SIMULATIONS OF HIGH DISRUPTION COLLIDING BEAMS *

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Abstract

Recent B-factory proposals[1,2] that use a linac beam colliding with the beam from a storage ring to achieve high luminosities ($L > 10^{34}$ cm^{-2}sec^{-1}) result in very high disruption of the linac beam. The effects of such high disruption have been studied using the relativistic, 3-D code SWARM. We discuss the assumptions, parameters, and results of a series of runs that model such collisions. Regimes of high beam loss and methods to avoid them are also discussed.

Introduction

Colliding beam experiments using a positron beam stored in a storage ring require that the electrons do not destabilize the positrons because of the collision. This requirement is summarized in the constraint that the beam-beam tune shift of the stored positrons remains low. Most B-factory designs require the beam-beam tune shift to remain under ≤ 0.06.

In this study we investigated collisions where the positron bunch and the electron bunch have parameters typical of linac-storage ring B-factory designs. In the first section we discuss the assumptions of the model, the forces, and the luminosity calculations. In the second section we confirm the pinching discussed in Ref. 3. In the third section we discuss a matching procedure that reduces the pinching, and hence the beam-beam tune shift of the circulating positrons. These results show that large electron disruption may be consistent with small positron tune shift, a necessary condition to achieve high luminosity in "disruption assymetric" colliding beam B-Factories.

Basic Assumptions

There are six main assumptions made in this model:

1. The beams are relativistic.[4]
2. The bunches can be characterized by thin transverse slices randomly populated by groups of particles called macroparticles.
3. The force between two macroparticles is zero when the distance between them is zero, linearly increases to the "radius" of the macroparticle, and decreases as $1/r$ for distances greater than the radius.
4. When the bunches overlap, the force on any macroparticle in a given slice is the sum of forces from the macroparticles in the overlapping slice in the other bunch. That is, there are no interactions between macroparticles in non-overlapping slices because the beams are relativistic.
5. The total luminosity is the sum of the individual luminosities due to the collision of the individual macroparticles.
6. The charge distribution in the bunch is parabolic longitudinally and gaussian in both transverse dimensions.

Fig. 1 is a schematic of the model.

The impulse delivered between two relativistic point charges goes inversely as the impact parameter. If two relativistic distributions of charge interact, and they do not overlap spatially, likewise the total impulse delivered goes inversely with separation of the centers of the distributions. If the macroparticles represent distributions azimuthally symmetrical about their centers, by symmetry the impulse delivered vanishes linearly with the separation between the centers. Therefore, a force law between macroparticles consistent with both these limiting behaviors is:

$$F = \frac{ar}{(1 + br^2)} \tag{1}$$

where r is the distance between the centers of the macro particles, $b = 1/{\sigma_M}^2$, σ_M characterizes the radius of the macroparticle, and a is proportional to the macroparticle charge. The macroparticle radius σ_M provides a short distance cutoff, i. e., it reduces unphysical collisional diffusion due to short wave noise in the model, much as finite grids in more common PIC simulations smooth shortwave fluctuations. It is important that the results of a calculation be independent of σ_M for that calculation to be significant.

The total charge of the bunch is divided among the macroparticles in the following fashion: the longitudinal charge is parabolic about the center of the beam bunch and Gaussian in both transverse directions.

The initial coordinates of the macroparticles are random within each slice. At each step in the iteration, the position of each macroparticle is changed due to the integrated forces on that macroparticle.

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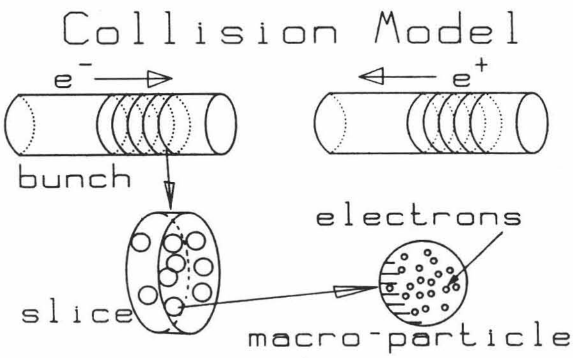

Fig. 1 The bunches are divided into slices, each slice has randomly distributed macroparticles containing the charged particles. The overall behavior of the particles in the bunch is approximated by the behavior of the macroparticles.

The luminosity is calculated by the evaluating the overlap integral:

$$L = f_c 2c \int n_1 n_2 dx dy dz dt \quad (2)$$

f_c is the collision frequency, c is the speed of light, n_1 and n_2 are the particle densities in the two bunches, and the integration is over the collision region and over the time of collision. If

$$n_i(\mathbf{x}) = \sum_j q_i n_{macro}(\mathbf{x} - \mathbf{x}_j) \quad (3)$$

where $n_{macro}(\mathbf{x})$ is the normalized macroparticle density function, and q_i is the number of particles per macroparticle. Eqn. 2 is evaluated by performing the sum:

$$L = \frac{f_c}{2\pi r_o} \sum_{ij} \sum_{nm} q_i q_j \frac{\alpha}{[1 + b(\mathbf{x}_n - \mathbf{x}_m)^2]^2} \quad (4)$$

where

$$\alpha = \frac{-2r_o b(1 + \beta_e \beta_p)}{(\beta_e + \beta_p)} \quad (5)$$

and r_o is the classical electron radius, β_e and β_p are v/c for the electrons and positrons, respectively, and the sum is over all macros in each overlapping slice and over all iteration steps as the bunches pass each other.

A relativistic collision code, SWARM, has been written to perform these calculations. The code models bunches in three dimensions, is vectorized, allows for large disruption parameters for the beams, and takes into account the finite length of the bunches. Particles in the bunches are tracked through the collision process. The code also calculates rms bunch sizes before, during, and after the collision along with the resulting luminosity. Although the code was written for asymmetric electron–positron colliding beams, it is applicable to any two relativistic colliding beams. A similar model has been used to discuss bunch dynamics at high disruption.[5]

Regimes of high beam loss

In an earlier 2-D model[3], individual electrons were tracked through a positron bunch. Here we report full 3-D calculations that track all the macroparticles in an electron bunch through the positron bunch.

These calculations confirm earlier results[3] that under certain conditions, the electron bunch pinches near the front of the positron bunch. Fig. 2 illustrates the effect. Positrons caught at the pinch point, which is stationary in the positron bunch, have a tune shift greater than 0.06. Therefore, if uncorrected, hard pinches would quickly destroy the positron bunch.

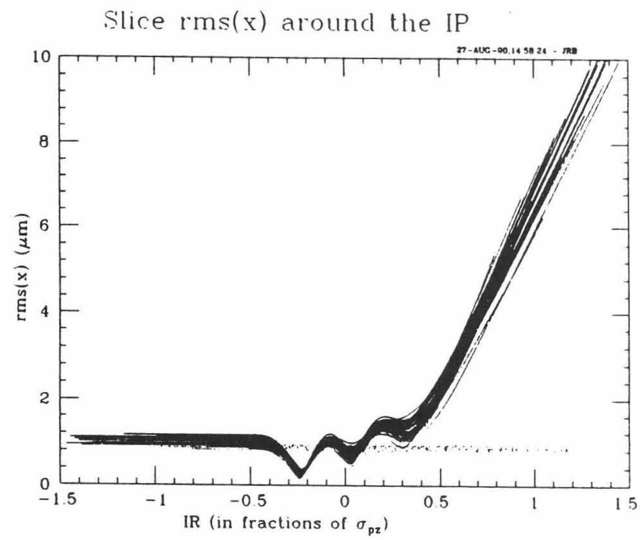

Fig. 2 The rms of the positions of all the macros in each slice is plotted relative to the center of the positron bunch. The solid lines are for electrons and the dotted lines are for the positrons (plotted relative to the center of the electron bunch). The narrow waist is the pinch discussed in the text.

Matching procedure to stabilize the beam

The matching procedure is the 3-D extension of the procedure used in Ref. 3. We assume that inside the central region of the collision process, electrons behave as if they are in a space charge lens. That is, the electrons are transported in the positron bunch in an adiabatic manner with a plasma frequency $k(s) = 1/\beta(s)$. The free parameter, z_{min}, marks the boundary of this central region. The matching requirement is that the bunch sizes of the two beams be the same at this z_{min}, i.e., that $\sigma_{ex} = \sigma_{px}$, $\sigma_{ey} = \sigma_{py}$.

Each slice in the electron bunch is populated at z_{min} with macroparticles that are then transported to "precollision" coordinates by free motion. In particular, the initial coordinates of each macroparticle are determined by:

$$x_e(-z_{min}) = \xi \sigma_{px} \left[\frac{D_{ex}}{2u} \sqrt{\frac{2}{\pi}} \right]^{\frac{1}{4}} \tag{6}$$

and

$$x'_e(-z_{min}) = \frac{\sigma_{px}}{\sigma_{pz}} \left[2uD_{ex} \sqrt{\frac{2}{\pi}} \right]^{\frac{1}{4}} (\eta - \xi/2) \tag{7}$$

where η and ξ are random numbers with a Gaussian distribution, the subscripts "px" and "pz" refer to the positron bunch coordinates x and z, z_{min} is the matching point, and $u = 2(z_{min}/\sigma_{pz})^2$. D_{ex} is the electron disruption in the x direction. Similar equations hold for the y direction.

Initial coordinates are found by applying free motion from the matching point to the starting point:

$$x_e(-L) = x(-z_{min}) - l x'_e(-z_{min}) \tag{8}$$

and

$$x'_e(-L) = x'_e(-z_{min}) \tag{9}$$

where we have defined $l = L - z_{min}$.

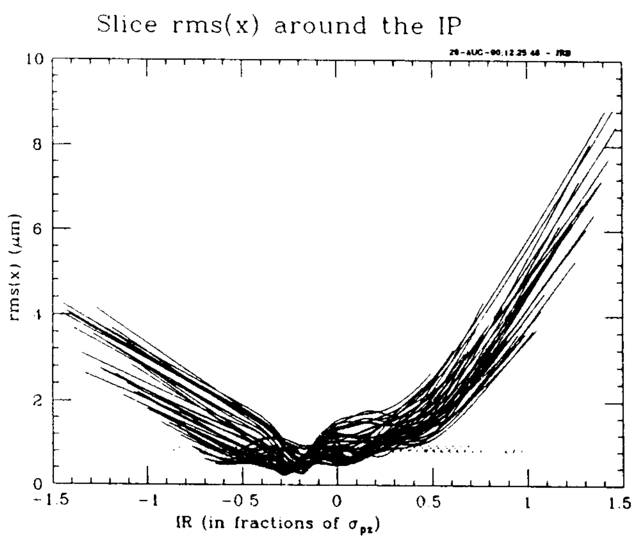

Fig. 3 The collision case shown in Fig. 2 was recalculated after applying the matching procedure discussed in the text. The nodes shown in Fig. 2 are smoothed out dramatically.

Results and Discussion

Results of applying the matching procedure to Fig. 2 are shown in Fig. 3. The nodes that were so clearly defined in Fig. 2 are smoothed out dramatically. The beam-beam tune shift on the positrons is reduced resulting in greater stability of the positron beam.

Figure 4 shows how the bunches appear just before collision. Note that the matching has effectively "pre-focused" the electron bunch, and that by so doing, the dissruptive pinch shown in Fig. 2, is reduced.

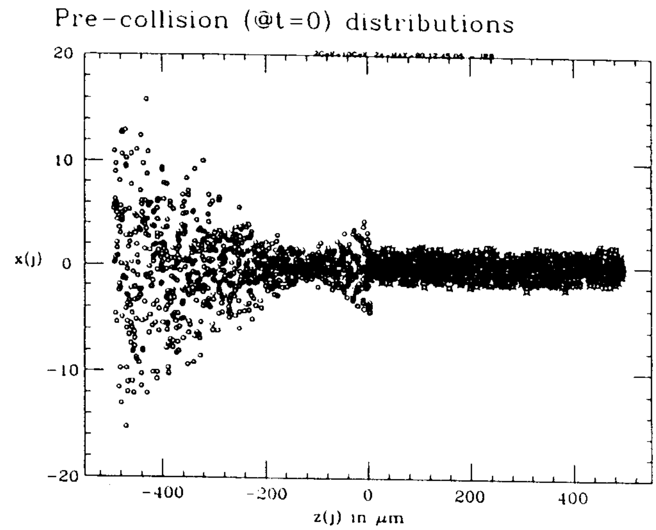

Fig. 4 The position of the negative macros (left of zero) and the positive macros (right of zero) just prior to the collision of the two bunches. The IP is at 0. Note the waist in the negative macro bunch. This "pre-focusing" is a result of the matching procedure.

Conclusion

We have studied colliding beams with high disruption using a "coulomb law" model. By matching, nodes in the disrupted electron bunch can be smoothed out if the electron bunch is properly shaped prior to the collision. Unfortunately, when matched, the enhancement factor is not large.

Further studies with better statistics, flat beams, and more realistic bunch parameters can now be undertaken.

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