Beam-Beam Interactions

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Abstract

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At the interaction point of a particle accelerator, various phenomena occur which are known as beam-beam effects. Incident bunches of electrons (or positrons) experience strong electromagnetic fields from the opposing bunches, which leads to electron deflection, beamstrahlung and the creation of electron/positron pairs and hadrons due to two-photon exchange. In addition, the beams experience a “pinch effect” which focuses each beam and results in either a reduction or expansion of their vertical size. Finally, if a beam’s disruption parameter is too large, the beam can develop a sinusoidal distortion, or two-stream (kink) instability. This project simulated and studied these effects as they relate to luminosity, deflection angles and energy loss in order to optimize beam parameters for the Next Linear Collider (NLC). Using the simulation program Guinea-Pig, luminosity, deflection angle and beam energy data was acquired for different levels of beam offset and distortion. Standard deflection curves and luminosity plots agreed with theoretical models but also made clear the difficulties of e-e- feedback. Simulations emphasizing kink instability in modulated and straight beam collisions followed qualitative behavioral predictions and roughly fit recent analytic calculations. Finally, a study of e-e- collisions under design constraints for the NLC provided new estimates of

how luminosity, beamstrahlung energy loss, upsilon parameter and deflection curve width scale with beam spotsizes.

Introduction

When electron and positron beams collide at the interaction point (IP) of a particle accelerator, phenomena known as beam-beam effects occur. Incident bunches of electrons (or positrons) experience the strong electromagnetic fields of the opposing bunches, which cause electrons to deflect at angles on the order of a few microradians from the IP. Also, as relativistic charged particles on a curved trajectory, some deflected electrons emit radiation in a process called beamstrahlung. In addition, low energy electron/positron pairs and hadrons are created due to the two-photon exchange process.

These effects have positive and negative consequences on the collider's ability to function as a tool for conducting high energy physics research. For instance, the vertical deflection angle has an approximate linear dependence on the vertical offset of the two beams for small offsets, which means this angle can be used as a feedback signal to correct the beams' vertical displacement. On the other hand, beamstrahlung takes away energy from some electrons, contributing to an energy spread which limits the precision in measurement of particle masses. Also, the particles produced in two-photon exchange are backgrounds to be dealt with during data reduction.

In order to adequately study subatomic particles with a particle accelerator, it is desirable to achieve a high rate of collision events. The event rate is determined by the luminosity of the interaction, which depends acutely on beam-beam effects. In an electron/positron linear collider, where the beam-beam forces are large, the Coulomb attraction between the beams results in a "pinch" effect which focuses each beam and

reduces its vertical size. Similarly, with an electron/electron collider, there is an opposite “anti-pinch” effect. In addition, if a beam’s “disruption parameter” $D_y = \frac{2Nr_e\sigma_z}{\gamma\sigma_y(\sigma_x+\sigma_y)}$ is too large, the beam can develop a sinusoidal distortion, or two-stream “kink” instability. Both of these effects contribute to a “luminosity enhancement factor” H_D in determining luminosity ($L = \frac{f_{rep}n_bN^2}{4\pi\sigma_x\sigma_y} H_D$) [1].

Our project focuses on performing computer simulations of electron/positron and electron/electron collisions in order to study some effects beam-beam interactions have on the performance of next-generation linear colliders. This involves testing mathematical models of beam-beam effects and finding beam input parameters (xyz cross-sections, vertical and waist offsets) that optimize selected output characteristics (energy spread, luminosity, deflection).

Materials and Methods

The simulations in our project can be divided into three subsets: production of standard deflection and luminosity plots, examination of electron/positron (e+e-) two-stream instability and optimization of electron/electron (e-e-) collision parameters. All simulations done in this project were carried out using Guinea Pig, a beam-beam simulation program written by Daniel Schulte [2].

Preliminary Work:

Guinea Pig simulates the collision of a single pair of particle bunches with a given set of input parameters (spotsize, offset, emittance, etc.). Since we wished to study interaction characteristics which varied with some of these input parameters, a preliminary task was to automate Guinea Pig. This was done using several MATLAB scripts which varied the desired parameters in the input files, ran a selected number of simulations and compiled the useful data from the output files of each simulation. In addition, we used these scripts to generate output data plots and to generate specific input particle distributions.

Production of Standard Plots:

Plots that are useful for determining optimal beam parameters include deflection curves (avg. vertical particle deflection angle vs. vertical beam offset) and luminosity plots (interaction luminosity vs. vertical offset) as well as deflection or luminosity as functions of vertical waist offset. Deflection and luminosity plots were generated over a y-offset range on the order of $10\sigma_y$ and a y-waist-offset range on the order of $5\sigma_z$ for both NLC and TESLA accelerator parameters [3] (Table 1). Two types of electron\positron beams were used. The first type was an ideal beam with a normal charge distribution in the 6 phase space dimensions (Figure 1a). The second type was from a set of non-ideal beams (six electron\positron beam pairs for each accelerator) generated by the program MatLiar, which simulates the beam through the course of the entire linear collider up to the interaction point. This second type was characterized by vertical “tails” toward the rear end of the beam caused by wakefields in the accelerator

cavities (Figure 1b). For e-e- beam collisions, the charge of the positron beam was simply inverted.

Examination of Two-Stream Instability:

In order to study effects of the disruption parameter and beam modulation on single bunch kink instability, we ran a set of simulations where the number of particles per bunch was increased and the post-interaction y-z particle distributions were examined. This was done with both uniform and normal initial longitudinal distributions for e+e- interactions under modified NLC accelerator parameters (Table 1). The set was run with both no offset and a $0.33 \sigma_y$ vertical offset. We also ran a simulation set where the incident uniform or normal electron beam was modulated by $0.33 \sigma_y$ in the vertical direction (Figure 2). The number of oscillations and number of particles were varied in order to investigate luminosity minima due to resonance.

Optimization of e-e- Parameters:

Two sets of simulations were run to optimize e-e- parameters. The first required steadily increasing one of several parameters in order to evaluate how luminosity, beamstrahlung energy loss and upsilong parameter scale in the e-e- case. The second involved generating deflection curves (as done earlier) with one additional parameter changed in order to determine which parameters affect the width of the curve's linear

region. Both of these sets involved ideal Gaussian beams and standard NLC accelerator parameters (Table 1).

Results

Figure 3 displays deflection curves and luminosity plots for e-e+ and e-e- Gaussian beam collisions under NLC parameters while Figure 4 shows the same simulations under TESLA parameters (Table 1). Notice how much narrower the linear region of the deflection curve is for e-e- interactions than for e-e+ in both cases. The same holds for the width of the luminosity peak. Figure 5 shows deflection curves and luminosity plots for several NLC MatLiar-generated beam interactions. In these non-ideal cases, the zero-deflection point and luminosity maximum, while still coinciding, do not occur at zero vertical offset; rather they are shifted up or down.

Figure 6 displays post-interaction y-z particle distributions for both uniform and Gaussian (z-distribution) incident beams with increasing particles per bunch. Superimposed on each distribution is a 10th degree polynomial fitted to the average vertical position of 50 particles at 400 longitudinal slices. Figure 7 shows the same simulations run with a $0.33\sigma_y$ vertical offset. A significant difference here is that the fitted curves now have more prominent oscillatory characteristics. Figure 8 shows luminosity vs. number of oscillations for modulated electron beam/straight positron beam interactions. This is for a uniform longitudinal charge distribution with increasing number of particles per bunch. There is a distinct minimum (between 90% and 60% maximum luminosity) occurring between 1/2 and 2 oscillations in each case. A

polynomial is fitted to this region in order to estimate the locations of the minima. Figure 9 shows the same plots for a normal longitudinal charge distribution, while Figure 10 plots the location of the minima vs. square root of N for both cases.

Figure 11 shows normalized deflection curves for e-e- Gaussian beam collisions (NLC parameters) as σ_x and number of particles per bunch are varied. Figure 12 shows normalized deflection curves as σ_y and σ_z are varied. The width of a curve's linear region can be viewed as the offset range where the deflection angle is between -90% and +90% of its maximum value (illustrated by the two red lines). This width appears to depend on σ_y , σ_x and number of particles. Figures 13, 14 and 15 show luminosity, beamstrahlung energy loss and maximum upsilon value, respectively, plotted against σ_x , σ_y , σ_z and number of particles per bunch.

Discussion and Conclusion

From our standard luminosity plots and deflection curves, we can make several observations. First, e-e- beam interactions have significantly smaller linear regions in their deflection curves (~4nm compared to ~30nm) and much narrower luminosity peaks than e-e+. This occurs because of Coulomb repulsion (anti-pinch effect) between the beams. When the beams are not offset, the repulsive force is straight along the z-axis; with an offset, there is a vertical component to this force. Contrarily, with e+e- there is a Coulomb attraction (pinch effect) and the electrostatic force pulls the beams together. As mentioned earlier and documented elsewhere, luminosity maxima and zero-deflection intercepts coincide, allowing for relatively straightforward feedback algorithms [4].

However, the narrower offset ranges for e-e- indicate the greater challenge posed by e-e- feedback, as ground motion jitter will introduce random offsets on the order of a few nanometers. As expected, e-e- has a fractional luminosity of e+e- (~30%), which may indicate the need for a new e-e- parameter set (again a consequence of the pinch/anti-pinch effect).

Our study of two-stream instability appears to be in agreement with qualitative predictions and analytic calculations. With no offset, no large-amplitude oscillations are observed. With a small vertical offset, as the number of particles per bunch (and hence disruption parameter) is increased, kink instability arises. As previously calculated for the uniform beam case, when $D_y > 11.4$ ($N \sim 6e9$), more than one period of oscillation is observed [5]. With the modulated beams (uniform z-distribution), it is predicted that as the number of oscillations is changed, a luminosity minimum occurs when the wavelength of the initial modulation of the beam equals twice the characteristic wavelength that occurs because of kink instability [5]:

$$\lambda = 2\lambda_o, \lambda_o = \frac{2\pi}{\sqrt{\frac{Nr_e}{\sqrt{3}\sigma_y\sigma_z(\sigma_x + \sigma_y)\beta^2\gamma}}} = \frac{2\pi\sqrt{2\sqrt{3}\sigma_z}\beta}{\sqrt{D_y}}$$

This means the minima location in terms of number of oscillations ($\#oscill. = 2\sqrt{3}\sigma_z / \lambda$) should increase with the square root of disruption. As figure 10 indicates, our results appear to agree with this prediction. The small discrepancy may be explained by inaccuracies with the fitting algorithm used to estimate the minima. There may have been too few points available to get an adequate polynomial fit, resulting in calculated minima slightly larger or smaller than expected.

The scaling found for e-e- parameters indicated the need for an analytical model to describe this interaction. For luminosity, upsilon and beamstrahlung energy loss, we found the following scaling:

$$L \sim \frac{N^{3/2}}{\sigma_x(\sigma_y\sigma_z)^{1/2}}, Y \sim \frac{N}{\sigma_x\sigma_z}, \delta_{BS} \sim \frac{N}{\sigma_z^{1/2}\sigma_x^{3/2}}$$

These are valid for $1\text{nm} < \sigma_y < 20\text{nm}$, $0.1\mu\text{m} < \sigma_x < 1\mu\text{m}$, $\sigma_z < 400\mu\text{m}$ and $N < 5\text{e}10$.

The luminosity scaling appears to be in partial agreement with past work. An earlier study found the following empirical equation for luminosity enhancement fit simulation results [6]:

$$H_D = \left[1 - 0.15 f(R) \left(\frac{A_y}{1+0.4D_y} \right)^{f(R)} \right] e^{-x} I_o(x) \cdot \min(1, 1 + 0.1 \ln D_y), \quad x = \frac{f(R)D_y}{3\sqrt{\pi}}, \quad f(R) = 1 + \frac{\sigma_y^2}{\sigma_x^2}$$

In the approximation of $f(R) = 1$ and $A_y = 0$, this implies that luminosity scales as:

$$L \sim \frac{N^{3/2}}{(\sigma_x\sigma_y\sigma_z)^{1/2}}$$

Although this is approximately true for $\sigma_x < 100 \text{ nm}$, it changes as σ_x increases. We have no explanation for this discrepancy at this time. Although there is no previous scaling estimate for Y , results seem reasonable because $Y \sim N / \sigma_x\sigma_z$ for e+e- [7]. δ_{BS} scaling is a mystery; there's no previous estimate for e-e-. However, e+e- scales as $\delta_{BS} \sim N^2 / \sigma_x^2\sigma_z$ and since we found $\delta_{BS} \sim \sigma_x^{-1}$ for smaller σ_x , it's possible $\delta_{BS \text{ e-e-}} \sim \sqrt{\delta_{BS \text{ e+e-}}}$ [7].

Some other interesting details came out of the scaling study. With all other parameters set at NLC standards, luminosity does not continue to increase as σ_y approaches zero; instead, it reaches a maximum around $0.33 \sigma_{y0}$ and decays as

$\sigma_y^{-1/2}$. This may be a result of limitations with Guinea Pig simulations, but it could also be an unknown real effect occurring for small vertical cross-sections. Another peculiar (and likely genuine) effect is a peak in luminosity (as well as $\bar{Y}$ and δ_{BS}) around $N = 5 \times 10^9$ ($D_y = 85.3$). This is likely the result of two counteracting contributions: an increase in luminosity due to an increase in the number of interacting particles and a decrease due to greater Coulomb repulsion within each beam, which causes the beams' spotsizes to increase. Although this peak occurs well outside NLC operating parameters, this is nevertheless an important effect as other next-generation linear collider designs (such as TESLA) use different beam spotsizes (which will change the location of the peak) and larger values for N . The presence of a peak means these designs may operate at a less than optimal number of particles per bunch; any collider on the right hand side of this peak can increase luminosity by increasing the repetition frequency, a win-win situation.

One final important result of the scaling study is the scaling of width of the linear region of the deflection curve. As e-e- feedback will likely require a larger linear region, it is important to understand how it varies with beam parameters and what trade-off in luminosity must be made. Defining the width as the interval the deflection varies between 90% of its maximum and minimum values, we found that it scales as:

$$\Delta y \sim \sigma_y \sqrt{\frac{\sigma_x}{N}}$$

However, under different width definitions, the N dependence may not be significant. In order to achieve a comparable width to e+e- (under standard NLC parameters), σ_y must be increased ~ 7 -fold, which leaves e-e- luminosity at only $\sim 10\%$ of nominal e+e-

luminosity (Figure 20). From this study, we can conclude that the following modifications should be made to e-e- beam parameters:

- Increase σ_y to the level where the deflection curve linear region is wide enough for feedback to be feasible.
- Shorten bunch length (if possible), keeping in mind that wakefields will increase with smaller σ_z .
- Increase N to compensate for luminosity loss due to larger σ_y (at a cost of lower repetition frequency).
- Adjust vertical and waist offsets for optimal luminosity.

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Table 1

Bunch Parameters	Simulations (actual parameters)		
	Standard plots / e-e- study		Two-stream instability study
	NLC	TESLA	
CM energy (GeV)	500	500	500
particles (10^{10})	0.75	2.0	variable
sigma-x (nm)	243	553 (554)	243
sigma-y (nm)	3.0	5.0	3.0
sigma-z (um)	110	300	110 (rms)
emittance-x ($\text{mrad} \cdot 10^{-6}$)	3.6	10	3.3288
emittance-y ($\text{mrad} \cdot 10^{-6}$)	0.04	0.03	0.04109
energy spread (%)	0.3% (0.25%) (uniform)	0.14% / 0.07% (0.04%) (Gaussian)	0.3% (uniform/Gaussian)

Figures

Figure 5: NLC Deflection & Luminosity (Non-ideal Beams)

Figure 6: y-z Distribution (no y-offset)

Figure 7: y-z Distribution (1 nm y-offset)

Figure 8: Lumi. vs. # Oscillations (Uniform)

Figure 9: Lumi. vs. # Oscillations (Gaussian)

Figure 10: Minima Location

Figure 11: e-e- Deflection Curves (sigma x, # particles)

Figure 12: e-e- Deflection Curves (sigma y, sigma z)

Figure 13: Luminosity

Figure 14: Beamstrahlung Energy Loss

Figure 15: Maximum Upsilon Value

Figure 16: D-Curve Width Scaling (log-log)