

## CLIC FEASIBILITY STUDY IN CTF3

A. Ghigo for the CLIC Collaboration, INFN/LNF, Frascati (Roma), Italy

### Abstract

The CLIC Test Facility, (CTF3), under construction and test at CERN is the product of a multilateral international collaboration to address all the key issues of the CLIC technology. The presentation, after the description of the CLIC scheme towards multi-TeV Linear Collider and of the main advantage of the two beams accelerator scheme, will focus on the status of the CTF3 project and of the technological developments; in particular the performances already achieved in the high field accelerating structures and in the RF power production. The results of the recombination process for the drive beam as well as the plans and schedule for the future are reported.

### INTRODUCTION

The High Energy Physics experiments, after exploration of the 100 GeV (center of mass c.m.) energy range by the hadrons colliders at CERN and Fermilab and by the electron-positron colliders LEP and SLC, are moving in these years in the range of TeV scale that will be first investigated at CERN by the Large Hadrons Collider (LHC).

New generation of  $e^+e^-$  colliders, with luminosity values larger than  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , will be needed to make the complementary precision measurements, as happened in the past, in the same energy range because of the cleanliness of the events. The  $e^+e^-$  accelerator candidate for TeV energy ranges, at the moment the only one, is the linear collider. Several projects have been proposed for different energy ranges. The effort in these years is converging on a worldwide project: the International Linear Collider (ILC) that has the goal to investigate with high luminosity the c.m. energy range of 500 GeV with the possibility to increase energy up to 1 TeV [1]. The ILC program foresees a technical design report for the construction of the collider using superconducting accelerating structures ready for the end of 2009.

Several theories beyond the Standard Model, that foresees supersymmetry, extra dimensions or new strong interactions, predict new dynamics at the TeV scale. Supersymmetry with relative sparticle production as well as heavy mass Higgs bosons can be studied by raising the energy up to 5 TeV [2].

The Compact Linear Collider (CLIC) can cover the c.m. energy range for  $e^+e^-$  collisions between 0.5 - 5 TeV adopting an unconventional technique to accelerate the beams limiting the overall length of the accelerator.

### CLIC

CLIC is based on two-beam acceleration method in which the RF power for the main linac sections is produced by a high intensity, low energy electron beam, called drive beam, running parallel to the main linac [3, 4]. The power is extracted by decelerating the

drive beam by special Power Extraction and Transfer Structures (PETS).

Increasing the accelerating gradient limits the length of the collider: this is possible using high frequency, normal conducting, and travelling wave accelerating structures.

The electron and positron beams are accelerated in 30 GHz RF cavities with a loaded accelerating gradient of 150 MV/m on 70 ns pulse length. The design and fabrication of the structures call for perfect structure straightness tight, alignment tolerance and long-range wake field suppression to preserve the beam emittance.

The CLIC parameters optimised at c.m. energy of 3 TeV are shown in Table 1. Figure 1 shows the layout of the accelerator complex.

The drive beam linear accelerator produces 94  $\mu\text{s}$  long electron pulses at the energy of 2.4 GeV using RF power from 350 klystrons with a power of 40 MW each. The compressor system formed by three recombination rings provides a series of pulses 70 ns long with a current of 180 A. These pulses pump 21 decelerator sectors 669 m long where the power is extracted and transferred to the 30 GHz accelerating structures. The main beams are generated in the 2.4 GeV pre-injectors, reduced in emittance in the damping rings, accelerated in a linac booster to 9 GeV, recombined reducing the bunch spacing to 8 cm and finally injected in the main linac to increase the energy up to 3 TeV.

Table 1: CLIC parameters

Parameter	Unit	
Energy (center of mass)	TeV	3
Total length	km	33.6
Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	$6.5 \times 10^{34}$
Luminosity (in 1% energy)	$\text{cm}^{-2}\text{s}^{-1}$	$3.3 \times 10^{34}$
Beamstrahlung mom. spread	%	16
Main Linac RF frequency	GHz	30
Gradient loaded/unloaded	MV/m	172 / 150
Linac repetition rate	Hz	150
No. of particle / bunch		$2.5 \times 10^9$
No. of bunch / pulse		220
Bunch separation	ns	0.267
Bunch train length	ns	58.4
$\sigma_H^* / \sigma_V^*$ before pinch	nm	60 / 0.7
Total site AC power	MW	418
Efficiency AC to Main beam	%	12.5

The foreseen luminosity value for CLIC is  $6.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  ( $3.3 \times 10^{34}$  in a 1% energy bin).

To obtain such high luminosity the beam size at the interaction point must be in nanometer range; this is a characteristic of the high frequency linac; in fact it is possible to reduce the bunch length and focus the beam with optical functions of the order of millimeters.

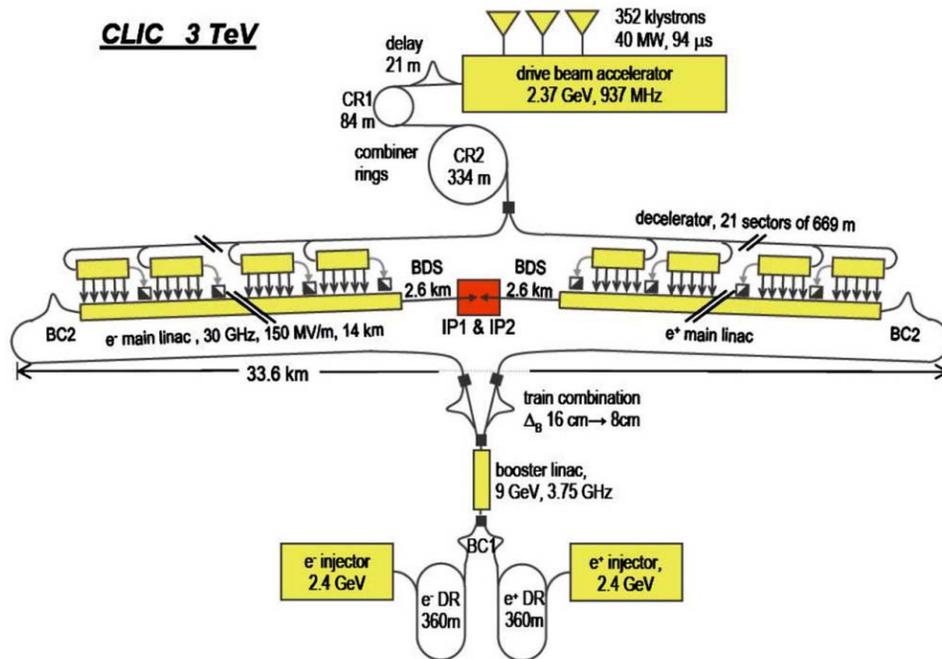


Figure 1: Layout of CLIC at 3 TeV.

In order to maintain the luminosity constant the beam delivery system has to be stabilized in the nm range. An R&D program dedicated to this important issue started at CERN using ultra stabilized optical bench and active feedbacks on mechanical positioning. Long term stability of quadrupole position within 0.5 nm has been demonstrated.

### CLIC TEST FACILITIES

The CLIC Test Facility programme addresses all the key issues of the CLIC technology.

The CLIC Study Group, in agreement with the recommendation of the International Linear Collider Review Committee (ILC-TRC), decided to focus the CTF3 activities on the R&D, test and validation of key feasibility issues [5]:

- Damped accelerating structure at designed gradient and pulse length.
- Drive beam generation with fully loaded linac.
- Power extraction and transfer structure (PETS).
- Structure with hard-breaking material (W, Mo).
- Stability and losses of drive beam decelerator.
- Linac sub-unit with the beam.

#### CTF1 and CTF2

CTF3 is not the first test machine for CLIC: in CTF1 and CTF2 the proof of principle of the dual beam acceleration was tested for short train of bunches [6]. A photoinjector was used to produce the electron beam that was accelerated by 3 GHz conventional linac sections. The beam was then decelerated by 30 GHz RF structure and the extracted power was sent to the input port of 30 GHz accelerating structures. A probe beam was accelerated demonstrating the two-beams accelerator scheme.

In CTF2 the possibility to achieve 190 MV/m accelerating gradient in a short pulse train was also demonstrated. This result was achieved after R&D activity on the 30 GHz RF accelerating structures; in particular, by changing the iris material to increase the damage threshold.

The accelerating gradient values achieved were 120, 150, 190 MV/m for copper, tungsten, molybdenum iris respectively.

#### CTF3 Preliminary Phase

The pre-injector of the Large Electron Positron collider (LEP) at CERN, composed by a 500 MeV linac and an accumulator ring (EPA) approximately 100 m long, will be not used in the new Large Hadron Collider (LHC). The complex became available after LEP decommissioning. The proposal to reuse the building, the infrastructures and the equipments to build a facility to test the CLIC components and validate the machine parameters was accepted.

The CLIC Test Facility 3 project started with a preliminary phase in which short trains of bunches (16 ns) were injected and recombined with interleaving technique in the slightly modified EPA ring [7].

The existing LIL Linac has been shortened to leave the first part of the linac tunnel free to install the new gun realized for CTF3 nominal phase.

CTF3 preliminary phase proved that it is possible to interleave up to five trains of bunches one inside the other. The beam is injected selectively by two 3 GHz RF deflectors used as injection kickers after fine tuning of the ring length and of the RF signal phase [8]. Reducing the bunch distance and the total pulse length the pulse current has been increased by a factor of five and the bunch frequency of 15 GHz has been obtained.

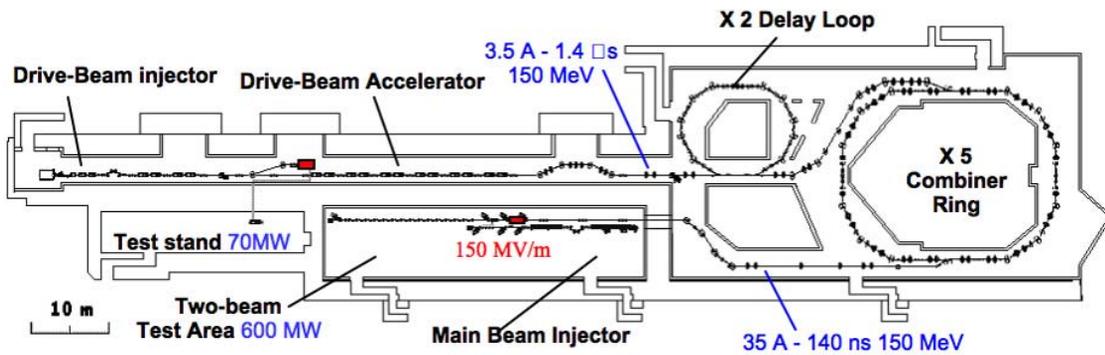


Figure 2: Layout of CTF3 Complex.

### CTF3

CTF3 must produce the drive beam with the characteristics necessary to test the CLIC components at the nominal parameters value.

In January 2002 the conceptual design report for the construction of CTF3 was ready [9] and the realization of the components started with contribution of the collaborating institutes (see Table 2).

The drive beam system is composed by a linac and a recombination system formed by two rings: the Delay Loop (DL) that provides a current/frequency multiplication by a factor of two and the Combiner Ring (CR) that allows multiplication by another factor of five [10]. The CLIC experimental area (CLEX) dedicated to the deceleration and acceleration test using the drive beam is now under construction (see Fig. 2).

#### Linac

The construction of the CTF3 complex started in 2003 with the installation of the injector in part of the LIL linac tunnel. This equipment has soon delivered full current of nominal pulse length.

In 2004 half of the 16 full loading sections of the linac and the transfer line, including a magnetic chicane and the beam measurement section have been installed.

The CTF3 3GHz fully loaded Linac produces a  $1.5 \mu\text{s}$  long train of bunches at 1.5GHz repetition rate with an average current along the train of 3.5 A. A sub-harmonic bunching system (bunch coding) permits to change the bunch phase along the train creating series of bunch subtrains 140 ns long with  $180^\circ$  phase difference [11]. This system is necessary to double the frequency and the pulse current using the Delay Loop ring, and to create a series of 140 ns long bunch trains and empty gaps along the  $1.5 \mu\text{s}$  train necessary for the recombination procedure in the Combiner Ring.

The fully beam-loaded operation of the travelling wave section of the Drive Beam Accelerator (DBA) has been successfully tested by reusing all existing 3 GHz klystrons and modulators. The developed DBA sections are composed by 34 cells (2 with couplers); to reduce the dangerous High Order Mode excited by the beam, radial slots are machined in the iris creating four wave guides with cut-off frequency above the fundamental. The HOM

power is dissipated in wide band Silicon Carbide loads placed inside the waveguides [12].

The linac was commissioned and transfer efficiency from the RF power to the electron beam of 95% has been measured without any beam break-up observation.

In 2005 the rest of the linac sections have been installed and successfully commissioned.

#### Power Production Station and Test Stand

To continue the R&D work during the installation of the pulse compressor system (DL & CR), a 30 GHz power production station has been installed parallel to the linac in the tunnel. A dogleg line joins the PETS to the linac to allow fast switch between 30 GHz RF power production and operation mode and the commissioning of the rest of the CTF3 complex. Using approximately one third of the linac length, the electron beam at the power station has an energy of 70 MeV, current of 6.4 A, bunch length of 1 mm and 3 GHz of bunch frequency [13]. The power extracted is transferred by means of a 17 m long waveguide to a neighbouring laboratory, the old CTF2 tunnel, where the 30 GHz accelerating structures are tested.

The power production station has been continuously operated for the conditioning and test of the accelerating structure. More than 100 MW of RF power at 30 GHz has been extracted by PETS in 70 ns long pulse, and transferred with 75% efficiency to the test stand [14].

The accelerating gradient of 140 MV/m at 70 ns pulse length has been routinely achieved.

Breakdown probabilities of different cavity configuration versus the peak gradient and peak gradient versus pulse length have been measured. The 30 GHz accelerating structures, 500 mm long, have been produced brazing 150 disks. In each disk, half cavity and HOM absorber aperture have been machined. A new fabrication method has been adopted in which the entire structure is longitudinally divided into quadrants. All the quadrant cavities are machined by single metal blocks including the cooling and vacuum channels. The quarter sections are then longitudinally brazed. Advantages in terms of electrical conductance and vacuum quality to lower the breakdown rate, employing this method are expected together with reduction of the production cost. The first accelerating section produced with this method is now under test.

Table 2: CLIC / CTF3 collaborating Institutes and their contribution

Ankara University (Turkey)	CTF3 beam studies & operation
Berlin Tech. University (Germany)	Structure simulations
BINP (Russia)	CTF3 magnet development and construction
CCLRC / RAL (England)	Laser for CTF3 and CLIC photo-injector
CERN	Study coordination, Structures R&D, CTF3 construction and commissioning
CIEMAT (Spain)	CTF3 septa and kicker, correctors, PETS
DAPNIA / Saclay (France)	CTF3 probe beam injector
Finnish Industry (Finland)	Sponsorship of mechanical engineer
INFN / LNF (Italy)	CTF3 Delay Loop, transfer lines & RF deflectors, ring vacuum chambers
JINR & IAP (Russia)	Surface heating tests of 30 GHz structures
KEK (Japan)	Low emittance beams in ATF
LAL / Orsay (France)	CTF3 Electron guns and pre-buncher cavities
LAP / ESIA (France)	CTF3 beam position monitor electronics, stabilization studies
LLBL / LBL (USA)	Laser wire studies
North-West University Illinois (USA)	Beam loss studies & CTF3 equipment
SLAC (USA)	CTF3 injector, high gradient structures design & test
Uppsala Univ. (Sweden)	CTF3 high frequency beam monitoring system

*Transfer Line and Magnetic Chicane*

The first part of the transfer line between the linac and the Delay Loop has been also installed in 2004 including a magnetic chicane and beam measurement station.

In particular the magnetic chicane is used to control the bunch length by changing the optical functions (R56 parameter), to avoid the beam degradation due to the coherent synchrotron radiation [15].

The measurement line is composed by a magnetic spectrometer to measure the energy and energy spread, an Optical Transition Radiation station to measure the beam transverse distributions and the emittance in conjunction with the upstream quadrupoles. An optical line that transfers the OTR light to an external laboratory equipped with a streak camera for the bunch length measurement has been also installed.

An alternative method to measure the bunch length with a resolution better than the 2 ps of the existing streak camera is the use of the RF deflector, already realized for CTF3, in the zero crossing mode. The bunch particles, passing through this RF structure, are differently deflected depending on their longitudinal position; the OTR monitor is used to detect the transverse distribution to deduce, after accurate calibration, the longitudinal one. The resolution obtained was better than 0.7 ps and a minimum bunch length of 0.5mm has been obtained setting the chicane in the bunch compression mode [16].

*Recombination System*

The pulse recombination system is composed by two rings: the Delay Loop and the Combiner Ring. To obtain the maximum power extraction efficiency the drive beam must have short bunches equally spaced. Design criteria of these rings are dictated in order to fulfil these requirements; the energy spread should be as small as possible and the machine lattice has to be isochronous in

order to avoid lengthening of bunches. Also the energy loss must be small to avoid that the bunches of different trains, performing a different number of turns in the ring, have different spacing.

All the vacuum chamber components are designed with very low coupling impedance to minimize the energy loss and energy spread in the beam. A simulation study of the coherent synchrotron radiation (CSR) has shown that the bunch length should be increased, through the chicane, in all bunches up to the limit in which the energy spread due to the CSR becomes acceptable.

The Delay Loop has been installed in 2005 sharing the time with the linac operation. The commissioning started at the end of the year showing good transmission efficiency between the injection/extraction by means of innovative 1.5 GHz RF deflector [17]. In April and May this year the recombination process has been successfully proved switching on the bunch coding system and setting the nominal isochronous optic for the Delay Loop.

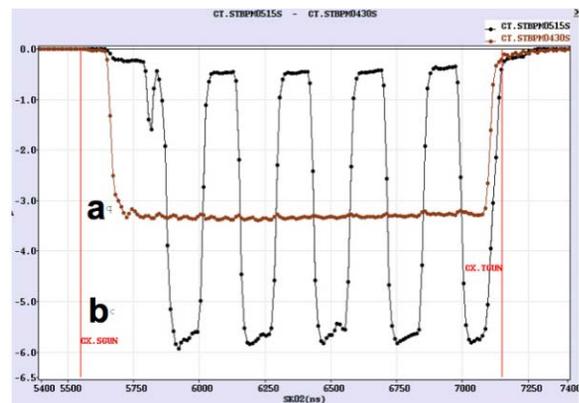


Figure 3: bunch trains recombination in the Delay Loop: a) train of bunches at the Linac end, b) bunch trains after Delay Loop.

In Fig. 3 the beam position monitor (BPM) signals are summed in order to give a total current measurement: trace a) shows the current distribution along the 1.5  $\mu$ s long train (the 1.5 GHz fine structure is not detected because of the low frequency response of the monitor. Trace b) shows the BPM signal after the Delay Loop in which the trains with opposite phase have been recombined doubling the current of the incoming beam up to 6 A on the five pulses with the nominal pulse duration of 140 ns [18].

### Future Program

In order to complete the CTF3 program within 2010 a new work program has been launched in 2004 organizing the project with a more extended collaboration as shown in Table 2.

The Combiner Ring design is accomplished and the layout frozen. The magnet positioning and the vacuum chamber realization have started with the target to complete the installation of the ring and the transfer line that joins the two rings by the end of the year. The commissioning activity is foreseen for the early 2007.

In the same period the realization the CLIC experimental area (CLEX) building will be completed. The building, placed parallel to the CTF3 drive beam linac tunnel, will host the injector that provides the probe beam that will be accelerated in the dual beam acceleration scheme. This injector will be used to test the acceleration in the 30 GHz structures, the effects of RF breakdown, wakefield and beam loading in the two beam test stand. Using an RF photoinjector and a velocity bunching system, also short bunches ( $\sigma_t < 0.8$  ps) with low emittance will be produced to test the high resolution diagnostic systems.

The Test Beam Line (TBL) is a scaled version of the CLIC decelerator sector. It is composed by 14 PETS structures; this will be used to extract the power from the drive beam. It will be used to validate beam stability in the drive-beam decelerator [19].

A Joint Research Activity to develop the high charge long pulse photoinjector for the CTF3 and CLIC drive beam has been founded by EU Commission in the FP6 program. The realization phase is well advanced; The first test with beam is foreseen next year [20].

### CONCLUSIONS

CLIC technology is not completely mature and it still requires challenging R&D. In CTF1, CTF2 and in the first step of new CTF3 many promising results have been obtained.

The CLIC Test facility 3 is in the installation phase by an international collaboration to demonstrate the CLIC feasibility before 2010. The construction of the CTF3 complex has been advanced in stages and so far the installed parts have been successfully commissioned.

### REFERENCES

- [1] <http://www.linearcollider.org/cms/>
- [2] M. Battaglia, A. De Roeck, J. Ellis, D. Shulte (eds.), "Physics at the CLIC multi TeV Linear Collider", CERN Reports Physics Dept. CERN-2004-005.
- [3] J.P. Delahaye for CLIC team, "The CLIC study of a multi-TeV  $e^+e^-$  linear colliders", Proc. PAC99 New York, USA.
- [4] G. Guignard (ed.), "A 3 TeV  $e+e-$  linear collider based on CLIC technology", CERN 2000-008 and R. Corsini (ed.) "The CLIC power source" CERN Yellow Report 99-06.
- [5] H.H. Braun for CLIC team "CLIC progress towards multi-TeV linear colliders", Proceedings of PAC 2005, Knoxville.
- [6] H.H. Braun "CTF2 description and performances", Proceedings of VIII International Workshop on Linear Collider, LC 1999, Frascati, Italy.
- [7] D. Allard et al., "CTF3 design report – Preliminary phase", CERN/PS, 2001-072 (RF).
- [8] D. Alesini et al. "RF beam deflector for CTF3 combiner ring", Proceedings of EPAC 2002, Paris, France.
- [9] G. Geschonke, A. Ghigo (ed.), "CTF3 Design Report", CERN/PS 2002-008(RF), LNF-02/008 (IR).
- [10] D. Alesini et al., "CTF3 compressor system", Proceedings of EPAC 2002, Paris, France.
- [11] G. Carron et al., "Beam dynamics and first operation of the sub-harmonic bunching system in CTF3 injector", these Proceedings.
- [12] G. Carron et al., "Design of a 3 GHz accelerator structure for the CLIC test facility (CTF3) drive beam", Proceedings of the XX International Linac Conference, Monterey 2000, California
- [13] C. Achard et al., "30 GHz power production in CTF3", Proceedings of PAC 2005, Knoxville, USA.
- [14] W. Wuensch et al., "A high-gradient test of a 30 GHz Molybdenum-iris structure", these Proceedings.
- [15] A. Ghigo et al., "Commissioning and First Measurements on the CTF3 Chicane", Proceedings of PAC 2005, Knoxville.
- [16] D. Alesini et al. "Longitudinal phase space characterization of the CTF3 beam with the RF deflector", Proceedings of PAC 2005, Knoxville.
- [17] F. Marcellini et al., "The RF deflector for the CTF3 Delay Loop" these Proceedings
- [18] C. Biscari et al., "Commissioning status of the CTF3 Delay Loop", these Proceedings.
- [19] E. Adli et al., "Progress on CF3-TBL", these proceedings.
- [20] G. Bienvu et al., "The PHIN photoinjector for the CTF3 drive beam" these Proceedings.