CTF3 - A DEMONSTRATION OF THE CLIC RF POWER SOURCE

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Abstract
The CLIC (Compact Linear Collider) RF power source is based on a new scheme of electron pulse compression and bunch frequency multiplication. In such a scheme, the drive beam time structure is obtained by the combination of electron bunch trains in isochronous rings. The next CLIC Test Facility (CTF3) at CERN will be built in order to demonstrate the technical feasibility of the scheme. It will also constitute a 30 GHz RF source with CLIC's nominal peak power and pulse length, which can be used to test accelerating structures and other RF components. CTF3 will be installed in the area of the present LEP pre-injector complex and its construction and commissioning will proceed in stages over five years. In this paper we present an overview of the facility and provide a description of the different components.

1. INTRODUCTION

The CLIC design of an e^+e^- linear collider aims at a centre of mass energy in the multi-TeV range. In order to demonstrate the feasibility of such a collider, a number of key issues must be addressed and, whenever possible, experimentally proven. Some of these issues are common to any multi-TeV collider (like the generation and preservation of small-emittance beams, final focus and collimation problems and detector performance in a high beamstrahlung regime), while others are specific to the technology chosen for CLIC.

The new test facility CTF3 has been proposed in order to test mainly the issues specific to CLIC, namely acceleration with high gradients (150 MV/m) in high-frequency (30 GHz) normal-conducting structures, and the use of a two-beam acceleration scheme to generate the RF power. The requested power is 240 MW per metre of linac length, with a pulse length of 140 ns. A very efficient and reliable RF source is required in a frequency region above the range of conventional sources, like klystrons. The proposed scheme is based on a high-current drive beam, with relatively low energy, running parallel to the high-energy main beam. The drive beam time structure carries a strong 30 GHz component and RF power is extracted from it periodically in Power Extraction and Transfer Structures (PETS) and transferred to the main beam.

A novel scheme has been proposed in order to generate, transport and make efficient use of the drive beam [1]. A long electron bunch train with low bunch repetition frequency is initially accelerated using cavities with low RF frequency, for which commercial sources are available. Efficiency is of utmost importance for CLIC, therefore the drive beam is accelerated in fully-loaded cavities, such that the RF power is fully converted into beam energy. The drive beam bunches are then interleaved by injection in isochronous rings with transverse RF deflectors, thereby increasing the bunch repetition frequency and shortening the bunch train. Schematically, the drive beam can be thought of as an intermediate energy-storage device, converting long RF pulses of low frequency to short RF pulses of high frequency and higher peak power. The process is analogous to "standard" RF pulse compression or delay distribution systems, with the advantage that high compression ratios can be achieved with very low losses, and RF frequency multiplication becomes possible.

The main goal of CTF3 is to demonstrate the technical feasibility of the key concepts of the new RF power generation scheme, that is the generation of high-charge, high-frequency electron bunch trains by beam combination in a ring using transverse RF deflectors and operation with a fully-loaded drive-beam accelerator. CTF3 will also be used to test the CLIC critical components and in particular will provide the 30 GHz RF power at the nominal peak power and pulse length such that all 30 GHz components for CLIC can be tested at nominal parameters.

2. CTF3 DESCRIPTION

The project is based in the PS Division of CERN with collaboration from other Divisions, as well as from INFN-Frascati, IN2P3/LAL at Orsay, and SLAC. The facility will be built in the existing LPI (LEP Pre Injector) complex and will make maximum use of equipment available following the end of LEP operation. In particular, the existing 3 GHz RF power plant from the LEP injector Linac (LIL) and most of the LPI magnets will be used.

CTF3 will be built in stages over five years. The new accelerating cavities with very strong damping of the transverse Higher Order Modes (HOMs), required in order to ensure the transverse stability of the high current drive beam, will not be available before 2003. Therefore, it is planned to perform at first a low-current test of the scheme, using the present accelerating structures from LIL (CTF3 Preliminary Phase). A new 80 keV electron gun, necessary to get the right time structure for this experiment, was designed and constructed at LAL/Orsay. The experimental programme of this phase will start in autumn 2001, with the goal to demonstrate the funneling injection scheme and bunch train compression in an isochronous lattice. Since the beam current will be limited, the 30 GHz RF power production and the study of collective effects will only be possible in later phases.

As the new hardware becomes available, it will be installed in the LPI complex. A second stage (CTF3 Initial Phase), using the new linac, will allow a test of fully-loaded acceleration and will have a limited power production capability. The final configuration of CTF3 will be reached in the third stage (CTF3 Nominal Phase). A layout of the facility in its final configuration is shown in Figure 1.

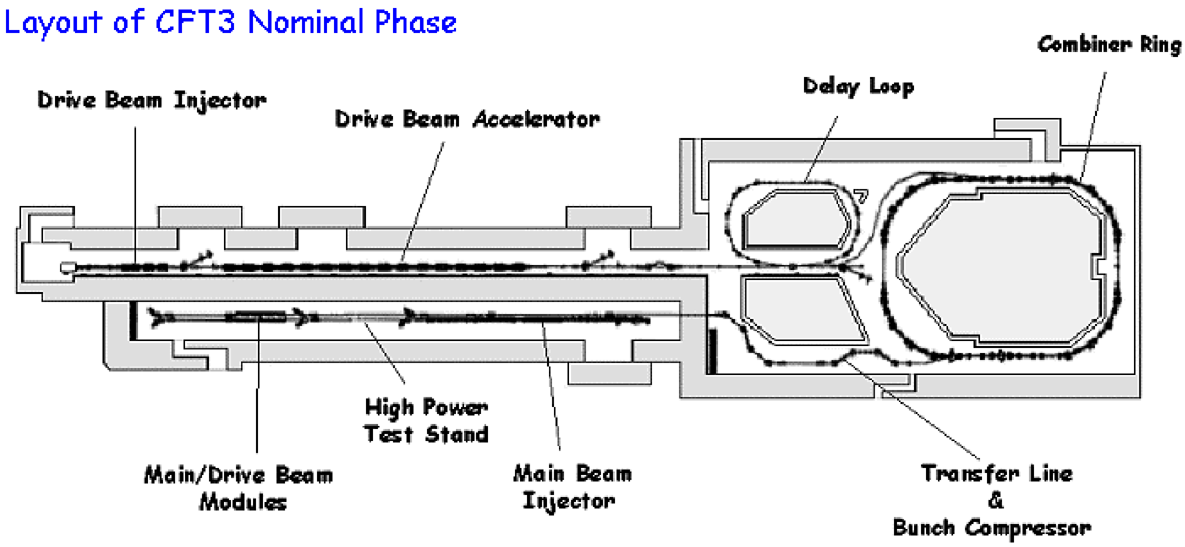

Fig. 1 Layout of the final configuration of CTF3 (nominal phase).

2.1 Drive Beam Injector

The drive beam injector [2] is to be built in collaboration with LAL/Orsay and SLAC. SLAC provides the gun triode and the beam dynamics design and LAL provides the gun electronics circuitry and the 3 GHz pre-bunchers. The 1.6 μs long drive beam pulse is generated by a 140 kV, 9 A thermionic triode gun. The time structure of the pulse is obtained in a bunching system 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 bunching cavities is switched rapidly by 180° every 140 ns, as needed for the phase-coding operation described in [3]. In order to obtain a fast enough phase switching time (• 4 ns), the RF power source for the sub-harmonic bunching system must have a relatively broad bandwidth (about 10 %), centered at 1.5 GHz, and a peak power level of up to 500 kW. The results of a feasibility study of a broadband klystron that satisfies these requirements are presented elsewhere at this conference [4].

The bunches thus obtained are spaced at 20 cm (two 3 GHz buckets) and have a charge of 2.3 nC per bunch, corresponding to an average current of 3.5 A. As a result of the phase switch of the sub-harmonic bunchers, the drive beam pulse is composed of 140 ns sub-pulses, which are phase-coded and can be separated by transverse RF deflectors working at 1.5 GHz.

The drive beam injector is completed by two 3 GHz fully-loaded travelling-wave structures (see Section 2.2), bringing the beam energy up to 24 MeV. Solenoidal focusing with a maximum on-axis field of 0.2 T is used all along the injector. A magnetic chicane with collimators downstream of the injector will be used to eliminate low-energy beam tails produced during the bunching process. The chicane region will also be instrumented to perform emittance and energy spectrum measurements on the drive beam.

An alternative option to the thermionic injector scheme described above, based on the use of an RF photo-injector, is also under study as a potential later upgrade for CTF3. The advantages of such a solution are smaller emittances in all of the three phase space planes, absence of low-charge parasite bunches in every second 3 GHz bucket, and easier tailoring of the 180° phase switching. A feasibility study was made by RAL/UK on the laser needed for such a scheme, with promising results [5], and experimental tests are also underway at RAL. The feasibility of photo-cathodes with the required performance in terms of average current has recently been experimentally demonstrated at CERN [6]. The injector layout is shown in Figure 2.

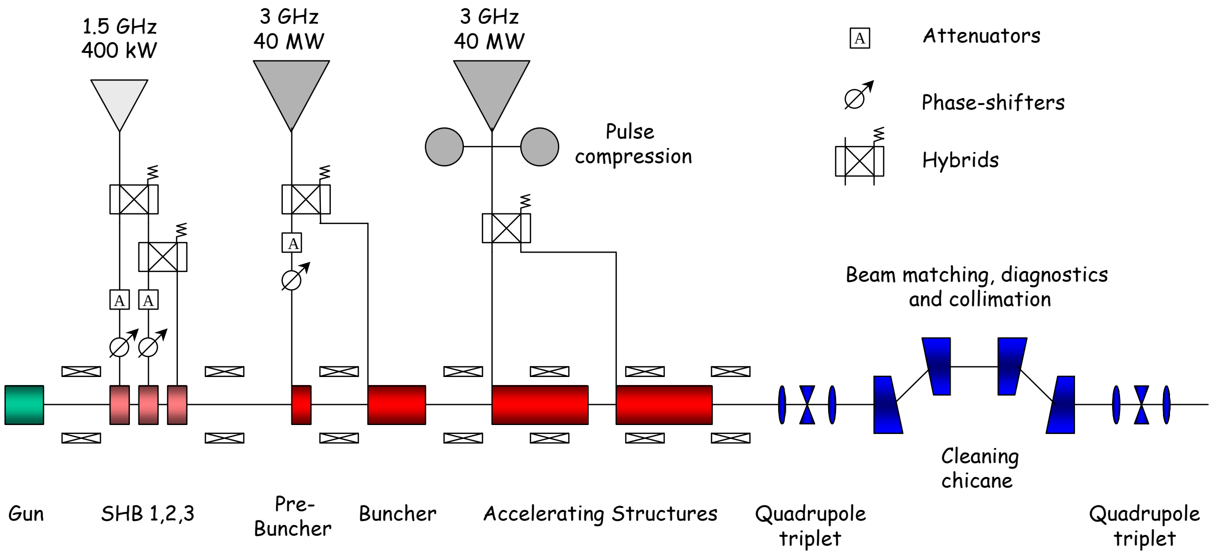

Fig. 2 Layout of the injector for the nominal phase of CTF3. The klystrons and the RF network are shown.

2.2 Drive Beam Accelerator

The drive beam is brought to its final energy (180 MeV) in the drive beam accelerator, composed of 8 modules of 4.5 m length. Each module consists of two travelling-wave accelerating structures, identical to the ones used in the injector, a beam position monitor, a quadrupole triplet and a pair of steering magnets. Beam simulations have shown that the use of triplets provides good transverse beam stability during acceleration despite the high beam current, providing that HOMs are suppressed [7].

The requirements of fully-loaded operation with a beam current of 3.5 A have lead to a 2π/3 mode travelling-wave structure design with about 100 ns filling time. The structures have an active length of 1.13 m and operate at a loaded gradient (at nominal beam current) of about 8 MV/m, with an RF-to-beam efficiency of 97 %. For effective suppression of the transverse HOMs, two different structure designs have been developed. The first is derived from the 30 GHz Tapered Damped Structure (TDS) of the CLIC main beam [8], using four waveguides with wide-band SiC loads in each accelerating cell. The waveguides act as a high-pass band filter, since their cut-off frequency is above the fundamental frequency but below the HOM frequency span. The *Q*-value of the first dipole mode is thus reduced to about 18. A further reduction of the long-range wake-fields is achieved by a spread of the HOM frequencies along the structure, obtained by varying the aperture from 34 mm to 26.6 mm. A full prototype of this structure has been built and power-tested up to 40 MW (see Figure 3). The second approach (called SICA, for Slotted Iris Constant Aperture) uses four radial slots in the iris to couple the HOMs to SiC RF loads (see Figure 3). The selection of the modes coupled to the loads is not made by frequency discrimination, but through the field distribution of the modes, therefore all dipole modes are damped. The *Q*-value of the first dipole mode is reduced to about 5. Also in this case, a frequency spread of the HOMs is introduced in the structure, by nose-cones of variable geometry. The aperture can therefore be kept constant at 34 mm, so that a smaller amplitude of the short-range wake-fields is obtained. A prototype is under construction. The RF power is supplied by eight 30 MW klystrons and compressed by a factor 2 to give a peak power at each structure input of about 30 MW. The pulse compression system uses a programmed phase ramp to get an almost rectangular RF pulse. A very good amplitude and phase stability on the RF pulse flat top is required to minimize the energy spread along the drive beam pulse. Also in this case, two approaches for the RF pulse compression system are possible, based on pairs of high-*Q* resonant cavities, as in the present system used in LIL [9], or on single barrel open cavities. Both approaches are described in detail elsewhere in this conference [10].

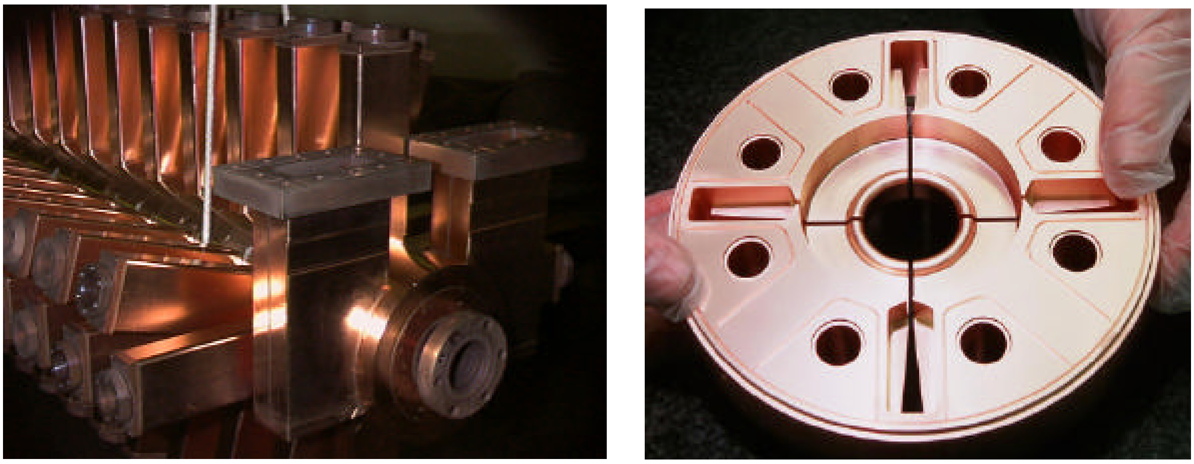

Fig. 3 Prototype of the TDS-type drive beam accelerator structure (left) and a prototype cell for the SICA drive beam accelerator structure (right). Notice the waveguide dampers sticking out of the TDS structure and the nose cones and radial slots used for damping in the SICA cell.

2.3 Delay Loop and Combiner Ring

After the linac, a first stage of electron pulse compression and bunch frequency multiplication of the drive beam is obtained, 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 every second one has been delayed in the loop. The process is illustrated in Figure 4.

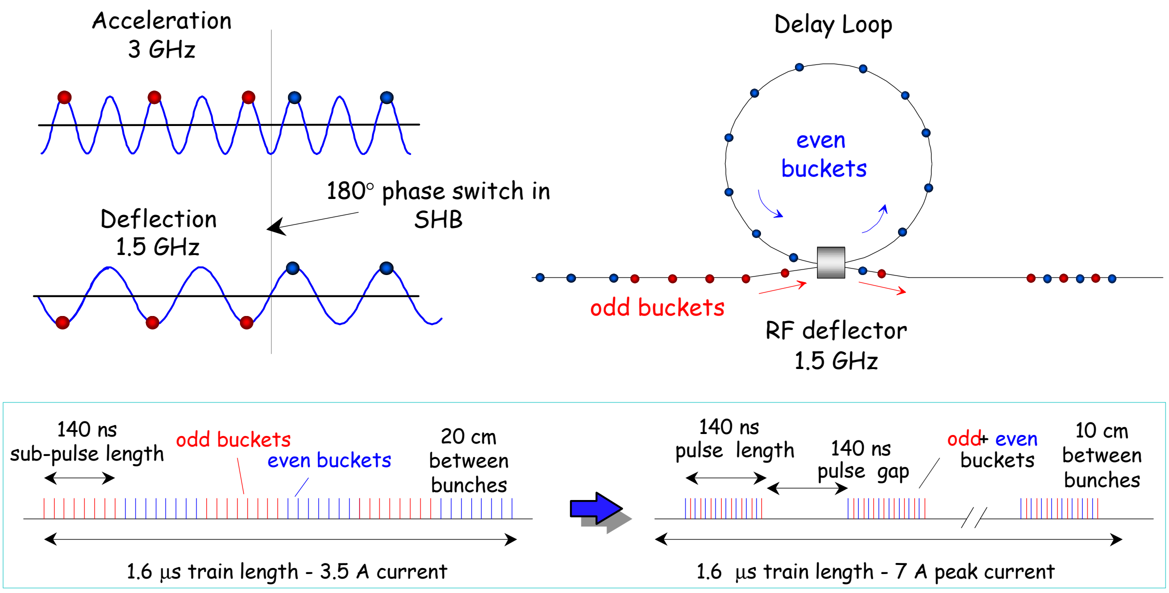

Fig. 4 Schematic description of the pulse compression and frequency multiplication process using a delay loop and a transverse RF deflector. The “odd” and “even” bunches are kicked in opposite directions by the RF deflector. When the “even” bunches come back after being delayed, they are kicked by the deflector onto the same trajectory as the “odd” ones. Note that, in reality,

the phase switch in the sub-harmonic buncher takes place over a few bunches rather than between two bunches as depicted above for illustration purposes. The time structure of the drive beam pulse before and after the delay loop is also shown.

An 84 m long combiner ring is used for a further stage of pulse compression and frequency multiplication by a factor five. After the combiner ring, the drive beam pulse is 140 ns long and has a current of 35 A. The 2.3 nC bunches are spaced at 2 cm. A schematic representation of the injection process using a pair of transverse deflectors at 3 GHz is shown in Figure 5. The delay line and the ring must both be isochronous in order to preserve the bunch length.

The design of the delay loop, the combiner ring and the related beam lines is made by INFN/Frascati [11]. Isochronous magnetic lattices, with second-order correction of the momentum compaction by sextupoles, have been developed for both the delay loop and the ring. The ring consists of four isochronous arcs, two short sections and two opposite long straight sections for injection and extraction. The ring arcs are triple-bend achromats, with negative dispersion in the central dipole. Wiggler magnets are used to adjust the circumference precisely to a (N+1/5)-multiple of the bunch spacing. Prototypes of these wigglers are under construction. A potential problem of the combination process with high bunch charge is the multi-bunch beam loading on the fundamental mode of the deflecting cavities. Studies have shown that the beam stability can be maintained by a proper choice of the deflectors and the ring parameters [12]. The short bunch length and the high bunch charge put stringent requirements on the ring impedance and make coherent synchrotron emission a serious issue. The main effects are beam energy loss and energy spread increase. In order to minimize these effects, the rms bunch length can be increased from its value of 1.3 mm in the linac to a maximum of 2.5 mm in the delay loop and ring, by a magnetic chicane placed at the end of the linac. After combination, the individual bunches are then compressed to about 0.5 mm rms in a magnetic bunch compressor. The drive beam pulse is then transported to the 30 GHz region, where is used to generate RF power.

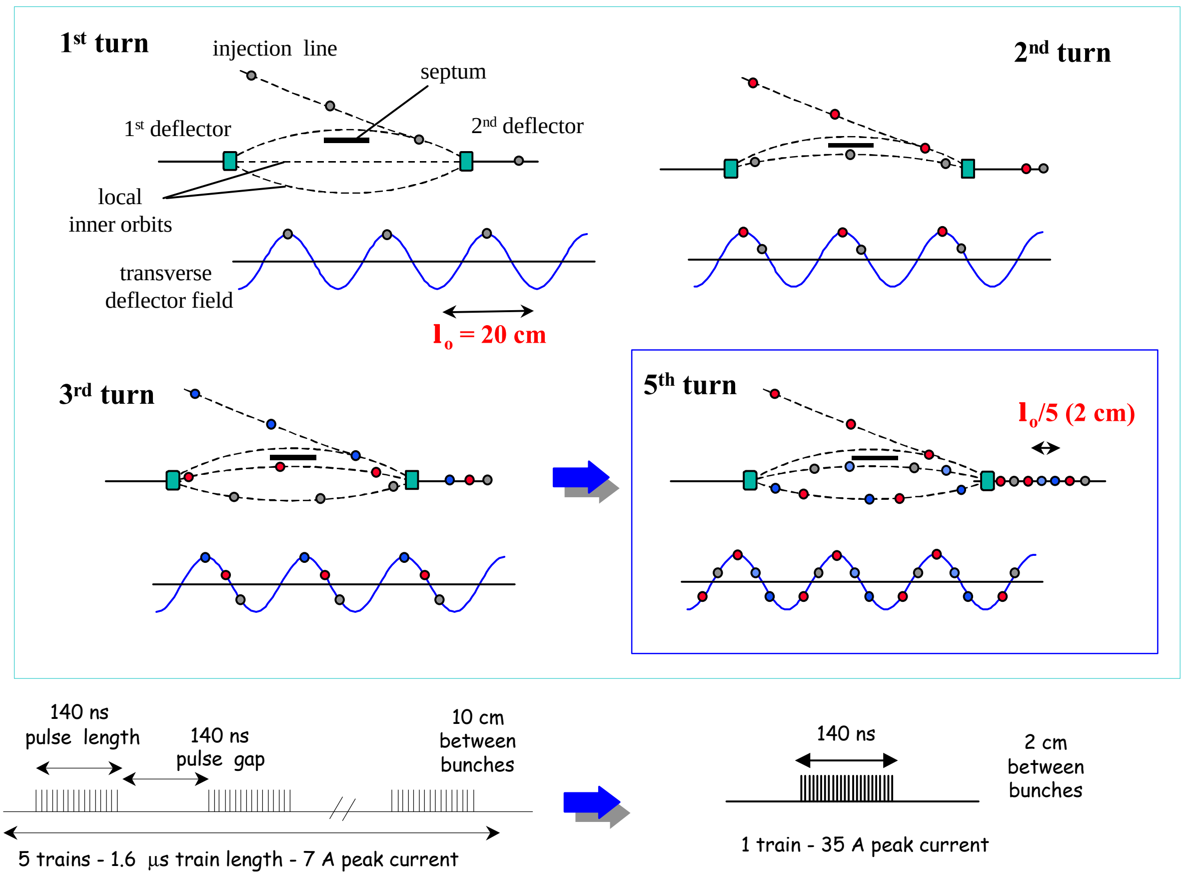

Fig. 5 Schematic description of the pulse compression and frequency multiplication by RF injection in a combiner ring. The two deflectors create a time-dependent local bump of the closed orbit in the injection region. 1) When the first train arrives, all of its bunches are deflected by the second deflector onto the equilibrium orbit. 2) After one turn the bunches of the first train arrive in the deflectors close to the zero-crossing of the RF field, and stay near the central orbit. The second train is injected into the ring. 3) The bunches of the first train are kicked on an inner trajectory, the second train bunches stay inside the septum, and the third

train is injected. The process is repeated twice more. The five trains are now combined into a single one and the initial bunch spacing is reduced by a factor five. The RF period is now full, and the train must be extracted on the other side of the ring; if not, the bunches will start hitting the septum on the next turn

2.4 Main Beam and 30 GHz Test Area

A single 30 GHz decelerating structure, optimized for maximum power production, will be used in a high-power test stand, where CLIC prototype accelerating structures and waveguide components can be tested at nominal power and beyond. Alternatively, 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. The probe beam is generated in a 3 GHz RF photo-injector and pre-accelerated to 150 MeV using standard 3 Ghz accelerating structures recuperated from LIL. It can be further accelerated to about 500 MeV in the 30 GHz CLIC accelerating structures powered by the drive beam, operated at a maximum gradient of 150 MV/m. This set-up will allow to simulate realistic operating conditions for the main building blocks of the CLIC linac.

3. SUMMARY

In this paper we have described the new CLIC Test Facility (CTF3), under construction at CERN. CTF3 will be built in stages over the years 2001 - 2005. Its main goal is the demonstration of the new CLIC RF power source concept, namely the acceleration of a long-pulse, high-current electron beam (1.6 μs, 3.5 A) in a fully-loaded linac, and its compression and bunch frequency multiplication by a factor 10 using transverse RF deflectors and rings. The power source concept can be described as analogous to RF pulse compression in a delay line distribution system (DLDS) in which the energy is temporarily stored in an electron beam, with the fundamental difference that frequency multiplication and high compression ratios with low losses become possible. The resulting drive beam pulse (140 ns, 35 A) will be used to generate 30 GHz RF power, with the nominal CLIC parameters, in resonant power extraction and transfer structures. The power will be used to test CLIC 30 GHz accelerating cavities and waveguide components at full power and pulse length.

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