RESULTS FROM THE CLIC TEST FACILITY CTF3 AND UPDATE ON THE CLIC DESIGN

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Abstract

The CLIC Test Facility CTF3 is being built and commissioned in stages. Up to now the facility consists of an electron linac, a magnetic chicane for changing bunch length, the Delay Loop and the Combiner Ring. Recent experience and commissioning results will be presented together with plans for the next steps which should lead to feasibility demonstration of CLIC technology by the year 2010. The CLIC design has been reviewed in detail. The resulting changes in parameters will be presented

INTRODUCTION

The community of high energy particle physicists has reached a consensus, that LHC physics results need to be complemented in the future by experiments done with a high-energy lepton collider in the TeV centre-of-mass energy range [1]. Since the energy reach of circular e^+ e^- storage rings is limited by the emission of synchrotron radiation, one alternative is linear colliders, where two opposing linear accelerators accelerate electrons and positrons, with the detector at the collision point in the centre. One candidate for such a facility is CLIC (Compact Linear Collider), which aims at a centre-of-mass energy of 3 TeV and a Luminosity in the range of 10^{34} cm^{-2} s^{-1} [2].

The CLIC technology is based on a number of novel concepts. Part of the R&D for CLIC is the feasibility demonstration of these key features in the CLIC Test Facility (CTF3) [3], which is being constructed at CERN by an international collaboration [4].

THE CLIC SCHEME

Linear Collider Constraints

The main constraints of the CLIC design are::

- Energy (nominally 3 TeV) and Luminosity (about 10^{34} $cm^{-2}s^{-1}$) of CLIC are given by physics requirements.
- The total length of the machine should not exceed 50 km and the mains power consumption must stay within practical limits. Power efficiency is of prime importance.

The beams can only be used once, after one collision they have to be dumped. The luminosity is given by

$$L = \frac{k_b N_b^2 f_{rep}}{4\pi\sigma_x^* \sigma_y^*}$$

where k_b is the number of bunches per bunch train, N_b the number of particles per bunch, f_{rep} the repetition frequency and σ_x^* and σ_y^* the horizontal and vertical rms beam size at the collision point. For a given beam power therefore the beam size and hence the beam emittances have to be as small as possible.

CLIC Acceleration System

CLIC is based on acceleration with normal conducting copper travelling wave structures. In order to find the optimum frequency and acceleration gradient, a systematic scan of accelerating structure parameters was started in 2006, making maximum use of available experimental data [5]. The maximum accelerating field is limited by RF breakdown and fatigue of the copper surface due to pulse power RF heating. The RF breakdown rate required for stable beam operation is estimated to be in the range of 10^{-7}. Models relating structure parameters to maximum achievable accelerating fields taking into account these constraints allow to design potential structures. These structures are then simulated with respect to beam emittance degradation in the linac due to wake fields. The final figure of merit is achievable luminosity per wall plug power consumption L/P_l . In addition a cost scaling has been done.

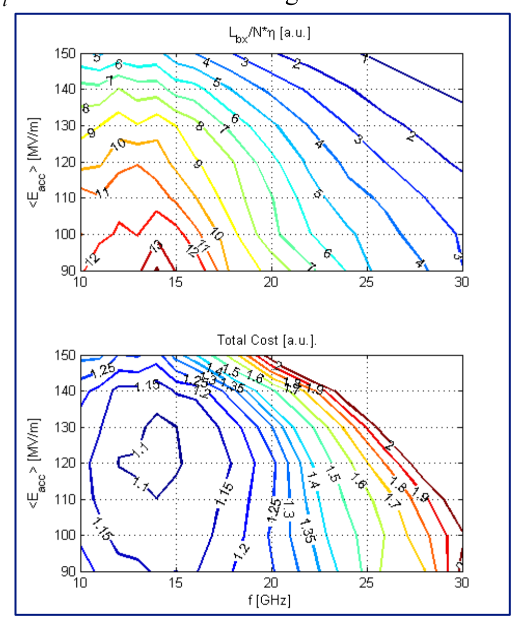

Figure 1: Luminosity per wall plug power (top) and cost (bottom) as function of frequency and accelerating gradient.

The result of an extensive programme (more than 60 *10^6 structures analyzed) is summarized in Fig. 1. Figure of merit and cost (in arbitrary units) have been scanned for frequencies between 10 and 30 GHz and accelerating gradients between 90 and 150 MV/m. These plots show, that the old parameters, 30 GHz acceleration frequency and 150 MV/m gradient were far from optimum both in terms of performance and cost. At the beginning of 2007 the parameters of the CLIC acceleration system were changed: The RF frequency was lowered to 12 GHz and the accelerating gradient is now 100 MV/m, close to the optimum.

The total active length of accelerating structures for both linacs is now 30 km. Development of acceleration structures is one of the high-priority items of the CLIC R&D programme [6]. The main parameters of accelerating structures are given in table 1:

Table 1: Parameters of CLIC accelerating structure

RF frequency	11.994	GHz
Loaded acceleration gradient	100	MV/m
Active structure length	0.229	m
Beam aperture (mean diameter)	5.5	mm
RF to beam efficiency	27.7	%

The development and testing of accelerating structures is done in collaboration between CERN, KEK and SLAC as major partners. Up to now a loaded gradient of more than 100 MV/m at a breakdown rate of about 10^{-7} has been achieved, however, with a structure with slightly lower RF to beam efficiency and without damping.

The CLIC Two Beam Scheme

The RF peak power required to achieve this high accelerating gradient amounts to 68 MW for each accelerating structure, i.e. 295 MW per m of active length. The RF pulse length is 240 ns with a repetition frequency of 50 Hz. In CLIC it is foreseen to extract this high RF peak power from a "Drive Beam" running parallel to the main beam. This beam is a high-current electron beam with a bunch structure which allows to extract RF power at 12 GHz. This is done by sending the beam through decelerating structures (PETS, Power Extracting and Transfer Structures). One PETS extracts RF power for a set of two accelerating structures in the main beam. This scheme is shown in the left part of Fig.2.

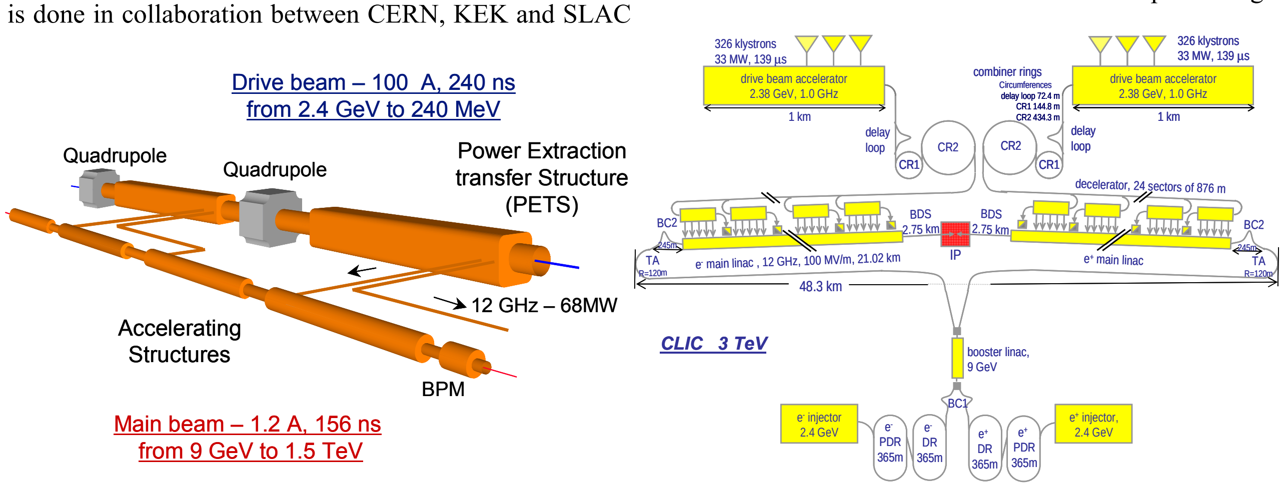

Figure 2: CLIC Two Beam scheme and CLIC layout (not to scale).

The Drive Beam consists of 24 trains of bunches with a repetition frequency of 12 GHz and a train length of 240 ns. The trains are spaced by 5.8 µs. The beam current in the pulse is 100 A, the initial energy is 2.4 GeV, going down to 240 MeV after deceleration. It is generated from a long train of electron bunches with large bunch spacing, which can be accelerated very efficiently by state-of-the-art klystrons running at relatively low frequency. This long bunch train is compressed into several short trains with small bunch spacing and high beam current by interleaving the bunches in between each other in three rings, first in the "Delay Loop", followed by two "Combiner Rings". This technique uses injection into the rings via RF deflectors, which allows to place bunches very close to each other. It is described in [7].

Power efficiency is of prime importance for all components of CLIC. The Drive Beam accelerator operates under full beam loading conditions, i.e. nearly all of the RF power is transferred to the beam. Pulse compression and frequency multiplication is done with the electron beam and is therefore essentially without losses. Main parameters of the drive beam complex are given in table 2.

Table 2: Drive beam parameters

Drive Beam Linac		
Linac RF frequency	999.5	MHz
Beam energy	2.38	GeV
Klystron peak power	33	MW
Number of klystrons	326*2	
Pulse length (bunch train)	139	µs
Beam current	4.2	A
RF-to-beam efficiency	93	%
Compressed beam		
total compression factor	24	
Pulse length	240	ns
Beam current	100	A
Beam energy after deceleration	240	MeV
Number of pulses per cycle	24	

The 24 bunch trains of the Drive Beam are spaced by 5.8µs, each train supplies RF power to the main linac for 868 m. After this distance it has lost 90 % of its energy and is dumped.

BASIC DESIGN PARAMETERS OF CLIC

The complete scheme of CLIC is shown in Fig. 2. The total length of both linacs including the beam delivery system is 48.2 km. Both the drive beam and the main beam are generated in the central area and are transported to the beginning of the linacs via transfer lines in the accelerator tunnel. The Drive Beam generation system consists of a 2.4 GeV linac, a Delay Loop and two Combiner Rings for each main linac.

High luminosity requires a small beam size at the collision point. In CLIC the beam dimensions are 0.7 and 40 nm rms in the vertical and the horizontal plane respectively.

The emittance at the output of the linac to get these dimensions is 20 and 660 nm rad (normalized) in the vertical and horizontal plane respectively. A set of two damping rings give 10 and 600 nm rad at the linac input [8]. Prototype work is being done to develop the required wigglers [9].

The beam emittance has to be preserved in the long transfer lines and in the main beam accelerator. Transverse wake fields in accelerating structures are controlled by damping and detuning of Higher Order Modes as well as precise alignment of accelerating structures and quadrupoles.

The main CLIC parameters are given in table 3.

Table 3: CLIC main parameters

Centre of mass energy	3	TeV
Luminosity (in 1% energy)	$2*10^{34}$	$cm^{-2}\ s^{-1}$
Number of particles per bunch	$3.72*10^{9}$	
Bunch separation	0.5	ns
Number of bunches per train	312	
Proposed site length	47.9	km
AC to beam power efficiency	8.8	%

CLIC TEST FACILITY CTF3

CLIC has many novel concepts which have never been used before and some parameters are approaching the limit of available technology. The main R&D effort within the CLIC study is aimed at answering these major feasibility issues. One line of this R&D goes into the development of accelerating structures, as mentioned above. The other major programme is the CLIC Test Facility CTF3. The aim is to demonstrate by the year 2010:

- The feasibility of the CLIC RF power source: Drive Beam generation using the bunch interleaving techniques with RF deflectors and generation of 12 GHz RF power with PETS
- A linac "sub-unit" consisting of an accelerating structure fed by a PETS with nominal CLIC parameters of power and accelerating field and acceleration of a probe beam.

CTF3 makes use of the infrastructure of the LEP injector, which became available after the end of LEP operation at the end of 2000. The building and the layout of CTF3 are shown in Fig. 3. The thermionic electron gun provides a beam current of up to 10 A. A system of 1.5 GHz bunchers "phase-codes" the beam, i.e. every 140 ns the phase of the 1.5 GHz system is rapidly switched by 180 degrees. The bunch train is 1.4 µs long and consists of ten 140 ns long phase-coded sub-trains. This beam is then further bunched and accelerated in a 3 GHz RF system up to 150 MeV. Nine S-band klystrons are available with power between 35 and 45 MW, most of which are equipped with a pulse compression system using LIPS or BOC cavities. After bunching the nominal current is 3.5 A, but up to 7 A is possible. The maximum energy is 300 MeV at 0 A beam current.

A magnetic chicane at the end of the linac with an R_{56} variable within ± 0.5 m allows lengthening of the bunches to control coherent synchrotron radiation effects in the following two rings. Bunch compression is also possible.

The next element is the Delay Loop with 42 m circumference. Every second sub-train of 140 ns is deflected into this ring by a 1.5 GHz RF deflector. After one turn these delayed bunches are placed exactly between the bunches of the following sub-train. The circumference of the Delay Loop can be adjusted with a wiggler magnet within a range of 9 mm.

Four subsequent bunch trains are injected into the Combiner Ring (84 m length) by a system of two 3 GHz RF deflectors, which create a time dependent closed orbit bump, different for each turn, such that in four successive injections the newly injected bunches can be placed immediately behind the already circulating bunches inside the same train. By doing this, four subsequent bunch trains are interleaved into one single 140 ns long train with a bunch repetition frequency of 12 GHz and a current of 28 A. After the fourth injection the extraction kicker is fired and the beam is ejected into the Transfer Line TL2.

TL2 compresses the bunches again to about 0.5 to 1 mm rms length and transports the beam into CLEX (CLIC Experimental Building), a hall of 42 m length and 8 m width. CLEX contains several beam lines:

a) Test Beam Line TBL [10]. Here the beam will be decelerated to about half its initial energy by up to 16 PETS structures. The aim is to demonstrate stability under significant deceleration, which will produce a bunch train with energy variation of a factor of two between the first and the last bunches. The basic lattice cell consists of a PETS and a quadrupole which will be on precision-movable supports, such that alignment errors and beam-based alignment can be simulated. A total of 2.5 GW of 12 GHz RF power will be extracted from the beam.

b) Probe Beam. This is a stand-alone electron accelerator providing a 200 MeV low-current electron beam [11], which will demonstrate particle acceleration with CLIC accelerating structures. This linac has a laser-driven RF gun with a CsTe photocathode, allowing single-bunch operation as well as bunch trains of 64 bunches with a bunch charge of 0.5 nC.

c) The Two Beam Test Stand (TBTS) [12]. This test stand will simulate the CLIC linac. The Probe Beam will pass through a CLIC accelerating structure and will be accelerated at the nominal CLIC gradient. The beam from

CTF3 runs parallel to the Probe Beam at a distance of 80 cm. A CLIC-type PETS, modified such that it can produce the nominal CLIC RF power with the 30 A beam, will feed the accelerating structure in the Probe Beam. This allows to demonstrate the complete two-beam scheme and to validate the PETS as well as the gradient in the accelerating structure. This test stand will be well instrumented to demonstrate the beam acceleration, but also to analyze the behaviour of these structures, in particular to study the effects of RF breakdowns on the Probe Beam as well as the Drive Beam.

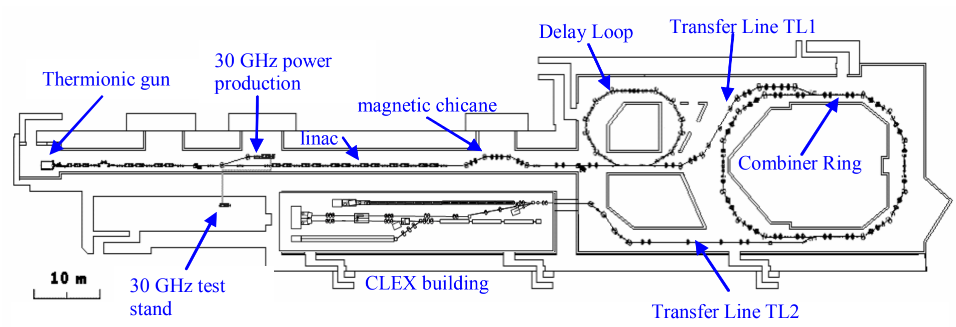

Figure 3: Layout of CTF3.

CTF3 is presently also used as a source of 30 GHz RF power for the development of CLIC accelerating structures. Even though the CLIC frequency has been changed from 30 to 12 GHz, experiments addressing RF breakdown and scaling laws of accelerating structures with respect to breakdown behaviour are still relevant and this facility is used routinely. At an energy of about 80 MeV the beam in the linac can be deflected into a beam line parallel to the main beam, where 30 GHz RF power is extracted in a specially developed PETS system and sent to a dedicated test stand. Experiments with up to 100 MW RF power can be done here.

CTF3 can not reproduce CLIC parameters in all respects, table 4 shows the main differences. Bench-mark experiments can be performed, which allow to scale to the CLIC parameters.

Table 4: Comparison CLIC – CTF3

	CLIC	CTF3
Drive Beam energy	2.4 GeV	150 MeV
Drive Beam current	100 A	28 A
Drive Beam RF Frequency	999.5 MHz	3 GHz
train length in linac	139 µs	1.5 µs

STATUS AND COMMISSIONING RESULTS

The installation of CTF3 is advancing according to schedule. The machine has been operated with beam up to the exit of the Combiner Ring. From end of July onwards, Transfer Line TL2 will be connected and beam can be sent into CLEX. In CLEX the Probe Beam and the Two Beam Test Stand will then also be operational, hardware commissioning has already started. The Two-Beam Test Stand will be equipped with the first PETS in fall 2008, and the first accelerating module in 2009.

The Test Beam Line will only be equipped with one PETS in October 2008. The remaining 15 will be installed in 2009 and 2010.

This will complete the installation of the CTF3 base-line programme.

The machine is routinely operated for about seven to eight month per year, partly for 30 GHz production, partly for commissioning and beam measurements.

Full Beam Loading Operation

An important feature of the CLIC scheme is the operation of accelerating structures in the Drive Beam under full beam loading conditions. Special travelling wave accelerating structures were developed for this application in the CTF3 linac. Their impedance has been designed such, that for a nominal beam current of 3.5 A all RF power is transferred to the beam and no RF power is dissipated in the RF absorber at the output of the structure. A picture of the RF power leaving the structure with and without beam is shown in Fig. 4. An efficiency of power transfer to the beam of 95.3% has been measured.[13].

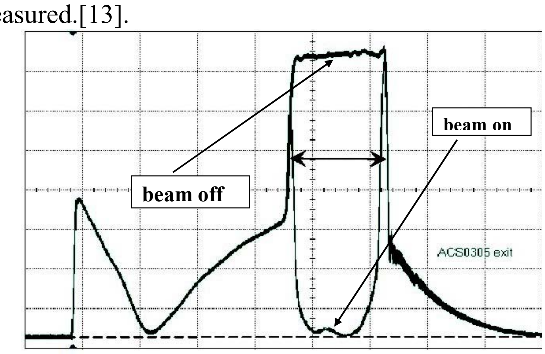

Figure 4: Demonstration of full beam loading.

The long bunch train of 1.4 µs together with the high bunch charge requires the higher harmonic modes in the accelerating structures to be damped very efficiently. In CTF3 SIC (Slotted Iris Constant Aperture) structures [14] are used. They contain 32 cells and two coupler cells and provide 6.5 MV/m with the nominal RF power of 30 MW and full beam loading. The higher order modes are coupled by radial slots in the pill box irises, which guide the dipole modes to SiC absorbers. The Q-values of the lowest dipole modes are less than 20.

Bunch Recombination

A proof-of-principle experiment of subsequent injections of bunch trains into one single train into an isochronous ring using RF deflectors has already been demonstrated in an early phase of CTF3 [15]. Five subsequent injections could be shown.

Delay Loop and Combiner Ring

In 2005 the 1.5 GHz sub-harmonic bunching system was installed and commissioned. The beam current before, in and after the Delay Loop are shown in Fig. 5.

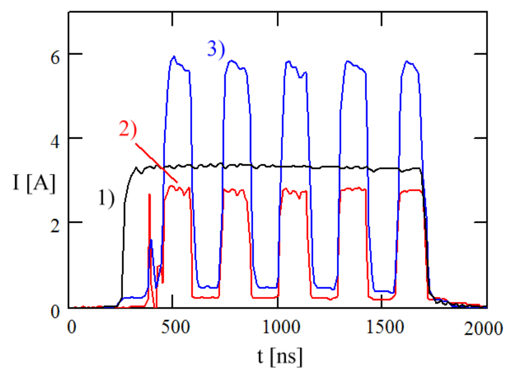

Figure 5: Beam current as function of time, measured: 1) before, 2) in, 3) after the Delay Loop. The sub-trains combined are 140 ns long.

140 ns long bunch-trains were injected into the Delay Loop and combined with the following train. About 8.5 % of the incoming beam is contained in "satellite" bunches.

Commissioning of the Combiner Ring was started in 2007. An instability of the beam in the vertical plane was discovered, which manifests itself in a growth of vertical beam oscillations and eventually beam loss.

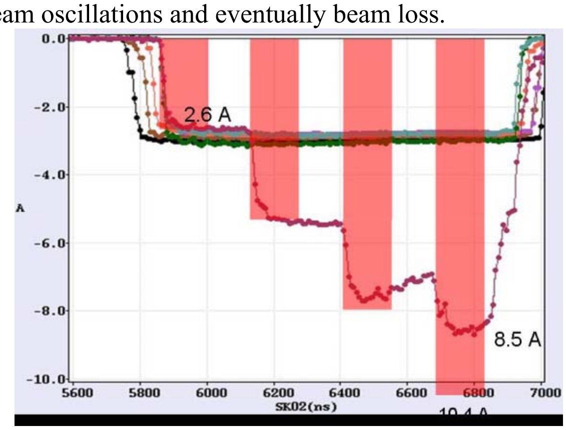

Figure 6: Interleaving of 4 bunch trains.

The instability is believed to be caused by the vertical deflecting mode in the RF deflectors, excited by the beam. This mode is shifted in frequency by polarising rods in the deflector cells, but not damped. New RF deflectors will be installed in October 2008. Each cell will have loop antenna to polarize and damp the vertical mode. Nevertheless bunch combination by a factor of four was already demonstrated. It is shown in Fig. 6.

NEXT STEPS AND CONCLUSION

A new consistent parameter set for CLIC has been developed. The design of sub-systems is advancing well. The CTF3 project is on schedule to fulfil its objective to demonstrate the feasibility of the main issues for CLIC by 2010. A number of questions have already been answered, such as full beam loading operation of the Drive Beam linac, and the bunch interleaving scheme.

A CLIC conceptual design report is scheduled to be finished by end 2010. The technical design would take another four years after this.

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