

Lessons from CTF3

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The CLIC Test Facility (CTF3) was built to demonstrate the feasibility of the CLIC two beam acceleration scheme. The main issues to be verified were the high current drive beam generation using a fully loaded highly efficient linac and a beam combination scheme, based on transverse RF deflectors, to increase beam current and bunch repetition frequency. The drive beam has been used for GW level RF power production and two beam acceleration experiments. CTF3 was also a test ground for development of many accelerator technologies. Its operation was concluded in 2016 and in this contribution the results relevant for the CLIC design as well as for the whole accelerator physics community will be presented.

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1. Introduction

The CLIC International Collaboration built at CERN the CLIC Test Facility CTF3 (see Fig.1) in order to prove feasibility of the two-beam acceleration technology [1]. It consisted of a 150 MeV electron linac, 42 m long Delay Loop (DL) and a 84 m Combiner Ring (CR). With help of RF deflector the delay loop was interleaving the 1120 ns beam pulse to produce four 140 ns pulses of double current, which were combined into single 140 ns pulse by the combiner ring. The recombined beam was delivered to the CLIC experimental area (CLEX) where it was decelerated to produce 12 GHz RF power accelerating a probe beam. The probe beam was generated with a 200 MeV injector (Concept d'Accélérateur Linéaire pour Faisceaux d'Electrons Sondes, CALIFES) located in the same area.

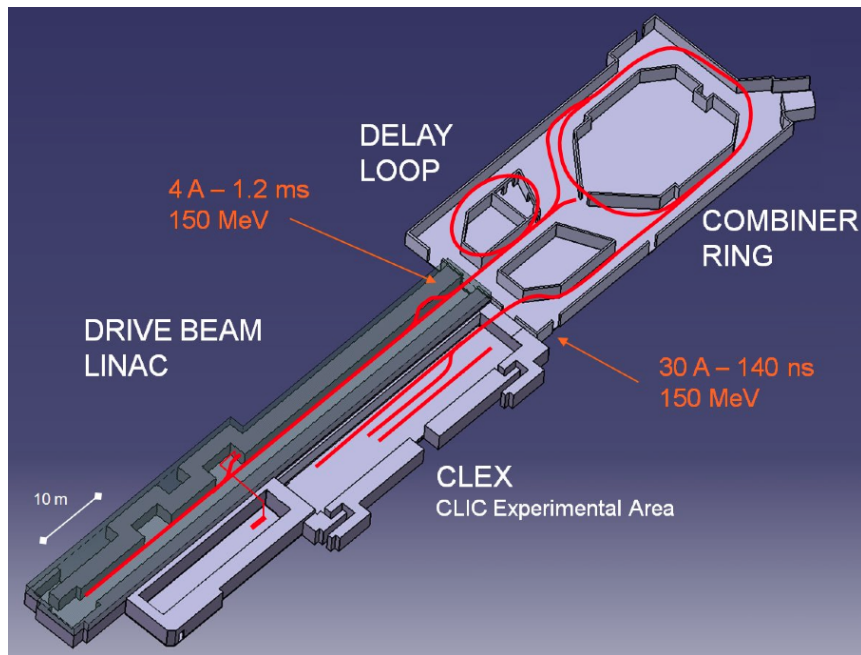


Figure 1: Schematic CTF3 layout.

The CTF3 studies can be divided into two categories [2]:

1. **Efficient production of high-current electron drive beam with time structure suitable for 12 GHz RF power production.** CTF3 tested a novel technique based on fully-loaded acceleration in normal conducting travelling wave structures followed by beam current and bunch frequency multiplication in a series of delay lines and rings. CTF3 was producing in this way a 28 A electron beam with 12 GHz bunch repetition frequency.
2. **RF power production and two-beam acceleration.** RF power is produced by decelerating the drive beam in dedicated cavities called PETS (Power Extraction and Transfer Structures). Using waveguides it is delivered to accelerating structures operating at gradient of 100 MV/m. Deceleration studies were performed using a string of PETS in the Test Beam Line (TBL) in CTF3 experimental area (CLEX). Alternatively, the drive beam was delivered

to another beam line called Two Beam Test Stand (TBTS) renamed later Test Beam Module (TBM), where one or more PETS powered one or more structures, further accelerating a 200 MeV electron beam provided by CALIFES.

CTF3 was constructed and commissioned in stages. The linac started operation in 2003, the delay loop in 2006 and the combiner ring in the following year. In 2009 CLEX beam lines, including the CALIFES injector, and the transfer line from the combiner ring were commissioned. Recombination with the DL and CR together was achieved in autumn of 2009 yielding up to 28 A of beam current. In 2010 the PETS started producing the nominal power level and the first two-beam test was performed, reaching a measured gradient of 100 MV/m. Ultimately, accelerating gradient of 145 MV/m was reached in 2011. The same year the PETS On-off mechanism was successfully tested. A 2 m long fully representative unit of the CLIC main linac called Two-Beam Module, TBM, replaced the TBTS at the end of 2014. In 2015 TBL decelerated the drive beam by 50% of its initial energy. The Drive beam stability and the overall performances of the facility were continually improved after the initial commissioning, until the final run in 2016. During the last years of operation CTF3 hosted several additional experiments and beam tests that were not in the initial planning. Most of them - but not all - were CLIC related.

2. Drive Beam generation

2.1 Injector - Beam Current and Time Structure

The drive beam injector consisted of a thermionic gun delivering up to 10 A beam, three 1.5 GHz sub-harmonic bunchers (SHBs) and a 3 GHz system composed of a pre-buncher and a buncher [3]. SHBs were 6-cell travelling wave (TW) structures with a nominal power of 40 kW. They generated the initial energy-time modulation and phase coding by means of fast 180° RF phase switches. Following, a 3 GHz single-cell pre-buncher and a TW buncher were installed to create the final bucket structure and accelerate the beam up to ~6 MeV/c. The nominal power of 2 cm long pre-buncher was 100 kW, while for the half-meter long buncher it was maximum 40 MW.

The optimization of the transverse emittance, the bunch length and the satellite population was carried out by means of exhaustive PARMELA simulations. The magnetic field distribution was optimized to keep the emittance at the exit of the injector below 50 μm , which was confirmed by measurements [4]. A streak camera at the end of the linac measured a bunch length of 1 mm [5]. Some electrons were forming unwanted satellite bunches in between the main 1.5 GHz ones. The measured fraction of the satellites was about 8%, compared to the design value of 7%. Figure 2 presents a projection of a streak camera image that shows the bunch population in function of time during the 180° phase switch. The switching time is less than 6 ns (eight 1.5 GHz periods), which is well below the 10 ns target [6].

2.2 Linac - Full Beam-Loading Acceleration

The overall efficiency is one of the key parameter of linear colliders. Full beam-loading operation is one of the key points in the CLIC design because it yields a very efficient RF energy transfer to the drive beam. It is achieved by the acceleration of a high beam current (about 4 A) by short travelling-wave RF structures with relatively low gradient. When the beam is present in the cavity

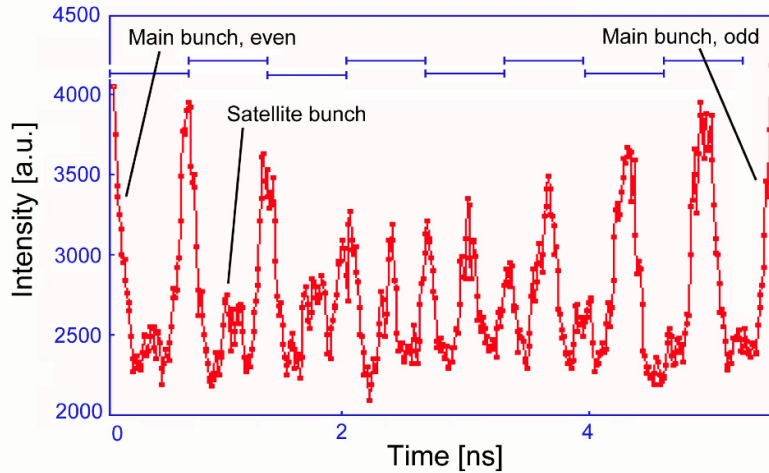


Figure 2: Fast bunch phase switch, measured by a streak camera. At the top the 1.5 GHz periods are shown.

no RF power is transmitted to the load and the resistive losses in the walls are minimal. In the case of the CLIC structures an overall efficiency of about 98% is achieved. However, at the beginning of the pulse there is an energy transient effect, such that the first bunches may have twice the energy of the steady-state part. This mode of operation also strongly couples beam current fluctuations to the beam energy. The CTF3 3 GHz TW accelerating structures worked in the $2\pi/3$ mode. They were 1.22 m long and operated at a loaded gradient (nominal current) of 6.5 MV/m [7]. The large average current leads to pronounced effects of transverse higher order modes (HOMs). They must be damped in order to avoid beam instabilities and emittance growth. Dedicated cavities called Slotted Iris - Constant Aperture (SICA) structures were designed for this purpose. They feature irises that are radially slotted to guide dipole and quadrupole modes into SiC loads. The damped modes are selected through their field distribution, strongly damping the HOMs (Q factor typically below 20), while monopole modes are not influenced. Nose cones of variable geometry yield additional HOM detuning along the structure. This improves their suppression and modulates the group velocity to control the gradient profile. Thanks to the aperture that is kept constant along the structure short range wake-fields are reduced. The structures were powered by 35 MW to 45 MW klystrons providing $5.5 \mu\text{s}$ RF pulses. Each unit was powering 2 accelerating structures and the pulses were compressed to $1.3 \mu\text{s}$ pulses and over 60 MW. The pulse compression system uses a programmed phase ramp to provide a constant RF power.

The design beam current and pulse length were rapidly established during beam commissioning in June 2003. The beam was remarkably stable and no sign of beam break-up was observed at high current. It proved for the first time the fully loaded beam operation [8]. As predicted by simulations the normalized emittance at the end of the CTF3 linac was about $\epsilon_{x,y} \approx 10 \mu\text{m}$ confirming negligible effects of the wake-fields. The energy spread of the initial beam transient (~ 100 ns) could also be reduced to a few percent by partial RF filling of the structures at beam injection.

The beam-to-RF phase was adjusted by maximizing the beam loading. It was achieved by minimizing the RF amplitude observed at the structure output couplers. The acceleration efficiency

was assessed in a dedicated experiment [9]. The beam current and RF power measurements were carefully calibrated to compute the beam energy gain. It was then compared with the measurements using a spectrometer. Figure 3 shows that the RF power is almost fully absorbed by the beam. The energy gain measurements were in excellent agreement with the computed values. The obtained RF-to-beam transfer efficiency was 95.3% including the resistive losses. CTF3 successfully proved the stable and highly efficient acceleration of the drive beam as it was routinely operated over several years with fully loaded structures.

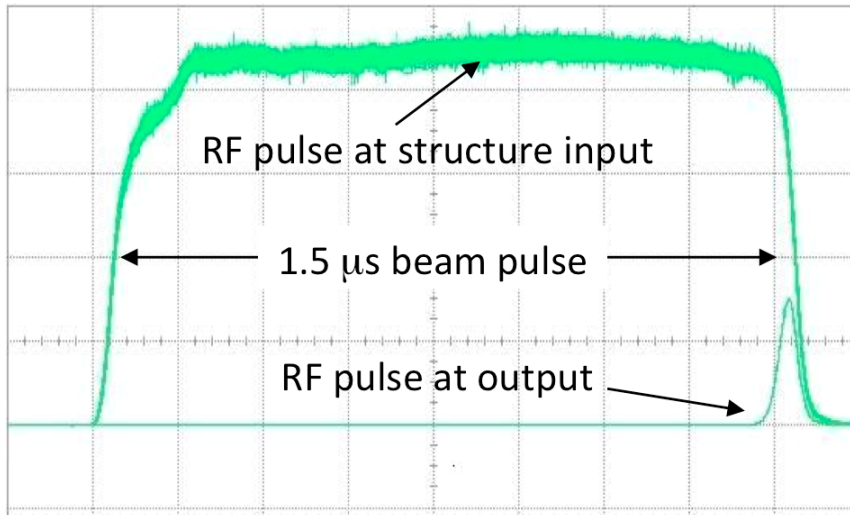


Figure 3: RF power measured at the accelerating structure input and output with beam.

2.3 Delay Loop and CR - Bunch Combination

CTF3 performed the beam recombination in two stages. First, the Delay Loop (DL) converted a 1120 ns long bunch train with a current of ~ 4 A into 4 pulses of 140 ns and ~ 7.5 A (not counting the charge contained in satellite bunches). Later, the Combiner Ring (CR) interleaved these 4 pulses to produce a single 140 ns long pulse with a maximum current of about 30 A.

The first RF deflector, operating at 1.5 GHz, sent odd phase-coded sub-pulses to the DL and the even ones straight towards the CR. The sub-pulse length must correspond to the length of the DL. The bunches leaving the DL were coming to the deflector at half of the wavelength distance from the bunches of the following even sub-pulse. Their orbits were merged obtaining 140 ns long pulses with twice the initial current and twice the bunch repetition frequency. In the CR a pair of RF deflectors created a time-dependent closed bump at injection to interleave the sub-trains.

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. Efficient RF power production in the PETS requires a short bunch length. The bunches get elongated if R_{56} transfer matrix element is non zero. Therefore the bunch length preservation requires the use of isochronous optics ($|R_{56}| \leq 1$ cm) in the DL, the CR and the transfer line connecting them. The CR layout was based on the use of three-dipole isochronous cells with three independent quadrupole families, whose tunability range

fits well the requirements. The DL loop was made out of 2 six-dipole cells with eight independent quadrupoles. Sextupoles could be used to control the second-order matrix term R_{566} . After the linac the bunch length was less than 1 mm r.m.s. In CLEX a bunch length of ~ 2 mm r.m.s. was estimated from RF power production and confirmed by direct streak camera measurements. Such length was consistent with required isochronicity conditions and entirely sufficient for CTF3 operation, avoiding also coherent synchrotron radiation, which would affect shorter bunches.

In the RF deflectors of the CR wake-fields in the vertical plane were minimized by detuning and damping [10]. The operational mode, i.e. the lowest order horizontal dipole one, naturally could not be damped or detuned. The turn-by-turn direct wake-field build-up was avoided because fill-time of the travelling wave deflectors was short enough (~ 100 ns). The residual amplification of the orbit errors by wake-fields was minimized by setting the fractional tune of the CR to about 0.6 in both planes. For the same reason the beam optics was chosen to minimize the beam size in the deflectors.

The recombination requires that the ring length is $(N \pm 1/N_f)\lambda_{RF}$, 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 was measured precisely by Fourier transform of the beam phase monitor signal. The ring length was adjusted using a dedicated wiggler which could elongate the trajectory up to 7 cm.

Demonstrating the very high beam quality required for CLIC was an integral part of the CTF3 experimental program. In the last years of the machine operation special effort was put into the drive beam performance optimization. The control of emittance growth, availability and stability was particularly improved. Emittance preservation required a good control of the optics, a very good closure of the DL and CR orbits, proper matching from the linac and control of spurious dispersion. The isochronous optics in DL, CR and the transfer lines were relatively strongly focusing. This, combined with a r.m.s. energy spread of about 0.6%, lead to a large nonlinear dispersion, which was the main source of emittance growth. The most important growth was in the DL, whose optics was particularly constrained by building space limitations. A new DL optics, which was optimized to reduce the growth, was commissioned. Also tools for more precise measurements of Twiss parameters and dispersion in the different beam-lines were developed. The spurious dispersion was minimized with help of Dispersion Free Steering and Dispersion Target Steering procedures. While the beam combined only by the CR met the CLIC emittance requirements of $< 150 \mu\text{m}$ in both planes, the minimum horizontal emittance for the full factor 8 recombined drive beam was about $250 \mu\text{m}$ ($100 \mu\text{m}$ in vertical). 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 [11].

2.4 Beam Stability Issues

The CLIC two-beam acceleration scheme imposes tight tolerances on the stability of the drive beam current, energy and phase. A maximum variation of $0.75 \cdot 10^{-3}$ for the drive beam current and about 2° at 12 GHz for the drive beam bunch phase after combination are allowed. This is because they contribute quadratically to the luminosity loss [12] and these values correspond to a maximum of 1% to the luminosity loss per parameter. This already assumes a feed-forward system - discussed later - capable of reducing the phase jitter to 2° at 12 GHz.

During the initial years of operation CTF3 suffered from relatively large beam jitters and drifts. Dedicated studies identified their sources, which were either removed or compensated by proper feedback systems [15]. In the final CTF3 runs, experiments aiming at demonstrating performances close to the CLIC requirements were added to the CTF3 program. For the CTF3 klystrons the short-term RF stability over 500 consecutive RF pulses (≈ 10 min.) was measured within the CLIC tolerances, for instance. The CLIC requires r.m.s. phase jitter below 0.05° and r.m.s. amplitude jitter below 0.2% [12]. In CTF3 the mean pulse-to-pulse phase jitter measured with respect to an external reference was 0.035° (3 GHz). The relative pulse-to-pulse amplitude jitter has been 0.21%.

The pulse-to-pulse current variations in the CTF3 linac were measured using inductive beam position monitors. Initially it was $\Delta I/I = 2 \cdot 10^{-3}$. It was improved by better stabilizing the gun heater power supply and by a feedback, to obtain $\Delta I/I = 0.54 \cdot 10^{-3}$ [13], better than the required current stability for CLIC of $\Delta I/I = 0.75 \cdot 10^{-3}$. After further improvements, in 2016 the r.m.s. current jitter at the end of the drive linac was at the level of the electronic noise floor of the BPMs $2 \cdot 10^{-4}$, meaning that the observed jitter was the same with and without the beam. Such a performance was achieved for periods of tens of hours [14]. The stability of the combined beam current in CLEX, at the end of the experimental lines, was also largely improved and $3 \cdot 10^{-3}$ r.m.s. was measured for periods longer than 5 hours [15].

2.5 The Drive Beam Phase Feed-Forward

To assure the required drive beam timing stability below 50 fs r.m.s., or equivalently a phase stability (jitter) below 0.2 degrees of 12 GHz, CLIC will be equipped with a 'phase feed-forward' system. This system poses a significant challenge in terms of bandwidth, resolution and latency. Therefore, a prototype was designed, installed and tested in CTF3. After one year of experience a phase jitter of 0.28 ± 0.02 has been demonstrated, very close to the CLIC specifications [16]. With additional fine-tuning in 2016, the final year of operation at CTF3, it was possible to further reduce the achieved phase jitter to below the CLIC requirement of 0.2° and to keep it at such level on time scales of about 10 minutes [17].

3. Two-beam acceleration

3.1 Power generation, PETS On-Off

In CTF3, PETS prototypes were tested with beam in TBL and in TBTS (and later TBM). The structures in the two lines had different lengths and a little bit different construction. The nominal CLIC parameters for power and pulse length were reached and exceeded for both of them. Maximum RF power reached at the nominal pulse length of 240 ns was about 300 MW, well above the nominal value for CLIC, 135 MW [18].

Another CLIC feasibility verification was the PETS On-Off mechanism. It switches off individual PETS whenever localized breakdowns threaten the normal machine operation. The system also needs to provide a gradual ramp-up of the generated power in order to reprocess afterwards either the main accelerating structure and/or the PETS itself. The prototype is a compact external extension to PETS consisting of two high power variable RF reflectors. It was extensively tested

with beam in the TBTS and the switching off of the PETS power production has been demonstrated with different beam and RF settings, up to 16 A and 200 MW [19]. The measurement of all the RF signals were in remarkable agreement with the model predictions in all conditions. When it is set to off the accelerating structure receives less than 1% of the power what makes any breakdowns impossible. Also the power inside PETS is attenuated to $\sim 25\%$ of the nominal value what reduces the likelihood of a breakdown by a factor 102-103.

3.2 Acceleration, Two-Beam Module

The key purpose of CTF3 was to demonstrate the CLIC two-beam acceleration scheme. An efficient power transfer to high-gradient structures and acceleration of a "probe" electron beam is the heart of this technology. In CLEX, along the drive beam, a probe beam accelerator was installed delivering single bunches or bunch trains at 1.5 GHz bunch repetition rate and energies up to 200 MeV. It consisted of a 24 m long electron injector linac CALIFES with ~ 5 MeV/c RF photo-cathode source [20]. The beam was accelerated in three 3 GHz accelerating structures recuperated from the LEP Injector Linac (LIL). A single 3 GHz klystron delivering 45 MW RF pulses during $5.5 \mu\text{s}$ via an RF pulse compressor powered the accelerating structures and the photo-injector. CALIFES was usually operated with bunch charges of around 0.1 nC and a normalized r.m.s. emittance of $10 \mu\text{m}$. The probe beam energy was measured in a spectrometer in function of the probe beam 3 GHz RF phase, which was phase-locked to the laser pulse timing. To adjust the relative timing between probe and drive beam for maximum acceleration phase scans were performed. The nominal CLIC accelerating gradient of 100 MV/m corresponded to an energy gain of $\Delta E = 21.4$ MeV. Energy gains of up to $\Delta E = 32$ MeV were reached with breakdown rates of a few 10^{-3} , while higher gradients, up to 165 MV/m were achieved with higher rates [18]. Figure 4 shows an example measurement of probe beam acceleration using a spectrometer screen. The value $\Delta E = 31$ MeV corresponds to an accelerating gradient of 145 MV/m. The effect of breakdown kicks on the probe beam was also extensively studied [21].

At the end of 2014 in place of the TBTS the Two-Beam Module, TBM, a 2 m long fully representative unit of the CLIC main linac, including an active alignment system, was installed. The module was conditioned to the nominal CLIC gradient/pulse length and extensive tests of the module functionality were carried out. This included precision and reliability studies of the active alignment system and measurements of transverse wake-field effects. A full analysis of the experimental results is still undergoing. So far all the results are consistent with specifications and simulations.

3.3 The Test Beam Line, TBL

The Test Beam Line (TBL) served to study the stability of the drive beam during deceleration. It consisted of a FODO lattice with 14 consecutive PETS installed in the drift spaces. Precise beam alignment was possible thanks to high precision BPM's and quadrupole active movers. 25 A drive beam was decelerated from its initial energy of 135 MeV down to a minimum of 67 MeV. This corresponds to the 50% deceleration milestone, which was one of the initial goals of CTF3. On average each PETS produced 90 MW of power and the total peak RF power produced in less than 20 m deceleration line reached 1.3 GW.

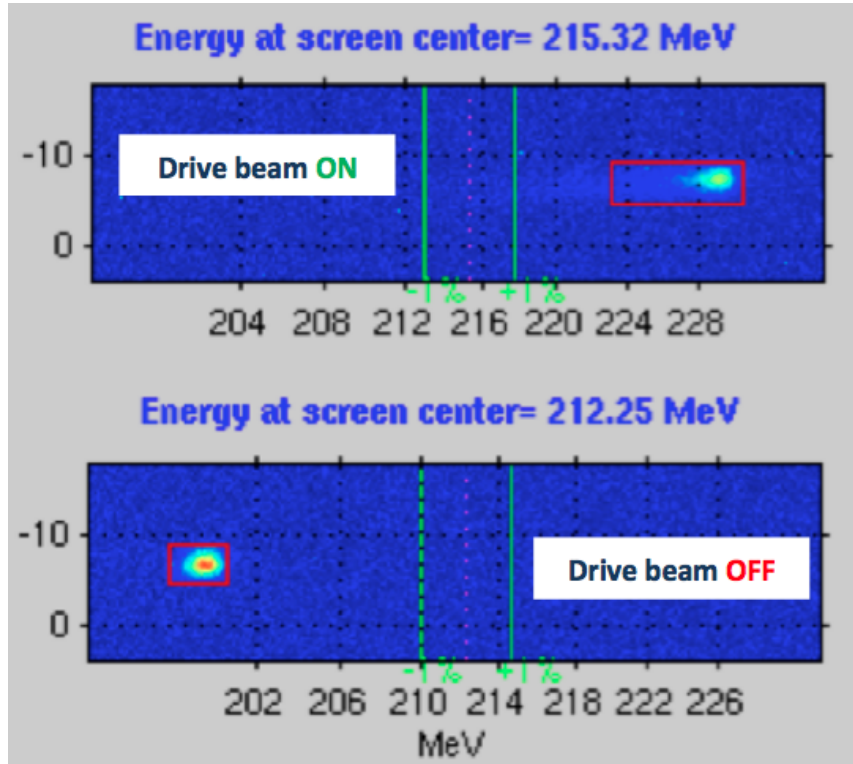


Figure 4: Probe Beam observed in the TBTS spectrometer screen with the 12 GHz RF power from the drive beam on (top) and off (bottom). The energy gain is about 31 MeV, corresponding to a gradient of 145 MV/m.

The dynamics of drive beam undergoing deceleration in the transverse planes was studied in detail. At the beginning and end of the line a time-resolved spectrometer provided measurement of the beam energy loss and its energy spread. Transverse Twiss parameters were measured with quadrupolar scans. Both longitudinal and transverse parameters agree very well with the simulations [22].

4. Other experimental tests in CTF3

4.1 The Beam-Loading Experiment

The RF breakdown rate (BDR) is critical for the luminosity performance of the CLIC linear collider. High power RF testing of a number of 12 GHz CLIC prototype structures demonstrated rates of 10^{-7} at the design gradient of 100 MV/m. Nevertheless, beam-loading significantly changes the field profile in the structures, and potential effects need to be understood. A dedicated experiment using the CTF3 drive beam was setup and data for different beam-loading configurations were collected in between 2014 and 2016 [23]. In some cases a BDR reduction up to an order of magnitude was measured. The results support the hypothesis of the BDR being dominated by the peak gradient and its reduction being associated to the modification of the gradient profile induced by the beam. Also, the measured distribution of the breakdowns inside the structure follows roughly the gradient profile, which additionally confirms this hypothesis. Therefore, a further

optimization of the CLIC structure is possible by profiling the gradient such that distribution of breakdowns along the structure during the operation with beam is constant.

4.2 Beam Diagnostics Tests

An extensive test program for the main CLIC beam instrumentation components was established in CTF3 in order to verify the performance of the prototypes in a realistic environment. These devices need to provide state-of-the-art performance, or above. In many cases their number is such that cost-effective solutions are mandatory. Additionally, they need to detect tiny signals in the direct vicinity of hundreds MW RF power and operate in highly radioactive environment.

Wake Field Monitors (WFM) detects particular HOMs excited by the beam in the CLIC accelerating structures. HOM signals are picked up by 4 waveguide antennas attached to one of the structure cells. Two different frequency bands are analysed to measure the beam offset with respect to the structure with a required resolution of $3.5\ \mu\text{m}$. Two slightly different versions were tested in CTF3, and both demonstrated performances better or close to the required ones [24, 25].

Prototypes of drive beam BPM were also tested yielding $2\ \mu\text{m}$ resolution. However, the performance of the initial version was largely degraded in presence of 12 GHz RF power from the drive beam. An improved design was successfully tested in 2015 [26]. Also, the cavity BPMs of the main linac initially showed worse than required time resolution when the position resolution was below specifications. Stainless steel was replaced with copper as the building material of the cavity and the Q value was optimized. The improved version showed a resolution below $1\ \mu\text{m}$, encouraging but still quite far from requirements [27].

At CLEX, along TBL and TBM lines, a cost effective optical fibre Beam Loss Monitor (BLM) system was installed. The system was successfully commissioned and various verification tests were performed. The provoked losses along the accelerator lines were localised by the BLMs with the expected accuracy below 2 m, within CLIC requirements [28, 29]. Also, the amplitude of the signals agreed very well with conventional ionization chambers.

As a part of development of non-destructive profile monitors based on diffraction radiation, optical transition radiation interference was studied. In particular, for the first time shadowing effects were measured in imaging conditions, confirming the theoretical predictions [30].

5. Conclusions

The CLIC Test Facility CTF3 conducted a rich experimental program, addressing various aspects of the accelerator technology needed for the CLIC concept and solving the vast majority of issues related to drive beam generation, power production and two-beam acceleration. In particular, high-gradient acceleration beyond 100 MV/m using X-band room temperature is now well established, as well as the production and use of a high-current drive beam as an efficient and reliable source of X-band RF power in the range of hundreds of MWs. CTF3 successfully completed its experimental program in December 2016 as planned, and stopped operation. The approval of the new CLEAR [31] program, using the CALIFES linac, will give the opportunity to maintain some local testing capability at CERN for CLIC instrumentation and high-gradient structure testing with beam, alongside with other non-CLIC-related accelerator R&D.

6. ACKNOWLEDGEMENTS

This paper documents, surely in a largely incomplete manner, over more than a decade long collective effort of a large collaboration. The authors wish to acknowledge all individuals who participated over this period to the conception, design, construction, commissioning and operation of the CLIC Test Facility, CTF3.

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