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CLIC Note 402

Proposals for Future CLIC Studies and a New CLIC Test Facility (CTF3)

CLIC Study Team

This report outlines the proposals of the CLIC study team for future CLIC studies and describes in particular a new test facility (CTF3) to demonstrate the technical feasibility of the CLIC RF Power Generation Scheme. A technically possible scenario is given which could lead to the construction at CERN of a linear collider based on CLIC technology. The dates given are the earliest possible dates and assume that LEP stops at the end of the year 2000. A number of key issues however remain to be solved. Those specific to the CLIC power generation scheme will be addressed in two stages. The first stage, which would take five years, would be to build and exploit a new test facility (CTF3) which would demonstrate the feasibility and test all the critical components, albeit on a much smaller scale. This facility which could be housed in the present LPI buildings is described in detail. The second stage would entail building a limited, first-phase version (CLIC1) of the real CLIC power source to power a ~ 625m long section of the CLIC linac capable of accelerating a multi-bunch beam to 75 GeV.

Geneva, Switzerland
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PROPOSALS FOR FUTURE CLIC STUDIES
AND A NEW CLIC TEST FACILITY (CTF3)

1. Introduction

The progress of the CLIC study was presented to the CERN SPC during its 203rd Meeting in June 1998. After discussion the SPC Chairman wrote the following in his Summary of Conclusions :

"The SPC congratulated the CLIC team, on the results already achieved, but also on the very interesting and innovative ideas elaborated in the past year which had improved very much the appeal of the two-beam accelerator concept. The SPC encouraged the continuation of the test on CTF2 in '98 and '99. The SPC looked forward to a plan identifying the main points to be tested in the future and outlining how a series of prototypes could gradually address those points. The plan should also specify the level of support both in money and manpower needed for the next steps in that very promising technique."

The plan requested by the SPC has been prepared and is ready for presentation to the SPC. In the meantime, the present report gives preliminary and advance information to the CERN management outlining a possible scenario that would lead to the building of a linear collider based on CLIC technology, but more specifically describing a new CLIC Test Facility (CTF3) that the CLIC study team intends to propose as a first step towards demonstrating the technical feasibility of the CLIC RF Power Generation Scheme [1]. A conceptual design of CTF3 will be ready by the end of 1999.

2. Background Information

The CLIC study of a two-beam accelerator began in 1986. The original idea for a two-beam accelerator came from A. Sessler in 1982 [2] and was based on the use of induction linac technology for drive-beam acceleration. The original CLIC scheme as proposed by W. Schnell in 1986 was for single bunch operation and was based on the use of super-conducting cavities for drive-beam acceleration [3]. In more recent years, CLIC has changed to a multi-bunch mode of operation to satisfy the increased luminosity requirement and the original single drive-beam scheme has been replaced by a multi-drive-beam scheme. The most significant recent change has been to replace the super-conducting drive-beam accelerator by a normal-conducting one. This continuous evolution combined with a series of new ideas over the last few years has finally produced a very attractive scheme [4] which is believed to be both technically feasible and cost effective. The recent changes have increased the energy reach of the system to centre-of-mass energies in the range 3-5 TeV (the CLIC design has been optimised for 3 TeV) based on high gradient (100-200 MV/m) acceleration.

It must be stressed that <u>not</u> <u>all</u> of the key issues of the CLIC scheme have been resolved.
Before a linear collider based on CLIC technology can be built, solutions to a number of key issues have still to be found. The key issues which are ***specific to high energy e+e- linear colliders*** in general are listed in **Table 1**; those which are ***specific to the CLIC scheme*** are listed in **Table 2**. The test facilities (existing or proposed) that address or provide comparative information on these issues are also included in these lists.

Table 1 - Key issues which are specific to high energy e+e- linear colliders.

KEY ISSUE	OBTAINED / [PLANNED]
Generation of ultra-low transverse emittance beams ε_{nx} = 600 nrad.m ε_{ny} = 10 nrad.m	**ATF (KEK)** ε_{nx} = 3800 nrad.m ε_{ny} = 40 nrad.m **SLC (SLAC)** ε_{nx} = 15000 nrad.m ε_{ny} = 15000 nrad.m **[NLC (500 GeV SLAC)]** ε_{nx} = 2000 nrad.m

	ε_{ny} = 50 nrad.m

Table 1 (Continued) - Key issues which are specific to high energy e+e- linear colliders.

KEY ISSUE	OBTAINED / [PLANNED]
Focusing and colliding very small beams at IP σ_x = 40 nm σ_y = 0.6nm	**FFTB (SLAC)** σ_x = 1000 nm σ_y = 70 nm **SLC (SLAC)** σ_x = 1400 nm σ_y = 600 nm **[NLC (500 GeV SLAC)]** σ_x = 200 nm σ_y = 5 nm
Design of reasonable length beam delivery section Scaling to 3 TeV from NLC: 21 km Scaling to 3 TeV from JLC: 10 km	**[NLC** (1.5 TeV) - 10 km **]** **[JLC** (0.5 TeV) – 2.6 km **]**
Studies of physics conditions in high beam-strahlung regime	-

CTF2 is the existing CLIC test facility which succeeded the first test station CTF1. CTF3 is the next step which should be followed by a last test (CLIC1) before construction.

Table 2 - Key issues which are specific to the CLIC scheme.

KEY ISSUE	TESTED IN
Feasibility of two-beam acceleration scheme	CTF1/CTF2
Multibunch beam acceleration with good emittance preservation in the presence of the high 30 GHz structure wakefields component pre-alignment beam-based trajectory correction damping of transverse higher order modes	CTF2 CLIC1 ASSET / CTF3 / CLIC1
Operating 30 GHz accelerating structures at high gradients (150 MV/m) during long pulses (130 ns)	NLCTA / CTF3
Drive-beam generation and transport with minimum losses Manipulations at medium intensity (35A) Manipulations at high energy and high intensity (244 A)	CTF3 CLIC1
Overall efficiency of the RF power production Power efficiency of individual components	CTF2 / CTF3
Drive-beam stability during deceleration	CLIC1
Testing of 30 GHz components Integration of 30 GHz components in two-beam accelerator	CTF2 / CTF3 CTF2 / CTF3
Detector operation with short intervals (0.67 ns) between bunches	-

It can be seen from Table 2 that the following key issues will be tested in CTF3:

(i) Drive-beam generation and RF power production.

This will be the first demonstration of beam power compression and frequency multiplication. The multiplication factor will be 10 (the CLIC factor is 32).
Because of the limited 3 GHz RF power, the drive-beam energy is only 180 MeV (compared to 1.24 GeV for CLIC) and this, in consequence, limits the final current to 35 A (compared to 244 A for CLIC).
Experience in operating a fully-loaded linac and beam combiner rings, and a good estimate of the overall power production efficiency will be obtained.

(ii) **Two-beam acceleration.**
This will be above all a test bed of the RF power source.
The number of modules is limited but they are equipped with nominal components working at nominal fields and power levels.
The compatibility of operating the two beams together will be tested.
The ability to integrate all the necessary components and systems (water, vacuum, alignment,..) in the very limited space of the modules will be demonstrated.
The pre-alignment system which holds the components in place within ± 5 microns will be operated in a real accelerator environment (a radiation environment).

(iii) **Nominal accelerating fields (150 MV/m) during the nominal pulse duration of 130 ns.**

(iv) **Acceleration and beam-loading compensation of multi-bunches (50) of nominal charge (4 10^9 e-).**
The number of bunches will be limited to 50 because of beam-loading effects in the four 3 GHz LIL structures of the main beam injector. The bunch train will however be long enough to demonstrate the ability to compensate beam-loading effects in one of the 30 GHz main linac structures.

The key issues which are not tested in CTF3 but which are tested in CLIC1 are given as follows:

(i) **Main beam stability during acceleration.**
CLIC1 will accelerate the main beam to 75 GeV.
This will be the first opportunity to test the beam-based trajectory correction scheme and to demonstrate that the very small emittances can be preserved along a short section (~ 624 m) of the main linac (this assumes that a suitable low emittance source of electrons is available for this test).

(ii) **Drive beam stability during deceleration.**
This will be the first test of the deceleration of the drive beam over the nominal length of 624 m.
The ability to correct the trajectory of a beam with a large momentum spread will be checked.
The stability of the drive beam will depend to a large extent on the level to which the higher order modes of the power extracting structure are damped – CLIC1 will provide the final confirmation that the design objectives have been obtained, and will determine the lowest energy to which the beam can be decelerated (this will determine the final overall power production efficiency).

(iii) **Drive-beam generation at high intensity (244 A) and energy (1.24 GeV).**
CLIC1 will test beam compression and frequency multiplication by the CLIC nominal factor of 32 and will for the first time have to operate with high beam powers (3 MW).
Handling these beam powers without significant losses will validate the beam loss management and hardware protection systems.

The key issues which are not tested in CTF3 or in CLIC1 are given as follows (see Table 1):

(i) **Generation of ultra-low emittances.**
(ii) **Focusing and colliding very small beams.**
(iii) **Designing a reasonable length beam delivery (collimation and final focus) section.**
Scaling from 1.5 to 3 TeV from NLC (U_r=E(TeV)/1.5) and assuming β_y=0.1 mm at the I.P. :
$L(\text{km}) = [L_{FF}]+[L_{COLL}] = [0.8(1+U_r)+2.4U_r^{3/2}]+[6U_r] \approx 21.2$ km
Scaling from 0.5 to 3 TeV from JLC (U_r=E(TeV)/0.5) and assuming β_y=0.1 mm at the I.P. :
$L(\text{km}) = [L_{FF}]+[L_{COLL}] = [U_r]+[1.6U_r^{1/2}] \approx 9.9$ km

(iv) Assuring that the physics conditions with beam/beam collisions in the high beamstrahlung regime are acceptable.

3. A Possible Scenario for a Linear Collider Based on CLIC Technology

A technically possible scenario leading to the construction at CERN of a linear collider based on CLIC technology is given in **Annex 1**. The dates given are the earliest possible dates and assume that LEP stops at the end of the year 2000 and that LHC will be paid by the year 2008. It focuses on the ***key issues that are specific to the CLIC scheme*** and gives no information about plans to resolve the ***key issues specific to high energy colliders.*** It goes without saying that these issues will nevertheless have to be studied in parallel with, and resolved within the same time frame as, the ***specific-to-CLIC*** activities.

It is proposed to demonstrate the feasibility of the ***key issues which are specific to the CLIC scheme*** in two distinct successive stages.

The first stage, which would take five years, would be to build and exploit a new test facility (CTF3) which would demonstrate the feasibility, and test all the critical components, of the RF power generation scheme albeit on a much smaller scale and with the drive linac at a different (higher) frequency. This facility which could be housed in the present LPI (LIL+EPA) buildings is described in detail in **Section 7.**

The second stage would entail building a limited, first-phase version (CLIC1) of the real CLIC power source to produce just one drive beam rather than the multiple drive beams it would ultimately be required to produce. This drive beam would have the nominal CLIC energy and current, and would provide enough power in a ~624m long section of the CLIC linac to accelerate a multi-bunch beam to 75 GeV. More details of this first-phase CLIC1 power source are given in **Section 6.** Since this is a final test of the CLIC scheme, all components will be definitive ones and, given a positive outcome of the test, would be used for the final construction.

4. Overall view of the CLIC RF Power Generation Scheme

The aim is to produce an RF power pulse at the entrance to each main linac accelerating structure that is as close as possible to the ideal power pulse shown in Fig.1. The ramp at the beginning of the pulse is required during the fill time of the structure to compensate bunch-to-bunch energy variations due to beam loading effects in the main linac.

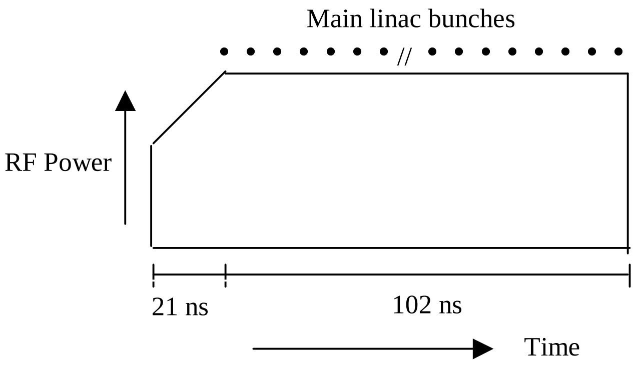

Figure 1 – Ideal RF input power pulse for main linac accelerating structures.

To be able to evaluate the merits of the Test Facility proposal it is first necessary to understand the main features of the new CLIC RF Power Generation Scheme. This can be described briefly as follows. The RF power for each main linac is obtained from a series of drive bunch trains, each drive train supplying the power for a ~ 624 m long section. A 3 TeV centre-of-mass collider with an accelerating gradient of 150 MV/m therefore needs 22 drive trains per linac. Use of multiple trains limits the power in each train to reasonable values and makes the generation of them possible with standard technology at an affordable cost. Twenty two drive bunch trains however does not mean 22 separate drive linacs, in fact the drive-beam generation scheme has the advantage that all drive trains are produced from one linac starting from one long pulse. The layout for a 3 TeV c.m. collider with 22 drive bunch trains per linac is shown in Fig.2.

Before giving a technical description of the various sub-systems of the new scheme it is first useful to get an overall view of how the scheme works by explaining the basic ideas.
The aim is to create multiple drive bunch trains, each train being capable of producing about 400 MW/m of 30 GHz peak RF power when it interacts with a power-extracting output structure (as in a klystron). The requirement is therefore to produce trains of high-intensity short electron bunches at an energy of about 1.24 GeV with a bunch spacing of 2 cm. Unfortunately such drive bunch trains cannot be created directly in an efficient way because the technology does not exist, so an alternative has to be found.

The essence of the scheme is as follows.

A very long bunch train is first generated with a bunch spacing of 64 cm because it can be easily accelerated using a low frequency (937 MHz) RF system. This long train contains all the bunches required for all the drive bunch trains for one pulse of the main linac.

The long bunch train is accelerated using a normal-conducting fully-loaded travelling-wave linac with an RF to beam efficiency of about 95%.

The bunch spacing is reduced in stages (this is referred to as frequency multiplication) and, at the same time, the bunch train intensity is increased (this is referred to as pulse compression) by interleaving trains of bunches first in a delay line (×2) and then in two combiner rings (each ×4). In the same process gaps are created in the train so that the initial single bunch train is split up into a series of separate bunch trains.

At the end of the process a series of bunch trains with a 2 cm bunch spacing are obtained and these trains separated by 4.2 µs are used to generate the 30 GHz power.

If the whole process is seen as a one big black box then RF power at ~1 GHz is put in on one side and pulsed-compressed 30 GHz RF power is obtained on the other side.

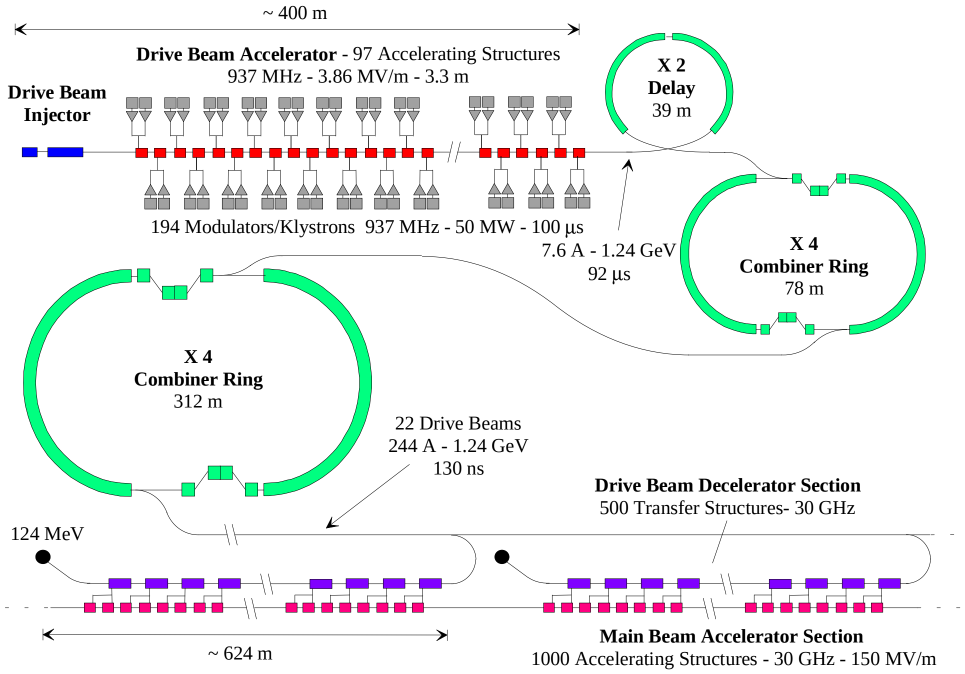

Figure 2 - General layout of the CLIC RF power generation scheme.

5. Brief technical description of the CLIC RF Power Generation Scheme

The energy for RF production is initially stored in one long bunch train which is efficiently accelerated to 1.24 GeV by a fully-loaded, conventional, low-frequency (937 MHz) linac. The length of the bunch train is chosen to be twice the length of the high-gradient linac, this is required to obtain the correct phasing of the multiple drive beams and is explained later. The required structure of the continuous bunch train is shown in Fig.3. It consists of a series of 39 m long trains with bunches in either even or odd RF buckets (this is important for the first frequency multiplication stage by the delay line). Two alternative ways of generating this train are being considered for the moment. The first creates the bunches directly using a photo-injector, the second uses a conventional injector consisting of a thermionic gun and a sub-harmonic buncher. To switch from even to odd RF buckets requires that the phase of the 937/2 MHz sub-harmonic buncher be changed by 180 degrees during the switching time. The optimum switching time is about 4 ns but this may not be feasible (further studies are required). The mean current of the train is 7.6 A and each bunch has a charge of 16.3 nC. The distance between bunches is 64 cm i.e. there is a bunch in every second RF bucket.

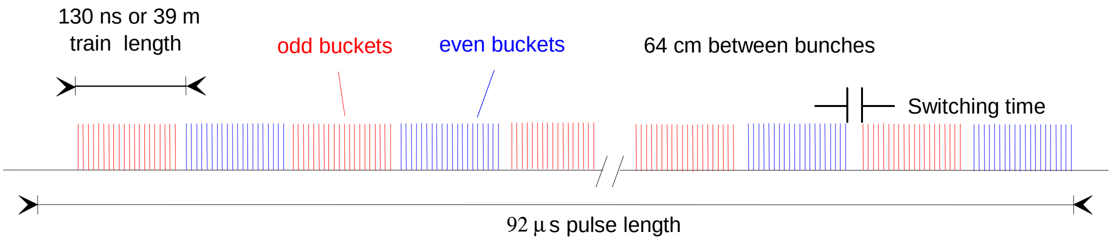

Figure 3 – Bunch train structure.

The linac is powered by 194 conventional 50 MW long-pulse (~100 μs) klystrons. By a judicial choice of structure length and accelerating gradient almost all of the RF energy (~ 95%) is transferred to the beam (this is the so-called "fully-loaded" condition). Having an almost continuous train produces a constant beam loading in the linac and minimises beam energy variations.

After leaving the linac the continuous train enters the delay line combiner where it is split into a series of 39 m long bunch trains spaced by 39 m long gaps. This is done as follows – see Fig.4. An RF deflector working at one half the linac frequency sends the first bunch train with bunches in even RF buckets into a delay line which introduces a delay of 39 m, and lets the second train with bunches in odd RF buckets go straight through. A second RF deflector then combines the two trains to form a single train by an interleaving-superposition of the bunches, this also naturally produces a gap of 39 m. The gap is essential for clean extraction by a kicker in the next combiner ring stage. The bunch spacing is now 32 cm and the intensity of the train is doubled.

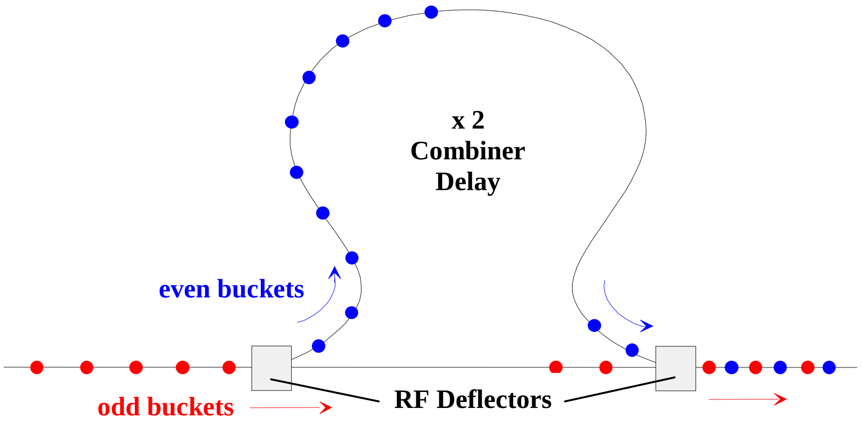

Figure 4 – Schematic layout of the times-two combiner.

The same principle of bunch train combination is now used to combine the trains four-by-four in the first combiner ring. This is shown schematically in Fig.5 and works as follows.

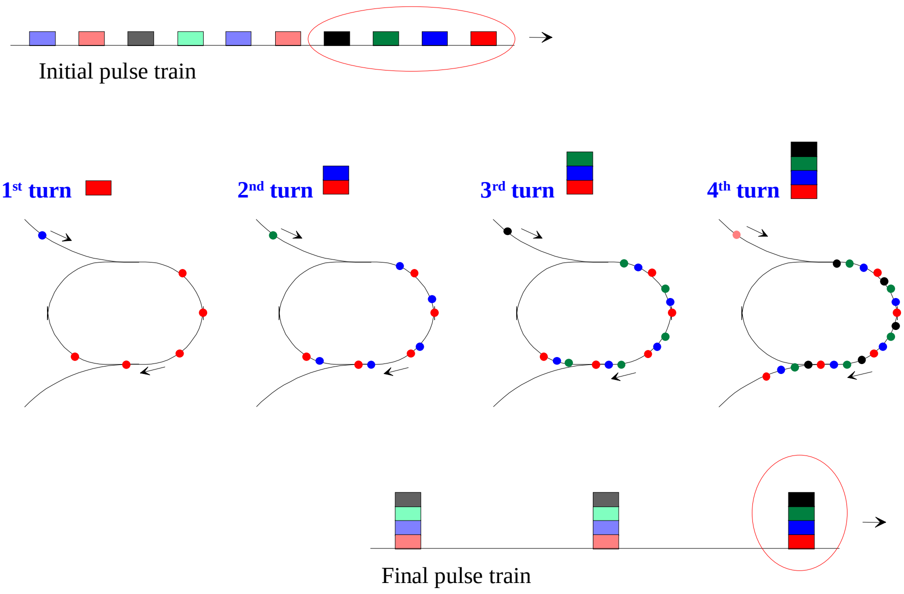

Figure 5 - The times-four train combination scheme.

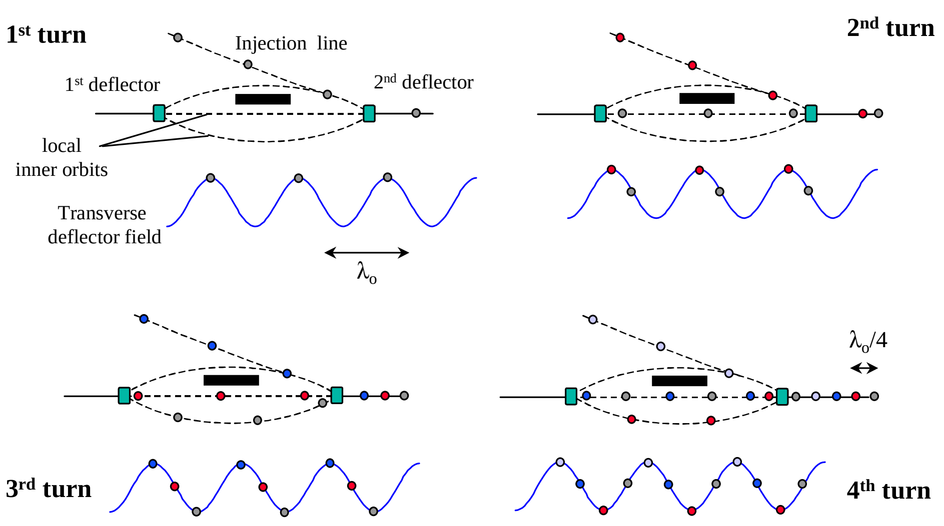

Figure 6 – Schematic description of the four-turn injection into the combiner ring. 1) When the first train arrives all of its bunches are deflected by the 2nd transverse deflector onto the equilibrium orbit. 2) When the first train comes back, its bunches arrive at the deflectors at the zero crossing of the RF field, hence they miss the septum and stay on the undeformed equilibrium orbit. The second train arrives 90° later, and its bunches are deflected by the 2nd deflector to the equilibrium orbit. 3) Now the 1st train bunches are kicked inside the ring, the 2nd train bunches arrive at the zero crossing, and the 3rd train bunches are injected. 4) The 1st train bunches arrive again at the zero crossing, the 2nd train bunches are in the inner orbit, the 3rd train bunches are also at the zero crossing and the 4th train bunches are injected; after the 2nd deflector the four trains are combined in a continuous train with one quarter of the initial bunch spacing.

Two RF deflectors operating at 937 MHz create a time-dependent local deformation of the equilibrium orbit in an 78 m circumference ring - see Fig.6. The first train is injected into the ring when this bump has a maximum outwards amplitude. The ring circumference is equal to the spacing between trains plus $\lambda/4$, where λ is the spacing between bunches (and the wavelength of the RF deflectors). The RF phase seen by the bunches circulating in the ring therefore increases by 90^o each revolution time. As a consequence when the second train is injected, the first train does not see any orbit deformation and its bunches are interleaved with the ones being injected. This is repeated two more times, then the four interleaved trains are extracted from the ring by an ejection kicker half a turn later, and the same cycle starts again (more details of this process are given in the caption of Fig.6).

After the first combiner ring the pulse is composed of 88 trains. The periodicity of the trains is equal to eight times the train length (1040 ns or 312 m), while the bunch spacing is 8 cm. The trains are combined again, using the same mechanism, in the second combiner ring which is 312 m long, yielding another factor four in frequency multiplication, to produce the required 22 trains with a bunch spacing of 2 cm. The periodicity of the trains is now 4.16 μs or 1248 m, and corresponds to twice the length of the main linac section that each bunch train will power. The evolution of the bunch train parameters in the three compression stages are given in Table 3.

Table 3 – Evolution of bunch train parameters along the compression system.

Parameter	Name	Initial	After Delay	After 1st Ring	After 2nd Ring	Unit
Pulse Length	τ_P	~ 92	~ 92	~ 92	~ 92	μs
Trains/Pulse	N_T	1	352	88	22	
Train Length	τ_T	92	0.130	0.130	0.130	μs
Bunch Separation	Δ_B	64	32	8	2	cm
Train Periodicity	Δ_T	-	0.26	1.04	4.16	μs
Pulse Current	I_P	7.6	15.2	61	244	A

In the scheme described here, one drive-beam generator is required for each of the two main linacs. The possibility of having a single generator for both linacs is however still being studied. The drive-beam trains are generated in a central facility with respect to the two main linacs of the collider. This means that they have to be first transported in the opposite direction to the main beams before being turned around and injected into the different drive linacs where they travel parallel to the main beams. The transport line is common for the drive-beam trains and is located near the roof in the main CLIC tunnel. Pulsed deflector magnets deflect each bunch train at the appropriate time into a turn around. At this stage all the bunches in the train have the same charge. The RF power ramp for the main linac beam energy compensation (see Fig.1) is created by leaving a few leading buckets of the first ten or eleven of the 32 constituent bunch trains empty. This is done by delaying the fast switch of the sub-harmonic pre-buncher from even to odd buckets or vice-versa. After the combination process in which 32 bunch trains are all interleaved into one, the average current in the first part of the pulse is reduced due to the missing bunches. The form of the ramp can be synthesised by a suitable set of 32 switching times. Each high-current, relativistic drive beam is then decelerated in a ~624 m long sequence of low-impedance decelerating structures, and the resulting output power is transferred to the main linac to accelerate the low-current, high-energy beam. At the end of each 624 m long section the drive beam is dumped and a new one takes over the job of accelerating the main beam. After 624 m most of the kinetic energy of the beam has been converted to RF energy. The energy of the bulk of the drive electrons is then 0.12 GeV which has been shown by extensive simulations to be a lower limit at which the energy spread over the train is too large for proper focusing and the beam must be dumped. The behaviour of the decelerated drive beam is one of the key issues that has to be tested in CLIC1. In CTF3, the drive beam is decelerated from 180 MeV to 125 MeV but it has only to be transported a relatively small distance (~10 m).

6. CLIC1

Although quite a number of issues can be addressed with CTF3 (see Table 2), a full scale prototype (CLIC1) to test one complete CLIC drive train will almost certainly be required before the community is convinced that the overall scheme will work. A proposed layout of CLIC1 is shown in Fig.7. The drive-beam generator for CLIC described above will produce 22 drive trains per linac for a 3 TeV centre-of-mass collider. All major problems associated with this scheme can however be studied by generating only one drive train. To obtain the nominal beam energy with only 50 klystrons installed requires building fifty 937 MHz RF power compressors (these compressors are not required for the final CLIC scheme). Klystrons working with a much reduced RF pulse (~ 25μs) could be used at this stage instead of the CLIC nominal value of 100 μs. This first-phase CLIC installation would produce beams with the nominal current and would be able to accelerate a multi-bunch beam to 75 GeV at the nominal accelerating gradient of 150 MV/m. CLIC1 and CLIC (3.0 TeV) drive-beam parameters are compared in Table 4 (see Section 7).

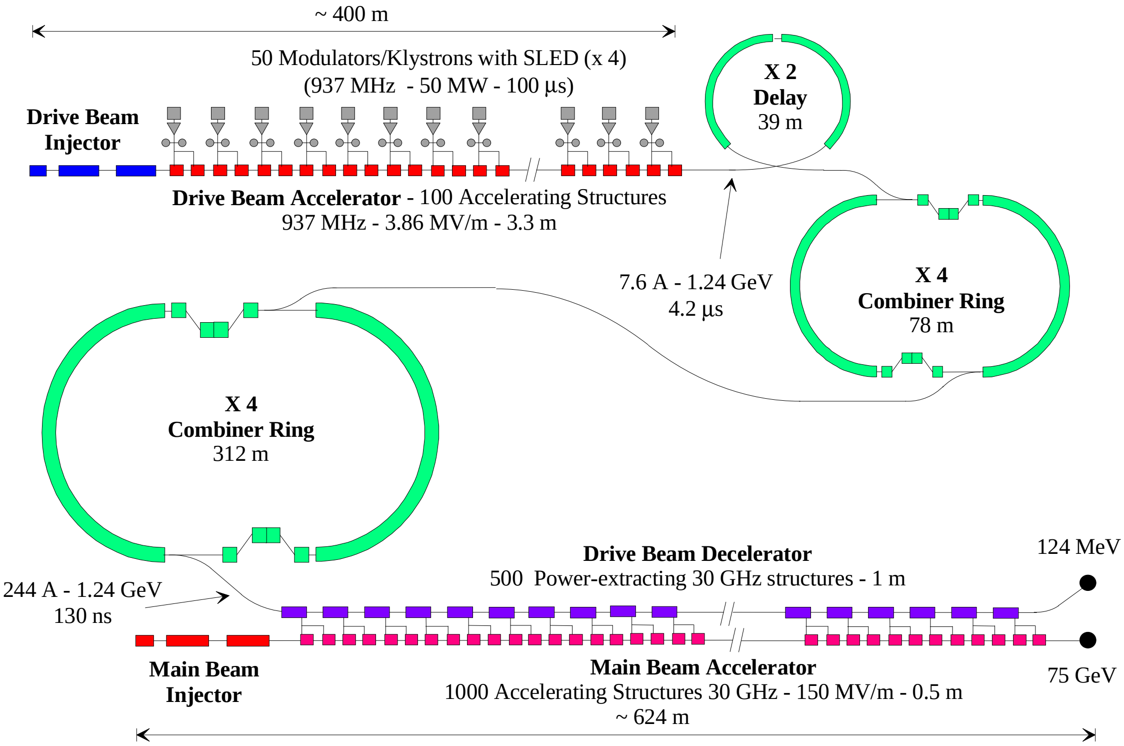

Figure 7: Schematic layout of CLIC1

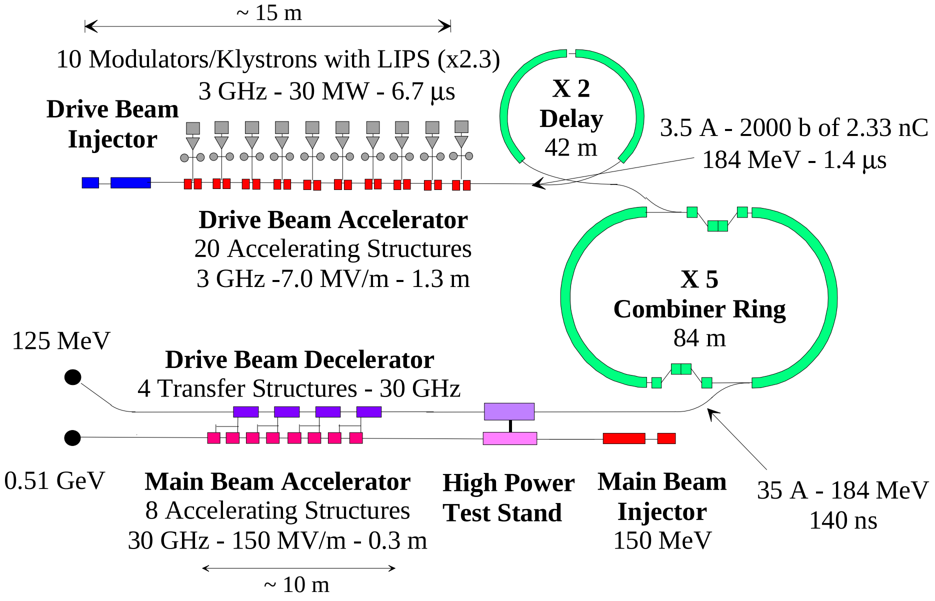

Figure 8: Schematic layout of nominal phase of CTF3

7. Brief description of the proposed new Test Facility CTF3.

Since CLIC1 is a very large and expensive installation a much smaller facility (CTF3) is proposed as an intermediate first step to demonstrate the technical feasibility of the key concepts of this new RF power source, e.g. generation of interleaved bunch trains, operation with a fully-loaded, drive-beam accelerator, and generation of accelerating gradients of 150 MV/m. The new CLIC Test Facility (CTF3) is shown in Fig.8. To reduce costs CTF3 differs from the RF power source proposed for CLIC in the following ways (Table 4).

The frequency of the drive-beam accelerator is chosen to be 3 GHz instead of 937 MHz. This enables the 3 GHz klystrons, modulators, RF power compression units and waveguides from the LEP Injector Linac (LIL) Complex to be used for power production which is always very costly. With ten of these modulator/klystron units the drive-beam energy for a current of 3.5 A (~ half the nominal CLIC current) is 184 MeV – this is very low compared to the 1.24 GeV for CLIC and obviously makes operation more difficult, but simulations indicate that it works. CTF3 only has the first two stages of the beam combination scheme namely, the times-2 Delay Line Combiner and the first Combiner Ring. The second (×4) large circumference Combiner Ring is very expensive and since it has the same scheme of combination it is not considered to be essential for this first demonstration test facility. The compression factor for the first Combiner Ring has however been increased from 4 for CLIC, to 5 for CTF3, to obtain an overall compression of 10. This gives a final bunch spacing of 2 cm (the same as in CLIC) for production of power at 30 GHz. Due to space limitations, it is unlikely that the circumference of the Combiner Ring can be made smaller than 84 m. This results in a final pulse length of 140 ns rather than the nominal CLIC value of 130 ns. The modulators produce a maximum RF pulse of 6.7 µs which after power compression with LIPS (×2.3) becomes ~1.6 µs. This beam pulse is long enough after a (×10) frequency multiplication to produce the required final 140 ns pulse. The drive-beam decelerator is limited to a total length of about 10m (4 transfer structures) compared to 624 m for CLIC. To limit the radiation produced by CTF3 it is proposed to run at 5 Hz instead of 75 Hz.

It is proposed to house the new facility in the existing LIL and EPA buildings (see Fig.9) and to make use of many of the LIL and EPA components. As mentioned above it seems unlikely that a 78 m circumference ring could be housed in EPA whereas an 84 m long ring appears just to fit. A detailed study is required to confirm this.

Table 4 - Comparison of CTF3, CLIC1 and CLIC (3 TeV) parameters

	CTF3	**CLIC1**	**CLIC**	
Accelerating frequency	30	30	30	GHz
Main linac accelerating gradient	150	150	150	MV/m
Number of accelerating structures per linac	8	1000	22 x 1000	
RF pulse length	140	130	130	ns
Main beam acceleration per drive beam	0.36	75	75	GeV
Number of transfer structures per linac	4	500	22 x 500	
Number of drive beams / linac	1	1	22	
Frequency of drive-beam accelerator	3000	937	937	MHz
Drive-beam energy	184	1240	1240	MeV
Average drive-beam current before compression	3.5	7.6	7.6	A
Number of klystrons	10	50	194	
Number of RF power compressors	10	50	0	
Drive-beam pulse length before compression	1.40	4.16	92	µs
Interval between bunches before compression	20	64	64	cm
Delay line combiner	42m (x2)	39m (x2)	39m (x2)	
Combiner ring	84m (x5)	78m (x4)	78m (x4)	
Combiner ring (x 4)	NO	312m (x4)	312m (x4)	
Overall frequency multiplication	10	32	32	
Final average drive-beam current after compression	35	244	244	A
Interval between bunches	2	2	2	cm
Drive-beam energy per pulse	0.8	39	867	kJ
Repetition frequency	5	75	75	Hz
Average beam power	4.1	2950	64.9x10^{3}	kW
Drive-beam energy on beam dump	125	124	124	MeV

[redacted]

8. Some design details.

8.1. Injectors

The injector consists of a pulsed thermionic gun followed by one or two sub-harmonic (1.5 GHz) pre-buncher cavities, two 3 GHz pre-buncher and buncher cavities, and two 3 GHz damped/detuned accelerating structures (as described in 8.2). All the injector components sit in a solenoidal-focusing field. The final beam energy is about 26 MeV. The pre-buncher creates bunches with a spacing of 20 cm. Depending on the phase of the sub-harmonic pre-buncher, these bunches fall into either even or odd RF buckets of the 3 GHz system where they are trapped and accelerated. With the phase set at 0 degree, most of the charge (the process is not 100%) goes into bunches occupying only even 3 GHz buckets (in fact every other even bucket). As the phase of the sub-harmonic cavities is varied from 0 degree to +180 degree, the intensity of the charge of the bunches in the even buckets is reduced and that in the odd buckets increased until there is only charge in the bunches in the odd buckets. This produces the drive-beam structure shown in Fig.3 but with the required 20 cm bunch spacing. It is hoped that the phase switch can be done within 4 ns. To be able to switch in such a short time requires a very broad-band power supply and a low-Q (~ 10) sub-harmonic buncher cavity. This may not be feasible but will only be known when the hardware has been tested. A longer switching time just makes the system less efficient. The normalised emittance of the bunched beam at the exit (~26 MeV) is required to be <100 mm.mrad with an rms bunch length < 1.5 mm.

An interesting alternative is to use a photo-injector consisting of a laser-illuminated photo-cathode in a high-gradient RF gun. This has the advantage of producing very short, low-emittance bunches. The bunch train structure (see Fig.3) could be generated directly by a suitable phasing of the laser pulses. The present CTF2 gun design with some modifications would be suitable for the RF gun but the laser required for such a system has a specification which is beyond anything that exists today and a strong R&D program would be necessary to determine if such a laser is indeed feasible and at what cost.

8.2. Drive-beam accelerator

The 3 GHz drive-beam accelerator increases the beam energy from ~26 MeV to 184 MeV using 16 normal-conducting TW structures operating at 7.0 MV/m. This linac has a conventional quadrupole FODO focusing. A provisional layout in the LEP Pre-Injector (LPI) building is shown in Fig.9. To maintain beam stability in both this linac and the 26 MeV injector linac the transverse wakefield levels have to be damped to Q values of ~100. This will be done by building new structures with waveguide damping and detuning (the accelerating structures of the LEP Injector Linac (LIL) cannot be used because of beam instabilities above 50 mA, and excessive beam loading effects). The structure design will be based on a design developed for the CLIC 30 GHz main linac accelerating structures. The RF power is supplied by 30 MW klystrons which, after compression by a factor 2.3 by the existing RF pulse compression system (LIPS) and splitting the power, provides ~34.5 MW at the input to each 1.3 m long structure. Operating this linac in the fully-loaded condition results in an RF to beam efficiency of $\approx$ 96%. Since the bunch train charge is essentially constant along the 1.4μs pulse, the beam induced energy spread is very small. A correlated single bunch energy spread is introduced in the drive-beam accelerator by a combination of off-crest running and beam loading for BNS stabilisation, and so that the bunches can be compressed at a later stage. At the end of the accelerator there are ~2000 bunches of 2.33 nC per bunch, this corresponds to a current of 3.5 A averaged over the train. The single bunch, and bunch-to-bunch, energy spreads are both expected to be ~ 1% rms.

The length of the accelerating structure (1.3 m) has been chosen to give maximum RF to beam efficiency with a current of 3.5 A when powered with 30 MW klystrons. Since this is also the optimum length of structure for 4 A when powered with 40 MW klystrons, it is proposed to replace 30 MW klystrons when they fail with 40 MW klystrons so that there will be a natural progression towards higher currents (4 A) and slightly higher energies (200 MeV).

8.3. Delay line combiner

The continuous train of bunches is split into a series of 42 m long bunch trains with 42 m gaps by the combiner delay line. It also produces a frequency multiplication (×2) by interleaving the bunches in the even buckets with the bunches in the odd buckets to produce a bunch spacing of 10 cm. The two RF transverse deflectors in this line are short, 1.5 GHz travelling-wave, iris-loaded structures whose fundamental mode is a deflecting hybrid mode. To prevent bunch lengthening the lattice has to be isochronous. At the exit of the delay line the pulse current is 7 A. A schematic layout of the delay line in the EPA building is shown in Fig.9.

8.4. Ring combiner

A further frequency multiplication (×5) is obtained in the 84 m circumference combiner ring to obtain a final bunch spacing of 2 cm. This ring is more like a transport line than a storage ring because there is no RF acceleration and the bunch trains only make at the most a few turns (the first train makes 4½ turns and the fourth train makes only ½ turn). Since the CTF3 and CLIC frequency multiplication factors are different, the way in which the trains are combined is also slightly different (see the caption of Fig.10). Injection into the ring is made using a septum and a two transverse RF deflectors (see Fig.10). The existing injection septum of EPA can be used for this purpose. The injection and extraction systems are located at a distance of half the ring circumference from each other. Beam loading and transverse wakefields in the 3 GHz transverse deflecting structures are a concern because the decrease of the transverse kick along the train will produce variations in transverse position of the bunches.

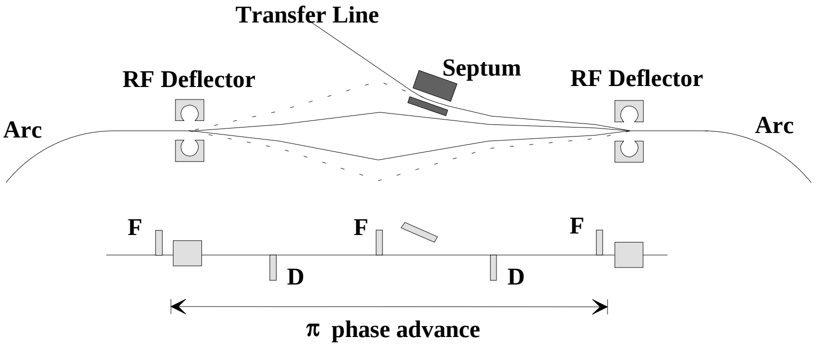

Figure 10 - RF Deflector injection insertion layout and lattice. Circulating bunches travel on the full-line orbits while the injected bunches are kicked by the 2nd deflector onto the equilibrium orbit of the ring. The max. outer trajectory (shown dotted and intercepting the septum) is never followed, since the whole bunch train is ejected before any of the circulating bunches will reach the corresponding phase in the 1st deflector. The max. inner trajectory (also shown dotted) is not used either.

To prevent bunch lengthening the combiner ring lattice has to be isochronous. In fact since the fifth bunch train only makes half a turn in the ring each half ring has also to be isochronous. The suitability of using existing bending and quadrupole magnets of the LPI Electron Positron Accumulator (EPA) in the ring is being studied. The bunch length is kept relatively long in the combiners (~1.5-2.5 mm rms) to prevent the emission of coherent synchrotron radiation which increases the single bunch energy spread as well as decreasing the average energy. The 140 ns bunch train is extracted from this ring using a pulsed kicker and a septum magnet both of which can be taken from EPA. At the exit of the ring the peak current is 35 A. A schematic layout of the combiner ring in the EPA building is shown in Fig.9.

8.5. Path length tuning chicane

The delay line and the combiner ring must have a path length tuning device, to tune exactly the relative phase of injected and circulating bunches, and to compensate for orbit variations due for instance to thermal effects. A tuning range of ± 0.5 mm is required. Actually in the ring two such devices (one for each arc) are needed, since each train makes an odd number of half turns in the ring. To make the variable path length it is proposed to use a simple magnetic chicane consisting of three bending magnets separated by drifts.

8.6. Bunch length tuning module

The bunch length will be tunable in the transfer line between the drive-beam accelerator and injection into the combiner ring so that coherent synchrotron radiation effects in the ring produced by the high-charge short bunches can be both controlled and studied. A design has been found which incorporates this bunch length tuning which is able to compress or stretch the bunches, in the strong-bending modules of the transfer line (see Fig.9).

8.7. Bunch compressor

Due to the unusual bunch energy correlation, the final bunch compression after extraction from the ring cannot be done with a simple three bending-magnet chicane because it’s optics does not have the correct sign of the R56 matrix element so a more complicated design has to be worked out which will certainly take up more space. The final rms bunch length for efficient production of 30 GHz RF power is ~ 0.5 mm.

8.8. RF power ramp

The RF power ramp for the main linac beam energy compensation (see Fig.1) is created by leaving a few leading buckets of three of the ten bunch trains empty. This is done by delaying the fast switch of the sub-harmonic pre-buncher from even to odd buckets or vice-versa. After the combination process in which the ten bunch trains are all interleaved into one, the average current in the first part of the pulse is reduced due to the missing bunches. The form of the ramp can be synthesised by a suitable set of ten switching times.

8.9. Two-beam test accelerator

The final 35 A drive beam will have an energy of 184 MeV and will consist of bunches with a charge of 2.33 nC/bunch with a spacing of 2 cm. It is proposed to use this drive beam alternatively either to power the four 30 GHz modules that have been build for CTF2, or to drive a high power RF test stand (see section 8.10) for the testing of prototype CLIC components. To be able to produce sufficient power to generate the nominal CLIC accelerating gradient of 150 MV/m with only 35 A requires a slightly modified power extraction structure which couples more strongly to the beam so four new power extracting structures will have to be built. After deceleration from an initial energy of 184 MeV to a final energy of 125 MeV the drive beam is sent to a dump. There is space in the modules for eight 86-cell 30 GHz accelerating structures with the potential to accelerate a beam from 150 MeV to 510 MeV. Five of these will be the constant impedance accelerating structures presently installed in CTF2, the others will be prototype damped/detuned CLIC structures which will be added when they become available. The main beam to probe the accelerating fields generated will be produced by a photo-injector which will be able to run in either a single bunch or a multi-bunch mode. In the multi-bunch mode there will be about 50 short bunches of about 0.64 nC/bunch (the exact number of bunches will be determined by beam loading considerations). One of the two CTF2 RF guns can be used for the photo-injector but a new laser and pulse train generator will be required. The beam will be accelerated to an energy of ~ 150 MeV by four 4.5 m long LIL accelerating sections operating at a gradient of about 9 MV/m. When operating with the 30 GHz modules, a single bunch main beam will be used because the constant impedance sections are not designed for multi-bunch operation.

8.10. High power RF test stand

The option of operating a high power RF test stand driven by the CTF3 beam either in series with (see Fig.8), or instead of, the four 30 GHz modules, or in a parallel line is being studied. The test stand would be a highly flexible experimental facility with a 1-2 m long test bed to quickly, easily and accurately measure a wide range of CLIC prototype components. This is in contrast to the modules where integration of prototype components into the very compact layout would always be problematic. The test stand would require instrumentation to allow precise measurements of beam energy spectra, beam profiles before and after interaction with RF structures, transverse wakefields (if feasible), RF power, dark current spectra and X-ray emission. A non-exhaustive list of possible tests includes: (i) comparison of 4,6 and 8-fold symmetric power extracting structures (ii) deceleration as a function of transverse off-set (iii) high power production, (iv) acceleration and phasing (v) main beam energy spread compensation (vi) high gradient performance (vii) dark current production (viii) power recirculation (ix) beam position monitor resolution measurements, etc.

8.11. Buildings

It is proposed to link the present CTF2 blockhouse to the EPA building by a simple tunnel made up from concrete blocks to have enough space to house the two-beam accelerator, the test stand and the main beam injector. This makes the maximum use of the existing facilities. The proposed blockhouse extension is shown in Fig.9. The shielding however will have to be modified to cope with the higher average power (~ 5 kW) of the beam.

8.12. Beam instrumentation

The instrumentation needs have been defined in terms of parameters to be measured rather than in terms of the specific devices to be built. The main parameters to be measured are listed as follows:

- beam current versus time
- total charge
- beam energy versus time
- transverse bunch emittance (average over the train and over a small part of the train)
- bunch length (average over the train and over a small part of the train)
- bunch phase (average over the train and over a small part of the train)

- transverse bunch position (average over the train and over a small part of the train)
- tune and turn-by-turn trajectory in the ring

Some of the devices needed to measure these parameters can be termed “standard” and can be provided by existing beam monitoring equipment, the rest require the development of special-purpose RF equipment for beams which vary in intensity and frequency from 3.5A and 1.5 GHz at the beginning of the line to 35 A and 15 GHz at the end of the line.

9. Preliminary beam tests using the LIL/EPA complex

The possibility of using the LIL/EPA complex to carry out preliminary beam combination tests at very low currents as a first stage CTF3 is being studied. The transformation of the LIL/EPA complex into CTF3 would be carried out progressively, the various stages are shown in Fig. 11. Recent studies and experiments have shown that the EPA lattice can be modified (without making any hardware changes) to make it isochronous. It is foreseen to use the complex with small modifications to try out the (×5) beam combination scheme (see Fig.11 - First CTF3 tests in LPI 2001). The idea is to combine five short (6.6 ns) pulse trains spaced at a distance equal to the circumference of EPA (~125.6 m or 420 ns) into a single 6.6 ns pulse. The total pulse train length is 2.1 µs. The initial bunch spacing will be 10 cm (3 GHz) and after the combination will be 2 cm (15 GHz). The combination will only be possible with very low pulse currents (0.3 A), the limitation being beam loading in LIL. The beam energy (~500 MeV) will be considerably higher than that for CTF3 (~ 184 MeV) and should therefore make operation somewhat easier. To produce five pulses at a spacing of 420 ns will however require a major modification of the present LIL gun pulse-forming network. In the next stage (see Fig.11 – CTF3 in 2002) longer pulses and higher currents will be possible when the new CTF3 linac is installed. This will again require either major modifications to the present injector or a new injector. Operation of this first-stage facility would enable the RF deflectors and RF diagnostic equipment to be tried out and debugged, and should result in an earlier first demonstration of the overall scheme albeit at a low current. The plan would be to move the present LIL injector closer, and to use only the part of the LIL linac used for acceleration of the positrons. This would free space in the LIL tunnel to enable the testing in parallel of CTF3 injector prototypes.

The fast switching of the sub-harmonic buncher between even and odd RF buckets is only required when the delay line combiner is installed. Until this moment CTF3 will operate with one bunch every 3 GHz RF bucket and in consequence one half of the nominal charge (the nominal current is always constant at 3.5 A).

10. Time schedule for CTF3

An indicative time schedule to complete CTF3 in five years is shown in Annex 1. The end of LEP operation (foreseen for the end of 2000) determines the starting date. Installation work has been planned where possible during the long winter shut-down when running-in cannot be done because the auxiliary services such as water cooling, power and controls are shut-down for maintenance work. Running-in is foreseen during the regular PS beam production periods. The construction budget is assumed to be available for five years starting in the year 2000.

11. References

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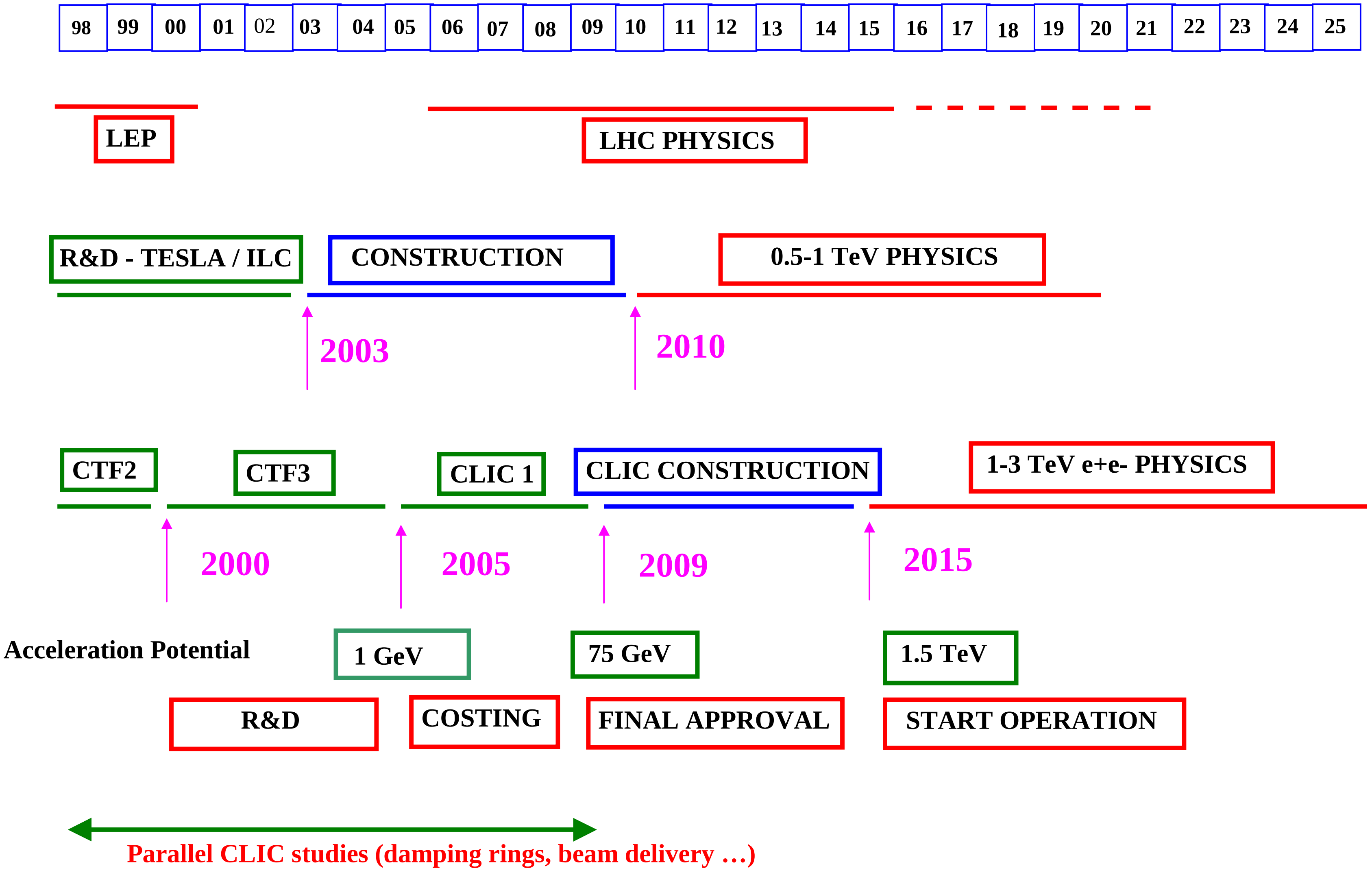
[redacted]

ANNEX 1 : UNOFFICIAL CLIC SCENARIO



98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

LEP

LHC PHYSICS

R&D - TESLA / ILC

CONSTRUCTION

0.5-1 TeV PHYSICS

2003

2010

CTF2

CTF3

CLIC 1

CLIC CONSTRUCTION

1-3 TeV e+e- PHYSICS

2000

2005

2009

2015

Acceleration Potential

1 GeV

75 GeV

1.5 TeV

R&D

COSTING

FINAL APPROVAL

START OPERATION

Parallel CLIC studies (damping rings, beam delivery …)