EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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OVERVIEW OF CLIC AND CTF3

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Abstract

The CLIC study aims at the design of a high-energy (0.5-5 TeV), high luminosity e+e- linear collider, as a possible facility for the post-LHC era. The beams are accelerated using high-frequency (30 GHz) normal-conducting structures operating at high accelerating gradients to reduce the length and, in consequence, the cost of the linac. The RF power for these structures is generated using the so-called Two-Beam Acceleration (TBA) scheme, where a low-energy, high-intensity electron beam (drive beam) runs parallel to the main linacs and is decelerated in resonant structures, which extract RF power from the drive beam. The drive beam is first accelerated in a low-frequency fully-loaded normal-conducting linac. Its time structure is then obtained by funneling in isochronous rings using transverse RF deflectors. CTF3, a new generation CLIC Test Facility, is being built at CERN to demonstrate the technical feasibility of this novel drive beam generation and RF power production scheme, albeit on a much smaller scale. CTF3 will also constitute a 30 GHz source with the CLIC nominal peak power and pulse length, for RF component testing. In this paper we give an overview of the CLIC study, focusing on the most recent progress and describe the CTF3 status.

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1 INTRODUCTION

The Compact Linear Collider (CLIC) design has been optimised for e± collisions at 3 TeV centre-of-mass and a luminosity of 10^{35} cm^{-2}s^{-1} [1]. However, its design is modular, such that its construction could be staged without major modifications. An overall layout of the complex is shown in Fig.1. Two central complexes produce the e- and e+ main beams and the high-current e- drive beam pulses. Each drive beam pulse is transported to a 625 m long decelerating section, running parallel to the main linac, where it generates ~ 460 MW/m of 30 GHz RF power in resonant structures. The main beams are accelerated in normal conducting travelling wave structures, operating at a gradient of 150 MV/m. A single tunnel houses both the main and the drive linac, the various beam transfer lines and the beam delivery system. No modulators or klystrons are located in the tunnel. Such an arrangement is simple, cost effective and easily extendable. Each 625 m long unit provides 70 GeV acceleration to the main beam. The lowest colliding beam energy (1 unit on either side) is then $E_{cm} \sim 140$ GeV, or even less with some adjustment of the drive-beam intensity. Then, E_{cm} can in principle be increased step by step, modulo ~ 140 GeV, by adding one unit on either side of the interaction point. The nominal energy of 3 TeV requires 2×22 units (about 14 km/linac).
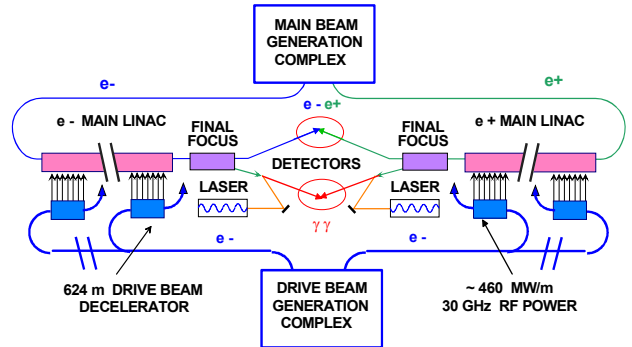

Figure 1: Overall layout of the CLIC complex

The main features of CLIC are the high-frequency, high-gradient acceleration needed to reach multi-TeV collision energies in a reasonable length, and the use of a TBA scheme in which the drive beam time structure is obtained by bunch train combination in isochronous rings using transverse RF deflectors [2]. Other critical issues are the generation and acceleration of very low emittance beams and their focusing to spot sizes in the nm range, implying severe requirements on component alignment and stability. All of these features are being addressed following both theoretical and experimental approaches. In this paper we will first describe recent progress on some of these issues, then we will concentrate on the status of the new test facility, CTF3.

2 PROGRESS IN CLIC CRITICAL AREAS

2.1 High-Gradient Accelerating Structures

Over the last few years it has become apparent that the main limitation in reaching the CLIC design gradient (150 MV/m for a pulse length of 130 ns) is given by RF breakdown and the consequent damage to the accelerating structures [3]. Transverse wakefields and pulsed surface heating are the other main constraints. An intense program of design development and high-power structure tests has been carried out at CERN with the goal of demonstrating the required performances. A number of different structures have been tested in the CLIC Test Facility CTF2, where deceleration of a high-current drive beam can produce 30 GHz pulses having power levels up to 250 MW with a maximum length of 16 ns. Results have shown that, for pulse lengths above 10 ns, the maximum surface field that can be obtained with copper is always around 300-400 MV/m. In large aperture structures this correspond to accelerating gradients of 60-70 MV/m. At this field level the structures suffer severe surface damage in the high-field region.

The most likely explanation is the occurrence of melting and erosion by field-emitted electrons, being accelerated from one side of the iris to the other during breakdown. Similar experimental results were obtained at SLAC where damage was detected in X-band structures conditioned up to accelerating gradients in the 50 to 70 MV/m range [4]. The strategy followed by the CLIC study group to resolve the problem is based on two complementary approaches: a) use of new materials, more resistant to arcing (e.g., tungsten), in the high-field region; b) decrease the ratio between the surface and the accelerating field, E_S/E_A.

The first approach was initially tested by replacing a damaged copper iris by a tungsten one, clamped to the end of the copper structure. The structure with the tungsten iris reached a somewhat higher gradient, being eventually limited by the (copper) output coupler. While the copper iris was severely damaged, the tungsten iris was not. A closer analysis has shown copper droplets deposited on the tungsten iris, evidently removed from the downstream copper iris, where the surface field was lower.

The ratio E_S/E_A can be reduced using smaller iris dimensions, but the price to pay is an increase of the short-range transverse wakes. However, by using an elliptical longitudinal profile of the iris itself and a lower phase advance per cell, E_S/E_A can be reduced to values close to 2 while still keeping reasonable performances in terms of short-range wakes. Particular attention must also be given to the input coupler, where the peak surface field is a maximum for conventional designs. A novel design, the so-called mode launcher coupler has been developed in order to solve this problem [5].

Recently, these approaches have shown success. A 30 cell structure, with a geometry optimised for $E_S/E_A \sim 2$ and equipped with tungsten irises and a mode-launcher coupler was conditioned in CTF2 up to an accelerating gradient of 125 MV/m (checked by measuring acceleration of a test beam) and was found undamaged after inspection [6]. It must be noted that the gradient reached in the first cell was 150 MV/m. The conditioning history of the structure is shown in Fig. 2.
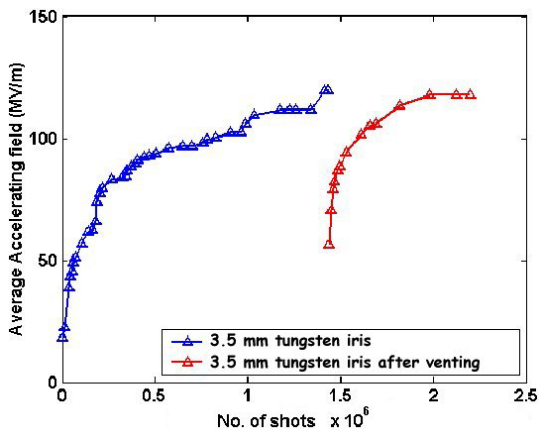

Figure 2: Average accelerating gradient reached during conditioning of the tungsten iris structure, before and after inspection.

Although the achieved gradient is close to the required performance, the RF pulse length (16 ns, limited by the maximum drive beam pulse length in CTF2) was still far below the CLIC nominal value of 130 ns. An experiment is planned where the pulse will be stretched to 32 ns, but the nominal pulse length will only become accessible in the Initial Phase of CTF3.

2.2 Alignment and Stability

The transverse spot size of the CLIC colliding beams is 60 nm (horizontal) times 0.7 nm (vertical). The associated magnet vibration tolerances are extremely tight (see Table 1), even if the use of beam-based feedbacks can cure the effect of magnet vibrations at frequencies below 4 Hz. A test stand for magnet vibration has been set-up at CERN to address this issue [7].

Table 1: Magnet stability requirements (> 4 Hz) for a 2 % loss in luminosity

Magnet		Ix	Iy
Linac	(2600 quads)	14 nm	1.3 nm
Final focus	(2 quads)	4 nm	0.2 nm

The properties of the test site were surveyed, and the rms floor vibration above 4 Hz was found to be about 6 nm. Though the stability of deep CERN accelerator tunnels is in the sub-nm range in quit conditions, technical noise can enhance vibration to the 5 nm level. The level of ground motion at the test stand can therefore be considered as representative of a realistic accelerator environment.

The experimental set-up consists of a honeycomb support table with minimized structural resonances, supported by actively stabilized feet (STACIS2000 from TMC), with integrated geophones, rubber pads for passive damping and piezo-electric movers for active damping. GeoSig geophones, with sub-nm accuracy in the 1 Hz – 315 Hz range, were used to monitor vibration on the floor, on the table-top and on a quadrupole doublet mounted on the table itself.

A vibration damping of up to a factor 20 was achieved from the floor to the table-top. Vibration was reduced in all directions. The rms residual vibration amplitudes above 4 Hz, measured on the quadrupole doublet, were 0.9 ± 0.1 nm, 0.4 ± 0.1 nm and 3.2 ± 0.4 nm, in the vertical, horizontal and longitudinal direction, respectively. Fig. 3 shows the measured vertical vibration on floor, table and quadrupole, integrated above a given frequency.

The influence of cooling water was also studied. The vertical rms motion above 4 Hz increases to 1.3 ± 0.2 nm for the nominal flow. The measured vibration levels meet the requirements for the 2600 linac quadrupoles while a further suppression by a factor 2-5 is needed to meet the tolerances for the Final Focus doublet. Further tests are planned, including the implementation of an alternative pneumatic system.
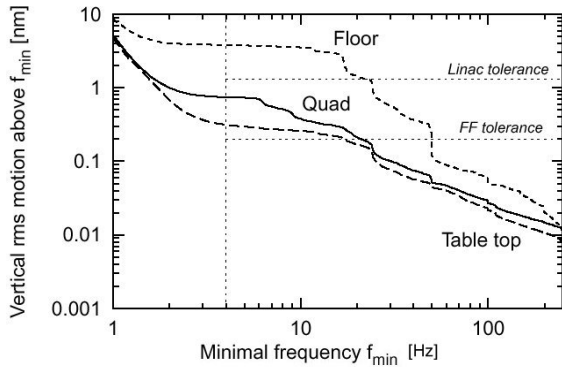
Figure 3: Vertical rms residual vibration versus frequency on floor, table-top and quadrupole in the CLIC test stand.

2.4 Other Recent Progresses

Some progress has been made in the design of a damping ring, although the very stringent requirements at 3 TeV have not yet been reached. The main limitation is intra-beam scattering, but electron cloud and fast ion-beam effects are also a concern [8]. On the other hand, some margin exists for emittance blow-up in the linac, which seems now to be well under control [9]. The beam delivery system has been shortened to ~ 2.5 km/side for all centre-of-mass energies from 500 GeV to 3 TeV [10].

A new design of the Power Extraction and Transfer Structures (PETS), used to generate RF power from the drive beam has been completed [11]. The new structure is circularly-symmetric with a large aperture (25 mm) and shallow sinus-type corrugations. The eight 1 mm-wide longitudinal loaded slots provide a much better damping of dipole modes (Q < 50) than the old 6-waveguides design. A new RF power extractor, based on the mode launcher concept has also been developed for the PETS. The PETS circularly symmetric mode is converted to a TE mode in rectangular waveguides, with 99 % efficiency. The extractor has the additional advantage of a very short length (~ 4 cm) and of relaxed fabrication tolerances due to the wide frequency band (~ 1 GHz).

3 THE CLIC TEST FACILITY CTF3

In CLIC, a very efficient and reliable RF source is required, in a frequency region (30 GHz) above the usual range of klystrons, to provide ~ 460 MW per meter of linac, with a pulse length of 130 ns. A two-beam acceleration scheme is proposed [2], in which the drive beam is accelerated using a low RF frequency, where klystrons are available. The accelerating cavities are fully-loaded, so that practically all the RF power is converted into beam energy. The drive beam bunch trains are then interleaved by injection with transverse RF deflectors in isochronous rings, thereby increasing the bunch repetition frequency and shortening the bunch train. The final drive beam time structure (2 cm bunch spacing) has a strong 30 GHz component and the RF power is extracted from it periodically in resonant structures and transferred to the main beam.

The main goal of the new test facility, CTF3 [12] is to demonstrate the key concepts of the new RF power generation scheme, namely the combination scheme and the fully-loaded accelerator operation, albeit on a much smaller scale and starting with a different frequency. CTF3 will also be the first high-power source of 30 GHz power with the nominal CLIC pulse length (130 ns), allowing a full-scale test of accelerating cavities and RF components. The project is based in CERN, with collaborations from INFN-Frascati, IN2P3/LAL at Orsay and SLAC. The facility will be built in stages and located in the former LEP Pre-Injectors (LPI) complex, making maximum use of equipment available after the end of LEP operation. In particular, the existing RF power plant at 3 GHz and most of the LPI magnets will be used.

The new accelerating structures, adapted to high current operation, will only become available in 2003. Therefore, a low current test of the combination process (CTF3 Preliminary Phase), which uses the existing LEP Injector Linac (LIL) structures, has been set-up and is now operational [13]. Its status is presented in Section 3.1. A second stage (CTF3 Initial Phase), using the new linac, will allow for a test of fully-loaded acceleration and will have a 30 GHz power production capability. The final configuration of CTF3 will be reached in the third stage (CTF3 Nominal Phase). The Initial and Nominal phases are also described in subsequent sections.

3.1 Results of The Preliminary Phase

The LPI complex, composed of a linac and a storage ring, was substantially modified in 2001 for the Preliminary Phase. The linac was shortened, freeing up space to install the injector for the later phases. A new matching and diagnostics section was added after the linac. The injection line and the ring were modified to be isochronous. The old gun was replaced by a new one (provided by LAL), which can produce several pulses (~ 6 ns, 1 A maximum current) spaced by 420 ns, corresponding to the revolution time in the ring. In order to measure the beam time structure, optical lines were built to transport the light generated by the beam at several locations in the machine (including synchrotron radiation ports, Cherenkov and transition radiation screens) to a streak camera.

The commissioning of the new installation started in September 2001, alternating beam operation with shut-down periods. Progress was fast, with the first circulating beam in the ring in December 2001. Measurements of Twiss parameters, bunch length, dispersion and betatron tune substantially confirmed the expected performances.

The two transverse RF deflectors needed for the combination experiment were installed in the ring after the winter shut-down. Bunch trains were successfully combined and combination factors of 4 (as required in CLIC) and of 5 (as in CTF3 Nominal Phase) were obtained. The beam time structure obtained by combining four pulses from the linac is shown in Fig. 4.
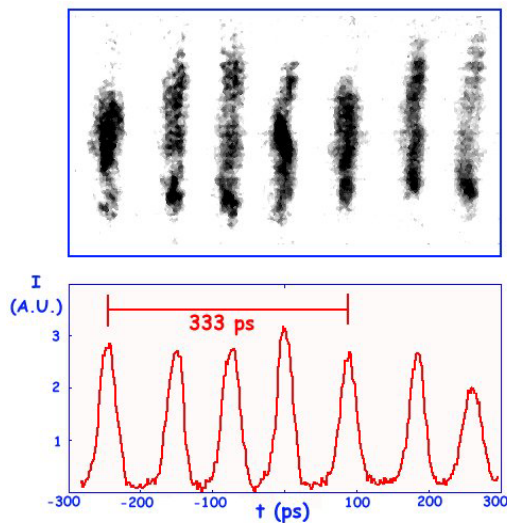
Figure 4: Streak camera image of the combined bunch train (top) and corresponding intensity profile (bottom). Only a fraction of the total pulse (~ 6 ns long) is shown.

Further tests are planned before the operation is stopped in October 2002, including the commissioning of a bunch phase monitor built in collaboration with Uppsala University [14] and of a pair of RF deflectors built by INFN-Frascati for the high-charge operation of the CTF3 Nominal Phase.

3.2 The Drive Beam Injector

The drive beam injector for the CTF3 Initial and Nominal phases is being built in collaboration with SLAC (gun triode and beam dynamics design) and LAL/Orsay, (gun electronics and 3 GHz pre-bunchers). Its installation in the former LPI building is foreseen for the beginning of 2003. The 1.6 μs long drive beam pulse is generated by a 140 kV, 9 A thermionic triode gun. The bunching system is composed of a set of 1.5 GHz sub-harmonic bunchers, a 3 GHz pre-buncher and a 3 GHz graded-β travelling-wave buncher. The phase of the sub-harmonic bunchers is switched rapidly by 180° every 140 ns. In order to obtain a fast switching time ($\leq$ 4 ns), the 1.5 GHz RF source must have a broad bandwidth (about 10 %) and a peak power of 500 kW. The 2.3 nC bunches are spaced by 20 cm (two 3 GHz buckets), corresponding to an average current of 3.5 A. The drive beam pulse is thus composed of 140 ns sub-pulses, which are phase-coded and can be later separated by transverse deflectors working at 1.5 GHz. In the Initial Phase, the sub-harmonic bunchers will not be installed, and the bunches will be spaced by 10 cm. Two 3 GHz travelling wave structures bring the beam energy up to about 20 MeV. Solenoidal focusing is used all along the injector. A magnetic chicane with collimators is used to eliminate low energy beam tails and to perform bunch compression in the Initial Phase.

As an alternative option to the thermionic injector, the use of an RF photo-injector is also under study for a potential later upgrade [15].

3.3 The Drive Beam Linac

The drive beam pulse is brought to 150 MeV in the drive beam accelerator, composed of 8 modules of 4.5 m length. Each module is composed of two travelling wave accelerating structures and a quadrupole triplet.

The structures [16] work in the $2\pi/3$ mode, have a total length of 1.22 m and operate at a loaded gradient (nominal beam current) of 6.5 MV/m, with an RF-to-beam efficiency of ~ 97 %. In order to suppress the transverse Higher Order Modes (HOMs) the structures (called SICA, for Slotted Iris Constant Aperture) use four radial slots in the iris to couple out the HOMs to SiC loads. The selection of the modes coupled to the loads is obtained through the field distribution, so that all dipole modes are damped. The Q-value of the first dipole is reduced below 20. A further reduction of the long-range wakefields is achieved by a spread of the HOM frequencies along the structure (detuning), obtained using nose cones of variable geometry. Beam simulations have shown that the normalised rms emittance ($100\,\pi$ mm mrad) is conserved during acceleration despite the high beam current and the long beam pulse. A 6-cell prototype structure has been built and successfully tested up to power levels of 100 MW, well above the nominal value of 30 MW (see Fig. 5). A full size prototype is now being prepared and an order for 18 structures has been placed with industry. The structures will become available in 2003-2004.

Figure 5: The 6-cell SICA prototype before the high-power tests.

The RF power is supplied by eight klystrons and compressed by a factor 2 to provide 1.5 μs pulses with 30 MW power at each structure input. The pulse compression system uses a programmed phase ramp to get a rectangular pulse. High-power tests of the system are under way to assess the required amplitude and phase stability on the RF pulse flat-top. In the Initial Phase, it is foreseen to compress the RF pulse to ~ 200 ns and to increase the beam current to 5 A, providing a beam suitable for 30 GHz power production at the end of the linac.

3.4 The Delay Loop and the Combiner Ring

After the linac, a first stage of electron pulse compression will be obtained in the Nominal Phase using a transverse RF deflector at 1.5 GHz and a 42 m delay loop. The phase-coded sub-pulses are first separated and then recombined by the deflector after half of them have been delayed in the loop, obtaining a sequence of five 140 ns long pulses with twice the initial current. An 84 m long combiner ring is used for a further stage of recombination by a factor five. After the ring, a single 140 ns long drive beam pulse with 35 A current and 2 cm bunch spacing is obtained. INFN/Frascati is responsible for the delay loop, the combiner ring and the related beam lines. Both the delay loop and the ring are isochronous in order to preserve bunch length and spacing. The ring arcs are triple-bend achromats, with negative dispersion in the central dipole. Three sextupole families in the arcs minimise the second-order momentum compaction and control the ring chromaticity. A potential problem at high current is transverse instability by multi-bunch beam loading of the deflector fundamental mode. Detailed studies have shown that the beam is stable for a proper choice of the deflector parameters, of the β-function at injection and of the ring tune [17]. The use of short, high-charge bunches also puts stringent requirements on the ring impedance and makes beam energy loss by coherent synchrotron emission a concern. In order to minimise these effects, the rms bunch length will be increased after the linac by a magnetic chicane from 1.3 mm to a maximum of 2.5 mm in the delay loop and ring. After combination, the bunches are compressed to ~ 0.5 mm rms and transported to the 30 GHz test area. The ring, loop and transfer line design is now essentially complete, and prototypes of several components (e.g., beam position monitors, low-impedance vacuum chamber equipment, extraction kickers) are presently under test at Frascati. The installation of the ring is planned for 2004.

3.5 30 GHz Power Production

A high power test stand, similar to the one used in CTF2 [3], will be used to test structure and RF components at the CLIC nominal power and beyond. The test stand will be equipped with a PETS optimised for power production and instrumented with breakdown-detection equipment and spectrometers to measure acceleration and deceleration. The commissioning of the test stand, placed half-way along the linac (~70 MeV beam energy) is planned for the end of 2003. Later, the test stand can later be moved to the end of the linac and used in parallel with low-charge commissioning of the ring. A dedicated area in a building extension is foreseen for the test stand in the Nominal Phase. Eventually, the drive beam can be used in a string of PETS to power a representative section of the CLIC main linac and to accelerate a probe beam, generated in a 3 GHz RF photo-injector and pre-accelerated using LIL structures. This set-up will allow us to simulate realistic operating conditions for the main building blocks of the CLIC linac.

6 CONCLUSIONS

The CLIC technology is at present the most promising route towards the multi-TeV energy range in future linear colliders. Although some challenges still need intense research and development efforts, substantial progress has been made in many critical areas.

The understanding of breakdown and damage problems in high-gradient structures has improved, and an accelerating structure with tungsten irises has recently reached a peak gradient of 150 MV/m, without damage. A test at the nominal pulse length of 130 ns is envisaged at an early stage in the next test facility, CTF3. It has also been shown experimentally that the stability requirements of the main linac quadrupoles can basically be met. Relevant progress has also been made in other areas, like RF power production by a drive beam, control of emittance blow-up and beam delivery system design.

The experimental program of the CTF3 Preliminary Phase is being completed as scheduled. In particular, the bunch train combination method by funneling in isochronous rings with RF deflectors on which the CLIC scheme is based has been demonstrated at low beam current. Finally, important steps in hardware development and construction for the following phases of CTF3 have been made.

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