

TOWARDS TEV-SCALE ELECTRON-POSITRON COLLISIONS COMPACT LINEAR COLLIDER (CLIC)

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The Compact Linear Collider (CLIC), a future electron-positron collider at the energy frontier, has the potential to change our understanding of the universe. Proposed to follow the Large Hadron Collider (LHC) programme at CERN, it is conceived for precision measurements as well as for searches for new phenomena.

The Higgs boson, the last pillar of the Standard Model of Particle Physics (SM), was discovered at the Large Hadron Collider (LHC) in 2012. Up to now, no direct signs for new physics beyond the Standard Model (BSM) were found at the LHC. Yet there are phenomena such as the matter-antimatter asymmetry, governing mechanisms at the early universe, or dark matter that cannot be explained within the existing SM. With the recently approved High-Luminosity upgrade of the LHC (HL-LHC), which will record collision data until ~2038, more than 10 times more statistics can be collected such that signs of potential new physics could still be revealed in the coming years. Following a complementary approach, several future collider projects using collisions between electrons

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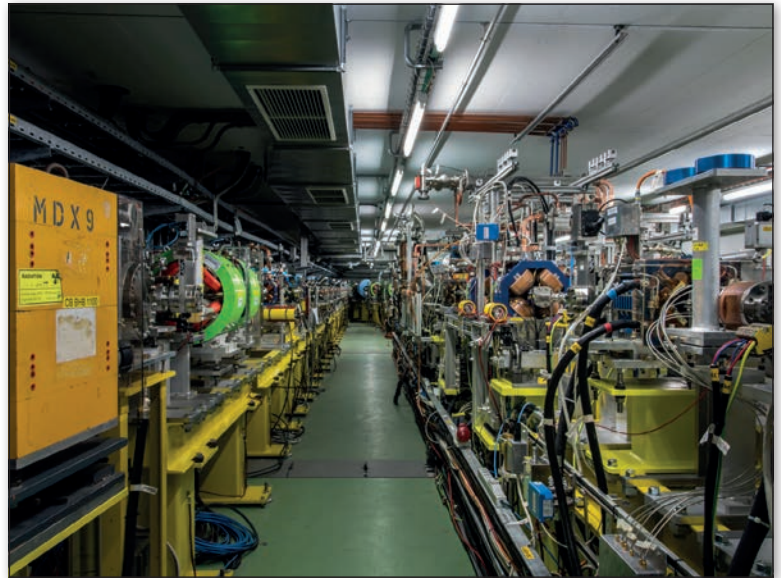
and positrons instead of collisions between protons are currently proposed for the time after the HL-LHC. These colliders focus on precision measurements of the Higgs boson and the top quark. Here, new physics could manifest itself via deviations from SM expectations. The Compact Linear Collider (CLIC) is one of these proposed future colliders. CLIC would provide a guaranteed physics programme of precision measurements of the Higgs boson and the top quark, the heaviest particle in the SM. CLIC would also be a powerful tool to perform both direct and indirect searches for new physics processes, complementary to the HL-LHC programme. CLIC is conceived as a staged machine with centre-of-mass energies ranging from 380 GeV up to 3 TeV, with a corresponding accelerator length from 11 to 50 km, respectively. The collision energy of CLIC can be



adapted easily to investigate potential future discoveries at either LHC or CLIC. CLIC is a global project of more than 70 institutes in more than 30 countries. It consists of two collaborations: the CLIC accelerator study and the CLIC detector and physics collaboration (CLICdp) [1, 2]. They are studying the possibility of building CLIC in the area around Geneva, across the Swiss-French border, with CERN as the host laboratory, although the technology could equally well be deployed at another location.

Precision measurements in a clean environment

The proton (p) is a compound object comprising several elementary particles, so-called partons: 3 valence quarks, gluons and sea quarks. This substructure limits the knowledge of the underlying processes taking place in an individual proton-proton (pp) collision. For instance, it is *a priori* unknown which parton takes part in the collision or which fraction of each proton's energy is carried by the colliding partons. Furthermore, more than one pair of partons can collide in the same pp collision. In electron-positron (e^+e^-) collisions, both incoming particles are elementary, without substructure. Therefore, the colliding particles and the collision energy are well defined, and their polarisations can be controlled. This superior knowledge about the colliding system in e^+e^- collisions enables one to interpret the data with higher precision than in pp collisions. Moreover, high rates of QCD (Quantum Chromo-Dynamics, the theory of the strong interaction) background events may hide the few interesting physics events in pp collisions, while e^+e^- collisions provide a cleaner experimental environment as well as lower radiation levels than in pp collisions.



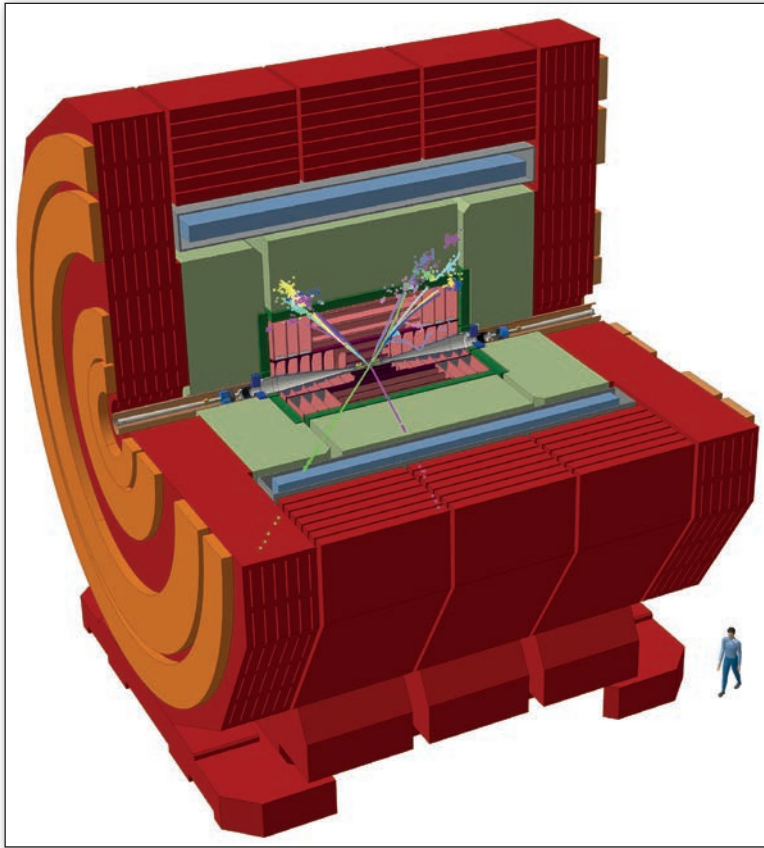
Revealing the mystery of the Higgs boson

For the first energy stage of CLIC with a total accelerator length of 11 km, a centre-of-mass energy of 380 GeV is foreseen [3]. This energy will enable precision measurements of the Higgs boson and the top quark. These are the heaviest particles of the SM and were both discovered in pp collisions. Measuring their properties for the first time in e^+e^- collisions would provide more detailed insight into the SM and could potentially challenge it.

In e^+e^- collisions at 380 GeV, Higgs bosons can be precisely measured in two different production processes: by being radiated off a Z boson, a process called Higgsstrahlung ($e^+e^- \rightarrow ZH$) and by the fusion of two W bosons ($e^+e^- \rightarrow H\nu_e\bar{\nu}_e$). For a comprehensive study of the Higgs boson at a single energy stage,

▲ FIG. 1: The CLIC Test Facility (CTF3). Using the two-beam acceleration technique, acceleration gradients of up to 150 MV/m have been obtained.
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▲ FIG. 2: The CLIC detector concept with a diameter of 13 m and a side length of 11.5 m. The detector consists of layers of cylinders and endcaps of different detector technologies and it hermetically surrounds the collision point located in the centre of the detector. Energy deposits of an example $e^+e^- \rightarrow ZH$ event at 380 GeV centre-of-mass energy are shown, where the Z boson decays into a pair of muons and the Higgs boson decays into a pair of quarks resulting into jets. ©CERN

such access to more than one Higgs-boson production process is advantageous, because a combined analysis leads to a better precision on the width of the Higgs resonance [4]. The width is the intrinsic spread of the Higgs-boson mass, which is wider the faster the Higgs boson decays. The Higgs-boson mass and width can be measured, as well as the Higgs-boson couplings to most other elementary particles at the percent-level of precision independently of any assumed model. This is possible due to measurements of the Higgsstrahlung process, where the Higgs boson is measured through its recoil against the Z boson, independently on the exact decay mode of the Higgs itself. Thanks to the low backgrounds in e^+e^- collisions, the coupling of the Higgs boson to charm quarks can also be studied, a process so far not accessible at the LHC due to larger background levels.

Discovered at Fermilab in 1995, the top quark is still of big interest in the particle physics community. At 380 GeV the probability of the top-quark pair production is close to its maximum, resulting in a large sample of top-quark pairs. A high-statistics threshold scan around the onset of the pair production near 350 GeV can provide a theoretically well-defined top quark mass measurement with unprecedented precision, about one order of magnitude better than expected at the HL-LHC. With the good precision of the Higgs-boson mass achieved at the LHC, the uncertainty on the top-quark mass is currently the leading uncertainty in tests of the SM vacuum stability.

The CLIC scheme: Two beams are better than one

The highest centre-of-mass energy in electron-positron collisions so far –209 GeV – was reached at the circular LEP (Large Electron Positron) collider at CERN. In a circular collider, the circulating particles emit synchrotron radiation and the energy lost needs to be replaced by a powerful radio-frequency (RF) system. Energy loss by synchrotron radiation scales with the fourth power of the energy/mass ratio. In LEP 3% of the beam energy was lost at each turn. Therefore, a circular accelerator option is not feasible for TeV-scale electron-positron collisions. Instead, CLIC follows the linear collider approach with two linear accelerators facing each other and beams colliding head-on in a central detector. This scheme has inherent consequences. Linear accelerators have to transfer the full energy to the particles in a single pass. Therefore, extremely high accelerating fields are required in order to limit the overall length and cost of the facility. CLIC is based on an unprecedented accelerating field of 100 MV/m leading to a very compact accelerator. Since the particle beams only collide once in a linear collider, they have to be very intense and focused to a minimal beam size at the interaction point in order to achieve the necessary event rate (luminosity) for the experiments. In CLIC the beams will be focused to a tiny rectangular spot size of $1 \text{ nm} \times 40 \text{ nm}$ (the smallest dimension is about 10000 times smaller than a human hair) and will carry a total instantaneous beam power of $\sim 14 \text{ MW}$ per beam at full energy. The overall energy efficiency has been a key parameter for the optimisation throughout the design of the accelerator.

CLIC uses normal conducting travelling-wave accelerating structures, operating at a high electric field of 100 MV/m, which results in a site length of 50 km for 3 TeV centre-of-mass energy. For comparison the LHC has a circumference of 27 km. To reach high accelerating gradients the CLIC structures are operating at a high frequency of 12 GHz using very short, powerful RF pulses of 240 ns duration. To create such high RF peak power for the accelerating structures distributed all along the main linear accelerator, CLIC uses a so called two-beam acceleration scheme. In this scheme, a second beam, the so-called drive beam, runs parallel to the main beam. The drive beam is a high current (100 A), low-energy (2.4 GeV) electron beam with a bunch repetition rate of 12 GHz. This beam passes through Power Extraction and Transfer Structures (PETS), inside which it decelerates and thereby generates the powerful RF pulse at 12 GHz. For collision energies above several hundred GeV such a two-beam acceleration scheme becomes more efficient and less costly than a classical RF powering scheme with klystrons.

The drive beam is generated efficiently at lower RF frequency (1 GHz). Long bunch trains of 140 μs are created in a fully loaded normal conducting accelerator converting 95% of its input energy into particle acceleration, exceeding

the typical efficiency of a superconducting linear accelerator. Subsequently beam bunches are interleaved in the injector complex comprising a delay loop and two combiner rings to arrive at the final 240 ns bunch trains with 12 GHz bunch separation. The feasibility of the entire two-beam concept including beam combination, efficiencies and accelerating gradient has been demonstrated successfully in the CLIC Test Facility (CTF3) at CERN shown in Figure 1 and documented in the Conceptual Design Report (CDR) published in 2012 [5].

Extremely high beam quality needs to be maintained throughout the accelerator complex with an unprecedented small final focus at the interaction point. To reach these objectives beamline elements have to be aligned to micron accuracy and some of the focusing elements have to be stabilised against vibrations and ground motion at the nanometre level. To this end the CLIC study developed and demonstrated sophisticated alignment procedures as well as sub-nanometre stabilisation of the final focus quadrupoles.

A detector for CLIC

The design and the technology choices for the detector are driven by the requirements of the high-precision physics programme as well as by the accelerator conditions, such as the bunch repetition rate and the abundance of beam-induced backgrounds. The CLIC detector concept, shown in Figure 2, is based on ultra-light vertex and tracking detectors as well as fine-grained calorimeters, optimised for particle-flow analysis (PFA) techniques [6]. PFA aims at improving the energy measurement of so-called jets, bundles of particles originating from one initial quark or gluon. For each of the particles in the jet, the detector sub-system with the most accurate measurement of the particle is used: the tracking system for charged particles, the electromagnetic calorimeter for photons, and the hadronic calorimeter for neutral hadrons. Several technology demonstrators for the most challenging detector elements have been developed and tested (see Figure 3 for an example). The research and development on the detector concepts for future linear colliders has had a significant impact also on other projects such as the HL-LHC detector upgrades, where for instance the fine-grained calorimeters will find a first large-scale application.

Search for the unknown

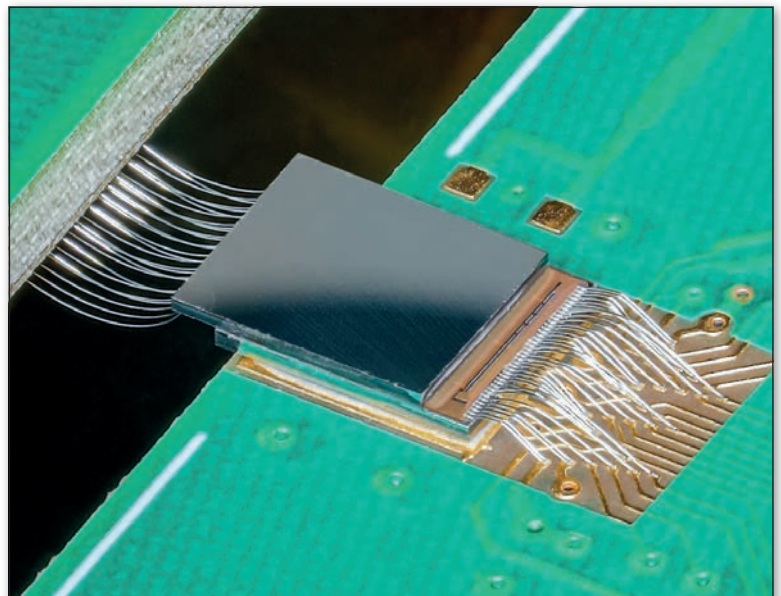
CLIC is currently foreseen to have three energy stages as shown in Figure 4. At each stage, collision data are taken for 5-7 years interleaved with 2 years for accelerator upgrade, leading to a physics programme spanning over two decades. The second and third energy stages are planned to be at 1.5 TeV and at 3 TeV. The energy choices for these stages can be adapted following discoveries from the HL-LHC. The higher energy stages will provide the best reach for direct and indirect searches for physics beyond the Standard Model.

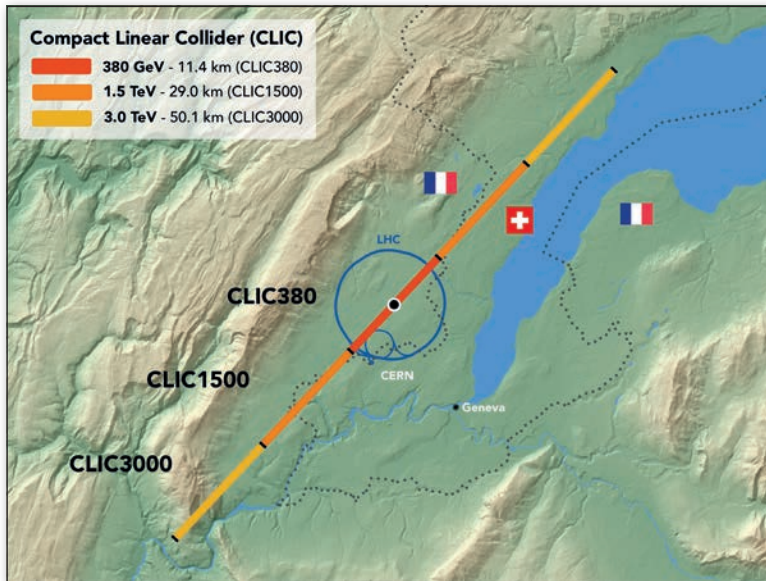
CLIC will push the boundaries of particle physics and search for physics effects that are not explainable by the Standard Model. Significant deviations from the SM observed in precision measurements would indicate new physics. Such measurements can probe energy scales far beyond the actual collision energy. In this way a 3 TeV CLIC accelerator could probe energy scales up to several tens of TeV.

CLIC also aims at direct detection of new particles, reaching particle masses up to 1.5 TeV for particles produced in pairs. Compared to hadron collisions, electron-positron collisions offer superior sensitivity to electroweak states. Taking Supersymmetry (SUSY) theory as an example, CLIC offers excellent sensitivity to Charginos, Neutralinos and Sleptons as well as to additional heavy Higgs bosons.

At the higher energy stages of CLIC, large samples of Higgs bosons produced in WW fusion enable the measurement of extremely rare Higgs-boson decays. The higher energies also give access to Higgs bosons produced together with a pair of top quarks ($t\bar{t}H$) or two Higgs bosons produced in the same collision event. Especially the double Higgs-boson production is a key process as it reveals the Higgs self-coupling, a central parameter for understanding the Higgs field [4]. Besides CLIC, several other e^+e^- colliders are being proposed, showing the strong interest in e^+e^- collisions. The International Linear Collider (ILC) is currently under consideration for construction in Japan. Its first energy stage is proposed at 250 GeV, where the Higgsstrahlung process is at its maximum. Later possible upgrades to 350 GeV and 500 GeV are being considered. In addition, two circular e^+e^- colliders are currently under study, the Compact Electron Positron Collider (CEPC) in China and the Future Circular Collider e^+e^- (FCC-ee) at CERN [7]. Both have a circumference of around 100 km. As they are circular, they are limited in e^+e^- energy reach due to synchrotron radiation. The proposed energies

▼ FIG. 3: A silicon pixel detector prototype currently under study for the innermost detector surrounding the collision point. The detector is made of a High-Voltage CMOS sensor (top) and a CLICpix2 readout chip (bottom) that are glued to each other. Both parts have a size of $3.3 \times 4.0 \text{ mm}^2$ and consist of an array of 128×128 pixels of $25 \times 25 \text{ }\mu\text{m}^2$ size each. ©CERN





▲ FIG. 4: The CLIC accelerator with energy stages of 380 GeV, 1.5 TeV and 3 TeV. The accelerator could be built close to Geneva in the border region of Switzerland and France. ©CERN

range from 91 GeV to 350 GeV, covering the Z peak, WW production, Higgs-boson and top-quark physics. Among these projects, CLIC offers the only technology for multi-TeV e^+e^- collisions, resulting in the strongest discovery reach beyond the Standard Model.

CLIC technologies: New ideas, not only for particle physics

The CLIC team is developing specific technologies due to the unique two-beam approach and the luminosity requirements. The focus of the technology developments is on high-gradient normal-conducting accelerating and decelerating structures, ultra-precision alignment and component stabilisation as well as high-efficiency power converters. For example, the CLIC collaboration has developed reliable accelerating structures capable of operating at a field gradient of 100 MV/m, and power production structures delivering 135 MW of peak power at 12 GHz (more than a million light bulbs of 100 W each switched on for a tiny fraction of a second). These are very attractive technologies facilitating the design of cost-effective and compact accelerators for industrial and medical applications. The CLIC team works with a number of partners to promote these technologies for user applications such as compact X-ray sources and free electron lasers to study materials, molecular or biological processes or for cancer therapy. Sophisticated alignment systems for CLIC accelerator components have demonstrated that precisions better than 10 microns can be achieved over several hundred metres. Moreover, solutions were found to stabilise final focus quadrupoles including feedback against ground motion to a sub-nm level. These techniques are meanwhile used in other accelerator projects such as the LHC. There is also a strong effort to develop high-efficiency power converters to reduce energy consumption. In collaboration with industry the CLIC team has focused on

developing multi-beam klystrons which reach an efficiency of over 70%, to power the drive beam. Such developments are attractive for all future particle accelerators.

An option for the future

Over the last 20 years, the CLIC team has developed a mature design for a TeV-scale linear e^+e^- collider. In particular the first stage at 380 GeV with its evident physics case exploring Higgs-boson and top-quark physics is an attractive option for the future of CERN and is ready to be launched. The priorities for future particle accelerators are set through the European Strategy for Particle Physics (defined by the CERN council). This strategy is foreseen to be updated in spring 2020. In case of a go ahead, the CLIC team and technology are ready to contribute to unravelling the intriguing open questions in particle physics. ■

About the authors



Steffen Doebert is a senior scientist working for more than 15 years on linear collider technologies at CERN and Stanford. He is a member of the CLIC Steering Committee and responsible for several hardware development projects within the CLIC study.



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