STATUS AND FUTURE OF THE CLIC STUDY

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Abstract

The Compact Linear Collider (CLIC) International Collaboration is carrying out an extensive R&D program towards a multi-TeV electron-positron collider.

The CLIC concept is based on the use of high-gradient normal-conducting accelerating structures in conjunction with a novel two-beam acceleration scheme, where the RF power needed to accelerate the colliding beams is extracted from a high-current drive beam running parallel to the main linac. In order to establish the feasibility of such concept a number of key issues were addressed, both experimentally and theoretically, and the results of the study were documented in the recently completed CLIC Conceptual Design Report (CDR). The conclusions reached in the CDR constitute also an important contribution to the European strategy group. A short summary of the present status will be given, together with an outlook on the program for the next period, aimed at the preparation of an implementation plan.

INTRODUCTION

CLIC is a high-energy linear e^+e^- collider with the potential to operate at centre-of-mass energies ranging from a few hundred GeV up to 3 TeV and with luminosities of a few 10^{34} cm^{-2}s^{-1}.

In CLIC the 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 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 main challenges for the CLIC main beam are the accelerating gradient needed to get to the high centre-of-mass energy and the good beam quality (i.e., the ultra low beam emittances and sizes) needed to reach high luminosity.

The RF power used to accelerate the electron and positron beams is extracted from a high-current, low-energy drive beam running in parallel to them. The drive beam is generated in a dedicated accelerator complex located in the central area. The other challenges for CLIC are related to the two-beam concept: the efficient generation of the drive beam, the power production in special RF structures called PETS (power extraction and transfer structures) and the stable drive beam deceleration. The fundamental CLIC parameters and its conceptual layout can be found in Table 1 and in Fig. 1. More details about the CLIC machine are given in the recently completed Conceptual Design Report.

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Table 1: Fundamental CLIC parameters at 3 TeV centre-of-mass. The luminosity quoted is within 1% of the nominal energy.

Centre-of-mass energy	3	TeV
Luminosity	2×10^{34}	cm^{-2}s^{-1}
Particles per bunch	3.72×10^{9}	
Horizontal beam size at IP	≈ 40	nm
Vertical beam size at IP	≈ 1	nm
Bunches per pulse	312	
Bunch separation	0.5	ns
Repetition rate	50	s^{-1}

The CLIC accelerator complex and the CLIC physics and detector studies are described in separate documents. The CLIC accelerator CDR [1] provides detailed descriptions of the accelerator layout, its components and the expected performance of CLIC. In particular, it describes technical solutions to the key feasibility issues, thus proving the validity of the CLIC concept. In this framework, prototypes of many of the technical subsystems have been successfully tested at the CLIC test facility CTF3 at CERN and at other facilities around the world. The test results are reported in detail in the CDR.

This paper gives a status update on the most important design challenges of CLIC, namely:

- 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 program 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 program are also briefly discussed at the end of the paper.

ACCELERATING STRUCTURES

Each main linac contains about 70000 23 cm long accelerating structures. The total ratio of active length to total linac length reaches almost 80%, resulting in an extremely high “real estate” gradient. The structure design has been carefully optimized using empirical constraints to achieve a gradient of 100 MV/m, as described in [1].

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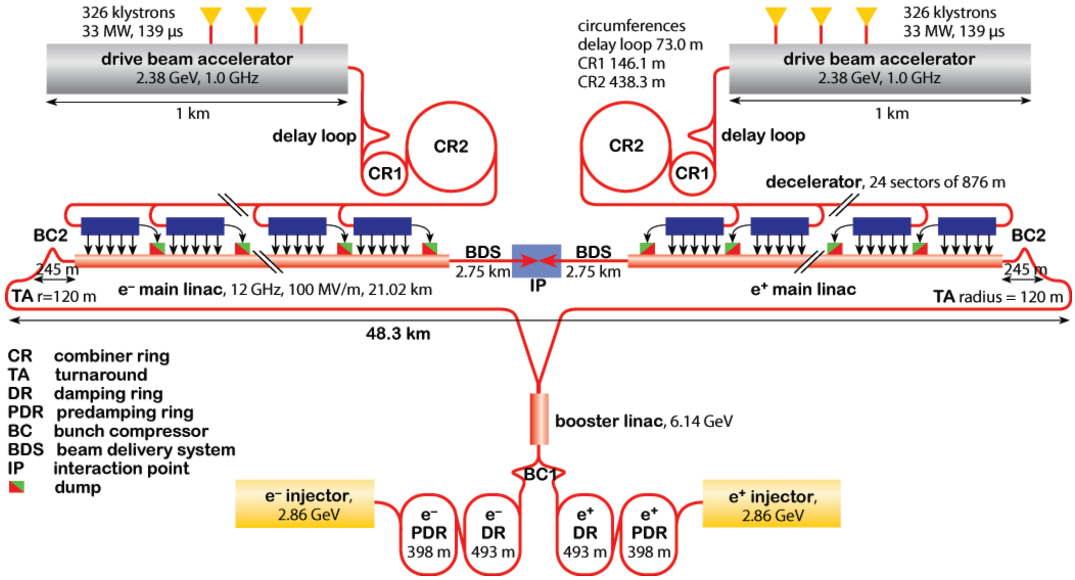

Figure 1: Conceptual CLIC layout.

The main limitation arises from RF breakdowns, i.e. electrical arching that may occur in the structure during the RF pulse. Breakdowns may damage the structure, reducing its performance, and can give transverse kicks to the beam. Typically the breakdown probability p increases with the gradient G and pulse length τ as $p \propto G^{30} \tau^{5}$ [2]. We conservatively assume that a single breakdown in a main linac structure completely spoils the beam pulse for luminosity. This must happen only in 1% of the beam pulses at the target gradient of 100 MV/m, which results in a required breakdown rate of $\leq 3 \times 10^{-7}$ m^{-1} pulse^{-1}. Four accelerator structure designs have recently been tested: T18, TD18, T24 and TD24 (see Fig.2). TD24 is the present CLIC baseline structure; T24 is a simplified version without damping waveguides. T18 and TD18 correspond to an earlier, less efficient design. Again "D" indicates the presence of damping waveguides. At SLAC and KEK [3] klystrons operating at 11.424 GHz are being used for testing such structure types, scaled in all dimensions to the klystron frequency.

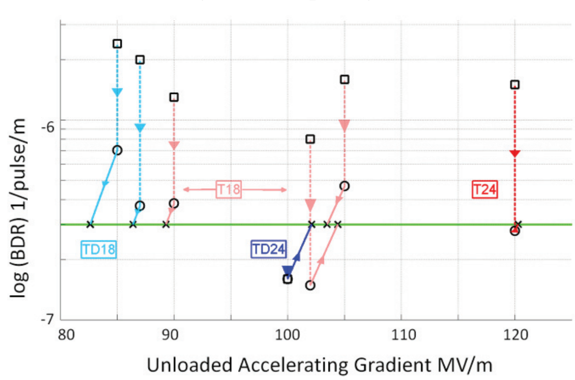

Figure 2: Gradient and breakdown rate achieved with different CLIC structures. Squares mark actual measurements, circles the expected breakdown rate at the nominal pulse length and crosses the expected gradient at the nominal breakdown rate.

At CERN 12 GHz power can be produced in the CTF3 two-beam test stand (TBTS), in which however the low repetition rate does not allow to fully condition the structures under test, and a 12 GHz klystron-based test stand has been recently put in operation.

The tests have been performed with pulse lengths and breakdown rates close to the CLIC ones. The measurement data is shown in Fig. 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 beam loading, expected to be in the range of 0 to -16% due to the changed power flow in the presence of beam.

TWO-BEAM ISSUES

The RF frequency of the CLIC drive beam accelerator (DBA) is 1 GHz. The injector produces a 140 μs long electron beam pulse composed by 240 ns long sub-pulses in which only odd or even RF buckets are alternatively filled. The DBA accelerates the beam to about 2.4 GeV with a nominal RF to beam efficiency of 97%. A 500 MHz RF deflector separates the sub-pulses and sends every other into a delay loop, so that its bunches can be interleaved with those of the next sub-pulse. This produces a sequence of 240 ns sub-pulses spaced by 240 ns long gaps. These are then merged (first with a three-fold, then a four-fold combination) in two rings using a time-dependent closed bump generated by transverse deflectors. Thus each of the 24 final sub-pulses has 24 times the initial current and only 2.5 cm bunch spacing. Each will feed one drive beam decelerator in the main linac. To demonstrate the two-beam scheme, the CLIC Test facility CTF3 has been build and commissioned at CERN by an international collaboration [4]. Its layout is shown in Fig. 3.

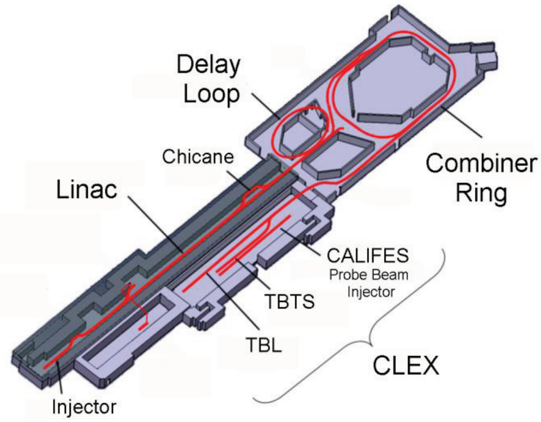

Figure 3: CTF3 Overall Layout.

CTF3 consists of a 120 MeV electron linac followed by a 42 m long delay loop and a 84 m combiner ring. The beam current is first doubled in the delay loop and then multiplied again by a factor four in the ring, for a total increase of the initial beam current by a factor eight. The drive beam can then be sent to the CTF3 experimental area (CLEX) to be used for two-beam experiments. In the CLEX area the Test Beam Line (TBL) is used to test drive beam deceleration in a string of PETS. The drive beam can alternatively be sent to a second beam line (Two-Beam Test Stand, TBTS), where a PETS powers one or more CLIC accelerating structures. A 200 MeV injector (CALIFES) provides the probe beam used in the TBTS to verify two-beam acceleration.

Drive Beam Generation

The CTF3 linac accelerates routinely a current of about 4 A. It is operated in full beam-loading, and a 95% RF-to-beam energy transfer efficiency was measured [5]. HOM damping is used to prevent any transverse instability. Isochronous operation of the loop, ring and transfer lines is needed in order to avoid bunch lengthening. Tuning of the momentum compaction below the required value ($\alpha_p < 10^{-4}$) was demonstrated already in the CTF3 preliminary phase, and is now part of standard operation [6]. In order to be able to separate and recombine sub-pulses in the delay loop, leaving a hole for ring extraction, the sub-harmonic bunching system RF phase is periodically switched by 180° to phase-code the bunches. A switching time of 6 ns was measured, well below the required value [7]. The residual charge in satellite bunches is ~ 7 %, acceptable for CTF3 and close to the CLIC needs. CTF3 target emittance for the drive beam is 150 π μm in both planes after combination; 50 π μm is routinely obtained in the linac, while measurements on the fully recombined beam typically give values 2 to 4 times the target. The main source of emittance growth was identified as orbit mismatch between delay loop and combiner ring, and non-perfect orbit closure in the ring itself. Several correcting measures were put in place, and we expect to reach the target before the end of 2012. The required CLIC drive beam current stability is extremely tight (7.5 10^{-4} for pulse-to-pulse rms charge variations). After reduction of slow drifts by a feedback, the rms pulse-to-pulse variation measured in the linac was ~ 5 10^{-3}, well below the CLIC specs [8]. The charge jitter is about 8 10^{-4} for the combination 4 beam. The same orbit errors causing emittance growth still push the jitter of the fully combined beam, to the percent level. One of the goals of this year run is reduce it to a few 10^{-3}. CLIC has also tight requirements for RF phase and amplitude stability in the linac (0.05° rms phase jitter for a coherent error along the drive beam train and 0.2% for the RF amplitude). In CTF3 an RF phase jitter of 0.035° has been measured with respect to the external reference; the amplitude stability was 0.21%.

RF Power Production, Deceleration and Two-Beam Acceleration

Each of the 48 CLIC drive beam decelerators contains about 1500 21.3 cm long PETS. All PETS have an aperture of 23 mm and produce about 130 MW RF power each, split by half in an RF waveguide network to be fed into two main linac accelerating structures [9].

In TBTS, in order to get high power at a limited drive beam current, a 1 m long PETS is used. Furthermore, part of the output power can be injected back at the PETS entrance, amplifying RF production. Thus, RF power levels above 200 MW, well beyond the 130 MW nominal values, were reached inside the PETS at the 240 ns nominal pulse length. In CLIC it is mandatory to rapidly switch off RF power production from individual PETS in case of repetitive breakdowns. A mechanism based on a variable external reflector, yielding full control of the RF power sent to the accelerating structure and a reduction of the power level inside the PETS by a factor of 4, has been developed and successfully tested [1]. A PETS was also tested at SLAC using klystrons. After some conditioning, the PETS ran for 80 hours with no breakdown, for an estimated breakdown rate of less than 2.4×10^{-7} m^{-1} per pulse [1] (CLIC target 1×10^{-7} m^{-1}). More than 100 MW of peak RF power was delivered to the first accelerating structure tested (CLIC nominal 65 MW). Gradients up to 150 MV/m have been achieved (see Fig. 4) [4].

The measured drive beam deceleration, the RF power produced and the probe beam acceleration are consistent

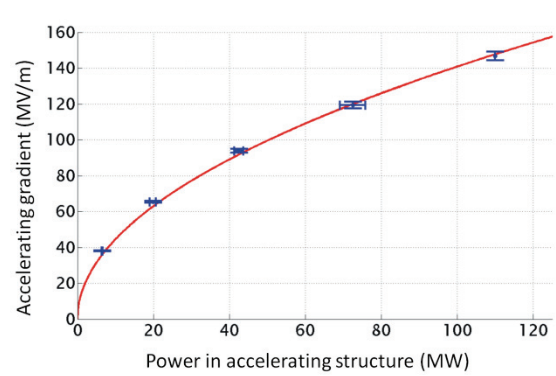

Figure 4: Measured accelerating gradient as function of the accelerating structure RF input power.

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between them and with the theoretical predictions. The TBTS is used to study in detail the physics of RF breakdowns. In this context, measurements on breakdown transverse kicks were recently performed [10].

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 impact of static and dynamic imperfections on drive beam stability in the decelerator were performed. They show that the beam remains stable with a good margin on the achievable wake-field damping and with alignment tolerances less stringent than for the main linac [11].

In CTF3 a test beam line (TBL) is being constructed to test the deceleration. It contains 13 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 last year with a total of 9 PETS and a beam current of 21 A. Under these conditions a beam deceleration of 26% was measured in the spectrometers. The energy loss was correlated with predictions from beam current and the PETS RF power [12].

LUMINOSITY AND OPERATION

CLIC has very small target normalized transverse emittances. A conceptual design of the CLIC damping ring exists that meets the CLIC specifications, according to extensive simulation studies including intra-beam scattering, electron cloud build-up and fast beam-ion instability. Existing third generation light sources and damping ring test facilities have normalized emittances that are not too far from the CLIC damping ring goal. In particular, the Swiss Light Source (SLS) has achieved a normalized vertical emittance slightly better than the CLIC target [13]. The Accelerator Test Facility (ATF) at KEK reached values 7 times larger in the horizontal plane and a 2.5 times larger in the vertical one than the CLIC nominal values. Such emittances would be sufficient to obtain in CLIC 40% of the nominal luminosity.

Emittance budgets have been defined for the RTML and the main linac to account for 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 the luminosity would be 20% larger than nominal.

Survey, Beam-Based Alignment, Stabilization

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 that can be moved with motors while sensors measure the offset of the girders to the wires. The beam position can be measured with high resolution beam position monitors (BPMs) at each quadrupole and with wake-field monitor in each accelerating structure [1]. The main linac performance target is a vertical emittance growth of less than 5 nm with a probability of 90%. Simulations were performed using a detailed model of the mechanical pre-alignment following methods verified in test-setups [1]. Dispersion free steering (DFS) is used to correct the dispersion by moving BPMs and quadrupoles. Girders holding structures are aligned to the beam by minimizing the signal in the wake-field 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. An rms misalignment of 10 µm 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].

The main beam is very sensitive to magnet motions in the main linac and BDS, due to site dependent ground motion or technical noise. As a conservative benchmark, we use a ground motion model based on measurements of the CMS experimental hall floor [14], which includes some technical noise. The main linac and BDS magnets are equipped with active stabilization systems, using 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 was measured and compared to simulations. The final quadrupoles are mounted on a large concrete block supported by air-springs [15]. 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. An improved stabilization system, under development, should lose only 3%.

A basic machine protection system concept has been developed to cope with a wide variety of failures [1]. Based on the LHC experience, a strategy was established: slow errors and drifts that grow over several pulses will be detected by a post-pulse analysis while faster failures that can develop between pulses are addressed by an interlock system detecting the equipment failure directly. Failures that occur immediately before the beam pulse and cannot be caught by the interlock system are avoided by “safe-by-design” components, with large enough inertia to slow down the process enough to catch it on the next pulse. Against even faster failures the machine is protected by masks and other passive protection. A first start-up procedure for the drive and main beam has also been defined based on the CTF3 experience.

IMPLEMENTATION STUDIES AND OUTLOOK

In order to satisfy the physics demands to provide luminosity at very different energies the construction of CLIC in stages is being studied. The stage choice will

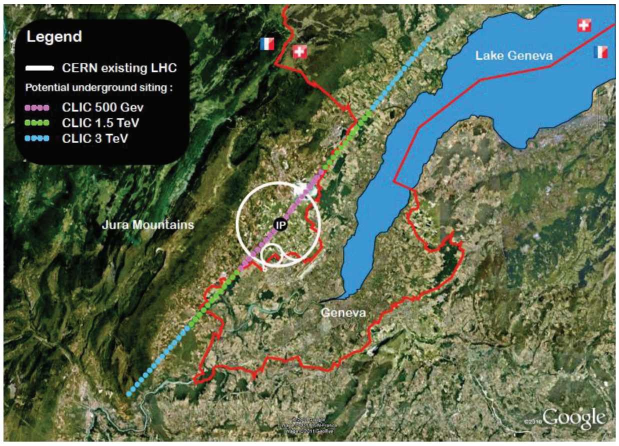

Figure 5: Linear Collider footprints near CERN, showing various implementation possibilities, as studied for example for the CLIC CDR.

depend on the results of the LHC, however with the current status one can draw the preliminary conclusion that a linear collider should be able to run from the 230 GeV up to the highest possible energy. For a given construction stage, unless other measures are taken, the luminosity at CLIC drops proportionally to the energy as this is decreased. Beam stability imposes further limitations and the bunch charge must be reduced with decreasing energy. This can be partly compensated by several measures, allowing for an energy flexibility of a factor 3 to 4, within which the luminosity will scale more favorably with the centre-of-mass energy [16]. As a result, a few stages may cover all the needed range up to Multi TeV, 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. Topics include fast and resource-optimized access to the initial physics goals; i.e. 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 risk reduction, flexibility and use of operational experiences, potential reuse 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 are discussed in the CDR they are also a main focus for the next phase.

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 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, where priorities are the measurements in CTF3, ATF and CLIC drive beam injector system tests. Further X-band structure development and tests are high priorities as well as the construction of 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 5, and these studies will continue. The 44 CLIC institutes are all participating in the planning and execution of these activities.

CONCLUSIONS

The focus of the CLIC R&D over the last years has been a set of key feasibility issues that are essential to prove the fundamental validity of the CLIC concept. The feasibility studies have successfully addressed the key technical challenges of such a machine and were described and summarized in a recently completed CDR [1]. Several large systems tests were performed to validate the two-beam scheme, and of particular importance are the results from the CLIC test facility, CTF3 [4]. 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. Performance issues linked to operation over a wide energy range, and considerations of a staged construction program are included in the final part of the CDR.

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