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PROGRESS ON THE CLIC LINEAR COLLIDER STUDY

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ABSTRACT

The CLIC study aims at a multi-TeV, high luminosity e^+e^- linear collider design. Beam acceleration uses high frequency (30 GHz), normal conducting structures operating at high accelerating gradients, in order to reduce the length and, in consequence, the cost of the linac. The cost-effective RF power production scheme, based on the so-called Two-beam Acceleration method, enables electrons and positrons to be collided at energies ranging from ~ 0.1 TeV up to a maximum of 5 TeV, in stages. A road map has been drawn up to indicate the research and development necessary to demonstrate the technical feasibility of a 3 TeV centre-of-mass collider with a luminosity of 10^{35} $cm^{-2}s^{-1}$. Considerable progress has been made in meeting the challenges associated with the CLIC technology and the present paper briefly reviews some of them. In particular, the status is given of the studies on the CLIC high-gradient structures, the dynamic time-dependent effects, the stabilisation of the vibration and the beam delivery system. The recent development of the new test facility CTF3 is described.

1 INTRODUCTION

The Compact Linear Collider (CLIC) study aims at centre-of-mass energies for $e^\pm$ collisions in the multi-TeV range and it has been optimised for a nominal energy of 3 TeV with a luminosity of 10^{35} $cm^{-2}s^{-1}$[1]. Its design is however such that its construction could be staged without major modifications (Fig.1). The lower energy phases will depend on the existence or not of other accelerator facilities, but the first stage could cover energies between ~0.1 and 0.5 TeV with $L= 10^{33}$-10^{34} $cm^{-2}s^{-1}$, where interesting physics and overlap with LHC are expected. This stage would be extended to 1 TeV with L above 10^{34} $cm^{-2}s^{-1}$. Next would come the desirable $e^\pm$ collisions at 3 TeV which should break new physics ground, while the final stage might be 5 TeV.

Fig.1 shows an overall layout of the complex which points out the existence of linear decelerator units running parallel to the main beam [2]. Each unit is 625 m long and decelerates a low-energy high-intensity e^- beam (so-called drive-beam) which provides the RF power for each corresponding unit of the main linac through energy-extracting RF structures. With a gradient of 150 MV/m, the main beam is accelerated by ~70 GeV in each unit. Consequently, the lowest colliding beam energy in the centre of mass E_{cm} is ~ 140 GeV (1 unit on either side), 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 (IP). The nominal energy of 3 TeV requires 2x22 units (linac length of ~14 km).

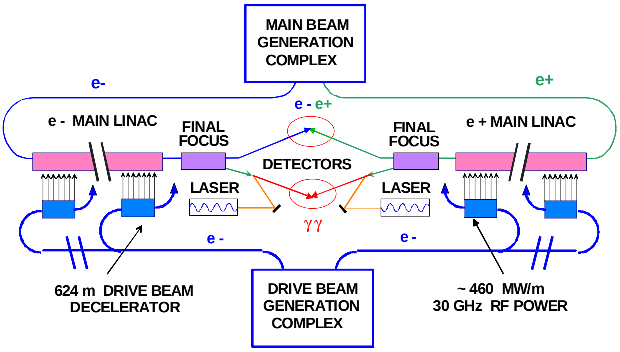

Fig. 1 Overall layout of the CLIC complex.

This modularity is possible since the complexes for the generation of all the beams and the IP are both in a central position. The main tunnel, of constant straight section, houses both linacs, the various beam transfer lines and, in its downstream part, the beam delivery system (BDS). The fact that there is such a single tunnel results in a simple and easily extendable arrangement. Fig. 2 gives examples of estimated tunnel lengths for various energies in the centre-of-mass.

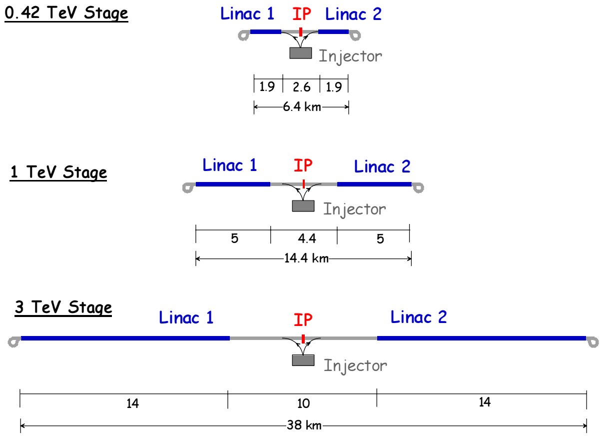

Fig. 2 Tunnel lengths (km) for the linacs and the BDS on each side of the IP, at various cm energies.

The general description of the CLIC two-beam technology, of the main-beam complex and of the RF power source at 30 GHz is given in Ref. 1. It also summarises the main-beam (main-linac) and drive-beam (decelerator and accelerator) parameters at the nominal energy of 3 TeV as well as some main-beam parameters at various other energies.

2 STRUCTURE DEVELOPMENT AND HIGH-GRADIENT STUDIES

The loaded design gradient of the CLIC accelerating structures is 150 MV/m at a pulse length of 130 ns [1]. These values imply demanding levels of surface fields and pulsed surface heating. Therefore, a program of experiments and developments is under way with the goal to demonstrate the required performance. RF breakdown studies and high-power tests of structures and components are going on.

Accelerating structures tested in the year 2000 were a constant impedance structure [3] with single-feed input and output couplers (tested from both ends), and a constant-impedance structure with symmetrical couplers. The ratio of surface to local accelerating gradient was 2.8, with additional factors of 1.4 in the single feed coupler and 1.12 in the symmetrical coupler respectively. Structures were baked out in situ at 120°C for two days before testing and they were typically conditioned for a few 10^5 shots. The maximum gradients achieved after conditioning are given in Table 1.

Structure	***E_{acc} \ $E_{surface}$***		***(MV/m)***
Pulse length (ns)	**4**	**8**	**16**
Single feed right	**133 \588**	**90 \ 398**	**59 \ 260**
Single feed left	**140 \619**	**100 \ 442**	**60 \ 265**
Symmetrical		**95 \ 361**	**70 \ 266**

Table1. Accelerating gradients and surface fields

The main features noticed during a breakdown are: i) irregular bursts of up to several 100 mA of emitted currents from the structure ends, ii) light pulses lasting many 100 ns, i.e. much longer than the 16 ns RF pulse, iii) missing RF energies of up to 50% with 16 ns pulses, and iv) some pressure rises and small reflected RF signals. After the conditioning process, the structures were inspected with an optical endoscope. An area of obvious damage, corresponding to a depth of removal of material of about 100 μm was observed in the iris between the input coupler and the first cell. The damage location corresponded very closely to the enhanced field region of the couplers. Surprisingly, the damage region was delimited by a very sharp boundary (Fig. 3).

Single-cell standing wave cavities, relatively simple to construct, represent a valid complement to complete structures for many high-gradient tests, since the maximum surface fields obtained after conditioning are very close to those achieved in travelling-wave structures. In an experiment planned to gain insight into breakdown, the optical-quality cavity [4] was powered while heated and cooled over a temperature range from 77 K to over 500 K. The resonant frequency and the surface resistance behaved as expected. Although the surface resistance changed by more than a factor 3, the breakdown threshold did not significantly change over the entire range of temperature.

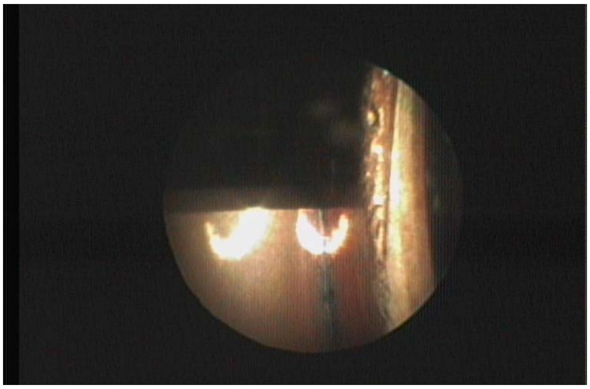

Fig.3 Damaged coupler iris. Looking from the beam axis towards the coupling aperture (section to the right).

The planned experiments aim at understanding the physical processes involved in breakdown and what are the important parameters which affect the breakdown level, limits and damage. Technologies are being developed in parallel that may contribute to: i) higher gradients through a geometry decreasing the ratio of the peak surface-field to the accelerating field, ii) arc resistant materials such as Tungsten, and iii) improved surface preparation and cleaning.

3 VIBRATION AND FEEDBACKS

Presently, the uncorrelated motion tolerances for the quadrupoles of the CLIC linac or of the final-focus doublets are estimated to be 1.3 nm (vertical) amplitude above ~4 Hz and 4 nm (horizontal) or 0.2 nm (vertical) amplitude above ~15 Hz, respectively. For comparison, the natural ground motion was measured in the LEP tunnel. In quiet areas, it is smaller than 0.2 nm above 4 Hz (machine off). The levels approach 20 nm with the equipment switched on. In large, noisy IP detectors, the motion is of the order of a few 100 nm [5].

Given these severe tolerances, launching a stability study was considered essential [6]. It aims at estimating the time-stability of the magnetic quadrupole centre and at predicting the achievable luminosity after application of correction schemes such as feedbacks. It should allow to estimate the spectrum of noise like ground motion, cooling water, or heat-induced errors, the transfer function to the magnet and the magnet supports, the lattice response and the feedback transfer function. It should also investigate the best available technologies, e.g. actively damped magnet supports, and predict the time-dependent effects. The final goal is to establish the feasibility of the design parameters in a realistic environment. A vibration test stand has been set up. It is equipped with a granite table and measurement devices, among which two geo-phones (GSV-310 from GeoSig^{TM}). The latter have a frequency range from 1 to 315 Hz. The first step was to demonstrate vibration measurements with sub-nm resolution and to characterise the ground motion in the test stand. The velocity measurements provide the power spectral density and the integrated rms motion above a given frequency [6]. Examples of these quantities are shown in Figs. 4 and 5. The measured rms motion of the concrete floor was found to be ~ 5 nm above 4 Hz and ~ 4 nm above 15 Hz, which is good but still 5-20 times above the CLIC goals.

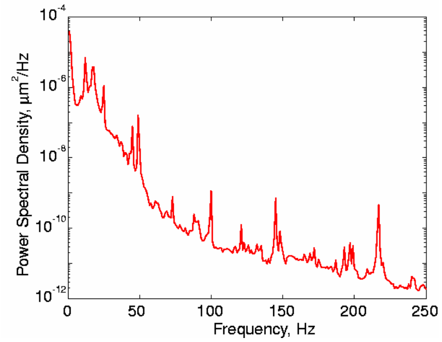

Fig. 4 Power spectral density measured in the vertical direction at the test stand.

As a first stabilisation test, the effect of putting rubber feet on one sensor was measured, while connecting the other sensor directly to the supporting table (Fig.5). This illustrates the benefit of passive damping for higher frequencies, while lower frequency perturbations are enhanced.

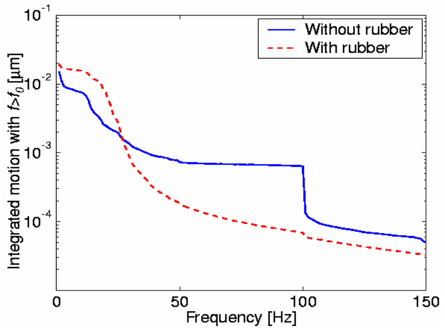

Fig. 5 Integrated rms motion above a given frequency with and without rubber feet at the test stand.

The tight tolerances needed on the stability of the linac quadrupoles require feedbacks steering the beam back to its original trajectory [7]. A pessimistic model of independent feedbacks (made of two dipoles and three monitors) has been simulated, in which none uses the information provided by the others. Fig.6 shows the emittance growth so obtained, modeling the ground motion by moving the girders that support the linac elements according to the ATL model with A= 5 10^{-7} $\mu m^2 s^{-1} m^{-1}$. The various curves correspond to different gains for a correction done by a set of 40 independent feedbacks and the blow-up without correction is also given for comparison.

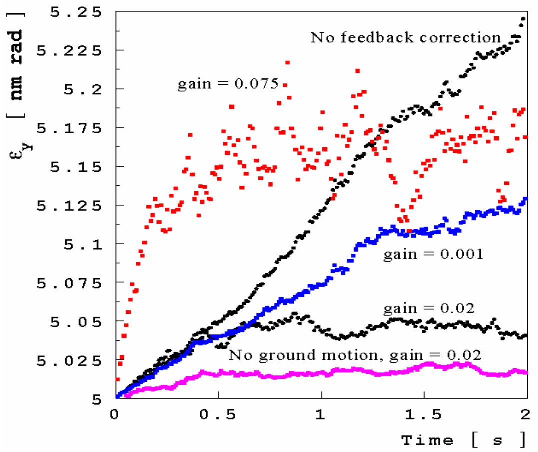

Fig. 6 Time evolution of the vertical emittance at 3 TeV, due to ground motion, with 40 independent feedbacks at various gains.

Vertical position displacements between the beam centres at the IP generate a loss of luminosity. In order to limit this loss, related to beam jitter at the IP, fast position feedback systems have been modelled [8]. They consist of correctors and beam position monitors located very close to each other on the same IP side. The estimated correction is applied to the bunch train moving in the opposite direction, as rapidly as possible. Estimates of the performance of such an intra-pulse IP feedback indicate that the luminosity loss due to small coherent offsets (of about one beam-size sigma) of the bunch trains is reduced by a factor 3. For larger offsets (10 nm at E_{cm} = 1 TeV) 50 % of the nominal peak luminosity is recovered.

4 BEAM DELIVERY SYSTEM

The new optics studied for a compact final focus (FF) system [9] derives from the NLC 1-TeV final focus [10] and is only 500 m long (Fig.7). To limit the effect of synchrotron radiation, the sextupole strengths are increased by a factor 3.4 from the NLC design and all bending angles are reduced accordingly. The beta functions are matched to the CLIC design values and their peak values are ~ 200 km. The upstream quadrupoles, sextupoles, and bending angles have been fine-tuned for maximum luminosity, using a Monte-Carlo optimization. The dispersion has a nonzero slope at the collision point (D' = 1.8 mrad), and is maximum across the final doublet (D = 5 cm). Two chromatic sextupoles are located here and three more are positioned upstream of the main bends in order to cancel the geometric aberrations induced by the first two. The free length between the last quadrupoles and the IP is 4.3 m (2 m for the base line optics [11]), which avoid having the final quadrupoles in the detector solenoid field.

The luminosity, computed by convoluting tracked particles on a grid, has been simulated with and without synchrotron radiation as a function of the beam energy spread (Fig.8). For comparison, results from MAD [12] and from Sixtrack90 [13] are given. Fig.8 identifies the synchrotron radiation (SR) as the dominant limitation, which reduces the luminosity to ~70 % of the ideal value.

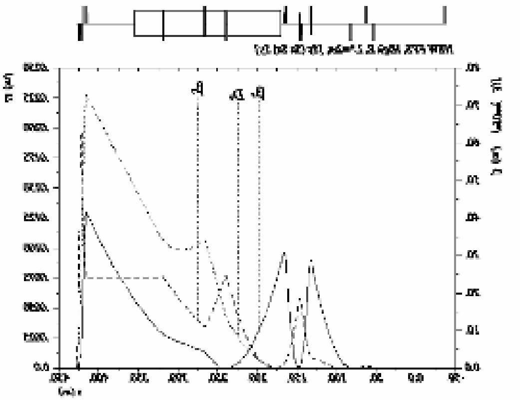

Fig. 7 Compact Final focus optics at 3 TeV.

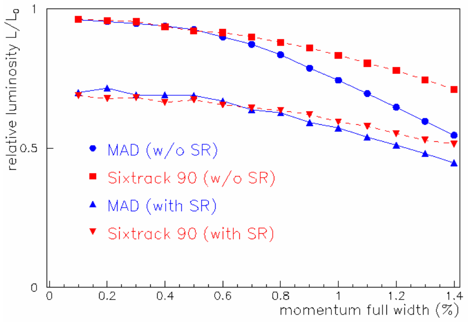

Fig. 8 Relative luminosity versus the full-width energy spread (1% nominal), with and without SR.

As for the FF, a preliminary design of a collimation optics [14] has been obtained by scaling from NLC [15] to the 3 TeV needs and by omitting the second half of the energy collimation. The two parts of the optics, related to energy and betatron collimation, are shown in Fig. 9.

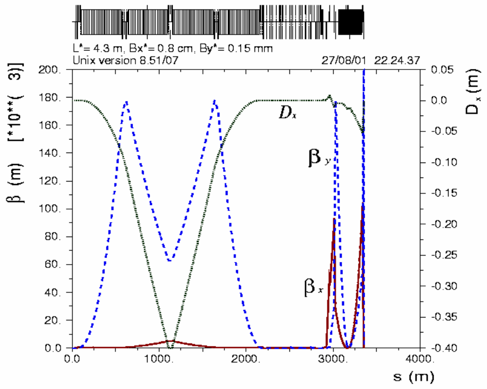

Fig. 9 Optics of a 3 TeV beam delivery system made of a collimation section and a compact final focus.

The length of the cut-down energy-collimation part is ~4 times larger than in NLC such as to get beam spots that allow the collimators to withstand the impact of a full bunch train of nominal emittance and to limit the effects of the synchrotron radiation on the emittance. Because of the latter, bending angles are reduced by 32. The betatron-collimation part has the same optics as that of NLC, since the collimators here are supposed to be replaceable or renewable. In the energy-collimation part, the rms radial (transverse) beam size defined as $(\sigma_x\sigma_y)^{1/2}$ is 147 μm and 1.862 mm at spoilers and absorbers, respectively. This should be sufficient to guarantee the survival of the spoilers, provided they are made from beryllium, carbon or possibly titanium [16].

5 THE NEW TEST FACILITY CTF3

CLIC requires a very efficient and reliable RF source, at a frequency well above the usual one of klystrons. This is why a two-beam acceleration scheme is proposed [1,2]. The drive-beam time structure (bunch spacing of 2 cm) has a strong 30 GHz component, and the RF power is extracted in structures and transferred to the accelerating cavities. The drive-beam is initially accelerated at low RF frequency where commercial power sources are available, and in a fully-loaded mode, so that all the RF power is converted into beam energy. The beam is subdivided into 130 ns bunch trains which are interleaved by injection with transverse RF deflectors into isochronous rings, that raises the bunch repetition frequency and the mean current of each train.

A new facility (CTF3) [17] is under construction at CERN in collaboration with INFN (Italy), LAL (France) and SLAC (US), for testing the main parts of this power production scheme, namely the fully-loaded accelerator operation and the bunch combination. The drive-beam pulse obtained after combination (140 ns, 35 A) will be sent to special structures to produce 30 GHz RF power at the nominal CLIC parameters, and to test accelerating cavities and waveguide components. To reduce costs, it is based on the use of 3 GHz klystrons and modulators from the LEP Injector Linac (LIL), and of most magnets of the LEP Pre-Injector (LPI). CTF3 will be built in stages over five years. Low current tests of the train combination scheme, will be performed in the Preliminary Phase [18], using the present LIL cavities (start in Autumn 2001). With limited beam current in this first stage, the 30 GHz RF power production and the study of collective effects will only be possible in later phases. The second stage (Initial Phase) is based on a linac rebuilt with specially designed cavities adapted for high current and fully loaded operation [19]. It will allow tests of fully-loaded acceleration and limited production of 30 GHz power. The final configuration of CTF3 will be reached in the third stage (Nominal Phase, see Fig. 10), with nominal power production and the capability to study effects associated with high charges.

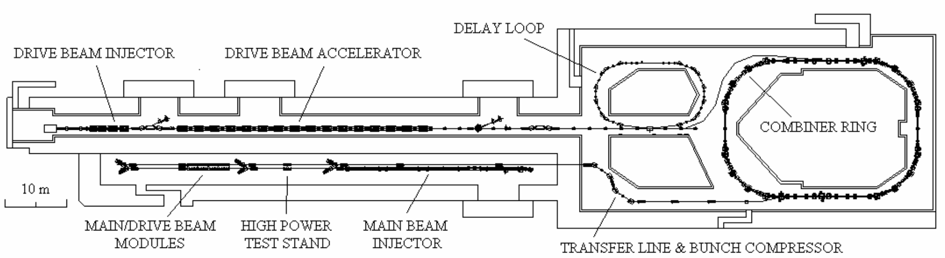

Fig. 10 Layout of the final configuration of the test facility CTF3 (nominal phase)

The drive beam injector [20], built in collaboration with SLAC and LAL, is made of a thermo-ionic triode gun and of a bunching system composed of 1.5 GHz sub-harmonic bunchers, a 3 GHz pre-buncher and a 3 GHz graded-β travelling-wave buncher. It is completed by two 3 GHz travelling wave structures, bringing the beam energy up to about 20 MeV.

The beam is brought to 150 MeV in the drive-beam accelerator, made of 8 modules (with two cavities and a quadrupole triplet) of 4.5 m length. The rms emittance is conserved during acceleration despite the high current and the long pulse, if the transverse Higher Order Modes (HOMs) are suppressed. Two different 3 GHz structure designs have been developed. The first is derived from the 30 GHz Tapered Damped Structure (TDS) of the CLIC main linac [21], using four wave-guides with wide-band SiC loads in each accelerating cell (Q~18 for the first dipole mode). HOM reduction is also achieved by spreading the frequencies (de-tuning). The Slotted Iris Constant Aperture approach [19] (SICA) uses four radial slots in the iris to couple the HOMs to SiC loads. The selection of the modes coupled to the loads is made through the field distribution, so that all dipole modes are damped (Q~5 for the first). HOM de-tuning is due to nose-cones of variable geometry and the aperture can then be kept constant at 34 mm.

The first stage of e^- pulse compression and frequency multiplication (starting from 3.5 A, 1.4 μs pulses) is obtained by using a transverse RF deflector at 1.5 GHz and a 42 m delay loop. A 84 m long combiner ring is then used for a further pulse compression and frequency multiplication by a factor five (ending with 35A, 140 ns pulses), via injection with 3 GHz transverse RF deflectors [2]. The design of these isochronous rings by INFN is now complete [22]. Studies of the multi-bunch loading on the fundamental mode of the deflecting cavities have shown that the beam stability can be kept within tolerance by a proper choice of deflector parameters, β-function at injection and ring-tune. A single 30 GHz decelerating structure, optimised for power production, will be used in a high power test stand where CLIC prototype accelerating structures and RF components can be tested at nominal power and beyond. Alternatively, the drive beam can be used in a string of decelerating structures to power a representative section of the CLIC main linac and to accelerate a probe beam.

6 COMMENTS AND CONCLUSION

The CLIC two-beam scheme is the most promising technology for extending the energy reach of a future linear collider to the multi-TeV range. There are several challenges in the scheme which are subjects of research and development. The progress made on the main ones is summarised here, but other topics are also under study. Among these is the damping ring design where certain collective effects have to be included in the design from the beginning. Intra-beam scattering is a major determinant of the emittances, and electron cloud effects can be severe [23]. Another topic is the study of possible failure modes. Certain modes have been simulated in the context of the performance requirements for the CLIC collimation system and of the collimator survival [24]. Taking up these challenges calls upon an intense research and development program over the next five to six years, before a conceptual design can be delivered.

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