

Achievements and Future Plans of CLIC Test Facilities

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Abstract

CTF2 was originally designed to demonstrate the feasibility of two-beam acceleration with high current drive beams and a string of 30 GHz CLIC accelerating structure prototypes (CAS). This goal was achieved in 1999 and the facility has since been modified to focus on high gradient testing of CAS's and 30 GHz single cell cavities (SCC). With these modifications, it is now possible to provide 30 GHz RF pulses of more than 150 MW and an adjustable pulse length from 3 to 15 ns. While the SCC results are promising, the testing of CAS's revealed problems of RF breakdown and related surface damage. As a consequence, a new R&D program has been launched to advance the understanding of RF breakdown processes, to improve surface properties, investigate new materials and to optimise the structure geometries of the CAS's. In parallel the construction of a new facility named CTF3 has started. CTF3 will mainly serve two purposes. The first is the demonstration of the CLIC drive beam generation scheme. CTF3 will accelerate a 1.54 μ s long electron pulse of 3.5 A in a fully beam-loaded S-band linac. The linac beam pulse is compressed in isochronous rings to 140 ns pulse-length, 35 A beam current and a micro-bunch repetition rate of 15 GHz. The second purpose of CTF3 is to test CAS's with nominal CLIC parameters. For this reason the drive beam extracted from the combiner ring is transported through a string of 30 GHz power extraction cavities feeding CAS's. The 30 GHz acceleration is measured with a probe beam provided by a small, separate S-band linac.

1 EXPERIMENTS WITH CTF2

CTF2 has been constructed to demonstrate the feasibility of the CLIC [1] two beam acceleration scheme. The layout of CTF2 as operated in 1999 is shown in figure 1a. The drive beam generates 30 GHz power, while the probe beam measures the accelerating field in the 30 GHz accelerator. Both beams are generated by S-band RF photo-injectors. The RF photo-injectors cathodes are illuminated by a short pulse (8 ps FWHM) laser. The maximum drive beam charge obtained is 750 nC distributed among 48 bunches with a bunch spacing of 10 cm. A magnetic chicane compresses the bunches to ≤ 5 ps for efficient 30 GHz power production. After compression, the beam is injected into the 30 GHz decelerator, where a part of its energy is converted into 30 GHz power. A downstream spectro-meter magnet measures the energy of the beam after power extraction.

The probe beam operates with a single bunch of ≤ 1 nC charge. Before being injected into the 30 GHz accelerator, the probe beam is accelerated to 46 MeV in an S-band travelling wave structure. This is necessary to obtain a small enough geometric emittance to fit into the 4mm \varnothing aperture of the 30 GHz accelerating structures. Magnetic spectrometers before and after the 30 GHz accelerator are used to measure the beam energy.

Two beam acceleration

With the 1999 CTF2 configuration two beam acceleration was successfully demonstrated with four 30 GHz power extraction structures decelerating the drive beam and a string of five 30 GHz accelerating structures, accelerating the probe beam by 60 MeV. More information and references about techniques developed for CTF2 and two beam acceleration results can be found in [2].

CTF2 used as 30 GHz high power test stand

Observation of RF induced damage in X-band structures at SLAC triggered the inspection of 30 GHz accelerating structures used in CTF1 [3] and CTF2. It was found that those structures that had been run at mean accelerating fields in excess of 60 MV/m showed signs of damage on the beam iris of the input coupler cell. This came as a surprise since the usual indication of RF breakdown, full reflection of power, was never observed. As a consequence of these observations it was decided to abandon the original plan of dismantling CTF2 and instead CTF2 was converted into a high power test stand for studying RF breakdown phenomena. A 1 m long, 30 GHz power extraction structure was constructed and installed in the drive beam line and the existing four 0.5 m structures were dismantled (fig. 1b). With this configuration 150 MW 30 GHz power is produced in a single WR28 waveguide. This allows to test CLIC prototype accelerating structures at mean accelerating fields up to 155 MV/m. On the probe beam side the string of 30 GHz accelerating structures was taken out and a testbed for one 30 GHz accelerating structure was installed. This testbed is equipped for measurements of:

- dark current charge and energy
- incident, reflected and transmitted RF power
- acoustic vibrations of the structure
- visible light emitted from the structure
- acceleration of the probe beam
- vacuum pressure

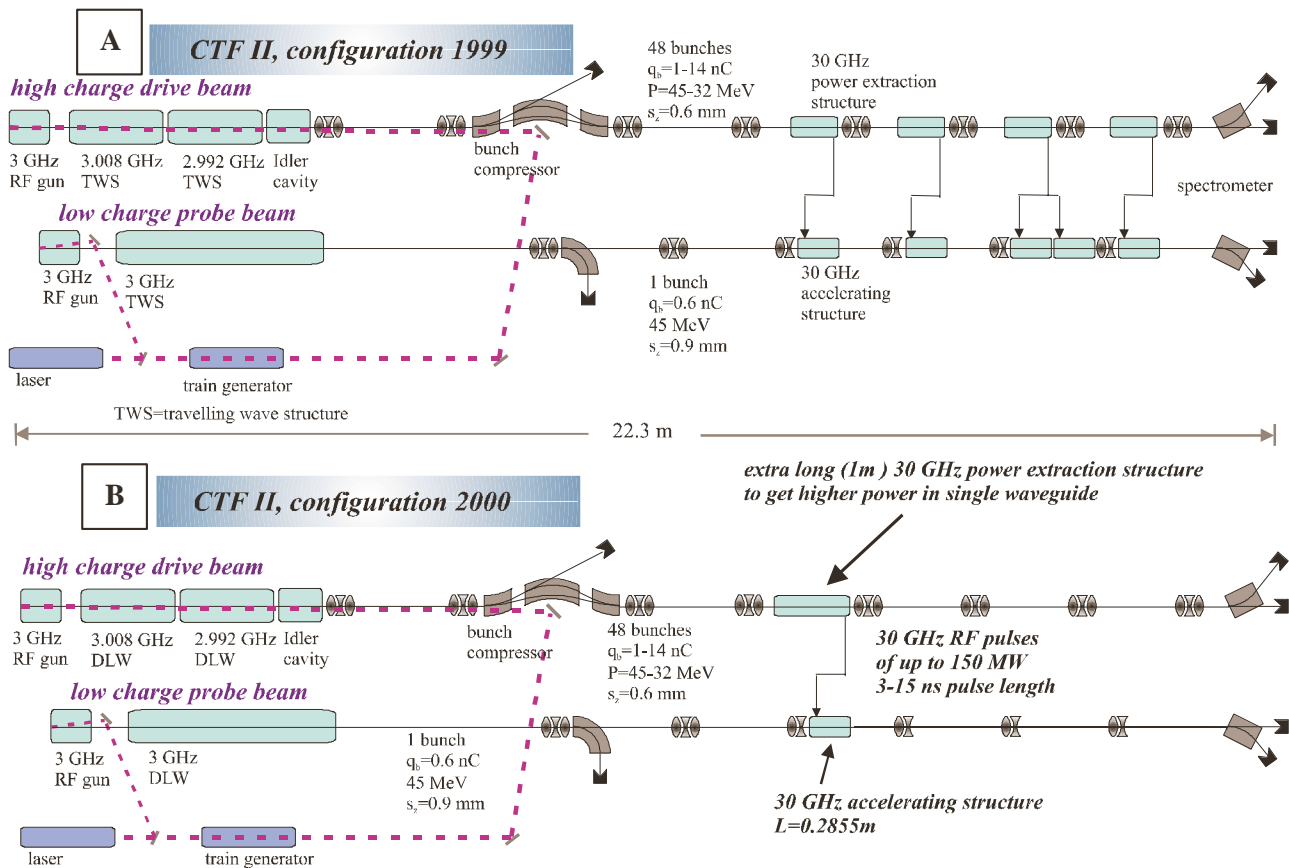


Figure 1 CTF2 configurations A: for two beam acceleration with a string of 30 GHz structures B: for high power testing of 30 GHz structures

Three different structures have been tested so far. Two are disk-loaded waveguides of 28.5 cm active length and constant impedance. The main difference between these two CAS is the coupler design, which is the standard CTF single feed design in one case and a prototype double feed design in the other. The third structure was a 12.3 cm long planar structure build at the Technische Universität of Berlin/Germany. The single port disk loaded structure was breakdown limited at a mean accelerating gradient of 60 MV/m corresponding to a peak surface field of 265 MV/m. The two port structure reached a mean accelerating gradient of 70 MV/m corresponding to a peak surface field of 266 MV/m. Both structures have the maximum surface field on the iris between the coupling cell and the first regular accelerating cell. Post-mortem inspection of both structures showed damaged surfaces at only this location. The planar structure reached an accelerating gradient of 50 MV/m. The peak surface field for this structure is estimated to be ≈ 300 MV/m. Post-mortem inspection showed slight damage in the coupler region for this structure as well. All field values quoted above are for 15 ns pulse length. Accelerating fields of 140 MV/m and surface fields of 620 MV/m have been reached for 3 ns pulses. A large quantity of data has been collected to

characterise the RF breakdown process. One important observation is that RF breakdowns in the CTF2 parameter regime hardly give reflected power as in more conventional RF cavities. This explains why we didn't observe these breakdown events in our past experiments. However, breakdowns produce intense electron bursts. The intensity of the electron bursts is strongly correlated with a reduction of the RF power transmitted through the structure. Another fascinating feature which has been observed are light pulses emitted during RF breakdowns which have a duration of few hundreds of ns, thus much longer than the RF pulse itself. First experiments with accelerometers show the presence of acoustic waves with amplitude proportional to the RF power. This amplitude increases strongly when a breakdown occurs. This system will be further improved with the goal to localize breakdown events in the structures.

30 GHz, single cell, high gradient experiments

High gradient experiments have been performed with a single 30 GHz cell powered directly by the CTF2 drive beam. After conditioning the cavity with $5 \cdot 10^5$ pulses the onset of breakdowns was observed for $E_{SURF} \tau 380$ MV/m. The cavity was powered while its temperature was varied from 100 K to 500 K. No significant influence of

temperature on the breakdown threshold was observed. The observation of a positive shift of the resonant frequency by about 200 MHz and the occurrence of delayed breakdown as seen in an earlier experiment with this cavity [4] was confirmed (unfortunately, due to a calibration error, all field values quoted in [4] have been too large by a factor $\sqrt{\pi}$). During this year we plan to continue this kind of experiments with cavities operating at 21, 30 and 39 GHz to gather information about the frequency scaling of RF breakdowns.

Structure R&D program

To overcome the RF breakdown and damage problems with the 30 GHz structures an R&D program has been established to find improved solutions. This program has two approaches:

- Improve the geometry of the structures. Since our present data seem to indicate that the peak surface field is so far our main limitation we try to reduce the ratio $\hat{E}_{\text{SURFACE}}/E_{\text{ACCEL}}$. A gain of almost a factor 2 in gradient without compromising much on the acceleration efficiency and transverse wakefield amplitudes is expected.
- Investigate new materials. A hybrid tungsten/copper structure will be built with tungsten in the regions where the electric field is highest.

Construction and testing of prototypes using these approaches is planned in CTF2 for 2001 and 2002.

Coherent synchrotron radiation experiments

Experiments have been performed with the CTF2 drive beam bunch compressor to measure the influence of coherent synchrotron radiation on beam emittance and energy. These experiments are used to benchmark CSR simulation programs. Details are found in [5].

2 CTF3, GOALS AND PLANS

The construction of a third phase of CLIC test facilities has started recently [6]. CTF3 will mainly serve two purposes. The first is the demonstration of the CLIC drive beam generation scheme [7]. CTF3 will accelerate a $1.54 \mu\text{s}$ long electron pulse of 3.5 A in a fully beam-loaded S-band linac. The linac beam pulse is compressed in isochronous rings [8] to 140 ns pulse-length, 35 A beam current and a micro-bunch repetition rate of 15 GHz. The second purpose of CTF3 is to test CAS's with nominal CLIC RF parameters for power and pulse-length. For this reason the drive beam extracted from the combiner ring is transported through a 30 GHz decelerator feeding CAS's. The 30 GHz acceleration is measured with a probe beam provided by a small, separate S-band linac. A schematic layout of CTF3 is shown in Fig. 2.

Drive beam injector

The drive beam injector [9] is built in collaboration with LAL/Orsay and SLAC, with SLAC providing the gun triode and the beam dynamics design; and LAL providing the gun electronics circuitry and the 3 GHz pre-bunchers. The injector features a 140 kV, 9 A thermionic triode gun, a set of 1.5 GHz subharmonic pre-bunchers with fast 180° phase switching every 140 ns as needed for the phase coding described in [7], 3 GHz pre-bunchers, a graded- β travelling wave buncher with higher order mode dampers and two TW accelerating structures (see below). The buncher and the accelerator structures are embedded in a long solenoid with a maximum on-axis field of 2 kG. A magnet chicane with collimators downstream of the injector will be used to eliminate low energy beam tails produced during the bunching process.

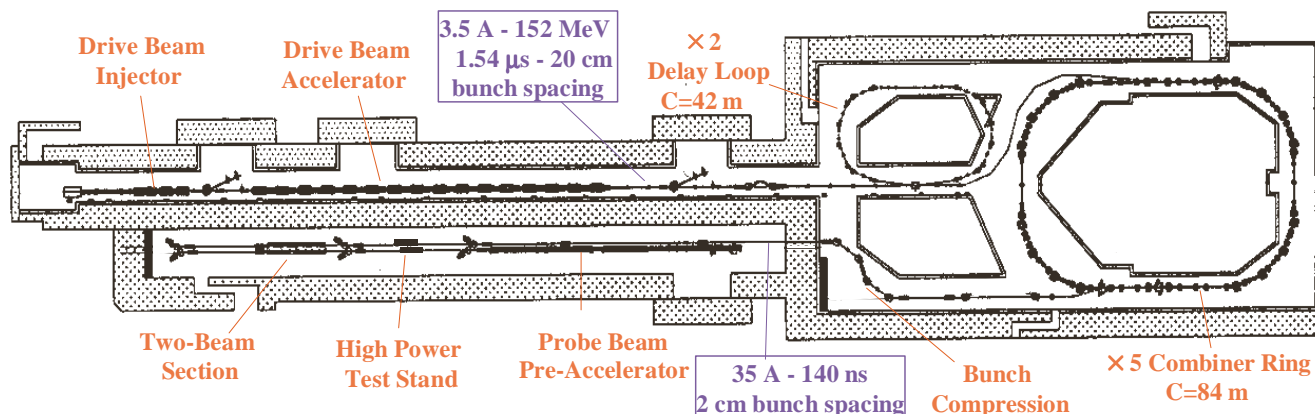


Figure 2 Layout of CTF3

RF photo-injector option

As an alternative to the thermionic injector discussed above an RF photo-injector for the drive beam is studied as a potential later upgrade for CTF3. The advantages of such a solution are smaller beam emittances in all three phase space planes, absence of low charge parasite bunches in every second 3 GHz bucket, no phase/energy tails as produced in conventional bunching systems, and easier tailoring of the 180° phase switching. The design of the RF gun for such an injector can be based on existing CTF2 guns [10] with moderate modifications, but producing the long drive beam train requires a new laser design. Moreover, the average cathode currents exceeds by far values achieved with RF photo-injectors presently in operation. The specification of the beam for the CTF3 photo-injector leads to the design requirements of the laser system:

- 1.5 GHz oscillator frequency,
- 1.54 μ s burst of 2310 pulses,
- 15 μ J/ pulse, 35 mJ/ train,
- pulse train intensity stability better than 0.3 %,
- synchronisation to better than 1 ps,

In order to meet the specifications RAL/UK has made a study of a laser system as needed for a CTF3/CLIC drive beam photo-injector [11]. It is concluded that such a laser is feasible with heavily saturated, diode-pumped ND:YLF laser amplifiers. When these are operated at the high bunch repetition frequency of the CTF3 beam, 33 kW of instantaneous diode pump power will be needed in the final amplifier to maintain equilibrium conditions during the train. Tests are underway at RAL to prove the validity of the proposed system including the construction of a 5 kW amplifier section. The cw laser oscillator needed for injection into the amplifier should be high power in order to reduce the gain requirement on the amplifier. Yet the high frequency (1.5 GHz) implies a short cavity of 667 ps round trip time. Such high power, mode-locked laser oscillators are studied at the Institute of Photonics in Glasgow/UK with especial attention to the CTF3 specifications. Tests are conducted on a 200 W CW oscillator based on a “thin disk” configuration where the active laser material is only 0.2 mm thick.

The feasibility of photo-cathodes with the required performance for CTF3 has recently been demonstrated with an experiment in the CTF photo-cathode laboratory. In this test a high power laser with 100 ns pulselength and $\lambda=262$ nm was used to illuminate Cs_2Te cathodes in a 80 kV electron gun. The spot size of the laser beam on the cathode was 6 mm FWHM. Vacuum levels were typically 10^{-9} mbar. During these tests quantum efficiencies of better than 1.5% were maintained for more than 2 weeks of operation with mean beam currents of 0.7 mA. This performance exceeds by far the CTF3 requirements and brings in reach the use of an RF photo-injector for the CLIC drive beam.

Drive beam accelerator

The drive beam accelerator will consist of 8 modules of 4.5 m length. Each module consists of two accelerating structures, a BPM, a quadrupole triplet and a pair of steering magnets. The structures are fed by one 35 MW klystron with RF pulse compression. The pulse compression uses a programmed phase ramp to get an almost rectangular RF pulse with a power multiplication of ≈ 2 . Extensive beam dynamics simulations have shown that this configuration conserves a small emittance along the linac despite of the high beam current. However, HOM suppression techniques as described below are a must.

3 GHz drive beam accelerating structures

The requirements of fully loaded operation with high RF to beam power efficiency and a beam current of 3.5 A lead to a $2\pi/3$ mode travelling wave structure design with 100 ns filltime. The active length is 1.13 m and the energy gain with full beam loading is 8 MeV. The high beam current together with the long beam pulse length of 1.54 μ s requires an effective suppression of higher order modes (HOM's). Two different structure designs have been developed to cope with the HOM's. The first design is derived from the 30 GHz tapered

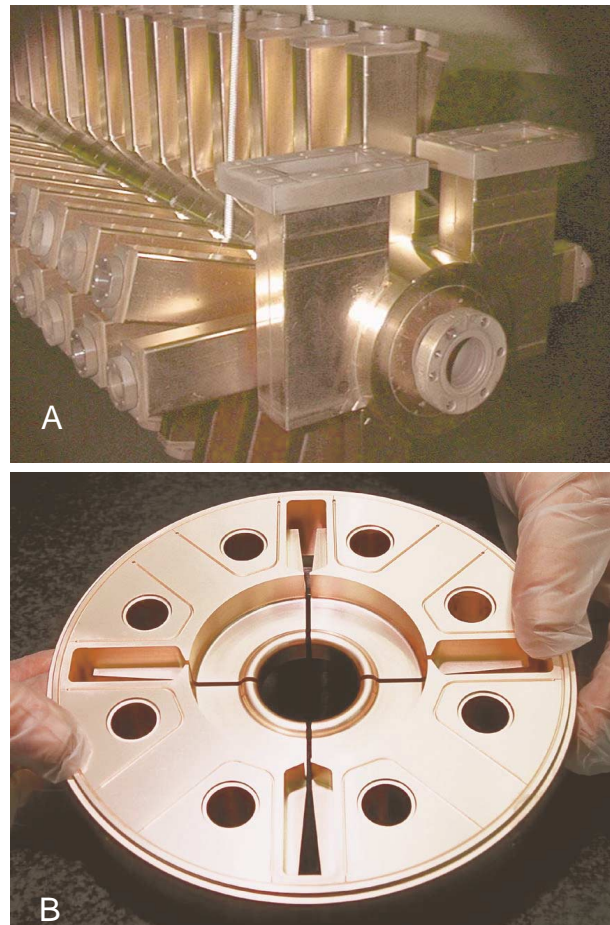


Figure 3 A) The TDS prototype structure
B) A SICA prototype cell

damped structure (TDS) of the CLIC main beam [12] using four waveguides with wideband SiC RF-loads per accelerating cell. The cut-off frequency of these waveguides is in-between the accelerating mode and the first HOM, thus acting as a high pass filter. With this method the Q value of the first HOM is reduced to about 18. Further reduction of long range wakes is achieved by spreading the HOM frequencies by varying the aperture diameter along the structure from 34 mm to 26.6 mm. A full prototype of this structure has been built and power tested up to 40 MW (fig. 3a).

The second approach, called SICA for slotted iris constant aperture, uses four radial slots in the iris to couple the HOM's to SiC RF-loads (fig 3b). In this approach the selection of modes coupled to the loads is due to the mode symmetry, thus all dipole modes are damped. The SICA structure has a Q value of the first HOM of ≈ 5 . As in the TDS the HOM mode frequencies are spread along the structure. The spreading is achieved by a nose cone of variable length keeping the aperture constant at 34 mm. A prototype for testing is under construction

Delay loop and combiner ring

The design of the delay loop, combiner ring and related beam transfer lines is done by INFN/Frascati [8]. Magnet lattices isochronous to 2nd order have been developed (fig. 4). Wiggler magnet chicanes are foreseen for adjusting the ring circumference precisely to a $N + \frac{1}{5}$ multiple of the bunch spacing. Prototypes of these wigglers are under construction. The design work for the 3 GHz RF deflectors used as injection kickers in the ring is under progress at Frascati as well. The short bunch length of $\sigma_z \approx 2$ mm and the high bunch charge of 2.33 nC puts stringent requirements on vacuum chamber impedance and makes coherent synchrotron radiation energy loss a serious issue.

Before the assembly of the different parts of CTF3 a prove of principle experiment at low beam current is planned to demonstrate bunch frequency multiplication by injection with RF deflector cavities in an isochronous

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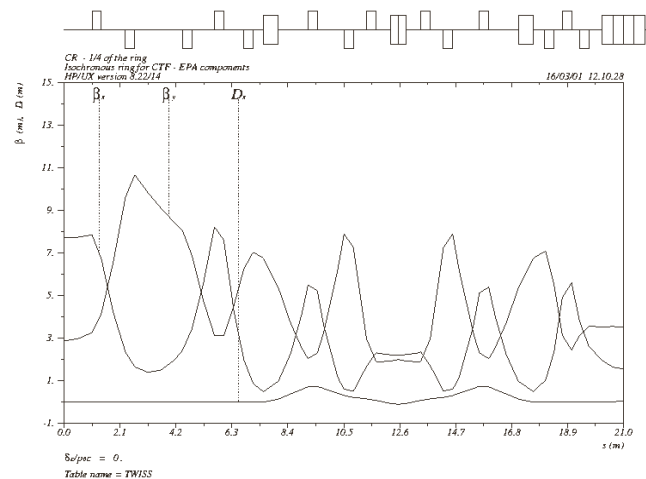


Figure 4 Optical functions of one combiner ring quarter.

ring [13]. This experiment will make use of the former LEP electron injector linac and accumulator ring with some appropriate modifications. A new 80 kV electron, necessary to get the right time structure for this experiment, has been designed and constructed at LAL/Orsay.

30 GHz test area

The beam extracted from the combiner ring consists of a 140 ns bunch train, with a bunch repetition rate of 15 GHz and a beam current of 35 A. This beam can be used to drive a single 30 GHz decelerator structure optimised for the given beam energy/current combination. This RF source will be used to test the performance and limitations of CLIC prototype RF structures and waveguide components at nominal power and beyond. It will allow to perform these tests with a pulse-length comparable to the nominal CLIC value of 120 ns, which is not possible with CTF2. Alternatively the extracted beam can drive a string of decelerating structures to power a representative section of the CLIC main linac and to accelerate a probe beam. This set-up will allow to simulate realistic operating conditions for the main building blocks of the CLIC linac.

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