CLIC FEASIBILITY DEMONSTRATION AT CTF3

Roger Ruber, Uppsala University, Sweden,
for the CLIC/CTF3 Collaboration

Abstract

The CLIC/CTF3 collaboration is studying the feasibility of a multi-TeV electron-positron collider, the so-called CLIC: Compact LInear Collider. The idea is to use a two-beam acceleration scheme at an RF frequency around 12 GHz. In this scheme, the RF power to accelerate the main beam is produced by a high current drive beam. To demonstrate the feasibility of this scheme, the CTF3 facility (CLIC Test Facility 3) has been constructed at CERN. Recently, the complex to generate the drive beam has been successfully commissioned producing a beam with a current 28 A. This beam is now being used to test the power production and main beam acceleration according to the two-beam scheme. The results of the test facility provide vital input for the CLIC conceptual design report that is presently being prepared.

INTRODUCTION

The near future of high-energy physics will be dominated by research done at the LHC, but eventually a high-energy electron-positron collider will be required in order to do precision measurements of the new physics expected to be discovered at the LHC. The CLIC/CTF3 collaboration aims to develop such a linear collider based on a two-beam acceleration scheme that efficiently solves the problem of power distribution to the acceleration structures. Such scheme was originally proposed using a superconducting drive linac [1], but later adapted to a normal conducting linac [2]. The required RF power is produced by decelerating a so-called drive beam, a low energy but high intensity electron beam, that runs parallel to the main beam that has to be accelerated. As shown in Figure 1, the RF field produced by the drive beam is then transferred to accelerating structures for the main beam. The accelerating structures are normal-conducting and are expected to achieve high-accelerating gradients, which is a requirement to keep the length of the accelerator within reasonable limits. The CLIC Test facility 3 (CTF3) was built at CERN in order to address the key technological challenges of the two-beam acceleration scheme [3]. Here, the Two-beam Test Stand (TBTS) is a key experiment where the power generation with subsequent acceleration of a second beam are tested and key beam dynamics questions will be answered.

The previous CTF1 and CTF2 test facilities have provided the proof of principle for the two-beam acceleration scheme, albeit with low intensity and low energy beams [4, 5]. The present CTF3 facility aims to demonstrate the feasibility of:

- Drive beam generation with appropriate time structure and fully loaded acceleration.
- Two-beam acceleration with prototype CLIC structures.

The CTF3 facility has two linacs: a 3 GHz drive beam linac with a thermionic gun, and a 3 GHz probe beam linac with a photoinjector. The drive beam linac is connected to two rings, the so-called delay loop (DL) and combiner ring (CR), to create a beam with 12 GHz bunch repetition frequency. Table 1 lists the main parameters of the resulting drive and probe beams as delivered to the two-beam acceleration experiments, which consists besides the TBTS also of a decelerator test line (TBL). A photoinjector (PHIN) and 12 GHz klystron powered test stand complete the CTF3 facility.

DRIVE BEAM GENERATION

The drive beam is generated in a 70 m long linac followed by two rings were beam manipulations are carried out: a 42 m long delay loop and a 84 m long combiner ring. The two rings form a pulse recombination system that multiplies the bunch repetition frequency and the beam current but simultaneously shortens the macro pulse length. The initial time structure as produced by the linac and the final time structure of the drive beam, after passing the delay loop and combiner ring, are shown in Figure 2. To obtain maximum power extraction efficiency during the drive beam deceleration, the drive beam bunches must be short and equally spaced at the desired RF frequency for power production.

In the injector, a thermionic gun produces a 5 A, 1.5 μs long electron pulse which then passes through a 1.5 GHz sub-harmonic buncher (SHB) system [6, 7] such that only every second 3 GHz RF bucket is populated. Unfortu-

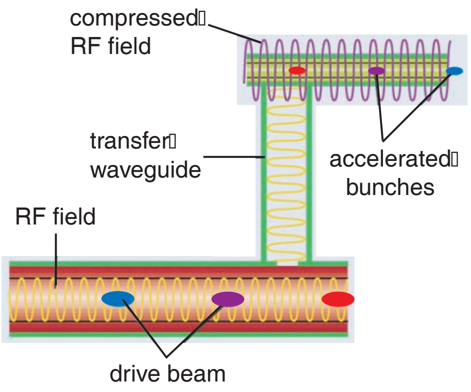

Figure 1: Two-beam acceleration scheme. The RF field created by the drive beam is transferred to main beam accelerating structures. Due to differences in structure volume and shunt impedance the field is compressed.

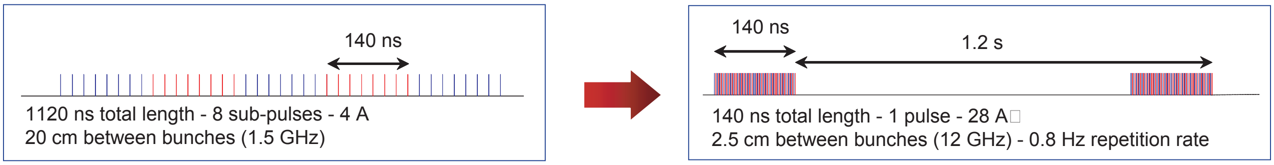

Figure 2: Time structure of the CTF3 drive beam generation scheme (mode 1, Table 2). Initial time structure from the linac at left, final time structure after the combiner ring at right.

Table 1: Main Parameters of the CTF3 Beams

	Drive beam	*Probe beam*
Energy	120 MeV	180 MeV
Energy spread (RMS)	2%	1%
Pulse length	140–1100 ns	0.6–150 ns
Bunch frequency	1.5–15 GHz	1.5 GHz
Bunch charge	up to 3 nC	0.085–0.6 nC
Intensity		
- short pulse	28 A	1 A
- long pulse	4 A	0.13 A
Repetition rate	0.8–5 Hz	0.8–5 Hz

Table 2: Different Scenarios for Drive Beam Generation

Operation Mode	*1*	*2*	*3*	
Rings in use	DL+CR	CR	-	
Linac frequency	1.5	3	3	GHz
Bunch frequency	12	12	3	GHz
Current	28	14	4	A
Pulse length	140	240	1400	ns

nately 7-8% of the current is captured in parasitic satellite bunches. The resulting bunches are compressed in a chicane with off-energy electrons removed by collimation slits, handing a 4 A, 1.4 μs bunch train to the linac. The SHB allows a 180° phase switch of the RF in 5-6 ns, such that the drive beam can be "phase coded" into eight 140 ns long sub-pulses in which the bunches occupy either even or odd buckets with respect to the 3 GHz RF.

The linac uses 3 GHz $2\pi/3$ mode structures operated in full beam-loading mode at a gradient of 6.5 MV/m [8]. The high beam current extracts almost all the RF power stored in the traveling wave accelerating structures. An overall RF-to-beam transfer efficiency of approximately 95% has been reached [9]. This high efficiency is a fundamental necessity for the CLIC feasibility.

The delay loop rearranges the beam pulse into four 140 ns pulses separated by 140 ns gaps. Simultaneously it increases the beam current and bunch repetition frequency by a factor 2. A 1.5 GHz transverse RF deflector bends the "even buckets" of the phase-coded sub-pulses into the delay loop, while the "odd buckets" are bend to bypass the delay loop. As the delay loop length of 42 m corresponds to the sub-pulse length of 140 ns, the "even buckets" return to delay loop input at the RF deflector at the same time as the "odd buckets" of the subsequent sub-pulse arrive there. A wiggler can tune the delay loop length to an integer number of the RF wavelength, thus bunches arriving with opposite phase receive opposite kicks at the RF deflector, making it possible to interleave them [10].

The combiner ring is designed to multiply the bunch repetition rate of the incoming beam pulse with factors from 1 to 5. The arriving bunch trains are injected by two 3 GHz transverse RF deflectors which creates a time dependent closed orbit bump. This bump is different for each turn, so successive bunch trains can be injected immediately behind the (already circulating) previous bunch train creating a single interleaved 140 ns long bunch train. The beam is extracted with a kicker magnet [11]. To avoid partial beam loss during extraction necessitates a gap in the bunch train, which is created by the delay loop. The combiner ring is routinely being operated at a 4 times multiplication factor, creating a bunch train with 12 GHz bunch repetition rate and currents around 14 A [12, 13].

While delay loop and combiner ring are regularly used independently, the challenge is to use them simultaneously with a high bunch charge and long train length. Last year, beam recombination was achieved in delay loop and combiner ring together creating a 12 GHz beam at around 28 A [14]. This opens the way to possible combinations of using or bypassing these rings, enabling different scenarios for drive beam generation as listed in Table 2. Note that the 1.4 μs bunch train from the linac is slightly longer than the 1.12 μs bunch train required for operation mode 1 with 12× recombination as shown in Figure 2, or the 0.96 μs bunch train required for operation mode 2.

Streak camera and RF phase monitor diagnostics are used in single shot measurements to study and optimize the bunch recombination scheme [15]. The Streak camera looks at the synchrotron radiation emitted in the arcs of the rings. The light is focused to spot sizes of 350 μs and can then be used for longitudinal bunch diagnostics studies at sweep speeds up to 50 ps/mm. The phase monitor is a four button RF pick-up that measures the magnitude of the beam power spectrum within selected frequency bands chosen as the ones sensitive to bunch spacing during the recombination process. The same button pick-ups are also used to measure the ring lengths by comparing the beam signal with a 3 GHz, phase adjustable, reference signal.

At present the transfer line from combiner ring to experiments is still under commissioning: part of the beam is lost and bunch lengthening and emittance growth are observed. Commissioning has been resumed this summer after replacement of the electronics of the beam position monitoring system that had been malfunctioning partly due to radiation damage. The present drive beam recombination scenario is according to operation mode 2 (Table 2), with a 3 GHz beam 4 times recombined in the combiner ring, as shown in Figure 3, to create a 12 GHz beam that is send to the PETS deceleration and power production structure in the TBTS. Work has been undertaken to improve the beam stability by introducing a klystron phase feed-back loop and temperature stabilization of the RF pulse compressors [16].

DRIVE BEAM TEST STANDS

A decelerator Test Beam Line (TBL) has been constructed to demonstrate beam stability under deceleration [17]. At present only a single PETS deceleration structure is installed, but when the TBL is fully equipped with 16 PETS deceleration structures, over 50% of the energy can be extracted from the drive beam. Beam stability, beam blow up and power extraction efficiency will be studied.

An RF photoinjector (PHIN) is being developed with the objective to demonstrate a laser-based electron source for CLIC. Compared to the present CTF3 drive beam thermionic injector it has the advantages of smaller beam emittances, absence of low charge parasitic bunches in every second 3 GHz bucket, decreased phase/energy tails as produced in conventional bunching systems and easier tailoring of the 180° phase switching. PHIN is a 2.5 cell 3 GHz RF gun with a Cs_2Te photocathode illuminated by an UV laser pulsed at 1.5 GHz. It has achieved bunch trains up to 1300 ns at 4 nC per bunch and beam energies up to 5.5 MeV at 0.7% energy spread and charge stability at 1-2% [18].

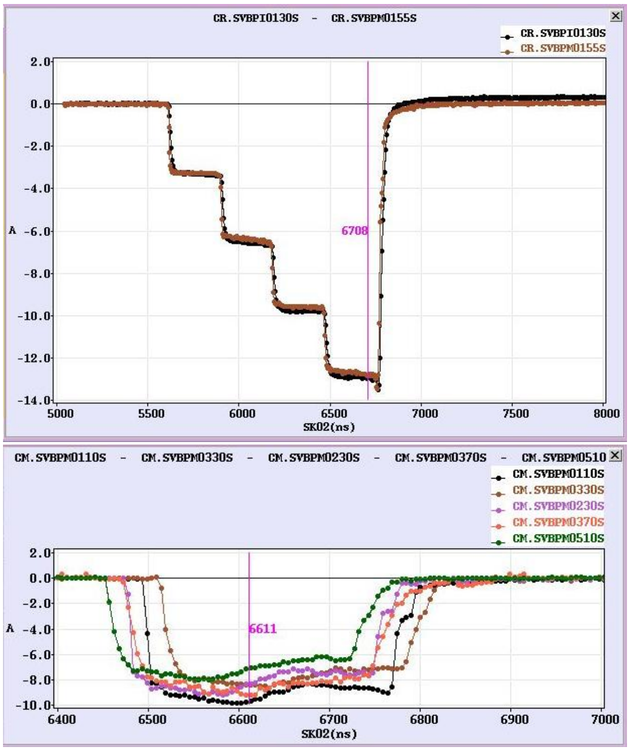

Figure 3: Four times bunch recombination of a 3 GHz beam in the combiner ring as seen by the current intensity signal from a beam position monitor. The bottom figure shows the resulting beam pulse current arriving at the PETS in the TBTS.

PROBE BEAM GENERATION

The probe beam is generated in the 24 m long CALIFES linac situated in the same experiment hall as the TBTS. It can produce single bunches and bunch trains at 1.5 GHz bunch repetition rate and energies up to 170 MeV (see Table 1). It is based on three LEP Injector Linac (LIL) 3 GHz accelerating structures of which one can be used as buncher [19]. The beam is generated in a laser triggered photoinjector of which the photocathode can be regenerated in an adjacent cathode preparation chamber [20]. The laser, which is shared with the PHIN installation, produces IR pulses at 1.5 GHz repetition rate, which are converted to green and then to UV before hitting the photocathode [21]. Excellent beam quality is required for the high gradient acceleration tests in the TBTS. Therefore the end of the linac has been equipped with a diagnostics sections to measure bunch train charge, energy, pulse length and beam emittance [22]. A 3 GHz traveling wave deflecting cavity is used for bunch length measurements by transverse tilting of the electron bunches.

TWO-BEAM ACCELERATION

The drive and probe beams are available in the CLIC experimental hall (CLEX) where they are used for experiments related to the two-beam acceleration concept. Foremost this is done in the Two-beam Test Stand (TBTS), devised to demonstrate the feasibility of the two-beam acceleration concept and its key components [23].

The TBTS is the only facility where CLIC type structures can be tested with beam. It will be used for an extensive program to investigate two-beam acceleration, the PETS power production structures and high gradient accelerating structures. It consists of two parallel beam lines fed with the drive and probe beam respectively. A PETS deceleration and power generation structure installed in the drive beam feeds RF power to an accelerating structure in the probe beam. Instrumentation is available to investigate acceleration, wakefield and breakdown phenomena. The TBTS will be adapted in the future for testing 2 m long CLIC prototype two-beam modules consisting of PETS and quadrupole magnets in the drive beam connected to accelerating structures in the probe beam.

The TBTS PETS is a 1 m long 12 GHz RF structure in eight octants separated by damping slots in order to provide strong damping of transverse modes [25]. Two pick-up antennas are installed at 90° angle in two of the damping slots. The downstream end is equipped with a special matching cell and output coupler. A configuration is provided for external recirculation of the RF power which amplifies the internal RF power as seen by the PETS. The loop recirculation time is in the order of 26 ns. In the near future the PETS will be tested with an on/off mechanism by an external RF reflector. The accelerating structure presently installed in the TBTS probe beam line has a 24 cell tapered design with an active length of 20 cm. In addition, there are two matching cells and input/output couplers. The aim is to reach an accelerating gradient of 100 MV/m which requires an input power of approximately 45 MW (unloaded) [26].

During the 2009 run, the PETS produced over 170 MW peak in full RF recirculation mode, well above the nominal 135 MW foreseen in CLIC, but in presence of pulse shortening. The performance was limited by this pulse shortening, linked to RF breakdown in the recirculation components (power splitter and phase shifter). These parts have been repaired and improved for the present 2010 run. Estimations of the drive beam energy transferred to RF power in the PETS are shown in Figure 4. Three different approaches are used: based on the beam energy measurements in the spectrometer line, based on the produced RF power and based on the measured beam intensity in a BPM (to predict the RF power production) [27]. This shows that our models of the beam energy loss and power production in the PETS agree with reality. Note the slight mismatch between the model based purely on beam intensity and the model incorporating the PETS RF power, which is probably linked to phase variation along the beam pulse. The measurements were done at beam currents around 5 A and RF recirculation in the PETS producing up to 20 MW of RF power.

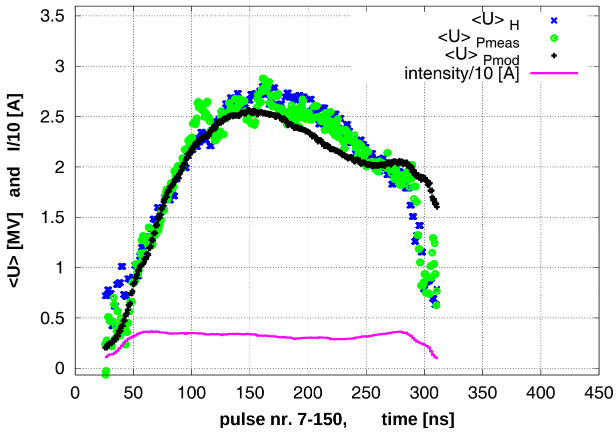

Figure 4: Drive beam energy loss measured in the TBTS. Estimates based on spectrometer measurement $\langle U\rangle_H$ (blue), produced PETS RF power combined with beam intensity $\langle U\rangle_{P_{\mathrm{meas}}}$ (green) and beam intensity measurement only $\langle U\rangle_{P_{\mathrm{mod}}}$ (black).

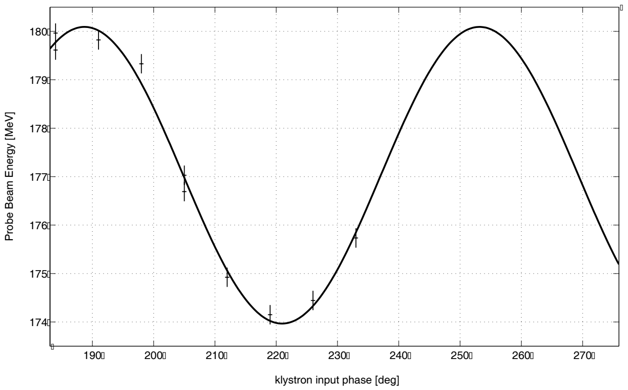

Figure 5: First results of probe beam acceleration in the TBTS: Probe beam energy after passing the accelerating structure as function of the CALIFES klystron phase input.

The 2010 run, which only started in August due to a fire in a high voltage pulse modulator, has already produced its first results by two-beam acceleration of the probe beam. Figure 5 shows the first results of the two-beam acceleration at low RF power into the accelerating structure. The beam energy is measured in the spectrometer line as a function of the 3 GHz input phase to the CALIFES klystron (in coherence with the phase of a 1.5 GHz signal used to trigger the laser for the photo cathode). The phase scan is used to fine tune the timing between probe and drive beam (RF generation). The probe beam energy without acceleration was 177 MeV (measured with RF off). Only 3 MeV of acceleration or deceleration was achieved due to low RF input power. Note that the phase scan gave a 64° phase difference over a full loop, while 90° would be expected in line with the 4 times frequency difference between drive and probe beam. This is presumed due to systematic variations in the probe beam, probably due to pulse compression variations and incoherent phase shift between RF power and laser timing.

Higher order modes and RF breakdowns in PETS and accelerating structures can cause kicks in the beam orbit. For the design of a stable two-beam accelerator it is important to understand these kicks. The present PETS and future accelerating structures will be installed with HOM monitors to study the possible relation between HOMs and beam kicks [28]. The TBTS has been equipped with several beam position monitors before and after the PETS and accelerating structures. Thus any kick can be determined by us-

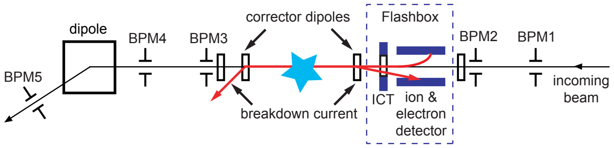

Figure 6: Measurement set-up for RF breakdown and beam kick in the TBTS.

ing the beam position measurements as shown in Figure 6. With a BPM resolution of 10 µs it is expected to resolve the kick angle with 10 µrad resolution [29]. The small steerer magnets before and after the structure are used as a small chicane to remove the breakdown current from the main beam in order to minimize disturbance of the kick measurements. Sensors are being prepared to install between the steerers used in the chicane to measure the breakdown currents and their energy. This is of special interest for the investigation of breakdown currents that are accompanied by ions.

CONCLUSIONS

CTF3 has reached its first milestones and is well on its way to complete its feasibility demonstration program. Drive beam generation with fully loaded acceleration has been demonstrated, and likewise two-beam acceleration with prototype PETS power production and CLIC accelerating structures. The CTF3 facility and its experiments will continue to optimize operation and study two-beam acceleration, drive beam deceleration the possible effects of RF breakdown on the beams. For this, the deceleration test beam line installation will be completed with 16 PETS structures. Work is ongoing to install and test a first prototype two-beam acceleration module with dedicated PETS and accelerating structure in the TBTS, replacing the present installation of PETS and accelerating structure in versatile vacuum tanks.

ACKNOWLEDGEMENTS

The colleagues in the CTF3 teams are acknowledged for their great efforts, advice and cheerful collaboration. We are greatly indebted to all CERN departments for their contributions to the construction and operation of the facility. Equally we warmly acknowledge all our technical colleagues in the collaborating institutes without whom the facility would not have been built. Furthermore we are grateful to all the funding agencies that support the collaboration.

REFERENCES

[1] W. Schnell, “A Two-stage RF Linear Collier using a Superconducting Drive Linac”, CERN LEP-RF/86-06, CLIC Note 13 (1986).

[2] G. Guignard (ed.), “A 3TeV e^+e^- Linear Collider based on CLIC Technology”, CERN, Geneva (2000) CERN 2000-008.

[3] G. Geschonke and A. Ghigo (eds.), “CTF3 Design Report”, CERN, Geneva (2002) CTF3 note 047.

[4] H.H. Braun et al., “Results from the CLIC Test Facility”, EPAC 1996, Sitges, Spain.

[5] H.H. Braun, “Experimental Results and Technical Research and Development at CTFII”, EPAC 2000, Vienna, Austria.

[6] H. Braun et al., “An Injector for the CLIC Test Facility (CTF3)”, LINAC 2000, Monterey, California, USA.

[7] P. Urschütz et al., “Beam Dynamics and First Operation of the Sub-harmonic Bunching System in the CTF3 Injector”, EPAC 2006, Edinburgh, Scotland, UK.

[8] E. Jensen, “CTF3 Drive Beam Acceleraring Structures”, LINAC 2002, Gyeongju, South Korea.

[9] R. Corsini et al., “First Full Beam Loading Operation with the CTF3 Linac”, EPAC 2004, Lucerne, Switzerland.

[10] A. Ghigo et al., “Status of the CTF3 Frequency Multiplication Rings”, APAC 2007, Indore, India.

[11] C. Biscari et al., “CTF3: Design of Driving Beam Combiner Ring”, EPAC 2000, Vienna, Austria.

[12] F. Tecker et al., “CTF3 Combiner Ring Commissioning”, PAC 2007, Albuquerque, New Mexico, USA.

[13] R. Corsini et al., “Experimental Studies on Drive Beam Generation in CTF3”, EPAC 2008, Genoa, Italy.

[14] P.K. Skowroński et al., “Progress Towards the CLIC Feasibility Demonstration in CTF3”, IPAC 2010, Kyoto, Japan.

[15] A.E. Dabrowski et al., “Measuring the Bunch Frequench Multiplication at CTF3”, IPAC 2010, Kyoto, Japan.

[16] A. Dubrovskiy and F. Tecker, “RF Pulse Compression Stabilization at the CTF3 CLIC Test Facility”, IPAC 2010, Kyoto, Japan.

[17] E. Adli et al., “Experimental Program for the CLIC Test Facility 3 Test Beam Line”, IPAC 2010, Kyoto, Japan.

[18] M. Petrarca et al., “Performance of the PHIN High Charge Photo Injector”, IPAC 2010, Kyoto, Japan.

[19] A. Mosnier et al., “The Probe Beam Linac in CTF3”, EPAC 2006, Edinburgh, Scotland, UK.

[20] J. Brossard et al., “Construction of the Probe Beam Photo-injector of CTF3”, EPAC 2006, Edinburgh, Scotland, UK.

[21] F. Peauger et al., “Status of the CTF3 Probe Beam Linac CALIFES”, LINAC 2008, Victoria, Canada.

[22] W. Farabolini et al., “CTF3 Probe Beam Linac Commissioning and Operation”, These proceedings.

[23] R.J.M.Y. Ruber et al., “The CTF3 Two-beam Test-stand Installation and Experimental Program”, EPAC 2008, Genoa, Italy.

[24] I. Syratchev et al., “CLIC RF High Power Production Testing Program”, EPAC 2008, Genoa, Italy.

[25] I. Syratchev and A. Cappelletti, “A New High-power RF Device to Vary the Output Power of CLIC Power Extraction and Transfer Structures (PETS)”, IPAC 2010, Kyoto, Japan.

[26] A. Grudiev, “TD24_vg1.8_disk CLIC_G disk at 12 GHz” CERN EDMS document 1070498.

[27] E. Adli, “Techniques for estimations of beam energy loss in the Two-Beam test stand PETS, applied to the first 12 GHz PETS tests with beam”, CERN CLIC Note 097 (2009).

[28] F. Peauger et al., “Wakefield Monitor Development for CLIC Accelerating Structures” These proceedings.

[29] M. Johnson et al., “RF-breakdown Experiments at the CTF3 Two-beam Test-stand”, EPAC 2008, Genoa, Italy.