CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC – Note – 1143 rev.

HIGH-LUMINOSITY CLIC STUDIES

Chetan Gohil, Andrea Latina, Daniel Schulte and Steinar Stapnes

European Organization for Nuclear Research (CERN), Geneva, Switzerland

Abstract

In 2018 the CLIC study submitted a number of reports as input to the update of European Strategy for Particle Physics, among them a detailed description of the CLIC accelerator complex and its performance. These reports, which include references to comprehensive background documents, are available at http://clic.cern/european-strategy. During 2019 additional questions have come up which concern the performance of CLIC in various operating conditions. These are: what are the margins for increasing the baseline luminosity performance by further improving the beam quality at the interaction point; is there a possibility of doubling the luminosity by operating at 100 Hz instead of 50 Hz; what is the performance of CLIC running at the Z-pole and what is the expected performance for gamma-gamma collisions? These questions are addressed in this note.

Geneva, Switzerland
31 August 2020

High-Luminosity CLIC Studies

Chetan Gohil, Andrea Latina, Daniel Schulte and Steinar Stapnes*
European Organization for Nuclear Research (CERN) Geneva, Switzerland

August 31, 2020

Abstract

In 2018 the CLIC study submitted a number of reports as input to the update of European Strategy for Particle Physics, among them a detailed description of the CLIC accelerator complex and its performance. These reports, which include references to comprehensive background documents, are available at http://clic.cern/european-strategy. During 2019 additional questions have come up which concern the performance of CLIC in various operating conditions. These are: what are the margins for increasing the baseline luminosity performance by further improving the beam quality at the interaction point; is there a possibility of doubling the luminosity by operating at 100 Hz instead of 50 Hz; what is the performance of CLIC running at the Z-pole and what is the expected performance for gamma-gamma collisions? These questions are addressed in this note.

1 Introduction

The CLIC project presented to the European Strategy update process proposes electron-positron collisions in three energy stages: 380, 1500, and 3000 GeV in the center of mass [1]. The baseline scenario consists of eight years of data taking at 380 GeV accumulating 1.0 ab^{-1}. Interest has been expressed in having higher integrated luminosity in the first stage. One can obviously consider running longer than eight years at the baseline luminosity but also scenarios in which CLIC is pushed to higher luminosities are feasible. There are two main possibilities: reducing the vertical emittance and increasing the repetition rate. Both these possibilities are described below. The possibilities of running at the Z-pole and of providing gamma-gamma collisions are also both of interest. The expected performances for these two operating modes are summarised.

2 Increasing luminosity through lower vertical emittance

The baseline luminosity of CLIC at 380 GeV is $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The luminosity is a function of the bunch charge N, the transverse beam sizes σ_x and σ_y, the number of bunches per train n_b and the train repetition rate f_r according to the formula:

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r.$$

The luminosity enhancement factor H_D, which includes the geometry of the collision and beam-beam effects, is on the order of one. It is convenient to re-write the equation for luminosity as

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} \frac{1}{\sqrt{\beta_y \epsilon_y}} N n_b f_r.$$

Most of the parameters in this equation are fixed by various constraints. The factor N/σ_x is proportional to the number of beamstrahlung photons emitted per beam particle and is fixed by experimental requirements. The bunch charge is limited by emittance growth due to wakefield effects in the main linac accelerating structures. The number of bunches per train is limited by long-range transverse wakefield suppression and by the maximum RF pulse length. The repetition

*Summarized on behalf of the CLIC accelerator study rate is limited by the power consumption. The vertical beta-function β_y is chosen to be equal to or greater than the bunch length, which together with the bunch charge is chosen to ensure beam stability in the main linac.

The remaining free parameter for the luminosity is the vertical emittance ϵ_y at the interaction point. A normalized vertical emittance of 30 nm has been used to estimate the baseline luminosity. This is based on an initial emittance of 5 nm from the damping ring and a 25 nm margin for emittance growth in the ring to main linac, main linac and beam delivery system. An emittance growth of 1 nm occurs in the ring to main linac due to coherent and incoherent synchrotron radiation in the bends. The remaining 24 nm emittance growth is due to static and dynamic imperfections in the ring to main linac, main linac and beam delivery system. However, if static and dynamic imperfections do not generate their full vertical emittance growth budget, a luminosity above the baseline can be achieved. The horizontal beam size is fixed to limit beamstrahlung, therefore if the horizontal emittance is smaller than the target, the horizontal beta-function will be increased to compensate. This means there is no luminosity to be gained by reducing the horizontal emittance.

Luminosity studies of CLIC at 380 GeV are presented in [2]. In a machine without imperfections, a vertical emittance of 6 nm is achieved at the interaction point. A start-to-end simulation of a perfect machine shows a luminosity of $4.3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is achieved. The impact of static and dynamic imperfections is studied in [2]. The dominant imperfections are the static misalignment of beamline elements and ground motion. Beam-based alignment (described in [2]) is used to minimise the impact of static imperfections. The beam-based alignment procedure for CLIC outperforms its requirement, which leads to significantly less vertical emittance growth than budgeted. This results in a luminosity above the baseline. 90% of machines with random static misalignments and ground motion achieve a luminosity of $2.3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ or greater. Expressed as a percentage of the baseline luminosity, this is a luminosity surplus of 53% or greater. The average luminosity achieved is $2.8 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is almost twice the baseline luminosity. Future improvements to the technologies used to mitigate imperfections, such as better pre-alignment and active stabilization systems, will also help further increase this luminosity surplus.

3 Increasing luminosity through higher repetition rate

An outcome of the technical studies made for the European Strategy update documents for the 380 GeV initial energy stage was the realization that the repetition rate of the facility, and consequently luminosity, could be doubled from 50 Hz to 100 Hz without major changes and with relatively little increase in the overall power consumption. This is because a large fraction of the power is used by systems where consumption is independent of repetition rate. Specifically, even though the power required by the RF systems increases by about a factor of two the total power consumption only increases from 170 to 220 MW, i.e. less than 30% [3]. There is a modest associated cost increase that must to be evaluated in detail, but is expected to be at the $\sim 5\%$ level.

A consideration for CLIC is the impact of external dynamic magnetic fields, termed 'stray fields'. The dominant stray field source is the electrical grid. This includes power lines and sub-power stations, as well as cabling and power sources connected to the grid inside the accelerator tunnel. The electrical grid in Europe operates at 50 Hz, which motivates the choice of 50 Hz for the repetition rate of the CLIC beam. Stray fields at 50 Hz will have the same impact on each pulse, meaning the stray field is effectively static and its effect can be tuned out. Operating at a repetition rate of 100 Hz, the beam is able to resolve perturbations at 50 Hz. Worse still, a beam-based feedback system which measures the offset of a pulse and corrects the following pulse will amplify perturbations to the beam at 50 Hz. In the current feedback design, the gain will amplify the perturbations at 50 Hz by 25%. However, it is possible to overcome this issue with a feedback system that measures the offset of a pulse and corrects the pulse two periods behind it. In such a scheme the correctors would continually alternate between two states: one for even numbered pulses and another for odd numbered pulses.

To mitigate the impact of stray fields a thin layer of mu-metal, which is a material commonly used for magnetic shielding, can be wrapped around the beam pipe. Measurements at the CLEAR facility (formerly the CLIC test facility) and in the LHC tunnel show the expected RMS amplitude of stray fields is well below 100 nT [4]. A 1 mm mu-metal layer around the beam pipe will reduce this stray field by a factor of 10^3, bringing it down to the level of 0.1 nT, which is within the tolerance for CLIC and therefore the stray field should not impact on performance. Furthermore, it is only necessary to shield the most sensitive regions of the beamline, these are the ring to main linac long transfer line and parts of the beam delivery system. Including a mu-metal shield also means it is not necessary to implement the feedback scheme described in the previous paragraph, however it can be included in addition to allow a margin of safety. Further details of the proposed mitigation techniques are described in [4].

The charging supplies of the modulators in the drive beam complex, would need to have double the charging capacity. This is technologically straight forward and is only a question of cost. The klystrons do not need to be modified since the peak power requirement is unchanged and the increased average power going from 50 to 100 Hz is less than the average power increase for the higher energy stages which require longer pulses. The kicker systems of the drive beam combination and transport systems need to be redesigned for the higher rate but this is expected to be straightforward. The cooling of the beam dumps for the drive beam decelerators need to be dimensioned for twice the power. The change of repetition rate also affects systems in the main beam injector complex. The repetition rate of the klystrons needs to be doubled but this not a problem, since 100 Hz operation is standard for the type of klystrons used. The damping time for a beam train is 20 ms, but for 100 Hz operation, two trains are cooled at the same time, extracting and replacing one of them every 10 ms. This requires doubling the RF to the beam power but has the beneficial effect that the transient beam loading is reduced because a larger fraction of the circumference is filled with beam.

In the main linac, the increased repetition rate doubles the heat deposited in the structures so the capacity of the cooling of the structures and the ventilation system will need to be improved. Finally, the detector will have to cope with a higher data rate.

4 Z-pole performance

Operating the fully installed 380 GeV CLIC accelerator complex but at the Z-pole results in an expected luminosity of about $2.3 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In this scenario the main linac gradient is reduced by about a factor four. The bunch charge is reduced by a similar amount but the normalized emittances and bunch length remain the same. The beam size at the interaction point will increase with the square root of 1/E in the transverse planes. In total this leads to a luminosity reduction roughly proportional to E^3.

On the other hand, an initial installation of just the linac needed for Z-pole energy factory, and an appropriately adapted beam delivery system, would result in a luminosity of $0.36 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for 50 Hz operation. One could operate with a short linac, approximately 1 km of main linac on each side, before the full 380 GeV machine is installed and quite feasibly using a klystron driven linac. In this scenario the bunch parameters remain unchanged, except for the energy and hence beam size at the interaction point. Therefore the luminosity roughly scales as E. The Z-pole operation could also be done before one moves to the next energy stage. In case of an energy upgrade the linac modules are foreseen to be partly rearranged anyway. However, one will need to intermediately store the modules that are not required in the tunnel. All of these options are worthwhile if one would operate for a couple of years at the Z-pole.

The resulting measurements of the electroweak couplings of the Z boson at CLIC, including dedicated running at the Z-pole, are summarized in [5].

5 CLIC as a gamma-gamma collider

It is possible to operate a linear collider in a gamma-gamma mode. In this mode, the electrons in both beams are focused at the IP but just before the IP an intense laser pulse collides with each beam. The electrons will Compton scatter photons in the direction of the collision point. The electron polarization is important for this process and 80% can be expected.

Although detailed studies of the interaction region configuration have not yet been performed a first-order approximation for the performance can be derived by considering three dimensionless parameters: x, k_L and ρ:

- The first parameter x is defined by the electron E_0 and photon $\hbar\omega_0$ energies as $x = 4E_0\hbar\omega_0/(mc^2)^2$. The default choice is $x = 4.82$ to extract the maximum energy from the electron while avoiding that the back-scattered high-energy photon is destroyed in collisions with the laser photons via pair production. For CLIC at 380 GeV center-of-mass energy, the optimum choice of photon energy would be 1.65 eV. The resulting colliding photons can

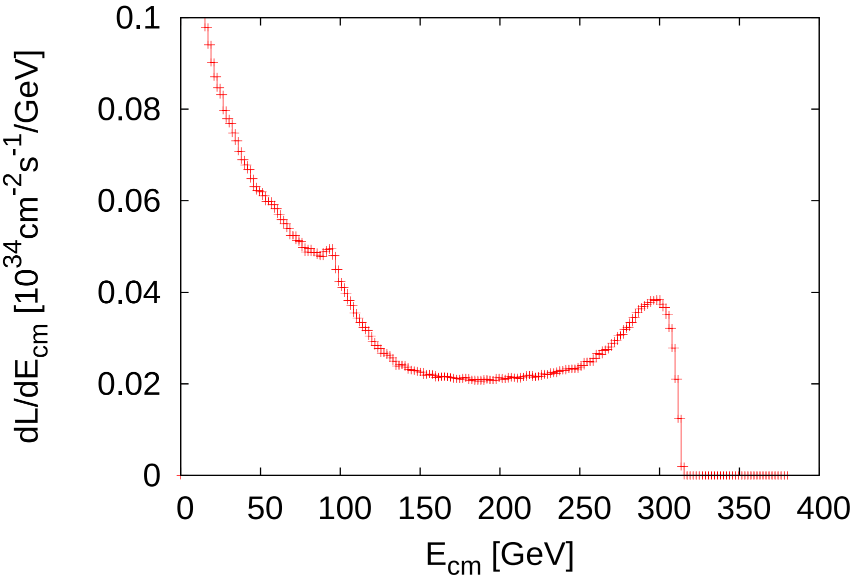

Figure 1: Example of a gamma-gamma luminosity spectrum that can be obtained with CLIC.

reach up to 157 GeV, i.e. 83% of the beam energy, providing center-of-mass gamma-gamma interactions at 314 GeV;

- The second parameter k_L describes the density of the laser pulse by the likelihood k of the electron to undergo Compton scattering at least once; it is defined via $k = 1 - \exp(-k_L)$. For the example we use $k_L = 1$. Larger values lead to more luminosity in the peak, but increase even more the luminosity at lower energies do to the electron performing more than one Compton scatter;
- The third parameter ρ describes the distance d between the laser and the photon-photon collision point, normalized to the beam size and energy. It is defined as $\rho = d/(\gamma\sigma_y^*)$. We chose $\rho = 1$, i.e. $d = 1.1\,\mathrm{mm}$. Larger values decrease the luminosity spectrum since the photons have small angles with respect to the original electron trajectories. However they reduce the low-energy part of the spectrum significantly faster than the high-energy part.

The colliding electrons will produce a limited luminosity, since they also experience scattering angles and since the beams will de-focus each other at the collision point unlike an electron beam colliding with a positron beam. The luminosity spectrum is shown in Fig. 1.

Using a laser pulse thickness of $K_L = 1$ and a distance between laser beam and photon-photon collision point such that $\rho = 1$, one finds a luminosity of about $1.3 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$ above a center-of-mass energy of 228 GeV.

6 Summary

In studies made following the submission of European Strategy Update documents and subsequent meetings and discussions, the CLIC study has found possibilities to increase the luminosity performance at 380 GeV by a factor of two to three without major additional costs or additional power consumption. High luminosity running at the Z-pole is possible with a staged installation or as a dedicated operating period with redistributed modules. Furthermore, gamma-gamma collisions at up to ∼315 GeV are possible with luminosity spectra interesting for physics. The luminosities discussed above can be delivered to one detector as in the baseline CLIC scenario, or shared between two detectors using either push-pull or by constructing a second beam delivery system and interaction point. The latter would add substantially to the costs (∼ 15%) of the accelerator.

References

[1] See list of submitted papers and background papers at: https://clic.cern/european-strategy

[2] C. Gohil, P. N. Burrows, N. Blaskovic Kraljevic, A. Latina, J. Ögren, and D. Schulte. 'Luminosity Performance of the Compact Linear Collider at 380 GeV with Static and Dynamic Imperfections'. To be published.

[3] A. Grudiev, *private communication.*

[4] C. Gohil, 'Dynamic Imperfections in the Compact Linear Collider', DPhil thesis, University of Oxford, 2020.

[5] Blaising, Jean-Jacques and Roloff, Philipp Gerhard, Electroweak couplings of the Z boson at CLIC, Aug. 2019, CLICdp-Note-2019-004, http://cds.cern.ch/record/2687329