# CLIC OVERVIEW

R. Tomás for the CLIC/CTF3 collaboration, CERN, Geneva, Switzerland.

## *Abstract*

The CLIC study is exploring the scheme for an electron-positron collider with a centre-of-mass energy of 3 TeV in order to make the multi-TeV range accessible for lepton physics. The current goal of the project is to demonstrate the feasibility of the technology by the year 2010. Recently, important progress has been made concerning the high-gradient accelerating structure tests and the experiments with beam in the CLIC test facility, CTF3. On the organizational side, the CLIC international collaborations have significantly gained momentum considerably boosting the CLIC study.

## INTRODUCTION

Electron-Positron linear colliders are considered as the most probable HEP facility to complement the LHC in the future. Two alternatives of linear colliders are presently being developed, the ILC based on super-conducting technology in the TeV range and CLIC based on the novel approach of Two Beam acceleration to extend linear colliders into the Multi-TeV range. These two studies are complementary in the preparation for the most appropriate facility after the LHC era. The decision will be based on the physics requests derived from the LHC physics results when available. A close CLIC/ILC collaboration has been established on subjects with strong synergies in 7 Working groups [6].

CLIC aims to collide electrons and positrons at a centre-of-mass energy of 3 TeV with a luminosity of $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, see [1–5]. To accomplish this at a reasonable cost the CLIC study proposes a two beam accelerating scheme featuring an accelerating gradient in the order of 100 MV/m. The power is extracted from a low-energy but high-intensity beam (the drive beam) and fed into the main beam via copper structures. Figure 1 and Table 1 display the layout and parameters of the CLIC complex at 3 TeV. The drive and main beams occupy the top and bottom halves of the plot, respectively. The facility would be built in phases with a first phase in the TeV energy range. The initial center of mass energy has been arbitrarily chosen to be 500 GeV to allow a direct comparison with ILC. However this energy will eventually be defined from the physics requests.

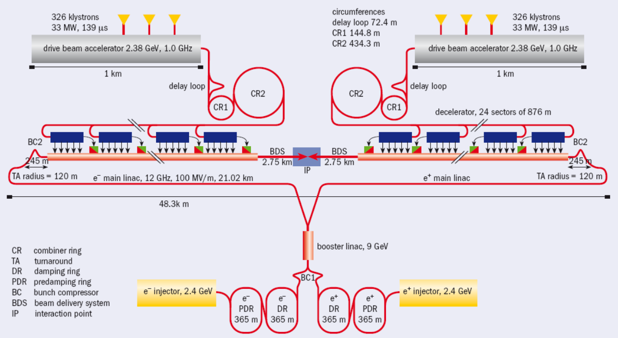

Figure 1: The CLIC layout for 3TeV (not to scale).

Table 1: CLIC Main Parameters

| | | |
|---|---|---|
| Centre of mass energy | 3 | TeV |
| Luminosity (in 1% energy) | $2 \times 10^{34}$ | cm$^{-2}$s$^{-1}$ |
| Number of particles per bunch | $3.72 \times 10^9$ | |
| Bunch separation | 0.5 | ns |
| Number of bunches per train | 312 | |
| Proposed site length | 48.3 | km |
| AC to beam power efficiency | 6.8 | % |

The CLIC study is presently in an R&D phase having established an international collaboration where 28 institutes [7] and many facilities around the world are exploring the technological frontier to assess the CLIC feasibility. Significant R&D is still required to demonstrate the CLIC feasibility. This effort will materialize by the end of 2010 in the Conceptual Design Report (CDR). This CDR will document the CLIC complex and the concepts for the technical realization of all subsystems. The technical subsystems have been reviewed and a prioritized list of the "critical items" has been established as follows:

- Accelerating structures at 100 MV/m.
- Power Extraction and Transfer Structures (PETS).
- Generation of the 100 A drive beam with 12 GHz bunch frequency,
- meeting the phase, energy and intensity stability tolerances.
- Generation and preservation of the main beam low emittances.
- Active alignment and stabilization of main quadrupoles to 1nm and the Final Doublet (FD) quadrupoles to 0.15nm (for frequencies above 4 Hz).
- Machine protection.

In the following the CLIC complex subsystems are briefly described with emphasis on their problematics and the related existing experimental facilities.

## INJECTION COMPLEX

The injection complex generates 2.4 GeV polarized e$^-$ and 2.4 GeV unpolarized e$^+$ with bunch populations of $6 \times 10^9$ particles [8]. Roughly 30% of these particles are produced in excess in order to cope with downstream losses. The e$^+$ are generated by shooting 5 GeV e$^-$ on hybrid targets. The experimental feasibility of the polarized e$^-$ source is investigated via collaborations with JLAB and SLAC while studies of unpolarized and polarized e$^+$ sources [9] are investigated via collaborations with LAL, KEK, ANL and CI. A CLIC/ILC e$^+$ generation working

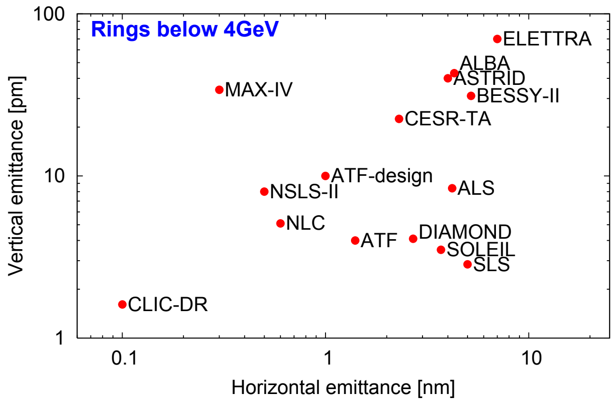

Figure 2: Chart of vertical versus horizontal geometric emittances for different projects with energies below 4 GeV, showing the challenge to generate the CLIC DR emittances.

group has been set-up [6]. The sources are challenged by the CLIC parameters at 500GeV since the bunch charge is doubled, at the sources, compared to the 3TeV study.

## DAMPING RINGS

The 2.42 GeV Damping and Pre-Damping Rings (DR and PDR) have the challenge to generate smaller emittances than ever achieved, namely $\gamma\epsilon_x$=500 nm and $\gamma\epsilon_y$=5 nm [10]. This requires the DRs to operate in a new regime where the synchrotron light emitted in the superconducting wigglers [11] is the main source of radiation damping. Figure 2 compares the geometrical emittances of the CLIC DR to present at future projects, showing the challenge. The DR features an energy loss per turn of 3.9 MeV with an RF voltage of 5 MV, a bunch length of 1.4 mm and an energy spread of 0.1%. Its energy acceptance of 2.6% is comparable to existing light sources. The DRs face unexplored regimes of intra-beam scattering and other collective effects as fast-ion instability and electron cloud. It is possible to alleviate the effect of intra-beam scattering by increasing the energy to 2.86 GeV [12]. To avoid the fast-ion instability the vacuum should be 0.1 nTorr. The electron cloud in the e$^+$ DR could be mitigated by the use of special carbon coating developed in CERN [13] that reduces the secondary emission yield below 1. Experimental tests with this new carbon coating are being performed in SPS and CESR-TA (summer 2009) to verify its performance.

Thanks to the CLIC/ILC collaboration many DRs critical points will be jointly addressed by experts from both projects and via devoted experiments in ATF and CESR-TA. Concerning the generation of the very low emittances CLIC should rely on the experience of the future light sources as NSLS-II or MAX-IV that will come a step closer to the CLIC DR horizontal emittance, Fig. 2.

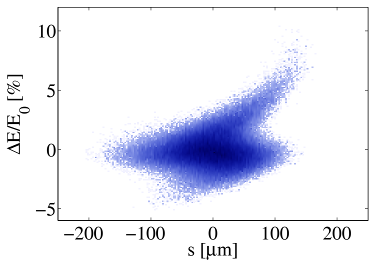

Figure 3: Longitudinal phase space of the bunch after tracking trough the entire RTML.

## RTML

The Ring To Main Linac (RTML) section takes the beams from the DRs on the ground down to the tunnel for injection in the main linac [14]. It consists of a booster linac that accelerates the beams to 9 GeV, two bunch compressors with a total compression factor of about 30 (final bunch length being 0.044 mm), a 21 km transfer line [15] and an isochronous and achromatic turn around loop where ISR processes must be observed. For the first time tracking studies trough the entire RTML have been performed. Figure 3 shows the negligible longitudinal deformation of a Gaussian 8 GeV beam at the end of the RTML. Since the emittance growth is more severe at the design energy of 9 GeV it has been proposed to reduce the energy to 8 GeV in order to alleviate the emittance growth due to ISR in the turn around loop. Vacuum levels in the long transfer line of the RTML should be kept in the order of 0.1 nTorr to avoid the fast-ion instability [16].

## DRIVE BEAM COMPLEX

The drive beam is generated as a long train of e$^-$ bunches with a large bunch spacing of 60 cm. This is accelerated to an energy of 2.38 GeV using conventional klystron amplifiers at 1 GHz in a normal conducting linac. To optimize the efficiency the RF cavities operate in a fully-loaded fashion, where 95% of the RF power is transmitted to the beam. At this stage the drive beam needs to be compressed in time in order to increase the peak beam current from 4.2 A to 100 A. Three rings are used to this end: the delay loop and two combiner rings. The bunches are interleaved between each other at injection in the different rings and by using RF deflectors. This is one of the important novel features of CLIC that finally leads to bunches with repetition frequency of 12 GHz in trains long by 239 ns, with a peak current of 100 A. In total, 24 trains follow each other spaced by 5.8 $\mu$s.

The drive beam generation is a critical feasibility point of the CLIC project which is presently being addressed in the CLIC Test Facility 3 (CTF3) set-up as an international collaboration. CTF3 represents a reduced version of the CLIC drive beam complex with a goal intensity of 28 A at 12 GHz, see the layout in Fig. 4. A more comprehensive description and status of CTF3 can be found at [17, 18]. Two very important recent achievements have to be men-

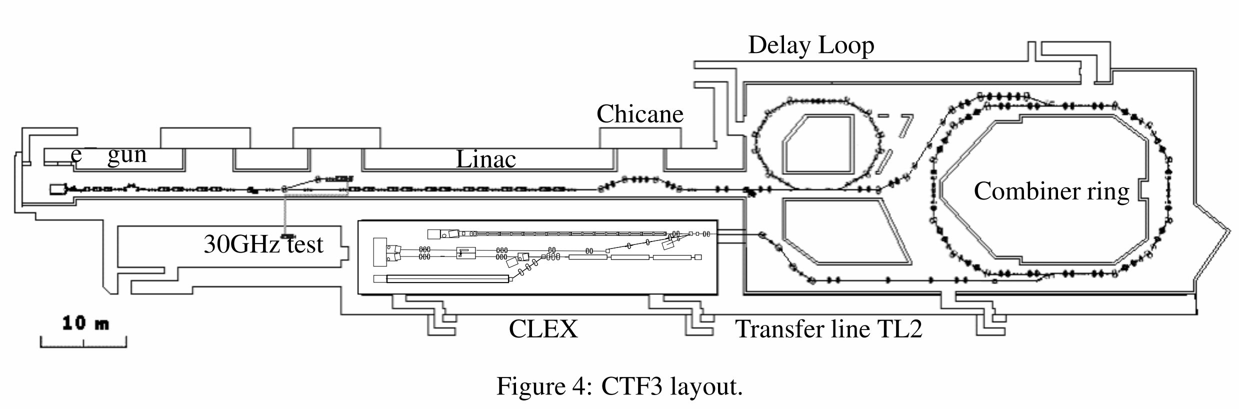

Figure 4: CTF3 layout.

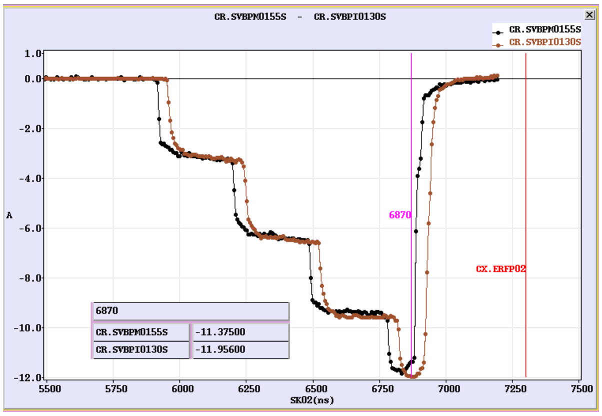

Figure 5: Intensity versus time as measured at two different devices of the CTF3 combiner ring, showing the bunch recombination from 3 A beam to 12 A.

tioned. First, the CTF3 combiner ring has demonstrated the recombination by a factor of 4, increasing the incoming intensity from 3 A to 12 A and the frequency from 1.5 GHz to 6 GHz, see Fig. 5. Second, the CTF3 PETS have demonstrated the power extraction from a low intensity drive beam, Fig. 6 from Ref. [19]. Moreover a new technique based on the recirculation of the electro-magnetic fields in the PETS has allowed the extraction of about eight times more power than without the recirculation (red and blue curves in the figure). The good agreement between the model prediction based on a simple model and the measurement as observed in the figure is remarkable. Adopting PETS recirculation for the CLIC baseline design is also being considered

In parallel the 11.424 GHz scaled version of the CLIC PETS is undergoing high RF power tests in ASTA at SLAC [20]. In this experiment the klystrons are used as an external RF power source. Testing PETS in ASTA gives a unique opportunity to understand the limiting factors for the PETS ultimate performance. At the moment of writing the paper, the PETS had reached 120 MW peak power in 132 ns (cf. 135 MW and 240 ns in CLIC).

CTF3 was not designed to prove the tight jitter tolerances of the CLIC drive beam RF phase and beam intensity. However CTF3 serves as a laboratory to test the new feedback technologies that will be used to guarantee the phase and intensity tolerances, see for example [21].

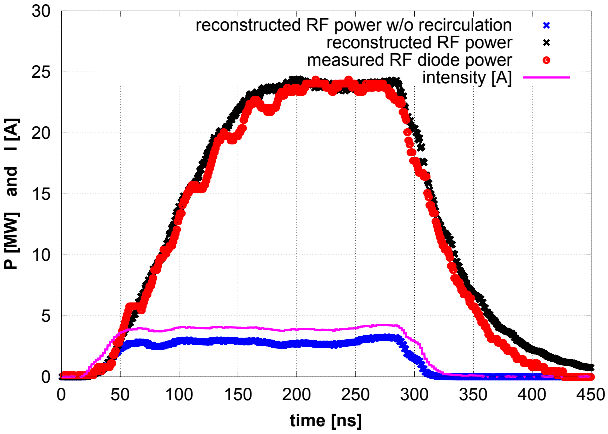

Figure 6: PETS measured and reconstructed power.

## MAIN LINAC

The linac is the 21 km section of the CLIC facility where the drive and the main beams share the tunnel. The PETS decelerate the drive beam in sections of about 800 m and transfer its power to the accelerating structures of the main beam. The main beam is accelerated from 9 GeV to 1.5 TeV. The challenges faced by the linac are the demonstration of 100 MV/m accelerating structures with an acceptable breakdown probability and the demonstration of the active stabilization down to 1.8 nm (for frequencies above 4 Hz) [22]. The fast-ion instability is less of a concern since 10 nTorr is enough to avoid it [24].

Thanks to the collaboration between KEK, SLAC and CERN a CLIC-like accelerating structure, named t18_vg2.4_disk, has been successfully tested [23]. The CERN design was built in KEK, see Fig. 7, and sent to SLAC for assembly and RF testing. This test structure does not yet incorporate the damping features that CLIC structures need. T18_vg2.4_disk demonstrated an unloaded gradient above 100 MV/m with the nominal pulse length and a breakdown probability of about $3\times10^{-7}$ per meter, see Fig. 8, corresponding to the CLIC specifications. The full demonstration of a CLIC structure with damping is presently under preparation.

The active stabilization level of the linac quadrupoles to 1.8 nm for frequencies above 4 Hz has been already demonstrated in laboratory environments by using ground isola-

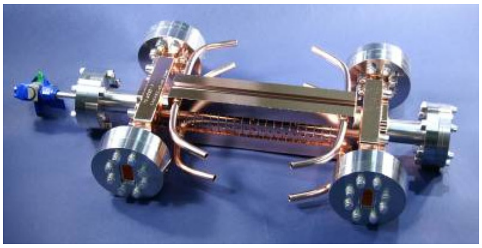

Figure 7: Test accelerating cavity for the CLIC main beam, T18_vg2.4_disk, designed at CERN, built at KEK and assembled and tested at SLAC.

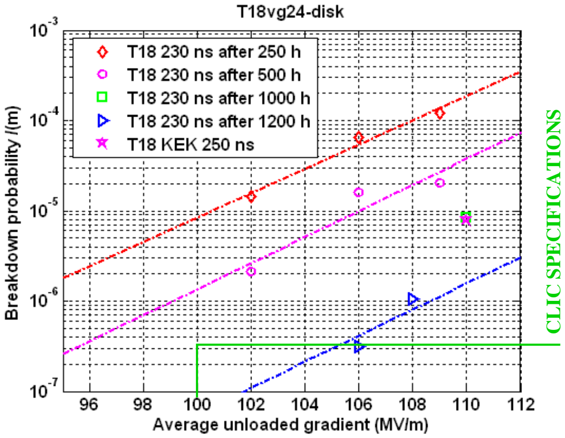

Figure 8: Performance of the CLIC-like accelerating structure T18_vg2.4_disk meeting the CLIC specifications during unloaded operation without damping and after 1200 hours of conditioning. CLIC structures operate loaded and with damping.

tion techniques [25, 26]. Of course, the challenge remains to apply this technology over 21 km in the real accelerator environment.

## BEAM DELIVERY SYSTEM

The CLIC Beam Delivery System (BDS) [27] has to safely guide the 15 MW beams with the strongest possible transverse focusing through the Interaction Point (IP) and unload them in the beam dumps. A collimation system ensures that neither stray particles nor their radiated photons hit the downstream machine or the detector. The first collimator is made of beryllium in order to survive the impact of a full train. The collimator apertures are defined by the aperture bottlenecks downstream, which occur in the Final Doublet (FD) quadrupoles, right before the IP. The survivability of the first collimator plus the collimation efficiency have been extensively revised by various experts within the CLIC/ILC collaboration [28, 29]. The wakefields that the beams experience at the collimators deteriorate the luminosity since it is assumed that the bunch trains come with a transverse jitter of $0.2\sigma$. An optimum solution in terms of collimator and FD apertures is still under investigation.

Table 2: Vertical IP Beam Sizes for Different Projects

| Project | Status | $\sigma_y^*$ [nm] |
|---|---|---|
| FFTB | Measured | 70 |
| ATF2 | Commissioning | 37 |
| ATF2 ultra-low $\beta$ | Proposed | 20 |
| ILC | Design | 6 |
| ILC low power | Proposed | 4 |
| CLIC | Design | 1 |

The CLIC Final Focus System (FFS) is based on the local chromaticity correction scheme presented in [30] with extra non-linear elements to cancel residual aberrations [31]. The experimental verification of this type of FFS is presently being investigated in the KEK ATF2 facility. ATF2 contains a scaled version of the ILC FFS with a vertical IP beam size of about 37 nm. However the CLIC FFS is about 4 times more chromatic than ILC and ATF2. An ATF2 R&D proposal has been made [32, 33] to reduce the ATF2 IP vertical beta function by a factor of 4. This proposal has a two fold motivation, reduce the IP vertical size as close as possible to ILC and CLIC values, see Table 2, and prove the CLIC chromaticity levels.

The ultra-low $\beta^*$ proposal for ATF2 will also serve to investigate the difficulty of tuning the FFS for different IP beam sizes. Simulations show that tuning difficulty increases for smaller IP beam sizes [33]. CLIC aims to focus the vertical beam size to about 1 nm, smaller than any other project, see Table 2.

Due to the nanometric IP beam size CLIC faces the challenge of the sub-nanometer stabilization of the last FFS quadrupole (QD0). In order to loose less than 2% luminosity the vertical jitter of QD0 has to be below 0.15 nm (for frequencies above 4 Hz) with the extra complication that QD0 is embedded in the detector at 3.5 m from the IP. There are very promising experimental results showing stabilization to these levels via active ground isolation and structure resonance rejection techniques in a laboratory environment, see Fig. 9 taken from [34]. The CLIC stabilization working group conducts the research in order to find solutions in the detector environment [35]. An original proposal from A. Seryi [36] in order to ease the stabilization is to move QD0 out of the detector to support it on the ground increasing $L^*$ to 8 m. This option shows a 28% lower luminosity than the current CLIC lattice [27], therefore it has been suggested to keep the 8 m $L^*$ optics as a fall-back solution.

QD0 technical specifications have been pushed to the limit of permanent magnet technology. It features an aperture of 3.5 mm with a peak magnetic field of 2.0 T. Its relative gradient jitter should be below $0.05\times10^{-4}$ and the relative octupolar aberration at 1 mm should be below $7\times10^{-4}$. The feasibility of such a magnet is presently under study [37].

## SCHEDULE

The present efforts of the CLIC study focus on the feasibility demonstration for the publication of the Conceptual Design Report (CDR) by the end of 2010 with preliminary estimates of performance and cost. The technical designs, the engineering optimization and the final cost studies will extend over a five year period after the CDR leading to the

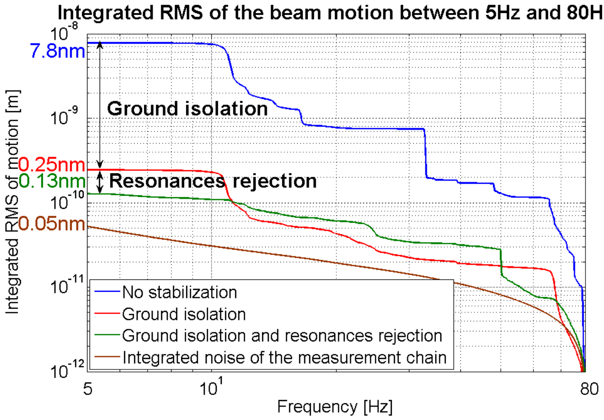

Figure 9: Demonstration of stabilization to the sub-nanometer level via ground isolation and structure resonance rejection in a quiet environment [34].

Technical Design Report (TDR) by the end of 2015. The CLIC proposal would then be ready to seek approval with a construction period of seven years for a 500 GeV facility and another 3.5 years for the upgrade to 3 TeV.

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