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UPDATING OF BEAM DYNAMICS IN THE CLIC MAIN LINAC

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Abstract

For the Compact Linear Collider (CLIC) study, the beam dynamics has been revisited in order to search for consistent beam parameters that simultaneously satisfy the emittance requirements and the experimental conditions. In the main linac, emphasis was put on the minimization of the energy-spread for limiting losses in the telescope acceptance, on the increase in the ratio between the bunch intensity and the vertical beam-size for improving luminosity, and on the preservation of the very small vertical emittance, in the presence of strong wakefields. Simultaneously, the emittance ratio and beam-size aspect ratio were adjusted in order to keep the average energy loss in the collisions low and boost the fraction of luminosity contained to within two percent of the centre-of-mass energy. The conclusions directly apply to single-bunch mode and can be extended to multibunch mode after adequate adjustments.

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UPDATING OF BEAM DYNAMICS IN THE CLIC MAIN LINAC

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I. INTRODUCTION

In a linear collider, the dynamics of the beam that travels in the linac is simultaneously constrained by the focusing conditions and the wakefields that are unavoidably present in the linac, and by the strong forces that disrupt the bunch when it collides with a counter travelling bunch of opposite charge. On the one hand, the three dimensions of the bunch as well as its population must satisfy criteria to ensure beam stability and bunch coherence while minimizing perturbations such as linear coupling and wakefield deflections in order to prevent emittance dilution. On the other hand, the same beam parameters must be carefully selected for optimizing the luminosity, its distribution at collision as a function of the energy of the leptons that interact and emit photons, and the intrinsic energy spread of the beam before collision. In the Compact Linear Collider (CLIC), the wakefields associated with the high frequency (R-band) of the accelerating structures are so strong that in the past our attention was focused mainly on the control of the emittance dilution, the optimization of the collision parameters coming later. However, this proved not to provide satisfactory physics conditions at the interaction point, the average energy loss during collision in particular being too large and unacceptable [1]. This consideration made obvious the necessity to perform a general optimization of the single-bunch parameters that includes all the conditions briefly recalled above. If the luminosity remains below the desirable values the multibunch option should be added. The present article deals with the reoptimization of the single-bunch parameters recently carried out for CLIC and reviews the arguments on which it was based.

II. BEAM-BEAM PHENOMENA

The beam–beam phenomena can be described approximately by algebraic formulae which are partly deduced from numerical simulations [2, 3]. Although they are not very reliable in the intermediate use of quasi-flat beams, they offer the advantage of giving good results for either round or flat beams and of providing simple scaling laws. They were therefore used in our search for optimized beam parameters, though verification by numerical simulations remains essential [4, 5]. The most important formulae are recalled hereafter, starting with the luminosity L and including the disruption effects at collision which pinch the transverse beam sizes and depend on the nominal beam aspect ratio $R = \sigma_x^*/\sigma_y^*$

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

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

with

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

N_b is the number of particles per bunch and f_{rep} the repetition rate. The pinch effect is described by the factors H_D, the behaviour of which are deduced from simulations [3]

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

with

$$D_{x,y} = \frac{2 r_e N_b \sigma_z}{\gamma \sigma_{x,y}^* (\sigma_x^* + \sigma_y^*)}\,, \qquad A_{x,y} = \frac{\sigma_z}{\beta_{x,y}^*}\,.$$

A is the ratio of the bunch length σ_z to the β-function at the interaction point and D is the so-called 'disruption parameter'. Starting from Eqs. (1) and (2), the consequent beam–beam phenomena can be characterized by three basic quantities: the beamstrahlung parameter Υ proportional to the fractional energy of the photons emitted in the collision, the average number n_γ of emitted photons per electron, and the relative energy loss δ_B due to beamstrahlung [2].

$$\Upsilon = \frac{5}{6}\frac{r_e^2 \gamma N_b}{\alpha\sigma_z(\bar{\sigma}_x^* + \bar{\sigma}_y^*)} \qquad n_\gamma \cong 2.54\frac{\alpha\sigma_z\Upsilon}{\lambda_e\gamma}\frac{1}{(1+\Upsilon^{2/3})^{1/2}}$$

$$\delta_B = \left\langle -\frac{\Delta E}{E}\right\rangle \cong 1.24\frac{\alpha\sigma_z\Upsilon^2}{\lambda_e\gamma}\frac{1}{[1+(1.5\Upsilon)^{2/3}]^2} \tag{3}$$

where the physics constants r_e, λ_e and α have their usual meaning. When the beam is flat and Υ is small, δ_B can be approximated by

$$\delta_B \sim \frac{N_b^2}{\sigma_z \bar{\sigma}_x^{*2}}\,, \qquad \text{with} \qquad L \sim \frac{N_b^2}{\bar{\sigma}_x^* \bar{\sigma}_y^*} \tag{4}$$

and these two relations can then be combined by eliminating $\bar{\sigma}_x^*$ and by using the relation $\sigma_z = \beta_y^*$ (minimizing the hourglass effect):

$$L \sim N_b \sqrt{\frac{\delta_B}{\epsilon_y}} \ . \quad (5)$$

The previous beam parameters of CLIC suffered from the fact that the aspect ratio R was as low as ~ 11 and, consequently, that the horizontal disruption was high (> 1).

Both transverse beam dimensions were therefore strongly pinched, leading to an average energy loss δ_B larger than 20–25%. Looking at Eq. (4), there are three ways to reduce δ_B:

- Decrease the bunch population, but this involves an unacceptable reduction in the luminosity.
- Increase the bunch length σ_z, which does not change L directly, but may boost wakefield effects and then raise σ_y^*. The complete dependence of δ_B on σ_z, shown in Fig. 1 for the CLIC parameters, indeed indicates that a significant gain on δ_B implies a prohibitive increase of σ_z by a factor of three or four. Moreover, the apparent gain on δ_B for small σ_z is not welcome for physics, since it corresponds to an enlarged spread of the L-distribution.
- Widen the horizontal beam size σ_x^*, with the advantage that, according to Eq. (4), L decreases less rapidly than δ_B. In addition, for constant δ_B, N_b and σ_x^* can be adjusted independently, as can be seen from Eqs. (4) and (5).

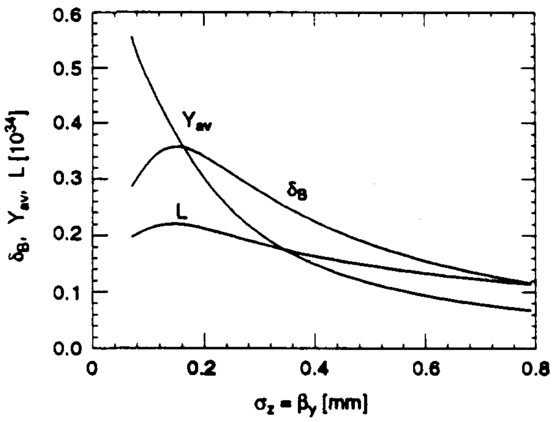

Figure 1: Variation of δ_B, Υ and L with σ_z.

These considerations indicate that a reoptimization should start from a given value of δ_B (say 3.5% for 500 GeV c.m. energy) that determines the requirement on the aspect ratio R(≈ 33). The other beam parameters must then be deduced from the dynamics in the linac, independently of the arguments based on beam–beam phenomena. The bunch length can hence be selected in order to minimize the energy spread and the ratio $N_b/\sqrt{\epsilon_y}$ has to be raised as much as possible, taking into account the emittance dilution along the linac due to wakefields, which are in turn proportional to N_b. The next section describes how this was done for CLIC.

III. BEAM DYNAMICS IN THE MAIN LINAC

Previous tracking in the main linac [6] indicated the possibility of obtaining a vertical normalized emittance $\gamma\epsilon_y$ of 2×10^{-7} rad·m at 250 GeV, in the presence of wakefields, for an intensity of $N_b = 6 \times 10^9$ and for an emittance at injection of 0.5×10^{-7}. As mentioned in Section II, the next step consisted in looking for the maximum of $N_b/\sqrt{\epsilon_y}$ when increasing N_b. Limited investigations, based on simulations with a simple one-to-few trajectory correction [6], produced a curve (Fig. 2) with a maximum at around $N_b = 8 \times 10^9$. Figure 2 shows also the emittance $\gamma\epsilon_y$, which begins to blow up significantly beyond this bunch current. Although this kind of threshold may depend on the kind of correction applied, this new value of 8×10^9 has been adopted for the bunch population. All the trackings have been naturally done with the betatron scaling with energy that is specific to CLIC ($\beta \sim \gamma^{0.35}$), for it gives the right balance between dispersion and wakefield effects.

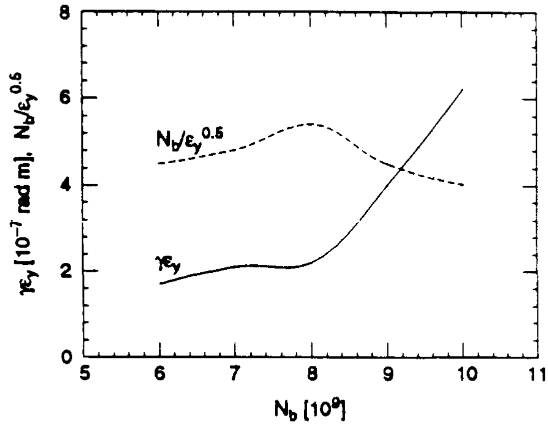

Figure 2: Variation of $N_b/\sqrt{\epsilon_y}$ with bunch population.

Once the intensity is fixed, one can turn to the determination of the bunch length σ_z. Let us recall at this point that there is no need in CLIC for a deliberate energy spread ensuring beam stability, since BNS damping is achieved with microwave quadrupoles [7]. This gives us all the necessary freedom for the selection of a positive RF phase ϕ_{RF} and of the appropriate σ_z, which ensures the best compensation of the longitudinal wakefield variation by the RF wave. In addition, the bunch can be shaped with a sharp edge in the front so as to obtain a quasi-linear increase of W_L that better matches the rise of the RF voltage. Such a shaping can be provided by momentum collimation in the first stage of the bunch compressor [8]; this momentum collimation then transforms into longitudinal cuts when the bunch is rotated by the second stage. The best cuts are determined by tracking through the linac and iterating until the charge distribution with energy, at the extraction, is perfectly symmetrical and does not exceed the acceptance of the final focus ($\sim \pm 5$‰) [9].

Figure 3 shows the distribution obtained with $\phi_{RF} = 12°$ and $\sigma_z = 0.2$ mm. It corresponds to a 'peak-to-peak' energy separation of $\sim$ 6‰ and to an r.m.s. energy spread of $\sim$ 2.3‰ . Such a minimization of the energy spread in the linac is a required condition for specific physics experiments.

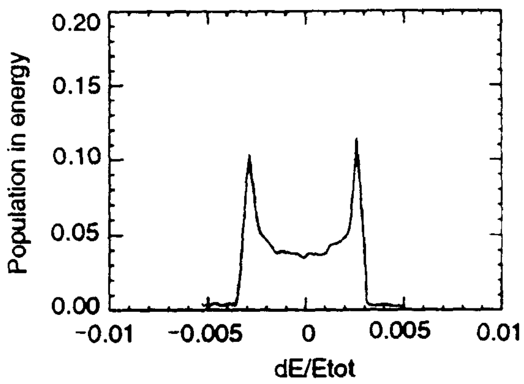

Figure 3: Relative energy distribution at the linac end.

The next critical parameters are of course the absolute values of the emittances, which depend directly on the control of the wakefields, on the misalignments of the linac components and on the quality of the trajectory correction. Because the aspect ratio must be large, the vertical emittance must be very small, and studies of the CLIC dynamics have shown that final values at 250 GeV of $\gamma\epsilon_y = 2 \times 10^{-7}$ can be considered. Such an emittance control has been obtained while coping with r.m.s. misalignments of accelerating structures and position monitors of 10 μm [10], using dispersion- and wake-free algorithms. Recent investigations of beam-based corrections [11] indicate that even better performance can be hoped for with the same misalignments and the higher bunch current retained. They are based on trajectory difference measurements made at full intensity and, say, at a tenth of the intensity, changing simultaneously the momentum by a few percent. With such a method and a good optimization of the microwave quadrupoles, one can achieve $\gamma\epsilon_y = 1.5 \times 10^{-7}$ at 250 GeV and $\gamma\epsilon_y = 2 \times 10^{-7}$ at 500 GeV. Then, experience tells us that such a minimization of $\gamma\epsilon_y$ is easier when $\gamma\epsilon_x$ is about 20 times larger (at the end of the linac). This explains the proposed values of $\gamma\epsilon_x = 3 \times 10^{-6}$ at 250 GeV and 3.9×10^{-6} at 500 GeV, which can be reached easily if $\gamma\epsilon_x = 2.5 \times 10^{-6}$ at injection (9 GeV). Now, given the required aspect ratio of 33 at the interaction point (Section II), the β^* ratio has to be equal to $\sim$ 55. In addition, the hourglass effect is minimum when β_y^* is about 90% of σ_z. These last two conditions dictate the β^*-values, that is $\beta_y^* = 0.18$ mm and $\beta_x^* = 10$ mm.

IV. NEWLY PROPOSED PARAMETERS

The updating of the beam dynamics in the CLIC linac, described in Sections II and III, reconcile the requirements for emittance preservation on the one side and for acceptable conditions in the physics experiments on the other side. Table 1 summarizes the parameter values corresponding to the new conditions obtained by the formulae quoted in II. One can emphasize the low values that are now achieved for the horizontal disruption, Υ, n_γ and δ_B. All these values have been cross-checked by programs simulating the collisions [4, 5] and found to agree to within approximately 20%. As an indication, single-bunch luminosities are also given for repetition rates dictated by power consumption considerations [12]. It is interesting to know that CLIC can deliver with one bunch only an already valuable luminosity of 1 or 2×10^{33} cm^{-2} s^{-1} for the energies retained. However, it relies on multibunch mode for improving the performance; using 10 bunches with lower repetition rates in order to keep the power constant increases the luminosity by a factor of 5, approximately. The beam dynamics of a train of bunches has still to be studied in detail before final conclusions can be drawn.

Table 1
Newly proposed CLIC parameters

Final energy (GeV) per linac	250	500
Bunch population	8×10^9	
Bunch length (mm)	0.2	
Final normalized emittances (10^{-7} rad·m)	30×1.5	39×2
Final Focus β^*-values (mm)	10×0.18	
Nominal FF beam sizes (nm)	247×7.4	200×6
Pinched FF beam sizes (nm)	232×5.6	194×4.75
Hourglass factor	0.94	
Disruption parameters	0.29×9.7	0.22×7.4
Parameter Υ	0.075	0.179
Number of photons n_γ	1.35	1.53
Energy loss δ_B (%)	3.5	7.5
Luminosity with pinch (10^{33} cm^{-2} s^{-1})	1.0	2.2
Repetition rate (kHz)	2.53	4.0
Luminosity in > 98% c.m. (%)	63	68

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