

2.22 Beam-Beam Effects in Linear Colliders

Daniel Schulte, CERN
CERN, 1211 Geneva 23, Switzerland
Mail to: daniel.schulte@cern.ch

2.22.1 Overview

Linear colliders are promising candidates for future high-energy lepton colliders. In the past the SLC [1] has successfully operated at the Z-resonance. Two future linear collider projects are under consideration, the International Linear Collider (ILC [2-6]) and the Compact Linear Collider (CLIC [7-10]). ILC aims at a centre-of-mass energy of 500 GeV, potentially starting at 250 GeV. CLIC is foreseen to be implemented in three stages ranging from a centre-of-mass energy of 380 GeV up to 3 TeV. Both projects are studied by global collaborations. The use of advanced acceleration techniques, such as plasma-based acceleration, is also considered by smaller teams.

Beam-beam effects are an important driver of their design choices and affect the performance of physics experiments. In the following a short reminder of the beam-beam effects is given and their impact on the parameter choice is highlighted; as it has for example been used in the recent optimisation of CLIC parameters for the first energy stage with a centre-of-mass energy of 380 GeV [10]. Some recent improvement in the understanding of the choices by studying the performance of physics event analysis is given in the section on the choice of horizontal beam size.

2.22.2 Introduction

In ILC and CLIC, the beams are produced in an electron and a positron source, respectively. They are slightly accelerated and transported to a damping ring. Here their emittance is reduced to very small values, especially in the vertical plane. Then the beams are transported through the Ring-To-Main-Linac system (RTML). During the transport they are slightly more accelerated and compressed longitudinally. In the main linac they are accelerated to full energy. In the Beam Delivery System (BDS) the beams are then focused to the very small sizes at the collision point. Then they are disposed off in beam dumps.

The main challenges of a linear collider are first to achieve the beam energy in the main linac. This requires very high gradients for the acceleration. The second challenge is to achieve the high luminosity in a single pass. This requires very dense beams at the collision point, which results in strong beam-beam interaction. Both, ILC and CLIC, will deliver short pulses of bunches that collide with longer intervals between pulses.

The ILC is based on the use of superconducting cavities to accelerate the beam. These allow the use of long beam pulses. To provide the accelerating field, the cavity needs to be filled with energy. This energy is lost very slowly in the walls of the cavity, hence one can afford a long pulse. In contrast, CLIC is based on high-gradient normal-conducting accelerating structures. These require very short pulses since the energy in the accelerating structures is lost rapidly in the copper walls. To achieve sufficient efficiency it is therefore necessary to use very short pulses and to increase the beam current in the pulse as much as possible. This requires short distances between the bunches. The advantage of the normal conducting accelerating structures is that they allow to use higher accelerating fields than superconducting cavities (about a factor 3 between CLIC and ILC). To achieve multi-TeV

energies at practical machine length and cost thus requires the use of normal conducting technology. The main beam parameters for ILC and CLIC are given in Table 1.

Table 1: Key parameters of the linear colliders. For ILC and CLIC nominal parameters are given, for the SLC typical parameters towards the end of the operation. The latter differ significantly from the target values.

Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
CMS energy	E_{cm} [GeV]	92	500	380	3000
Geometric luminosity	L [$10^{34} \text{cm}^{-2} \text{s}^{-1}$]	0.00015	0.75	0.8	4.3
Luminosity	L [$10^{34} \text{cm}^{-2} \text{s}^{-1}$]	0.0003	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34} \text{cm}^{-2} \text{s}^{-1}$]	0.0003	1	0.9	2
Beam power	[MW]	0.065	10.5	0.9	28
Gradient	G [MV/m]	20	31.5	72	100
Particles per bunch	N [10^9]	37	20	5.2	3.72
Bunch length	σ_z [μm]	1000	300	70	44
Interaction point beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/6	149/3	40/1
Normalised emittances	$\varepsilon_{x,y}$ [nm/nm]	3000/3000	$10^4/35$	950/30	660/20
Initial beam energy spread	σ_E [%]	-	O(0.1)	0.35	0.35
Bunches per train	n_b	1	1312	352	312
Bunch distance	Δz [ns]	-	554	0.5	0.5
Repetition rate	f_r [Hz]	120	5	50	50
Horizontal disruption	D_x	0.6	0.3	0.24	0.2
Vertical disruption	D_y	1.7	24.3	12.5	7.6
Photons per beam particle	n_γ	-	1.9	1.5	2.1
Average photon energy	$2E_\gamma/E_{\text{cm}}$ [%]	-	2.4	4.5	13
Coherent pairs	N_{coh} [10^8]	-	-	-	6.8
Their energy	E_{coh} [10^8TeV]	-	-	-	2.1
Incoherent pairs	N_{incoh} [10^3]	-	196	58	300
Their energy	E_{incoh} [TeV]	-	484	187	2.3×10^4

2.22.3 Beam-Beam Physics

In this section a short reminder of the beam-beam physics is given. More detailed information can be found for example in [11-14]. In the next section novel results for the choice of parameters will be presented.

2.22.3.1 Beam Parameters and Luminosity Drivers

The luminosity target for linear colliders is in the range of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ following the requests of the experiments. In Table 1, one can note that ILC and CLIC use flat beams to achieve this ambitious goal and that the vertical beam size is only of the order of nm. In the following we will discuss the reason.

The luminosity L in a linear collider is given by the following formula:

$$L = H_D \frac{N^2 n_b f_r}{4\pi\sigma_x\sigma_y} \quad (1)$$

Here, N is the number of particles per bunch, $\sigma_{x,y}$ are the horizontal and vertical beam sizes at the collision point, n_b is the number of bunches per train, f_r is the rate of trains per second and H_D is a factor that contains the impact of beam-beam forces and other relevant effects. H_D is typically in the order of 1.5-2. It is useful to rewrite the formula in the following form:

$$L = H_D \frac{N}{\sigma_x} \frac{1}{\sigma_y} N n_b f_r \quad (2)$$

The term $N n_b f_r$ represents the beam current. Its upper limit arises from the power consumption of the collider and the efficiency to turn this power into beam power. As can be seen in Table 1, the beam power is quite high. It is therefore important to maximise the luminosity per beam current, i.e. the factors N/σ_x and $1/\sigma_y$. However a lower limit to the beam size arises from the beam-beam effects.

2.22.3.2 *Beam-Beam Dynamics and Disruption*

At collision, the beams generate strong electromagnetic fields that focus each other in an electron-positron collider. In circular colliders this deflection is quite small and can be understood as a thin-lens kick. In a linear collider the beams are so dense that the particles move strongly during the collision. This so-called pinch effect reduces the effective beam size and leads to an increase in luminosity.

The focusing is described using the so-called disruption parameters: $D_{x,y}$ for the horizontal and the vertical plane, respectively. $D_{x,y}$ is calculated as

$$D_{x,y} = \frac{2N r_e \sigma_z}{\gamma \sigma_{x,y} (\sigma_x + \sigma_y)} \quad (3)$$

Here, r_e is the classical electron radius and γ the relativistic factor. For $D_{x,y} \ll 1$ particles with small offsets x and y and no initial angle will receive final angles $x' = (D_x/\sigma_z) x = x/f_x$ and $y' = (D_y/\sigma_z) y = y/f_y$. This implies that in each plane, the core of the beam is focused to a single point at distance $f_{x,y}$ behind the collision plane and $D_{x,y}$ is the ratio of the bunch length to this distance. Hence $D \ll 1$ corresponds to a thin lens kick. In contrast $D \gg 1$ indicates that the particle motion during the collision is important. In ILC and CLIC $D_x \ll 1$ and $D_y \gg 1$.

For large disruption analytical models are difficult to develop and computer codes are used to simulate the effect. The two most widely used codes are GUINEA-PIG [14] and CAIN [15]. They represent the beam by a number of macro-particles. Their predictions have been experimentally verified in the SLC [16], where under some conditions the luminosity was more than doubled in good agreement with the simulations. The codes also include the beamstrahlung effect, which is described in more detail below, and the generation of the different electron-positron background processes. GUINEA-PIG also includes the generation of hadronic background and the generation of muons, both processes will not be discussed here.

2.22.3.3 *Beamstrahlung*

When the particle is forced on a curved trajectory by the other beam, it will emit radiation in a similar fashion as in a bending magnet. This radiation is called beamstrahlung. For typical parameters each particle emits one to a few photons each of which carries some percentage of the particle's energy. It is therefore important to be aware of the stochastic nature of the beamstrahlung. Due to beamstrahlung the particles lose energy during the

collision and can therefore collide with less than the initial energy. This leads to the formation of a luminosity spectrum. This obviously impacts the performance of the physics experiments. The importance depends on the physics analysis that is being carried out.

The beamstrahlung can be described by the so-called beamstrahlung parameter Ψ , which is related to the average critical energy of the radiation emitted by the beam particles. It can be calculated as

$$\Psi = \frac{2}{3} \frac{E_{crit}}{E_0} = \frac{\hbar \gamma^3 c}{\rho E_0} \quad (4)$$

Here ρ is the bending radius of the particle trajectory and γ the relativistic factor. The average $\langle \Psi \rangle$ is given by the beam parameters and the fine structure constant α as

$$\langle \Psi \rangle \approx \frac{5}{6} \frac{Nr_e}{\alpha \sigma_z (\sigma_x + \sigma_y)} \quad (5)$$

The beamstrahlung spectrum is described by the Sokolov-Ternov spectrum. For $\Psi \ll 1$ the spectrum corresponds to synchrotron radiation and one speaks of the classical regime. For $\Psi \gg 1$ the radiation is partially suppressed since the critical energy is above the beam energy. This is the so-called quantum regime. Only CLIC at 3TeV will operate in this regime. In the classical regime, the number n_γ and average energy E_γ of photons emitted per beam particle depends on the bunch charge and transverse dimensions

$$n_\gamma \propto \frac{N}{\sigma_x + \sigma_y} \quad E_\gamma \propto \frac{N}{(\sigma_x + \sigma_y) \sigma_z} \quad (6)$$

Typically one is only interested in collisions with energies very close to the nominal. In this case often the emission of a single photon is sufficient to place the particle outside of this energy range. Hence the number of emitted photons has to be limited. More detail will be given in the final section on horizontal beam size choice.

For a given N and σ_z , one has to use a relatively large sum of the transverse beam sizes $\sigma_x + \sigma_y$. The luminosity is proportional to $1/(\sigma_x \sigma_y)$, so one aims to minimise the product of the two beam sizes. Both goals can be simultaneously achieved by using a flat beam $\sigma_x \gg \sigma_y$; the horizontal beam size is chosen to be larger than the vertical, since the damping rings naturally deliver a horizontal emittance that is larger than the vertical. Using $\sigma_x + \sigma_y \approx \sigma_x$ one finds that N/σ_x in Eq. (2) is proportional to the number of beamstrahlung photons. As one can see in Table 1, all projects have a value of n_γ in the range of 1.5-2. The rationale for this choice will be revisited in section on the choice of the horizontal beam size. The typical angular distribution of the photons is small, similar to the one of the beam particles after collision. Hence the beamstrahlung does not generate direct background in the detector.

2.22.3.4 Vertical Beam Size and Waist Shift

The vertical beam size is limited by the beam emittance and by the ability to focus the beam. Here, the practical limitations for the focusing will be ignored and only the impact of the vertical beta function will be considered assuming perfectly linear behaviour of the beam. For weak beam-beam effects, the luminosity is limited by the hourglass effect similar to circular colliders. The left-hand side of Fig. 1 shows the luminosity ignoring hourglass effect (“geom.”) and including it (“hourg.”). The optimum is at $\beta_y = 0.25 \sigma_z$. The beam-beam forces shift the optimum to much larger beta functions around $\beta_y \approx \sigma_z$ (“ILC” and “CLIC”). The pinching of the beams is more efficient if their divergence is smaller.

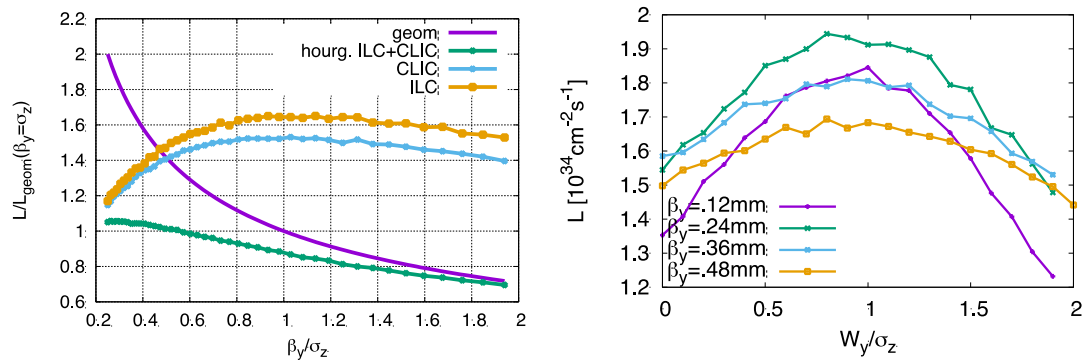


Figure 1: Left: Luminosity as a function of the vertical beta function (normalised to the bunch length). Right: The luminosity in ILC as a function of the longitudinal shift of the vertical waist for different vertical beta functions.

If the beam-beam forces are weak the maximum luminosity is obtained when the vertical waists of the two beams are placed at the collision point. A distance W_y of the waists to the collision point leads to a reduced luminosity. In presence of beam-beam forces it can be better to have the vertical waists before the collision point [16], which can increase the luminosity by up to 25%. The exact location and the luminosity gain also depend on the beta function. This is shown in Fig. 1 for ILC. A small beta function of $\beta_y=0.12\text{mm}$ gives worse performance for centred waists than $\beta_y=0.48\text{mm}$. After the optimisation of the waist it however yields more luminosity.

2.22.3.5 *Beam Offsets*

The beam-beam forces also modify the luminosity reduction resulting from vertical beam-beam offsets. For weak disruption the luminosity decreases somewhat more slowly with offset than for rigid beams because the beam attract each other. In contrast, for larger disruption, already very small offsets can lead to a large loss of luminosity. This is due to the fact that the collision becomes unstable, the so-called kink instability, which is a typical two-stream instability. Again for larger offsets, the beam-beam forces maintain more luminosity than for rigid beams. Figure 2 illustrates this for different disruption parameters.

To avoid luminosity reduction, control of the beam-beam offset is required at the level of a fraction of a nanometre. The motion of the ground and vibrations of technical components make this a challenging task. Two main methods are used to address this challenge. First, in case of CLIC, the beam guiding magnets are stabilised with active feedback systems that sense the motion of the magnet and correct it using movers. Second, in both ILC and CLIC, the beam-beam offset is measured and corrected with a beam-based feedback system. In case of ILC this feedback system can correct from one bunch to the next within the pulse, in CLIC it has a latency of a few bunch crossings and mainly acts from one pulse to the next. This feedback can easily detect an offset even of a fraction of a nm, since the resulting deflection of the beams is in the order of tens of μrad . A few metres downstream of the collision point such an angle has translated into an offset that can be easily measured with a beam position monitor.

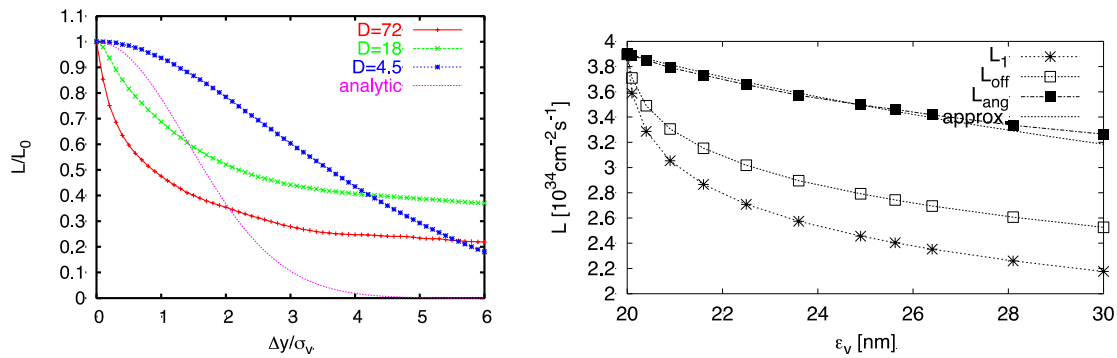


Figure 2: Left: Luminosity as a function of offset for different vertical disruption parameters. Right: The luminosity as a function of the emittance in the case of TESLA an older linear collider design.

2.22.3.6 *The Banana Effect*

For strong vertical disruption (typically $D_y \geq 15$) correct modelling of the full 6D phase space of the beam. The projected emittance is not a good measure of the luminosity any more. This is due to the so-called banana effect described in [17] for TESLA, an older linear collider design similar to the ILC. The luminosity drops much faster with increasing beam emittance than anticipated from the projected emittances [18].

The right-hand side of Fig. 2 shows an example where the main linac wakefield effects are included. Similar results are obtained for other sources of emittance growth, e.g. ground motion in the beam delivery system [19]. In the figure, the horizontal scale indicates the emittance at the interaction point, which consists of an uncorrelated part of 20 nm and an additional contribution from the main linac wakefields. The luminosity is shown on the vertical axis. The curve “approx” assumes that the luminosity scales with $1/\sqrt{\epsilon_y}$. The curve “ L_1 ” shows the luminosity if both beams are centred in position and angle. Even a small emittance increase yields a very strong luminosity loss since the collision is unstable as a result of the high disruption.

The luminosity can be recovered if a full luminosity optimisation is performed at the interaction point by varying the beam-beam offset (L_{off}) and by varying offset and angle (L_{ang}). This procedure however requires that the luminosity is measured online. Hence it takes much more time than a simple beam position monitor based feedback. In ILC it is foreseen to perform such an optimisation during each bunch train. For a smaller disruption, as in CLIC, the banana effect is negligible. Hence a luminosity optimisation scan during the train is not required.

2.22.3.7 *Beam-beam Background and its Impact on the Detector Design*

The beam-beam effects lead to the generation of background for the physics experiments. This includes the production of electrons and positrons, muons, and hadrons. These effects can significantly impact the detector design and close interaction of accelerator and detector design is required. However, this subject cannot be covered in this paper.

2.22.4 *Choice of Horizontal Beam Size*

A lower limit of horizontal beam size and beta function arises from the beamstrahlung to limit the degradation of the luminosity spectrum. It is important to note that the luminosity

spectrum is also affected by another process. If particles collide, they can emit a photon just before the collision as a part of the physics process, this is called Initial State Radiation (ISR). This emission is a radiative correction to the physics process. In contrast to beamstrahlung, it therefore happens only to colliding particles that undergo some physics process. However, it will degrade the luminosity spectrum in a similar fashion to beamstrahlung; the typical centre of mass energy spectrum of the colliding electrons and positrons is shown on the right-hand side of Fig. 3.

Usually the experiments require that the degradation of the luminosity spectrum due to beamstrahlung is similar to the degradation due to ISR. As a measure one uses the ratio of the luminosity $L_{0.01}$, i.e. the part above 99% of the nominal centre of mass energy, and the total luminosity. In case of CLIC at 380 GeV a ratio of 60% has been targeted.

The total and peak luminosity is shown in Fig. 3 for CLIC at 380 GeV and ILC at 500 GeV as a function of the horizontal beta function. One can observe that the total luminosity increases strongly for smaller beta functions. It increases even faster than the geometric luminosity. This is a result of the fact that a smaller horizontal beam size increases the disruption and therefore leads to an increase in the pinch enhancement factor H_D . However the peak luminosity only increases slightly for smaller beam sizes. Hence the ratio of peak to total luminosity decreases rapidly for small beta functions, which yields a lower limit. It should be noted that additional lower limits for the horizontal beta function exist, e.g. from the ability to design the beam delivery system. With the chosen value, CLIC indeed reaches a ratio of 60%, as one can see on the left-hand side in Fig. 3.

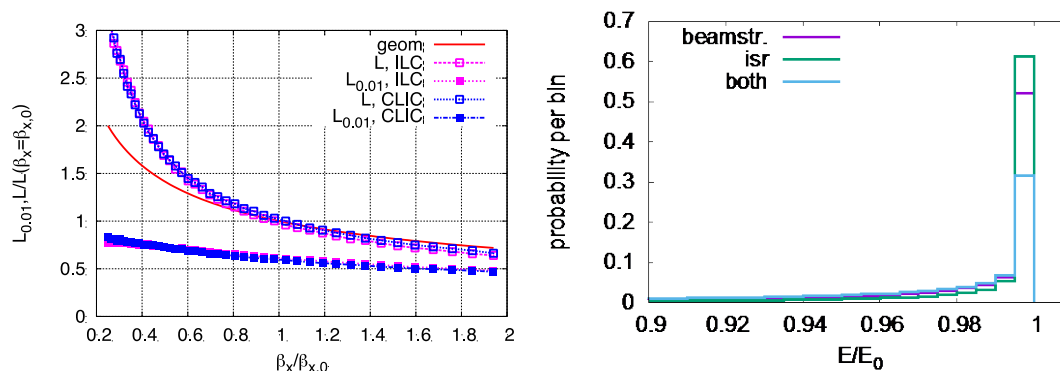


Figure 3: Left: Luminosity as a function of the horizontal beam size. Right: The luminosity spectrum from beamstrahlung and from ISR.

Recently a study has been carried to identify the optimum choice of beamstrahlung level for CLIC and ILC [20]. To this end one of the main physics processes that should be studied at 380 GeV has been selected. This is the reconstruction of the total higgs production cross section in the channel $e^+e^- \rightarrow Zh$. In this analysis only the Z is measured and from the initial beam conditions and the Z energy and momentum the missing particle is reconstructed indirectly. It is then determined whether this particle is consistent with the higgs. This measurement has the advantage that the higgs production rate can be measured independent of the higgs decay. One would even be able to see invisible higgs decays (even if they are not expected). This measurement is expected to be very sensitive to beamstrahlung since the beamstrahlung will change the initial conditions. In particular the assumed energy of the colliding particles will be wrong. This leads to a wrong reconstruction of the missing particle.

In the study the beam parameters have been optimised assuming a constant time of operation. The horizontal beam size has been varied and all other parameters were left constant. A wide beam will give less beamstrahlung but also less integrated luminosity. For each beam size the luminosity spectrum has been simulated with GUINEA-PIG and the corresponding higgs events been generated using WHIZARD [21]. In addition, also the main background events that could fake the signal have been produced; their number is larger by some orders of magnitude. The particle energies have then been randomly modified corresponding to the detector resolution. Finally the events have been analysed using TMVA [22] a boosted device tree classifier. This allowed to determine the expected accuracy of the measured higgs production cross section.

The study concluded that pushing the horizontal beam size further would improve the performance slightly. However the improvement is only a few percent compared to the nominal parameters, in spite of the fact that the luminosity would about double. Given the difficulty to obtain narrower beams this small improvement appears not too relevant. This supports that the choice that has been made for the acceptable level beamstrahlung is good.

It should be noted that in case of CLIC at 3TeV, the requirement on the spectrum quality is somewhat relaxed (30%), since also the tail of the luminosity spectrum contributes to the creation of interesting physics events. An important example is the double Higgs production, which allows to measure the Higgs self-coupling. Basically the whole luminosity spectrum contributes to this production process at high energies, increasing the importance of the total luminosity with respect to the peak luminosity.

Further studies of the optimum beam parameter choice will be useful in order to obtain the optimum exploitation strategy for future linear colliders.

2.22.5 Conclusion

Beam-beam effects drive the choices of linear collider designs; in particular the choice of flat beams. For otherwise fixed beam parameters the horizontal beam size choice is driven by the emission of beamstrahlung that leads to a degradation of the luminosity spectrum. This in turn limits the luminosity that can be achieved. Up to now, the acceptable level of beamstrahlung has been chosen by comparing to initial state radiation. An example is the recent optimisation of the CLIC parameters for the first energy stage of 380 GeV centre-of-mass. A recent study has used an important physics experiment at this energy in order to verify this choice for CLIC and ILC. It concluded that slightly higher levels of beamstrahlung would still improve the resolution of the physics analysis by a few percent. Hence a more aggressive choice of beamstrahlung level is acceptable but can yield only minor improvements of the physics in spite of a much higher luminosity.

2.22.6 References

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