STATUS AND PLANS FOR COMPLETION OF THE EXPERIMENTAL PROGRAM OF THE CLIC TEST FACILITY CTF3

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Abstract

The CLIC Test Facility CTF3 was build, commissioned and operated at CERN by an international collaboration, with the aim of validating the CLIC two beam acceleration scheme, in which the RF power used to accelerate e+/e- beams is extracted from a high intensity electron beam. In the past years the main issues of such a scheme were assessed, demonstrating its feasibility. The CTF3 experimental program is complementing these results by addressing cost and performance subjects, mainly using the CALIFES test beam injector and a full scale two-beam module. In this paper we document the present status and give an outlook to the 2016 run, when the experimental program should be completed.

CONTROL OF THE BEAMS AND MACHINE DEVELOPMENT

In the last experimental runs, a large fraction of beam time has been dedicated to improvements of the drive beam performance, in terms of stability, availability and control of emittance growth. Apart from enabling a better exploitation of the beam by the users, this is an integral part of the CTF3 experimental program, aimed at demonstrating a beam quality close to the one required for CLIC.

Stability Improvement

During initial years of operation CTF3 suffered from large beam jitters and drifts. Dedicated studies discovered most of the sources, which were either removed or corrected by proper feed-back systems. During the past year additional measures, including new feedbacks, allowed to improve further the drive beam current and position stability. A large gain was obtained through reduced emittance and improved dispersion control, which of course improved the dynamic aperture and allowed to avoid losses leading to beam current jitter. The rms beam current jitter at the end of the drive linac is now better then $2 \cdot 10^{-4}$, 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 of tens of hours. The stability of the combined beam current in CLEX, at the end of the experimental lines, was also largely improved and $3 \cdot 10^{-3}$ rms was measured for periods longer then 5 hours. A more detailed discussion is presented in a dedicated contribution to this conference [1].

Dispersion Control

Spurious dispersion is one of the main mechanisms causing emittance growth in linacs. In the case of CTF3, where different recombined pulses follow different paths and may see different dispersion patterns, this is even more important. Therefore, first a dedicated tool to precisely measure dispersion in the different beam-lines was put in place, then automatic Dispersion Free Steering and Dispersion Target Steering were implemented and applied. However, controlling and correcting dispersion to first order is not sufficient.

The CTF3 drive beam has a rms energy spread of about 0.6%. The isochronous optics of Delay Loop (DL) and Combiner Ring (CR) are relatively strong. The two together lead to a large nonlinear dispersion that is the main source of emittance growth. Especially the contribution from the DL was large, see Figure 1. During the past year a new DL optics was commissioned and the measurement confirmed a reduction of non-linear dispersion and improved emittance. More details can be found in a dedicated contribution to this conference [2].

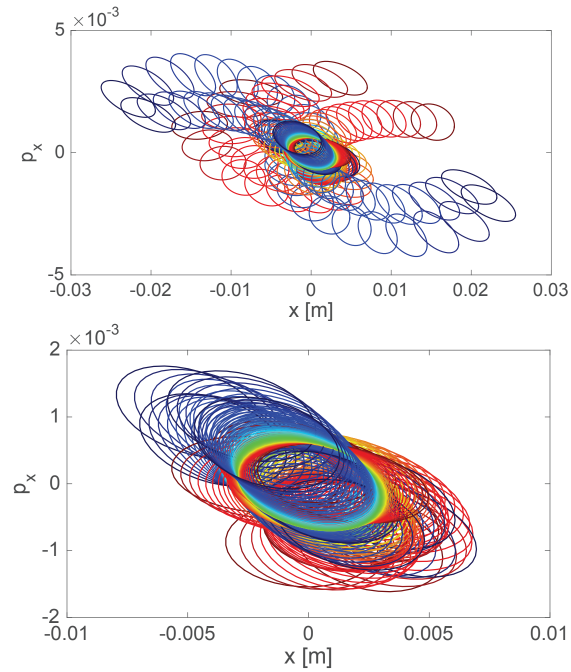

Figure 1: Comparison of beam phase space after CR for old (top) and new (bottom) DL optics.

TWO BEAM ACCELERATION

Two Beam Module

The core component of CLIC is the Two Beam Module (TBM), a 2 m long unit integrating all the sub-systems. In total there are 4 variants of it, and the 3 TeV CLIC design consists of more then 20000 modules. Its design is highly

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optimized, taking into account all aspects that may impact performance and cost of the machine.

Towards the end of 2014 the first version of the module was installed in CTF3. The module was completed during 2015, with the installation of an additional PETS and two accelerating structures, for a total of 2 PETS powering 4 high gradient accelerating structures in the present state. The performance of the beam module has been studied using RF priming from an upstream PETS and power recirculation for the first two structures, in order to provide power levels at and above the CLIC specs in spite of the limited CTF3 beam current with respect to CLIC (28 A instant of 100 A). After some initial conditioning, powers reached around 45 MW in the first two structures and an acceleration of about 65 MV/m was measured. Further RF conditioning is required in order to increase the accelerating gradient above such value at a reasonable breakdown rate. Measured acceleration and RF power levels agreed well with each other and with expectations, taking into account some efficiency loss caused by phasing errors between the different structures, identified by dedicated phase measurements of the beam induced fields, and now corrected by careful longitudinal realignment of the structures. A more precise longitudinal alignment procedure will therefore be requested in future module generations. The active alignment functionality was also tested, for the moment without beam, basically confirming measurements performed on the modules during mechanical testing in the lab. Tests of the complete system with beam will be carried out soon.

Test Beam Line

Power production performance and drive beam stability during deceleration is studied in the Test Beam Line (TBL) consisting of 14 consecutive PETS. The 24 A drive beam was decelerated from it initial energy, 135 MeV, down to 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, which agrees very well with the measured beam energy loss and expectations based on its current, see Figure 2. The total peak RF power produced in less then 20 m deceleration line reached 1.3 GW.

The dynamics of drive beam while undergoing deceleration was studied in detail in previous runs, at somewhat lower currents and milder deceleration (at the level of 35%), and both transverse and longitudinal parameters were in agreement with the simulations [3]. Further beam dynamics measurements are planned in 2016, with a maximum deceleration of about 50%.

Phase Feed Forward

To limit luminosity losses caused by energy jitter to the percent level, the CLIC design requires a drive beam phase jitter below 50 fs rms (or 0.2 degrees of 12 GHz). In order to assure this a low-latency 30 MHz Phase Feed Forward (PFF) system is to be installed at each drive beam turn around loop. A prototype of such a system was installed and successfully commissioned at CTF3 from mid-2014. After one year of experience and several improvements, namely: compensation of residual momentum compaction, increased incoming phase stability, optimisations of the phase monitor resolution to 0.1 degrees at 12 GHz and doubling of the amplifier output voltage, a pulse-to-pulse phase jitter of 0.28±0.02 and a phase flatness along the pulse of 0.26±0.01 have been demonstrated, very close to the CLIC specifications. Details can be found in the following contribution [4].

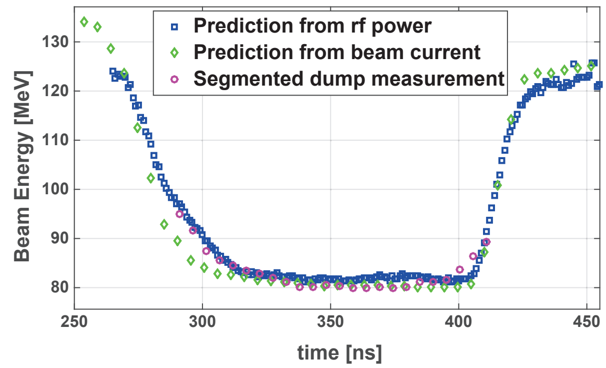

Figure 2: Comparison of measured RF power with predictions from the measured beam intensity and drive beam energy loss.

Experiment on Break-down Rate with Beam

The presence of the beam modifies the distribution of the electric field along the accelerating structure. An experiment has started to measure the effect of beam loading on the breakdown rate, using one CLIC structure installed in a dedicated stand and powered by a high-power X-band klystron. Up to 1.5 A beam current from the drive beam linac can be sent through it, loading the structurectf.v4.tex to levels similar to the ones of CLIC. The break-down rates with and without beam can then be compared. The first results show a breakdown rate dominated by the maximum peak gradient inside the accelerating structure rather than by the average gradient for loaded and unloaded cases. The beam presence does not seem to alter the breakdown rate when the input power is kept constant. Breakdown cell distributions inside the structure seems to support these conclusions. The results and a more detailed description of the experiment is presented in a dedicated contribution to this conference [5].

BEAM INSTRUMENTATION TESTS

The CLIC beam instrumentation needs to provide state-of-the-art performance. At the same time, in many cases their number is such that cost-effective solutions are required. Additional issues are the need to detect tiny signals in the direct vicinity of hundreds MW RF power and operation at high radiation levels. Therefore, an extensive prototype test program was established in CTF3 in order to verify the performance of the main diagnostics components in a realistic environment.

Wake Field Monitors (WFM) capture selected HOMs induced in the CLIC accelerating structures. In particular, one

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of the structure cells is equipped with 4 waveguide antennas, detecting HOM signals in to different frequency bands. WFM are used as beam position monitors, measuring directly the misalignment of the structures with respect to the beam with a required resolution of 3.5μm. Two different versions have been tested so far in CTF3, which are different by the cell number the antennas are attached to. The first model, using a cell in the middle of the structure, demonstrated in the past the needed performance. A new version, using a cell at the beginning of the structure and somewhat different frequency bands is presently under test, and has reached for the moment a the resolution of a factor 2 below the specification. More details can be found in [6]

The drive beam BPM's were successfully tested in the past, yielding 2μm resolution. However, it was found that the performance was largely degrading in presence of 12 GHz RF power from the drive beam. A new version has been successfully tested last year. It has longer striplines (37.5 mm vs. 25 mm) and they are terminated instead of being simply shorted. The details are presented in [7].

The initial tests of the cavity BPMs for the main beams showed a position resolution below specifications and higher time resolution than required. To improve this the Q value was optimised and stainless steel replaced with copper as the building material of the cavity. A first test carried out on the improved version yielded a resolution below 1μm, still quite far from requirements [8]. Radiation hardness of the local electronics was also shown to be a critical issue. Such problem has been mitigated now, and further tests are foreseen in 2016.

A cost effective optical fibre based BLM system was installed along TBL and TBM lines and successfully commissioned. Various tests were performed, where losses were provoked along the accelerator lines and localised by the BLMs. Their signals agreed very well with conventional ionization chamber BLMs and provided a loss localisation accuracy below 2 m, within CLIC requirements. For more details see [9, 10].

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. All the results confirmed the theoretical predictions [11].

PLANS

The CTF3 scientific program is being completed in 2016, which will be its last year of operation. The CLIC feasibility issues identified to be tested have already been proven and almost all of the planned goals have been achieved, including a few (like the PFF demonstration) that were added after the start of the facility exploitation. The remaining part of the program is mainly centred on the completion of the TBM tests with the aim to gather all possible information, and fed it back into the next generation module design. Such tests include RF conditioning, at and beyond the CLIC nominal level, checks of stability and control of the RF profile, measurements of RF phase/amplitude drifts, full verification of two-beam acceleration (power transfer and phasing) and active alignment tests with beam. Some further improvements on the drive beam performance are as well expected, from improved dispersion free-steering, dispersion matching, orbit control and possibly chromatic corrections in order to minimise horizontal emittance growth. As mentioned, we expect to consolidate deceleration of the drive beam in TBL at the 50% level and complete beam dynamics measurements. The remaining PFF issues are linked to some increase in reproducibility and long term stability. We aim as well to demonstrate a factor 10 phase jitter reduction, pulse-to-pulse and along the pulse, by introducing artificially phase noise. A relevant part of the beam time will again be given to diagnostics studies. The main goals are:

- Wake-Field Monitors: confirm 3.5 μm resolution with its new version, and further studies DB noise issues.
- Drive Beam BPMs: confirm 2.5 μm resolution.
- Main beam BPM prototypes: improve presently measured sub-micron resolution towards the 100s of nm level and check the time resolution.
- Optical Fiber BLMs: study response to multiple location losses.

Yet another activity, not CLIC-related, has recently already emerged with the development of an irradiation test bench intended to qualify electronic components to fulfill a request of the European Space Agency (ESA) regarding a future space probe JUICE [12] to be launched in the Jovian environment.

The CLIC collaboration is now seeking the possibility to extend beyond the end of CTF3 the operation of the CALIFES linac, as a stand-alone user facility. The proposed activities include studies relevant for existing and possible future machines at CERN, as well as more general accelerator-related R&D. These include impedance measurements of components and beam instrumentation tests which can not be easily conducted elsewhere at CERN, due to long shutdowns and limited availability of operational machines. Further items being considered are X-band high-gradient testing for X-FEL applications and plasma wake-field acceleration studies the would complement AWAKE experiments.

CONCLUSIONS

CTF3 conducted a rich experimental program developing various aspects of the accelerator technology needed for the CLIC concept. Acceleration with 12 GHz and gradients beyond 100 MV/m are now well established, and interest in X-band high-gradient technology is now worldwide, especially for free electron lasers applications. CTF3 has proven as well that the drive beam can be a reliable source of RF power in the range of hundreds of MWs. The facility will stop operation at the end of 2016, but there are plans to keep operational the probe beam linac CALIFES, to continue CLIC-related beam tests on accelerating cavities and diagnostics and to pursue more general accelerator-related R&D.

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