

CLIC ENERGY SCANS

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Abstract

The physics experiments at CLIC will require that the machine scans lower than nominal centre-of-mass energy. We present different options to achieve this and discuss the implications for luminosity and the machine design.

INTRODUCTION

The linear collider physics working group requires that CLIC can be operated at different centre-of-mass energies, the detailed requirements are being discussed [1]. In particular, a scenario must be supported in which the machine is first operated at full energy to discover new particles and then at lower energies to perform threshold scans to further study the properties of these particles. The possibility to operate at lower energy has thus to be built into the design from the very beginning. In the following we will present the current baseline solution for CLIC.

In all scenarios, we assume that the beam energy is only modified in the main linac, not in the injection complex. It is further assumed that the beam delivery system magnets are simply scaled down in strength proportionally to the beam energy by modifying the magnet currents. The exception are the magnets of the final doublet which would be replaced with magnets of appropriate strength as needed. It remains to be studied if the beam delivery system could be further optimised at lower energies with acceptable hardware modifications.

One can consider three main schemes to change the beam energy without major hardware changes after construction.

- **Early extraction:** The beam could be accelerated in the first part of the main linac and then be extracted. This requires extraction lines at different positions of the main linac, which compromises the fill factor and leads to emittance growth. An additional transport line would also be required in the already densely populated tunnel. The bunch charge could remain the same as at full beam energy. Here, we will not consider this option as it would require significant changes in the tunnel layout and the main linac design.
- **Gradient reduction:** The gradient can be reduced along the main linac in order to reach a lower final energy. This requires no additional hardware but the bunch charge has to be reduced linearly with the gradient in order to keep the beam stable. This will be discussed below.

- **Introduction of a gradient profile:** The beam can be accelerated in the first part of the main linac and then be transported through the rest of the main linac with no further acceleration. Also in this case the bunch charge needs to be reduced to keep the beam stability unaltered. In the extreme case one could even accelerate above the target energy and then decelerate.

In the following we will focus on gradient reduction.

IMPACT OF GRADIENT REDUCTION

We scale the bunch charge N proportionally to the linac gradient G , which is almost proportional to the centre-of-mass energy, hence $N/N_0 \approx E_{cm}/E_{cm,0}$. The bunch length σ_z remains unaltered. The relative beam energy spread δ in the main linac is then independent of the final energy, except at the beginning of the linac where the constant initial energy spread is more slowly reduced in proportion to the beam energy at lower gradients. The lattice strength is maintained, i.e. all magnet currents are simply adjusted to the beam energy.

With this scaling the impact of wakefields on a jittering beam remains the same at all gradients. The relative correlated energy spread to fulfill the BNS damping condition remain unchanged.

$$\delta_{BNS}(s) \approx \beta_1^2(s) \frac{Ne^2 W_{\perp}(2\sigma_z)}{E(s)}$$

Here, $W_{\perp}(2\sigma_z)$ is the wake function at a distance of twice the RMS bunch length, $\beta(s)$ the local beta-function, $E(s)$ the local energy and e the electron charge.

The emittance growth due to static imperfections is a concern in CLIC. The two main contributions are due to dispersive effects and wakefields. The spurious dispersion due to imperfections is independent of the gradient. Hence the constant energy spread will result in a constant emittance growth at all energies. Only the incoming energy spread will be somewhat more important at lower gradients. Wakefield induced emittance growth will be reduced at lower energy. Full simulations for 1 TeV show an emittance growth somewhat below the 3 TeV case [2].

The total and peak luminosity (i.e. the fraction within 1% of the nominal energy) per bunch crossing are shown in Fig. 1 normalised to the full energy case for the scenarios where the bunch charge remains constant and when it is scaled linearly with the centre-of-mass energy. One can draw the following conclusions:

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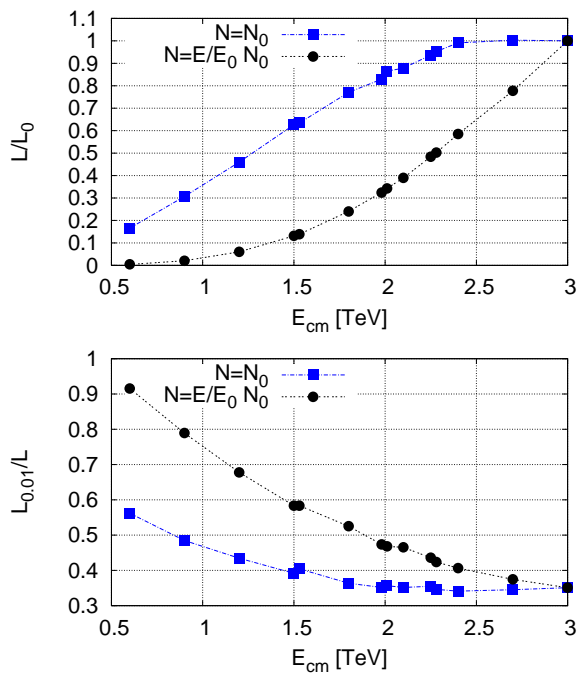


Figure 1: The relative total (upper plot) and peak (lower plot) luminosity per single bunch crossing as a function of the beam energy. The case of a constant bunch charge is shown together with a scaling of the bunch charge proportional to the beam energy.

- For constant bunch charge, the total luminosity does not follow the $\mathcal{L} \propto E_{cm}$ scaling that would be expected from the geometric emittance.
- The quality of the spectrum improves toward lower energies. This implies that we lose peak luminosity less rapidly than total luminosity.
- If the charge scales with the energy, the luminosity per bunch crossing drops rapidly.

OPTIONS TO IMPROVE LUMINOSITY

The main linac gradient can be reduced by reducing the drive beam current $I \propto G$, i.e. by reducing the bunch charge or the number of bunches per unit time or both. We will describe in the following how we can exploit these options in order to improve the luminosity at lower energy by increasing the main beam repetition rate and the main beam pulse length, limiting the power consumption to less than the level at 3 TeV.

Increase of Repetition Rate

The drive beam current can be reduced by reducing the bunch charge $N \propto I$. This will also reduce the deceleration of the drive beam in the decelerator, which allows to reduce the initial drive beam energy $E_D \propto I$. This reduces the RF power in the drive beam accelerator as $P \propto I^2$, maintaining full beam loading. In principle, this allows to increase the repetition rate of CLIC. It is preferable to change the

repetition rate only in multiples of 50 Hz, to remain coupled to the frequency of the mains power.

Klystrons that are operated below their nominal power do usually achieve a lower efficiency. In order to avoid this problem we propose to combine the power of pairs of klystrons with hybrids. In normal operation both klystrons would be used simultaneously. Operation at 100 Hz repetition rate can be obtained by using both klystrons with a repetition rate of 50 Hz but shifted in time by 10 ms. This allows to accelerate 70% of the beam current to 70% of the nominal energy. This scheme allows to double the luminosity in the case that one runs with less than 70% of the nominal centre-of-mass energy.

One has to ensure that all systems are compatible with the operation at 100 Hz, this applies for example to all klystrons in the main beam injector and ring-to-main-linac transport complex. The damping rings have sufficient circumference to allow the damping of two main beam pulses simultaneously. The RF needs to be adjusted since the total beam current can be increased by up to 40% (two pulses of 70% of the nominal charge). Also the main and drive beam sources will have to provide 40% larger average currents. However, none of these requirements seem to be prohibitive and they should not lead to a significant cost impact. The proportional reduction of drive beam current and energy leaves the beam stability unaltered or even improves it depending on the effect in a similar fashion as discussed above for the main beam. However, the absolute beam size will grow with respect to the aperture by 15%. This reduction in margin may be acceptable. If this would turn out not to be the case, the original beam size can be recovered at the end of the decelerator—where it most matters—by reducing the beam energy by a few percent less than the current, which increases the initial energy and decreases the deceleration. In this case the doubling of the repetition rate would be possible at 68% percent of the nominal main beam energy with 68% of the drive beam current at 74% of the initial energy.

Increase of Pulse Length

The drive beam current can also be reduced by reducing the number of bunches per unit time of final pulses. This reduction can be exploited to increase the pulse length as we will describe. This increase in pulse length does not increase the breakdown rate in the main linac accelerating structures since the gradient is reduced.

The drive beam is generated in a central complex as a long stream of bunches, which is later split into shorter pulses that are then merged to form pulses of higher intensity. These short high intensity pulses are sent into the main linac tunnel and will produce the RF power needed to accelerate the main beam. More details can be found in [3].

In order to modify the pulse length two modifications must be applied to the scheme. The length of the delay loop must be changed and the pattern of the switching between filling odd and even buckets must be adjusted. The

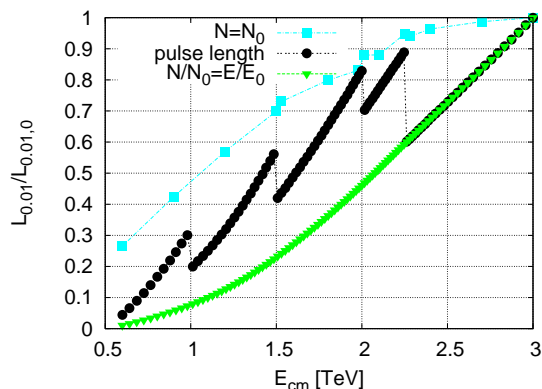


Figure 2: Luminosity in the peak at lower than nominal centre-of-mass energy, normalised to the luminosity in the nominal machine for an increase in pulse length. “pulse length” corresponds to the solution with longer pulses.

Table 1: Combined luminosity recovery options. The maximum energy E/E_0 is given to which each option is valid, together with repetition frequency f_r , number of main beam bunches n_b , luminosity improvement factor $n_{\mathcal{L}}$, maximum charge per main beam pulse Q and maximum average main beam current I .

E/E_0	f_r	n_b	$n_{\mathcal{L}}$	$Q_p/Q_{p,0}$	I/I_0
1.0	50	312	1.0	1.0	1.0
0.75	50	472	1.5	1.125	1.125
0.68	100	312	2.0	0.7	1.4
0.51	100	472	3	0.79	1.58
0.45	100	552	3.5	0.82	1.64
0.34	100	792	5	0.88	1.75

delay loop is a relatively straightforward and inexpensive beam line. One can therefore afford several lines with different lengths, potentially integrated into a single design. This allows to produce a number of different pulse lengths with different beam currents [4]. We consider patterns with drive beam currents of 3/4, 2/3 and 1/2 of the nominal value and pulse lengths of 4/3, 3/2 and 2 of the nominal value, respectively. This allows to accelerate 472, 552 or 792 main beam bunches per pulse. The achievable luminosity is shown in Fig. 2.

In this scheme the requirements for the drive beam source remain unaltered but the main beam systems need to be able to handle longer pulses and larger charges per pulse. The resulting design modifications appear to be minor but detailed studies remains to be performed. The damping rings allow to increase the main beam pulse length from 156 to 400 ns without difficulty as the circumference is large enough. In this scheme not every bucket of the flat top of the drive beam pulse is filled in the decelerator. Simulations show that the impact is negligible on the beam stability and envelope growth [5].

03 Linear Colliders, Lepton Accelerators and New Acceleration Techniques

A03 Linear Colliders

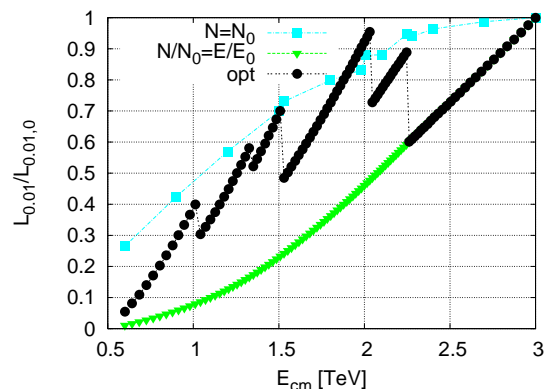


Figure 3: Luminosity in the peak for the combination of the two schemes described (labelled “opt”). No limitations from the sources and damping rings are assumed.

Combination of Options

The two options can be combined. This pushes the requirements for the sources even further, e.g. on the photocathodes. A limitation can arise from the damping ring, for which two design options exist. In the first one, which uses 2 GHz RF, the circumference allows to damp two long main beam pulses simultaneously, shifted by 10 ms in time. In the second, which only differs by the use of 1 GHz RF, the main beam pulses are formed by merging two trains of bunches after the damping ring. In this case the circumference is not sufficient for four long trains. However, one might be able to damp the beam in less than 10 ms in this scheme.

The luminosity that can be achieved if these difficulties are overcome is shown in Fig. 3. The modes of operation are detailed in Table 1.

CONCLUSION

Physics requires the possibility to operate CLIC at lower than nominal energy with high luminosity. The energy can be reduced by reducing the main linac gradient, which in turn requires a reduction of the bunch charge. This leads to a strongly reduced luminosity per bunch. We presented two schemes to improve the luminosity by either increasing the repetition frequency of CLIC or by increasing the main beam pulse length. The two methods can be combined to further improve the performance.

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