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Studies of High Luminosity, High Disruption Beam-Beam Interactions

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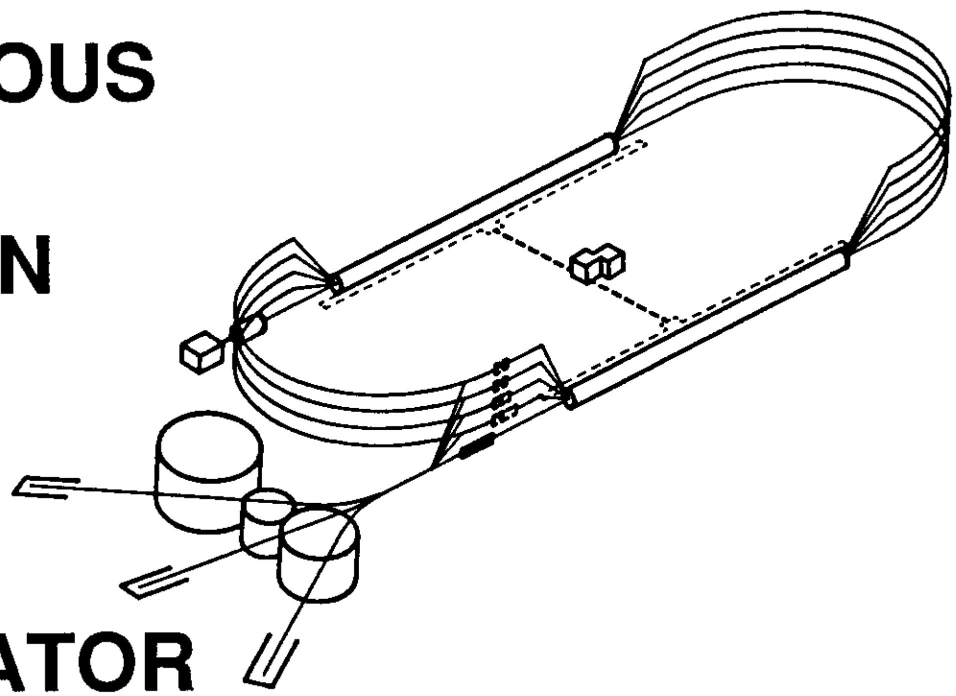

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STUDIES OF HIGH LUMINOSITY, HIGH DISRUPTION BEAM-BEAM INTERACTIONS*

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ABSTRACT

The e^+ e^- linac-on-ring collider concept requires special attention due to the highly asymmetric nature of the beam-beam interaction. A brief review of recent studies is presented followed by some specific offset collision studies. Luminosity as a function of offset is also presented.

INTRODUCTION

In conventional ring colliders a circulating positron beam collides with a circulating electron beam. Collisions must have low disruption for obvious reasons. Consequently, the positron bunch acts as a weak focusing lens for the electron bunch. The collisions are symmetric.

In linear collider designs, more charge is contained in each bunch with the result that colliding bunches each experience a stronger effective focus due to the other. Again the collisions are symmetric.

Linac-ring collider concepts[1,2], however, present quite an asymmetric problem: The positrons in one bunch experience a weak focusing effect from the electron bunch while electrons in the other bunch experience a very strong focusing effect due to the positrons.

The accelerators are asymmetric: linac for e^-, and storage ring for e^+; the number of particles in a bunch: 10^9 for e^-, and 10^{12} for e^+; the energy of the beams: 2 GeV for e^-, and 8 GeV for e^+; and the disruption of the beams: of order 100 for e^-, and less than 1 for e^+. Furthermore, this scheme is very useful for B-Factories because the Bs produced travel in the same direction of the positrons while the disrupted electrons travel in the opposite direction.

For the purpose of the studies reported here, only a brief description of the following is included: the collision model, the computer code SWARM[3], the individual charged particle tracking results, and the "matching" scheme used to reduce potential instabilities. More detailed discussion is found elsewhere[4,5,6]. Here the studies concentrate on the effects of collision offset on the collision process, the angular distribution of the disrupted electrons, and the luminosity.

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THE MODEL

The approach to working with this highly asymmetric problem was to develop a general purpose code that models the collision of two oppositely charged beams. SWARM is a 3-D code that can handle, for example, round or flat beams and energy spread within the beams.

The collision model[4] is based on the following assumptions:

1. The two beams are relativistic.
2. Bunches are characterized by transverse slices populated with clusters ("macroparticles").
3. The force between macroparticles is approximated by:

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

   where a is the constant containing the appropriate units, and b is the square of the inverse radius of the macroparticle.
4. During the collision only macros in overlapping slices experience the force.
5. The total luminosity is the sum of luminosities due to collision of individual macroparticles.
6. The charge distribution in bunches is parabolic longitudinally, and gaussian transversely.

Figure 1 is a schematic representation of the model.

Previously, this model was used to track individual electrons through a positron bunch[5]. The result showed dramatic foci within the positron bunch when the incident electrons were in a parallel beam. The same effect was also evident when the electrons were incident with more realistic trajectories. Such longitudinal concentration of electrons along the positron bunch indicates a fluctuating tune shift within the positron bunch. This could easily destroy the positron bunch within a short time if the collision frequency is in the MHz range, as many B-Factories propose.

This instability effect can be reduced, if not eliminated, by diffusing the foci if the electron bunch is properly matched to the positron bunch. Essentially the electron bunch is "pre-focused" prior to the collision such that electrons have different foci. Figure 2 summarizes the individual tracking studies.

These studies were extended from individual electrons to the full bunch configuration using the slice/macro model described above. Similar foci were observed and the matching technique was successful in smoothing out the foci[6].

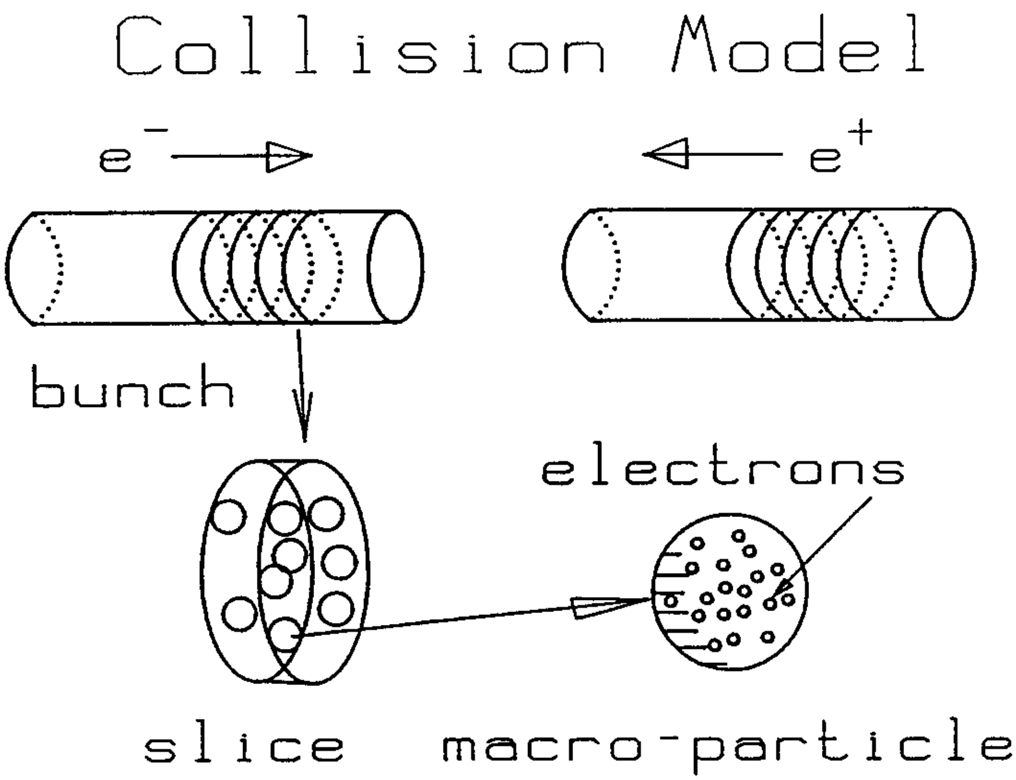


Figure 1. Colliding bunches are divided into slices, with each slice populated with a random distribution of macroparticles containing the charged particles. The overall behavior of the particles in the bunches is approximated by the behavior of the macroparticles.

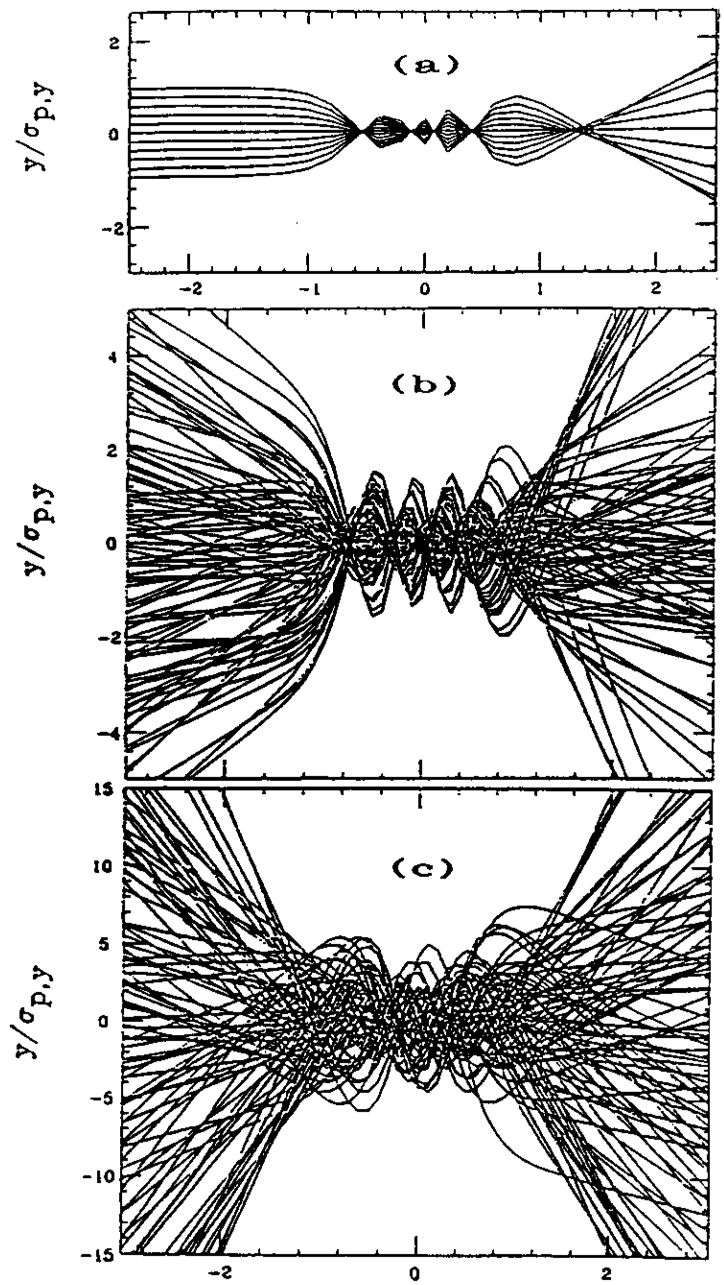


Figure 2. The trajectories of individual electrons traveling from left to right through a positron bunch are plotted with respect to the center of mass of the positron bunch. The positron bunch extends from -1 to +1 along the abscissa. (a) Individaul electrons with parallel trajectories colliding with a strong positron bunch exhibit localized pinching or foci. (b) Colliding electrons with more realistic pre-collision trajectories also show the pinching effects, though not as strong. (c) Electron trajectories after bunch optics have been "matched" according to the procedure discussed in Ref. 5. The foci have been reduced significantly.

OFFSET STUDIES

All of the studies to date were with head on collisions. The effects of offset were investigated and are reported here. For these studies, the two bunches were 1 micron size round bunches of 0.5 mm in length. Two sets of calculations were performed: one with matching and one without.

Figures 3 and 4 show the base set of calculations; i.e., head on collision with no matching. Figure 3a is the pre-collision distribution of both positive and negative macroparticles about the interaction point, ez=0.0. Figure 3b shows the tracking of the tracking of the tenth macroparticle in each slice plotted in the rest frame of the positron bunch as it traverses the positive bunch. Figure 4a shows the tracking of the average x of all macro particles for each slice, again plotted in the rest frame of the positive bunch. And finally, Figure 4b plots the trace of the slice rms (x) in the rest frame of the positrons. It is clear from these figures that there is at least one strong focus which would tend to disrupt the positron bunch with repeated collisions.

Figures 5 and 6. show the results of two different offset calculations. Figure 5a and 5b are for x and y offsets of one sigma. Figure 6a and 6b are for x and y offsets of two sigma. No matching was attempted for these calculations. Figure 7 and 8 are for the same conditions as for Figures 5 and 6 but matching was included.

The angle of the disrupted electrons is obviously needed for input to any detector design where the background due to electrons must be kept to a minimum. The code SWARM bins the resulting angles of the negative macroparticles after emerging from the positive bunch. Figures 9 and 10 show these results. The only conclusion that can be made from these plots is that further studies with more realistic beam sizes and better statistics are needed before any detector design is attempted.

Finally, the luminosity for each of the collision cases was calculated and is shown in Figure 11. Three plots are shown. There is clear degradation of the luminosity due to offset but it is not as severe as some might imagine. (For all of these cases, the standard method of calculating luminosity yields 4×10^{34} cm^{-2}sec^{-1}.)

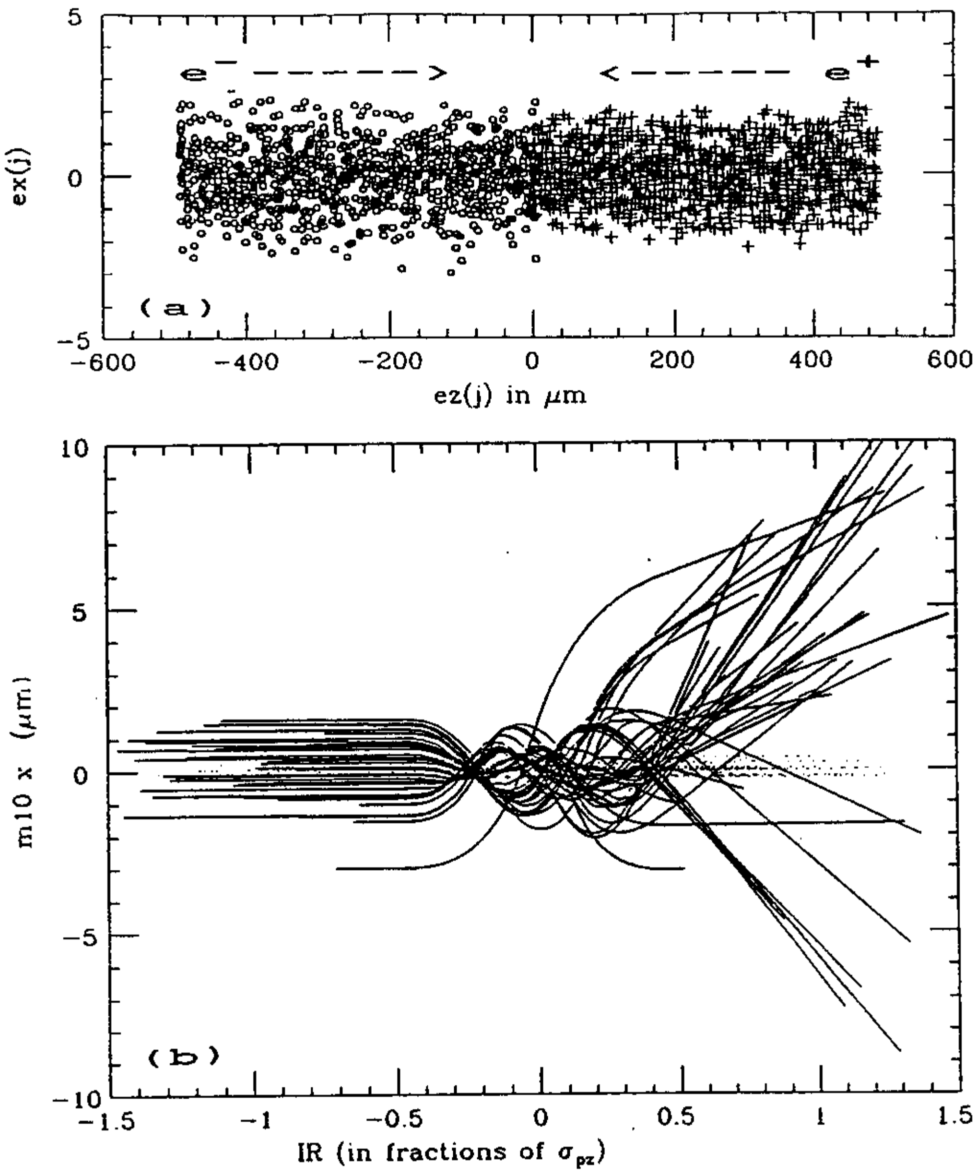


Figure 3. (a) The pre-collision location of two round bunches that are 1 micron in radius and 500 microns in length and that are colliding with no offset. The Interaction Point (IP) is at ez = 0. The electron bunch has not be matched. (b) The trajectory of the tenth macroparticle in each slice for the bunches shown in Fig. 3 is plotted relative to the rest fram of the positron bunch as the bunches collide. The ordinate is the transverse coordinate of the macroparticle in microns and the abscissa is in fractions of the positron bunch length. Electrons are traveling from left to right. At least one strong focus is evident. This is the base line collision.

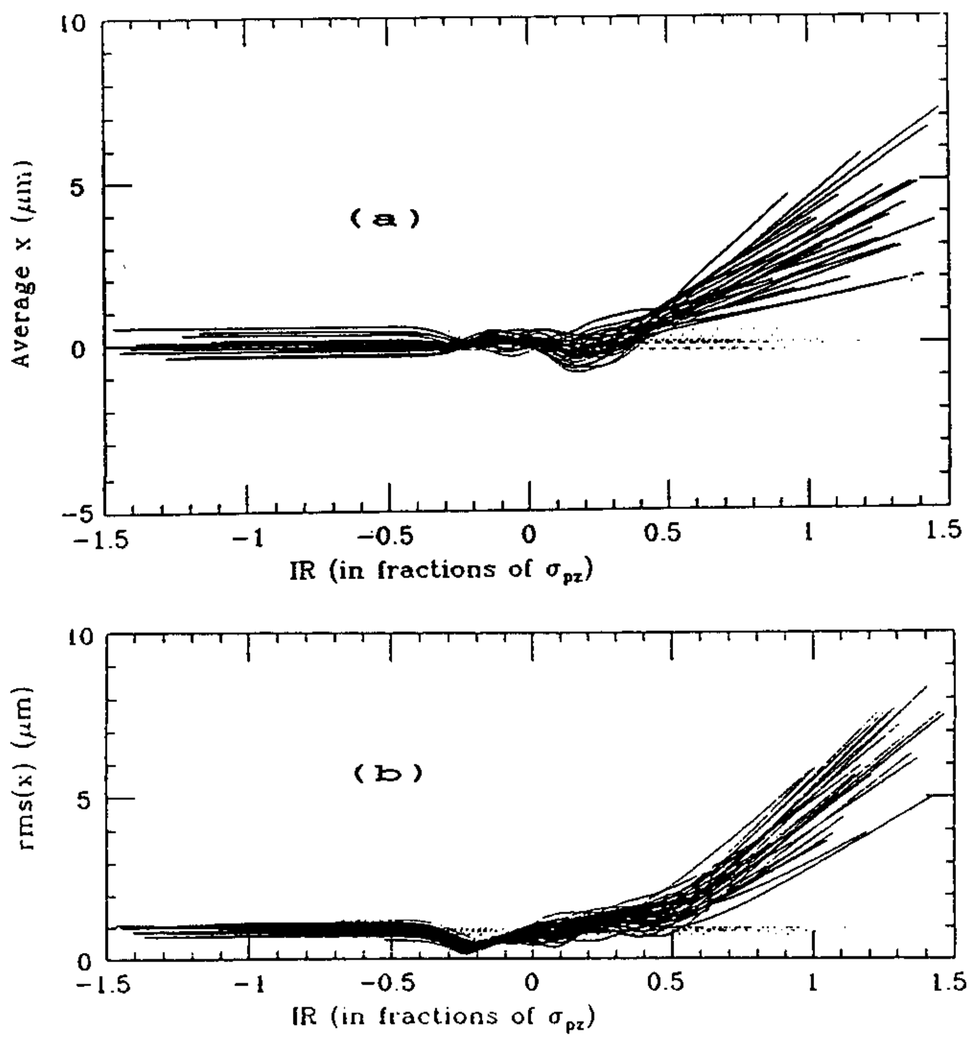


Figure 4. (a) The trace of the average of the x coordinates for all macroparticles in each slice is plotted through the base line collision in the rest frame of the positron. (b) A different view of the base line collision is shown by the trace of the rms of the x coordinate for all macroparticles in each slice plotted in the rest fram of the positron bunch.

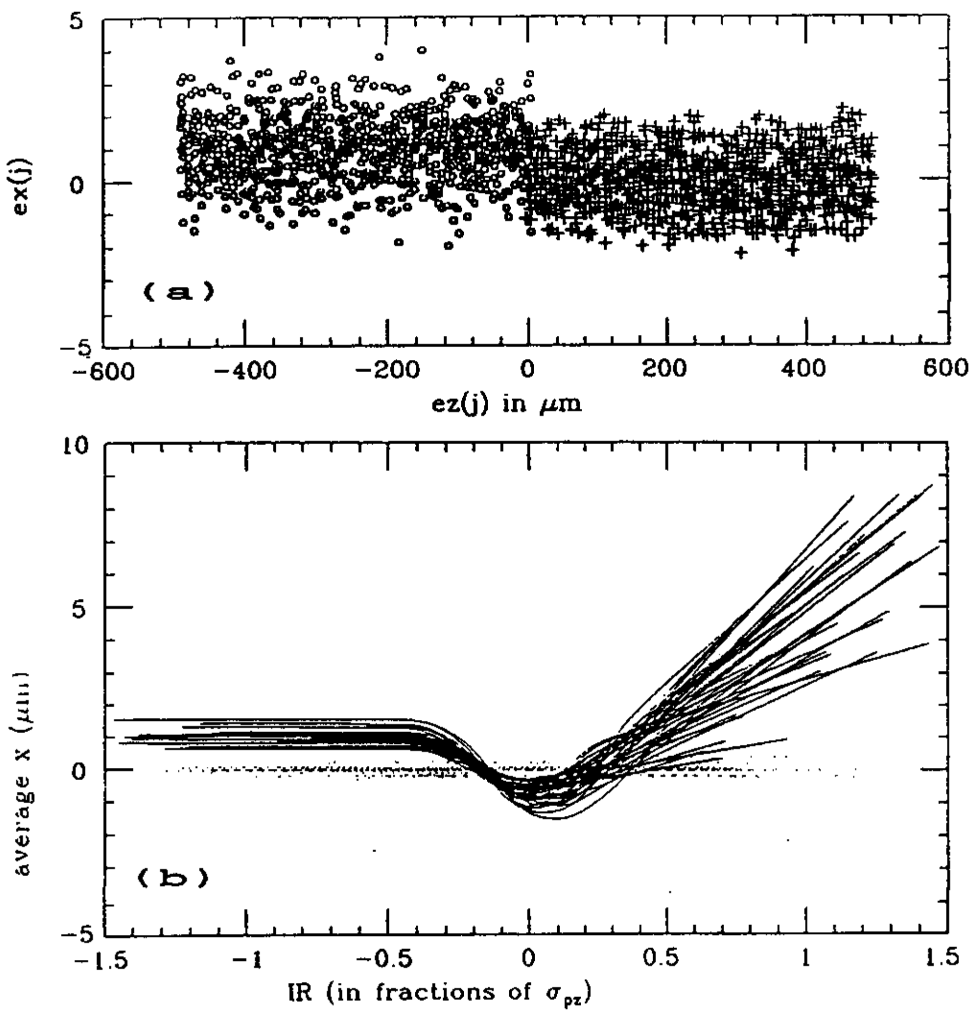


Figure 5. (a) Pre-collision positions for offset of 1.41 sigma (one sigma in x and one sigma in y). (b) Average of x coordinates for each slice traced through the collision. The dotted horizontal lines are the equivalent traces for slices in the positive bunch and plotted in the rest frame of the electron bunch.

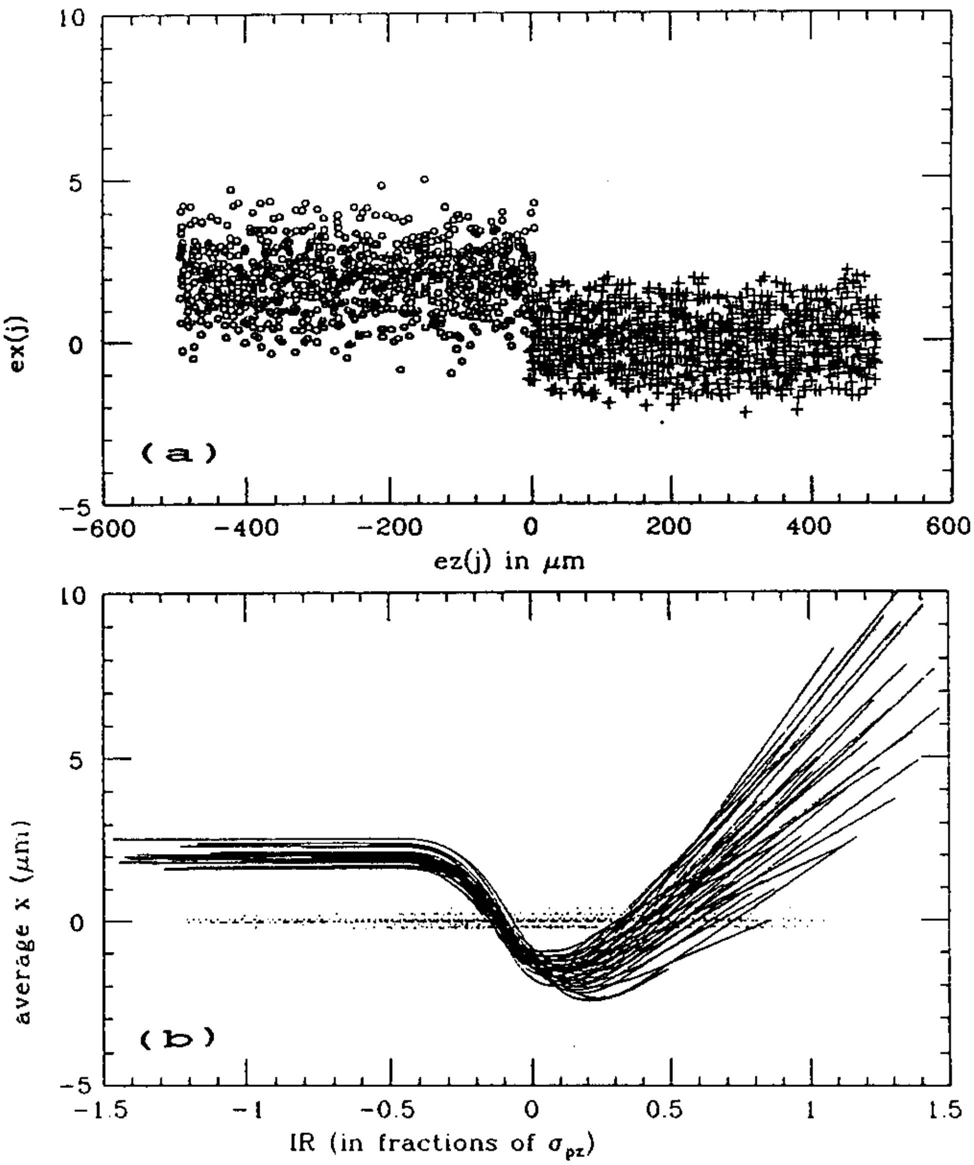


Figure 6. These plots are for the base line case with an offset of 2.83 sigma. (a) Pre-collision positions of the macro particles. (b) Trace of rms (x) of each slice plotted in the rest frame of the positron bunch.

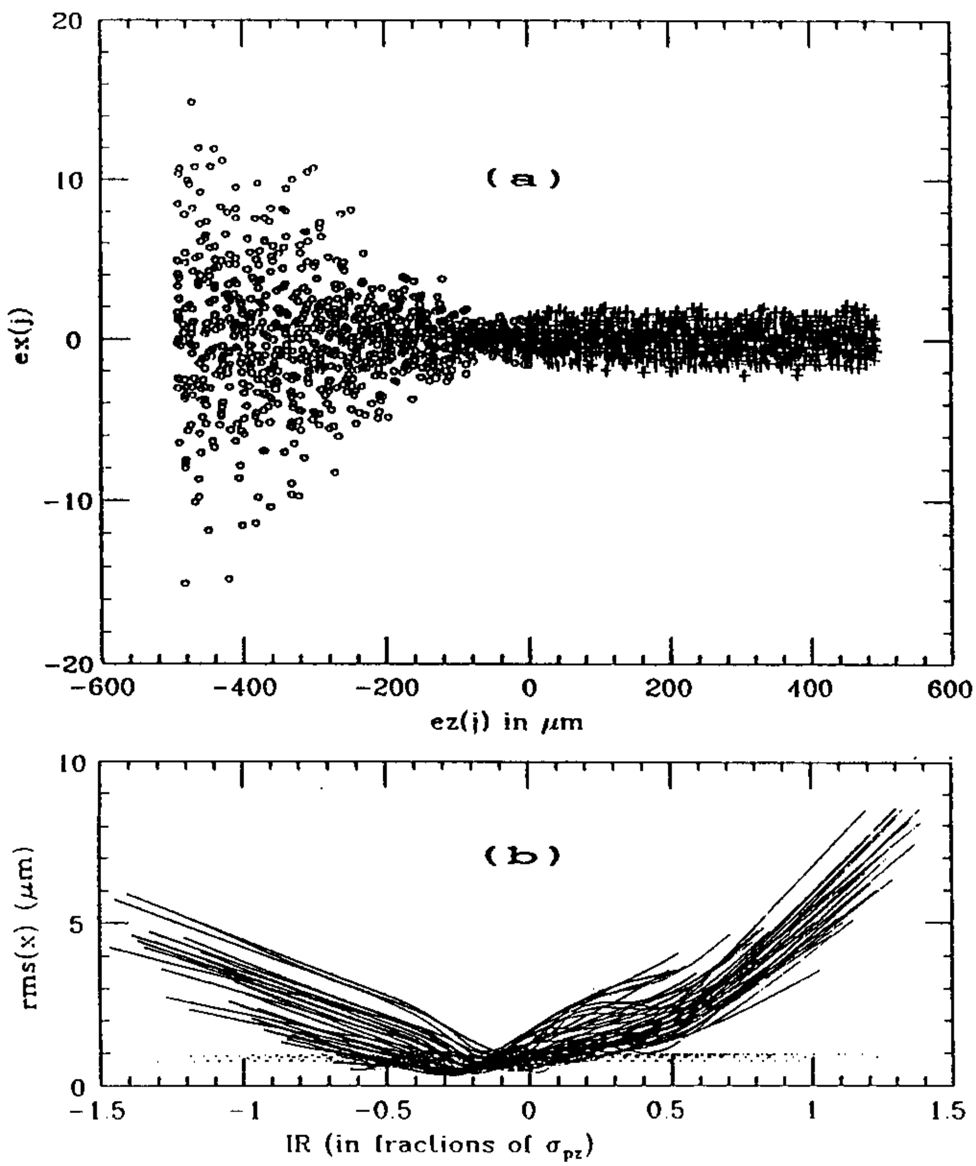
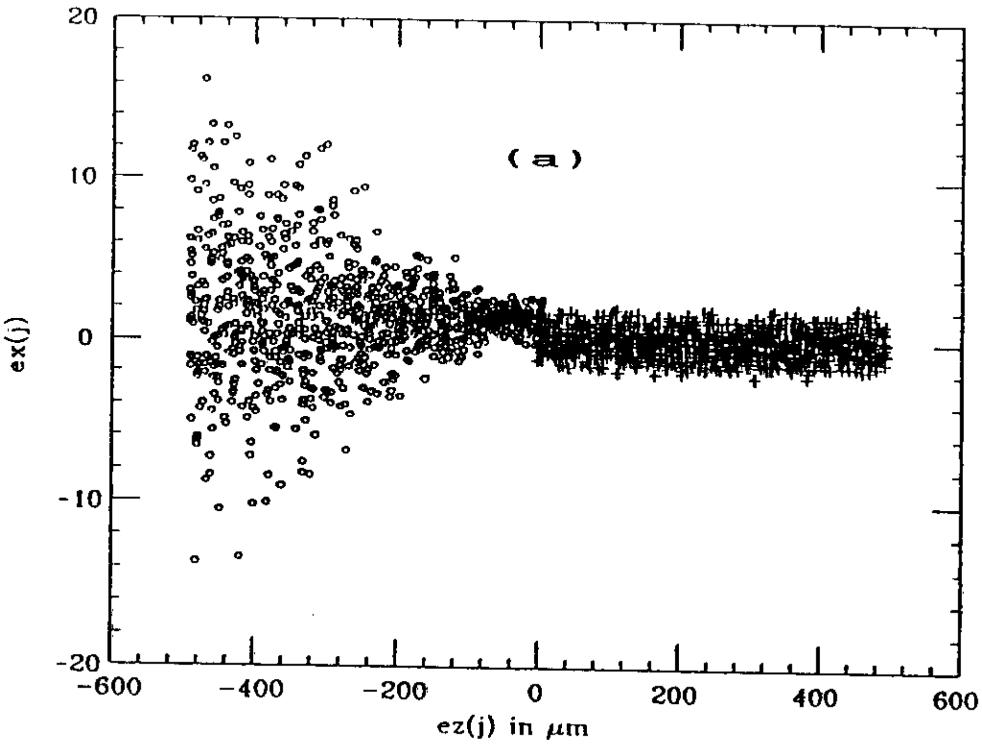


Figure 7. These plots are the result of applying matching to the base line, head on collisions. (a) Pre-collision positions of the macro particles. (b) Trace of rms (x) of each slice plotted in the rest frame of the positron bunch.



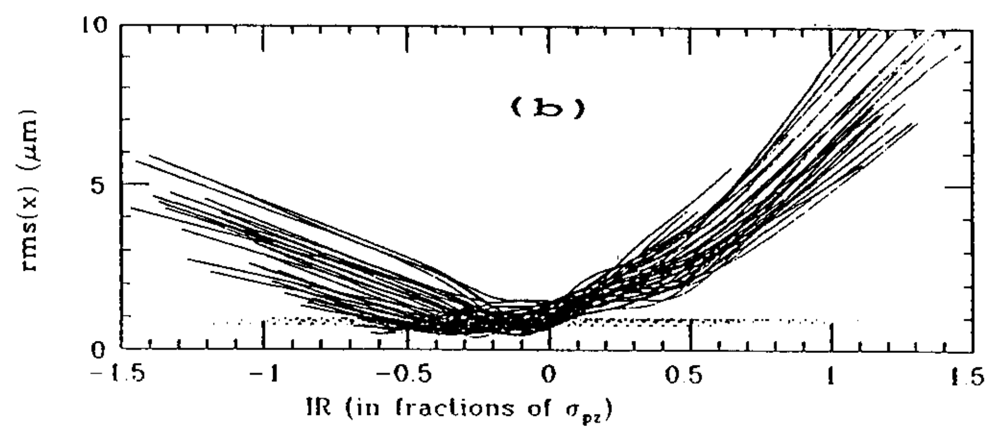


Figure 8. These plots are for the same conditions as Figure 7, but with an offset of 2.83 sigma. (a) Pre-collision positions of the macro particles. (b) Trace of rms (x) of each slice plotted in the rest frame of the positron bunch.

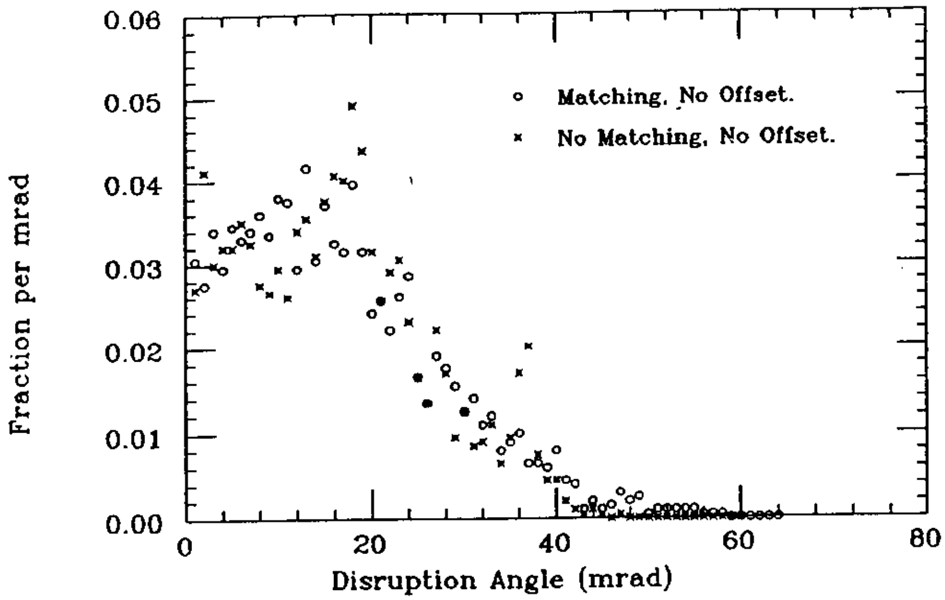


Figure 9. The angle that each macroparticle takes with respect to the centerline was binned in one mrad bins to obtain these angular distributions of the disrupted electrons. The data are somewhat ragged due to statistics – only 2000 macroparticles in each bunch. Here the comparison is between head-on-collisions with and without applying the matching procedure. Matching does not seem to improve the angular distributions.

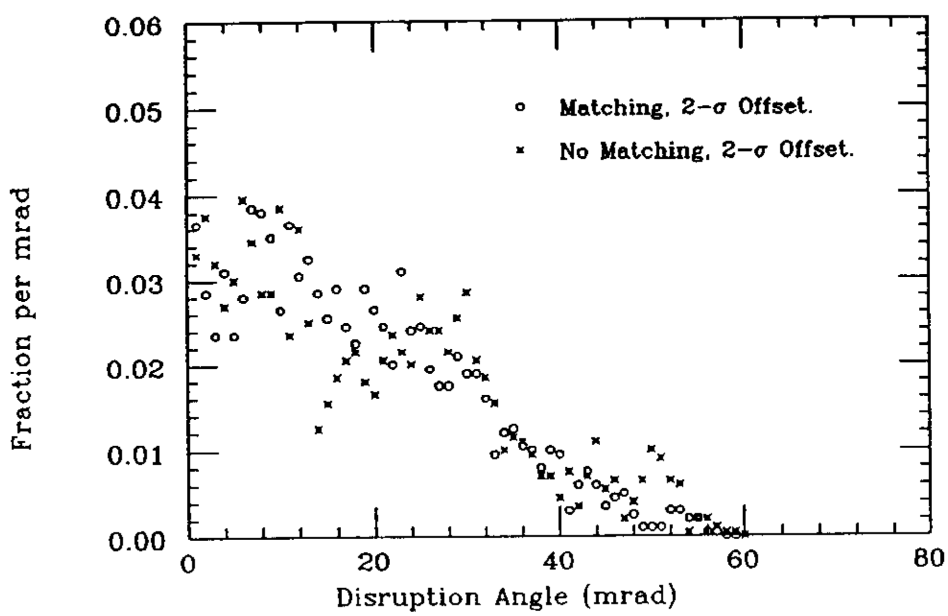


Figure 10. Disrupted electron bunch angular distributions for the two cases of 2.83 sigma offset: one with and one without matching.

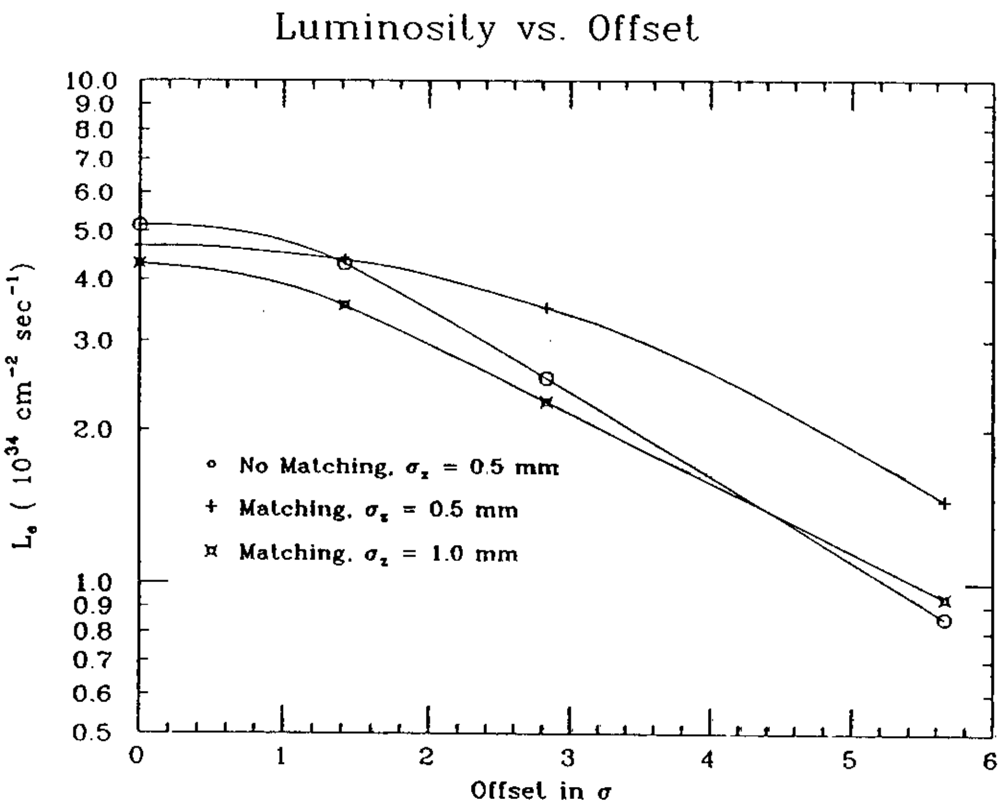


Figure 11. The luminosity of the offset collisions is plotted as a function of offset for three cases: 1) Matching is not applied to the problem; 2) Matching is applied; and 3) Matching is applied and the length of the bunches is increased from the base case of 5 mm to 1.0 mm.

DISCUSSION AND CONCLUSIONS

The problem of asymmetric colliding beams of positrons and electrons has been modeled and incorporated into a general purpose code SWARM. Investigations with this model and code have revealed new possible instabilities to stored beam. A method to mitigate the instabilities has been developed and incorporated into the code.

SWARM is fully operational on two machines: An HP workstation where the main function of the code is macroparticle tracking, and a VAX computer where the main function is slice tracking, angular distribution, and luminosity. In progress is a version that incorporates multiple passes of a ring where the collision is followed by a matrix calculation that transports the positron bunch around the ring for the next collision. This ring incorporation version is on a CRAY.

In these studies we have shown the effects of offset on the collision process in disrupted beam angular distribution and in final luminosity values. The results are encouraging but clearly not definitive. More studies must be conducted.

One final remark must be made. No model or code will substitute for a good high disruption experiment!

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