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A BEAM-BEAM SIMULATION FOR THE SINGLE-PASS COLLIDER

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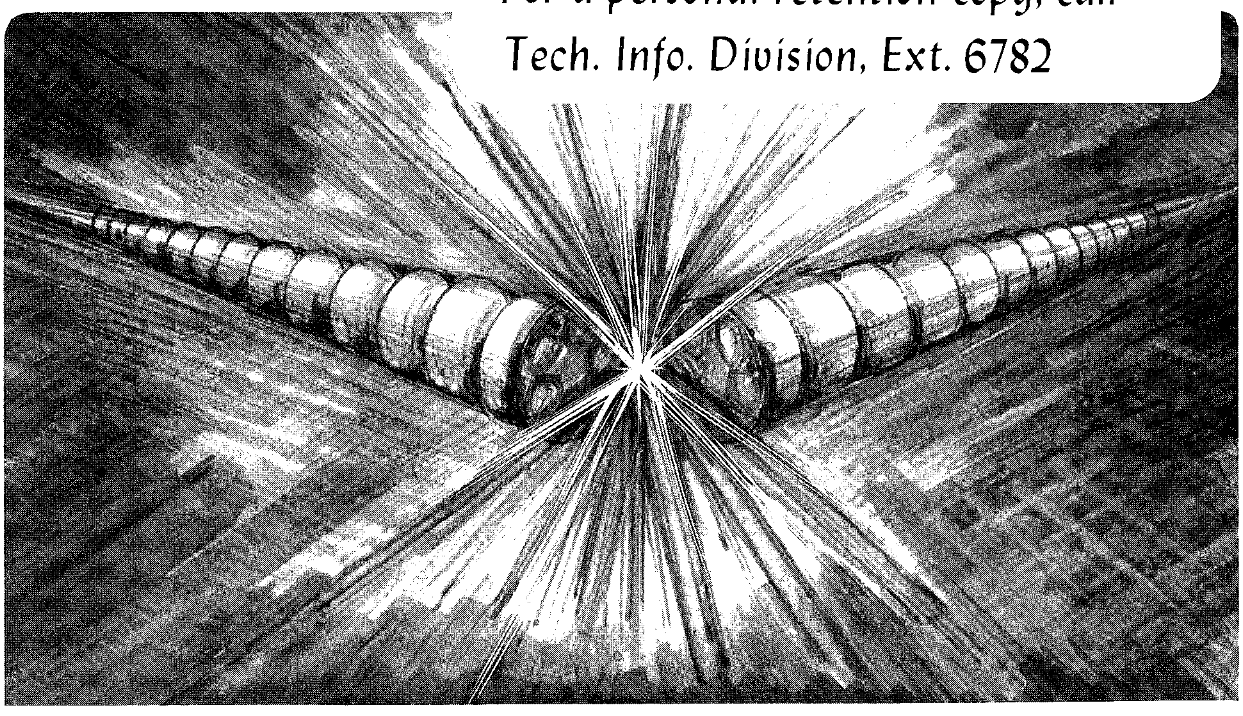

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A BEAM-BEAM SIMULATION FOR THE SINGLE-PASS COLLIDER*)

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ABSTRACT
The beam-beam interaction for the single-pass collider has been investigated by means of a computer simulation. The collision of a single intense bunch of electrons with a single intense bunch of positrons has been simulated using a macroparticle code in which the interaction between each two macroparticles is calculated directly. The simulation reveals the pinch effect of one bunch upon the other, the luminosity enhancement due to the pinch effect, the attraction between offset bunches, and the large opening angles of particles in the disrupted bunches. Finally, the effects of synchrotron radiation emitted during the collision are simulated.

1. INTRODUCTION

In the single-pass collider, bunches of electrons and positrons would collide only once before being discarded. Therefore, it is reasonable to consider accelerator design parameters which correspond to very intense beam-beam interactions, since it would not be necessary to preserve the bunches throughout many collisions. The characteristics of these beam-beam interactions are investigated here by simulations with the three-dimensional macroparticle code named SMASH. In this computer program, the electron bunch and the positron bunch are simulated by collections of macroparticles, each of which represents many electrons or positrons. This approach provides great flexibility in investigating collisions between bunches with lateral offsets.

When macroparticles from opposite bunches pass near one another, their interaction consists mainly of a change in transverse momentum. In the case shown in Figure 1, particle 1 (with charge q_1 and velocity v) passes particle 2 (at rest) at a distance b, and the transverse momentum transfer is given in MKS units by

$$\Delta p_1 = \Delta p_2 = \frac{1}{4\pi\epsilon_0} \frac{2q_1q_2}{bv} . \tag{1}$$

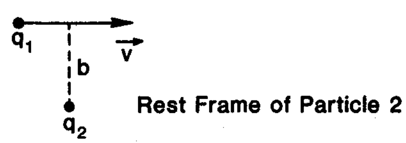

Figure 1

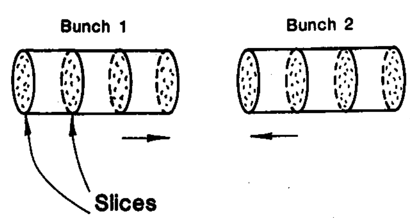

Figure 2

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The forces are attractive for oppositely charged particles. In the program SMASH, the collision of two bunches is simulated as follows: two bunches are generated, each with macroparticles arranged in slices as shown in Figure 2; the bunches are advanced step by step so that they pass through one another; at each step, Equation 1 is used to calculate all the transverse momentum changes; and macroparticle trajectories and bunch shapes are calculated throughout the collision. A form factor is used to avoid the infinity in Equation 1 when the impact parameter b approaches zero. This method of simulating the collision is unusually simple because the particles are not binned in order to calculate electric fields.

In order to calculate the total luminosity of the collision of two bunches, it is necessary to calculate the luminosity contribution of every collision of slices. This calculation requires the derivation of a macroparticle density function, and in the program SMASH the calculation of average densities in a series of annular regions provides the appropriate smoothing.

2. BEAM-BEAM INTERACTION

The beam-beam interaction is investigated here by considering a standard case which corresponds to the Stanford Linear Collider: $E = 50$ GeV, $N_+ = N_- = 5 \times 10^{10}$, $\sigma_x = \sigma_y = 2\mu m$, $\sigma_z = 1$ mm, $\sigma_{x'} = \sigma_{y'} = 0.2$ mrd, and both bunches have gaussian density distributions. For convenience, a disruption parameter D has been defined[1)] such that $D > 1$ corresponds to a significant distortion of the bunches due to the pinch effect.

$$D = \frac{e^2}{4\pi\epsilon_o} \frac{\sigma_z N}{E \sigma_y^2} \qquad (2)$$

Since the standard case defined above ($D = 0.36$) exhibits a rather weak beam-beam interaction, more intense interactions (up to $D = 14$) are also investigated by considering cases with larger numbers of particles. In these simulations there are 2400 macroparticles arranged in 25 slices in each bunch. Each case requires about three minutes of computation on a CDC 7600 computer. The effects of synchrotron radiation are

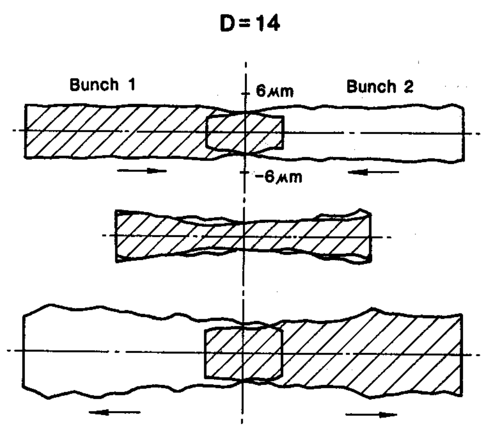

Figure 3

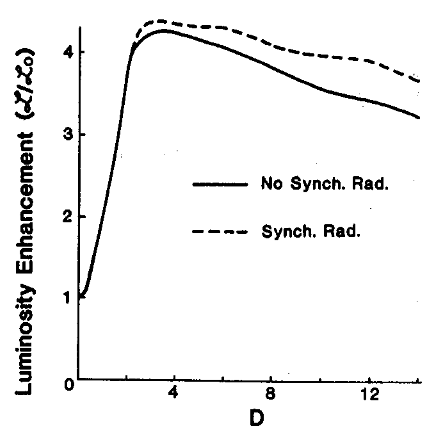

Figure 4

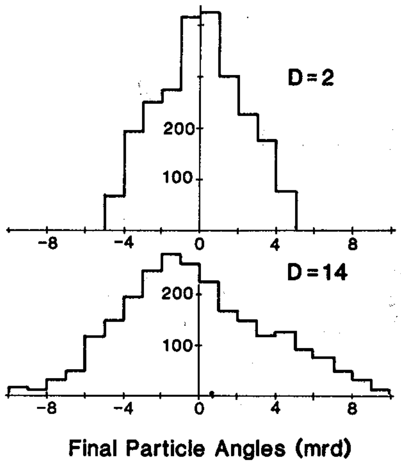

Figure 5

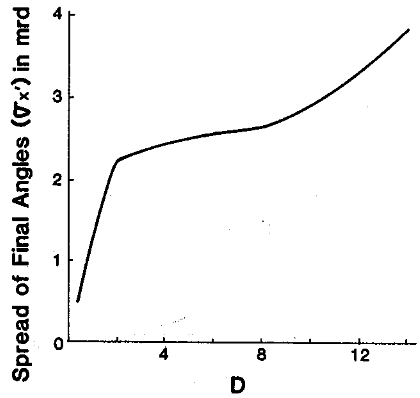

Figure 6

included only in the simulations described in the last section of this paper.

Three cross-sectional views of a collision are shown in Figure 3. Twice σ_x is plotted as the bunch radius, and the three views (top to bottom) reveal the time evolution of the collision. The pinch effect causes a transverse compression of each bunch, the pinched bunches pass through one another, and the particles emerge from the collision with a wide spread in angle. The solid curve in Figure 4 shows that for $D > 2$, the pinch effect causes a substantial luminosity enhancement. In Figure 4, L_0 is the luminosity of the collision in the absence of any pinch effect. Since the number of particles N is varied to change the value of D, L_0 varies as N^2 and as D^2. However, the luminosity enhancement L/L_0 does not exhibit the D^2 dependence. Figure 5 shows that larger final particle angles accompany larger values of D. In fact, for D = 2 and D = 14, some particles emerge at angles as large as 5 and 10 mrd, respectively. Figure 6 shows the dependence of the final $\sigma_{x'}$ on the value of D, and these large opening angles may pose difficulties in the design of experimental detectors.

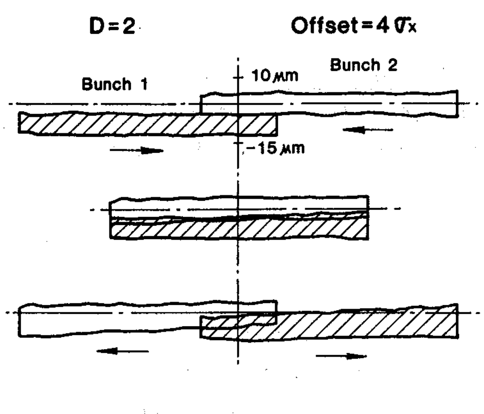

Figure 7

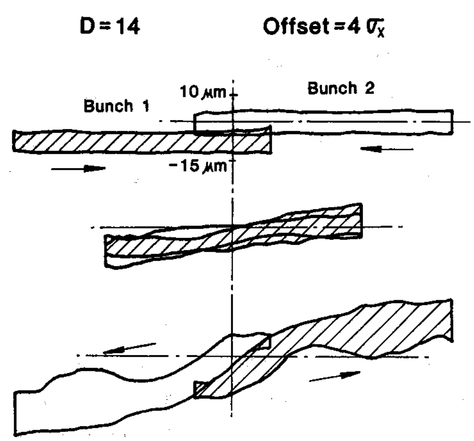

Figure 8

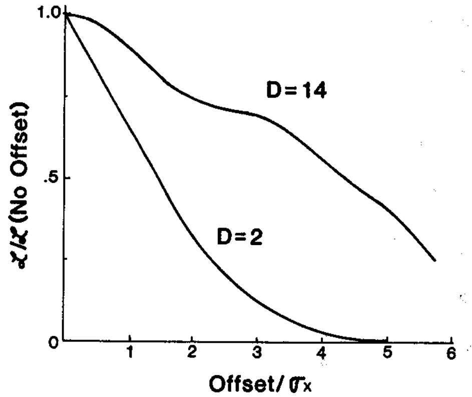

Figure 9

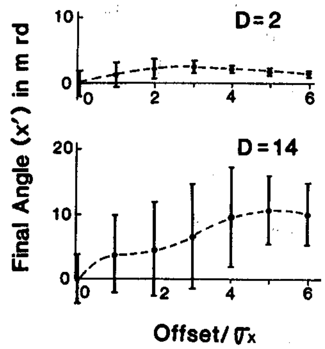

Figure 10

3. EFFECTS OF TRANSVERSE OFFSETS

It is difficult to achieve exactly head-on collisions of extremely small bunches, so we consider here the effects of transverse offsets on the collisions. Figures 7 and 8 show the effects of a $4\sigma_x$ offset on D = 2 and D = 14 collisions. Note that each bunch as a whole is deflected by the attraction of the other bunch. In the D = 2 case the two bunches mainly pass by one another, but in the D = 14 case the stronger attraction between the bunches cause them to interweave through one another and to emerge greatly disrupted. This greater overlapping of the bunches and the resulting greater luminosity in the D = 14 case can be seen in Figure 9. Figure 10 shows that offset collisions can also cause larger final particle angles. The error bars in Figure 10 represent one standard deviation; and particles emerge at angles as large as 5 mrd in the D = 2 case; and as large as 25 mrd, in the D = 14 case.

Lastly, we consider the effect of colliding two dissmiliar bunches of particles. Simulations for the D = 14 case show that neither a 10 percent imbalance in the numbers of particles nor a 10 percent imbalance in the transverse area of the bunches has a substantial effect on luminosity.

4. SYNCHROTRON RADIATION

The effects of synchrotron radiation emitted during the collision are simulated in SMASH by using a classical formula to obtain the average synchrotron radiation energy loss at every step along the macroparticle trajectories. This energy loss ΔE in GeV is given by

$$\Delta E = (8.85 \times 10^{-5} \frac{m}{GeV^3}) \frac{(\Delta\theta)^2 E^4}{2\pi (DZ)} \qquad (3)$$

where $(\Delta\theta)$ is the change in particle direction, E is the macroparticle energy in GeV, and (DZ) is the step length in meters. Throughout the collision, this energy change is substracted from the particle energies and added to the energy of the flux of synchrotron radiation. The direction of the radiated energy is assumed to be the current direction of the macroparticle.

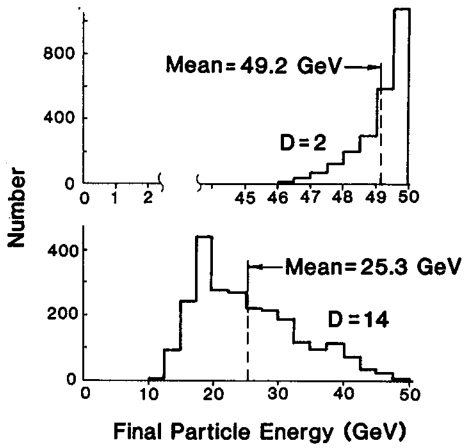

Figure 11

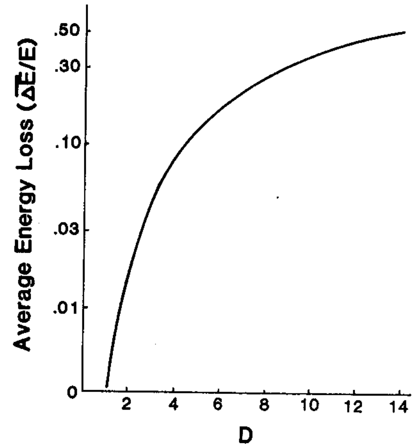

Figure 12

Figure 11 shows that, depending on the parameters, the emission of synchrotron radiation can greatly reduce the average particle energy and can also broaden the particle energy spectrum. The average energy loss, as a function of D, is shown in Figure 12. Simulations show that the synchrotron radiation flux is largely emitted in the same directions that the particles emerge from the collision, although the radiation is slightly more forward peaked. This intense spray of undesired photons may pose a significant problem to experimenters when there are offset collisions for larger values of D. Interestingly enough, the particle trajectories are not greatly changed when synchrotron radiation is included in the simulations. Note that in Figure 4, the luminosity is only slightly changed by synchrotron radiation effects.

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* * *

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