RESULTS ON CLIC PROOF OF PRINCIPLE FROM CTF3

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Abstract

The CLIC Test Facility CTF3, built at CERN by an international collaboration, aims at demonstrating the feasibility of the CLIC scheme of multi-TeV electron-positron collider by 2010. CTF3 consists of a 150 MeV drive beam linac followed by a 42 m long delay loop and an 84 m combiner ring. The installation will include in its final configuration a two-beam test stand and a test decelerator. The linac and delay loop have been already commissioned, while the combiner ring has been completed by the first half of 2007. High gradient testing of accelerating structures is also under way. The status of the facility, the experimental results obtained and the future plans will be presented.

INTRODUCTION

The aim of the CLIC (Compact Linear Collider) Study is to investigate the feasibility of a linear e+ e- collider with a centre of mass energy reach of E_{CMS} = 3 TeV and high luminosity [1]. In order to minimize the total length, CLIC employs normal-conducting accelerating structures operating at a very high gradient, well above the fundamental limit for superconducting RF (~ 50 MV/m).

Recently, combined results from RF structure testing [2, 3] and an optimisation study of overall cost and efficiency [4] have led to a major parameter revision for CLIC. The main modification are the reduction of the main linac RF frequency from 30 GHz to 12 GHz and the decrease of accelerating gradient from 150 MV/m to 100 MV/m. This brings to a total length including beam delivery system of 48.25 km for 3 TeV. A first coherent and complete set of parameters has been worked out and is presently being revised [5]. A subset containing the main parameters is given in Table 1.

The high peak RF power required in CLIC to feed the accelerating structures is obtained using a two-beam acceleration concept [6], in which a high current electron beam (drive beam) runs parallel to the main beam and is decelerated to produce the RF power. Since the drive beam is generated in a central area no active high power components are required in the linacs and a single tunnel with a limited diameter (~ 4.5 m) can be used.

Two-beam acceleration was already successfully demonstrated in the former CLIC test facility CTF II, where accelerating fields of almost 200 MV/m were achieved [7]. However, in CTF II the drive beam pulses were produced directly from a photo-injector, a method that cannot be used in CLIC and presents several drawbacks. In particular, the RF pulse length was limited below 30 ns and the power efficiency of drive beam acceleration was poor. The generation of high-intensity drive beam pulses with the right time structure is indeed one of the main challenges in CLIC.

Table 1: New CLIC parameter set - provisional

Center-of-mass energy	3 TeV
Peak Luminosity	$7\ 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2\ 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	41.7 km
Bunch charge	$4\ 10^{9}$
Beam pulse length	200 ns
Average current in pulse	1 A
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size before pinch	53 / ~1 nm
Total site length	48.25 km
Total power consumption	390 MW

In the adopted scheme, a long pulse is accelerated using a low frequency normal-conducting linac operated in full beam loading regime. Funnelling techniques in delay lines and rings are then used to give the beam the desired time structure. In this process the electron bunches are interleaved by the use of transverse RF deflectors. The bunch spacing is thus reduced and the beam current is increased. It is generally accepted that CLIC technology is the only possible path to multi-TeV colliders. However, several critical issues still need to be addressed. The experimental program of the present CLIC Test Facility, CTF3 [8], tackles most of the main issues of the study, related to the generation and use of the drive beam and the testing of accelerating structures and RF components, as raised by the International Linear Collider Technical Review Committee in 2003 [9]. The Committee listed a number of crucial items, needed to prove feasibility (the so-called R1 items), and to arrive at a conceptual design (the R2 items). CTF3 will concentrate on all the CLIC technology-related R1 and R2 issues, as opposed to issues which are common to all linear collider studies. The goal is to get an answer on the feasibility of the CLIC scheme before 2010. By then the first LHC results should be available and the energy required for a future linear collider would be better known. The main points that will be covered by the experimental program are:

1. Test of a prototype CLIC accelerating structure (including design features to damp higher order modes) at design gradient and pulse length (R1).

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2. Validation of the drive beam generation scheme with a fully-loaded linac (R1).
3. Design and test of an adequately damped power extraction structure, which can be switched on and off (R1).
4. Validation of beam stability and losses in the drive beam decelerator, and design of a machine protection system (R2).
5. Test of a relevant linac sub-unit with beam (R2).

The recent change of parameters affects the CTF3 experimental program only partially. The inherent flexibility of the CLIC RF power source scheme allows for an easy adaptation to the new frequency of 12 GHz and the corresponding power with no hardware changes. It suffices to change the combination factor of the combiner ring from 5 to 4 with the path-length tuning wiggler, while shortening the initial electron pulse from 1.5 μs to 1.2 μs and increasing the beam current from 3. A to 4 A. However, the maximum final beam current (~ 30 A) is reached only up to a pulse length of 140 ns. In the following only the new parameters will be mentioned.

CTF3 is presently being built and commissioned at CERN by an international collaboration with an organisation structure similar to large particle physics experiments. It includes at present, beside CERN, 20 institutes from 11 countries. Other institutes have observer status, some of them being in the process of formally joining the collaboration or already providing some kind of support with no formal agreement yet.

CTF3 DESCRIPTION AND EVOLUTION

The facility is located in the buildings of the former LEP Pre-Injector, LPI (see Fig. 1), whose hardware is partly re-used. It is designed for a lower beam current (4 A to 30 A instead of 5.4 A to 95 A) and at a much lower momentum than the CLIC drive beam (150 MeV/c instead of 2.4 GeV/c). It includes a 70 m long drive-beam linac followed by two rings, where the beam manipulations are made: a 42 m delay loop and an 84 m combiner ring. After such manipulations the drive beam will have a current of 30 A and will be transported to the CLic EXperimental area (CLEX) to produce 12 GHz RF power for structure tests. In the same area, another linac will provide a probe beam for a Two-Beam Test Stand – TBTS and a decelerator (Test Beam Line – TBL) will be used for drive beam stability studies. CTF3 has also a second RF power station, working at 30 GHz, located nearly halfway along the linac.

The drive beam injector is made of a thermionic gun, three 1.5 GHz sub-harmonic bunchers (SHB) followed by a pre-buncher, a tapered phase velocity travelling-wave buncher and two accelerating structures, all operating at 3 GHz. Solenoidal focusing is used all along. Depending of the beam current a momentum of about 25 MeV/c is achieved at the end of the injector. A three-bends chicane with collimators is then used to eliminate off-energy particles and to perform bunch compression.

The CTF3 linac is composed of 11 modules. A module is 4.5 m long and contains a quadrupole triplet. At present 6 modules are equipped with two structures each and three with beam instrumentation.

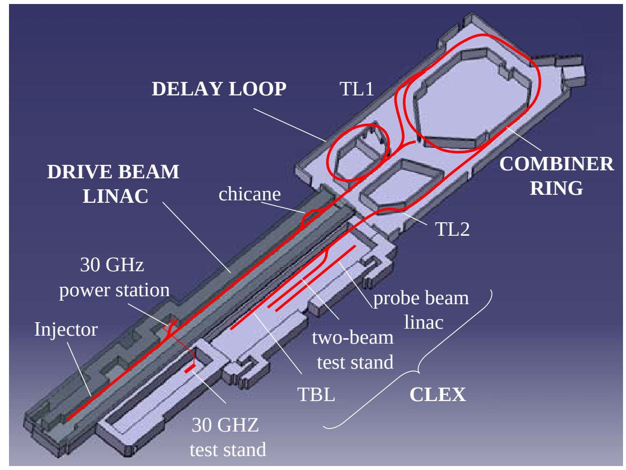

Figure 1: Schematic layout of the CTF3 complex.

The travelling-wave 3 GHz structures have a length of 1.22 m and operate at a full-loaded gradient of 6.5 MV/m. They use radial slots in the iris to damp transverse modes into SiC loads. The Q-value of the first dipole is thus reduced below 20. A further reduction of the long-range wake-fields is achieved by detuning the higher order modes frequencies along the structure by different cell geometries. Each module is powered by a klystron with peak power in the 35 MW to 45 MW range, doubled by RF compression to provide more then 30 MW at each structure input. The pulse compression system uses a programmed phase ramp to obtain a 1.5 μs flat top.

A dog-leg beam line branches off halfway along the linac. The drive beam can be sent there to be decelerated in a Power Extraction and Transfer Structure (PETS) and produce 30 GHz RF power, brought via a low-loss waveguide to a test stand in the former CTF II hall.

A four-bend magnetic chicane with variable momentum compaction factor is located at the end of the linac. This chicane is used to optimize the bunch length before the beam is sent to the rings. For operation with high bunch charge, simulations have shown that longer bunches are needed in the delay loop and in the combiner ring to avoid coherent synchrotron radiation effects.

The delay loop has a two-fold symmetry, with double injection/extraction septa and 10 bending magnets. It includes an RF deflector used for injection/extraction (as described later) and a wiggler for path length tuning. The design optics is achromatic and isochronous. A four dipole transfer line (TL1) with tuneable momentum compaction connects the delay loop to the combiner ring.

The combiner ring (see Fig. 2) has four achromatic and isochronous arcs, with three dipoles each. Injection and extraction regions are located in the long straight sections. For injection, two RF deflectors separated by a π betatron phase advance and located at each side of the injection septa are used, as described later. On the opposite side, a fast kicker is used for extraction. The ring has also a path-length tuning wiggler in one of the two short straights.

Another transfer line (TL2) with variable momentum compaction joins the ring to the beam lines in CLEX.

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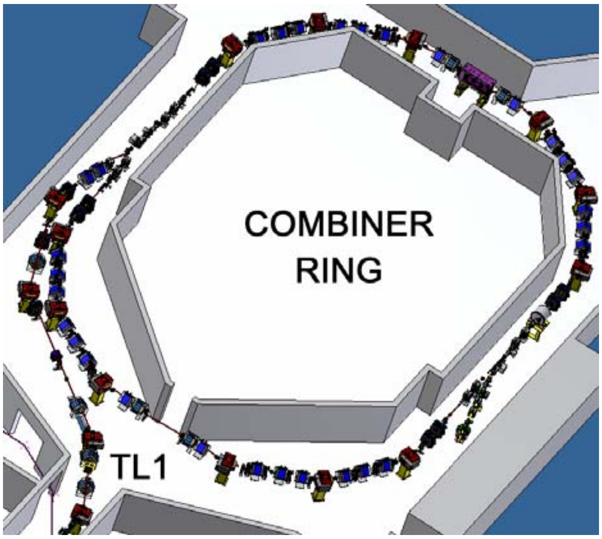

Figure 2: Combiner ring layout. On the left the transfer line from the delay loop to the ring is also represented.

The construction of the CLEX building was recently completed and the area is now ready for installation. It is a hall of 42 m length and 8 m width, partly covered by a gallery for klystrons, power supplies and other equipment. CLEX will house several beam lines, described below.

In the TBL [10] the drive beam will be decelerated to about half its initial energy by up to 16 PETS. The aim is to demonstrate beam stability under significant deceleration, which will produce a momentum difference of up to a factor of two between the first and the last bunches. The TBL is composed of modules including a PETS, a beam position monitor and a quadrupole on a precision movable support, in order to experiment beam-based alignment procedures. The modules are arranged in a FODO lattice whose magnetic strength can be tapered to follow the deceleration pattern. A total of about 2 GW of 12 GHz RF power can be extracted from the beam.

In the probe beam injector [11] a low current electron beam will be provided by a photo injector and accelerated to 200 MeV using structures from the former LPI. The hardware allows both single-bunch and bunch-train operation to up to 64 bunches. The probe beam could then be accelerated further by 12 GHz CLIC structures in the two-beam test stand described below.

The Two-Beam Test Stand (TBTS) [12] will allow testing of both a CLIC PETS prototype with the 30 A beam and of different accelerating structures with the RF power thus produced. It will be well instrumented to analyse the behaviour of these structures as well as the effect of RF breakdowns on the probe beam. The PETS have the same cross section as in CLIC, being only longer in order to produce the same power with a lower beam current, and will be equipped with an on/off mechanism.

In 2003-2004 the injector, the linac, the mid-linac power station and the end-of-linac magnetic chicane were installed and commissioned. The first part of the linac is used since 2005 as a source of 30 GHz RF power. The delay loop was installed during 2005 and commissioned in 2006, while the combiner ring installation was completed in 2006. Commissioning of the transfer line TL1 and of the combiner ring is presently under way. As mentioned, the equipment installation in the CLEX building is starting. The installation of the transfer line TL2 from ring to CLEX will begin as well during 2007. The goal is to start commissioning the probe beam linac and the TBTS in early 2008. From then on tests of the CLIC PETS and accelerating structures at 12 GHz with nominal power levels will become possible. The TBL will be installed from 2008 onwards. The whole CTF3 installation should be complete by 2009.

DRIVE BEAM GENERATION IN CTF3

The 4 A, 1.2 µs long beam-pulse from the gun is bunched by the three sub-harmonic buncher (SHB) cavities such that only every second 3 GHz RF bucket is populated (apart from an unwanted small fraction of the charge, captured in "satellite" bunches). The SHB cavities and travelling wave tubes powering them are wide-band systems and allow a very fast (5-6 ns) switch of the RF phase by 180° [13]. The drive beam can thus be easily "phase coded" into eight 140 ns long sub-pulses, in which the main bunches occupy either even or odd buckets.

The bunched beam is accelerated in the linac in full beam-loading mode. The beam current is high and extracts all the RF power stored in the structure. After a filling time (~ 100 ns), a steady state is reached in which the gradient is about half of the initial one and the beam energy is constant. Since the structures are relatively short, ohmic losses are only a few percent of the total RF pulse energy. This kind of acceleration is a fundamental ingredient of the CLIC scheme, for which high efficiency in the drive beam acceleration process is paramount.

The role of the delay loop in CTF3 is to rearrange the 1.2 µs beam-pulse from the drive-beam linac into four 140 ns pulses, separated by 140 ns gaps, increasing at the same time by a factor 2 both the current and the bunch repetition frequency. The procedure is schematized in Fig. 3. A transverse RF deflector working at 1.5 GHz sends the first phase-coded sub-pulse (labelled as "even buckets" in the figure) into the delay loop. The loop length of 42 m corresponds to the sub-pulse length of 140 ns, thus the "even" bunches are coming back at the deflector at the same time as the "odd" bunches of the next sub-pulse from the linac. The delay loop length can be precisely tuned to be an integer number of the RF wavelength, thus odd and even bunches arrive with opposite phases and receive opposite kicks. However their incoming angles are also opposite, so they are interleaved and combined into the same orbit. The bunch spacing is halved to 10 cm and the beam current is doubled. The process also naturally produces a gap of 140 ns, essential in the next stage for clean extraction from the combiner ring. The four 140 ns pulses are then combined in the ring using a similar principle. The ring length is equal to the distance between pulses and for a four-fold bunch interleaving it is precisely tuned to $(n + 1/4)\,\lambda$, where n is a (large) integer.

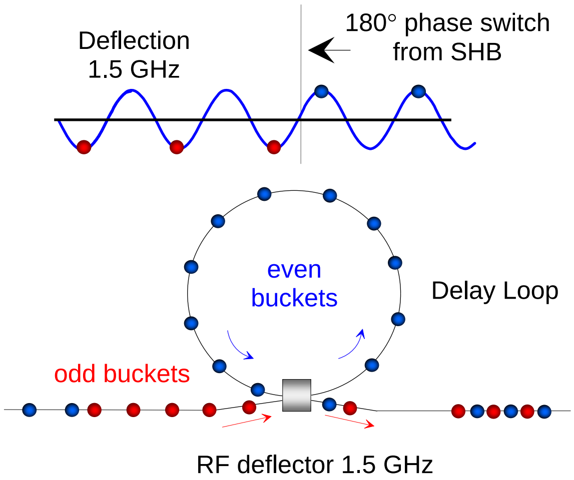

Figure 3: Schematic of the delay loop recombination.

A 3 GHz RF deflector located after the injection septa kicks each incoming pulse into the closed orbit. Another deflector before the septa is synchronized with the first one to generate a closed bump, such that whenever the injected pulses come round they are kept on the closed orbit. After four turns, the first injected pulse would experience the maximum kick and hit the septum from the inside. Before this happens, the four pulses combined into one are extracted by the kicker on the other side of the ring to be sent to the CLEX area. The beam current is now eight times the initial one and the bunch distance is 2.5 cm, i.e., 12 GHz.

MAIN ACHIEVEMENTS AND COMMISSIONING STATUS

Full beam loading operation

The first key result obtained in CTF3 was the proof of stable operation under full beam-loading. The beam was remarkably stable even at high current and no sign of beam break-up was observed. The RF signals at the structures input/output couplers (see Fig. 4) were used to set-up easily the beam-to-RF phase by maximizing the beam loading. The RF signals were also used to assess the RF-to-beam efficiency. A dedicated experiment was performed [14], with uncompressed 3 GHz RF pulses. The power and phase of three subsequent linac modules, fed by independent klystrons, were adjusted such that no power was detected at the output on the pulse flat top.

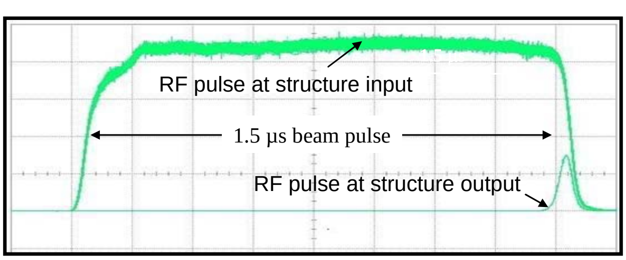

Figure 4: RF signals for full beam-loading operation. No power is left at the end of the structure in the beam pulse.

The stations were turned on and off in turns, allowing a precise determination of the energy gain through a relative beam momentum measurement in a downstream spectrometer. The measured energy gain per module was in excellent agreement to theoretical predictions and an RF-to-beam energy transfer efficiency of 95.3%, including structure losses, was evaluated.

30 GHz power production and structure testing

The 30 GHz power station was commissioned in 2004. Structure testing started in 2005 and since 2006 routine operation has been established, with automatic control and remote supervision from the CERN central control room. For power production a special operation mode is used, with higher beam current in the linac (5 A) and twice the nominal RF power in the linac structures. This is possible since the 3 GHz pulse length (50-400 ns) is much shorter than for nominal operation. The beam momentum is ~ 100 MeV/c. Up to 100 MW are produced in the PETS, and transported to the test stand with ~ 70 % efficiency. Due to the relatively low beam current in the linac, the PETS coupling must be high and the aperture (6.5 mm) is much smaller than the one for CLIC and the TBTS (23 mm). This makes beam transport difficult and simulations showed that even in the best conditions a few percent losses are to be expected. Indeed, the best performances are at the 5% loss level, often drifting up during operation. The availability of high RF power at 30 GHz with pulses significantly longer than CTF II enabled a vigorous experimental program. Eight different structures have been tested up to now in CTF3 [2]. Results of RF structure testing in CTF3 have been fundamental in the recent CLIC parameter revision. In particular, parallel testing of scaled structures at 30 GHz in CTF3 and at 11.4 GHz at SLAC have provided clear information on frequency scaling, giving a decisive input to the cost and efficiency optimization study.

Delay loop and combiner ring commissioning

Beam commissioning of the delay loop [15] started in November 2005. A circulating beam was obtained in a short time and a first re-combination test with limited current could be performed. During these tests, a setting-up procedure to determine the optimum power and phase in the RF deflector was developed and validated. Commissioning continued in 2006, when current and pulse length values close to the then-nominal ones (3.5 A, 1.5 μs) were used. Systematic optics measurements were performed and Transverse emittance and Twiss parameters determined at the entrance of the delay loop through quadrupole scans. The dispersion function at the position of the BPMs was measured as well. Synchrotron light from two dipoles was sent to a streak camera, to check the bunching structure. The bunch length was also measured for different settings of the upstream chicane with good agreement with expectations. Eventually, a full beam recombination was obtained, as shown in Fig. 5. The 1.5 μs, 3.3 A incoming pulse is converted in a series of five 140 ns pulses with a current of 5.8 A.

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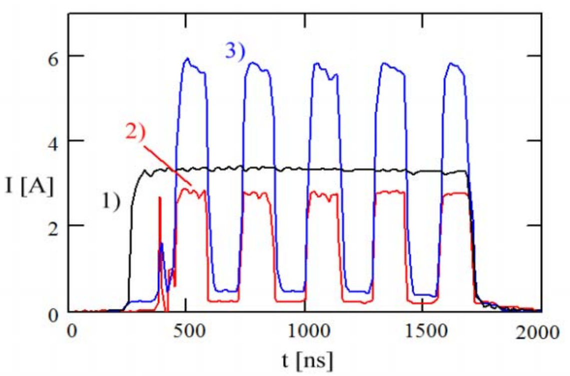

Figure 5: Beam current as a function of time, measured: 1) before the delay loop 2) in the loop 3) after the loop, showing the final recombination in five 140 ns pulses.

About 8.5 % of the initial current is contained in "satellite" bunches, as expected from simulations [13]. This fraction of the beam is not combined in the main pulses and can be seen in the space between them.

In 2006 a short period was dedicated to commissioning of the transfer line TL1 and combiner ring injection region. Short pulses of 200 ns were used. The beam was rapidly transported to the end of the line and a current of 3 A could be injected into the ring. The commissioning restarted at the end of March 2007, with some interruptions for further installation work. The delay loop was bypassed and a first recombination test, over two turns, has been recently performed [16] (see Fig. 6).

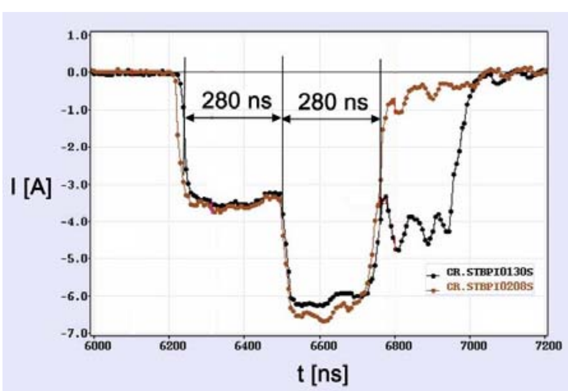

Figure 6: First recombination in the Combiner Ring. The traces show the beam current in 2 BPMs. The incoming beam pulse has twice the length of the ring (2 x 280 ns). During the second part, the bunches are interleaved with the bunches that made one revolution in the ring.

CONCLUSIONS

The test facility CTF3 is the main tool used to demonstrate the feasibility of the CLIC technology for a multi-TeV linear collider. It already addressed key issues like generation and control of high current beams, full beam-loading linac operation and high charge bunch train recombination in the delay loop. It is now routinely used as a 30 GHz power source for accelerating structure testing, and the results obtained are advancing the knowledge on fundamental limitations of high-gradient structures. Commissioning of the combiner ring has started and could be completed in 2007, proving the feasibility of the CLIC drive beam generation scheme. In 2008 the first beam is expected in the new CLEX area, where several beam lines will be used to fulfill the CTF3 experimental program.

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REFERENCES

[1] G. Guignard (Ed.), "A 3 TeV e+e- linear collider based on CLIC technology", CERN 2000-008, 2000.

[2] J.A. Rodriguez et al., "30 GHz high-gradient accelerating structure test results", these Proceedings.

[3] S. Döbert et al., "High power test of an X-band slotted-iris accelerator structure at NLCTA", these Proceedings.

[4] A. Grudiev, D. Schulte, W. Wuensch, "Optimum frequency and gradient for the CLIC main linac accelerating structure," Proc. EPAC'06 and CLIC note 677, 2006.

[5] http://clic-meeting.web.cern.ch/clic meeting/clictable2007.html

[6] R. Corsini (Ed.), "The CLIC RF power source", CERN 99-06, 1999.

[7] H.H. Braun for the CLIC study team, "Achievements and future plans of CLIC test facilities," Proc. HEACC 2001 and CLIC note 473, 2001.

[8] G. Geschonke and A. Ghigo Eds, "CTF3 Design Report", CERN/PS 2002-008 (RF).

[9] "International Linear Collider Technical Review Committee, 2nd report," SLAC Report 606, 2003.

[10] S. Döbert, G. Rumolo, D. Schulte, I. Syratchev, D. Carrillo, "Progress on the CTF3 Test Beam Line", Proc. EPAC'06 and CLIC note 690, 2006.

[11] A. Mosnier et al., "The probe beam linac in CTF3," Proc. EPAC'06.

[12] T. Ekelöf et al., "The Two-Beam Test-Stand in CTF3", Proc. EPAC'06.

[13] P. Urschütz et al., "Beam dynamics and first operation of the sub-harmonic bunching system in the CTF3 injector", Proc. EPAC'06 and CLIC note 683, 2006.

[14] P. Urschütz et al., "Efficient long-pulse fully-loaded CTF3 linac operation," proc. LINAC'06 and CLIC note 697, 2006.

[15] D. Alesini et al., "Commissioning status of the CTF3 delay loop", proc. EPAC'06 and CLIC note 675, 2006.

[16] Frank Tecker et al., "CTF3 combiner ring commissioning", these Proceedings.

