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STATUS OF THE CLIC TEST FACILITY (CTF3)

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Abstract

The CTF3 project, being built within the frame-work of an international collaboration involving presently 15 institutions, is advancing as planned. To date, the electron linac with its sub-harmonic bunching system, the magnetic chicane for bunch-length variations, and the Delay Loop have been installed. The 1.5 GHz sub-harmonic bunching system with fast phase switching allows the longitudinal position of the bunches to be changed every 140 ns. This phase-coded beam has been successfully injected into the Delay Loop using an RF deflector and bunch interleaving of 140 ns long sub-bunch trains which double the bunch repetition frequency has been demonstrated in the extraction line. In addition to its role as a test bed for the CLIC RF power source, CTF3 is being used as a source of high-power RF at 30 GHz for the testing of CLIC accelerating structures. In this power-generating mode, about 100 MW of 30 GHz power is routinely extracted from the beam half-way up the linac by special-purpose power-extracting structures and transported to the high-gradient test area by low-loss waveguides. This paper describes the overall status of the CTF3 project and outlines the plans for the future.

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STATUS OF THE CLIC TEST FACILITY (CTF3)

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Abstract

The CTF3 project, being built within the frame-work of an international collaboration involving presently 15 institutions, is advancing as planned. To date, the electron linac with its sub-harmonic bunching system, the magnetic chicane for bunch-length variations, and the Delay Loop have been installed. The 1.5 GHz sub-harmonic bunching system with fast phase switching allows the longitudinal position of the bunches to be changed every 140 ns. This phase-coded beam has been successfully injected into the Delay Loop using an RF deflector and bunch interleaving of 140 ns long sub-bunch trains which double the bunch repetition frequency has been demonstrated in the extraction line. In addition to its role as a test bed for the CLIC RF power source, CTF3 is being used as a source of high-power RF at 30 GHz for the testing of CLIC accelerating structures. In this power-generating mode, about 100 MW of 30 GHz power is routinely extracted from the beam half-way up the linac by special-purpose power-extracting structures and transported to the high-gradient test area by low-loss waveguides. This paper describes the overall status of the CTF3 project and outlines the plans for the future.

INTRODUCTION

A likely option for the next major facility for high energy elementary particle physics is an e+e- linear collider. Two alternative designs for such a machine are presently being studied, ILC (International Linear Collider) [1] for 0.5 TeV to 1 TeV and CLIC (Compact Linear Collider) [2]. CLIC is being developed for a centre of mass energy of 3 TeV, to be achieved in a total length of about 33 km for both linacs. In order to reach this energy over this length, a very high accelerating gradient (150 MV/m with present parameters) at an acceleration frequency of 30 GHz and a very high peak RF power are required. The CLIC scheme is based on a two-beam system, consisting of the main beam to be accelerated to 3 TeV, and a second lower energy, high current electron beam, the Drive Beam. This Drive Beam runs parallel to the Main Beam and has a bunch structure which allows the RF power at 30 GHz, needed to accelerate the Main Beam, to be generated. This power will be extracted by specially developed RF structures, called PETS (Power Extraction and Transfer Structure), and transferred to the Main Beam via a network of waveguides.

PURPOSE OF CTF3

The aim of CTF3 [3] is to demonstrate the major feasibility issues inherent to the CLIC scheme. Most of these issues have been defined by the International Linear Collider Technical Review Committee [4]:

a) Demonstration of the CLIC accelerating structure at design gradient and pulse length. CTF3 is already used as RF power source for 30 GHz testing. The 30 GHz CLIC accelerating structures are being tested in a well instrumented test stand. A vigorous development programme of accelerating structures is under way.

b) Demonstration of the Drive Beam scheme. The main issue here is the generation of the Drive Beam, i.e. acceleration of a long bunch train with conventional klystrons and subsequent bunch manipulations in order to increase the bunch repetition frequency, together with an increase in peak electron current in short, compressed bunch trains. A very important feature of the Drive Beam acceleration is the operation of the accelerating structures under full beam loading. The parameters of CTF3, however, have to be scaled from CLIC. The main differences are given in Table 1.

Table 1: Comparison CLIC – CTF3

	CLIC	CTF3
Drive Beam energy	2.4 GeV	150 MeV
Drive Beam current	180 A	35 A
RF Frequency	937 MHz	3 GHz
train length in linac	94 µs	1.5 µs

Since the CLIC Drive Beam has a lower RF frequency, the bunch train compression will be done in three stages, one Delay Loop (DL) and two Compressor Rings (CR) each giving a compression factor of four. CTF3 uses also one DL, but only one CR with a nominal compression factor of five.

c) Test of Power Extraction Structure (PETS) with on/off capability. Special PETS are being used to provide the 30 GHz RF power for structure testing in the linac test stand, but PETS close to the CLIC design will be tested once the 35 A beam is available following completion of the Combiner Ring.

d) Beam stability and beam loss control of the Drive Beam under deceleration for RF power production will be tested in the Test Beam Line (TBL), where several PETS will decelerate the beam to about half its energy.

e) Test of a relevant linac sub-unit with beam. The full scheme will be tested with acceleration of a low-charge beam, the Probe Beam. The principle of two-beam acceleration was already demonstrated in CTF2 [5], however, limited to short pulse length. CTF3 allows tests with nominal RF pulse length.

As a consequence of these objectives, operation of the CTF3 facility is split between two main activities: Testing the Drive Beam generation complex and operation for 30 GHz power production for the development of CLIC accelerating structures. This second task uses only the first part of the linac and a dedicated structure test stand.

LAYOUT OF CTF3

CTF3 makes use of the infrastructure of the LEP injector, which became available after the end of LEP

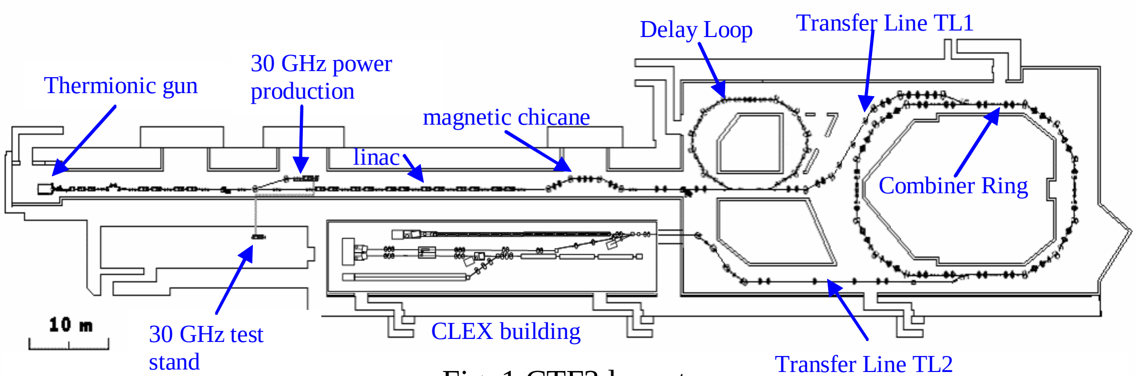

Fig. 1 CTF3 layout

operation at the end of 2000. The building and the layout of CTF3 are shown in Fig. 1.

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 resulting bunch position with respect to the 3 GHz acceleration is shown in Fig. 2. 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. After bunching the nominal current is 3.5 A, up to 7 A is possible.

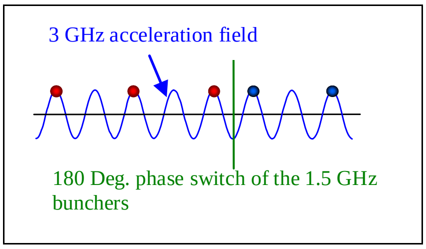

Fig. 2: Phase-coding of bunches with respect to 3 GHz acceleration. The dots represent the bunches.

The maximum energy is 300 MeV at zero beam current. The magnetic chicane at the end of the linac with a variable R_{56} [6] between ± 0.5 m allows lengthening 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.

In the Combiner Ring (84 m length) five subsequent bunch trains are injected by a system of two 3 GHz RF deflectors, which create a time dependent closed orbit bump, such that in the five successive injections the newly injected bunches can be placed immediately behind the already circulating bunches. By doing this, five subsequent bunch trains are interleaved into one single 140 ns long train with a bunch repetition frequency of 15 GHz and a current of 35 A. After the fifth 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). Here the beam can be switched to different beam lines, described in more detail below.

CTF3 is presently the only source of 30 GHz RF power available for the development of CLIC accelerating structures. In the linac the beam with an energy of about 100 MeV can be deflected into a beam line parallel to the main beam, where 30 GHz RF power can be extracted in a specially developed PETS system and sent to a dedicated test stand.

RF HIGH POWER PLANT

The RF plant is described in detail in [7]. Presently nine 3 GHz klystrons are available, one of which is used for the 3 GHz bunching system, the others for the linac and for the RF deflector in the Combiner Ring. They operate at an output power of between 35 and 45 MW at a pulse length of 5 µs. All klystrons feeding accelerating structures of the linac are equipped with pulse compression systems of either the LIPS or of the BOC [8,9] type. They give a power output of about 80 MW in 1.5 µs long RF pulses. Initial problems with stability of the pulse compression system – they rely on water temperature for frequency tuning – were cured by commissioning a new stabilized water cooling system in 2005. This system allows the temperature to be stabilised to within 0.02 Degrees with a response to power changes of some minutes, in the worst case stability is reached within 15 min.

The pulse compression systems have to provide a pulse with a flat top in amplitude and phase for at least 1.5 µs. This is achieved by applying a programmable phase function to the input of the klystrons. This gives a residual phase and amplitude error of 6 Degrees and ±1% respectively over the pulse duration.

A new 1.5 GHz klystron, especially developed in industry for the RF deflector in the Delay Loop was commissioned in 2005. It provides 22 MW in pulses of 5 µs length. The RF power is transported to the RF deflectors via SF_6 filled Al waveguides.

30 GHZ POWER TEST STAND

At an energy of about 100 MeV the beam can be diverted out of the linac into a parallel beam line, where a specially developed PETS allows RF power at 30 GHz to be extracted. The layout is shown in Fig. 3.

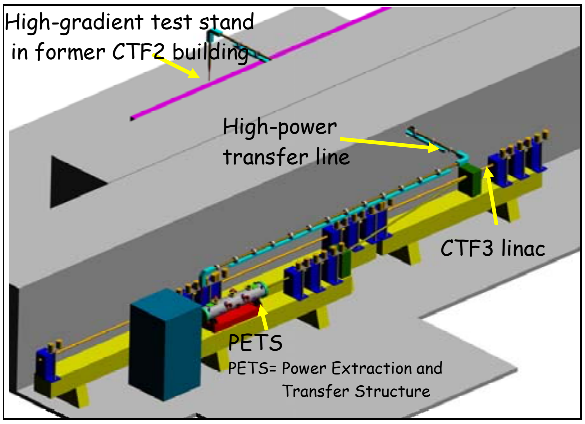

Fig. 3: 30 GHz power extraction from CTF3 linac. The beam comes from the right.

The power is transported over 17 m in a low loss waveguide, through the shielding wall to the test stand. This line uses over-moded circular waveguides, operated in TE_{01} mode [10].

For this type of operation a special "power mode" is used, with a higher beam current (5 A) and twice the nominal RF power in the linac structures. This is possible, because the pulse length is much shorter, only 50 to 400 ns, than in nominal operation. This gives up to 100 MW 30 GHz RF power from the PETS, transported to the test stand with 65 % efficiency. Results of RF structure testing are presented in this conference [11].

PROJECT STATUS AND PLANNING

Presently the machine has been commissioned with beam up to and including the Delay Loop. Installation of the transfer line TL1 and the Combiner Ring will be completed by the end of 2006 and commissioning will be done in 2006/2007.

The first part of the linac is routinely used as a source for 30 GHz RF power production.

Construction of the CLEX building is under way and will be finished by mid 2007, equipment can be installed from this date on. The transfer Line TL2 will be installed during 2007, such that beam will become available in CLEX from early 2008 onwards. The Probe Beam will be commissioned in 2008, the Two-Beam Test Stand should be ready to receive beam in April 2008. From then on tests of the CLIC PETS and tests of CLIC accelerating structures with nominal power levels will become possible. The Test Beam Line will be installed from 2008 onwards.

The whole CTF3 installation should be complete by 2009, such that the major CLIC feasibility questions can be answered by 2010.

COMMISSIONING RESULTS

Full beam loading operation

An important feature of the CLIC scheme is the operation of accelerating structures under full-beam loading conditions. Special travelling wave accelerating structures were developed for this application. 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.

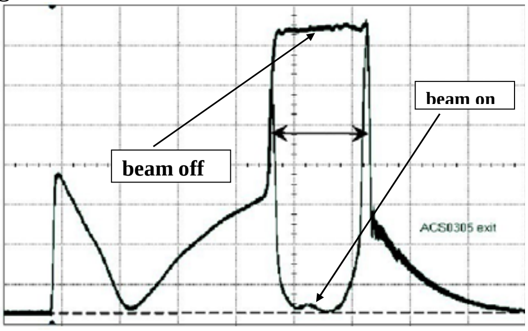

Fig. 4: Demonstration of full beam loading

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 SICA (Slotted Iris Constant Aperture) structures [12] are used.

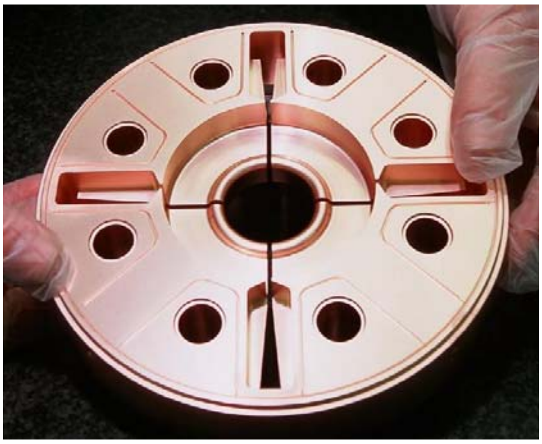

Fig 5: One cell of a SICA structure.

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. The geometry of the cells is shown in Fig. 5. Precise measurements of beam loading efficiency are shown in this conference [13].

Bunch interleaving in Delay Loop

In 2005 the 1.5 GHz sub-harmonic bunching system was installed and brought into operation. Since the RF phase of the bunchers has to be changed by 180 Degrees every 140 ns, the system has to be broad-band. It consists of three 8-cell travelling wave bunchers, each one driven by a travelling wave tube. These tubes were specially developed for this application. They give an output power of 40 kW and have a bandwidth of 200 MHz. Special care was taken to stabilize the high voltage supply of these tubes in order to avoid phase variations of the output signal. A stability of a few V in 18 kV was finally achieved, leading to a phase variation of 1.6 Degrees over a 3 μs long RF pulse.

The switching transient was measured with beam in an RF pick-up. The switching time is about 5 ns, i.e. the transient spreads over about 7 bunches.

The Delay Loop has been designed and installed by the collaboration partner INFN Frascati during the year 2005, first beam was injected in December 2005 and commissioning continued in 2006. Fig. 6 shows a view of the injection region.

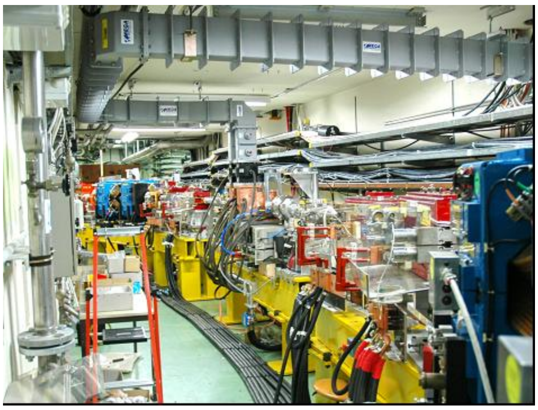

Fig. 6: Injection region of Delay Loop with the waveguides feeding the 1.5 GHz RF deflectors

Results of commissioning are given in [14]. The beam current before, in and after the Delay Loop are shown in Fig. 7. One clearly sees, that 140 ns long sub-trains were injected into the Delay Loop and combined with the following sub-train. About 8.5 % of the incoming beam is contained in “satellite” bunches.

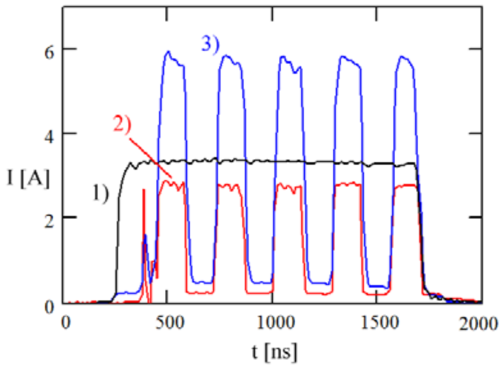

Fig. 7: Beam current as function of time, measured: 1) before, 2) in, 3) after the Delay Loop. The sub-trains combined are 140 ns long.

FUTURE INSTALLATIONS

TL1, Combiner Ring and TL2

Presently the Combiner Ring and transfer line TL1 between the Delay Loop and the Combiner Ring is being installed. Installation will be completed by the end of 2006 and commissioning will start towards the end of 2006, to be completed in 2007. The layout is complete and all components are either already available or are being manufactured. The two 3 GHz RF deflectors were already tested with beam.

Transfer Line TL2 is being designed, installation is foreseen during 2007. This line includes a magnetic bunch compressor, such that the bunches can be longitudinally compressed to about 0.5 mm rms length before being used for 30 GHz experiments in the CLEX building.

CLEX

The CLEX building (CLIC Experiment hall) is being constructed in the moment. It is a hall of 42 m length and 8 m width, partly covered by a second floor for installation of klystrons, power supplies and auxiliary equipment. It will be ready for installation of beam lines in summer 2007.

A schematic floor plan is shown in Fig. 8. CLEX will house several beam lines:

a) Test beam Line TBL[15]. 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

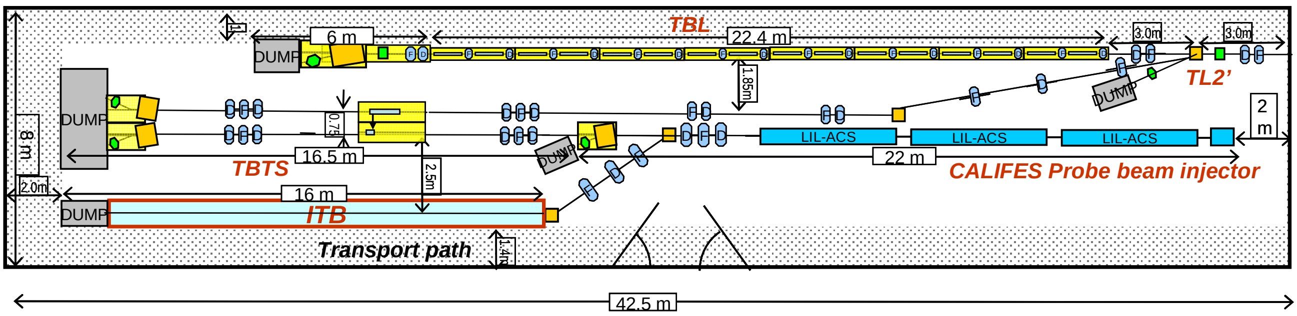

Fig. 8: Schematic layout of beam lines in CLEX

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 30 GHz RF power will be extracted from the beam.

b) Probe Beam. A 200 MeV low current electron beam will be provided [16], which will be accelerated further by CLIC accelerating structures in the TBTS (described below), such that the nominal CLIC accelerating gradient can be verified and the full CLIC scheme can be demonstrated. This linac (called CALIFES in Fig.8) has a photo injector allowing single bunch operation as well as bunch trains of up to 64 bunches.

c) The Two Beam Test Stand (TBTS) [17] will allow testing of CLIC accelerating structures with RF power extracted by a special PETS from the 35 A beam, as well as acceleration of the Probe Beam by a test structure. It will be well instrumented to analyse the behaviour of these structures, in particular to study the effect of RF breakdowns on the Probe Beam as well as the Drive Beam.

PHOTO INJECTOR DEVELOPMENT

A programme, partly funded by the European Union is in progress with the aim of developing a photo injector for CTF3 which could eventually replace the presently installed thermionic injector [18, 19]. Its advantages are a significantly smaller transverse emittance of 25*pi*mm*mrad and a cleaner phase coding, eliminating the “satellite” bunches, which populate the 3 GHz RF buckets in between the 1.5 GHz ones. A cross section of the gun is shown in Fig 9. The RF cavity has two and ½ cells, the Cs_2Te photo cathode would be mounted in the left cell.

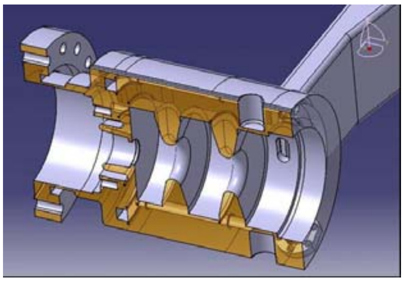

Fig. 9: Cross section of the RF gun. The Cs_2Te cathode will be installed on the left into the first cell.

The laser is based on a Diode pumped Nd:YLF system consisting of an oscillator and two multi-pass amplifiers.

CONCLUSION

The CTF3 project is following 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 accelerating structures, which has become routine operation. The Bunch interleaving scheme has been demonstrated in the Delay Loop, and the next steps with the commissioning of the Combiner Ring are well under way.

ACKNOWLEDGEMENT

This work is done by the CTF3 collaboration. Presently it consists of 15 members: Ankara University Group, Budker institute of Nuclear Physics (BINP) Novosibirsk, CEA (Dapnia Saclay), CERN, CIEMAT Madrid, CNRS IN3P3 (LAL Orsay, LAPP Annecy), Helsinki Institute of Physics (HIP), IAP Nizhny Novgorod, INFN Frascati, JINR Dubna, Northwestern University Illinois, SLAC, University of Uppsala, RAL Rutherford, RRCAT Indore.

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