EXPERIMENTAL VERIFICATION OF THE CLIC TWO-BEAM SCHEME, STATUS AND OUTLOOK

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Abstract

The feasibility of the CLIC novel scheme of two-beam acceleration was extensively tested in the CTF3 facility over the last few years. In particular, efficient full beam loading acceleration, isochronous ring operation, beam recombination by transverse RF deflectors have been fully proven. 12 GHz RF power production by high-current drive beam is now part of CTF3 routine operation, and two-beam acceleration up to 150 MV/m has been achieved. Drive beam deceleration tests were carried out as well. In this paper we summarize the main results obtained, including the more recent ones. We also outline and discuss the future experimental program, both in CTF3 and in other beam facilities, as well as the path to a possible facility needed in the initial stage of the CLIC project, CLIC0.

STATUS OF FEASIBILITY STUDIES

The aim of CTF3 (see Fig. 1), built at CERN by the CLIC/CTF3 international collaboration [1], is to prove the main feasibility issues of the CLIC two-beam acceleration technology. The two main points to be demonstrated are:

1) Efficient generation of a high-current electron beam with the time structure needed to generate 12 GHz RF power: 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 is meant to use such technique to produce a 30 A drive beam with 12 GHz bunch repetition frequency. CTF3 consists of a 120 MeV electron linac followed by a 42 m long delay loop and a 84 m combiner ring. The beam current is first doubled in the delay loop and then multiplied again by a factor four in the ring by interleaving bunches using transverse deflecting RF cavities. The drive beam can then be sent to the CTF3 experimental area (CLEX) to be used for deceleration and two-beam experiments.

2) RF power production and two-beam issues: 12 GHz high-power RF pulses are generated by decelerating the drive beam in travelling wave resonant structures called PETS (Power Extraction and Transfer Structures) and then fed to high gradient accelerating structures, operated at 100 MV/m. In the CLEX area the Test Beam Line (TBL) is used to test drive beam deceleration in a string of PETS. The drive beam can alternatively be sent to a second beam line (Two-Beam Test Stand, TBTS), where a PETS is used to power one or more CLIC accelerating structures. In the same area a 200 MeV injector (CALIFES) produces a probe beam that can be used in the TBTS to verify two-beam acceleration.

CTF3 is being installed and commissioned in stages from 2003, starting from the linac. The delay loop commissioning was completed in 2006.

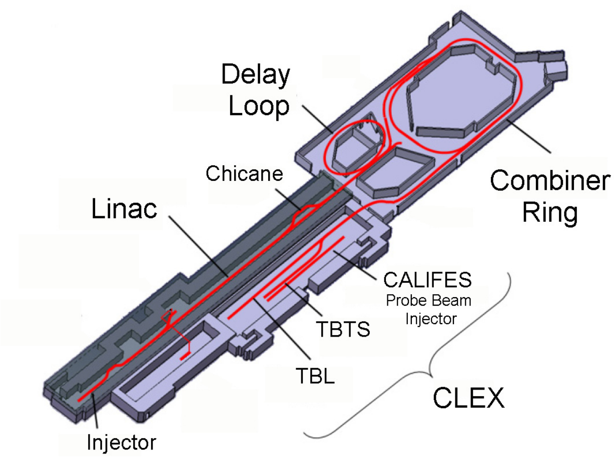

Figure 1: CTF3 Overall Layout.

The transfer line to the combiner ring and the ring itself were installed and put in operation in 2007. In the years 2008-2009 the transfer line to CLEX and the various beam lines in CLEX were commissioned, together with the CALIFES probe beam injector. The first factor 8 recombination was then obtained, reaching 28 A of beam current. In 2010 nominal power production from the PETS was established and the first two-beam test was performed. In 2011 drive beam stability was improved, a gradient of 150 MV/m was reached in two-beam tests, the PETS on/off mechanism was successfully tested and a 21 A drive beam was decelerated in TBL by 26% of its initial energy in a string of 9 PETS structures.

Drive Beam Generation Studies

The CTF3 linac accelerates routinely a current of about 4 A. HOM damping is used to prevent any transverse instability. It is operated in full beam-loading, and a 95% RF-to-beam energy transfer efficiency was measured [2]. Isochronous operation of the loop, ring and transfer lines is needed in order to avoid bunch lengthening. The ability to tune the momentum compaction below the required value ($\alpha_p < 10^{-4}$) was demonstrated already in the CTF3 preliminary phase, and is now part of standard operation [3]. In the delay loop, the bunches must be separated and then recombined to increase the current by a factor 2 and create a hole for ring extraction. This is done by using an RF deflector and a sub-harmonic bunching system, whose phase is periodically switched by 180° to phase-code the bunches. A switching time of 6 ns was measured, well below the required value [4]. The residual charge in satellite bunches is ~ 7 %, acceptable for CTF3, even if an improvement is needed for CLIC. CTF3 did not reach yet the target emittances for the drive beam after combination, 150 π μm in both planes.

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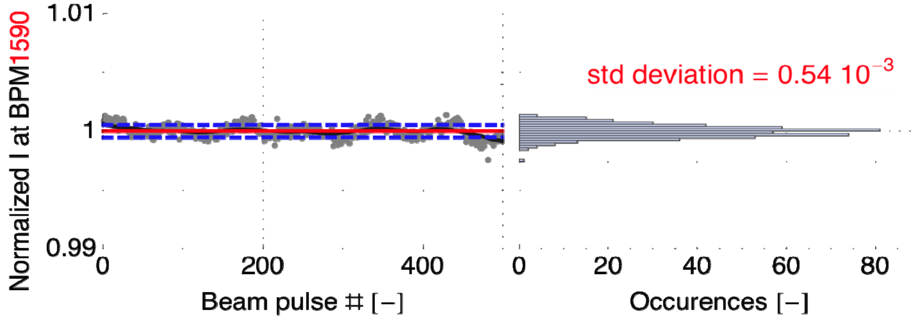

Figure 2: Pulse charge stability measurements in CTF3 (last linac BPM, with gun feedback on).

Although 50 π µm is routinely obtained in the linac, measurements on the fully recombined beam typically give values 2 to 4 times the target. Better results are obtained for the combination 4 beam, where the goal has been reached in the vertical plane. 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 being put in place, and in 2012 we expect to reach the target. Bunch length control to < 1 mm rms was shown in the past after the linac. No time was then dedicated to get such bunch length in CLEX as well, since the present value (< 2 mm rms), 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. Nonetheless, we plan to tune the machine for shorter bunches later this year.

The required CLIC drive beam current stability is extremely tight (7.5 10^{-4} for rms pulse-to-pulse variations). The initial performance of the CTF3 gun was only ~ 2 10^{-3}, but could be rapidly improved by stabilizing the gun heater power supply. After further reduction of slow drifts by a feedback, the rms pulse-to-pulse variation measured in the linac was ~ 5 10^{-3} (including the BPM noise level, estimated as 3 10^{-4} by correlation analysis of the different BPMs), well below the CLIC specs [5]. The current jitter is about 8 10^{-4} for the combination 4 beam. The same orbit errors causing emittance growth for the full combination beam still limit its current jitter, by differential losses, to the percent level. One of the goals of this year run is reduce it to a few 10^{-3}. CLIC has also tight requirements for RF phase and amplitude stability in the linac (0.05° rms phase jitter for a coherent error along the drive beam train and 0.2% for the RF amplitude). In CTF3 an RF phase jitter of 0.035° has been measured with respect to the external reference, while the amplitude stability was 0.21%.

RF Power Production and Two-Beam Issues

In the TBTS, in order to get to high power levels at a limited drive beam current, recirculation is used, where part of the output power of the PETS is injected back at the PETS entrance, seeding RF production. Thus, RF power levels above 200 MW, well beyond the 135 MW CLIC nominal values, were reached inside the PETS at the 240 ns nominal pulse length. More than 100 MW of peak RF power was delivered to the accelerating structure (CLIC nominal 65 MW). Gradients up to 150 MV/m have been achieved (see Fig.3) [6]. The measured drive beam deceleration, the RF power produced and the probe beam acceleration are consistent between them and with the theoretical predictions. Aside from the demonstration of accelerating gradients at and above the CLIC target, the TBTS is used to study in detail the physics of electrical breakdowns. In this context, new measurements on breakdown transverse kicks were recently performed [7].

One of the feasibility issues of the CLIC two-beam scheme is the possibility of rapidly switching off RF power production in individual PETS in case of breakdowns, either in the PETS or in the main beam accelerating structures. The proposed solution is to use a variable external reflector connected to the PETS, which allows to change gradually the RF power transfer to the accelerating structure and to reduce power production in the PETS itself by a factor of 4. Such a mechanism was successfully tested at nominal power in TBTS and compared with expectations at the end of 2011 [8].

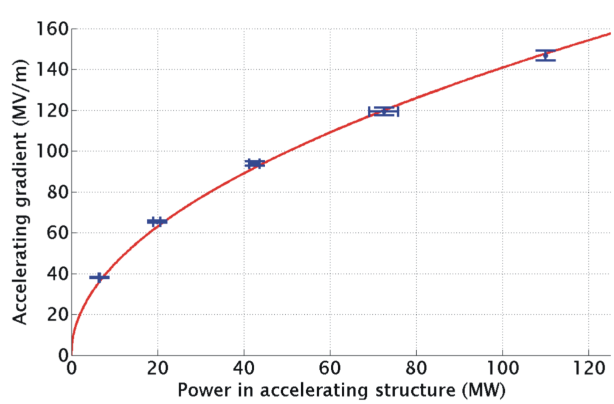

Figure 3: Measured accelerating gradient as function of the accelerating structure RF input power.

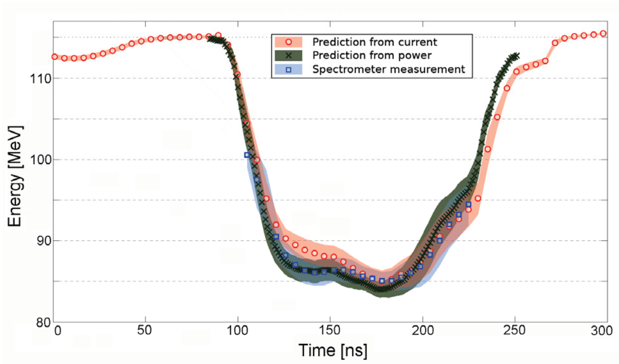

Figure 4: Comparison between the measured time-resolved beam energy profile and the predictions from beam current and power production measurements. Data were averaged over 48 consecutive pulses. The shaded areas indicate the standard deviation.

TBL was build to test drive beam stability and transport during the deceleration process. At the end of 2011 run, it contained a string of 9 PETS, 8 of which equipped with HOM damping material. The maximum power produced so far was 70 MW per PETS, or 630 MW total, limited by the available beam current of 21 A. No sign of breakdown has been observed so far in the PETS. The beam was decelerated from 117 MeV by more than 30 MeV corresponding to about 26% of the beam energy extracted [9]. The 12 GHz power produced agrees well with the theoretical predictions (see Fig.4). The optics was well understood and the beam could be transported without losses, within the accuracy of the current monitor.

FUTURE PROGRAMME

Completion of Feasibility Studies

Most of the CLIC feasibility goals for CTF3 have been reached already. We expect to complete the CTF3 program in 2012, by obtaining low-loss transport of the fully combined beam to CLEX, with transverse emittance below 150 π μrad and charge stability ~ 2 10^{-3}. A different optics, with low R_{56} value, has been prepared for the end-of-linac chicane and its implementation should allow us to get ~ 1 mm rms bunch length in CLEX. During the winter shut-down additional PETS tanks were installed in TBL, bringing the total number up to 13. Therefore we will be able to decelerate the drive beam by more than 40% of its initial energy. In TBTS, two new accelerating structures equipped with wake-field monitors will be installed in summer to be conditioned and tested. Also planned in TBTS are the continuation of breakdown kick tests and experiments on RF pulse shape control.

CTF3 During the Next Phase

A detailed work program for the next phase of the CLIC study, the CLIC Project Preparation Phase (2012-2017), where CTF3 will again play a major role [10], has been recently completed. The important issue of the drive beam phase stability will be addressed in collaboration with INFN-Frascati and JAI/Oxford University. Such activity will result in a complete test of a drive beam feed-forward prototype in CTF3 before 2016. The first step in 2012 is the test with beam of a new high-resolution phase monitor developed and built by INFN. TBL will evolve towards a power production facility, to complement the high-power RF testing program of CLIC. A first testing slot, using a new PETS tank with RF recirculation, will be installed in the next winter shutdown. Finally, a string of three full-fledged CLIC modules, including active alignment and stabilization, will be installed and tested with beam in CLEX, substituting TBTS. The first module is planned for installation in mid 2013. A special experiment on the effect of beam loading on breakdown rate is also planned for 2013. The CTF3 experimental program is supported by a consolidation plan aimed at further improving the stability, reliability and availability of the installation, including an upgrade of the repetition rate from 1 Hz to 10-20 Hz.

Towards CLIC 0

A fundamental milestone in the CLIC path is the construction and commissioning of the so-called CLIC 0 facility [10], essentially a large fraction of the drive beam generation complex (20% of the final energy), followed by 10% of a decelerator sector. CLIC 0 is meant to be the tool to qualify structures and two-beam modules during the CLIC construction phase. It will be the test bed for all mass-produced components and will constitute a comprehensive final system test. All hardware will be re-usable for CLIC. As a first step towards CLIC 0 during 2012-2017, the construction and commissioning of the 20 MeV front-end for CLIC 0 (including gun, sub-harmonic bunching system and first accelerating structures) is under preparation.

REFERENCES

[1] G. Geschonke and A. Ghigo Eds, "CTF3 DesignReport", CERN/PS 2002-008 (RF).
[2] P. Urschütz et al., "Efficient long-pulse fully-loaded CTF3 linac operation," Proc. LINAC'06 and CLIC note 697.
[3] R. Corsini et al., "Experimental results on electron beam combination and bunch frequency multiplication", Phys. Rev. S.T. Accel. Beams 7 (2004).
[4] P. Urschütz et al., "Beam dynamics and first operation of the sub-harmonic bunching system in the CTF3 injector", Proc. EPAC'06 and CLIC note 683, 2006.
[5] G. Sterbini, "Beam Current Stability in CTF3", Geneva, LCWS 2010 and T. Persson, P. Skowronski, "Beam Stability at CTF3", TUPPR032, these proceedings.
[6] P. Skowronski et al., "The CLIC feasibility demonstration in CTF3", CERN-ATS-2011-177.
[7] A. Palaia et al., "RF-breakdown Kicks at the CTF3 Two-beam Test Stand", MOEPPB01, these proceedings.
[8] I. Syratchev, et al., "High Power Operation with Beam of a CLIC PETS Equipped with On/Off Mechanism", TUPPR019, these proceedings.
[9] R. Lillestol et al., "First Results from the CLIC Decelerator Demonstration Experiment in the CLIC Test Facility 3", TUPPR031, these proceedings.
[10] R. Corsini, "CLIC TDR Plans", Geneva, LCWS 2010, https://espace.cern.ch/LC2010/default.aspx

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