

# CLIC STATUS AND OUTLOOK

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## Abstract

The Compact Linear Collider study (CLIC) is in the process of completing a Conceptual Design Report (CDR) for a multi-TeV linear electron-positron collider. The CLIC-concept is based on high gradient normal-conducting accelerating structures. The RF power for the acceleration of the colliding beams is produced by a novel two beam acceleration scheme, where power is extracted from a high current drive beam that runs parallel with the main linac. In order to establish the feasibility of this concept a number of key issues have been addressed. A short summary of the progress and status of the corresponding studies will be given, as well as an outline of the preparation and work towards an implementation plan by 2016.

## OVERVIEW

In CLIC the necessary RF power for the main linac accelerating structures is extracted from a high-current, low-energy drive beam that runs parallel to the colliding beams and is generated in a central complex.

The main colliding beams are produced in conventional electron and positron sources and accelerated to about 2.8 GeV. The beam emittances are reduced in a pre-damping ring followed by a damping ring. In the ring-to-main-linac transport system (RTML) the beams are compressed longitudinally and accelerated to 9 GeV. The main linac (ML) uses 100 MV/m, 12 GHz, normal conducting accelerating structures to achieve the final beam energy. In the beam delivery system (BDS) the beams are cleaned by collimation and compressed to their final sizes at the collision point.

The fundamental CLIC parameters and the conceptual layout for the machine can be found in Table 1 and in Figure 1 below. More details about the CLIC machine are given in the CDR currently being completed [1] and this paper briefly describes some of the studies documented there.

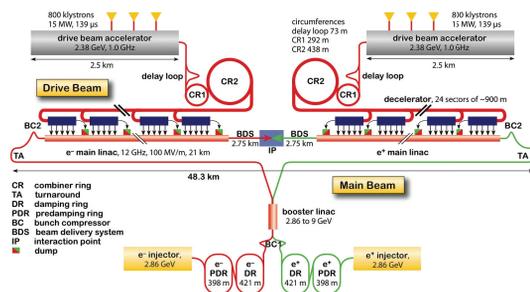


Figure 1: Conceptual layout of CLIC.

\* On behalf of the CLIC collaboration

Table 1: Fundamental CLIC parameters. The luminosity quoted is within 1% of the nominal centre-of-mass energy. Similar parameter sets exist for other CLIC machine energies.

Centre-of-mass energy	3	TeV
Luminosity	$2 \times 10^{34}$	$\text{cm}^{-2}\text{s}^{-1}$
particles per bunch	$3.72 \times 10^9$	
horizontal IP beam size	$\approx 40$	nm
vertical IP beam size	$\approx 1$	nm
bunches per pulse	312	
bunch separation	0.5	ns
pulse rate	50	$\text{s}^{-1}$

The most important design challenges of CLIC that will be discussed in the following, are:

- The main linac gradient and issues related to the accelerating structures.
- The experimental verification of the two beam concept, which is essential to provide the main linac RF power.
- The ultra low beam emittances and sizes to reach high luminosity. In particular alignment and stabilization of the main linac and BDS components.

In order to have energy flexibility a possible staged implementation of the machine is being studied. The future programme of the studies is focused on an implementation plan by 2016, at the same time as results from LHC running at full energy are expected to provide results guiding the way for a possible implementation. The main elements of the future programme are briefly discussed at the end of the paper.

## MAIN LINAC GRADIENT

Each main linac contains about 70000 23 cm-long accelerating structures with a total ratio of active length to linac length reaching almost 80%. The structure design has been carefully optimized using empirical constraints to achieve a gradient of 100 MV/m, as described in [1]. The main limitation arises from so-called breakdowns, i.e. sparks that can occur in the structure during the RF pulse, which can give transverse kicks to the beam. Typically the breakdown probability  $p$  increases with the gradient  $G$  and pulse length  $\tau$  as  $p \propto G^{30}\tau^5$  [2]. We conservatively assume that a single breakdown in a main linac structure renders

the beam pulse useless for luminosity. This should happen only in 1% of the beam pulses at the target gradient of 100 MV/m, which results in a target breakdown rate of  $\leq 3 \times 10^{-7} \text{ m}^{-1}\text{pulse}^{-1}$ .

Four accelerator structure designs have recently been tested: T18, TD18, T24 and TD24. TD24 corresponds to the CLIC baseline structure; T24 is simplified by the absence of the damping wave guides. T18 and TD18 correspond to an earlier, less developed design, which would be less efficient; again “D” indicates the presence of damping waveguides. At SLAC and KEK [3] klystrons with 11.424 GHz are being used for testing of such structures and the structures have simply been scaled in all dimensions to the klystron frequency. At CERN 12 GHz power can be produced in the CTF3 two-beam test stand (TBTS), and a klystron system currently being commissioned. In TBTS the low repetition rate does not allow to condition the structure fully.

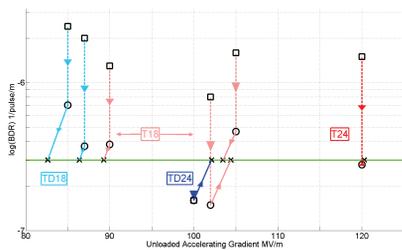


Figure 2: Gradient and breakdown rate achieved with different CLIC structures [4]. The actual measurements are marked with squares, the expected breakdown rate for the nominal pulse length with circles and the expected gradient for the nominal breakdown rate with crosses.

The tests have been performed with pulse lengths and breakdown rates similar to the CLIC parameters. The measurement data is shown in Figure 2 together with the expected CLIC gradients, obtained by scaling the pulse length and breakdown rate to the CLIC values using the scaling formula above.

The TD24 structure has achieved an unloaded gradient of 103 MV/m. A dedicated experiment is planned in CTF3 to investigate the effect of loaded gradients, expected to be in the range of 0 to -16% due to the changed power flow in the presence of beam.

### TWO BEAM SCHEME

The RF frequency of the drive beam accelerator (DBA) is 1 GHz. The injector produces a 140  $\mu\text{s}$ -long electron beam pulse; switching from filling odd to filling even buckets every 240 ns. The DBA accelerates the beam to about 2.4 GeV with a nominal RF to beam efficiency of 97%. An 0.5 GHz RF deflector separates the 240 ns-long sub-pulses and sends every other into a delay loop, so that its bunches can be interleaved with those of the next un-delayed sub-pulse. This produces a sequence of 240 ns-long sub-pulses

Table 2: Typical CLIC and CTF3 Drive Beam Parameters

parameter	unit	CLIC	CTF3
accelerated current	A	4.2	3.5
combined current	A	101	28
final energy	MeV	2400	$\approx 120$
accelerated pulse length	$\mu\text{s}$	140	1.2
final pulse length	ns	240	140
acceleration frequency	GHz	1	3
final bunch frequency	GHz	12	12

spaced by 240 ns-long gaps. Three of these sub-pulses are merged in the first combiner ring and subsequently four of the new sub-pulses in the second. Thus each of the 24 final sub-pulse have 24-times the initial current and only 2.5 cm bunch spacing. Each will feed one drive beam decelerator in the main linac.

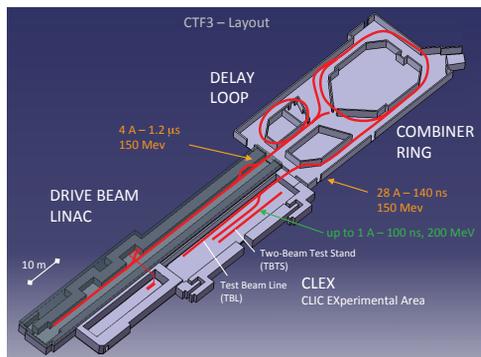


Figure 3: Layout of CTF3.

To demonstrate the two-beam scheme, the CTF3 facility has been constructed and commissioned at CERN; the layout is shown in Figure 3 and its fundamental parameters in Table 2. CTF3 consists of a drive beam source, the drive beam accelerator operating at 3 GHz, the delay loop and one combiner ring. This allows to increase the initial beam current by a factor eight. The produced drive beam is used in the two-beam test stand (TBTS), which also includes a probe beam that simulates the CLIC main beam. Alternatively it can be sent into the test beam line (TBL), which is a small decelerator. Recent results from CTF3 are presented in [5].

### Drive Beam Performance

The drive beam accelerator of CTF3 accelerates routinely a current of about 3.5 A. It has shown full beam-loading, in which case 95% of the RF that is coupled into the accelerating structure is transmitted to the beam [1]. Using the delay loop and the combiner ring, the beam combination by a factor eight has been demonstrated, yielding a current of up to 28 A. Figure 4 shows the combination for a slightly smaller final current.

The required CLIC beam current stability is 0.075% and

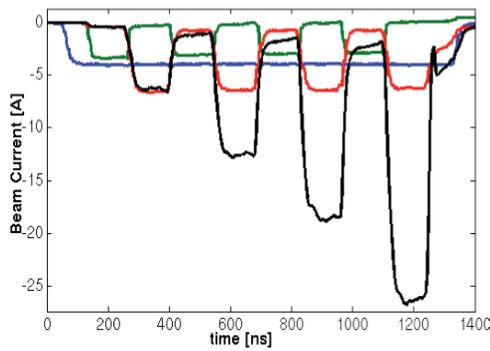


Figure 4: The drive beam combination by a factor eight in CTF3. The blue, green and red line show the current before, in and after the delay loop. The black line is the current in the combiner ring, showing the build-up turn by turn.

measurements at the end of the CTF3 drive beam linac give a value of 0.054% [1]. Emittance measurements are in agreement with expectations. The final evaluation of the current jitter after the beam combination system remains to be done, once the operation of these systems has been optimized. Measurements of phase and amplitude stability of a drive beam klystron [6] have been done verifying the required performance and further measurements are foreseen on the DBA itself.

### Power Extraction and Transfer Structure (PETS)

The 48 drive beam decelerators each contain about 1500 21.3 cm-long PETS. They have an aperture of 23 mm and each produce about 130 MW RF power, which feeds two main linac accelerating structures. Details can be found in [7].

Since individual accelerating structures or PETS could break down at a lower than nominal gradient or output power, it is mandatory to be able to switch off individual PETS or even better to control their output power. A mechanism has been developed and successfully tested [1] that allows control of the output of each individual PETS.

A PETS has also been tested at SLAC using klystrons; this prototype did include damping material but not the on-off mechanism. An input coupler for the klystron power had to be integrated in this PETS. Since the pulse power varied during the tests, only those exceeding the CLIC target have been considered for the statistics. After some conditioning, the PETS ran for 80 hours with no breakdown. Based on this an expected breakdown rate of less than  $2.4 \times 10^{-7} \text{ m}^{-1}$  per pulse has been estimated [1], which is not far from the CLIC target of  $1 \times 10^{-7} \text{ m}^{-1}$ . Significantly more testing time will be needed to determine the breakdown rate more precisely.

### Two-Beam Acceleration

The TBTS currently consists mainly of one PETS, one accelerating structure and the necessary instrumentation. A

full two-beam module will be installed later. The CTF3 drive beam generates power in the PETS and a probe beam can be sent through the accelerating structure. Since the drive beam current is lower in CTF3 than in CLIC recirculation is used. A part of the output power of the PETS is injected at the PETS entrance, which seeds the produced RF and increases the output power at the cost of a reduced pulse length at full power.

Gradients up to 145 MV/m have been achieved in the TBTS [1]. The deceleration of the drive beam, the RF power measured and the probe beam acceleration are all consistent, also with theoretical predictions.

### Drive Beam Decelerator

The CLIC decelerator will decelerate the beam from 2.4 GeV to 0.24 GeV. It is mandatory to achieve small losses and avoid any instability. Simulations of the decelerator have been performed to study the drive beam stability and the impact of static and dynamic imperfections. They show that the beam remains stable even if the wakefield damping is less efficient than expected and that alignment tolerance are less stringent than for the main linac [8].

In CTF3 a test beam line (TBL) is being constructed to test the deceleration. It contains 9 PETS and has space available for 16. The initial TBL beam energy (120 MeV) is much smaller than even the final CLIC decelerator energy (240 MeV). The resulting larger beam size will limit the maximum deceleration. The TBL has been operated with a total of 9 PETS and a beam current of 21A. Under these conditions a beam deceleration of 26% was measured in the spectrometers. The measured energy loss was correlated with predictions from beam current and the PETS RF power [9]. The optics has been understood and the beam can be transported without losses, within the limitation of the current monitor accuracy.

## LUMINOSITY AND OPERATION

CLIC has very small target normalized transverse emittances, see Table 3. The emittance is a factor 7 smaller in the horizontal plane than that achieved in ATF (Accelerator Test Facility) at KEK and a factor 3 in the vertical [10]. However, with the ATF emittances CLIC would already reach 40% of the nominal luminosity. Detailed simulation studies of the damping and intra-beam scattering in the CLIC DR lattice design show that the target performance can be reached with some margin [1]. Also other effects, e.g. electron cloud build-up and fast beam-ion instability have been studied but are not covered in this paper.

Emittance budgets have been defined for the RTML and the main linac for the design, the static and dynamic imperfections. In the BDS the beam develops tails, hence the performance budget has been defined in terms of the luminosity: with no imperfections in the BDS and the target emittance the luminosity would be 20% larger than nominal.

Table 3: Normalized Main Beam Target Emittances in CLIC

	$\epsilon_x$ [nm]	$\epsilon_y$ [nm]
DR/RTML/ML exits	500/600/660	5/10/20

### Survey and Beam-Based Alignment

Transverse misalignments of the main linac and BDS components are the main source of static emittance dilution. The survey reference system consists of overlapping wires that run along the machine. The beam line elements are mounted on girders, with some sharing one girder. The girders measure the offset to the wires with sensors and can be moved with motors. The beam position can be measured with high resolution beam position monitors (BPMs) at each quadrupole. Each accelerating structure also contains a wakefield monitor [1].

The main linac performance target is a vertical emittance growth of less than 5 nm with a probability of 90%. Simulations have been performed using a detailed model of the mechanical pre-alignment and the main pre-alignment methods have been verified in test-setups [1]. Dispersion free steering (DFS), which minimizes the orbit of the nominal beam and its difference to off-energy beams, is used to correct the dispersion by moving BPMs and quadrupoles. The structure supporting girders are aligned to the beam minimizing the signal in the wakefield monitors. The performance target has been clearly met [1].

The target for the BDS is to achieve 110% of the nominal luminosity with 90% probability, in presence of static imperfections and starting with beam emittances from the main linac corresponding to Table 3. An RMS misalignment of 10  $\mu\text{m}$  is assumed for all components, which is close to the main linac accuracy. Beam-based alignment is used followed by optimization of tuning knobs that change the beam properties at the IP. Currently, 70% of the simulated machines reach the target of 110% luminosity and 90% reach at least 90% [1].

### Component Stabilisation

The main beam is very sensitive to magnet motions in the main linac and BDS, due to site dependent ground motion or technical noise. The studies have focused on the former, since the latter can also be addressed by careful component design. As a conservative benchmark, we use a ground motion model based on measurements of the CMS experimental hall floor [11], which includes some technical noise.

The main linac and BDS magnets are equipped with active stabilization systems, which use motion sensors and piezo-electric actuators controlled by a local feedback/feed-forward system [1]. A prototype system has been developed and the transfer of the ground motion to the magnet has measured and compared to simulations. The final quadrupoles are mounted on a large concrete block

that is supported by air-springs [12]. The different transfer functions are implemented in the simulation code.

The luminosity budget for dynamic imperfections is about 20%. Simulations show that 13% of this budget is used assuming the calculated curve of the prototype stabilization and beam-based feedback. The improved stabilization system will loose only 3%.

Also a basic machine protection system concept has been developed [1]. The beam interlock system will switch the beam off if the previous pulse has been bad or if an equipment failure is detected between pulses up to 2 ms before the next pulse. Very fast failures will need an inherently robust design.

One of the most critical failures is a large energy error of the main beam at the end of the main linac, e.g. due to failure of one drive beam sector. The beam delivery system and the detector are protected against these failures by the energy collimation system, which has been designed with the intention to allow for the impact of a full beam train with no damage; studies are still ongoing. A first start-up procedure for the drive and main beam has also been defined based on the CTF3 experience.

## IMPLEMENTATION STUDIES AND OUTLOOK

With the current status of results for the Large Hadron Collider and other projects one can draw the preliminary conclusion, subject to rapid changes as new data is becoming available, that a linear collider should be able to run from the 230 GeV up to the highest possible energy.

In general, unless other measures are taken, the luminosity at CLIC will drop proportionally to the energy as the energy is decreased. For CLIC, optimized for a given energy, beam stability considerations impose further limitations and the bunch charge has to be reduced with decreasing energy [1]. This can partly be compensated for by lengthening the Drive Beam pulse-length allowing more bunches per pulse, maintaining the pulse repetition rate at 50 Hz. This scheme allows an energy flexibility of a factor around 3 to 4, within which the luminosity will scale as shown in Figure 5 for a 3 TeV starting point. As a result of this the possibility of construction CLIC in stages is being studying, at each stage having the possibility to lower the energy by a factor 3 or so without excessive luminosity losses.

The possibility of constructing the machine in stages has advantages and imposes constraints, most of which have not yet been studied in detail. Some of the topics for detailed investigations over the coming years will be:

- fast and resource-optimized access to the initial physics goals; i.e. define scope (energy, luminosity) and schedule for each stage, based on the best knowledge of the physics potential of the machine;
- approval and construction planning for civil engineering and key technology components;

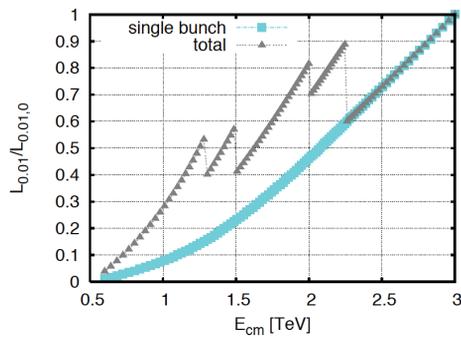


Figure 5: Luminosity in the peak (within 1%) for operation below the nominal centre-of-mass energy, normalized to the luminosity at 3 TeV. The luminosity per bunch is shown together with the total value.

- risk reduction, flexibility and use of operational experiences, as well as re-use of parts going from one stage to another;
- power and energy consumption as function of energy and luminosity taking into account optimized yearly and daily operation scenarios.

While several of these issues are discussed the CLIC CDR they are also main focusses for the next phase of the projects.

The overall objective for the next phase of the project is to develop an implementation plan for the project by 2016, and a detailed work-plan for these studies has been prepared. Key studies will address stability and alignment, timing and phasing, stray fields and dynamic vacuum including collective effects. Other studies will address failure modes and operation issues. The collaboration will continue to identify and carry out system tests and priorities are the measurements in CTF3, ATF and related to the CLIC injector. Further X-band structure development and tests are high priorities as well as constructing integrated modules where a number of key elements are included and need to be optimized. Initial site studies have already been carried out and preliminary footprints have been identified for an initial 500 GeV machine as well as an ultimate 3 TeV layout, as shown in Figure 6, and these studies will continue. The 44 CLIC institutes are all participating in the planning of these activities.

## CONCLUSIONS

The focus of CLIC R&D over the last years has been on addressing a set of key feasibility issues that are essential for proving the fundamental validity of the CLIC concept. The status of these feasibility studies are described and summarized in a CDR [1] in preparation and the studies have successfully addressed the key technical challenges of such a machine. Several larger systems tests have been performed to validate the two-beam scheme, and of particular

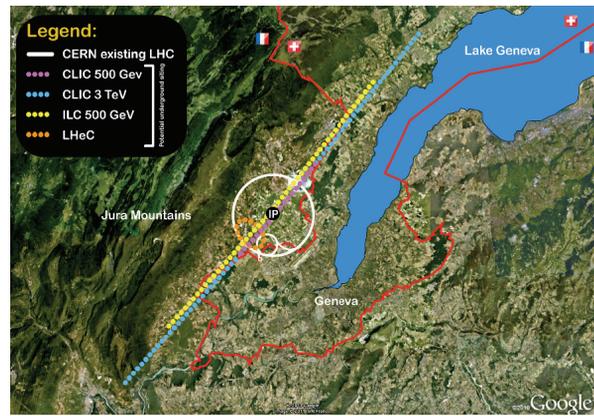


Figure 6: Linear Collider footprints near CERN [13], showing various implementation possibilities, as studied for example for the CLIC CDR.

importance are the results from the CLIC test facility at CERN (CTF3) [5].

Both the machine and detector/physics studies for CLIC have primarily focused on the 3 TeV implementation of CLIC as a benchmark for the CLIC feasibility. The performance and operation issues related to operation at reduced energy compared to the nominal, and considerations of a staged construction programme are included in the final part of the CDR.

## ACKNOWLEDGMENT

The material in this paper is a brief extract of some of the topics presented in detail in the CLIC accelerator CDR [1] and I would like to acknowledge the authors of the various chapters and sections of the CDR. The main part of the paper is based on [14] by Daniel Schulte, shortened for some topics and updated based on recent results for others.

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