INTRODUCTION TO INTERACTION REGION ISSUES; CLIC INTERACTION POINT LAYOUT AND ISSUES

D. SCHULTE
CERN, CH-1211 Geneva, Switzerland

In future linear $e^+e^-$-colliders, the beam-beam interaction will strongly affect the experimental conditions. A short overview over the main effects of this interaction and the resulting background is given. Emphasis is put on the case of CLIC at a centre-of-mass energy of 3 TeV.

1 Introduction

A number of international working groups are studying the feasibility of future high energy linear $e^+e^-$-colliders, as well as the conditions for physics experiments in these machines. The main projects are TESLA, JLC, NLC, and CLIC. Sample parameters of these projects are shown in Table 1 on page 2. Some of the projects have a variety of parameter sets and JLC even has two acceleration frequencies. In the following, an overview over the most important beam-beam effects in these machines is given, with an emphasis on CLIC at a centre-of-mass energy $E_{cm} = 3$ TeV. Since this machine is planned on a somewhat longer timescale than the others, the background studies have started only recently. In general, the normal conducting machines (i.e. all but TESLA) should, at the same centre-of-mass energy, have background levels of the same order of magnitude. TESLA differs because of the long pulse duration which allows the bunches to be separated by $\approx 300$ ns. CLIC differs because of the high centre-of-mass energy.

2 Beam-Beam Effects

2.1 Pinch effect

In an electron-positron collider the particles of each beam are accelerated towards the centre of the oncoming bunch by the electric and magnetic forces. In the proposed colliders, this effect is so strong that the transverse dimensions of the bunches are significantly reduced during the collision, leading to the so-called pinch effect. This enhances the luminosity typically by a factor 1.5–2 compared to the one without pinch effect for the proposed machines. Since it is hard, if not impossible, to treat this problem analytically, simulation programs have been developed which include also most of the following effects. The
Table 1: The parameters of the main projects.

<table>
<thead>
<tr>
<th>name</th>
<th>TESLA</th>
<th>NLC/JLC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{cm}$ [TeV]</td>
<td>0.5</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>$\mathcal{L}$ [$10^{34} \text{cm}^{-2} \text{s}^{-1}$]</td>
<td>3.1</td>
<td>5.7</td>
<td>0.65</td>
</tr>
<tr>
<td>$f_r$ [Hz]</td>
<td>5</td>
<td>3</td>
<td>120</td>
</tr>
<tr>
<td>$N_b$</td>
<td>2820</td>
<td>4500</td>
<td>95</td>
</tr>
<tr>
<td>$\Delta_b$ [ns]</td>
<td>337</td>
<td>189</td>
<td>2.8</td>
</tr>
<tr>
<td>$N$ [$10^{10}$]</td>
<td>2.0</td>
<td>1.4</td>
<td>0.95</td>
</tr>
<tr>
<td>$\sigma_z$ [$\mu$m]</td>
<td>400</td>
<td>300</td>
<td>120</td>
</tr>
<tr>
<td>$\epsilon_x$ [$\mu$m]</td>
<td>10</td>
<td>8</td>
<td>4.5</td>
</tr>
<tr>
<td>$\epsilon_y$ [$\mu$m]</td>
<td>0.03</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>$\sigma^*_z$ [mm]</td>
<td>553</td>
<td>391</td>
<td>332</td>
</tr>
<tr>
<td>$\sigma^*_y$ [mm]</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>$\delta$ [%]</td>
<td>2.8</td>
<td>4.7</td>
<td>3.8</td>
</tr>
<tr>
<td>$n_\gamma$</td>
<td>1.6</td>
<td>1.5</td>
<td>1.16</td>
</tr>
<tr>
<td>$N_{\perp}$</td>
<td>44</td>
<td>63</td>
<td>9.8</td>
</tr>
<tr>
<td>$N_{H_{\perp}}$</td>
<td>0.23</td>
<td>0.6</td>
<td>0.07</td>
</tr>
<tr>
<td>$N_{MJ}$ [$10^{-2}$]</td>
<td>0.61</td>
<td>3.1</td>
<td>0.20</td>
</tr>
</tbody>
</table>

$E_{cm}$: centre-of-mass energy, $\mathcal{L}$: actual luminosity, $f_r$: repetition frequency, $N_b$: no of bunches per train, $\Delta_b$: distance between bunches, $N$: no of particles per bunch, $\sigma$: bunch dimensions at IP, $\gamma\epsilon$: normalised emittance, $\Upsilon$: average beamstrahlung parameter, $\delta$: average energy loss, $n_\gamma$: no of photons per beam particle, $N_{\perp}$: no of particles from incoherent pair production, produced with $p_\perp > 20 \text{MeV}$, $\theta > 0.15$, $N_{H_{\perp}}$: hadronic events, $N_{MJ}$: minijet pairs $p_\perp > 3.2 \text{GeV}/c$ (*numbers are for $p_\perp > 10 \text{GeV}/c$).

Pinch effect calculated by these programs has been successfully compared to SLC data. In the following, the program GUINEA-PIG is used.

Since the trajectories of the particles are bent, they emit a radiation that is equivalent to synchrotron radiation and is called beamstrahlung. The number of emitted photons typically is of the order of one per beam particle and they are quite hard. The particles therefore loose a significant amount of energy during the collision ranging from about 3% for the machines at $E_{cm} = 0.5 \text{TeV}$ up to 40% for CLIC at $E_{cm} = 5 \text{TeV}$.

2.2 Coherent Pair Creation

A photon can turn into an electron-positron pair in a strong magnetic field. For machines with a centre-of-mass energy of 1 TeV or less, this effect is either not important at all or forms some background only. In the case of CLIC at
2.3 Luminosity Spectrum

Because of the energy loss due to beamstrahlung the centre-of-mass energy of the electron-positron collisions can differ from the nominal one. The same effect arises from initial state radiation. In all low energy designs the beamstrahlung is kept to a level where it is comparable to this effect, see Fig. 1 for CLIC. At high energies the energy loss is larger in order to achieve high luminosity. It is however possible to trade off luminosity versus sharpness of the spectrum. In Fig. 2 the absolute luminosity with $E_{\text{cm}} > 0.99E_{\text{cm},0}$ and $E_{\text{cm}} > 0.95E_{\text{cm},0}$ is shown for different transverse beam sizes $\sigma_x$. Also the fraction of luminosity in this region is given. The effect of the beam energy spread and the initial state radiation are ignored in this comparison.

To illustrate the effect of the trade off, Fig. 3 shows the resolution of a top threshold scan with CLIC for different horizontal beam sizes. The fit resolution is based on an event reconstruction efficiency of 50% using only the total cross...
Figure 3: Resolution of the top threshold scan using ten scanning points with one day of running for each.

Figure 4: The energy spectrum and transverse distribution of the coherent pair particles in CLIC at $E_{\text{cm}} = 3$ TeV.

section. The case with the highest beamstrahlung is best, since the gain in luminosity outweighs the smearing of the spectrum.

3 Background

3.1 Coherent Pairs

The simulation of the coherent pair creation predicts $3.4 \cdot 10^5$, $8 \cdot 10^8$ and $2.9 \cdot 10^9$ pairs per bunch crossing for $E_{\text{cm}} = 0.5, 1, 3$ and 5 TeV, respectively. The spectrum of the particles at $E_{\text{cm}} = 3$ TeV peaks at $E \approx 100$ GeV, see Fig. 4. They initially have small angles. An electron that flies in the same direction as the electron beam is focused by the positron beam and thus starts to oscillate. A positron flying in the same direction is defocused by the positron beam and can reach relatively large angles. While these particles still enter the mask around the quadrupoles, the secondaries they produce can be a hazard to the detector if they hit material. The final quadrupoles provide an (almost field free) exit hole. Its required radius can be estimated from Fig. 4. The total energy of coherent particles per bunch crossing is shown as a function of
the minimum particle angle. In TESLA at \( E_{cm} = 0.5 \, \text{TeV} \) the total energy lost per bunch crossing due to incoherent pair production and bremsstrahlung is of the order \( 10^6 \, \text{GeV} \) per bunch crossing. To reach a comparable level in CLIC an exit hole subtending an angle of the order of 10 mradian is necessary.

### 3.2 Spent Beam

Due to the pinch effect, the transverse emittance of the beam will be significantly increased after the collision. In addition, particles can lose a significant fraction of their energy. The beam line that extracts the spent beam from the interaction point has to be able to transport all these different energies. Figure 5 shows the energy spectrum of the beam particles in CLIC after the interaction for \( E_{cm} = 0.5 \, \text{TeV} \) and \( E_{cm} = 3 \, \text{TeV} \). The first case is only slightly more difficult than the other low-energy machines, the difference being due to the larger beamstrahlung parameter. In the high energy machine the number of particles at very low energies is significant. A large fraction of these particles is produced by coherent pair production, as can be seen in the righthand part of Fig. 5.

### 3.3 Incoherent Pairs

The production of \( e^+e^- \) pairs through two-photon processes can lead to significant background. It is important at all energies. The main contribution arise from \( ee \rightarrow ee(e^+e^-) \), \( e\gamma \rightarrow e(e^+e^-) \) and \( \gamma\gamma \rightarrow (e^+e^-) \). The photons are from the beamstrahlung. The processes involving one or two beam particles can be approximately calculated using the equivalent photon approach. This also allows the effects of the beam size and the strong beam field onto the cross section to be taken into account.
Figure 6: Particles from incoherent pair creation after the collision. Each dot presents one particle. The masking system as foreseen for TESLA, the one for CLIC is expected to have similar properties.

Figure 7: The particle density in the vertex detector as a function of the radius for constant coverage angle. The longitudinal hit density for $B_z = 4T$.

3.4 Impact on the Detector

Incoherent pairs can have rather large angles to the beam axis, so they can produce significant background in the detector, especially in the vertex detector. In Fig. 7 the density of particles that hit the inner layer of a vertex detector is shown as a function of the radius of this layer. The angular coverage is kept constant at $|\cos \theta| < 0.98$ and different magnetic fields are used. The steep rise observed at one point in each of these curves corresponds to the edge in the scatter plot in Fig. 6. The longitudinal distribution of actual hits produced by the particles is shown in Fig. 7, based on GEANT simulations of a magnetic field of 4T and different radii. It is relatively uniform except for low radii where the ends of the detector are hit by the particles below the edge in Fig. 6.

While the other particles hit a small area in the front and back of the detector only, secondaries produced by them can cause significant background. To prevent this, the final quadrupoles are surrounded by tungsten masks, as shown in Fig. 6. The thickness of these masks is chosen to suppress primarily
photons; about 5–10 cm seems sufficient\(^5\). In the case of TESLA, the outer angle of this mask can be as low as 83 mradian.

Low-energy electrons and positrons are also scattered back. The field of the main solenoid guides these particles directly into the vertex detector region, as it guided the low-energy particles out in the first place. The increase of hits in the inner layer of the vertex detector due to this effect can be a factor ten\(^5\). However almost complete suppression of the backscattering can be achieved by introducing an inner mask, with an inner radius smaller than that of the vertex detector. This mask consists of a tungsten layer towards the quadrupoles and layer of a low-Z material towards the detector. Charged particles penetrate this layer with a small probability of interaction. So, low-energy secondaries have to pass a significant length of material loosing energy by ionisation before exiting the mask. For CLIC and JLC similar systems are foreseen. For CLIC they are not yet simulated. This inner mask should be instrumented in order to be able to measure the total electromagnetic energy deposited in it for luminosity instrumentation as will be explained below.

### 3.5 Measuring the Luminosity

The experiment needs a precise absolute measurement of the luminosity and its spectrum. In contrast, the machine needs a fast relative measurement to be able to tune beam parameters during operation. The transverse offsets between the two beams in the interaction point can easily be determined using beam position monitors and corrected using small correction dipoles. An increase of the spot size is more difficult to detect. A common reason for this increase is a longitudinal shift of the vertical beam waist.

Several signals can in principle be used to optimise the luminosity\(^6\). For example measuring the rate of particles that emitted bremsstrahlung of a certain hardness. Also the total energy deposited by the incoherent pairs in the inner mask can be used. Maximising it, by changing the position of the vertical waist for example, leads to optimal luminosity. The beamstrahlung can be used in some cases but not as straightforwardly as the other options.

### 3.6 Hadronic Background

In two-photon collision hadrons can also be produced. The total cross section for this process is not dominated by the pair production of quarks. In most cases one or both of the photons interact as hadrons (once- and twice-resolved processes). For the total cross section different estimates exist, the one used in Tab. 1 is a pessimistic version of a parametrisation due to Schuler and Sjöstrand\(^7\). Hadronic background especially affects the reconstruction
of masses. In the top threshold scan, it can also increase the rate of non-top events which are incorrectly accepted as top events\(^5\). The number of events per bunch crossing is significantly lower than one at \(E_{cm} \leq 1\) TeV but increases drastically towards higher energies (\(\approx 8\) in CLIC at \(E_{cm} = 3\) TeV). In the normal conducting designs very fast detectors are necessary to distinguish the different bunch crossings. While most of these events produce visible energy\(^5\) only a small fraction, the minijet events, are hard.

### 3.7 Neutrons

Neutrons are produced in the electro-magnetic showers induced by the electrons and positrons lost in the final quadrupoles. They can be a hazard for the vertex detector and a background source especially for the endcap calorimeter. A former study of the TESLA detector with a somewhat different layout indicated that the neutron levels were acceptable but close to the limit\(^5\). Given the uncertainty due to the different approximations made, confirmation that this was not an underestimate is mandatory. Also the showers induced by the beamstrahlung photons in the collimators can cause problems, even so the study indicated that the inner mask can shield the vertex detector sufficiently.

### 4 Conclusion

The studies of the background induced by beam-beam interaction are far advanced at energies up to \(E_{cm} = 1\) TeV. To gain more insight, reconstruction of interesting events including background has to be done. The study of \(E_{cm} = 3\) TeV has only just begun, offering an interesting and challenging field of investigation. In this regime, coherent pair creation plays an important role and background levels increase significantly.

### References

2. CAIN. Program is developed by K. Yokoya and others, see http://www-acc-theory.kek.jp/members/cain/.
4. T. Barklow and 14 co-authors. PAC 1999 and SLAC-PUB-8043.
5. D. Schulte. TESLA 97-08.