2.15 CTF3 Status, Progress and Plans

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2.15.1 Introduction

The aim of the CLIC Test Facility CTF3 (see Fig. 1.1), built at CERN by the CLIC International Collaboration, is to prove the main feasibility issues of the two-beam acceleration technology [1]. CTF3 consists of a 150 MeV electron linac followed by a 42 m long Delay Loop and a 84 m Combiner Ring. The beam current from the linac is first doubled in the delay loop and then multiplied again by a factor of four in the combiner ring by interleaving bunches using transverse RF deflecting cavities. The high current beam can then be sent in the CLIC experimental area (CLEX) where it can be decelerated to extract 12 GHz RF power to be used for high gradient acceleration. In the same area a 200 MeV injector (CALIFES) generates a Probe Beam for two-beam experiments.

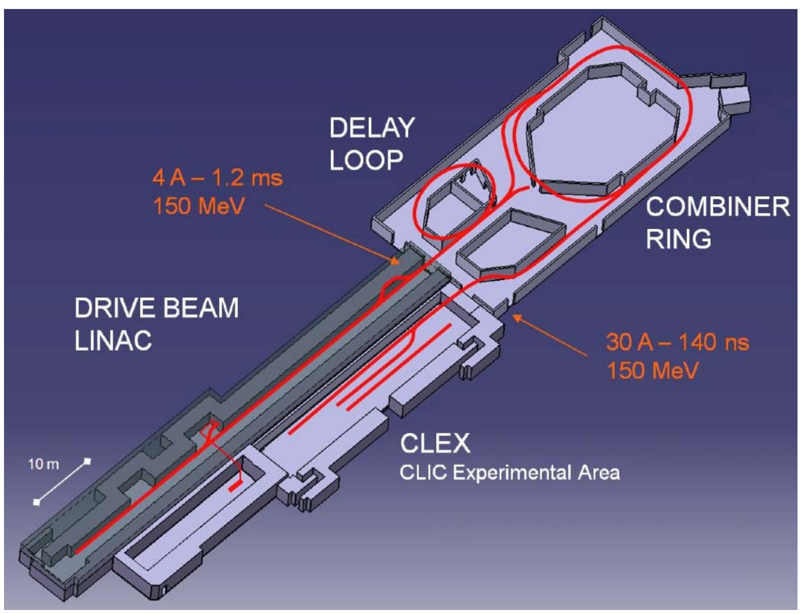

Figure 1.1: CTF3 overall layout.

CTF3 was built in order to demonstrate the following two main issues [2]:

1. Drive Beam Generation: efficient generation of a high-current electron beam with the time structure needed to generate 12 GHz RF power. CLIC relies on a novel scheme of fully loaded acceleration in normal conducting travelling wave structures, followed by beam current and bunch frequency multiplication by funneling techniques in a series of delay lines and rings, using injection by RF deflectors. CTF3 is meant to use such a technique to produce a 30 A Drive Beam with 12 GHz bunch repetition frequency. The Drive Beam can be sent to an experimental area (CLEX) to be used for deceleration and two-beam experiments.

2. RF power production and two-beam acceleration: in CLIC the needed 12 GHz high power RF is obtained by decelerating the high-current Drive Beam in travelling wave resonant structures called PETS (Power Extraction and Transfer Structures). Such power is transferred efficiently to high gradient accelerating structures, operated at 100 MV/m. In the CTF3 experimental area (CLEX) one line (Test Beam Line, TBL) is used to decelerate the Drive Beam in a string of PETS. The Drive Beam can alternatively be sent to another beam line (Two-Beam Test Stand, TBTS), where a PETS is used to power one or more structures, used to further accelerate a 200 MeV electron beam provided by a dedicated injector, CALIFES.

CTF3 has been installed and commissioned in stages since 2003. Delay loop running-in was basically completed in 2006. The Combiner Ring and the connecting transfer line were installed and put in operation in 2007, while the transfer line to CLEX was installed in 2008. In 2009 this last beam-line and the various Drive Beam lines in CLEX were commissioned, together with the CALIFES Drive Beam injector. During the autumn of 2009, recombination with the DL and CR together was achieved, yielding up to 28 A of beam current. In 2010 the nominal power production from the PETS was obtained, and the first two-beam test was performed, reaching a measured gradient of 100 MV/m. In 2011 a gradient of 145 MV/m was reached in two-beam tests and the PETS ON/OFF mechanism was successfully tested. In 2012 and 2013 the Drive Beam stability and the overall performances of the facility were improved and a 23 A Drive Beam was decelerated by 35% of its initial energy in a string of 12 PETS structures.

2.15.2 The Injector: Beam Current and Time Structure

The CTF3 Drive Beam injector consists of a high current thermionic gun, three 1.5 GHz sub-harmonic bunchers, and a 3 GHz system composed of a pre-buncher, a buncher and the first two accelerating structures in the linac [3].

The sub-harmonic bunchers (SHBs) are used to give the first energy-time modulation to the beam and to perform the phase coding by means of fast 180° RF phase switches. The SHBs have six 2.6 cm long cells each, and their nominal power is 40 kW. To compensate the growing beam loading, different in each one of the structures, they are tuned in a different way. Downstream of this system, a 3 GHz single-cell pre-buncher and a traveling wave buncher are installed to create the final bucket structure and to accelerate the beam up to about 6 MeV. The 2 cm long pre-buncher nominal power is 100 kW, while the TW buncher is about half a meter long and is fed a maximum power of 40 MW.

The first two accelerating cavities follow this system to bring the beam to an energy of about 20 MeV. These cavities are of the same type as those installed in the rest of the linac and described later. Exhaustive simulations have been performed using PARMELA to optimize the bunch length, the satellite population and the transverse emittance. The magnetic field distribution has been optimized to keep the emittance at the exit of the injector below 50 μm. Measurements in the CTF3 linac gave emittances in agreement with the predicted ones [4]. A bunch length of 1 mm at the end of the linac and less than 2 mm has been measured in the combiner ring by means of streak camera measurements [5].

The sub-harmonic bunchers perform 180° phase jumps to create the correct bunch train structure. Some particles captured by the 3 GHz system form satellites in between the 1.5 GHz buckets. The measured fraction of the satellites is about 8% to be compared with the 7% of the design. Figure 1.2, a projection of a streak camera image, shows the bunch population vs. time during the 180° phase switch. The measured phase switch time is less than 6 ns, which corresponds to eight 1.5 GHz periods, well below the target time of 10 ns [6].

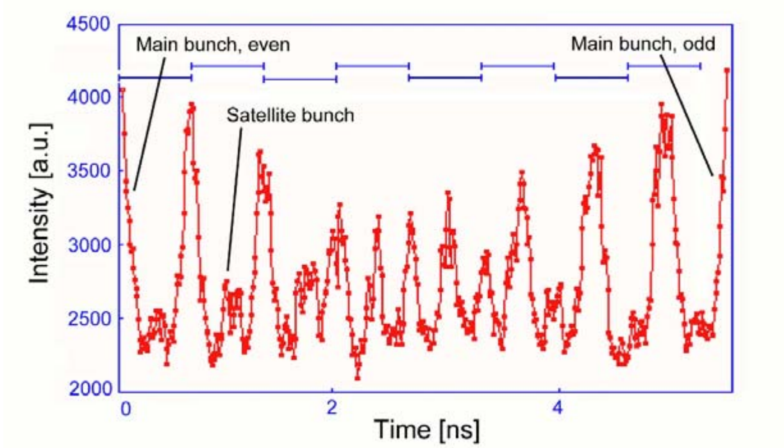

Figure 1.2: Fast bunch phase switch, measured in CTF3 by a streak camera.

2.15.3 The Linac: Full Beam-Loading Acceleration

As the overall efficiency is paramount for a linear collider, a very efficient energy transfer to the Drive Beam is crucial. An essential ingredient of the Drive Beam linac is full beam-loading operation. The high pulse current of both CLIC and CTF3 (about 4 A in both cases), in conjunction with the use of short travelling-wave accelerating structures with relatively low gradient, results in an extremely high energy transfer efficiency to the beam, as depicted in Figure 1.3. No RF power is transmitted to the load when the beam is present, and the resistive losses in the cavity walls are minimal. In this condition, an overall transfer efficiency of about 98% is expected for CLIC. However, an energy transient is present at the beginning of the pulse, where the first bunches have twice the energy of the steady-state part, reached after the filling time. This mode of operation also strongly couples beam current fluctuations to the beam energy. One of the main goals of CTF3 is the validation of the CLIC Drive Beam generation scheme with fully loaded linac operation.

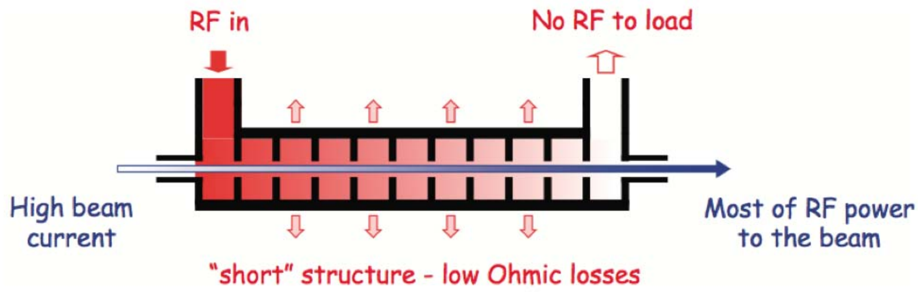

Figure 1.3: Acceleration of a beam in a travelling wave structure. Under full beam loading operation no RF power is leaving the structure.

The 3 GHz travelling wave accelerating structures designed and built for CTF3 [7] work in the $2\pi/3$ mode, have a total length of 1.22 m and operate at a loaded gradient (nominal current) of 6.5 MV/m. The large average current also implies that transverse higher order modes (HOMs) must be damped in order to prevent transverse beam instability and control emittance growth to the desired level. A Slotted Iris — Constant Aperture structure (SICA) has been designed to be used in the Drive Beam linac. Irises are radially slotted to guide dipole and quadrupole modes into SiC loads situated outside the cells. In this approach the selection of the damped modes is obtained through their field distribution, so that all dipole modes are strongly damped (Q typically below 20), while monopole modes are not influenced due to the symmetry. In addition to strong damping, SICA uses detuning of the dipole modes along the structure; this improves the suppression of HOMs and allows one to change group velocity along the structure, so providing the desired gradient profile. The HOM detuning is obtained by nose cones of variable geometry. The aperture can therefore be kept constant along the structure, which helps in reducing the short-range wake-fields.

The RF power is supplied by klystrons with power ranging from 35 MW to 45 MW and compressed by a factor of two to provide 1.3 μs pulses with over 30 MW at each structure input. The pulse compression system uses a programmed phase ramp to produce a constant RF power.

Beam commissioning started in June 2003. The design beam current and pulse length were rapidly reached, successfully demonstrating the operation under nominal working conditions of the structures with their novel damping scheme [8]. The main result obtained was the first proof of stable operation under full beam loading. The beam was remarkably stable and no sign of beam break-up was observed at high current. The measured normalized emittance at the end of the CTF3 linac was routinely about $\varepsilon_{x,y} \approx 50\ \mu$m. This confirms that the Drive Beam accelerator wake-field effects are small, as predicted by simulations.

The energy spread during the initial beam transient (about 100 ns) could be reduced to a few percent by partial RF filling of the structures at beam injection. The observation of the RF signals at the structures' output coupler was particularly useful. It allowed one to easily adjust the beam-to-RF phase by maximizing the beam loading and to determine the phase errors between structures.

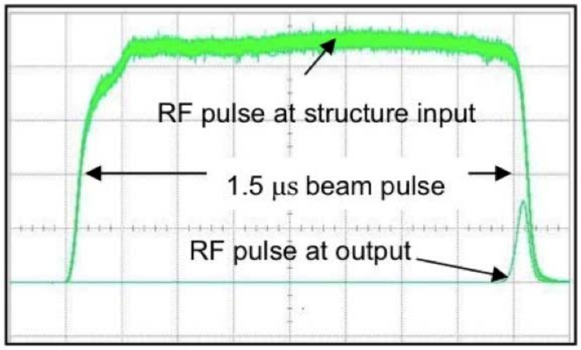

Figure 1.4: RF power measured at the accelerating structure input and output with beam.

The efficiency of the acceleration was demonstrated in a dedicated experiment [9]. After careful calibration of beam current and RF power measurements, the energy gain of the beam was calculated and compared to spectrometer energy measurements. Figure 1.3 shows an example of the RF power measured at the structure input and output, showing that the RF power is almost fully absorbed by the beam. The measurements were in excellent agreement with the theoretical energy gain. Including the ohmic losses, the obtained RF-to-beam transfer efficiency yielded 95.3%.

In summary, CTF3 has been stably operated over several years with fully loaded structures. The highly efficient acceleration of the Drive Beam has been successfully demonstrated.

2.15.4 **The Delay Loop and Combiner Ring: Isochronicity Requirements and Bunch Combination Process**

Beam recombination is done in two stages. First, using the Delay Loop (DL) a 1120 ns long bunch train with a current of 4 A is converted into 4 pulses of 140 ns and 7.5 A (taking into account the satellite bunches content). Later, the pulses are interleaved in the Combiner Ring (CR) to produce a single 140 ns long pulse with a maximum current of 30 A.

The first RF deflector, operating at 1.5 GHz, sends odd and even phase-coded sub-pulses either straight to the CR or into the DL, whose length is equal to the sub-pulse length. The sub-pulses circulating in the DL come back in the deflector at half a wavelength distance, and their orbits are merged with the following ones to obtain 140 ns long pulses with twice the initial current and twice the bunch repetition frequency. The pulses are combined again in the CR. A pair of RF deflectors is employed to create a time-dependent closed bump at injection, which can be used to interleave the bunches. The combination process must preserve transverse and longitudinal beam emittances: isochronous lattices, smooth linear optics, low impedance vacuum chambers and diagnostics, HOM free RF active elements are all needed to accomplish this task. CTF3 routinely provides a recombined beam of 28 A, slightly lower than the expected value [10] (see Fig. 1.5).

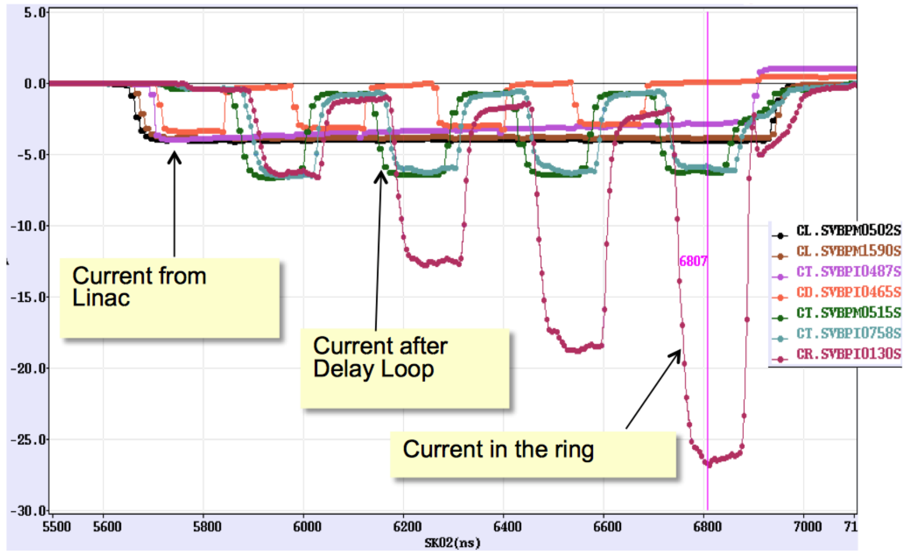

Figure 1.5: Beam current multiplication in CTF3.

Initially, the recombined current was limited by losses. In 2011, several improvements reduced drastically the losses, but the satellite content increased due to the unavailability of one of the three 1.5 GHz RF sources used in the bunching system, such that the DL recombined beam had a current of 7.2 A.

2.15.4.1 *Isochronicity and Other Lattice Requirements*

A short bunch length is fundamental for efficient RF power production in the PETS. Bunch length preservation requires the use of isochronous optics (which implies R_{56}=0) in the DL, the CR and the transfer line connecting them. The DL and CR arcs are based on the use of three-dipole isochronous cells. The isochronicity requirement is $|R_{56}| \leq \pm 1$ cm. The range of tunability of such a cell with three independent quadrupole families fits well the requirements. It is envisaged, but not yet implemented, to correct with sextupoles also the second-order matrix term R_{566}. Bunch length control to < 1 mm r.m.s. was shown in the past after the linac. No time was then dedicated to get such a bunch length in CLEX as well, since the present value (< 2 mm r.m.s.), estimated from RF power production in CLEX and by direct streak camera measurements in the ring is entirely sufficient for CTF3 operation and in agreement with expectations.

Emittance preservation requires good control of the optics, a very good closure of the DL and CR orbits and that the beam from the linac is properly matched. The RF bump in the combiner ring must not introduce any distortion. Therefore the phase advance between the RF deflectors in the horizontal plane must be 180°, so that any distortion introduced by the first RF deflector is corrected by the second one. CTF3 has not yet reached the target emittances for the Drive Beam after combination, 150 μm in both planes. Although 50 μm is routinely obtained in the linac, measurements on the fully recombined beam typically give values two to four times larger than the target. Better results are obtained for the factor 4 beam combination, where the goal has been reached. The main source of emittance growth was identified as orbit mismatch between delay loop and combiner ring, and non-perfect orbit closure in the ring itself. Several correcting measures are now being put in place.

Damping and detuning is used in the RF deflectors of the ring in order to minimize wake-fields in the vertical plane, which are not extracted from the output coupler [11]. The lowest order horizontal dipole mode is the operational one, therefore it cannot be damped or detuned. However, the fill-time of the travelling wave deflectors is short enough to avoid turn-by-turn direct build-up. In order to avoid any residual amplification of the orbit errors from RF deflector induced wake-fields, the fractional tune of the Combiner Ring is set to be about 0.6 in both planes. Also, the β function in the deflectors should be as small as possible.

2.15.4.2 *Recombination Process Setting-up*

Besides demonstrating the feasibility of the CLIC bunch combination principle, CTF3 has allowed us to develop an optimized setting-up procedure of such a process, validating also the special diagnostics needed. For instance, to set-up the Delay Loop, initially the 1.5 GHz RF deflector is not used and magnetic correctors are employed to inject the beam on the DL design orbit. The design injection orbit is established, adjusting septa and main bend current. If needed, the injected beam is then matched to the DL closed solution: the Twiss parameters of the beam are measured using the quadrupole-scan technique, in two Optical Transition Radiation (OTR) screens, located upstream and downstream of the DL injection and the optics of the transfer line from the linac is re-adjusted based on the results obtained.

In order to define the proper phase and amplitude in the RF deflector, the beam is sent straight past the DL into a dump. The RF deflector is powered, and its phase adjusted at zero crossing so it does not affect the beam trajectory. Afterwards, the phase is moved by 90° and the magnetic correctors used for injection are disabled. If the bunches don't follow exactly the reference orbit, the amplitude needs to be adjusted, and the procedure is repeated. The recombination with RF deflectors requires the length of the DL and the CR to be precisely adjusted such that the bunches, going again through the RF deflectors, see the proper RF phase with an accuracy of a few degrees. The length of both DL and CR can be tuned in a maximum range of 9 mm using 4-pole wigglers, and can be precisely measured with 3 GHz phase monitors (BPRs), which compare the bunch phase with a 3 GHz reference signal. In the last step, phase switching is introduced in the sub-harmonic bunching system, and the sub-pulses are recombined.

The Combiner Ring setup also starts with RF deflectors disabled. A static magnetic corrector is used to inject the beam on a good orbit through the first half of the ring. As in the DL case, we need to find precisely the correct amplitude and phase of the RF deflectors. The pulse is shortened to less than the CR circumference (280 ns) and only the first RF deflector after injection is powered. The zero-crossing phase is determined as the phase that leaves the beam orbit unchanged. This is done for different RF amplitude values, thus measuring the phase dependence on the amplitude. In the next step the RF deflector phase is moved by 90° so bunches arrive at the crest and the corrector is disabled. The amplitude is adjusted in order to inject on the reference orbit, with the phase following according to the dependence found in the previous step. The timing of the klystron that feeds the deflectors is adjusted such that it stops just after the last bunch is injected. Since the RF deflectors are travelling wave structures with very short filling time, the train can thus make tens of thousands of turns in the ring. At this stage the orbit in the whole ring is corrected, as well as the ring length. The ring length must be $(N \pm 1/N_f)\ \lambda_{RF}$, where N is an integer number, N_f the combination factor (here 4), and λ_{RF} is the RF wavelength. The fractional part λ_{RF}/N_f, can be determined precisely from Fourier transform of the BPR phase monitor of the coasting beam. To adjust the ring length the 4-pole wiggler is used. In the next step the phase and amplitude of the second RF deflector are adjusted. The RF pulse for the deflectors is extended by 280 ns such that the field is present when the train makes the second turn. This should not change the orbit since the ring length was adjusted before. Attenuation of the second deflector is removed and phase adjusted such that the orbit stays unchanged. The RF pulse is extended by another 280 ns and the amplitude of the second deflector is fine tuned to keep beam position unaltered. If all is done properly, extending the RF pulse to the 4th turn will not affect the orbit. Putting back the beam pulse length to the nominal value gives the recombined beam.

2.15.5 **Stability Issues**

The two-beam acceleration scheme puts tight constraints on the Drive Beam current, energy and phase stability. The CLIC Main Beam should experience the correct RF phase and amplitude within tight tolerances in order to avoid energy fluctuations, causing luminosity reduction mainly due to emittance increase in the main linac and through the limited energy bandwidth of the Beam Delivery. The stability of the Drive Beam used to produce the RF power is therefore of crucial importance, since both bunch charge and phase jitter contribute quadratically to the luminosity loss [12].

The main concern is that energy jitter generated in the Drive Beam accelerator would be transformed into beam phase jitter during the final bunch compression. The tolerances on the linac RF are therefore extremely tight: the r.m.s. RF phase jitter tolerance is 0.05◦ for a constant error along the whole Drive Beam train and 0.2% for the RF amplitude. A CTF3 klystron was used to measure the short-term RF stability over 500 consecutive RF pulses (≈ 10 min). The mean pulse-to-pulse phase jitter measured with respect to the external reference is 0.035°. The pulse-to-pulse phase jitter for a fixed 10 ns time slice is 0.07° (3 GHz). The relative pulse-to-pulse power jitter has been 0.21% [12]. The measurements show that the RF stability of the klystron is very close to the CLIC requirements.

Due to the fully loaded acceleration, any current variation will also result in an energy variation of about the same relative amplitude, even if any high frequency variation will be averaged over the fill time of the Drive Beam accelerating structure. Taking this into account, a maximum variation of 0.75×10^{-3} for the Drive Beam current and 0.2° at 1 GHz for the Drive Beam bunch phase after combination are allowed. Such tolerances are evaluated for a maximum contribution of 1% to the luminosity loss per parameter and assuming a feed-forward system (discussed below) capable of reducing the Drive Beam phase jitter by the factor of 10 (from 0.2° to 0.02° at 1 GHz). The pulse-to-pulse current variations in the CTF3 linac were measured using the current measurements of the beam position monitors. Initially, the stability was only of the order of $\Delta I/I = 2 \times 10^{-3}$ but it could be improved by replacing the gun heater power supply with a more stable one. A slow drift was still present that could be reduced by a feedback. Finally, a variation on a single BPM as low as $\Delta I/I = 0.54 \times 10^{-3}$ was measured [13] (see Fig. 1.6). This is already better than the required current stability for CLIC of $\Delta I/I = 0.75 \times 10^{-3}$. A correlation analysis of different BPMs showed also that the BPM noise level was of the order of $\Delta I/I = 0.3 \times 10^{-3}$, indicating that the real current variation is even lower, well below the CLIC target.

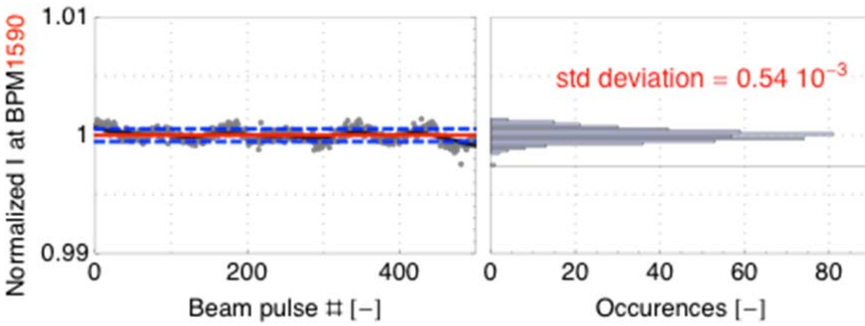

Figure 1.6: Beam current fluctuations measured at the end of the CTF3 linac.

The current stability after the recombination process is not as good as in the linac. The main source of variations and jitter is the RF system. While at least part of the klystrons have very good amplitude and phase stability, as discussed above, the RF pulse compression system is very sensitive to temperature fluctuations, which lead to a changing beam energy. Through dispersion, energy fluctuations lead in turn to fractional losses of the beam current. In order to improve the beam performances, a feedback has been developed that takes into account the ambient temperature around the compression cavities, as the thermal isolation of these cavities is not perfect. The set point of the temperature stabilization system is corrected according to the variations in the ambient temperature. This system works well and significantly suppresses the RF variations [14]. A further feedback acts in addition to this on the setup of the RF pulse compression and keeps the RF power constant along the beam pulse [15] (see Figure 1.7).

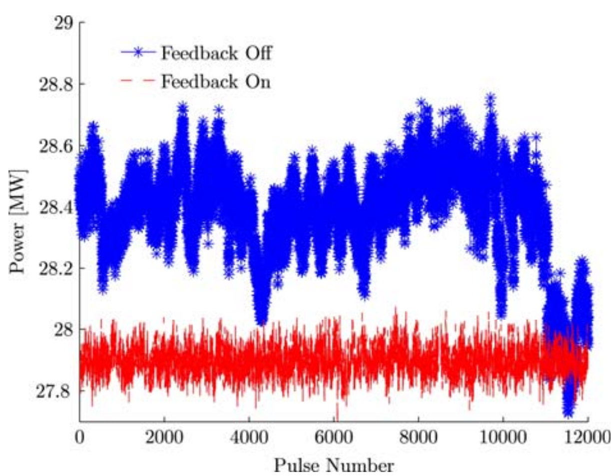

Figure 1.7: Average compressed RF power time evolution measured in one of the CTF3 klystrons, with and without the RF amplitude feedback.

It must however be noted that RF pulse compression is specific to CTF3 and will not be used in CLIC. Still another feedback stabilizes the input RF phase of the different linac accelerating structures at a given phase reference by adjusting the low-level RF phase.

After a factor of four combination in the Combiner Ring, a current stability of 1×10^{-3} was measured. The beam current variation increases after extraction from the Combiner Ring. This increase is probably due to an emittance increase during the combination together with the aperture limitation for the extraction channel. As the operation for the full factor 8 recombination is more complex, the beam becomes more sensitive to deviations from the nominal parameters. For the factor eight combination with Delay Loop and Combiner Ring, a stability of the order of 1% has been reached up to now.

As mentioned before, in CLIC a drive beam phase feed-forward system is foreseen in order to reduce the phase jitter by about a factor ten [2], from is specified value at the exit of the ring complex (2° at 12 GHz) to the level needed at injection in the decelerator sections (0.2° at 12 GHz). The CLIC feed-forward for CLIC will utilize a four bend C-shaped chicane after each turnaround. The phase of the drive beam bunches is measured prior to the turnaround. Based on this measurement the orbit of the beam through the chicane is change by altering a series of four fast kickers. Early bunches will take longer paths through the chicane and late ones shorter paths, thus correcting their longitudinal position (phase) back to nominal. As the distance the beam travels between the phase monitor and the chicane is much greater than the cable lengths between the monitor and the kickers, the same bunches that was originally measured can be corrected, which makes the system a real feed-forward.

The installation of a proof-of-principle experiment and R&D ground for the proposed CLIC drive beam phase feed-forward scheme at CTF3 is currently in progress [16]. Due to space constraints the system installed at CTF3 utilizes the existing four bend dog-leg chicane in the transfer line TL2, linking the ring area to CLEX, as opposed to a four bend C-chicane like in the CLIC scheme. One of the main challenges is the bandwidth of the whole system, whose overall bandwidth should be at least 30 MHz. This includes the amplifiers, which need to deliver a peak power of 65 kW at a bandwidth of 50 MHz. Three phase monitors are installed in the transfer line between the Stretching Chicane and the Delay Loop, prior to TL2, and after TL2 at the beginning of the TBL. The first monitor provides the input to the digital processor which calculates the voltage applied to the kickers to perform the correction. The second monitor, placed just before the first kicker, is used to assess any phase variation occurring between the first phase monitor and where the correction is made. Finally, the last monitor measures the corrected beam. The two kickers are placed prior to the first and last dipoles of the TL2 chicane. At a maximal voltage of ±1.2 kV the kickers will be able to deflect the drive beam by ±1 mrad. The feed-forward system will be tested using an uncombined beam, i.e. a Drive Beam pulse bypassing the delay loop and making only half a turn in the combiner ring, in order to prove the principle. In a second stage the system may be implemented for the combined beam, to enhance phase stability for the beam users in CLEX. The beam time of flight between the first phase monitor and the first kicker is 380 ns, which defines the maximum latency of the feed-forward system. The estimated total latency of the components (phase monitor, digital processor and amplifier) is around 150 ns, with cable delays adding an additional 120 ns. This gives a total of 270 ns, well within requirements. It is also possible to store the beam in the combiner ring for additional turns to relax the latency demands.

Beam phase errors within ±15° at 12 GHz and 30 MHz bandwidth can be corrected. It was recently confirmed [17] that the main source of phase jitter in CTF3 is energy jitter of the beam (from RF phase and power jitter of klystrons in the injector) transformed into phase jitter and amplified when passing through a magnetic chicane, for non-zero momentum compaction factor. When the chicane is set to low momentum compaction (R_{56}=0), the beam phase jitter is reduced below 2° at 12 GHz, which will allow a full demonstration of CLIC requirements if the expected factor ten gain will be reached (see Figure 1.8).

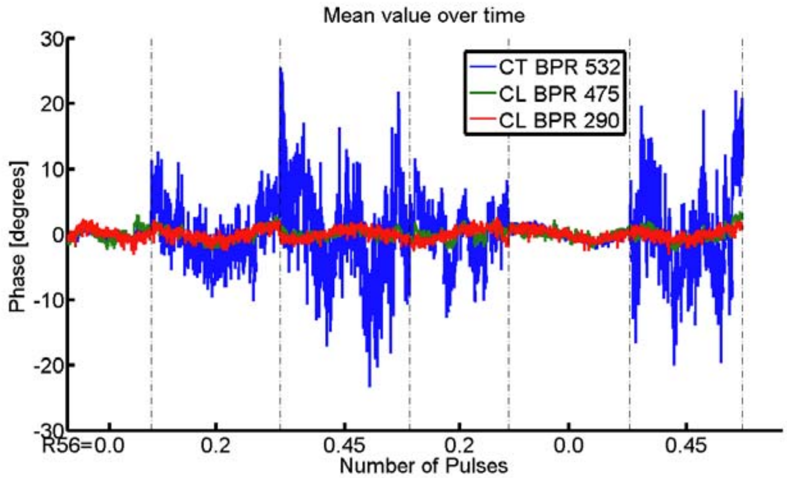

Figure 1.8: Mean phase value vs. time measured before the stretching chicane red and green traces) and after it (blue trace). The phase is measured in 12 GHz degrees, and the different R_{56} values used in the chicane during the measurement are indicated on the horizontal axis. For R_{56}= 0 the phase jitter is very close in all positions, and its rms is below 2°.

2.15.6 **The Two-Beam Test Stand: Power Production**

The RF power for the Main Beams is produced by the Drive Beam interacting with a periodically-loaded constant impedance structure, the Power Extraction and Transfer Structure (PETS). The Drive Beam excites preferentially the synchronous mode with frequency $\omega_{RF} = 2\pi \times 11.994$ GHz. Extensive studies have been performed to arrive at the current CLIC PETS design, including studies of high-power behavior and higher-order mode behavior [18]. In CLIC each of the 140000 PETS will generate 240 ns RF pulses of 135 MW. High-power testing of the PETS using a klystron has been performed at the ASTA test stand at SLAC [19] demonstrating satisfactory high-power performance with a breakdown rate less than 2.4×10^{-7} per pulse per meter at nominal PETS power and pulse length.

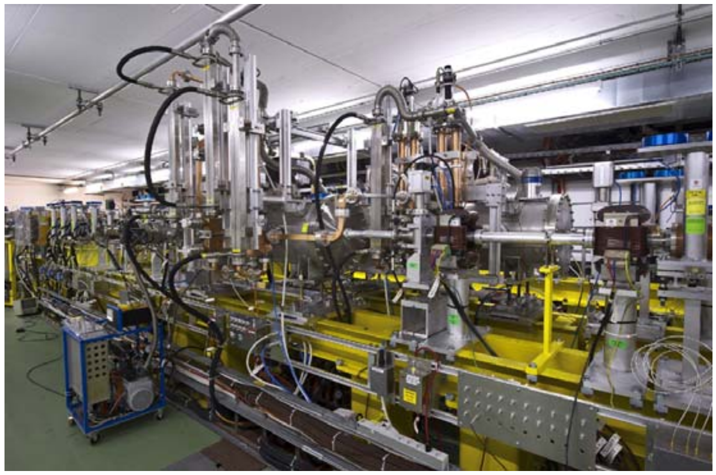

Figure 1.9: Photo of the TBTS test area with vacuum tanks for the PETS (to the right) and accelerating structure (at the left).

In CTF3, PETS prototypes are tested with beam in the Test Beam Line (TBL) and the Two-Beam Test Stand (TBTS). The TBTS consists of two parallel beam lines, fed respectively with the Drive Beam from TL2 and the Probe Beam from CALIFES (see Figure 1.9). In the TBTS a PETS extracts RF power from the Drive Beam, which is then fed to an accelerating structure in the Probe Beam line. The TBTS PETS (see Figure 1.10) 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. The downstream end of the PETS is equipped with an output coupler. The initial configuration had an external waveguide loop, allowing for recirculation and resonant build up of RF power in order to amplify it. Towards the end of the 2011 run the external recirculation circuit was replaced by an On/Off mechanism including external RF reflectors at both ends of the PETS. The recycling loop was equipped with a variable power splitter and RF phase shifter. With feedback coupling above zero the PETS operates in the amplification mode, and depending on the settings (feedback coupling and circuit phase advance) the PETS peak power can reach levels more than 10 times higher than in the case without recirculation. The extracted RF power can then be amplified by about a factor four. This gives greater flexibility in handling the RF power level delivered to the accelerating structure and in particular it gives the possibility to generate a CLIC parameter PETS RF pulse (135 MW, 240 ns) from the CTF3 factor four combined Drive Beam [20, 21].

The commissioning of the TBTS PETS with recirculation started in November 2008 with power levels up to 30 MW. The power level produced in the PETS was then gradually increased. Using a Drive Beam current of more than 15 A the PETS power routinely reached levels of more than 300 MW in the recirculation loop, twice the nominal PETS power.

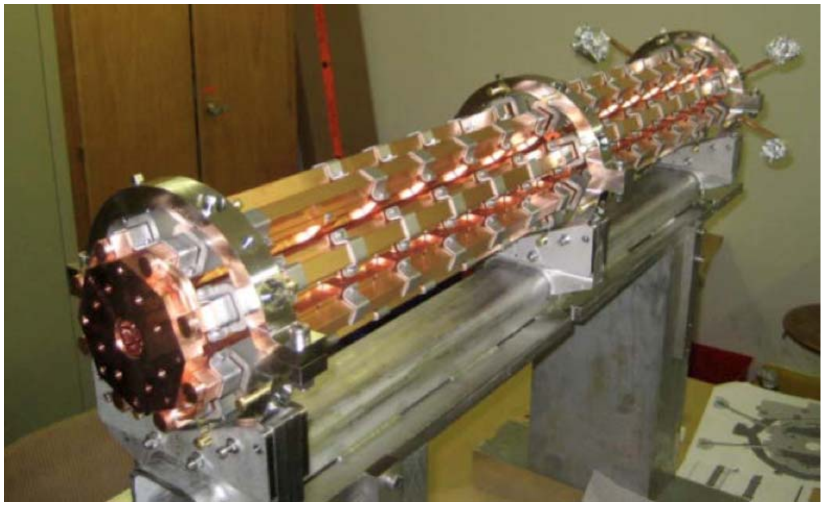

Figure 1.10: The 12 GHz PETS prototype installed in the TBTS. The PETS is based on the CLIC baseline design but longer (one meter as opposed to 0.21 m for CLIC) in order to reach and exceed the CLIC nominal power in spite of the lower CTF3 Drive Beam current (30 A maximum, as opposed to 100 A for CLIC).

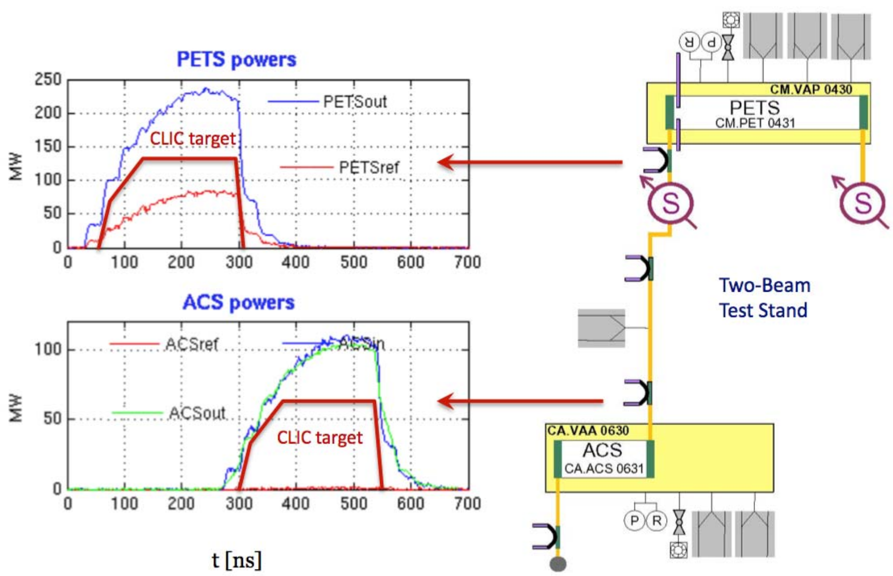

Figure 1.11: RF signals measured in different locations of the TBTS. The use of recirculation allowed to reach in the PETS (above) and in the accelerating structure (below) RF power levels and pulse lengths well beyond the CLIC nominal value.

The PETS was operated with power levels at and above the nominal CLIC power (see Figure 1.11) for long periods, showing very small vacuum activity and a relatively low breakdown rate. The analysis of the structure of the RF pulses during breakdown events showed evidence that in most of the cases, the activity was associated with waveguide components in the recirculation loop and not the PETS itself.

2.15.6.1 ***PETS On/Off Mechanism***

The PETS On/Off mechanism is required in CLIC in order to be able to switch on and off individual PETS whenever localized breakdowns threaten the normal machine operation. The system should also provide a gradual ramp-up of the generated power in order to reprocess either the main accelerating structure and/or the PETS itself. Therefore a suitable mechanism has been developed, based on an external high-power variable RF reflector [22]. The reflector can be tuned to stop any power transfer to the accelerating structures, effectively preventing any further break-down in the structures. The reflected RF power is sent back to the PETS, where internal power recirculation is established by another reflector placed at its upstream end. The reflector positions are chosen such that the back-propagating power is in anti-phase with the forward one, achieving partial cancellation of the beam generated power inside the PETS as well. For the CLIC case, the RF power extracted from the Drive Beam in the PETS is suppressed down to 25% of its original value, which is expected to be enough to prevent or to reduce dramatically the probability of RF breakdown in the PETS itself.

To test a prototype with beam in CTF3, a variable RF reflector and a variable RF short circuit were installed on the TBTS PETS tank, substituting the external recirculator. At the beginning the variable short circuit was set at the position that provided destructive phase advance in the loop for the case of full reflection in variable reflector. During experiments with beam, the variable reflector settings were changed gradually from full reflection to full transmission. The RF power produced by PETS and delivered to the accelerating structure was measured at different intermediate positions. The results are summarized in Figure 1.12.

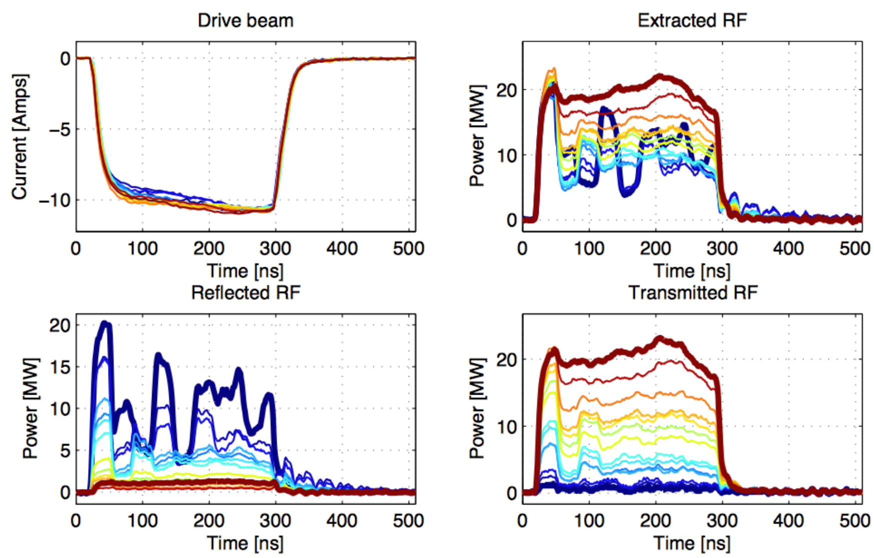

Figure 1.12: PETS On/Off demonstration with beam. Here the coloured lines correspond to different setting of variable reflection. The colours are gradually changed from red (On) to blue (Off).

These experiments successfully demonstrated the PETS On/Off operational principle [23]. They were in good agreement with computer simulations based on the low RF power measurements of all the RF components and the measured Drive Beam current pulse shape (see Figure 1.13).

However, the Drive Beam current limitation in CTF3 made it impractical to run the system at nominal CLIC RF power level. To demonstrate the power capability of the On/Off RF circuit, we set the recirculation parameters to their amplification mode, as was routinely done in the TBTS PETS when it was equipped with external recirculation. The processing of the PETS with the On/Off circuit went rather fast. In about five days (2×10^5 pulses) the system was conditioned up to 130 MW × 200 ns. In conclusion, the PETS On/Off capability was successfully demonstrated in experiments with the Drive Beam in CTF3. Currently the system is used to provide RF power for the two-beam experiments in the TBTS.

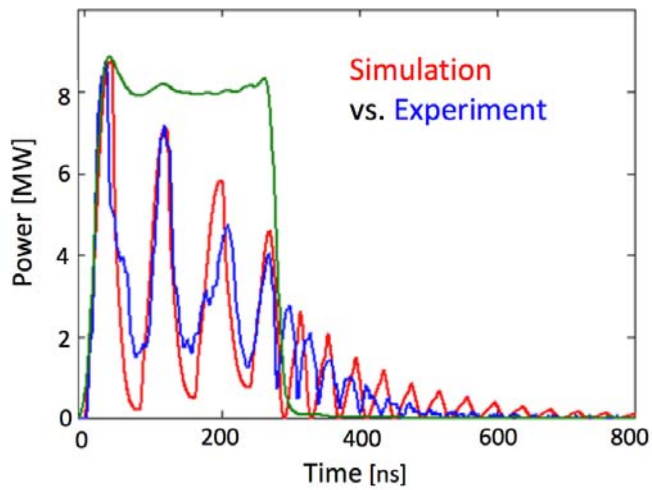

Figure 1.13: The simulated (red) and measured (blue) RF pulses generated by PETS in the Off state. The direct power production (On state) is shown in green.

2.15.7 **The Two-Beam Test Stand: Two-Beam Acceleration**

One of the key purposes of CTF3 is to demonstrate the CLIC two-beam acceleration scheme, i.e., the production of RF power from the Drive Beam and its transfer to high-gradient structures to accelerate the Main Beam (represented by the Probe Beam in CTF3). This is done in the Two-Beam Test Stand (TBTS), used for an extensive program to investigate both the PETS power production structures and high gradient accelerating structures.

The Probe Beam is provided by the 24 m long injector linac CALIFES (Concept d'Accélérateur Linéaire pour Faisceaux d'Electrons Sondes) [24], situated in CLEX like the TBTS. It has been developed by CEA Saclay, LAL Orsay and CERN to deliver single bunches and bunch trains at 1.5 GHz bunch repetition rate and energies up to 200 MeV. The beam is generated in a photo-injector. A Nd:YLF laser produces 1047 nm infra-red pulses at 1.5 GHz repetition rate, which are converted to green and then to ultra-violet before impinging on the photocathode. The bunches have an energy of about 5 MeV at the exit of the photo-injector and are further accelerated in three 3 GHz accelerating structures recuperated from the LEP Injector Linac (LIL). The three LIL accelerating structures and the photoinjector are powered by a single 3 GHz klystron which delivers 45 MW RF pulses during 5.5 μs to an RF pulse compressor.

The nominal bunch charge produced by the photo-injector is 0.6 nC, however for trains longer than 32 bunches the total beam charge is limited to 19.2 nC due to the beam loading in the LIL structures. CALIFES is usually operated with bunch charges of around 0.1 nC which can also be used for long bunch trains. A new laser system is being developed to provide UV pulses with energy over 1 μJ, far beyond the present 220 nJ, to ease operation at higher charges. A normalized beam emittance of 10 μm has been achieved.

As mentioned, the TBTS consists of two parallel beam lines, fed respectively with the Drive Beam from TL2 and the Probe Beam from CALIFES. In the central part of the TBTS large vacuum tanks contain a PETS and one accelerating structure (two since 2012). The TBTS PETS has been fully described in the previous section. During the 2010 and 2011 runs, the accelerating structure installed in the TBTS Probe Beam line was of the type TD24_vg1.8, a 24+2 cell detuned and damped design with a 2π/3 phase advance and an active length of 20 cm. It was designed to reach an accelerating gradient of 100 MV/m at an input power of approximately 45 MW (unloaded) [2].

During the 2009 run, the PETS produced over 170 MW peak in full RF re-circulation mode, well above the nominal 135 MW foreseen in CLIC, but in the presence of pulse shortening due to RF break-down in the recirculation components (high power splitter and phase shifter). These parts were repaired and improved for the 2010 run, when RF power levels in the 300 MW range were reached at the nominal pulse length. During the 2010 run the first two-beam acceleration of the Probe Beam was achieved. The Probe Beam energy with two-beam acceleration can be measured in the spectrometer line as a function of the Probe Beam 3 GHz RF phase, which is phase-locked to the laser pulse timing. A phase scan is then used to adjust the relative phase between Probe and Drive Beam for maximum acceleration. The nominal CLIC accelerating gradient of 100 MV/m corresponds to an energy gain of ΔE = 21.4 MeV.

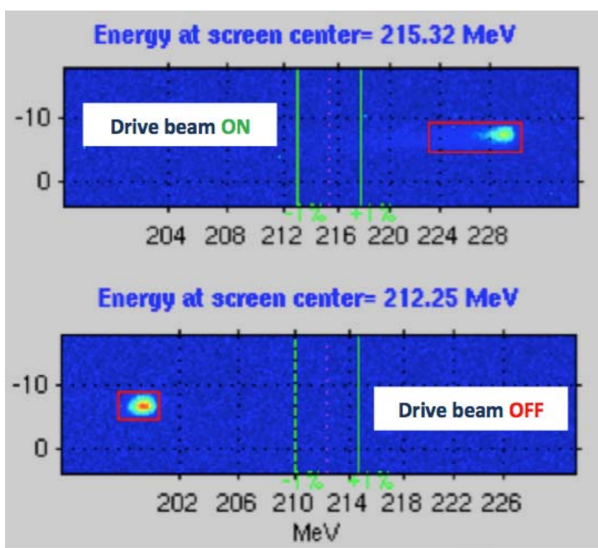

Figure 1.14: Probe Beam observed in the TBTS spectrometer screen with the 12 GHz RF power from the drive beam on (top) and off (bottom). The energy gain is about 31 MeV which corresponds to a gradient of 145 MV/m in the accelerating structure.

Due to an extensive conditioning campaign during the 2011 run, energy gains of up to ΔE = 32 MeV were achieved [25] in the last month of operation with relatively low breakdown rate. Accelerating gradients up to 165 MV/m were achieved during periods with higher breakdown rate.

Figure 1.14 shows an example of ΔE = 31 MeV Probe Beam acceleration measured on the spectrometer screen, corresponding to an accelerating gradient of 145 MV/m. The accelerating gradient and energy gain as function of the RF input power is shown in Fig. 1.15, and compared to the expectations for this structure (red line).

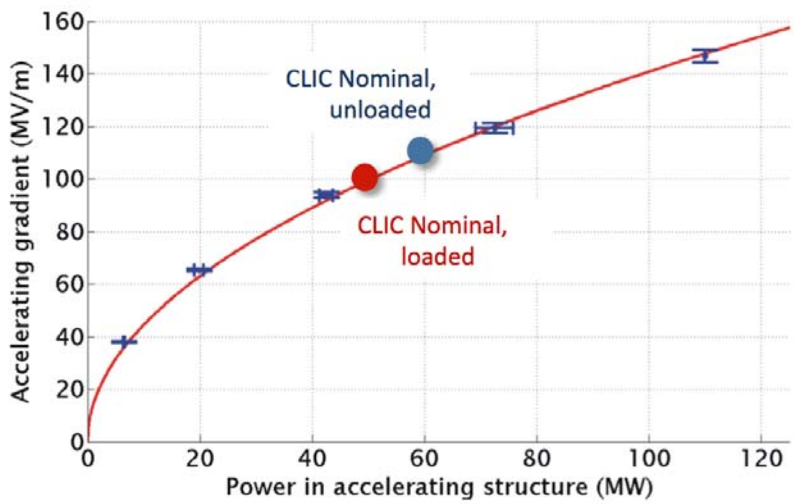

Figure 1.15: Measured (crosses) and expected (red line) accelerating gradient as function of the RF input power for accelerating structure TD24_vg1.8 used in the 2011 run. The Nominal CLIC conditions (100 MV/m loaded and 110 MV/m unloaded) are also reported.

2.15.8 **The Test Beam Line (TBL): Drive Beam Deceleration.**

The test beam line (TBL) was installed in the CLEX building of CTF3 to study the CLIC decelerator beam dynamics and 12 GHz power production. The beam line consists of a FODO lattice with high precision BPM's and quadrupoles on movers for precise beam alignment as shown in the schematic of Figure 1.16.

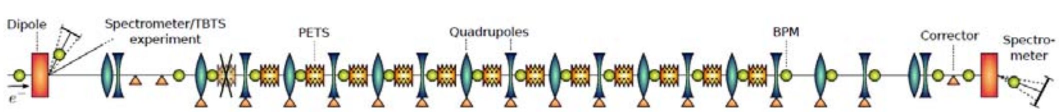

Figure 1.16: Schematics of the Test Beam Line showing the F0D0-lattice with the PETS structures in the drift spaces and the diagnostic section before and after.

Vacuum tanks containing a Power Extraction and Transfer Structures (PETS) each are installed in the drift space between the quadrupoles to extract 12 GHz power from the Drive Beam coming in CLEX from the ring area of CTF3. The PETS in TBL have the same RF design as the CLIC PETS but their active length is a factor 4 longer compared to CLIC to compensate for the lower Drive Beam current. Therefore the end of the structure as well as the coupler will see the full nominal power of CLIC, 135 MW when the fully combined Drive Beam with a bunch-train length of 140 ns and an average current over the train of 28 A is injected into the TBL.

The TBL lattice and the available diagnostics are comparable to the CLIC decelerator. The beam will fill 2/3 of the aperture after deceleration in TBL due to the much lower Drive Beam energy. Therefore the beam transport of the high energy spread beam is considered more challenging than in CLIC. On the other hand the effect of the wake-fields will be smaller in TBL due to the much shorter decelerator. The quadrupoles have been installed on moving tables developed by CIEMAT [26] which allows positioning in the micrometer range. Beam based alignment studies are foreseen using the precision BPM's developed by IFIC Valencia and UPC Barcelona [27]. Due to the lower initial beam energy the maximum amount of beam energy which can be extracted in TBL is 54% compared to the 90% envisaged in CLIC.

The emphasis for the experimental program of TBL is on 12 GHz power production and the transport of the decelerated beam. The final goal of TBL is to decelerate the Drive Beam by at least 50% of its initial energy of 120 MeV at the end of the beam line. In this case the beam will contain particles with energies between 60 MeV and 120 MeV.

The commissioning of the beam line started at the end of 2009 with nine PETS tanks installed, all constructed by CIEMAT [28] and CERN. Other tanks were installed in the next years, bringing the present total to 13. The maximum power produced so far was about 80 MW per PETS, limited by the maximum transported beam current of 22 A. No sign of breakdown has been observed so far in the PETS. The beam was decelerated from 120 MeV by more than 40 MeV corresponding to about 35% of the beam energy extracted. The 12 GHz power produced by the beam agrees well with the theoretical predictions. To check the consistency of the power production and beam deceleration we can measure a time resolved beam spectrum at the end of the TBL line using a novel segmented dump [29].

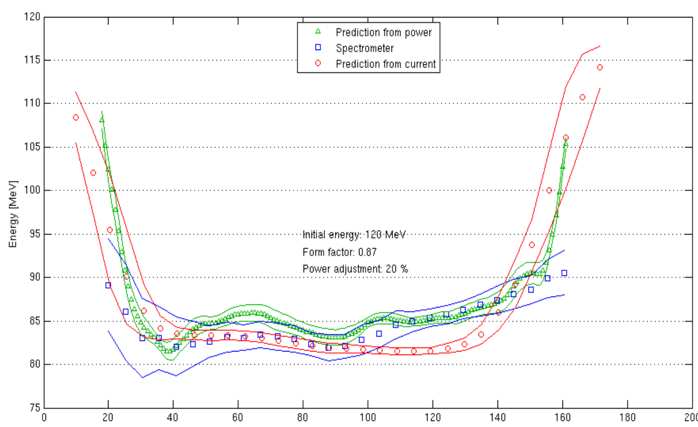

Figure 1.17: Comparison between the measured time resolved energy profile of the beam along the pulse with a segmented beam dump and the predictions from beam current and power production measurements. The data points shown are the average of 48 consecutive pulse and the shaded areas indicate the standard deviation for the measurement over this pulses.

Figure 1.17 shows a comparison of the time resolved energy measurement along the 140 ns long bunch train with the predicted energy profile from the 12 GHz power measurements and the beam current measurements. The three independent measurements are consistent assuming a bunch form factor of 0.87 for the prediction from the beam current and power measurements and a 20% calibration error in the 12 GHz power measurements. The form factor has been confirmed by bunch length measurements using a streak camera.

It is essential for CLIC that the 12 GHz power production is efficient and stable. The current stability after Drive Beam generation as well as the stability of the 12 GHz power produced in terms of amplitude and phase can be measured directly. For a beam of 12 A obtained by a factor 4 combination in the combiner ring only, a current stability around 1% has been obtained regularly [30], the corresponding amplitude stability of the 12 GHz power scales roughly with the current squared. The phase stability along the pulse has been measured to be within 2° and the phase jitter pulse to pulse to ±5° total. The pulse phase jitter likely comes from a timing jitter of the incoming beam in the ps range.

A first measurement of the BPM resolution measuring the trajectory of the beam in three consecutive BPMs to take out the effects of beam jitter has been performed. For a beam with 13 A average current, 9 μm resolution was measured corresponding well to the specified resolution of 5 μm for the nominal beam current of 28 A. Beam based alignment studies have been started using the micrometric quadrupole movers. The beam could be aligned with a residual misalignment of 250 μm r.m.s. limited to date by beam jitter and residual dispersion coming from upstream of the beam line.

Two more PETS tanks will be installed during the shutdowns in 2014 and 2015 to bring the total of installed PETS to 15. These last PETS will have input and output couplers and will be equipped with internal recirculation systems, based on the PETS On/Off mechanism. This will allow more flexibility in power production and will make easier to reach the 50% deceleration goal with moderate currents.

2.15.9 **Conclusions, Ongoing Activities and Outlook.**

All identified feasibility issues of the CLIC two-beam scheme, from drive beam generation to its deceleration to produce RF power, and to the use of such power for high gradient acceleration of a second beam have been successfully addressed in CTF3 and were documented in the CLIC CDR [2].

CTF3 will continue its experimental program until 2016 in order to give further indications on cost and performance issues, to act as a test bed for the CLIC technology, and to conduct beam experiments aimed at mitigating technological risks. Additional improvements in beam quality and stability are expected in the near future, in particular from a number of additional feedbacks, meant to stabilize further beam energy and injector phases. The TBTS activities are now concentrating on the full characterization of the wake-field monitors, essential tools for emittance preservation in the CLIC linac. In particular, it is important to assess their resolution in presence of the full power RF pulse and the electromagnetic noise generated by the Drive Beam running in parallel. Also breakdown kicks studies [31] are continuing.

A new experiment studying the breakdown effect is now being implemented [32]. Indeed, the breakdowns limits of accelerating structures have been studied so far without a beam. The presence of the beam modifies the distribution of the electrical and magnetic field, which determine the breakdown rate. Therefore a dedicated experiment was designed: a special beam line allows extracting a beam with nominal CLIC beam current and duration from the CTF3 linac and send it into a structure, powered by an X-band klystron. It will then be possible to measure the breakdown rate in the presence of beam-loading and in its absence, and to compare them. The beamline installation has been completed, the beam transport through the structure has been established and the RF signal acquisition system has been set up. In 2014 the structure will be connected to the klystron and conditioned, and in the second half of 2014 the measurements should start.

The Drive Beam deceleration studies in TBL are ongoing at present, with the aim of reaching soon 40% with the present set-up and eventually 50% with the installation of the two new PETS tanks. The new tanks would also allow for the installation close to them of accelerating structure for RF conditioning and high-power testing.

A central role in the CTF3 experimental program in the next years will be played by the Drive Beam phase feed-forward experiment described before, and by the test of a full-fledged two-beam module in CLEX. The module program should cover the following points: a) test of the RF behavior of the module (system conditioning, breakdown rate and potential PETS/structures cross talk), b) two-beam acceleration tests (energy gain, set-up with beam and two-beam phasing), c) test of the active alignment system and of the stabilization system, in presence of radiation and electromagnetic noise, d) verification with beam of alignment and fiducialization using wake-filed monitors and high resolution BPMs and e) phase drift studies.

In parallel with CTF3 operation, we are also planning to build a new test facility, the Drive Beam front-end, in order to help the CLIC study advance towards a project implementation plan. Such a facility will consist of a 10-20 MeV Drive Beam injector and will be a first step towards the CLIC0 facility. It will drive the technology development of modulators, klystrons, and accelerating structures for the CLIC Drive Beam linac at the correct CLIC parameters and will address the issues related to high average power and long-pulse beam handling. An active R&D program on the essential components of the front-end has started, and from 2016 we should have all components to start assembling the test accelerator.

2.15.10 **References**

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2.16 The CTF3 Two-beam Test Stand

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Abstract

The Two-beam Test Stand (TBTS) is the main location to demonstrate the feasibility of the CLIC two-beam acceleration scheme. Drive and main beam, here also called probe beam, are available to test and verify both RF production and high gradient acceleration. Individual components and complete two-beam CLIC modules can be tested. The TBTS is particularly well suited to investigate the effects on the beam of RF breakdown in the high gradient accelerating structures.

2.16.1 **Introduction**

In the CLIC two-beam acceleration scheme the required radio-frequency (RF) power needed to accelerate the main beam to high energies is generated by decelerating the so-called drive beam, a second, lower energy but higher intensity and higher power density electron beam that runs parallel to the main beam, in the context of CTF3 also called the probe beam. This process is schematically shown in Figure 1. The RF field is produced in so-called power extraction and transfer structures (PETS) which, as the name implies, also transfer it to the accelerating structures of the main beam. These accelerating structures are normal-conducting, designed for 12 GHz (X-band) operation, and are expected to achieve high-accelerating gradients, which is the requirement for keeping the length of the accelerator within reasonable limits.