STATUS OF THE CLIC STUDY
putting the emphasis on new developments since LC99

Ian Wilson

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List of scientific members of CLIC study team

Brief overview will certainly not do justice to huge amount of work accomplished by CLIC team since LC99

This is a good opportunity for me to acknowledge the excellent work that has been done
Collaborating with many other laboratories

- BERLIN Technical University (Germany): Planar structure design studies
- DARESBURY (England): Damping ring design studies
- DESY (Germany): CSR studies, beam delivery design, ground motion studies,……
- INFN / LNF (Italy): Combiner rings, transfer lines and RF deflectors for CTF3
- FERMILAB (USA): Structure studies
- Jefferson National Laboratory (USA): CSR studies
- JINR and IAP (Russia): Surface heating tests using 30 GHz RF power source
- KEK (Japan): ATF -photo-injectors - modulators
- LAL (France): Electron guns and pre-buncher cavities for CTF3
- LLBL/LBL (USA): Two-beam scheme with Relativistic Klystron
- RAL (England): Lasers for CTF3 and CLIC photo-injectors
- Royal Institute of Stockholm (Sweden): Beam loading compensation cavities for CTF2.
- SLAC (USA): High gradient testing, GaAs photo-cathodes, structure design, multi-TeV LC designs, CTF3 drive beam injector design, ……………
- UPPSALA University (Sweden): Beam monitoring systems for CTF3, FEL studies
Contrary to other LC projects which are hoping to start construction soon, the CLIC study is above-all a feasibility study with the aim to propose a technically viable multi-TeV e± Linear Collider for post-LHC era covering a range of centre-of-mass energies from ~ 0.5 - 5 TeV.

Want to build machine for lowest possible cost using most cost-effective technological solution - the two-beam scheme provides that possibility.

As far as a schedule is concerned - the only medium term goal we have at present is to prepare a Zero-ORDER CONCEPTUAL DESIGN REPORT for 2007.
The CLIC scheme has two very distinctive features

1. It accelerates the beam using 30 GHz normal-conducting structures operating at 150 MV/m – to reduce the LENGTH and COST of linacs.
   (For 3 TeV - two-linac length 27.5 km)

In choosing 30 GHz one of assumptions was - higher frequencies enable you to obtain higher gradients - however recent CTF2 results (see in a moment) with beam-driven single-cell cavities did not show any increase over range 21-39 GHz

It’s just possible that once you are in the “high frequency” range - no further gains are obtained by going to even higher frequencies (?) – this is a topic that deserves further investigation.
Frequency scaling experiment

First experiment where
- material
- machining
- cleaning
- conditioning
identical

For pulse lengths >10ns

Plot shows HIGGS results and other CLIC-built multi-cell structures at different frequencies

NO increase in surface field with frequency

Max. surface field ~ 300-400 MV/m
2\textsuperscript{nd} distinctive feature of CLIC scheme

2. Two-Beam Acceleration Scheme (shown schematically below) which requires in particular
- The generation of a train of low-energy high-intensity drive beams
- Fabrication of power extracting and transfer structures to generate the 30 GHz RF
CLIC RF POWER SOURCE FOR 3 TeV COLLIDER

22 drive beams of 1952 bunches at 1.18 GeV
Charge 31.25 micro C / beam - Energy 36.9 kJ / beam

92 micro s

39 m

92 modulators / klystrons
50 MW - 92 micro-s

182 modulators / klystrons
50 MW - 92 micro-s

FULLY-LOADED
DRIVE BEAM ACCELERATOR
937 MHz - 1.18 GeV - 3.9 MV/m
RF/beam efficiency 97 %

1248 m
39 m
2 cm between bunches

92 micro s

1 bunch every 2nd bucket
39 m long pulses

42944 bunches up to 16nC/bunch at ~50 MeV
Total charge 688 micro C

Mean current 7.5
64 cm between bunches

To generate more or fewer drive beams to power a higher or lower energy collider only requires a longer or shorter modulator pulse but the number of klystrons does not change

32 cm between bunches

78 m
39 m
32 cm between bunches

78 m
39 m
92 micro s

352 trains of 122 bunches at 1.18 GeV
Total energy 812 kJ
New design of Power Extracting Structure - previous 6 waveguide PETS design was abandoned - insufficient damping of dipole modes.

New structure is circularly-symmetric with a large aperture (25 mm) and has a very shallow sinus-type corrugation and eight 1 mm-wide longitudinal damping slots.

An 80 cm length of this structure produces ~560 MW - enough 30 GHz RF power to drive two CLIC accelerating structures.

Table 1. Parameters of the C-PETS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam chamber diameter, mm</td>
<td>25</td>
</tr>
<tr>
<td>Synch. mode frequency, GHz</td>
<td>29.9855</td>
</tr>
<tr>
<td>Synch. mode $\beta_g$</td>
<td>0.85 c</td>
</tr>
<tr>
<td>Synch. mode $R'/Q, \Omega/m$</td>
<td>244</td>
</tr>
<tr>
<td>Synch. mode Q-factor</td>
<td>12000</td>
</tr>
<tr>
<td>Peak transverse wakefield V/pC/m/mm</td>
<td>0.83</td>
</tr>
<tr>
<td>Transverse mode Q-factor (damped)</td>
<td>&lt; 50</td>
</tr>
</tbody>
</table>

* Indicates parameters that are critical for the design.

CLIC

CLIC

Power Extraction and Transfer Structure (PETS)
New RF power extractor designed for new C-PETS which converts C-PETS circularly symmetric field to rectangular WG and extracts power with an efficiency of ~ 99%. Device is a clever mode launcher, combiner and diffractor all rolled into one. Get an idea of how it works from E-field plot.

Characteristics:

#1. High efficiency (~ 99% at 30 GHz)
#2. Short extraction length (~4 WL)
#3. Wide frequency band (~ 1 GHz) and hence reduced fabrication tolerances
#4. High mode purity and rejection (~ -30 db)
Overall Layout of the CLIC complex at 3 TeV c.m.

- **Detectors**
- **Drive Beams DECELERATOR** 624 m
- **e- MAIN LINAC** (30 GHz -150 MV/m)
- **Drives Beams** 22 drive beams/linac made of 1952 bunches 16 nC/bunch 7.5 A at 1.18 GeV/c
- **2 cm** between bunches
- **130 ns or 39 m** pulse length
- **FROM MAIN BEAM GENERATION COMPLEX**
- **FROM DRIVE BEAMS GENERATION COMPLEX**
- **Detectors**
- **Laser**
- **e-**
- **e+ POWER SECTION**
- **e+ MAIN LINAC**
- **e+ MAIN LINAC**
- **e+ POWER SECTION**
- **4.16 µs or 1.248 km** between beams
- **20 cm**
- **~ 460 MW/m** RF power at 30 GHz
- **92 µs**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.5 TeV</th>
<th>1 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam param. at I.P.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity ($10^{34} \text{ cm}^{-1}\text{s}^{-1}$)</td>
<td>1.7</td>
<td>2.7</td>
<td>10.0</td>
</tr>
<tr>
<td>Mean energy loss (%)</td>
<td>3.8</td>
<td>11.2</td>
<td>31</td>
</tr>
<tr>
<td>Photons / electron</td>
<td>0.7</td>
<td>1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Coherent pairs per X</td>
<td>700</td>
<td>$3 \times 10^6$</td>
<td>$6.8 \times 10^8$</td>
</tr>
<tr>
<td>Rep. Rate (Hz)</td>
<td>200</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>$10^9 e^\pm / \text{bunch}$</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Bunches / pulse</td>
<td>154</td>
<td>154</td>
<td>154</td>
</tr>
<tr>
<td>Bunch spacing (cm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>H/V $\varepsilon_n$ ($10^{-8} \text{ rad.m}$)</td>
<td>200/2</td>
<td>130/2</td>
<td>68/2</td>
</tr>
<tr>
<td>Beam size (H/V) (nm)</td>
<td>208/1.9</td>
<td>115/1.75</td>
<td>43/1</td>
</tr>
<tr>
<td>Bunch length ($\mu$m)</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Accel. gradient (MV/m)</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Two linac length (km)</td>
<td>5</td>
<td>10</td>
<td>27.5</td>
</tr>
<tr>
<td>Power / section (MW)</td>
<td>229</td>
<td>229</td>
<td>229</td>
</tr>
<tr>
<td>RF to beam effic. (%)</td>
<td>24.4</td>
<td>24.4</td>
<td>24.4</td>
</tr>
<tr>
<td>AC to beam effic. (%)</td>
<td>9.8</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>AC power (MW)</td>
<td>100</td>
<td>150</td>
<td>300</td>
</tr>
</tbody>
</table>
Question: What is the effect on the luminosity spectrum of letting the mean energy loss parameter go as high as 31%?

The table shows the percentage of luminosity contained in 1% and 5% of the c.m. energy:

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>0.5</th>
<th>1</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>L in 1% $E_{cm}$</td>
<td>71%</td>
<td>56%</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td>L in 5% $E_{cm}$</td>
<td>87%</td>
<td>71%</td>
<td>42%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Spectrum does deteriorate with $E$ – can still do very good physics.
Beam-beam simulations have shown that there are significant differences between the luminosities calculated using projected end-of-linac emittances instead of using the real bunch profiles.

Usual technique: determine end-of-linac SB blow-up

then use projected emittance to calculate luminosity

should use real bunch profiles

16% reduction in luminosity for case with 20% $\Delta\varepsilon$ in linac
New design of 3 TeV Beam Delivery System

Have total one-side length of 2.5 km with
~ 0.5 km for FF, ~ 1.4 km for energy collimation (set at ± 1.5%)
~ 0.6 km for betatron collimation (set at ± 10 σx and ± 80 σy)

Relative luminosity (without-pincho) shown in plot as function of momentum spread.
Have assumed an end-of-linac εν of 10 nm. The reference Lo is $4.6 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ which corresponds to $10^{35}$ cm$^{-2}$ s$^{-1}$ with pinch. With present β values - only get 75% Lo for 1% energy spread. Can get 85% by reducing βx to 6 mm and βy to 70 μm giving un-pinched spot sizes of 56 nm in x and 1.6 nm in y.
Vertical spot size at IP is 1 nm \((\text{size of water molecule})\)

Maintaining such small beams in collision in presence of ground motion is major concern especially when you look at the jitter tolerances required to avoid the luminosity falling by more than 2\% - for the main linac quads this is 1.3 nm in vertical plane but is only 0.2 nm for the final doublet of the FF

<table>
<thead>
<tr>
<th></th>
<th>horiz</th>
<th>vert</th>
</tr>
</thead>
<tbody>
<tr>
<td>linac quads</td>
<td>1.3 nm</td>
<td></td>
</tr>
<tr>
<td>FF quads</td>
<td>4 nm</td>
<td>0.2 nm</td>
</tr>
</tbody>
</table>

Can see from ground-motion plot - this is at limit of even the quiet-LEP site value and accepting that even with a very careful design there will be a certain amount of cultural and technical services noise have to conclude that an active stabilization system is required for both main linac quads and the final doublet
CLIC stability study created in January 2001 to demonstrate feasibility of colliding nanometre size beams!
Collaborating with SLAC and have contacts with DESY and FNAL

Group has made good progress and has already

- specified stability **requirements**
- made a critical analysis of our measurement capability (**resolution and errors**) to demonstrate that we can achieve **sub-nm accuracy**
- developed necessary **data analysis** tools

- launched a new campaign of measurements (vibration test stand, CTF2, LEP (OPAL), CNRS,…)
  **first results** on:
  - ground vibration
  - correlation
  - effect of magnet supports
  - effect of cooling water
  - simple passive damping
  - horizontal stability

- **Bought**
  **STACIS active piezoelectric vibration control system**
  **state-of-the-art stabilization equipment** - in process of installing in a new Test Stand – should be operational within a few months
  - aim here is to demonstrate feasibility of stabilizing components to the 1-2 nm level to start with.

CLIC study team is organizing an ICFA workshop on “Nano-metre-size colliding beams” in September 2002.
Use of INTRA-PULSE FEEDBACK being studied to keep beams in collision

Not so easy - CLIC has relatively short pulse length ~ 100 ns - scheme is as follows: When beams collide with vertical off-set - receive strong kick from beam/beam interaction. Position of this deflected outgoing beam is measured at short distance from IP (RED bunch) and compensating signal is sent to a nearby kicker on the same side of the IP which corrects the incoming beam (BLUE bunch). Results in response time of ~ 20 ns.

With a BPM resolution of 10 µm simulations show luminosity loss for small vertical off-sets can be reduced by factor 3.
Are our emittance goals realistic?

Plot shows CLIC DR emittance requirements compared to present ATF state-of-the-art damping ring performance.

ATF improved on performance of SLC by two orders of magnitude - huge step forward

Still ~ order of magnitude missing in both planes for 3 TeV

\[
\gamma \varepsilon_x = 450 \, \text{nm} \\
\gamma \varepsilon_y = 3
\]
CLIC Damping Ring for 3 TeV

To get very small emittances had to re-think the design of our DR

Studies at moment being focused on 2.4 km circumference ring

- with a relatively high energy (4–6 GeV) to counteract intra-beam scattering
- which is wiggler-dominated to give rapid radiation damping
- which has arcs containing many TME cells to minimise quantum excitation effects

Concerns which have not yet been addressed include

- Electron cloud
- Fast ion-beam effects

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population</td>
<td>( N_b )</td>
<td>( 4.1 \times 10^9 )</td>
</tr>
<tr>
<td>No. of bunches/train</td>
<td>( k_{bt} )</td>
<td>154</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>( f_r )</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>( x \gamma \varepsilon )</td>
<td>( 4.5 \times 10^{-7} ) m</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>( y \gamma \varepsilon )</td>
<td>( 3 \times 10^{-9} ) m</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>( l_b )</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Min. kicker rise time</td>
<td>( T_{kicker} )</td>
<td>25 ns</td>
</tr>
</tbody>
</table>

Table 1: Beam parameters required for 3 TeV CLIC

\[
\log_{10}(\varepsilon / m)
\]
How are we doing on limiting the blow-up in the linac?

In parameter list - budgeted for 100% blow-up.
Our beam simulations however predict only 20%.
(so for moment have some margin - at least on paper)

Pre-align cavities and BPMs in linac to 10 microns.
Use ballistic method to align BPMs with greater precision
Correct beam position by moving quads ("few-to-few" correction)
Re-align structures to new beam position by moving girders.
Use 10 emittance bumps (as in SLC) to locally reduce blow-up
(uses a few RF structures and a few quadrupoles).
Starting emittances deteriorate with time unless we apply beam correction schemes and readjust our initial settings.

1. Initial condition at start of run after beam alignment
2. After about one day ($10^5$ s) of beam running and continuous one-to-one beam correction in feedback mode
3. After about 10 days ($10^6$ s) of beam running with continuous one-to-one correction and readjustment of emittance bumps

Operational procedure
- Emittance bumps readjusted every day
- BPMs realigned by “ballistic method” every week
Work is focusing on three major concerns

- suppression of long-range transverse wakefields with time
- breakdown and surface damage
- pulsed surface heating
For suppression of Wt - work still being focused on WG damped structures of type shown here. Each cell is damped by 4 radial WGs terminated by discrete SiC RF loads.

Photo shows 15 GHz model that was tested in ASSET. Excellent agreement was obtained between theory and experiment - believe we can solve damping problem.
Over the years - built and tested a whole series of copper accelerating structures with different geometries and frequencies.

Our experience indicates that for RF pulses >10 ns, max. surface field that can be obtained with copper is always around 300-400 MV/m.

At these field levels structures with large apertures (or rather with large a/λ ratios) seem to suffer severe surface damage.

We believe that the damage can be explained by field-emitted electrons being accelerated from one side of the iris to the other during breakdown by the very high RF fields and that this bombardment of the copper surface leads to melting and erosion.
Example of surface damage in large aperture ($a/\lambda = 0.2$) 30 GHz structure after HG testing with 16 ns pulses. This structure has a single-feed coupler where $E_s/E_a \sim 4.4$ on the first iris – see from photo - copper iris severely damaged.

Note however - also tested small aperture ($a/\lambda = 0.1$) 11 GHz structure to similar surface fields – found no damage for 150 ns pulse!
Cross-section of damaged iris

**RF input**

*Expected* direction of bombarding electrons

Damage below red line was not made during high-gradient test but when the disk was sawn off the structure
By putting the structure in an external vacuum can – able to machine-off damaged front ends and clamp in and test coupler irises of different materials.

Focusing on tungsten for the moment - a material with a high melting point and a known resistance to damage due to arcing.
Microscopic comparison between Cu and W

After high gradient testing to the same field level

Copper  

Tungsten
Tungsten after conditioning

copper droplets

copper residue
The way forward to obtaining 150 MV/m

Based on the results obtained to date, the CLIC study group is adopting a two-pronged approach to solving the breakdown problem.

- We know that the max. surface field in copper structures must not exceed ~ 300 MV/m and the $a/\lambda$ should not be too large - so we are modifying the RF design to obtain $E_s/E_a = 2$ and using smaller $a/\lambda$ values which should enable us to obtain our design accelerating field of 150 MV/m.

- Investigating new materials that are resistant to arcing - tungsten looks promising and has already yielded excellent results but its true potential will only become clear when we have built and tested an all-tungsten-iris structure - this is foreseen in the CTF2 experimental program this year.
RF Pulsed heating experiments in JINR, Dubna

The 30 GHz FEM test area

30 GHz FEM produces ~ 20 MW with 150-200 ns long pulses

Set-up allows on-line measurements of Q-factor using TE_{31} mode launcher to detect surface cracking

Planned to start tests mid 2002
CLIC Test Facility CTF2

CTF2 goals:

- to demonstrate feasibility of CLIC two-beam acceleration scheme
- to study generation of short, intense e-bunches using laser-illuminated PCs in RF guns
- to demonstrate operability of μ-precision active-alignment system in accelerator environment
- to provide a test bed to develop and test accelerator diagnostic equipment
- to provide high power 30 GHz RF power source for high gradient testing ~90 MW 16 ns pulses

All-but-one of 30 GHz two-beam modules removed in 2000 to create a high-gradient test stand.
Active Alignment System

- Positioning motor
- Position pickup's with stretched wire
CTF3 - Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10

- Drive Beam
  - Injector
  - 10 Modulators/Klystrons
  - 3 GHz - 30 MW - 6.7 μs
- Drive Beam Accelerator
  - 16 Accelerating Structures
  - 3 GHz - 7.0 MV/m - 1.3 m
- 30 GHz Test Stand
  - 3.5 A - 2100 b of 2.33 nC
  - 150 MeV - 1.4 μs
- Combiner Ring
  - 84 m
- Delay
  - 42 m
- Main Beam Injector
  - 35 A - 150 MeV - 140 ns
- Main Beam
  - Modules
  - 10 Modulators/Klystrons
  - 3 GHz - 30 MW - 6.7 μs
  - 100 MeV
- Drive/Main Beam Modules
  - 30 GHz - 150 MV/m - 140 ns
  - 280 MeV
- CTF3 - Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10
- ~ 50 m
- X2 Delay
- ~ 50 m
- X5 Combiner Ring

Generic layout of CTF3
CTF3 layout in LPI

Housing of the CLIC Test Facility (CTF3) in the LEP Pre-injector building
CTF3 Preliminary Phase

Old LPI complex modified to do some proof-of-principle beam combination tests at low currents (0.3 A)
Aim – combine 5 short (6.6 ns) pulse trains spaced at distance equal to circum. of EPA (125.6 m or 420 ns) into a single pulse.

LPI

installed new gun designed and built by LAL

CTF3

Status - gun operational, linac and transfer line commissioned, end of December we successfully injected and circulated beam in ring.
On schedule to start beam combination experiments in first half of 2002
CTF3 DB Accelerating Structures:

Old LIL linac can only be used to accelerate very low currents because of beam-loading and transverse beam instability effects. To accelerate the 3.5 A CTF3 beam requires new 3 GHz damped-detuned accelerating structures.

Designed a novel Slotted-Iris Constant Aperture (SICA) structure which provides:
- strong damping of Wt via slotted irises (Q<20)
- detuning by varying the nose-cone dimensions
- constant 34 mm iris diameter – low short-range wake

Built and successfully tested short prototype:
- 34 MW in 2 µs pulses after very short conditioning

Order for 18 structures placed with industry
CLIC feasibility studies were extended in 2000 and 2001 to include:

**Civil Engineering**
- Layouts for
  - Central Area with Injectors
  - Tunnels for 937 MHz klystrons
  - Main tunnel - Shafts
  - Detector cavern

**Cooling and Ventilation**
- Cooling towers
- Water flows and pumping stations

**Electrical Power**
- Choice of system voltages
- Layouts of distribution system
- Connections to grid
In April 2000 - in response to a growing interest in the physics potential of a multi-TeV e+e- collider CERN management created CLIC Physics SG with following goals:

1. Identify and investigate key processes that can help to optimize the machine design 
   luminosity spectrum, accelerator induced background, beam-beam background

1. Explore the physics program for CLIC and define a concept of the detector

1. Make a comparative assessment of the CLIC physics potential

http://clicphysics.web.cern.ch/CLICphysics/

By the end 2000- WG had put together the necessary analysis tools and had started to simulate events at 3 TeV
CLIC physics example – simulation of an event in which a pair of heavy charged Higgs bosons have been produced
\[ e^+ e^- \rightarrow H^+ H^- \]
Proposing a two-beam scheme of power generation and acceleration which we believe is the most cost-effective way of reaching multi-TeV c.o.m. colliding energies.

Demonstrated feasibility of this two-beam scheme of acceleration in CTF2.

Developed drive beam generation scheme based on a fully-loaded normal-conducting low-frequency linac, and frequency multiplication in combiner rings.

Presently building a new test facility CTF3 to demonstrate the feasibility of this scheme.

Have made substantial progress in understanding the breakdown and surface damage problems and are optimistic that we can reach our design gradients by a combination of structure design changes and the use of new materials.

Created new working group to study the feasibility of colliding nanometre-size beams.

According to the new CLIC Physics Study Group the CLIC 3 TeV e+e- collider is capable of providing some very interesting physics.