CLIC and CTF3

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Abstract. The CLIC study is exploring the scheme for an electron-positron Collider (CLIC) with high luminosity \(10^{34} - 10^{35} \text{ cm}^2/\text{s}\) and a nominal centre-of-mass energy of 3 TeV in order to complement LHC physics in the multi-TeV range. The CLIC Test Facility CTF3, built at CERN by an international collaboration, aims at demonstrating the feasibility of the CLIC scheme by 2010. CTF3 consists of a 150 MeV electron linac followed by a 42 m long delay loop and an 84 m combiner ring, followed by a two-beam test stand and a test decelerator. The linac and delay loop have been previously commissioned, while the combiner ring has been recently completed. After a presentation of the recent CLIC parameters, the status of the test facility, the experimental results achieved and the future plans will be presented.

1. CLIC

The aim of the CLIC (Compact Linear Collider) Study is to investigate the feasibility of a high luminosity linear e+ e- collider with a centre-of-mass energy reach of \(E_{\text{CMS}} = 3 \text{ TeV}\) [1]. CLIC is based on normal-conducting accelerating structures operating at a very high gradient, well above the fundamental limit for superconducting RF (\(\sim 50 \text{ MV/m}\)), in order to minimize the total length.

A recent optimisation study of overall cost and efficiency [2] including combined results from RF structure testing [3] has led to a major parameter revision for CLIC. The main modification are the change of the main linac RF frequency from 30 GHz to 12 GHz and the decrease of accelerating gradient from 150 MV/m to 100 MV/m. This brings the total length including beam delivery system to 48.25 km for 3 TeV. A first coherent and complete set of parameters has been worked out. Table 1 shows a subset containing the main parameters.

The high peak RF power required in CLIC to feed the accelerating structures is obtained using a two-beam acceleration concept [4], in which a high current electron beam (drive beam) runs parallel to the main beam and is decelerated to produce the RF power. Since the drive beam is generated in a central area, no active high power components are required in the linacs and a single tunnel with \(\sim 4.5\) m diameter can be used.

The generation of high-intensity drive beam pulses with the right time structure is indeed one of the main challenges in CLIC. In the adopted scheme, a long pulse is accelerated using a low frequency normal-conducting linac operated in full beam loading regime. Funnelling techniques in delay lines and rings are subsequently used to generate the desired time structure. In this process the electron bunches are interleaved by the use of transverse RF deflectors. The bunch spacing is thus reduced and the beam current is increased. The principle has already been demonstrated at low charge [5].
Table 1: New CLIC parameter set - provisional

| Parameter                          | Value       |
|-----------------------------------|-------------|
| Center-of-mass energy             | 3 TeV       |
| Peak Luminosity                   | $7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Peak luminosity (in 1% of energy) | $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Main linac RF frequency           | 12 GHz      |
| Loaded accelerating gradient      | 100 MV/m    |
| Repetition rate                   | 50 Hz       |
| Beam pulse length                 | 200 ns      |
| Average current in pulse          | 1 A         |
| Bunch charge                      | $4 \times 10^9$ |
| Hor./vert. normalized emittance   | 660 / 20 nm rad |
| Hor./vert. IP beam size before pinch | 53 / ~1 nm   |
| Overall two-linac length          | 41.7 km     |
| Total site length                 | 48.25 km    |
| Total power consumption           | 390 MW      |

It is generally accepted that CLIC technology is the only possible path to multi-TeV colliders. However, several critical issues still need to be demonstrated. The experimental program of the present CLIC Test Facility, CTF3 [6], addresses most of the main issues of the study, related to the generation and use of the drive beam and the testing of accelerating structures and RF components, as raised by the International Linear Collider Technical Review Committee in 2003. The Committee listed a number of crucial items, needed to prove feasibility (the so-called R1 items), and to arrive at a conceptual design (the R2 items). CTF3 will concentrate on all the CLIC technology-related R1 and R2 issues, as opposed to issues which are common to all linear collider studies. The goal is to get an insight on the feasibility of the CLIC scheme before 2010 when the first LHC results should be available and the energy required for a future linear collider would be better known.

2. The Test Facility CTF3

CTF3 is presently being built and commissioned at CERN by an international collaboration with an organisation structure similar to large particle physics experiments. At present, it includes 22 institutes from 12 countries. Other institutes have observer status, some of them being in the process of formally joining the collaboration or already providing some kind of support with no formal agreement yet.

The facility is located in the buildings of the former LEP Pre-Injector, LPI (see figure 1), whose hardware is partly re-used. It is designed to work at a lower beam current (30 A instead of 95 A) and at a much lower momentum than the CLIC drive beam (150 MeV/c instead of 2.4 GeV/c). It includes a 70 m long drive-beam linac followed by two rings, where the beam manipulations are made: a 42 m delay loop and an 84 m combiner ring. After such manipulations the drive beam will have a current of 30 A and will be transported to the CLic EXperimental area (CLEX) to produce 12 GHz RF power for structure tests. In the same area, another linac will provide a probe beam for a Two-Beam Test Stand – TBTS and a decelerator (Test Beam Line – TBL) will be used for drive beam stability studies. CTF3 has also a second RF power station, working at 30 GHz, located nearly halfway along the linac.

The recent change of parameters affects the CTF3 experimental program only slightly. The inherent flexibility of the CLIC RF power source scheme permits an easy adaptation to the new frequency of 12 GHz and the corresponding power with no hardware changes. It is sufficient to change the combination factor of the combiner ring from 5 to 4 with the path-length tuning wiggler, while shortening the initial electron pulse from 1.5 μs to 1.2 μs and increasing the beam current from 3.5 A to 4 A. However, the maximum final beam current (~ 30 A) is reached only up to a pulse length of 140 ns, shorter than the CLIC nominal pulse length.
The injector, the linac, the mid-linac power station and the end-of-linac magnetic chicane were installed and commissioned in 2003-2004. The first part of the linac is used since 2005 as a source of 30 GHz RF power. The delay loop was installed during 2005 and commissioned in 2006, while the combiner ring (see figure 1) installation was completed in 2006. Commissioning of the transfer line TL1 and of the combiner ring is presently under way.

Another transfer line (TL2) with variable momentum compaction will link the ring to the beam lines in CLEX. CLEX is a hall of 42 m length and 8 m width, partly covered by a gallery for klystrons, power supplies and other equipment. It will house several beam lines, described below. The construction of the CLEX building was recently completed and the first components are installed in the area.

In the TBL [7], the drive beam will be decelerated to about half its initial energy by 16 power extraction structures (PETS). The aim is to demonstrate beam stability under significant deceleration, which will produce a momentum difference of up to a factor of two between the first and the last bunches. The TBL is composed of modules including a PETS, a beam position monitor and a quadrupole on a precision movable support, in order to experiment beam-based alignment procedures. The modules are arranged in a FODO lattice whose magnetic strength can be tapered to follow the deceleration pattern. Up to a total of about 2 GW of 12 GHz RF power can be extracted from the beam. The TBL will be installed from 2008 onwards.

In the probe beam injector [8], a photo injector will generate a low current electron beam that will be accelerated to 200 MeV using structures from the former LPI. The hardware allows both single-bunch and bunch-train operation to up to 64 bunches. The probe beam could then be used for acceleration studies in 12 GHz CLIC structures in the two-beam test stand described below.

The Two-Beam Test Stand (TBTS) [9] will allow testing of both a CLIC PETS prototype with the 30 A beam and of different accelerating structures with the RF power produced there. It will be well instrumented to analyse the behaviour of these structures as well as the effect of RF breakdowns on the probe beam. The PETS have the same cross section as in CLIC, being only longer in order to produce the same power with a lower beam current, and will be equipped with an on/off mechanism.

The start of commissioning the probe beam linac and the TBTS is foreseen for early 2008. From then on, tests of the CLIC PETS and accelerating structures at 12 GHz with nominal power levels will become possible. The whole CTF3 installation should be completed by 2009.
3. Main achievements and Commissioning status

3.1. Full beam loading operation
A first key result obtained in CTF3 was the proof of stable operation under full beam-loading. This kind of acceleration is a fundamental ingredient of the CLIC scheme, for which high efficiency in the drive beam acceleration process is paramount. The beam was remarkably stable even at high current and no sign of beam break-up was observed. The RF signals at the structures input/output couplers were used to set-up easily the beam-to-RF phase by maximizing the beam loading. The RF signals were also used to assess the RF-to-beam efficiency where a dedicated experiment was performed [10]. The measured energy gain per module was in excellent agreement to theoretical predictions and an RF-to-beam energy transfer efficiency of 95.3%, including structure losses, was evaluated.

3.2. 30 GHz power production and structure testing
The 30 GHz power station was commissioned in 2004. Structure testing started in 2005 and since 2006 routine operation has been established, with automatic control and remote supervision from the CERN central control room. For power production a special operation mode is used, with higher beam current in the linac (5 A) and about twice the nominal RF power in the linac structures. This is possible since the 3 GHz pulse length (50-400 ns) is much shorter than for nominal operation. The beam momentum is ~100 MeV/c. Up to 100 MW are produced in the PETS, and transported to the test stand with ~70% efficiency. Due to the relatively low beam current compared to CLIC, the PETS coupling must be high and the aperture (6.5 mm) is much smaller than the one for CLIC and the TBTS (23 mm). This makes beam transport difficult and simulations showed that even in the best conditions a few percent losses are to be expected. Indeed, the best performances are at the 5% loss level, often drifting up during operation. The availability of high RF power at 30 GHz with pulses significantly longer than CTF II enabled a vigorous experimental program. Nine different structures have been tested up to now in CTF3 [3]. Results of RF structure testing in CTF3 have been fundamental in the recent CLIC parameter revision. In particular, parallel testing of scaled structures at 30 GHz in CTF3 and at 11.4 GHz at SLAC have provided clear information on frequency scaling, giving a decisive input to the cost and efficiency optimization study.

3.3. Delay loop and combiner ring commissioning
Beam commissioning of the delay loop started in November 2005. A circulating beam was obtained in a short time and a first re-combination test with limited current could be performed. During these tests, a setting-up procedure was developed and validated to determine the optimum power and phase in the RF deflector. Commissioning continued in 2006, when current and pulse length values were close to the then-nominal ones (3.5 A, 1.5 μs). Systematic optics measurements were performed and Transverse emittance and Twiss parameters determined at the entrance of the delay loop through quadrupole scans. The dispersion function at the position of the BPMs was measured as well. Synchrotron light from two dipoles was sent to a streak camera, to check the bunching structure. The bunch length was also measured for different settings of the upstream chicane with good agreement with expectations.

Eventually, a full beam recombination was obtained, as shown in figure 2. The 1.5 μs, 3.3 A incoming pulse is converted in a series of five 140 ns pulses with a current of 5.8 A. About 8.5 % of the initial current is contained in “satellite” bunches, as expected from simulations. This fraction of the beam is not combined in the main pulses and can be seen in the space between them.

A short period in 2006 was dedicated to commissioning of the transfer line TL1 and combiner ring injection region. Short pulses of 200 ns were used. The beam was rapidly transported to the end of the line and a current of 3 A could be injected into the ring. The commissioning restarted at the end of March 2007, with some interruptions for further installation work. The delay loop was bypassed and a first recombination test, over two turns, has been recently performed [11] (see figure 2).
4. CONCLUSIONS

The CLIC study aims at demonstrating the feasibility of a multi-TeV linear collider. The recent parameter study has lead to a new optimized design. The test facility CTF3 addresses the key issues of the CLIC technology. It has already shown the generation and control of high current beams, stable full beam-loading linac operation and high charge bunch train recombination in the delay loop. Furthermore, it is routinely used as a 30 GHz power source for accelerating structure testing, and the results are increasing the knowledge on fundamental limitations of high-gradient structures. Commissioning of the combiner ring is ongoing and could be completed in 2007, proving the feasibility of the CLIC drive beam generation scheme. In 2008, the first beam is expected in the new CLEX area, where several beam lines will be used for studies of the remaining CLIC feasibility issues.

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