11\mu$m	$\sigma^*_{x+,0} = 1.11\mu$m
$\sigma_{z-} = 2.64$ mm	$\sigma_{z+} = 3.3$ mm
$D_{x-,0} = 69.6$	$\nu_s = 0.07$
$D_{y-,0} = 273.7$	$\tau_x = 0.9$ msec
	$\tau_y = 2.4$ msec
	$\tau_\delta = 6.9$ msec
	$\xi_{x+,0} = 0.002$
	$\xi_{y+,0} = 0.056$
$\mathcal{L}_0 = 1.1 \times 10^{34}\text{cm}^{-2}\text{sec}^{-1}$	

Table 3: Parameters for Simulation Model

	e^-	e^+
Number of Slices	9	45
Number of Macros	360	1000
Aspect Ratio of Macros	3.93	
Size of Macros	0.5 × beam sizes	

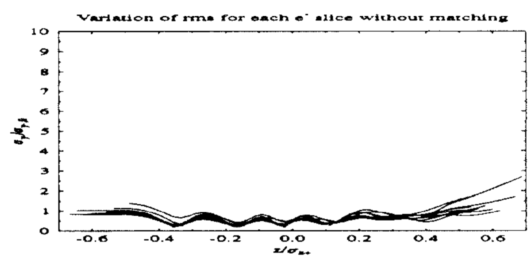

Figure 2: Variation of the vertical rms size for the e^- slices in the $y-z$ plane in the rest frame of the e^+ bunch *without* matching.

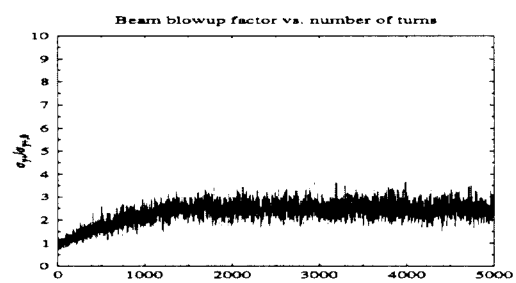

Figure 3: Beam blowup for the e^+ beam during 5000 turns for parameters in Table 2.

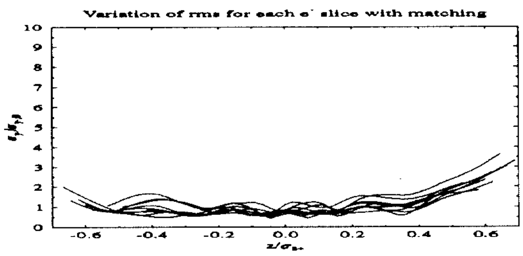

Figure 4: Variation of the vertical rms size for the e^- slices in the $y - z$ plane in the rest frame of the e^+ bunch *with* matching.

To reduce the effect of pinches, a matching scheme was developed by S. Heifets[9], where the transverse bunch sizes for the e^- and e^+ beam are set to be equal at IP and then the matched e^- bunches are tracked back to the beginning of the interaction region. The pre-collision phase space distribution of the e^- macros thus chosen allows the spreading out of the focusing points and produces a much smoother envelope distribution for the e^- bunches, as shown in Fig. 4. The long-term behavior of the e^+ beam, similar to that in Fig. 3, can also be obtained in the case of matching.

We then proceed to study the beam-beam effect for both matched and unmatched cases by varying $\xi_{y+,0}$ while fixing $D_{y-,0}$. The dependence of the equilibrium values of the beam blowup factor and the luminosity with respect to $\xi_{y+,0}$ is shown in Fig. 5. As shown in Fig. 5(a), for the non-matching case, the beam starts to blowup around $\xi_{y+,0} = 0.02$, whereas the blowup takes place around $\xi_{y+,0} = 0.05$ if matching applies. In Fig. 5(b), it is shown that for $\xi_{y+,0}$ above the value of 0.06, the luminosity in the matching case increases slowly with values larger than the saturated value in the non-matching case. The above comparison of the beam-beam effect with and without matching manifests the effect of envelope modulation of the e^- beam.

The above results are obtained for the fractional betatron tune $(Q_x, Q_y) = (0.64, 0.54)$ for the e^+ beam in the storage ring. Further investigation shows that for the high-disruption case without matching, the above beam blowup occurs over almost all the tune plane. This agrees with the results obtained by Gerasimov [11] using weak-strong simulation with envelope-modulated electron bunches.

Effect of Jitter

The effects of the white noise jitters for the linac beam has been estimated analytically[12] using a linear model, and simulated[13] using weak-strong simulation without damping. Previous results shows that the required jitter tolerences are at the margin of the precision of the measurement. Here the effect of 10% intensity jitter in the linac beam on the stability of the storage ring beam is also tested using our strong-strong simulation. With the inclusion of all the possible dynamics in the simulation, the predicted extremely unstable situation for the positron bunch is not observed.

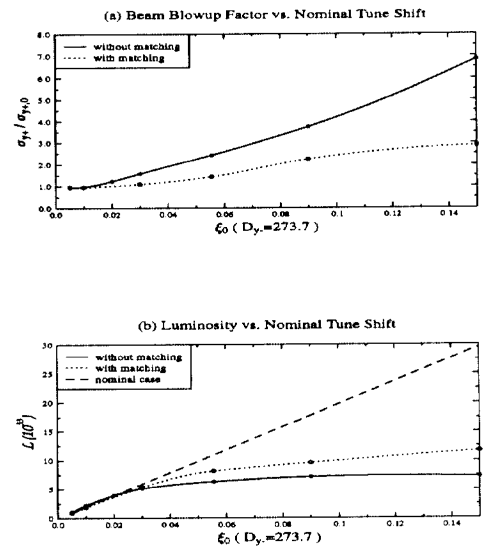

Figure 5: Results of beam-beam effect for a linac/ring B factory using parameters in Table 2. Here $\xi_{y+,0}$ is changed by varying only the electron current.

Acknowledgement

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