TWO-BEAM LINEAR COLLIDERS - SPECIAL ISSUES

R. Corsini for the CLIC/CTF3 collaboration, CERN, Geneva, Switzerland

Abstract

The path towards a multi-TeV e+e- linear collider proposed by the CLIC study is based on the Two-Beam Acceleration (TBA) scheme. Such a scheme is promising in term of efficiency, reliability and cost. The rationale behind the two-beam scheme is discussed in the paper, together with the special issues related to this technology and the R&D needed to demonstrate its feasibility.

INTRODUCTION

There is a large consensus in the high energy physics community on the fact that LHC physics results will have to be complemented by experiments done at 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 synchrotron radiation losses, one alternative is linear colliders, where two opposing linacs accelerate electrons and positrons towards a central interaction point (IP), where the detector is located. One candidate for such a facility is the ILC (International Linear Collider) [2] based on the use of super-conducting cavities for acceleration. A complementary approach is CLIC (Compact Linear Collider), aiming at an higher energy, in the Multi-TeV range (E_{CMS} = 3 TeV), with a luminosity around 10^{34} cm^{-2} s^{-1} [3]. The current goal of the project is to demonstrate the feasibility of the technology by the year 2010, in view of the definition of the most appropriate facility, based on physics requests derived from the LHC results.

The CLIC technology is based on several novel concepts. First of all, 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 super-conducting RF (~ 50 MV/m).

The main limitation to the accelerating field in copper cavities is given by RF breakdowns, the maximum breakdown rate required for stable beam operation in a multi-TeV linear collider being in the range of a few 10^{-7} per meter. The improved knowledge of this phenomenon, combining results from RF structure testing and optimisation studies of overall cost and performance [4], led at the beginning of 2007 to a major parameter revision for CLIC. The CLIC RF frequency was lowered from 30 GHz to 12 GHz and its accelerating gradient reduced from 150 MV/m to 100 MV/m. Recent experimental tests confirmed that such a gradient is accessible, at the required pulse length and breakdown rate [5].

The second key ingredient in CLIC is the use of a two-beam acceleration concept [6] to produce the high-power RF required to feed the accelerating structures. A high current electron beam (drive beam) runs parallel to the main beam. The drive beam has a bunch time structure which allows the production of RF power at the desired frequency by decelerating it through 12 GHz resonant cavities (PETS, Power Extraction and Transfer Structures).

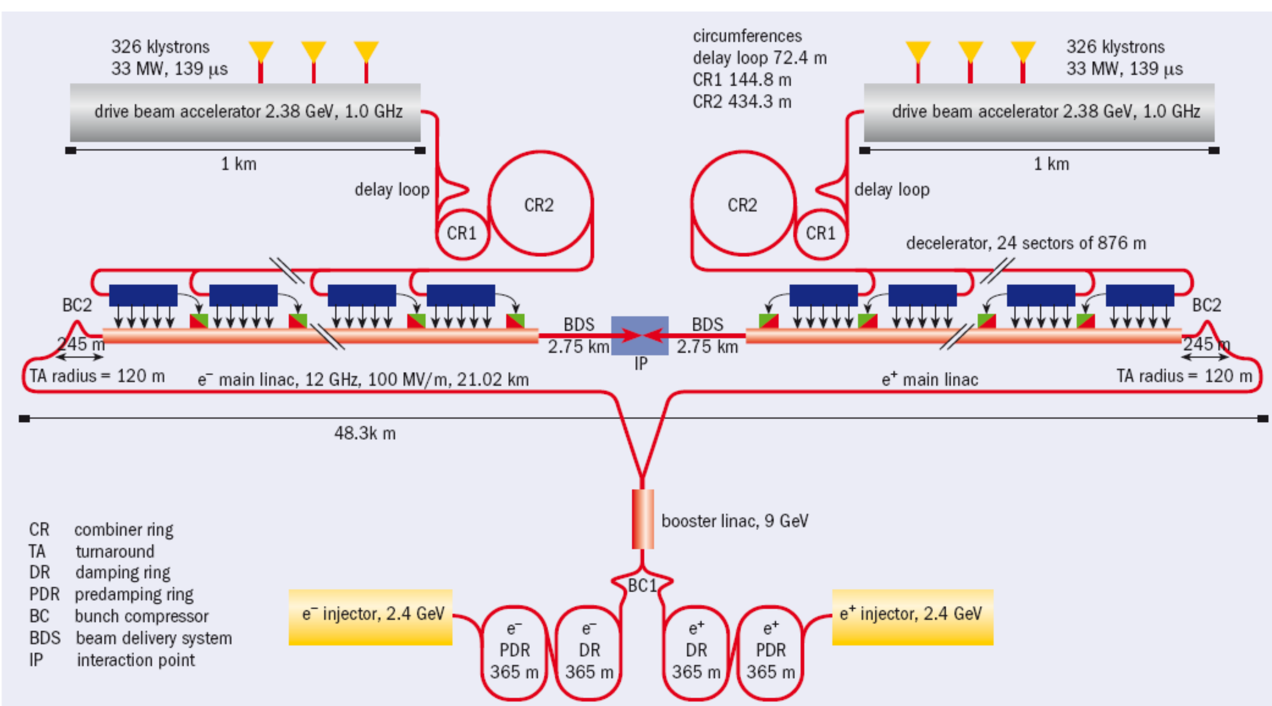

Figure 1: CLIC schematic layout. The drive beam generator complex is at the top.

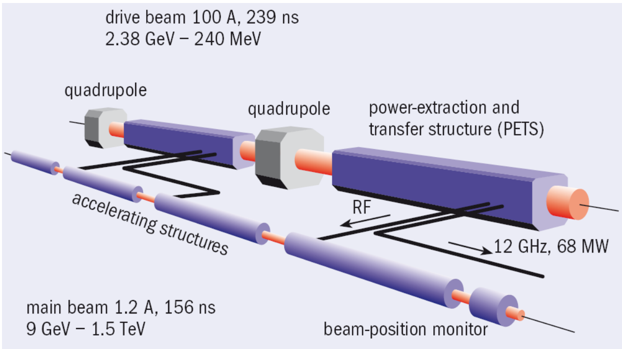

Figure 2: The CLIC two-beam module.

Each PETS extracts 136 MW of RF power and feeds it to a set of two accelerating structures in the main beam, as shown in Figure 2.

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 for short RF pulses [7]. However, in CTF II the drive beam pulses were produced directly from a photo-injector, a method that can provide neither the desired pulse length nor the needed acceleration efficiency. The efficient generation of high-intensity drive beam pulses with the right time structure is indeed one of the main challenges in CLIC. A relevant part of the present CLIC R&D program consists in the feasibility demonstration of such key feature in the CLIC Test Facility (CTF3) [8], constructed and operated at CERN by an international collaboration of 28 institutes [9].

Finally, the CLIC scheme relies on generation and preservation of very small emittance electron and positron beams, and on the capability of focusing them to extremely small dimensions at the IP, and keeping them in collision. These requirements impose extremely tight tolerances on alignment, control of vibrations and mechanical precision of components.

In the paper we will concentrate only on two-beam issues, not dealing with the aspects related to high-gradient acceleration and to low emittance, small size beams.

THE TBA CONCEPT

Motivation and Initial Evolution of the Concept

The TBA concept is motivated by the need to obtain at the same time high-gradient acceleration and efficient energy transfer to the beam. The use of high-frequency RF to power accelerating cavities maximises the electric field in the cavity itself for a given stored energy. However, standard RF sources scales unfavourably to high frequencies, both in for maximum delivered power and for efficiency. A way to overcome such a drawback is using a two-stage approach, in which a high current electron beam is accelerated using standard low-frequency RF sources (which can efficiently generate high power pulses) and later decelerated to produce RF power at high frequency. The high current beam is therefore used for intermediate energy storage.

The original idea of TBA came from A. Sessler in 1982 [10], and was not based on RF, but rather on the use of induction linac modules to accelerate the drive beam. An RF based scheme was proposed by W. Schnell in 1986 [11], when he proposed it for the seminal CLIC project. The drive beam was in this case brought to ultra-relativistic energies by superconducting cavities fed by low-frequency klystrons. Both schemes included several alternating stages of power extraction and drive beam re-acceleration. An important ingredient was introduced later in the CLIC scheme, namely the multi-pulse drive beam solution [12], in which an initially long pulse is divided in many shorter ones which are sent and distributed to the two-beam sectors through counter-propagating beam lines. This method (similar to the delayed distribution system in RF [13]) allows to use all of the time between two main beam pulses to generate the total charge needed in the drive beam and to use long pulse, moderate peak power klystrons for the initial acceleration (instead of a larger number of short-pulse, high-power tubes). Finally, the use of fully-loaded acceleration [14, 15] made possible to use with high efficiency normal conducting structures for drive beam acceleration rather than superconducting ones, with clear advantages in term of cost, simplicity and beam peak current. In order to make an effective use of the full-loading technique, a special mechanism of bunch phase-coding was also devised.

The present CLIC TBA scheme, described below [6], was therefore developed over several years, evolving as the sum of ideas and techniques devised to overcome limitations and optimize the whole process. The fact that its basics were virtually untouched in the last years, including the transition from 30 GHz to 12 GHz, is an indication of its maturity, at least at the conceptual level, as confirmed by the fact that a very similar scheme was recently proposed for plasma wake-field acceleration [16].

The CLIC TBA Scheme

The CLIC RF power source can be thought of as a “black box” that transforms a long, low-frequency RF pulse into many short, high-power pulses at high frequency. During the process, the energy is stored in a relativistic electron beam, which is manipulated in order to obtain the desired time structure and then transported to the place where the energy is needed. The energy is finally extracted from the electron beam in the PETS decelerating structures, running parallel to the main accelerator. The key points of the system are efficient acceleration of the drive beam, the use of transverse RF deflectors to manipulate the drive beam, and the counter-flow distribution of several drive-beam pulses, each one powering a different section of the main linac.

The drive-beam generation complex is located at the centre of the linear collider, near the final-focus system. The energy for the RF production is initially stored in a 140 μs long electron pulse (corresponding to twice the length of the high-gradient main linac), accelerated to about 2.4 GeV by a normal-conducting, low-frequency (999.5 MHz) travelling wave linac.

The drive beam is accelerated in short structures, to minimize the ohmic RF losses. The structures are fully beam-loaded, i.e., the accelerating gradient is zero at the downstream end of each structure and no RF power flows out to a load. In this way, up to 98% of the RF energy can be transferred to the beam [14, 15]. The beam pulse is composed of 24 × 24 sub-pulses, each one 240 ns long. In each sub-pulse the electron bunches occupy alternately only the even or odd number buckets of the fundamental frequency (999.5 MHz). Such a time structure can be produced after a thermionic gun in a sub-harmonic buncher, whose phase is rapidly switched by 180° every 240 ns. Alternatively, the phase switch can be obtained by manipulation of the laser pulse timing if using a photocathode gun. This provides a mean to separate the sub-pulses after acceleration, while keeping a constant current in the accelerator and avoiding transient beam-loading. By varying the phase-switching time, it is possible to obtain sub-pulses of different lengths. When the different sub-pulses are superimposed, one can thus obtain a current ramp of about 85 ns at the leading edge of the pulse. This in turn produces a ramp in the PETS power output, which is used for beam-loading compensation in the main linac.

As the long pulse leaves the drive-beam accelerator, it passes through a delay-line combiner where odd and even sub-pulses are separated by a transverse RF deflector at the frequency of 499.8 MHz. Each even bunch train is delayed with respect to the following odd one by 240 ns. The sub-pulses are then recombined two-by-two by interleaving the electron bunches in a second deflector at the same frequency. The long pulse is thus converted to a periodic sequence of drive-beam pulses with gaps in between. The peak power and the bunch frequency are doubled and the pulse is now composed of 12 × 24 sub-pulses whose spacing is equal to the sub-pulse length. The same principle is then used to combine the trains three-by-three in a first ring, 145 m long. Two 999.5 MHz RF deflectors create a time-dependent local deformation of the equilibrium orbit. This bump is used for injection of a first train in the ring (all of its bunches being deflected by the second RF deflector onto the equilibrium orbit). The ring length is equal to the spacing between trains plus $\lambda/3$, where λ is the wavelength of the RF deflectors, equal to the spacing between bunches. Thus, for each revolution period, the RF phase seen by the circulating bunches increases by 120°, and when the second train is injected, the first one is deflected away from the septum and its bunches are interleaved with injected ones (at a $\lambda/3$ distance). This is repeated once, then the three interleaved trains are extracted by an ejection kicker, and the same cycle starts again. After the first combiner ring the pulse is composed of 4 × 24 trains. The trains are combined again by a factor 4, using the same mechanism in a second combiner ring 434 m long, and obtaining the final 24 pulses required for the main linac. Such drive beam pulses are distributed down the main linac via a common transport line, in a direction opposite to the main beam. The distance between trains is now corresponding to twice the length of the linac section which they will power, such that they will arrive at the appropriate time to accelerate a main beam pulse travelling in the opposite direction. Pulsed magnets deflect each beam at the appropriate time into a turn-around. After the turn-around each pulse is decelerated in a 868 m long sequence of low-impedance PETS down to a minimum energy close to 0.24 GeV, and the resulting output power is transferred to accelerate the high-energy beam in the main linac. As the main beam travels along, a new drive-beam train periodically joins it and runs in parallel but ahead of it to produce the necessary power for a 868 m long linac unit. At the end of a unit the remaining energy in the drive beam is dumped while a new one takes over the job of accelerating the main beam.

THE CLIC TEST FACILITY CTF3

CTF3 [8] is a small scale version of the CLIC RF power source (see Figure 2), and is presently being commissioned at CERN by an international collaboration between 28 institutes, with an organisation structure similar to large particle physics experiments.

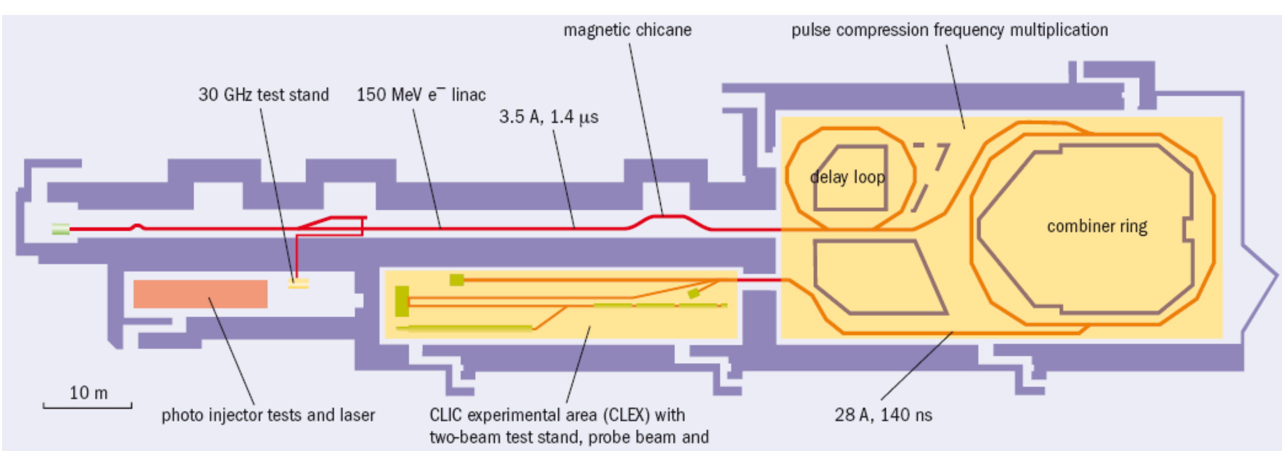

Figure 3: Schematic layout of the CTF3 complex.

CTF3 is composed by a 70 m long drive-beam linac followed by a chicane for bunch length control and two isochronous rings, where the beam current is multiplied by a factor eight: a 42 m delay loop and an 84 m combiner ring. The drive beam is then transported to the CLIC experimental area (CLEX) to produce 12 GHz RF power for structure tests. In the same area, the CALIFES linac provides a probe beam for a Two-Beam Test Stand (TBTS) and a decelerator (Test Beam Line – TBL) is used for drive beam stability studies.

The CTF3 experimental program tackles the issues related to the generation and use of the drive beam and the testing of accelerating structures and RF components. The main points that are being covered are:

1. Test of a prototype CLIC accelerating structure (including design features to damp higher order modes) at design gradient and pulse length.
2. Validation of the drive beam generation scheme with a fully-loaded linac.
3. Design and test of an adequately damped power extraction structure, which can be switched on and off.
4. Validation of beam stability and losses in the drive beam decelerator.
5. Test of a relevant linac sub-unit with beam.

The recent change of parameters did not affect the CTF3 program. The inherent flexibility of the CLIC RF power source scheme allowed for an easy adaptation to the new frequency of 12 GHz and the corresponding power with no hardware changes. It was sufficient to change the combination factor of the combiner ring from 5 to 4 (using a path-length tuning wiggler) while shortening the initial electron pulse from 1.5 µs to 1.2 µs. However, the maximum final beam current (~ 30 A) can be reached only up to a pulse length of 140 ns.

MAIN ACHIEVEMENTS IN DRIVE BEAM GENERATION AND USE

The CTF3 Preliminary Phase

An early experimental demonstration of the bunch combination scheme was carried out in 2001 and 2002 using a modified layout of the former LEP Pre-Injector (LPI) complex, during the so-called preliminary phase of CTF3 [17]. The technical feasibility of manipulating the drive beam to increase current and bunch frequency was successfully demonstrated at low current (0.3 A). Up to five bunch trains were interleaved over five turns in a combiner ring to reach 1.5 A, without measurable losses. Another issue demonstrated in the preliminary phase was the possibility to achieve a momentum compaction below 10^{-4} in a ring and to keep it under control. Such level of isochronicity is needed in the CLIC TBA scheme to preserve the drive beam bunch structure.

Full Beam Loading Operation

The first key result obtained in CTF3, in 2004, was the proof of stable operation under full beam-loading [14]. 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 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 (see Figure 4). A dedicated experiment was performed later [15], 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. 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.

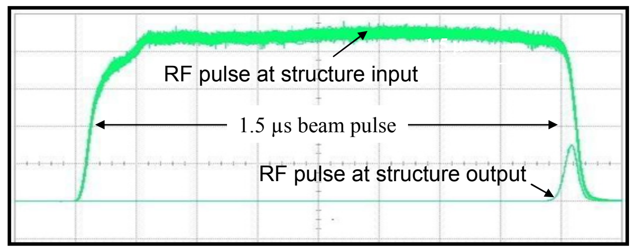

Figure 4: RF signals for full beam-loading operation. No power is left at the end of the structure in the beam pulse.

Phase Coding, High Current Bunch Combination

The first run in 2006 of CTF3 was dedicated to the commissioning of the sub-harmonic bunching system and the Delay Loop. As mentioned before, a fast RF phase switch of 180° is mandatory in order to multiply bunch frequency and beam current. The switch time was measured to be 5.7 ns by means of a streak camera, and the amount of unwanted charges in satellite bunches was estimated to be 8.5% of the main bunches. Both results are in good agreement with the specification of the system and predictions from simulations. Five 140 ns long bunch-trains were injected into the delay loop and combined with the following train, thus doubling the beam current [18].

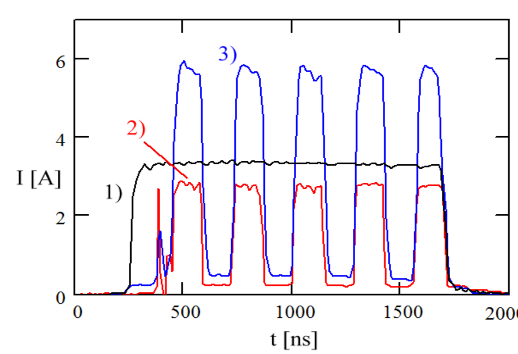

Figure 5: Beam current as a function of time, measured: 1) before the delay loop 2) in the loop 3) after the loop, showing the final recombination in five 140 ns pulses.

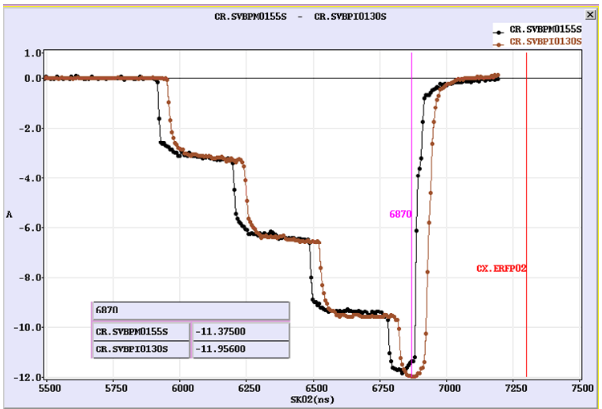

Figure 6: Recombination by a factor four in the CTF3 combiner Ring. The beam current as a function of time in the first two BPMs is shown.

In 2007 and 2008 the combiner ring and the following beam lines up to CLEX had been commissioned [19]. Initial combination tests were only partially successful, mainly due to a vertical instability induced by the RF deflectors at the injection bump. New damped RF deflectors were installed in 2008. Once the new deflectors were put in operation the multiplication factor 4 was immediately demonstrated and 12 A were reached, starting with about 3 A injected, as shown in Figure 6. Another important result was the precise determination of the ring length, fundamental since the recombination process relies on a precise control of the revolution time, to the 10^{-5} level. The measurement was done using a 3 GHz RF phase monitor and showed a very good agreement with expectations, demonstrating the capability to measure and control the orbit length by a path-length tuning wiggler to the sub-millimetre level as required.

In the second half of 2008 the transfer line to CLEX and the TBTS were installed and their commissioning started. At the end of last year the drive beam was transported to the end of TBTS and a 12 GHz PETS was tested there for the first time with beam. Since only a limited current was expected initially, a re-circulation concept was used, in which part of the produced power can be sent back in the same PETS, amplifying its output. Up to 30 MW were thus produced with a 5 A drive beam, in excellent agreement with predictions [20, 21].

CONCLUSION AND OUTLOOK

The CLIC TBA scheme, motivated by the desire to couple high-gradient acceleration and efficiency in linear colliders, evolved during the years as ideas and techniques were devised and tested. The concept basics were virtually untouched in the last few years as the concept reached maturity. The CTF3 facility is the main tool to demonstrate the feasibility of the scheme. A number of issues were already addressed, such as isochronicity, full beam loading operation, bunch phase coding, path length control and the interleaving scheme. Commissioning of the complete facility is under way and a full current combination test is expected soon. The next major step, to be completed by 2010, is the study of drive beam deceleration in a string of PETS in the TBL line, presently under installation. Other future studies include an assessment of the drive beam stability, both in current and phase, and the identification of the main sources of jitter. In the medium term, after the 2010 milestone, other experimental tests are under evaluation, including the construction and use of a series of full-fledged CLIC TBA modules and the implementation of a fast phase feed-back system in order to demonstrate the very tight phase stability (better than 0.2 degrees at 12 GHz) required to the CLIC drive beam.

REFERENCES

[1] http://council-strategygroup.web.cern.ch/councilstrategygroup
[2] ILC Reference Design Report, August, 2007.
[3] R. Tomas, “CLIC overview”, this Conference.
[4] F. Tecker (Ed.) et al., “CLIC 2008 Parameters”, CLIC Note 764 (2008).
[5] S. Döbert, “High Power test of a low group velocity X-band Accelerator Structure”, CLIC- Note-767 (2008).
[6] R. Corsini (Ed.), “The CLIC RF power source”, CERN 99-06, 1999.
[7] H. Braun, “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] http://clic-meeting.web.cern.ch/clic-meeting/CTF3_Coordination_Mtg/Table_MoU.htm.
[10] A. Sessler, “The FEL as a power source for a high gradient accelerating structure”, AIP Conf. Proc. 91 (1982).
[11] W. Schnell, “A two-stage RF linear collider using a uperconducting drive linac”, CERN-LEP-RF/86-06 and CLIC Note 13 (1986).
[12] R. Corsini, J-P. Delahaye, “The CLIC multi-drive beam scheme”, CERN/PS 98-008 and CLIC Note 331 (1998).
[13] H. Mizuno and Y. Otake, “A New RF Power Distribution System for X Band Linac Equivalent to an RF Pulse Compression Scheme of Factor 2N”, Proc. LINAC’94.
[14] R. Corsini et al., “First full beam loading operation with the CTF3 Linac”, Proc. EPAC’04 and CLIC note 604.
[15] P. Urschütz et al., “Efficient long-pulse fully-loaded CTF3 linac operation,” Proc. LINAC’06 and CLIC note 697.
[16] S. Pei et al., “Conceptual Design of the Drive Beam for a PWFA-LC”, this Conference.
[17] R. Corsini et al. “Experimental results on electron beam combination and bunch frequency multiplication”, Phys. Rev. ST Accel. Beams 7, 040101 (2004).
[18] D. Alesini et al., “Commissioning status of the CTF3 delay loop”, proc. EPAC’06 and CLIC note 675, 2006.
[19] S. Bettoni et al., “Achievements in CTF3 and Commissioning Status”, this Conference.
[20] V. Ziemann, “Data Analysis for PETS Recirculation”, CTF3 Note 94, 2009.
[21] E. Adli, “Analysis of the first 12 GHz PETS tests with beam using a constant parameter recirculation model”, CTF3 Note 96, 2009.