A POTENTIAL SIGNAL FOR LUMINOSITY OPTIMISATION IN CLIC

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Abstract

Luminosity optimisation will be challenging in the compact linear collider (CLIC) studied at CERN. In particular, the signals which can be used for luminosity optimisation need to be identified. The strong beam-beam interaction in CLIC will give rise to the emission of a few megawatts of beamstrahlung; this is a potential candidate for such a signal. In this paper luminosity optimisation using the beamstrahlung is attempted for realistically shaped bunches.

INTRODUCTION

In the Compact Linear Collider (CLIC) [1], very small emittance beams are focused to a vertical spot size of about $0.7\mathrm{nm}$ in the interaction point, see table 1. The collision parameters, such as collision offset and angle, need to be carefully tuned in order to maximise luminosity. In order to optimise these parameters a fast luminosity signal is needed. Three candidate processes that could provide such a signal have been investigated in [3], beamstrahlung, bremsstrahlung and incoherent pair creation. In CLIC also a fourth process, the coherent pair creation is significant enough to be used as a signal.

Beam-Beam Interaction and Beamstrahlung

Due to the high beam density at collision each beam produces strong electro-magnetic fields, which focus the oncoming beam. The resulting acceleration of the particles towards the beam axis leads to a reduction of the effective beam size during collision, which results in increased luminosity. However, this acceleration also leads to the emission of beamstrahlung, a process comparable to the emission of synchrotron radiation in a magnetic field. Due to this effect, each particle emits on average about 1.5 photons, which carry away about 20% of the particle energy. The total energy of the photons depends on the dimensions and charges of the beams but also on other parameters, e.g. their relative offsets.

Bremsstrahlung

The bremsstrahlung or radiative Bhabha scattering has frequently been used for luminosity measurements. If two charged particles collide the exchange of a virtual photon can induce the emission of a real photon by one of the beam particles and hence a significant energy loss. The emitting particles receive little transverse kick and needs to be seperated from the beam by use of dispersion. In CLIC, these particles cannot be distinguished from beam particles which lost most of their energy by emission of beamstrahlung.

Incoherent Pair Creation

Two colliding beamstrahlung photons can produce a secondary electron-positron pair. Equivalently a pair can be produced by the collision of a photon and an electron or positron, in which case the original electron or positron is preserved. Finally a colliding electron-positron pair can create an additional pair. The total number of these particles is of the order of 10^5 per bunch crossing and most of them have small transverse momenta at production but are deflected by the beam fields. The electron of the pair can either fly into the direction of the electron or the positron beam. If it follows the electron beam it will be focused by the positron beam. If it flies in the other direction it will be deflected away from the axis by the electron beam. The pair particles can therefore reach quite large angles. This makes it possible to detect them at some distance from the beam. While the total number of pairs depends on many variables it is strongly dependent on the luminosity. By measuring the integrated energy of the pairs above a certain angle with respect to the beam axis it is thus possible to obtain a signal for luminosity optimisation [2][3]. The procedure consists of modifying one beam parameter at the time (e.g. the longitudinal position of the waist) and aiming to maximise the pair signal. In the case of CLIC the low energy tail of the particles from coherent pair creation may mask the incoherent pairs.

Coherent Pair Creation

In a very intense field the beamstrahlung photons can directly turn into an electron-positron pair. This is called coherent pair production because the photon interacts with the coherent field of the oncoming particles. The number of these pairs depends strongly on the field strength; in the case of CLIC it is only one order of magnitude smaller than the number of original beam particles.

The coherent pairs are deflected by the beam fields in the same way as the incoherent ones. The coherent pairs add a significant positron component to the spent electron beam and vice versa, which can easiliy be seperated from the rest of the spent beam using a dipole field. The power of the coherent pairs will in many cases depend in a similar fashion on the beam properties as the beamstrahlung, so it can also be used as a tuning signal. The relative changes

Table 1: Important main beam parameters of CLIC.

parameter	symbol	unit	value
centre-of-mass energy	E_{cm}	TeV	3
particles per bunch	N	10^9	4
hor. beam size at collision	σ_x	nm	≈ 60
vert. beam size at collision	σ_y	nm	≈ 0.7
hor. emittance end of linac	ϵ_x	nm	680
vert. emittance before linac	ϵ_y	nm	5
vert. emittance end of linac	ϵ_y	nm	10

of the pair power, e.g. with offset, can be even more pronounced than the change in the beamstrahlung, since the field strength during collision enters twice, in the generation of the beamstrahlung photons and in the transformation of these photons into coherent pairs.

SIMULATION PROCEDURE

In order to use realistic bunch shapes at the interaction point the beam transport through the main linac and the beam delivery system is fully simulated using the code PLACET [4]. The elements of the main linac are offset according to the anticipated alignment errors. Full beam-based alignment of the linac is then simulated. It is assumed that the beam delivery system is aligned perfectly but the non-linear and synchrotron radiation effects in this system are taken into account. The beams obtained in this way are collided pair-wise using the beam-beam simulation code GUINEA-PIG [5].

A number of random processes occur in the simulation procedure. The initial misalignments of the elements in the main linac is random. This corresponds to the real situation where each element has a fixed, if unknown, position error. One can thus only predict the mean luminosity with an uncertainty due to the fact that the actual misalignments are unknown. The luminosity for a fixed machine can be simulated only with limited precision. To chose the initial particle distribution in PLACET a random number generator is needed. Also the emission of sychrotron radiation in the beam delivery system is a stochastic process. In the beam-beam simulation the generation of beamstrahlung as well as the generation of coherent pairs from beamstrahlung photons require random number generators. Since the number of macro-particles used in the simulation is much smaller than the number of beam particles in the real machine (5×10^4 as compared to 4×10^9), the simulations tend to fluctuate noticeably. In order to reduce the fluctuation each machine is simulated five times and the average luminosity and luminosity signal is used.

RESULTS

Optimisation of Collision Offset and Angle

The tuning is performed in two steps. First the vertical offset between the beams is varied in order to find the position that minimises the production of coherent pairs. Then the crossing angle is varied in the same way again minimising the total energy in the coherent pairs. A total number of 50 machines has been simulated. In the first step, using the machines optimised with the pairs an average of about 99.6% of the optimum performance was obtained. The optimisation of the crossing angle yields again 99.7% of the achievable optimum luminosity.

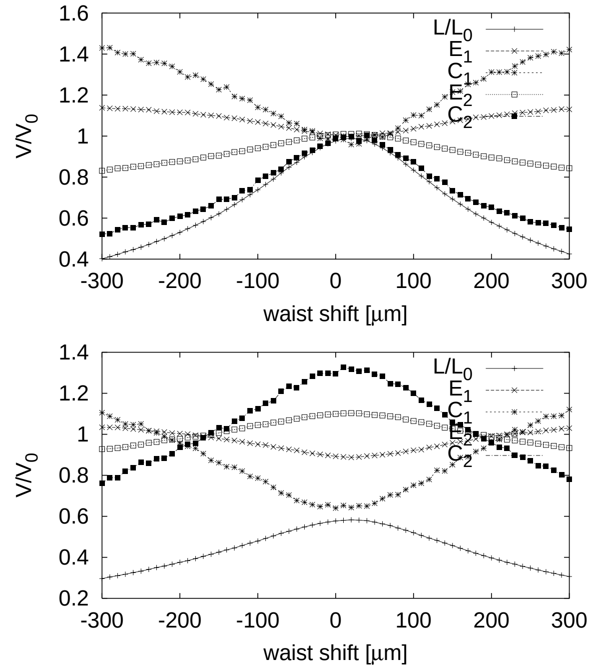

Figure 1: Examples of the waist optimisation. In the upper plot, the waist of beam 2 is in optimum position and beam 1 is scanned. The variables E_i and C_i are the beamstrahlung and coherent pair power of beam 1 and beam 2, respectively. The coherent pair power gives a more pronounced signal. In the lower plot, beam 2 has a waist shift of $200\mu\mathrm{m}$.

Optimisation of the Waist Position

The longitudinal position of the beam waists will need to be frequently optimised. Here we base the algorithm on the observation from reference [2]. If the vertical size of the first beam is larger than that of the second, the first beam will emit more beamstrahlung and the second less. In principle, the size of one beam can thus be minimised by minimising the beamstrahlung it emits. It should be noted that the beamstrahlung is almost independent of the absolute vertical beam size but only depends on the relative size of the two beams.

Figure 1 shows two examples of a beam size scan using simplified Gaussian beams at the interaction point. The size of beam 1 is changed by moving it's vertical waist; in one case the waist of the unmoved beam 2 is in optimum position, in the other it is shifted by $200\mu\mathrm{m}$. The optimum waist position of beam 1 is recovered in both cases.

To evaluate the procedure with realistic bunches the same simulation procedure as for the offsets was used to generate the bunches. Then the waist of one beam was scanned and the position with the minimum power of coherent pairs used. The average luminosity achieved was 98.8% of the actual optimum. A slightly better result can be obtained by using the minimum of $P_{coh,1} - P_{coh,2}$, namely 99.1%. Using the beamstrahlung yields similar results.

The coherent pairs or beamstrahlung thus provide a signal that can be used for waist optimisation. In contrast, reference [3] concluded that this is not the case. The difference arises from the fact that the angular acceptance of the beamstrahlung monitor in that reference was limited, while here the full power is measured.

Optimisation of a Tuning Bump

The results above indicate that an increase in the vertical beam size may be tuned out using the coherent pair signal. However, in some cases the vertical beam size increase is not coherent along the bunch. Transverse wakefield effects for example introduce a correlation of the vertical offset of the beam particles with their longitudinal position in the bunch. The projected beam size is in this case increased but for short slices of the bunch it is not.

In order to stay below the tolerable emittance growth in the main linac, emittance tuning bumps will be used in the main linac. These bumps consist of accelerating structures that can be moved transversely. This allows to compensate the integral of the transverse wakefield kicks due to the misalignment of the accelerating structures in the linac. The strength of the kick the structure applies to the beam particles depends on their longitudinal position. After some initial optimisation in order to minimise the emittance, these bumps can also be used to directly optimise the luminosity.

Here, only a single bump is simulated for each of the 50 realistic machines. The same procedure as for the waist shift was applied, only that the position of the structures in the tuning bump was varied rather than the waist position, see Fig. 2. This procedure was able to recover 99.2% of the possible luminosity. It remains to be investigated if the coherent pair monitor performs equally well if a number of tuning bumps is optimised one after the other.

A potential disadvantage of using the coherent pair signal or some other luminosity related signal to optimise the bumps is that in this case the electron and positron linac cannot be treated independently as is the case if the emittance of the two linacs is optimised. However, there are potential advantages. First, one wants to optimise the luminosity and use a signal as closely related to luminosity as possible should give best performance. Secondly, the emittance measurement is a lengthy procedure. The beam profile has to be scanned using a laser wire, so a number of pulses are required for each measurement. The pair signal is available parasitically for each pulse. The best strategy for the bump optimisation will need to be determined taking into account the advantages and disadvantages of both methods.

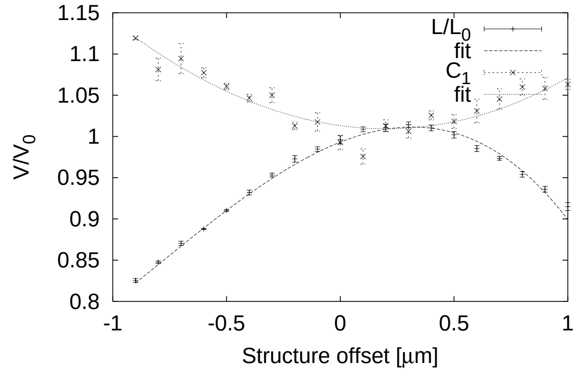

Figure 2: Example of the optimisation of a main linac bump for beam 1. The luminosity (normalised to the mean of the 50 different machines) and the coherent pair power of beam one are shown (also nomralised to the mean of 50 machines). The error bars were derived running the smae case five times using different seeds for the random number generators.

CONCLUSION

Fast signals are needed that can aid to speed up the luminosity optimisation in CLIC. Several signals can be used for this purpose, e.g. the incoherent pair creation, the beamstrahlung and the coherent pair creation. While the latter two are not proportional to the luminosity they can be used to optimise single collision parameters. The vertical offset between the beams can be optimised by performing an offset scan in order to minimise the total beamstrahlung or coherent pair power. In the same fashion one can optimise the collision angle.

A more complex tuning of the collision is also possible. The longitudinal position of the waist can be optimised. Also the main linac tuning bumps can employ the beamstrahlung and coherent pairs as a tuning signal.

Further studies should derive a more complete tuning strategy and include dynamic effects, such as the jitter of beamline elements or of the accelerating RF.

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