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SINGLE-BUNCH PARAMETERS PROPOSED FOR 500 GEV AND 1 TEV CLIC OPTIONS

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Abstract

Single-bunch parameters are updated for the 500 GeV (centre-of-mass) option in order to get a luminosity that is as high as possible, together with acceptable beam-strahlung effects. With the same requirements, single-bunch parameters are proposed for the 1 TeV option. They are all based on simulations of the beam behaviour in the main linac and of the beam–beam phenomena at collision. The expected single-bunch luminosity is in excess of 10^{33} cm^{-2} s^{-1} for the 500 GeV option, and lower than 10^{34} cm^{-2} s^{-1} for the 1 TeV option, where multibunch mode might be required.

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Corrigendum

February 1995

To: Those on CLIC Note Distribution List

From: Hannelore Guemara

Please replace pages 1 and 2 of CLIC Note 264 with the enclosed page.

1 INTRODUCTION

The last list of parameters for a 2 × 250 GeV CLIC collider [1] was established on the basis of the beam characteristics and emittances at the linac end, obtained by tracking, and on an optimization of the final focus parameters with the code RBEAM developped at CERN (L. Wood). These were based on a single bunch of 6×10^9 going through the final focus acceptance. The rationals [2] were to fix β_y^* from the bunch length σ_z, deduce the nominal beam sizes σ_x^* and σ_y^* from the Oide limit, check aberration effects and keep the relative energy loss δ_B low enough (~ 5%, because of the unavoidable presence of initial state radiation). The 'beam strahlung parameter' Υ and the loss δ_B (Appendix) were estimated to be 0.18 and 5.9% respectively [4], from the analytical expression and the code RBEAM existing at the time. Since then, the analytical expressions have changed [6, 7], the code found to be incorrect [3] and other values have been subsequently published in CLIC parameter lists [5], with a much higher δ_B. This fact and the necessity to control beam-beam quantities at collision lead to a reevaluation and a search for better sets of CLIC beam parameters.

2 STARTING POINT

The first thing to do was to re-evaluate the most relevant quantities, for the basic parameters of Ref. [1]. This was done by using the recent analytical description [6, 7] of beam–beam phenomena, recalled in the Appendix. In parallel, independent numerical simulations were run by P. Chen using ABEL [8] and V. Telnov using his own code [9]. The values obtained are listed in Table 1.

Table 1

Beam–beam quantities with previous 2 × 250 GeV CLIC [1]

Analytical computation (App.)	
Luminosity with pinch	2.2×10^{33} cm^{-2} s^{-1}
σ_z to β^* ratio, A_x/A_y	0.077/1.0
Disruption parameter D_x/D_y	1.34/15.3
Enhancement factor H_{D_x} / H_{D_y}	5.1/3.13
Nominal beam sizes σ_x^* / σ_y^*	90/8 nm
Beam sizes with pinch $\overline{\sigma}_x^* / \overline{\sigma}_y^*$	40/5.5 nm
Luminosity enhancement H_{D_t}	3.3
Beamstrahlung parameter Υ	0.35
Photon number n_γ	4.7
Relative energy loss δ_B	0.36
Chen's	
Luminosity enhancement H_{D_t}	3.0
Photon number n_γ	3.66
Relative energy loss δ_B	0.20
Telnov's	
Luminosity enhancement H_{D_t}	2.6
Relative energy loss δ_B	0.23
Luminosity fraction (> 98% c.m. energy) δ_L	18%

Table 1 teaches us a certain number of things. The discrepancy between approximate formulae and numerical simulations is relatively large, probably because the beam is quasi-flat ($R = \sigma_x^*/\sigma_y^* = 11$). The scaling laws are good only to ±10%, or more in this case. Nevertheless, two independent simulations give very consistent results. The number of emitted photons per electron and the energy loss δ_B (calculated to be between 20 and 23%) are too large with the old set of parameters, while the fraction of the luminosity spectrum contained within 2% of the centre-of-mass energy δ_L is too low. Beam parameters must be found in order to improve this situation, and to get a δ_B of around 5 to 7% and a δ_L near to or larger than 50%.

3 SEARCH FOR PARAMETER OPTIMIZATION

Starting from simplified formulae for L and δ_B (Appendix), it is easy to indicate three possibilities for decreasing δ_B and their incidence on L:

$$L \sim \frac{N_b^2}{\sigma_x^* \sigma_y^*} \qquad \delta_B \sim \frac{N_b^2}{\sigma_z \sigma_x^{*2}} . \tag{1}$$

Combining these two relations and eliminating σ_x^* and σ_z in favour of the vertical emittance ε_y, one can write

$$L \sim N_b \sqrt{\frac{\delta_B}{\varepsilon_y}} . \tag{2}$$

1. The number of particles per bunch can be reduced, but this gives a corresponding reduction in luminosity, which cannot be recommended.

2. The bunch length σ_z can be increased, which does not change L directly, but may boost wake-field effects and then raise σ_y^*. However, with CLIC parameters, the scaling laws show that the dependence of δ_B on σ_z is low (Fig. 1). To gain significantly, σ_z would need to be increased by a prohibitive factor of three or four.
   It must be noted that the apparent gain on δ_B for small σ_z is not welcome for physics and luminosity distribution. The amplitude dN/dE of the photon spectrum decreases with the energy and is truncated at the electron energy. When σ_z gets smaller, both γ-spectrum and L-distribution spread more and the resulting δ_B decreases in an undesirable way (luminosity peak is wider).
   The conclusion is therefore that the bunch length σ_z can be selected independently of the arguments based on beam–beam phenomena, but in order to minimize the energy spread in the main linac (bunch shaping included) [10].

3. The horizontal beam size of σ_x^* can be enlarged, with the advantage that, according to Eq. (1), L decreases less rapidly than δ_B. Moreover, for constant δ_B, it is possible to adjust independently the intensity N_b and the dimension σ_x^*, as can be seen by using the scaling laws (Fig. 2). The resulting luminosity varies, however, proportionally to N_b and depends nonlinearly on ε_y. Our search for the optimum values for these two parameters has been guided by formula (2). Keeping δ_B constant and near the desired value, N_b has to be pushed up until the maximum of the quantity $N_b/\sqrt{\varepsilon_y}$ has been passed and found by beam tracking in the main linac [11]. Limited investigations (with a simple one-to-few trajectory correction) gave a curve (Fig. 3) with a maximum

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around $N_b = 8 \times 10^9$ (beyond this value, the emittance begins to blow up significantly). By comparison with the case $N_b = 6 \times 10^9$, for which the target value of $\gamma\varepsilon_y$ is 2×10^{-7} rad m [11, 12], the value at 8×10^9 is approximately 30% larger, making it possible to boost L by ~ 17%.

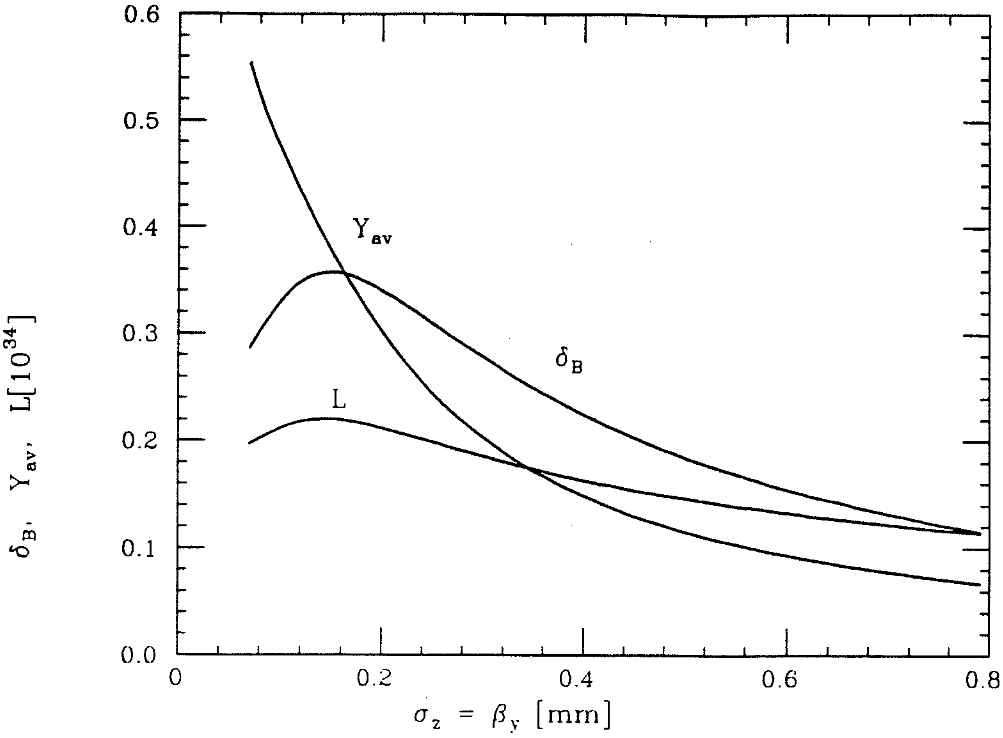

Fig. 1 Variation of the beamstrahlung parameter, relative energy loss and luminosity, with the bunch length.

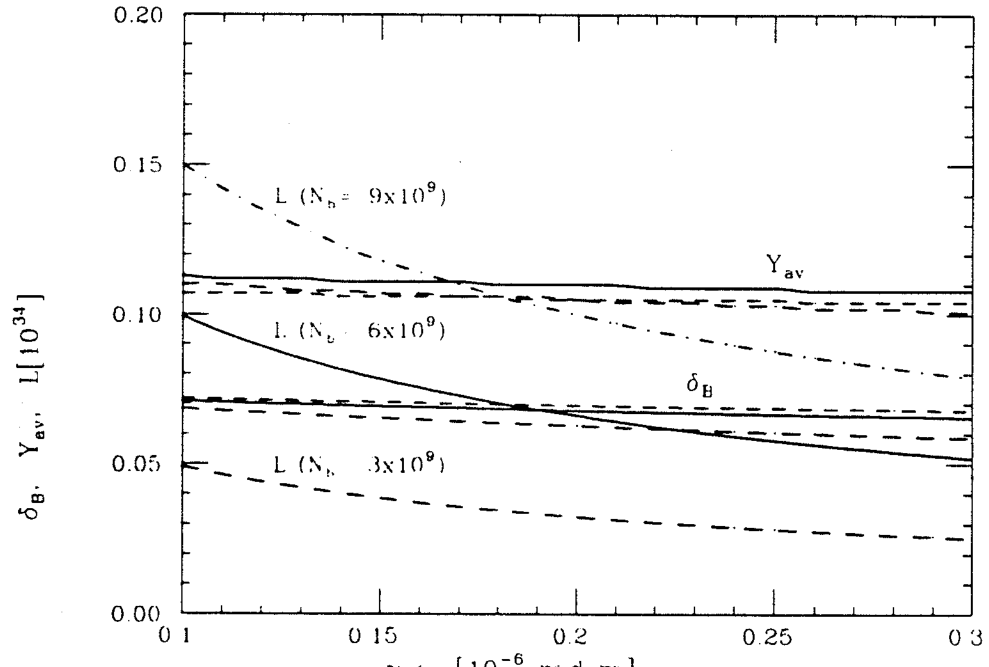

Fig. 2 Variation of luminosity with the vertical emittance at almost constant energy loss, but different bunch population.

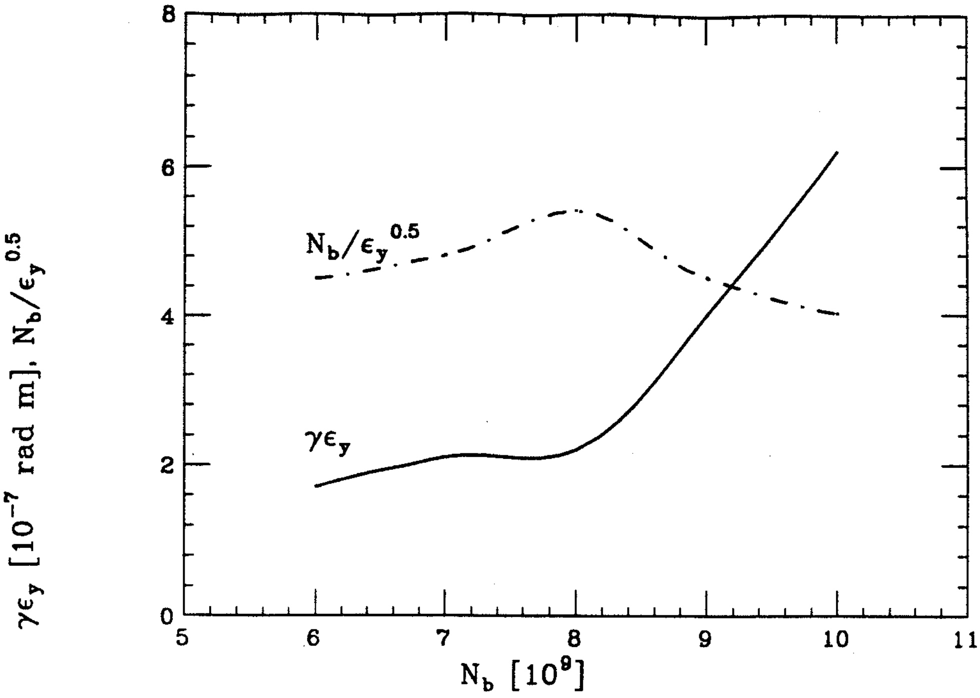

Fig. 3 Approximate variation of $N_b / \sqrt{\varepsilon_y}$ with the bunch population.

The vertical emittance $\gamma\varepsilon_y$ is obviously a very critical parameter. The quoted target value of $\gamma\varepsilon_y = 2 \times 10^{-7}$ rad m has been obtained by tracking the beam in a 250 GeV linac, with one-to-few trajectory corrections, different energy scaling [12], wake-free or dispersion-free algorithms that allows coping with 10 µm r.m.s. alignment tolerances for cavities, and position monitors [13]. The question that one may ask is whether better results are still possible by using even more elaborate algorithms. Two methods of correction had not yet been considered for CLIC up to this point. The first consists of having non-dispersive bumps in limited regions of the linac in order to position the beam off-centre there and globally compensate for the wake-field perturbations [14]. This has been recently studied [15] and found hardly applicable to CLIC, because the local strong wake-fields destroy the required characteristics of the nondispersive bumps. The second method exploits the beam-based alignment technique for correction, presented elsewhere [16]. In CLIC, this would mean measuring and then correcting, on top of the trajectory itself, a trajectory difference obtained with nominal bunch intensity (full wake-fields) on one side and with strongly reduced intensity (factor 10, i.e. almost no wakes) on the other [17]. Assuming that the pickup resolution can be maintained in a large range of beam intensity by improving the electronics, first simulated results look promising. If they are confirmed, the value of $\gamma\varepsilon_y$ at 250 GeV could perhaps be reduced by a factor of ~ 2 for unchanged alignment tolerances.

4 PROPOSED PARAMETERS AT 500 GEV C.M.

On the basis of the preceding, we can now propose single-bunch parameters for 500 GeV in the centre of mass. They imply a certain number of assumptions briefly listed as follows

- The population per bunch can be increased to 8×10^9 before the vertical emittance breaks up.

- The normalized vertical emittance can probably be improved by a factor of ~ 2 at constant intensity using additional corrections, but will blow up by some 30 to 50% when N_b is raised to 8×10^9. This gives an altogether new target value of about 1.5×10^{-7} rad m for $\gamma\varepsilon_y$.
- The bunch length σ_z is set to minimize the energy spread in the linac (0.2 mm at $N_b = 8 \times 10^9$) and β_y^* is taken as equal to 0.9 σ_z (i.e β_y^* = 0.18 mm), to reduce the hourglass effect as much as possible.
- The ratio of nominal beam sizes is set equal at ~ 33, in order to get an energy loss δ_B of below 7% and to make sure that the integrated luminosity in the last two percentage points below the c.m. energy exceeds ~ 50% of the total luminosity (important in the search for a mass resonance, since it improves the signal-to-noise ratio and reduces the duration of the experiment).
- The normalised horizontal emittance has been relaxed to 3×10^{-6} rad m, since tracking shows that a larger $\gamma\varepsilon_x$ helps the minimization of $\gamma\varepsilon_y$ through a fine adjustment of the microwave quadrupoles. This choice implies that β_x^* = 10 mm.
- The repetition rate is adjusted to give a maximum RF consumption of 100 MW.

The resulting beam parameters are summarized in Table 2, together with the expected performance deduced either from the scaling laws of the Appendix or from numerical simulations of the collisions.

5 PROPOSED PARAMETERS AT 1 TEV C.M.

Similarly, we are in the position to propose single-bunch parameters for 1 TeV in the centre of mass, following the same logic as in the 500 GeV case. Many assumptions are unchanged, excepting however the transverse emittances; they are therefore listed below:

- The bunch population N_b, the bunch length σ_z and the β– functions at the collision point have the same values as before (Section 4) since the arguments remain unchanged.
- Since the linac is now twice as long, the vertical emittance (normalized) is allowed to grow a little more and reach a value of 2×10^{-7} rad m (to be checked by tracking). As γ is twice as high though, the vertical beam size becomes 6 nm.
- Keeping the same beam-size ratio of 33 and β_x^* of 10 mm gives a horizontal-beam dimension of 200 nm. This then corresponds to a normalized horizontal emittance of 3.9×10^{-6} rad m, which equally allows a larger blow up.
- The repetition rate is maintained at the same value, accepting that the power required now doubles to about 200 MW.

The resulting set of beam parameters is summarized in Table 3, together with the expected performance, which has been estimated in two different ways: the first estimate comes from the formulae recalled in the Appendix and giving convenient scaling laws, while the second is obtained from numerical simulations of the beam–beam collisions.

6 CONCLUSIONS

The present paper gives an update of the single-bunch beam parameters for CLIC at 500 GeV (Table 2) and 1 TeV (Table 3) in the centre-of-mass, and gives a brief summary of a work still in progress. This proposal aims at reasonable beam–beam parameters with a single-bunch luminosity as high as possible. Tables 2 and 3 simultaneously give performance estimates obtained from the approximate formulae recalled in the Appendix and from two independent numerical simulations done with different codes [8, 9]. This shows the rather good agreement between the different calculations, although checking the results through actual simulations once the parameters are fixed remains important.

Table 2 indicates that, for the 500 GeV CLIC, the single-bunch option makes it possible to get a luminosity in excess of 10^{33} cm^{-2} s^{-1} and to control the beam–beam phenomena. By contrast, for the 1 TeV CLIC, Table 3 shows that the single bunch option does not permit the reaching of a luminosity of 10^{34} cm^{-2} s^{-1}. Therefore, multibunch mode must still be considered for the expansion in energy. However, it must be noted that because of the long range wake fields, the parameters of each individual bunch in a train will have to be optimized again and will likely differ from those of Table 3.

Acknowledgements

The authors are very grateful to P. Chen and V. Telnov who introduced the physics of the collisions and kindly ran the simulation codes.

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APPENDIX

According to the formalism elaborated in Refs. [6, 7], the beam–beam phenomena in linear colliders can be described approximately by algebraic formulae which are partly deduced from numerical simulations. These formulae give good results in the asymptotic cases of either a round or flat beam (with a large and fixed horizontal dimension) but are less reliable in the intermediate case of quasi-flat beams. In spite of their limitation, they offer the advantage of providing simple scaling laws that become very useful in the search for optimized beam parameters, though verification by simulations are eventually essential. Let us recall here the relations we have used in the course of the work reported in this note.

The single bunch luminosity is given by the basic relation,

$$L = \frac{N_b^2}{4\pi} \frac{f_{rep}}{\bar{\sigma}_x^* \bar{\sigma}_y^*} , \tag{A1}$$

where N_b is the number of particles per bunch and f_{rep} the repetition rate (for k_b bunches per pulse, then L is simply multiplied by k_b). In order to properly describe the beam-beam phenomena, the disruption effect must be included in both transverse dimensions. Therefore, in Eq. (A1), the nominal beam sizes have been replaced by effective beam sizes, defined by

$$\bar{\sigma}_x^* = \frac{\sigma_x^*}{(H_{D_x})^{1/2}} \qquad \bar{\sigma}_x^* = \frac{\sigma_y^*}{(H_{D_y})^{f(R)}} , \tag{A2}$$

where the exponent f(R) depends on the nominal beam aspect ratio $R = \sigma_x^* / \sigma_y^*$ at the interaction point. The analytic derivation of the H_D factors is very difficult and their behaviour comes from simulations [4]

$$H_D = 1 + D^{1/4}\left(\frac{D^3}{1+D^3}\right)\left[\ell n(\sqrt{D}+1) + 2\ell n\left(\frac{0.8}{A}\right)\right] , \tag{A3}$$

where D is written for either D_x or D_y, the 'disruption parameters' in the two transverse directions

$$D_{x,y} = \frac{2 r_e N_b \sigma_z}{\gamma \sigma_{x,y}^* (\sigma_x^* + \sigma_y^*)} , \tag{A4}$$

and A is the ratio of the bunch length σ_z to the β-function in either plane, at the interaction point

$$A_{x,y} = \frac{\sigma_z}{\beta_{x,y}^*} . \tag{A5}$$

The last term in (A3) takes into account the hourglass effect or variation of $\beta_{x,y}$ along the bunch.

Computer simulation using ABEL [8] gave the variation of H_D with R and the following approximation for the exponent f(R)

$$f(R) = \frac{1+2R^3}{6R^3} . \tag{A6}$$

The combination of all these relations gives the total factor for the luminosity enhancement due to disruption

$$H_{D_t} = (H_{D_x})^{1/2} (H_{D_y})^{f(R)} . \tag{A7}$$

As well as the single-bunch luminosity being of obvious importance, it is necessary to get quantitative information about the adverse effects of bunch deformation and beam–beam phenomena. We have retained three basic quantites for this purpose. The first is the beamstrahlung parameter Υ proportional to the fractional critical energy of the photons emitted in the collision [6]:

$$\Upsilon = \frac{5}{6} \frac{r_e^2 \gamma N_b}{\alpha \sigma_z (\overline{\sigma}_x^* + \overline{\sigma}_y^*)} . \tag{A8}$$

The other two are the average number of emitted photons n_γ per electron and the relative energy loss δ_B due to Beamstrahlung [6],

$$\begin{aligned} n_\gamma &\cong 2.54 \frac{\alpha \sigma_z \Upsilon}{\lambda_e \gamma} \frac{1}{(1+\Upsilon^{2/3})^{1/2}} \\ \delta_B &\cong \langle -\frac{\Delta E}{E} \rangle \cong 1.24 \frac{\alpha \sigma_z \Upsilon^2}{\lambda_e \gamma} \frac{1}{[1+(1,5\Upsilon)^{2/3}]^2} , \end{aligned} \tag{A9}$$

which both depend on the parameter Υ and some physics constants ($r_e = 2.8179 \times 10^{-15}$ m, $\lambda_e = 3.8616 \times 10^{-13}$ m and $\alpha = 7.2993 \times 10^{-3}$).

Another important beam characteristic is the energy spectrum of the electrons that results from beamstrahlung. It is difficult to get an analytical expression of it, because of the possibility of multiphoton emission, and therefore simulations will be required. They give the differential luminosity spectrum, which extends toward low energies and has a peak near the centre-of-mass energy that should be as narrow as possible.