# BEAM TESTS AT THE CLIC TEST FACILITY, CTF3

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*Abstract*

The CLIC Test Facility CTF3 has been built at CERN by the Compact Linear Collider (CLIC) International Collaboration, in order to prove the main feasibility issues of the two-beam acceleration technology on which the collider is based. After the successful completion of its initial task, CTF3 is continuing its experimental program 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. In this paper we discuss the status of the ongoing experiments and present the more recent results, including improvements in beam quality and stability.

## INTRODUCTION

The Compact Linear Collider (CLIC) [1] is one of the two machine design studies being pursued by the Linear Collider Collaboration. Essential for the verification of key issues of the CLIC design is the work carried out at the CLIC Test Facility CTF3 [2], located at CERN. In particular, CTF3 was built in order to demonstrate the following two main issues:

1. Drive Beam Generation: efficient generation of a high-current electron beam with the correct 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 using RF deflectors for injection in a series of delay lines and rings. CTF3 is using a 120 MeV $e^-$ linac followed by a stretching chicane, a 42 m Delay Loop (DL) and an 84 m Combiner Ring (CR) in order to produce a 30 A Drive Beam with 12 GHz bunch repetition frequency. The Drive Beam can be sent to an experimental area (CLEX) where it is 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 CLEX, one line (the Test Beam Line, TBL) is used to decelerate the Drive Beam in a string of PETS. The Drive Beam can be alternatively sent to another beam line (the Two-Beam Test Stand, TBTS), where a PETS is used to power one or more structures and further accelerate a 200 MeV electron beam provided by a dedicated injector, CALIFES.

CTF3 was build, installed and commissioned in stages. The commissioning of the Delay Loop, Combiner Ring and transfer lines connecting them and delivering the beam to CLEX was completed in 2009, together with the CALIFES probe beam injector. In autumn of 2009, the first full recombination with the DL and CR together was also achieved. 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.

## RESULTS OF THE FIRST 2014 RUN

The first CTF3 run in 2014 lasted from mid-February to the end of June. A summer shut-down started after that in order to allow for modulator/klystron maintenance and the installation of a full-fledged CLIC Two-Beam module in CLEX. The complex is now restarting gradually its experimental activity, as detailed later in the paper. The main areas of activity during the first run are summarized below.

### *Improvements in Drive Beam Generation*

Most of the experimental activity was dedicated to improvements in the reliability, repeatability and stability of the Drive Beam generation.

The main problem in the previous runs was the availability of the travelling-wave tubes (TWTs) used to power the 3 sub-harmonic bunchers (SHB) of the drive beam injector. Most of the time in 2013 the injector was operated with only two or even a single SHB cavity, severely limiting the overall performance. A consolidation campaign took place during the 2013-2014 shut-down, reconfiguring the power supply/control units, and one new design TWT prototype from a different manufacturer has been procured. During the 2014 run the uptime for all TWTs was then close to 100%. Only one of the tubes showed gradual signs of aging (as expected from its 12000 hours of operation, well above the nominal lifetime of 6000 hours) and its power gradually decreased over time. We had been able to compensate for this behaviour during operation, and the tube will be substituted with a spare before the next run.

Other improvements were obtained in repeatability by implementing several tools and procedures [3] and additional feed-back loops [4]. An online dispersion measurement has been used extensively in operation and the feed-backs include now an injector feed-back, beam-loading and energy feed-backs.


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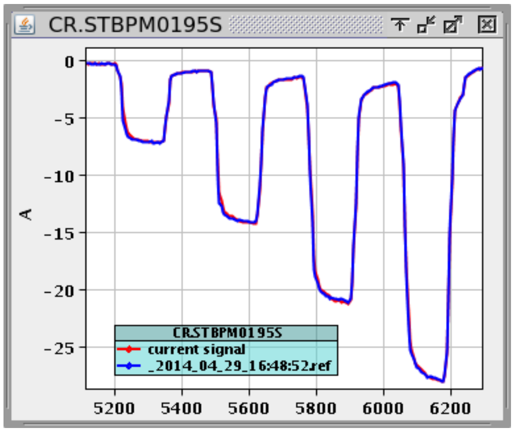


Figure 1: Beam current vs. time (ns), showing the four-fold increase during beam combination in the combiner ring. The two overlapping traces (red and blue) were taken on two different days, with identical machine settings.

These improvements allowed for routine operation during most of the run with a fully recombined beam (factor 8 current increase, 28 A, see Fig. 1). Repeatability was excellent, in many cases recovering the maximum performance after a night stop in a few minutes after restart. Several studies on emittance preservation, both experimental and theoretical, were done [5]. The main mechanism of emittance growth is now well understood and good progress was made in reducing it. The measured rms normalized emittance for the factor 8 combined after transport to CLEX is about 400 μm in the horizontal plane and 140 μm in the vertical, against a target value of 150 μm in both planes and typical values at the end of the CTF3 linac of 80 to 100 μm. The beam stability has been also improved, with about 0.5% rms charge jitter measured in good conditions for the factor 8 combined beam, and an order of magnitude smaller routinely achieved in the linac. This goes together with an improved management of beam losses, now at the level of 10% overall.

### *Two-Beam Experiments*

From mid-2012, the Two Beam Test Stand (TBTS) in CLEX is hosting two high-gradient accelerating structures powered by a single PETS in a scheme very close to the CLIC basic cell. The TBTS was used to validate the two-beam acceleration principle, measuring energy gain and energy spread in relation with RF phases and power. Extensive measurements of breakdown rate and breakdown locations within the structures were also made. These structures are the first to be fitted with Wake Field Monitors (WFMs), an essential tool in CLIC to ensure emittance preservation and high integrated luminosity. Such monitors were tested earlier in 2013 and used to further improve the structure alignment on the beam line. This year improvements made in the acquisition electronics and signal treatment, followed by extensive testing, gave an improved resolution of better than 5 μm for beam offsets <0.4 mm [6]. Taking into account the low charge used in the TBTS tests, the achieved resolution is well in line with the CLIC requirements (3.5 μm).

A dedicated experiment was performed to assess an earlier observed effect of octupolar focusing in 12 GHz accelerating structures, originating from the HOM waveguide dampers equipping each cell. The strongest effect is observed for zero crossing phase, while it is zero at the accelerating RF crest. The measurements agree very well with the RF model, demonstrating that the effect is negligible for CLIC operation.

Measurements of the RF breakdown kicks on the accelerated beam were done using time resolved cavity BPMs and beam profile diagnostics; 200 ns long pulses were observed, comparing bunch position before and after a breakdown event. The average transverse kick strength was 25 keV/c [7] confirming earlier measurements [8].

### *Test Beam Line Status*

Even though the beam time in the TBL line was very limited, a beam of 21 A was decelerated in a string of 13 PETS. A maximum deceleration of 37% has been measured, which is up to date the highest in CTF3. The measured energy difference shows a very good agreement with predictions based on the beam current and the RF power produced in the PETS, when bandwidth limitations and a multi-bunch form factor from the phase distribution of the drive beam pulse were taken into account [9].

### *Experimental Activities with CALIFES*

The CALIFES probe beam injector has been used to test a large variety of beam diagnostics equipment related to the CLIC project, including high accuracy cavity BPMs, stripline BPMs, beam loss monitors and a longitudinal profile monitor based on electro-optic spectral decoding system (EOS) [10]. The EOS system was tested using bunches with different charge (0.17, 0.3 and 0.7 nC) and resulting bunch length due to space charge (5.3, 6.4 and 9.0 ps, respectively). The obtained results agreed well with a streak camera but provided three times better signal to noise ratio.

### *First results on Phase Feed-Forward System*

The CLIC scheme relies on a beam-based feed-forward system to stabilize the phase of the drive beam with respect to the main beam with a specified tolerance of 50 fs rms [1]. Such a system will be situated in each of the drive beam decelerating sections and will include a phase monitor at the entrance and a correction system, consisting of fast kickers within a magnetic chicane, at the exit of each turnaround. A prototype is being developed at CTF3 [11], in order to demonstrate the phase stabilisation required for CLIC. The system is composed of a high-bandwidth, high-resolution phase monitor, two kickers placed in a dog-leg chicane, driven by high-power, high-bandwidth amplifiers and a fast digital feed-forward controller.

Initial tests of the Phase Feed-Forward system started. The 12 GHz beam phase monitors where commissioned to the required resolution of 0.2 degree. A dedicated optics was successfully commissioned at the dog-leg chicane. Beam phase correction using steering magnets installed around the kickers was successfully tested. It will later provide a slow correction to compensate phase drifts outside the correction range of the fast kickers. The first tests of the amplifiers and the controller were successfully performed with the beam. The latency was proven to be within the budget of 375 ns. More details can be found in a dedicated paper [12].

### *Status of the Beam Loading Experiment*

In order to experimentally measure the effect of beam loading on breakdown rate, an experiment has been installed at CTF3 using a 12 GHz klystron connected to a CLIC prototype accelerating structure loaded by the drive beam of the facility. The drive beam with a current of 1.2 A was set up through the structure, and the measured RF beam loading fits very well with that expected from the incident beam current. The structure was connected to the 12 GHz klystron and the RF conditioning started mid July 2014. The conditioning has been fully automated and is presently progressing [13].

## STATUS AND OUTLOOK

During recent CTF3 runs the drive beam of 24 A intensity was routinely delivered to the experiments at CLEX. The beam reached satisfactory stability and reproducibility. The dispersion control and emittance preservation were improved, although these points still require further optimization in the next run. Currently an alignment campaign is carried out since performance of the newly developed automatic steering tools was proven to be limited by misalignments. This made chromatic corrections with sextupoles difficult. Improvements in the alignment and in the steering algorithms, namely development of dispersion steering, should further reduce the emittance and remaining losses.

The TBTS has proven to be an essential facility to demonstrate the CLIC acceleration scheme validity. In the 2014 summer shut down, the TBTS is being heavily modified, to include the first CLIC full-fledged two-beam module, including all the features to be tested as an integrated system: drive beam line with 2 PETS, 2 quadrupoles and 2 BPMs, Main beam with 4 accelerating structures and 2 WFMs, and a complete set of instruments for active alignment of the girders.

While this installation is ongoing until the end of September, the whole facility is gradually resuming operation. A PHIN Photo-Injector run for photo-cathode testing has started beginning of August. The experiment for the effect of beam-loading on RF breakdowns will restart beam operation at the end of August 2014. Once a sufficiently low breakdown rate has been reached in the accelerating structure, the breakdown rate will be measured with and without the presence of the beam. Finally, the preparation of RF and beam for the running of the full complex will start from the beginning of September. A 14$^{th}$ PETS was installed in the TBL and should allow reaching a beam deceleration in the 40-45% regime.

## ACKNOWLEDGMENT

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