THE COMPACT LINEAR COLLIDER CLIC

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Abstract

A high luminosity ($10^{34} - 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$) electron-positron Collider (CLIC) with a nominal centre-of-mass energy of 3 TeV has been under study for a number of years at CERN within an international collaboration of laboratories and institutes to provide the HEP community with a new accelerator-based facility for the post-LHC era. In order to achieve the very high design luminosity, very low emittance beams have to be produced and focused down to very small beam sizes at the interaction point. Beam acceleration using high frequency normal-conducting structures operating at high accelerating fields significantly reduces the length and, in consequence, the cost of the linac. The overall-length of the 3 TeV collider is about 33 km. The goals of the CLIC scheme are ambitious, and require further R&D to demonstrate that they are indeed technically feasible. A new test facility is being built at CERN for this purpose with the aim to demonstrate the key feasibility issues before 2010.

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1 INTRODUCTION

A high luminosity ($10^{34} - 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$) electron-positron Collider (CLIC) with a nominal centre-of-mass energy of 3 TeV has been studied for a number of years at CERN within an international collaboration of laboratories and institutes to provide the HEP community with a new accelerator-based facility for the post-LHC era [1]. The physics case for such a machine is outlined by the CLIC Physics Study Group in [2]. An overall layout of the complex is shown in Fig.1. The rf power for the main linac is provided by drive-beam-decelerator units which run parallel to the main linac. Each unit is 624 m long and obtains its power by decelerating a low-energy high-intensity electron beam (the so-called drive beam) using special power extraction structures. One unit accelerates the main beam by $\sim 70 \text{ GeV}$ allowing a staged construction of a collider with centre-of-mass energies increasing in steps of 140 GeV starting from 140 GeV with just one unit on each side of the interaction point (IP). The nominal energy of 3 TeV requires 44 units (22 on each side of the IP). This modularity is facilitated by the fact that the complexes for the generation of all the beams including the power sources are located in the central region of the facility. A single tunnel (see Fig.2), housing only the two linacs and the various beam transfer lines, but no active RF system, results in a very simple, cost effective and easily extendable configuration to higher energies without making major modifications.

Fig. 1: Overall layout of the CLIC complex.

Fig. 2: X-section of CLIC tunnel.

In order to achieve the very high design luminosity, very low emittance beams have to be produced and focused down to very small beam sizes at the interaction point (0.7 nm in the vertical plane). Beam acceleration using high frequency (30 GHz) normal-conducting structures operating at high accelerating fields (150 MV/m) significantly reduces the length and, in consequence, the cost of the linac. The overall-length of the 3 TeV

collider is about 33 km. The goals of the CLIC scheme are ambitious, and require further R&D to demonstrate that they are indeed technically feasible.

2 MAIN BEAM AND LINAC PARAMETERS

The main-beam and linac parameters are listed in Table 1 for two colliding beam energies. The luminosity L normalised to the total input power, P , can be expressed as a function of the effective transverse beam sizes $\sigma_{x,y}$ at the interaction point, the number of particles per bunch N , and the efficiencies of power transfer from the mains to the RF η_1 , and from the RF to the beam η_2 :

$$L/P \propto H_D (N/\sigma_x) \eta_1 \eta_2 / (\sigma_y)$$

These parameters are not independent and the dependencies are in general complex. H_D is the luminosity enhancement factor which is a measure of the self focussing of the beams during collision and is usually in the range 1-2. The ratio of N/σ_x strongly affects the beam-beam interaction; large values of N/σ_x increase the total luminosity but degrade the luminosity spectrum and background. The optimum value for CLIC at 3 TeV is around $4 \times 10^9 / 60 \text{ nm}$ or $6 \times 10^{16} \text{ m}^{-1}$. The efficiency of power transfer from the mains to the RF depends on the RF technology chosen for the main linac and for CLIC η_1 is around 40%. The efficiency of power transfer from the RF to the beam depends on the structure design and beam parameters. For CLIC η_2 is around 25%. This is obtained by using a large number of bunches, by choosing an optimum accelerating section length, and by reducing the time between bunches. The vertical beam size σ_y should be as small as possible - it is 0.7 nm for CLIC and is limited by the difficulties of creating and colliding sub-nanometre beams. Luminosity spectra normalised to the total luminosity as a function of maximum beam energy are given for two centre-of-mass energies in Fig.3.

Table 1: Main beam and linac parameters

Beam parameters at IP	0.5 TeV	3 TeV
Luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	2.1	8.0
RF frequency of main linac (GHz)	30	30
Linac repetition rate (Hz)	200	100
Particles / bunch ($\times 10^9$)	4	4
Bunches / pulse	154	154
Bunch separation (ns)	0.67	0.67
Bunch length σ_z^* (μm)	35	35
Crossing angle at IP (mrad)	20	20
Emittance $\gamma \epsilon^*$ (10^{-8} rad.m) H/V	200/1	68/1
$\beta x^* / \beta y^*$ (mm) H/V	10 / 0.05	16 / 0.07
Beam size before pinch (nm) H/V	202/1.2	60/0.7
Loaded accelerating gradient (MV/m)	150	150
Total two-linac length (km)	5	28
Overall site length (km)	10.2	33.2
Number of 50 MW klystrons	448	448
Klystron pulse length (μs)	16.7	92
RF-to-beam efficiency (%)	23.1	23.1
AC to beam efficiency (%)	9.3	9.3
Total site AC power (MW)	175	410

Fig. 3: Normalised luminosity distribution with energy (normalised to total luminosity L_0)

3 CLIC RF POWER GENERATING SCHEME

The pulsed RF power (460 MW per metre length of linac) to feed the accelerating structures is produced by the so-called “Two-Beam Scheme” in which the 30 GHz power is extracted from high-intensity/low-energy electron drive beams running parallel to the main beam by special PETS structures (Power Extraction and Transfer Structures). A short section of the two-beam accelerator is shown in Fig.4.

Fig. 4: One main-beam and drive-beam module.

For the 3 TeV collider, 22 drive beam pulses are required per linac, and each linac has its own drive beam generation complex (Fig.5) [3]. The 22 drive beam pulses are produced as one long train with a bunch spacing of 64 cm. A fully-loaded normal-conducting linac operating at a low frequency (937 MHz) is used to accelerate the drive beams to about 2 GeV. The bunch spacing is then reduced in three successive stages in the delay loop and two combiner rings to 2 cm (a factor of 32) using funnelling techniques to repetitively interleave 130 ns-long slices of the trains. Operating the linac in the fully-loaded condition enables the beam to be accelerated with an RF-power-to-beam efficiency of $\approx 97\%$. The RF power for each drive-beam accelerator is supplied by about 200 50 MW multi-beam klystrons. A particularly attractive feature of the CLIC scheme is that energy upgrading of the collider only requires a change in the pulse length of the modulators which drive the 937 MHz klystrons and not an increase in the number of klystrons (the nominal pulse length for the 3 TeV collider is 92 microsec). By initially sending this drive beam train in the opposite direction to the main beam, different time pulses in the train are used to power different sections of the main linac. In this configuration, each drive beam pulse powers a 624m long section of linac.

Fig. 5 : Layout of CLIC RF power generation scheme

4 CLIC POWER EXTRACTING STRUCTURES

The structures to extract the power from the high-intensity drive beam are referred to as PETS (Power Extraction and Transfer Structures). Details are given in [4]. Each structure must extract an rf power of the order of 560 MW from the 150 A drive beam. The structures are passive microwave devices in which the bunches of the drive beam interact with a large aperture (25 mm diameter) structure with a shallow periodically corrugated inner surface to preferentially excite the synchronous TM₀₁ mode at 30 GHz. In the process, the beam kinetic energy is converted into electromagnetic energy at the mode frequency. This energy travels along the structure with the mode group velocity and the RF power produced is collected at the downstream end by a power extractor and conveyed to the main linac structure by means of rectangular waveguides. For stability in the drive beam decelerator, these structures have to be damped to reduce long-range transverse wakefield effects. The damping is provided by eight 1.4 mm wide longitudinal slots connected to broad-band SiC RF loads (see Fig.6). In case of problems, the power generated by these structures can be turned off [5] by inserting thin metal foils into the volume of the PETS via four of the eight damping slots. This detunes the synchronous mode frequency of the structure and prevents the coherent build up of the excited field.

**Fig. 6 : PETS geometry (half) with damping slots and SiC loads.
Left : Power ON Right : Power OFF**

5 MAIN LINAC ACCELERATING STRUCTURES

The main linac uses normal-conducting 30 GHz travelling-wave structures to produce a loaded accelerating gradient of 150 MV/m. An rf pulse length of 130 ns is required to fill each structure, and to accelerate the 154 equally spaced bunches. In order to maintain stability of this bunch train, long-range transverse wakefields in the accelerating structures must be suppressed by a factor of about 100 in the interval between bunches which should be as small as possible to get good rf-to-beam efficiency. A combination of strong damping and detuning are used for wakefield suppression. A successful experimental demonstration of an early design of a heavily damped and detuned accelerating structure and a verification of the tools developed to compute the wakes was made in ASSET [6]. The damping topology that has been adopted for the most recent design of structure [7] uses both slotted irises and radial damping waveguides terminated by SiC absorbers to reduce dipole mode Q 's to the order of 10. Concentrations of both peak surface electric and magnetic field are minimised by profiling the transverse cross-sections of the iris and the outer-cell wall. The new Hybrid Damped Structure (HDS) is shown in Fig.7. The structure consists of (basically) only four parts which have no current carrying contacts when assembled. The wakefield suppression of this structure is so good that the present bunch spacing of 0.67 ns could if desired be halved reducing the present rf pulse length from 130 ns to 60-70 ns.

Following the observation of damage in earlier prototype CLIC structures, an experimental investigation of the relative high gradient performances of copper, tungsten and molybdenum was made in the CLIC Test Facility 2 (CTF2) using three identical geometry, thirty cell, 30 GHz accelerating structures. One was made entirely from copper, the second was made from copper cavity walls with tungsten irises, and the third was made from copper cavity walls with molybdenum irises. Tungsten and molybdenum have high melting points and low vapour pressures, and are expected to be more resistant to damage. After conditioning with 15 ns rf pulses (the maximum pulse length available in CTF2), the copper, tungsten-iris and molybdenum-iris structures achieved peak accelerating gradients of 110, 150 and 193 MV/m respectively after conditioning (see Fig.8), clearly demonstrating the potential of these refractory metals at short pulse lengths [8].

Fig. 7: The HDS geometry

Fig. 8 : Comparative high-gradient performance of Cu, W and Mo with short (15ns) rf pulses

It will only be known in 2005 when 30 GHz high-gradient testing resumes in the CLIC Test Facility 3 (CTF3) in long-pulse operation if this improved performance is also valid at the longer pulse length required for CLIC.

6 MAIN BEAM INJECTOR COMPLEX

The main beam injector complex is located centrally (see Fig.1). The general layout of the main-beam injection complex is given in Fig. 9. The polarised electrons are obtained from a laser-driven DC gun, and the primary electrons for positron production from a laser-driven 1.5 GHz RF gun. The electron and positron beams are accelerated to 2.42 GeV in stages by 1.5 GHz linacs. To reduce cost a common linac is used for the final stage of acceleration from 0.2 GeV to 2.42 GeV. The electron and positron beams are damped transversely in specially designed damping rings for low emittances. The positrons are pre-damped in a pre-damping ring. The present design of damping ring is based on compact TME (Theoretical Minimum Emittance) arc cells with short-period wigglers in two long straight FODO sections [9]. The energy is 2.42 GeV and the ring has a circumference of 360 m, the installed rf voltage is 2.5 MV and the wiggler strength is 1.634 T. Optimisation of the ring parameters takes into account the effects of synchrotron radiation and intra-beam scattering. The design does not, however, quite meet the specified goals, the simulated final equilibrium emittances in the horizontal and vertical planes are $\gamma\epsilon_x = 631$ nm and $\gamma\epsilon_y = 9$ nm respectively compared to the nominal values of $\gamma\epsilon_x = 450$ nm and $\gamma\epsilon_y = 3$ nm. For the moment only the longitudinal emittance of 4453 eVm is less than the design value of 5000 eVm. More details of the main beam injector complex are given in [1].

Fig. 9 : Main beam injector layout

7 THE BEAM DELIVERY AND INTERACTION POINT

The beam delivery system (BDS) proceeding the interaction point consists of a collimation section and a final focus section [1]. Collimators are required to remove beam halo and reduce detector background, and to protect the machine from errant beam pulses. The most recent BDS design has a SLAC-type compact Final Focus [10] which features a nonzero dispersion across the final doublet and chromaticity sextupoles located next to the final quadrupoles. The free length between the final doublet and the interaction point (IP) is 4.3 m. The length of the compact Final Focus system is 550 m. A high fraction (80%) of the ideal luminosity is obtained for a 1% full-width energy spread of the beams. Simulations show that the rms spot sizes in both planes are 20-30% larger than calculated from the simple calculation using the emittance and the beta function at the IP. The BDS length per side is 2.6 km.

A minimum crossing angle of 20 mrad at the IP is required to extract the disrupted beam and to avoid parasitic collisions away from the IP. This however means that crab-cavities will have to be used to avoid a reduction in luminosity. The crab cavity phases on either side of the collision point should be stable to within 0.1 degree. Extraction of a spent beam with 100% energy spread and with a large beam divergence is a concern and will make bending and focussing without beam loss particularly challenging.

The feasibility of maintaining 1 nm beam sizes in collision in the presence of ground movement and component jitter is a concern and needs to be demonstrated. The vertical position jitter tolerances on the main linac and final-focus quadrupoles are very tight; they are typically 1.3 nm and 0.2 nm above 4 Hz respectively for a 2% luminosity loss. The technical feasibility of stabilising these elements to these levels has been investigated using an experimental test stand at a fairly noisy location on the CERN site [11]. The test stand is equipped with water-cooled CLIC prototype magnets, three-axis motion sensors with sub-nanometre resolution (4-250 Hz), a honeycomb support table (2.4m x 0.8m x 0.8m) with minimized structural resonances, and state-of-the-art industrial stabilization equipment. The system provides active vibration damping using piezo-electric movers mounted together with motion sensors in the support feet.

The best measurements (Fig. 10) indicate transverse rms vibration amplitudes (above 4 Hz) of (0.79 ± 0.08) nm horizontally and (0.43 ± 0.04) nm vertically, and maximums of less than (1.47 ± 0.15) nm and (1.00 ± 0.10) nm, respectively, have been maintained over a period of several days. With the nominal water flow (30l/h), the level in the vertical plane becomes (1.38 ± 0.14) nm. Simulations using measured vibration spectra have shown that if this level of stabilization is obtained in CLIC, and if the beam-based position feedback can be made to work, approximately 70% of the CLIC nominal luminosity is obtained.

Fig. 10 Integrated vertical rms motion (nm) above f_{min} (Hz)

8 TEST FACILITIES

The first CLIC Test Facility (CTF1) operated from 1990 to 1995 and demonstrated the feasibility of two-beam power generation. A 30 GHz peak power of 76 MW was extracted from a low-energy high-intensity beam by one power extracting structure, and was used to generate a gradient of 94 MV/m in one 30 GHz accelerating structure for 12 ns.

A second test facility (CTF2) with a string of four power-extracting structures driving five accelerating structures operated from 1996 to 2002 and further demonstrated the two-beam scheme by increasing the energy of a single electron bunch of the probe beam by 60 MeV [12]. Both the high intensity drive beam and the probe beam were generated by laser-illuminated photo-cathodes in RF guns. The 48-bunch 450 nC drive beam train was generated by a laser-driven S-band RF gun with a Cs₂Te photo-cathode. The beam was accelerated to 40 MeV by two travelling-wave sections operating at slightly different frequencies to provide beam loading compensation along the train. After bunch compression in a magnetic chicane, the bunch train passed through four power extraction structures, each of which powered one 30 GHz accelerating section (except the third which powered two) with 16 ns long pulses. The single probe beam bunch was generated by an RF gun with a CsI+Ge photo-cathode. It was pre-accelerated to 50 MeV at S-band before being injected into the 30 GHz accelerating linac. The drive beam RF gun produced a single bunch of 112 nC and a maximum charge of 755 nC in 48 bunches. The maximum charge transmitted through the 30 GHz modules was 450 nC. A series of cross-checks between drive beam charge, generated RF power, and main beam energy gain showed excellent agreement. The maximum RF power generated by one 0.5 m structure was 27 MW. The highest average accelerating gradient was 59 MV/m and the energy of an 0.7 nC probe beam was increased by 55 MeV by the five structures. Unexpected surface damage was found at these field levels. The 30 GHz part of this facility was equipped with a few-microns-precision active-alignment system. This facility was converted in the final years of operation into a high-gradient test stand for the development of 30 GHz structures. The emphasis of the studies was placed on alternative materials to copper after discovery of damage in prototype copper structures after rf conditioning to relatively low gradients of 60 MV/m. After replacing the irises of the copper structures by molybdenum, peak accelerating gradients of 190 MV/m were obtained for rf pulse lengths of 16 ns.

A new facility CTF3 is being built at CERN to demonstrate the technical feasibility of the key concepts of the novel CLIC RF power source albeit on a much smaller scale and re-using in particular existing equipment, buildings and technical infrastructure that have become available following the closure of LEP [13]. The new facility is being built in collaboration with INFN (Frascati), IN2P3 (LAL), SLAC, the University of Uppsala, the North-Western University of Illinois and Finnish Industry. This facility will also be used to demonstrate the key CLIC-technology-related feasibility issues that were identified by the ILC-TRC in 2003 [14]. These are given as follows :

- R1.1 Test of damped accelerating structure at design gradient and pulse length
- R1.2 Validation of the drive beam generation scheme with a fully loaded linac
- R1.3 Design and test of an adequately damped power-extraction structure, which can be switched ON and OFF
- R2.1 Validation of beam stability and losses in drive beam decelerator, and design of a machine protection system
- R2.2 Test of a relevant linac sub-unit with beam

A schematic layout of CTF3 and principal parameters is given in Fig. 11.

A physical layout of the CTF3 facility in the former LEP Pre-injector (LPI) complex is shown in Fig. 12.

Fig. 11: Schematic layout of CTF3

Fig. 12 : CTF3 frequency multiplication and pulse compression system

CTF3 will demonstrate the CLIC-type production of short-pulse RF power at 30 GHz from 3 GHz long-pulse RF power by carrying out sophisticated bunching manipulations of intense electron beams in combiner rings using transverse RF deflectors. The aim is to create a 140 ns long train of high-intensity electron bunches with a bunch spacing of 2 cm starting from a 1.4 μ s continuous train of bunches spaced at 20 cm. The 2 cm spacing is required to generate 30 GHz RF power in an efficient way. This is done by interleaving trains of bunches and is done in two stages.

The first combination takes place in the delay loop where every-other 140 ns slice of the 1.4 μ s continuous train is sent round the 42 m circumference (or 140 ns) of the loop before being interleaved with the following 140 ns slice. This results in a reduced bunch spacing by a factor of two and an increase in the train intensity by a factor of two (see Fig.13).

Fig. 13: Frequency multiplication and pulse compression in the delay loop

The second stage of combination – this time by a factor five – takes place in the combiner ring. After passing through the delay loop, the $1.4 \mu\text{s}$ train from the linac is made up of five 140 ns pulses with bunches spaced at 10 cm, and five inter-spaced 140 ns long gaps. The combiner ring combines these five pulses into a single 140 ns pulse using a novel system of beam interleaving which uses two 3 GHz RF deflectors to create a time dependent variation of the closed orbit of the isochronous ring.

Fig. 14 : Low-charge demonstration of electron pulse combination and bunch frequency multiplication by a factor 5

Before dismantling the former LEP Pre-injector (LPI) complex to make way for CTF3, the LPI injector was equipped with a new gun and the layout of the ring was modified in order to make an experimental demonstration of the principle of the CLIC bunch combination scheme. Five bunch trains were used for this test which was successfully completed in November 2002. The results are given in Fig. 14. Although this result confirms the basic feasibility of the scheme, the test was made using very low charge bunches. CTF3 will confirm the technical feasibility of the combination scheme at high charge.

The LPI equipment was dismantled at the end of 2002 and the new equipment installed at the beginning of 2003. A bunched beam of the nominal current, pulse length and energy was obtained from the drive-beam injector

(Fig. 12) for the first time in August 2003, and this enabled a successful demonstration of full-beam-loading operation to be made (Fig. 15).

Fig. 15 : Full beam-loading operation using the CTF3 injector

(The upper trace shows the RF power pulse with and without beam – the lower trace is the phase)

The present status (May 2004) is that the first part of the drive-beam accelerator linac and the high power line for the linac-driven high-gradient test stand are installed. It is planned to complete installation of the linac by the end of 2004, and to install the delay loop in 2005 and the combiner ring in 2006. The linac-driven high-gradient test stand should be operational in 2005 to enable the 30 GHz high-power test programme on the use of alternative materials such as tungsten or molybdenum to resume. The CLIC Experimental Area (CLEX) must be completed by 2007 to be able to demonstrate the key feasibility issues mentioned above before 2010. This area houses the two-beam test stand where the damped power-extraction structure (PETS) will be tested, the relevant linac sub-unit and probe linac where a representative PETS/accelerating module will be tested with beam, and the Test Beam Line (TBL) where a well instrumented 10-15 m length of drive beam linac will be bench-marked against beam simulation codes to demonstrate the validity of extrapolating the behaviour of the CTF3 35 A drive beam to the CLIC 150 A drive beam.

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