STATUS AND FUTURE PROSPECTS OF CLIC

S. Döbert, for the CLIC/CTF3 collaboration, CERN, Geneva, Switzerland

Abstract

The Compact Linear Collider (CLIC) is studied by a growing international collaboration. Main feasibility issues should be demonstrated by 2010 with the CLIC Test Facility (CTF3) constructed at CERN. The CLIC design parameters have recently been changed significantly. The rf frequency has been reduced from 30 GHz to 12 GHz and the loaded accelerating gradient from 150 MV/m to 100 MV/m. A new coherent parameter set for a 3 TeV machine will be presented.

The status and perspectives of the CLIC feasibility study will be presented with a special emphasis on experimental results obtained with CTF3 towards drive beam generation as well as progress on the high gradient accelerating structure development.

The frequency change allows using high power x-band test facilities at SLAC and KEK for accelerating structure testing at 11.4 GHz. The design gradient of 100 MV/m has been achieved in a recent test at SLAC with a very low breakdown-rate.

INTRODUCTION

There is a consensus in the community of high energy particle physicists 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]. A promising candidate for such a facility is CLIC, a linear collider aiming at a centre-of-mass energy of 3 TeV and a luminosity in the range of 10^{34} cm^{-2} s^{-1} presently studied by a large international collaboration [2, 3].

In a linear collider the particles have to be accelerated in a single pass to the final energy, 80% of the facility length is used for acceleration. Naturally the emphasis for the R&D on CLIC is on the rf system which has to reach a maximum accelerating gradient and efficiency to keep the length and cost limited. The CLIC scheme uses high-frequency normal conducting accelerating structures and a two beam scheme to cope with these challenges. In 2007 the rf frequency has been reduced from 30 GHz to 12 GHz and the accelerating gradient from 150 MV/m to 100 MV/m for CLIC. This change was motivated by high gradient constraints found experimentally which made the ambitious goal of 150 MV/m unrealistic. A general optimization study taking into account these rf constraints showed that the new parameters represent an optimum with respect to luminosity and cost [3].

The CLIC Test Facility CTF3 [4] is being built at CERN by the CTF3 collaboration to investigate and demonstrate the key technical issues of the CLIC scheme. This feasibility study should conclude in 2010 with a Conceptual Design Report for CLIC.

COMPACT LINAER COLLIDER CLIC

The compact linear collider CLIC uses high-frequency high-gradient normal conducting rf accelerating structures to accelerate the electrons. An accelerating gradient of 100 MV/m at 12 GHz allows to keep such a facility bellow a length of 50 km. The 12 GHz rf power needed to energize the accelerating structures is extracted from a drive beam running parallel to the main beam. This two beam scheme is an efficient and less costly way to provide the rf power needed for acceleration as compared to the use of 12 GHz klystrons. In order to achieve the luminosity needed for the experiments the electrons and positron beams need to be produced with extremely small emittances, accelerated and transported without significant degradation and finally focused to spot sizes in the nm range. The main parameters of CLIC can be found in table 1.

Table 1: 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	48.4	km
AC to beam power efficiency	7.2	%

The Facility Layout

A schematic layout of CLIC is shown in figure 1. A central injector complex prepares the ultra low emittance beams needed for high luminosity collisions. The complex contains the positron and polarized electron sources, pre-damping and damping rings, bunch

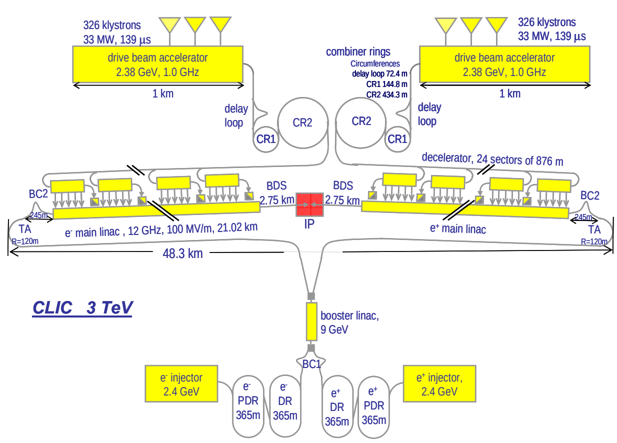

Figure 1: Schematic CLLC layout (not to scale).

compressors and a 9 GeV booster linac. These beams are then transported by a long transfer line to both ends of the linear collider. The corresponding drive beams providing the rf power for acceleration are also generated in a central location. The high-current low-energy drive beams are than decelerated along the main linacs transferring the power to the main beam which is accelerated in parallel.

Drive Beam Generation

A unique feature of the CLIC scheme is the rf power source using a high current drive beam. A long 139 µs long pulse train with 4.2 A average current and a 500 MHz bunch spacing is accelerated efficiently to 2.38 GeV using 1GHz klystrons and fully loaded accelerating structures. This bunch train is then combined into 24 beam pulses with a pulse length of 240 ns with 100 A average current and 12 GHz bunch spacing in a sequence of delay loop and combiner rings. The details of the beam combination are explained in the test facility section below. The generated drive beam pulses are then sent along the linac towards the extremities and then with precision timing injected into the corresponding decelerator section (see layout). The drive beam can be seen as a very efficient rf pulse compression system which allows to transform the rf power generated efficiently with low peak power and long pulse length into short pulses with high peak power needed for acceleration. The drive beam parameters are listed 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	

Decelerator

Each decelerator sector is designed to extract 90% of the drive beam energy. During this process the size and the energy spread of the beam increases significantly.

The key equipment of the decelerator sector is the Power Extraction and Transfer Structure (PETS) [5]. These structures are large-aperture travelling wave structures resonant at 12 GHz with an active length of 21 cm. They have a high group velocity (v_g/c =48%) and are equipped with damping slots all along the structure loaded with rf damping material. Each PETS extracts 136 MW of 12 GHz rf power to feed a pair of accelerating structures. A total of 36000 of these structures are needed for CLIC. Prototypes of these unconventional structures fabricated in octants have been built and will be high power tested this fall both with klystrons at 11.4 GHz and with beam in CTF3 at 12 GHz. The CTF3 program includes a test beam line to study and bench mark the challenging beam dynamics of the CLIC decelerator.

Accelerating Structure

A sophisticated optimization procedure taking into account constraints from beam dynamics, cost and high gradient constraints resulted in a new accelerating structure for CLIC [3]. An optimum was obtained at 12 GHz with a loaded gradient of 100 MV/m. The structure has a constant gradient design with a rather small aperture and a group velocity of only 1.7 % at the entrance of the structure. The rf pulse length needed to accelerate the 312 bunches is 240 ns including the filling time. This requires strong higher order mode damping provided by four waveguides in each cell. The low power consumption and the short bunch spacing made possible by the HOM damping results in a high rf-to-beam power efficiency of 27.7% for this structure. A total of 30 km active acceleration will be needed for both linacs which imposes a trip rate better than 3 10^{-7} per meter. The main parameters of the CLIC accelerating structure are listed in table 3.

Table 3: Accelerating Structure Parameters

RF frequency	11.994	GHz
Loaded acceleration gradient	100	MV/m
Input Power for 100 MV/m	64	MW
Maximum surface field	245	MV/m
Active structure length	0.23	m
$\langle a/\lambda \rangle$	0.11	
RF to beam efficiency	27.7	%

A recent high power test of a low group velocity prototype at 11.4 GHz reached 100 MV/m unloaded gradient with a pulse length of 230 ns and a trip rate below 10^{-7}/m [7]. The structure tested had a constant loaded gradient design with a strong tapering of the aperture towards the end. The electrical surface field reached therefore more than 300 MV/m.

Beam Quality Issues

One of the biggest challenges for the CLIC scheme is to generate the ultra low emittance beams required to achieve the high luminosity. The normalized emittance needed at the IP is 660 nm in horizontal and 20 nm in the vertical plane. The beam has to be focused down to a spot size of 40 nm in horizontal and 1 nm in vertical. The damping ring is designed to reach emittances of 381 nm in the horizontal plane and 4.1 nm in the vertical plane using high field wigglers [8]. Therefore the beam transport and acceleration allow only very small emittance growth. This imposes very strict alignment and jitter tolerances. CLIC will have to rely extensively on beam based alignment procedures and active vibration stabilisation of focusing elements. The most severe constraints are on the final focus quadrupoles which have to be stabilized in the sub-nm range for frequencies above 4 Hz. Some R&D has been done already showing a proof of principle stabilization of a quadrupole to the level of 0.5 nm [9].

THE CLIC TEST FACILTY CTF3

The CLIC scheme comprises a number of novel concepts and challenging parameters which have to be validated experimentally. Therefore the CLIC Test Facility was designed to demonstrate the feasibility of the following key issues until 2010.

- The feasibility of the CLIC rf power source: Generating a drive beam using bunch combination with rf deflectors with high efficiency.
- Demonstrating the main linac rf structures by operating a two-beam acceleration sub-unit at nominal rf parameters.
- Validating the CLIC decelerator concept by operating several deceleration modules in series and extracting 12 GHz power.

The test facility was constructed in stages starting in 2001 re-using equipment and infrastructure from the former LEP pre-injector. The layout of the facility is shown in figure 2. A thermionic electron gun provides a beam current of nominal 3.5 A. The beam is subsequently bunched by a 1.5 GHz subharmonic system and by a 3 GHz travelling wave buncher. The high-bandwidth 1.5 GHz buncher cavities allow the phase coding of the beam by switching the phase of their TWT-drivers by 180 deg. This results in a 1.2 µs long bunch train which consists of eight 140 ns long sub-trains captured alternately in odd or even buckets of the following 3 GHz rf acceleration system. A total of 16 accelerating structures are used to accelerate this beam up to 150 MeV at the end of the linac. The one meter long acceleration sections have been optimized for full beam loading at nominal current and are equipped with strong higher order mode damping in each cell [10] to avoid beam break up in the linac. At the end of the linac a magnetic chicane allows for bunch compression or stretching. The nominal operation mode foresees bunch stretching to avoid coherent synchrotron radiation effects in the rings. After the rings the bunches are compressed again in the second transfer line (TL2 [11]) for efficient rf power production. The phase coded 140 ns long sub-trains are alternately injected into the delay loop with 1.5 GHz deflectors. After one turn the bunches of the delayed trains are interleaved in between the bunches of the following sub-train. After the delay loop the beam consists of four 140 ns long sub-trains with an average current of 7 A and 3 GHz bunch spacing and a 140 ns gap between them. A second stage of bunch combination and frequency multiplication is done in the combiner ring. Here 3 GHz rf deflectors are used to create a time-dependent closed orbit bump, which allows to interleave the bunches of four subsequent sub-trains into one. Finally the fully generated drive beam has a pulse length of 140 ns with an average current of 28 A and 12 GHz bunch spacing. This beam is then sent to the CLIC Experimental hall (CLEX), where 12 GHz rf power is extracted by power extraction structures (PETS). The CLEX area comprises an independent 200 MeV probe beam (Califes [12]) which will be used for the two beam acceleration demonstration experiments in the two beam test stand (TBTS [13]). One PETS will be powering up to two accelerating structures. In addition a test beam line (TBL) [14] will be installed consisting out of 16 deceleration modules which will produce a total of 2.4 GW of 12 GHz rf power by extracting roughly 50 % of the drive beam energy. This experiment will be used to validate the CLIC decelerator concepts. CTF3 cannot achieve CLIC parameters in all aspects due to the financial constraints of this R&D effort but is believed to demonstrate the key technical issues and provide relevant bench marks for scaling to the nominal CLIC parameters. Table 4 shows the main differences between CTF3 and CLIC parameters.

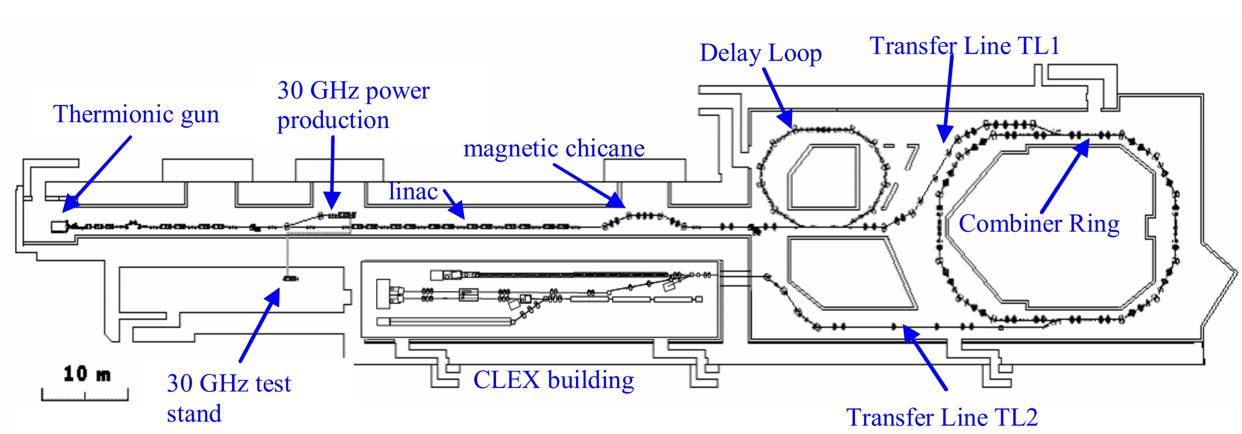

Figure 2: Layout of CTF3.

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 FIRST RESULTS

The construction of CTF3 is advancing according to schedule. This installation of TL2, the two beam test stand and the probe beam have been completed and commissioning with beam started in CLEX this summer. The first PETS in the two beam test stand and the prototype module in TBL are scheduled to be tested this fall. The remaining 15 modules of TBL will be installed in stages during 2009 and 2010. This will complete the installation of the CTF3 base line program. The facility is operated routinely for about 7 months a year. A number of milestones towards a feasibility demonstration of the CLIC scheme have been already achieved.

Full Beam Loading Operation

It is essential for the CLIC scheme that the rf power source reaches a high efficiency. Therefore the drive beam accelerator is operated with full beam loading. An efficiency of power transfer to the beam of 95.3% has been measured [15]. Figure 3 shows the measured rf power signals with full beam loading. Each structure provides 6.5 MV/m of acceleration for 30 MW input power. The shape of the rf signals before the beam are caused by an rf pulse compression system, which will, however, not be used in CLIC. The CTF3 linac is routinely operated with full beam loading for several years and no signs of beam break up have been found thanks to the strong high order mode damping in each cell of the drive beam accelerator structures.

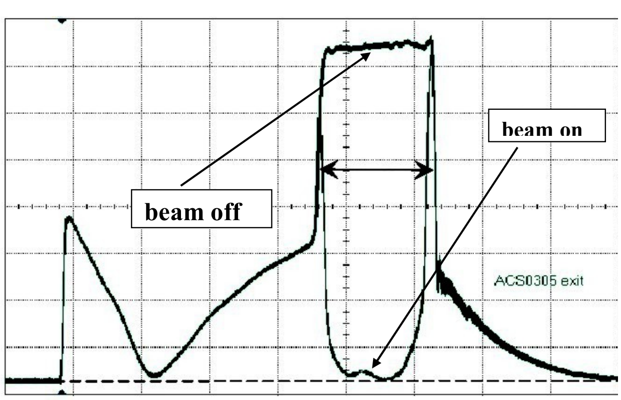

Figure 3: Demonstration of full beam loading.

Bunch Phase Coding

The phase coding of bunches within sub-trains with a sub-harmonic bunching system was commissioned in 2005 [16]. The rf phase of these bunches can be switched by 180 deg in about 4 ns. The bunching process is not perfect yet and produces satellites in the wrong 3 GHz bucket with about 8% intensity of the main bunch. These satellites are lost during recombination in the delay loop. This inefficiency can be avoided in CLIC if a photo-injector is used and the phase coding can be done by the laser.

Delay Loop Operation

Every other phase coded sub-train can now be delayed and combined with the following one as shown in figure 5. A 1.5 µs long bunch train consisting out of ten 140 ns long sub-trains was combined by separating the odd trains with the 1.5 GHz rf deflector and interleaving them with the even sub-trains, again with the rf deflector after one turn in the delay loop. In this example the combination was done for 5 sub-trains. The missing intensity in the delay loop is the 8% satellites from the bunching process which are lost later on.

The delay loop has an isochronous lattice to avoid bunch lengthening and uses a wiggler magnet to fine tune the path length of the beam to be an integer of the rf wavelength.

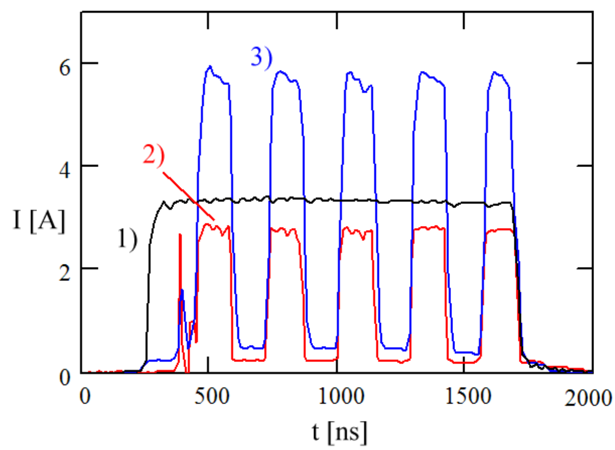

Figure 4: Beam current as function of time, measured: 1) before, 2) in, 3) after the delay loop. The sub-trains combined are 140 ns long.

Combiner Ring Commissioning

The last step of the drive beam generation in CTF3 is done by the combiner ring. Four 140 ns long sub-trains with 3 GHz bunch spacing are combined to a current of 28 A. Two 3 GHz rf deflectors are used in the ring to inject the bunch trains and to keep them on a closed orbit while circulating in the ring. A wiggler magnet is used to adjust the path-length of the ring to insure the correct phasing in the rf deflectors.

For initial commissioning a 1.2 µs long 3 GHz bunch train was used straight from the linac without going through the delay loop, it has therefore no gaps between the sub-trains. A combination of such a beam is shown in figure 6, where 2.6 A beams from the linac were interleaved to reach 8.5 A. The combination suffered from a vertical instability discovered during commissioning. The instability is caused by the vertical deflecting mode of the rf deflectors. This mode had been shifted by polarising rods but not actively damped. HOM-damping has to be incorporated in a new set of deflectors required to demonstrate combination at full current. More details on the combiner ring commissioning can be found in [17].

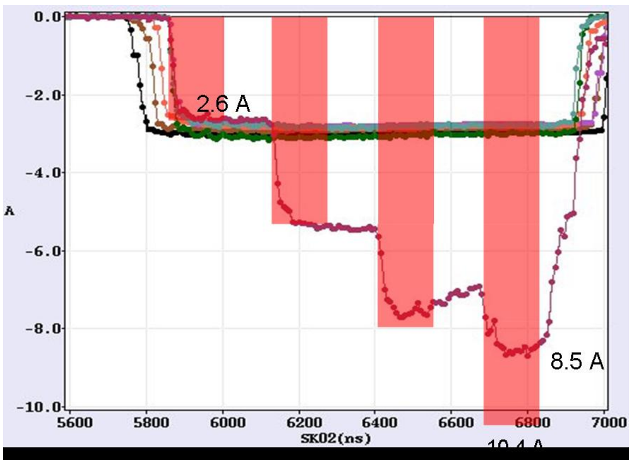

Figure 5: Interleaving of 4 bunch trains.

CONCLUSIONS AND OUTLOOK

The CLIC collaboration has worked out a new consistent parameter set for CLIC with a luminosity in the range of $2*10^{34}$ cm^{-2} s^{-1} at 3 TeV, using 12 GHz rf and 100 MV/m accelerating gradient. First very promising results from a prototype test of a CLIC type accelerating structure at 11.4 GHz have been already obtained. Currently a conservative parameter set for a 500 GeV machine together with an upgrade scenario to 3 TeV is under development [2].

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 detailed technical design is expected to take another five years after this.

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