FINAL RESULTS FROM THE CLIC TEST FACILITY (CTF3)

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Abstract

The unique CLIC Test Facility (CTF3) has been built more than a decade ago to demonstrate the feasibility of the CLIC two beam acceleration scheme. The emphasis was on the high current drive beam generation using a fully loaded highly efficient linac and a complex combination scheme to increase beam current and bunch repetition frequency. This drive beam has been used for deceleration experiments and two beam acceleration. A wealth of relevant results for accelerator physics even beyond CLIC has been obtained and will be presented. The RF to beam efficiency of the linac exceeds 95%, after combination the 28 A drive beam with 12 GHz bunch repetition rate has been used to extract more than 50% of its energy producing 1.3 GW of 12 GHz power as well as performing two beam acceleration at 12 GHz with gradients up to 150 MV/m.

INTRODUCTION

The aim of the CLIC Test Facility CTF3 (see Fig. 1), built at CERN by the CLIC International Collaboration, was 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 (DL) and a 84 m Combiner Ring (CR). The beam current from the linac is first doubled in the loop and then multiplied by a further factor of four in the ring, by interleaving bunches in transverse RF deflectors. The beam can then be sent in the CLIC experimental area (CLEX) where it can be decelerated to extract from it RF power at 12 GHz and use it to accelerate a probe beam, delivered by a 200 MeV injector (Concept d'Accélérateur Linéaire pour Faisceaux d'Electrons Sondes, CALIFES) located in the same area. The main issues explored in CTF3 can be divided in two main aspects [2]:

1. *Drive beam generation*: efficient generation of a high-current electron beam with the proper time structure to generate 12 GHz RF power. In order to achieve this CLIC relies on a novel technique: 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 by injection with RF deflectors. CTF3 used such method to produce a 28 A electron beam with 12 GHz bunch repetition frequency. The drive beam was then sent to the experimental area, CLEX.

2. *RF power production and two-beam acceleration*: in CLIC the needed 12 GHz RF power is obtained by decelerating the high current drive beam in special resonant structures called PETS (Power Extraction and Transfer Structures). The power is then transferred to high gradient accelerating structures, operated at about 100 MV/m. In the CTF3 experimental area (CLEX), the drive beam is decelerated in a string of PETS in the Test Beam Line, TBL). The drive beam can alternatively be sent to another beam line (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 installed and commissioned in stages starting from 2003. The beam commissioning of the DL was basically completed in 2006. The CR 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 CLEX beam lines, including the CALIFES injector, were commissioned. 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 and the PETS On-off mechanism was successfully tested. At the end of 2014 the TBTS was replaced by the Two-Beam Module, TBM, a 2 m long fully representative unit of the CLIC main linac. In 2015 the drive beam was decelerated by 50% of its initial energy in TBL. Drive beam stability and the overall performances of the facility were continually improved after the initial commissioning, until the final run in 2016. In the last years of operation, CTF3 was hosting several experiments and beam tests not initially planned, most of them – but not all – CLIC related.

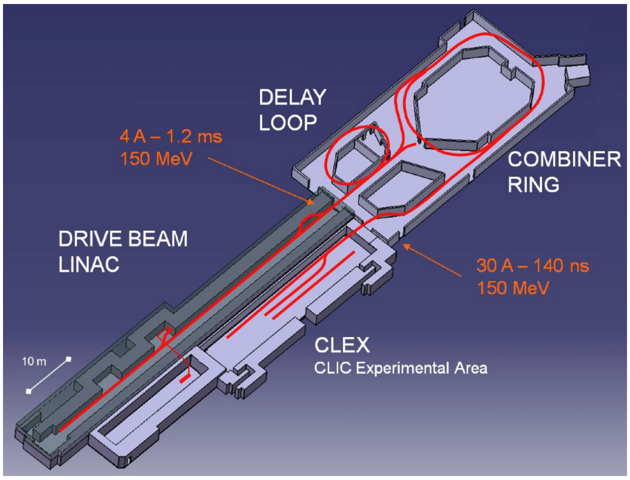

Figure 1: Schematic CTF3 layout.

DRIVE BEAM GENERATION

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 and a buncher [3]. The sub-harmonic bunchers (SHBs) give the first energy-time modulation to the beam and perform the phase coding by means of fast 180° RF phase switches. The 6-cell traveling wave (TW) SHBs have a nominal power of 40 kW. Downstream, a 3 GHz single-cell pre-buncher and a TW buncher are installed to create the final bucket structure and accelerate the beam up to ~ 6 MeV/c. The 2 cm long pre-buncher nominal power is 100 kW, while the half-meter long buncher is fed a maximum power of 40 MW. Exhaustive simulations were performed using PARMELA to guide the optimization of the transverse emittance, the bunch length and the satellite population. The magnetic field distribution was optimized to keep the emittance at the exit of the injector below 50 µm, as confirmed by measurements [4]. A bunch length of 1 mm was measured with a streak camera at the end of the linac [5]. Some particles form unwanted satellites in between the 1.5 GHz main bunches; the measured fraction of the satellites is about 8%, compared to the design figure of 7%. Figure 2, a projection of a streak camera image, shows the bunch population vs. time during the 180° phase switch. As can be seen from the figure, he measured switch time is less than 6 ns (eight 1.5 GHz periods), well below the 10 ns target [6].

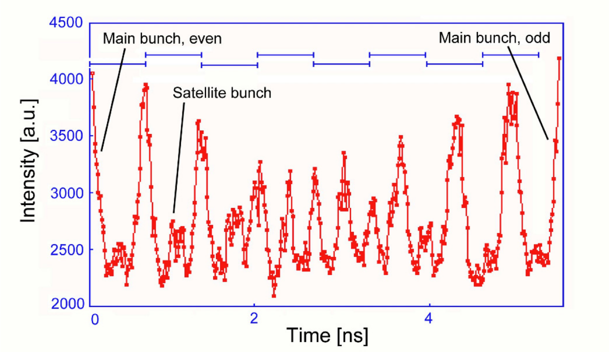

Figure 2: Fast bunch phase switch, measured by a streak camera. At the top the 1.5 GHz periods are shown.

Linac – Full Beam-Loading Acceleration

The overall efficiency is paramount for linear colliders, and a very efficient RF energy transfer to the drive beam, obtained by means of full beam-loading operation, is one of the key ingredients in CLIC. The high pulse current in both CLIC and CTF3 (about 4 A in both cases), accelerated in short travelling-wave RF structures with relatively low gradient, results in an extremely high transfer efficiency. No RF power is transmitted to the load when the beam is present and the resistive losses in the cavity walls are minimal, such that an overall efficiency of about 98% is calculated in the CLIC case. However, an energy transient is present at the beginning of the pulse, and 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 3 GHz TW accelerating structures designed and built for CTF3 [7] work in the 2π/3 mode, have a 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 beam instability and control emittance growth. A Slotted Iris - Constant Aperture structure (SICA), in which irises are radially slotted to guide dipole and quadrupole modes into SiC loads, was designed for the purpose. The selection of the damped modes is obtained through their field distribution, strongly damping the HOMs (Q typically below 20), while monopole modes are not influenced. In addition HOM detuning along the structure (by nose cones of variable geometry) is used; this improves their suppression and modulates the group velocity to control the gradient profile. The aperture is therefore kept constant along the structure, reducing short range wake-fields. The RF is supplied by klystrons with power ranging from 35 MW to 45 MW, compressed by a factor 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 provide a constant RF power.

Beam commissioning started in June 2003. The design beam current and pulse length were rapidly reached. The beam was remarkably stable and no sign of beam break-up was observed at high current, thus proving for the first time operation under full beam loading [8]. The measured normalized emittance at the end of the CTF3 linac was routinely about $\varepsilon_{x,y} \approx 50$ µm, confirming negligible wake-field effects as predicted by simulations. 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 observation of the RF signals at the structure output couplers was particularly useful, allowing to easily adjust the beam-to-RF phase by maximizing the beam loading. The acceleration efficiency was demonstrated in a dedicated experiment [9]. After careful calibration of beam current and RF power measurements, the beam energy gain was calculated and compared to spectrometer measurements. Figure 3 shows an example of the RF pulse 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 resistive losses, the obtained RF-to-beam transfer efficiency was 95.3%. CTF3 was routinely operated over several years with fully loaded structures, successfully proving the stable, highly efficient acceleration of the drive beam.

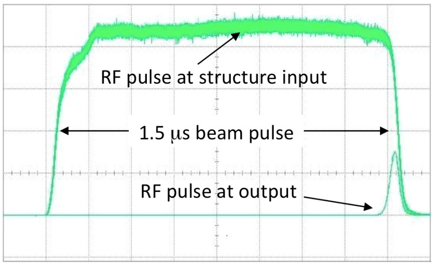

Figure 3: RF power measured at the accelerating structure input and output with beam.

Delay Loop and CR – Bunch Combination

Beam recombination in CTF3 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 (not counting the charge contained in satellite bunches). Later, the pulses are interleaved in the Combiner Ring (CR) 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, 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, used to interleave 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.

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 isochronicity requirement is $|R_{56}| \leq \pm 1$ cm. The DL and CR are based on the use of three-dipole isochronous cells with three independent quadrupole families, whose tunability range fits well the requirements. Sextupoles can be used to control the second-order matrix term R_{566}. Bunch length control to down to less than 1 mm r.m.s. was shown after the linac. 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 is consistent with required isochronicity conditions and entirely sufficient for CTF3 operation, avoiding also coherent synchrotron radiation, which would affect shorter bunches.

Damping and detuning is used in the RF deflectors of the ring in order to minimize wake-fields in the vertical plane [10]. The lowest order horizontal dipole mode is the operational one and 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 by wake-fields, the fractional tune of the CR is set to be about 0.6 in both planes. Also, the β-function in the deflectors is kept small to minimize amplification. 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 beam phase monitor signal, and when needed the ring length can be adjusted using a dedicated wiggler.

In the last experimental runs, a large fraction of beam time has been dedicated to improvements of the drive beam performance, especially control of emittance growth, availability and stability. Apart from enabling a better exploitation of the beam by the users, this was an integral part of the CTF3 experimental program, aimed at demonstrating a beam quality close to the one required for CLIC. Emittance preservation requires 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 CTF3 drive beam has a rms energy spread of about 0.6%, and the isochronous optics in DL, CR and transfer lines are strongly focusing. This leads to a large nonlinear dispersion, which is the main source of emittance growth. The main contribution was coming from the DL, whose optics is constrained by building space limitations. A new more forgiving DL optics was developed and deployed, and tools to precisely measure Twiss parameters and dispersion in the different beam-lines were put in place. Dispersion Free Steering and Dispersion Target Steering procedures were implemented and applied. While the beam combined in the CR met the CLIC emittance requirements (<150 µm) in both planes, the minimum horizontal emittance for the factor 8 recombined drive beam was about 250 µm (100 µm 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].

Beam Stability Issues

In CLIC, the two-beam acceleration scheme puts tight constraints on the drive beam current, energy and phase stability. In particular, both bunch charge and phase jitter contribute quadratically to the luminosity loss [12]; a maximum variation of 0.75×10^{-3} for the drive beam current and about 2° at 12 GHz for the drive beam bunch phase after combination are allowed, for a maximum of 1% to the luminosity loss per parameter and assuming a feed-forward system – discussed later – capable of reducing the phase jitter to 0.2° at 12 GHz. During the first years of operation CTF3 suffered from relatively large beam jitters and drifts; dedicated studies discovered most of the sources, which were either removed or corrected by proper feedback systems. Dedicated tests aimed at demonstrating performances close to the CLIC requirements (including a feed-forward experiment, see later for a lull description) were added to the CTF3 experimental program in its final years. The CLIC tolerances on the drive beam linac RF, for instance, were verified for the CTF3 klystrons, measuring the short-term RF stability over 500 consecutive RF pulses (≈ 10 min). The mean pulse-to-pulse phase jitter measured with respect to an external reference was 0.035° (3 GHz) and the relative pulse-to-pulse amplitude jitter has been 0.21%, to be compared with the CLIC requirements of 0.05° r.m.s. phase jitter and 0.2% r.m.s. amplitude jitter [12].

The pulse-to-pulse current variations in the CTF3 linac were measured using inductive beam position monitors. The initial stability ($\Delta I/I = 2 \times 10^{-3}$) was improved by better stabilizing the gun heater power supply and by a feedback, to obtain $\Delta I/I = 0.54 \times 10^{-3}$ [13], better than the required current stability for CLIC of $\Delta I/I = 0.75 \times 10^{-3}$. After further improvements, in 2016 the r.m.s. current jitter at the end of the drive linac was routinely better then

2×10^{-4}, corresponding to the electronic noise floor of the BPMs (the observed jitter is the same with and without beam). Such a performance is currently achieved for long periods, even 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 3×10^{-3} r.m.s. was measured for periods longer then 5 hours [15].

The Drive Beam Phase Feed-Forward

In CLIC a drive beam 'phase feed-forward' system is required to achieve a timing stability of 50 fs rms, or equivalently a phase stability (jitter) of 0.2 degrees of 12 GHz. This system poses a significant challenge in terms of bandwidth, resolution and latency and therefore a prototype of the system 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].

TWO-BEAM ACCELERATION

Power Generation, PETS On-Off

In CTF3, PETS prototypes were tested with beam in TBL and in TBTS (and later TBM). The prototypes tested in both lines were very similar, differing mainly for the length and some construction detail. In both cases the nominal CLIC parameters for power and pulse length were reached and exceeded. In particular during the 2010 run, RF power levels of about 300 MW were reached at the nominal pulse length of 240 ns, well above the nominal value for CLIC, 135 MW [18]. Another milestone was the validation of the PETS On-Off concept. 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. A prototype of the CLIC PETS On-Off mechanism, a compact external extension to PETS, consisting of two high power variable RF reflectors, was developed, manufactured and extensively tested with beam in the TBTS. 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 model describing the RF behaviour agreed with the measurements in all conditions. When the PETS is switched off, the accelerating structure sees less than 1% of the extracted power, basically making breakdown events impossible. The likelihood of a breakdown in PETS is also reduced, by a factor 10^2-10^3 due to significant power attenuation, to ~ 25% of the nominal value.

Acceleration, Two-Beam Module

The key purpose of CTF3 is to demonstrate the CLIC two-beam acceleration scheme, including efficient power transfer to high-gradient structures and acceleration of a "probe" electron beam. The probe beam is provided by the 24 m long injector linac, CALIFES [20], located in CLEX and delivering single bunches or bunch trains at 1.5 GHz bunch repetition rate and energies up to 200 MeV. The beam is generated and accelerated to ~ 5 MeV/c in a photo-injector and is further accelerated in three 3 GHz accelerating structures recuperated from the LEP Injector Linac (LIL). The accelerating structures and the photo-injector are powered by a single 3 GHz klystron which delivers 45 MW RF pulses during 5.5 µs to an RF pulse compressor. CALIFES is usually operated with bunch charges of around 0.1 nC and a normalized r.m.s. emittance of 10 µm. The probe beam energy can be measured in a spectrometer as a function of the probe beam 3 GHz RF phase, phase-locked to the laser pulse timing. A phase scan is then used to adjust the relative timing between probe and drive beam for maximum acceleration. The nominal CLIC accelerating gradient of 100 MV/m corresponds to an energy gain of $\Delta E = 21.4$ MeV. Energy gains of up to $\Delta E = 32$ MeV were achieved with relatively low breakdown rates (a few 10^{-3}), while higher gradients, up to 165 MV/m were achieved with higher rates [18]. Figure 4 shows an example of $\Delta E = 31$ MeV probe beam acceleration measured on the spectrometer screen, corresponding 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 the TBTS was replaced by the Two-Beam Module, TBM, a 2 m long fully representative unit of the CLIC main linac, including an active alignment system. The nominal CLIC gradient/pulse length was again established, and extensive tests of the module functionality, including precision and reliability studies of the active alignment system, and measurements of transverse wake-field effects were carried out. The experimental results are still undergoing a full analysis, but are so far consistent with specifications and simulations.

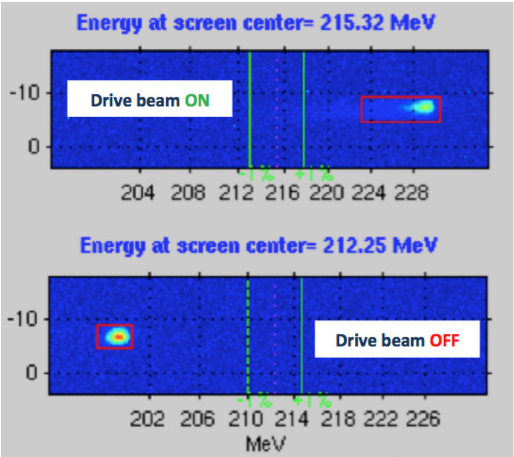

Figure 4: Probe Beam observed in the TBTS spectrometer screen with the 12 GHz RF power from the drive beam on (top) and off (bottom). The energy gain is about 31 MeV, corresponding to a gradient of 145 MV/m.

The Test Beam Line, TBL

The stability of the drive beam during deceleration was studied in the Test Beam Line (TBL), consisting of a FODO lattice with 14 consecutive PETS installed in the drift spaces. High precision BPM's and quadrupole active movers are used for precise beam alignment. In TBL a 25 A drive beam was decelerated from it initial energy, 135 MeV, down to a minimum of 67 MeV, reaching the 50% deceleration milestone which was one of the initial goals of CTF3. On average the produced power was 90 MW per PETS. The total peak RF power produced in less then 20 m deceleration line reached 1.3 GW. The beam energy loss and its energy spread was measured in a time-resolved spectrometer, and agreed very well with simulations. The dynamics of drive beam while undergoing deceleration was studied in detail, and both transverse and longitudinal parameters were in agreement with the simulations [22].

OTHER EXPERIMENTAL TESTS IN CTF3

The Beam-Loading Experiment

The RF breakdown rate (BDR) is crucial for the luminosity performance of the CLIC linear collider. The required BDR of 10^{-7} at the design gradient of 100 MV/m has been demonstrated without beam, by high power RF testing a number of 12 GHz CLIC prototype structures. Nevertheless, beam-loading significantly changes the field profile in the structures, and potential effects need to be understood. A dedicated experiment was installed in the CTF3 drive beam linac and collected data from 2014 to 2016 [23]. A BDR reduction by beam loading up to an order of magnitude was measured. The results complement the hypothesis of the BDR being dominated by the peak gradient, its reduction being associated to the modification of the gradient profile induced by the beam. Additional support is given by the measured distribution of the breakdowns inside the structure, which follows roughly the gradient profile. These results suggest the possibility to further optimise the CLIC structure by profiling the gradient in order to have a constant distribution of breakdowns along the structure during the operation with beam.

Beam Diagnostics Tests

In the last years of CTF3 operation, an extensive test program was established in CTF3 in order to verify the performance of prototypes of the main CLIC beam instrumentation in a realistic environment. The CLIC diagnostics components need to provide state-of-the-art performance, and in many cases their number is such that cost-effective solutions are mandatory. Additional issues are the need to detect tiny signals in the direct vicinity of hundreds MW RF power and operation at high radiation levels. Wake Field Monitors (WFM) capture selected HOMs induced in the CLIC accelerating structures. In particular, one of the structure cells is equipped with 4 waveguide antennas, detecting HOM signals in two different frequency bands. WFM are used as BPMs, directly measuring the misalignment of the structures with respect to the beam, with a required resolution of 3.5 μm. Two slightly different versions were tested in CTF3, and both demonstrated performances better or close to the required ones [24, 25]. Drive beam BPM prototypes were also tried, yielding 2 μm resolution. However, it was found that their performance was largely degraded in presence of 12 GHz RF power from the drive beam. A new version was successfully tested in the last two years of CTF3 operation [26]. Initial checks of cavity BPMs for the main linac showed a position resolution below specifications and worse time resolution than required. The Q value was therefore optimised and stainless steel replaced with copper as the building material of the cavity. Recent tests carried out on the improved version showed a resolution below 1μm, encouraging but still quite far from requirements [27]. A cost effective optical fibre based Beam Loss Monitor (BLM) system was installed along TBL and TBM lines and successfully commissioned. Various tests were performed, with losses were provoked along the accelerator lines and localised by the BLMs. Their signals agreed very well with conventional ionization chambers and provided a loss localisation accuracy below 2 m, within CLIC requirements [28, 29]. 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].

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.

ACKNOWLEDGEMENTS

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