Normal Conducting CLIC Technology

E. Jensen for the CLIC Study Team

Abstract

The CLIC (Compact Linear Collider) multi-lateral study group based at CERN is studying the technology for an electron-positron linear collider with a centre-of-mass energy up to 5 TeV. In contrast to the International Linear Collider (ILC) study which has chosen to use super-conducting cavities with accelerating gradients in the range of 30-40 MV/m to obtain centre-of-mass collision energies of 0.5-1 TeV, the CLIC study aims to use a normal-conducting system based on two-beam technology with gradients of 150 MV/m. It is generally accepted that this change in technology is not only necessary but the only viable choice for a cost-effective multi-TeV collider. The CLIC study group is studying the technology issues of such a machine, and is in particular developing state-of-the-art 30 GHz molybdenum-iris accelerating structures and power extraction and transfer structures (PETS). The accelerating structure has a new geometry which includes fully-profiled RF surfaces optimised to minimize surface fields, and hybrid damping using both iris slots and radial waveguides. A newly-developed structure-optimisation procedure has been used to simultaneously balance surface fields, power flow, short and long-range transverse wakefields, RF-to-beam efficiency and the ratio of luminosity to input power. The slotted irises allow a simple structure fabrication by high-precision high.

*Submitted to the 7th International High Energy Density and High Power RF Workshop,
Kalamata, Greece, 13-17th June 2005*

*Geneva, Switzerland
05/09/2005*

Normal Conducting CLIC Technology

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Abstract. The CLIC (Compact Linear Collider) multi-lateral study group based at CERN is studying the technology for an electron-positron linear collider with a centre-of-mass energy up to 5 TeV. In contrast to the International Linear Collider (ILC) study which has chosen to use super-conducting cavities with accelerating gradients in the range of 30-40 MV/m to obtain centre-of-mass collision energies of 0.5-1 TeV, the CLIC study aims to use a normal-conducting system based on two-beam technology with gradients of 150 MV/m. It is generally accepted that this change in technology is not only necessary but the only viable choice for a cost-effective multi-TeV collider. The CLIC study group is studying the technology issues of such a machine, and is in particular developing state-of-the-art 30 GHz molybdenum-iris accelerating structures and power extraction and transfer structures (PETS). The accelerating structure has a new geometry which includes fully-profiled RF surfaces optimised to minimize surface fields, and hybrid damping using both iris slots and radial waveguides. A newly-developed structure-optimisation procedure has been used to simultaneously balance surface fields, power flow, short and long-range transverse wakefields, RF-to-beam efficiency and the ratio of luminosity to input power. The slotted irises allow a simple structure fabrication by high-precision high-speed 3D milling of just four pieces, and an even easier bolted assembly in a vacuum chamber.

Keywords: Linear Collider, Two-Beam Accelerator, Accelerating Structure.

INTRODUCTION

The aim of the CLIC study is to develop the technology for an electron-positron linear collider with a centre-of-mass energy of 1 to 5 TeV. The CLIC scheme is complementary to the ILC, which even with future progress for the maximum achievable gradient in superconducting accelerating structures will not reach a centre-of-mass energy significantly beyond 1 TeV. There is, however, a well established physics need in the multi-TeV energy range [1].

The “CLIC Accelerated R&D” programme [2] will provide the main focus for the CLIC study for the next five years. The principal aim of this programme is to demonstrate all of the key feasibility issues of the CLIC scheme before 2010 within the framework of an International Collaboration in which Laboratories, Universities and Funding Agencies around the world are invited to take full technical responsibility for partial, complete, or several clearly-identified work-packages.

CLIC MAIN FEATURES

High Gradient

It is the extremely high loaded accelerating gradient of 150 MV/m that makes the relative compactness of CLIC possible, but at the same time, it is probably also its greatest challenge. Note that a 3 TeV CLIC would have the same footprint as an 800 GeV ILC based on the gradient range of 18 to 45 MV/m presently being discussed. The ambitious gradient of 150 MV/m can be obtained only in normal conducting accelerating structures; tests in CTF2 have in fact demonstrated a peak accelerating gradient of 193 MV/m (albeit at a relatively short pulse length), using molybdenum irises [3].

CLIC works at a high frequency of 30 GHz. While the exact dependence of the breakdown limit on operating frequency is not well understood, past experience indicates that higher frequency allows higher gradient; the CLIC operating frequency was chosen for this reason. But even ignoring the exact frequency dependence of the maximum surface electric field, high frequency has certain advantages, for example the smaller structure size, which for a given gradient requires less stored energy and less RF peak power than an otherwise equivalent, scaled structure operating at lower frequency. However, higher frequencies set higher demands on tolerances, both for machining and alignment. Frequency-scaling studies are presently being carried out to determine the best frequency for CLIC taking into account all the above-mentioned effects as well as the complexities of the various CLIC sub-systems.

Two-Beam Scheme

One seeming disadvantage of the choice of 30 GHz as an operating frequency is the lack of available high power RF sources compatible with accelerator operation. This is why the CLIC RF power source is an essential, integral part of the concept. It consists of a second beam (drive beam) running in parallel to the main beam. The drive beam is a high current, moderate energy beam, which is conveniently accelerated at relatively low frequency (L-band) and which contains a 30 GHz frequency component in its current. The drive beam power is extracted in decelerating structures at 30 GHz and transferred to the main linac. These power extraction and transfer structures (PETS) are distributed over the entire length of the linac. Since all necessary power for the main beam acceleration is transported by the drive beam to where it is needed, there is no need for complex infrastructure inside the accelerator tunnel. This is reflected on the conceptual view of the CLIC tunnel cross-section sketched in Fig. 1.

The two-beam scheme – initially a necessity to overcome the lack of suitable power sources – became a virtue on closer investigation and thanks to the invention of two distinctive features of the CLIC power source concept. The first is the “full beam loading” operation, which allows drive beam acceleration with unprecedented efficiency: The travelling wave structures are fed with a power equal to the beam loading power created by the nominal beam current. In this way, the RF power is completely transferred to the beam in each accelerating structure by design. Including the ohmic losses in the normal conducting copper structures, an overall RF-to-beam

efficiency in excess of 95 % can be obtained – larger than what is possible with superconducting structures, if one correctly takes the cryogenic power into account. The present test facility CTF3 (see below) is routinely operated in this regime.

FIGURE 1: Cross-section of the CLIC tunnel.

The second distinctive feature is an elegant and efficient drive beam combination scheme, which at the same time multiplies the drive beam current and its frequency while compressing its pulse length by the same factor. The basic idea (compression by a factor of two) is to delay the first part of a long bunch train with a given bunch spacing by sending it once around a delay loop, then, by means of an RF deflector, recombining it with the second part of the same bunch train such that the bunches are interleaved. The bunch spacing is halved in this manner, the current is doubled. The scheme can be equally used to compress by factors larger than two; the CLIC scheme involves three such loops for a total compression by a factor of 32. Compression by factors of four and five has been demonstrated successfully in CTF3 [4].

CLIC LAYOUT

The overall layout of CLIC at 3 TeV is sketched in Fig. 2. Both drive beam and main beam are generated in a central area, geographically close to the detector region.

FIGURE 2: CLIC overall layout.

This central region contains all major installations, which allows construction in phases and easy upgrade. Both drive beam and main beam are transported outwards through a transfer line in the accelerator tunnel.

One drive beam consists of 21 bursts of 70 ns, spaced $4.5\ \mu\text{s}$ apart; each burst feeds one decelerator section. Only the first of these bursts travels to the beginning of the linacs to the first decelerator section; subsequent pulses are bent to downstream decelerator sections so as to provide the RF power to that part of the main accelerator, where and when it is needed. The drive beam energy decreases in a decelerator section from 2.4 GeV to 240 MeV.

DRIVE BEAM GENERATION COMPLEX

The CLIC drive beam generation complex is sketched in Fig. 3. It consists of the injector, the drive beam accelerator and the loops for beam pulse compression and frequency multiplication.

FIGURE 3: Layout of the drive beam generation complex.

The injector provides $94\ \mu\text{s}$ long pulses of 5.7 A current. The drive beam accelerator consists of 176 travelling wave structures, powered by 352 highly efficient, 40 MW multi-beam klystrons (MBKs) [5]. The length and the impedance of the accelerating structures are designed for nominal input power and beam current for the fully loaded condition. This means that if the forward power in the structures is fully transferred to the electron beam in the structure length, the RF power out of the structure is virtually zero. The resulting RF-to-beam efficiency can reach 97 %. The

data shown in Fig. 4 was measured in CTF3 and demonstrates the full beam loading operation [6]. The output power from an accelerating structure is shown versus time for two cases. When the beam is off, the output power is just the input power reduced by the structure losses. When the nominal beam is switched on, the output power is reduced to virtually zero, *i.e.* practically all of the power is absorbed by the beam. The price to pay for this high efficiency is a reduced accelerating gradient of approximately half the unloaded gradient.

FIGURE 4: Demonstration of full beam loading.

In order to allow for the necessary high beam current, the drive beam accelerating structures further require strong transverse mode damping and detuning. This is obtained with the “slotted iris – constant aperture” (SICA) structures [7], the 3 GHz versions of which are now routinely operated in CTF3.

The drive beam accelerator operates with a frequency of 937 MHz ($30 \text{ GHz}/32$), but the drive beam bunches are modulated at half of this frequency, thus filling only every other RF bucket. This is obtained with a subharmonic prebuncher operating at 468.5 MHz. The phase of the prebuncher is switched every 70 ns by 180° , such that the 70 ns “sub-pulses” fill subsequently even and odd RF buckets. This phase-coding allows subsequent sub-pulses to either pass through the delay loop or not, so that these sub-pulses will be merged at the exit of the delay loop, interleaving bunches, such that the drive beam will consist of 672 pulses of 70 ns and 11.5 A with gaps of 70 ns between them. This presents the first step of the beam pulse compression.

The next two steps of the beam pulse compression apply another factor of 16, resulting in 42 pulses of 70 ns duration and a beam current of 180 A. Due to the geometry of the compressor rings, the pulses arrive in pairs to provide power for the two main linacs, the pairs are spaced by $4.46 \mu\text{s}$. This pulse spacing assures the correct timing of power production in subsequent decelerator sections.

DRIVE BEAM DECELERATOR

The drive beam decelerator, consisting of 21 sections of 669 m length for each linac, runs parallel to the main linacs. Each decelerator section contains 559 PETS (power extraction and transfer structure) – the actual decelerating structures.

FIGURE 5: Layout of a decelerator module containing 2 PETS and eight accelerating structures.

Each PETS [8] has an active length of 0.6 m, a beam aperture of 22.5 mm, a moderate R/Q of $320 \Omega/\text{m}$ and a high group velocity of $0.8 c$. It extracts 640 MW from the drive beam, enough power to feed four accelerating structures in the parallel-running main accelerator. For the nominal beam current of 180 A, this corresponds to an average drive beam energy loss of 3.5 MeV. A decelerator module consisting of 2 PETS and eight accelerating structures (HDS) is sketched in Fig. 5.

FIGURE 6: The PETS machining prototype consisting of eight octants.

Figure 6 shows machining prototype of the CLIC PETS. It consists of eight racks with longitudinal slots between them. Silicon carbide (SiC) loads inside these slots

provide strong transverse mode damping, as required for beam stability. The racks with a length of 77 cm can be fabricated by high-speed milling as a single piece, a process compatible with the required tolerances and allowing for much fewer parts than the formerly-used turning of discs required for each cell.

The longitudinal slots allow for an additional feature, which was identified as necessary by the ILC Technical Review Committee in 2003: Introducing perturbing elements (wedges) through four of the slots, an individual PETS can be detuned enough to effectively take it off-line while the drive beam remains on (see R1.3 in Table 1 below). Figure 7 shows schematically the PETS On/Off mechanism [8]; in the ON position, the wedges are retracted – in the OFF position inserted. The wedges are profiled so as to prevent field enhancement or increased transverse mode excitation also in any intermediate position; thus they allow not only switching a single PETS on or off, but also operation at intermediate power levels.

FIGURE 7: PETS ON/OFF mechanism.

MAIN LINAC ACCELERATING STRUCTURES

The main linac consists of normal-conducting 30 GHz accelerating structures that provide a loaded accelerating gradient of 150 MV/m. The structures use a combination of strong damping and detuning of transverse wakefields in order to assure beam stability. Between subsequent bunches, wakefields must be reduced by at least a factor 100.

Development of structures with these characteristics has been successful over many years. The numerical tools for the design of these structures are mature and reliable, including the prediction of wakefields and their damping and detuning. A 15 GHz version of the so-called TDS (tapered damped structure, see Fig. 8) was measured at SLAC's ASSET test facility – the agreement between the measurement results and the calculated predictions was remarkable [9].

FIGURE 8: Inner part of the 15 GHz TDS (Tapered Damped Structure) measured at SLAC's ASSET facility.

However, one weak point of the TDS was that, due to the relatively large openings in the cavities' side walls for the damping waveguides (*cf.* Fig. 8), the surface current density led to intolerably high pulsed surface heating, which would not allow for an acceptable accelerating structure lifetime.

FIGURE 9: Microscopic image of an iris damaged during conditioning.

Around the same time, it was found at SLAC that structures with relatively high group-velocity suffered severe damage during conditioning [10]; later the same observation was made also with some 30 GHz structures at CERN. An example of a severely damaged iris is shown in Fig. 9.

The CLIC study adopted a two-pronged approach to solving the breakdown damage and the pulsed surface heating problems: it consists in *i)* optimisation of the RF design towards a fully profiled geometry in order to maximize the accelerating field to surface field ratio and to prevent hot spots and *ii)* investigating new materials that are resistant to arcing for the high E -field regions – refractory metals like tungsten (W) and molybdenum (Mo) look promising – and materials with a higher fatigue-stress limit for the high H -field regions.

Encouraging results were obtained in high power tests with tungsten and in particular with molybdenum – Fig. 10 shows the conditioning history of three

structures of identical shape but made of different metals. Conditioning of these structures was performed in CTF2 with 16 ns long pulses [3]. The molybdenum structure achieved an accelerating gradient of more than 190 MV/m in this test, well above the CLIC nominal gradient, but results indicate a different optimum conditioning strategy, since this high value is obtained after 2.5 million pulses. Tests with longer pulses are underway.

FIGURE 10: Conditioning history of accelerating structures from different materials.

The present design of the CLIC accelerating structure is the HDS (hybrid damped structure), where the large wakefield reduction is obtained using a combination of radial damping waveguides and iris slots (“hybrid”). Damping by more than a factor 100 is achieved after only eight RF periods, which allows correspondingly small bunch spacing and consequently a relatively short RF pulse (60 ns).

The HDS is a result of an extensive optimization of luminosity per unit “wall-plug” power. For this optimization [11], the loaded accelerating gradient and the frequency were fixed parameters, whereas the structure geometry parameters and the bunch charge were varied. The optimization included beam stability limits for both short and long range wakefields, plus a number of physical and technical constraints.

The first constraint is the maximum surface electric field before breakdown occurs. It depends on the material used, and for the CLIC HDS, molybdenum iris tips are used, which allow for a maximum surface electric field around 380 MV/m. Given this limit, the HDS obtains an optimum accelerating field with fully profiled, rounded (but not circular) irises, as can be seen in Fig. 11. Also a smaller iris aperture will result in a higher ratio of accelerating gradient to peak surface electric field, but it drastically increases the short-range wakefields and thus reduces the possible stable charge per bunch.

The second limitation is given by material fatigue. During each pulse, the surface currents in the skin of the cavity side walls cause instantaneous heating, which leads to material deformation and consequently local stress. For a reasonable lifetime of an

accelerating structure, the surface temperature increase in every pulse must be limited, in order to allow for many billions of pulses (at 150 Hz, 10^{10} pulses correspond to 20,000 h of operation). The CLIC HDS uses copper-zirconium (UNS C15000) for the cavity side walls, which has a larger fatigue stress limit, allowing for a pulse-to-pulse temperature variation of $\Delta T < 56$ °K. Given this limit, again an optimization of the cavity inner contour helps to prevent dangerous hot spots.

A third limitation has been observed in many independent experiments, but it is not yet fully understood: if, for a given geometry $P\sqrt{\tau}$ (P : peak power, τ : pulse length) exceeds a certain limit, the breakdowns in the structure (which otherwise are quite normal during conditioning) become so violent that the structure surface gets eroded – it is certainly this limit which is related to the iris damage mentioned above. The limit used in the CLIC structure optimization is $P\sqrt{\tau} < 1200 \text{ MW}\sqrt{\text{ns}}$.

FIGURE 11: HDS geometry. Two cells are shown; one quadrant is removed for illustration.

Figure 11 shows the basic geometry of an HDS cell. It features four iris slots which couple to transverse modes and thus allow strong transverse wakefield damping. As for the PETS, the slotted iris geometry has opened up new possibilities for fabrication of the accelerating structures: Instead of turning single discs, now it is possible to apply high-speed milling. Since quadrants (*cf.* Fig. 12) of the whole structure length can be machined at once, this technique allows a sensible reduction in the number of pieces and thus reduces cost. Further advantages include a free choice of joining techniques and excellent vacuum pumping transversely through the slots.

An additional feature is the possible use of composite metal structures: First tests using high isostatic pressing (“HIPing”) to diffusion-bond a CuZr matrix around a cylindrical Mo insert, followed by quenching and ageing, were performed and the results are encouraging [12]. Machining an accelerating structure out of such a

bimetallic block would be made such that the iris tips are made of Mo and the cavity back-walls of CuZr, as assumed earlier for the CLIC HDS.

FIGURE 12: Detail of a machined prototype HDS quadrant.

CTF3

Earlier CLIC Test Facilities, namely CTF1 (1990 – 1995) and CTF2 (1996 – 2002), have demonstrated 30 GHz power generation and subsequent acceleration with short RF pulse lengths; in CTF1, 76 MW of power at 30 GHz was produced during 12 ns, and acceleration of a probe beam with a gradient of 94 MV/m was obtained, CTF2 demonstrated the acceleration of a probe beam to 60 MeV in four 30 GHz accelerating structures.

One of the main goals of the present test facility CTF3 is to demonstrate the key concepts of the CLIC RF power source, *i.e.* to demonstrate the generation of the drive beam with the appropriate time structure and the extraction of 30 GHz RF power from this beam. This RF power will serve to condition and test 30 GHz accelerating structures and eventually demonstrate acceleration of a probe beam with them [13]. Comparing the CTF3 layout (Fig. 13) and the CLIC power source (Fig. 3) reveals the similarities and differences: Instead of using L-band, CTF3 reuses the 3 GHz installation formerly used in LIL (lepton injector for LEP), which became available after the LEP closure in 2000. Instead of a pulse compression by a factor 32, compression by a factor 10 is used. All other key elements of the CLIC power source are included in CTF3.

FIGURE 13: Schematic layout of CTF3.

CTF3 will also be used to demonstrate main feasibility issues related to CLIC technology, which were identified in 2003 by the ILC-TRC (International Linear Collider Technical Review Committee) 2nd report [14]. The issues with ranking 1 (R&D needed for feasibility demonstration) and 2 (R&D needed to finalize design choices and ensure reliability of the machine) are summarized in Table 1.

TABLE 1. Ranking 1 and 2 issues identified by ILC-TRC 2003 [14]

Ranking	Issue
R 1.1	Test of damped accelerating structure at design gradient and pulse length.
R 1.2	Validation of the drive beam generation scheme with a fully loaded linac.
R 1.3	Design and test of an adequately damped power-extraction structure, which can be switched ON and OFF.
R 2.1	Validation of beam stability and losses in drive beam decelerator, and design of a machine protection system.
R 2.2	Test of a relevant linac sub-unit with beam.

At present, the tests of damped accelerating structures are continuing, the fully loaded operation of the drive beam linac has been demonstrated with beam currents of up to 6.5 A, the design of the PETS structure with ON/OFF possibility is in the conception phase (see above), the points R 2.1 and R 2.2 can only be tested after the installation of the delay loop and the combiner ring, scheduled for 2005 and 2007, respectively.

Figure 14 shows the ground plan of CTF3 in the former LIL-EPA complex and indicates the location of the different elements. Since the fully compressed drive beam will not be available before 2007, the high gradient test stand is presently located in the former CTF2 building, fed with 30 GHz power by low-loss waveguides from a special PETS inserted after approximately the first third of the drive beam linac. This special PETS is adapted to the presently available lower current and energy and

consists of 400 cells of iris apertures between 6.7 and 9 mm. During the 2004 run of CTF3, it produced 73 ns long pulses of 72 MW, resulting in available 53 MW in the high gradient test stand [15].

FIGURE 14: Ground plan of the CTF3 installation.

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