CLIC: The CLIC Accelerator Design and Performance

CERN Academic Training
Wednesday March 7, 2018

Daniel Schulte
For the CLIC collaboration

No names at individual contributions, have to omit many important contributions
CLIC Introduction

CLIC aims to provide multi-TeV electron-positron collisions with high luminosity at affordable cost and power consumption.

2012 CDR: Shows feasibility of 3 TeV design

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion
To reach multi-TeV energies:

• Linear collider to avoid synchrotron radiation

• High accelerating field to achieve high energy
  ⇒ Normal conducting accelerating structures

• High beam current and quality to achieve the luminosity
  ⇒ High quality of components
  ⇒ Little imperfections
  ⇒ Fancy beam dynamics

\[ \Delta E \propto \left( \frac{E}{m} \right)^4 \frac{1}{R} \]

LEP2 lost about 3 GeV/turn at E = 100 GeV
CLIC Staged Scenario

Plenty of physics at low centre-of-mass energies

Energy and luminosity targets from Physics Study Group

<table>
<thead>
<tr>
<th>Stage</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( \mathcal{L}_{\text{int}} ) (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Top above threshold Higgs via Zh and WW fusion

Study top at threshold

To be updated with more input from LHC and stage 1

Implementation in stages

- detector
- BDS
- accelerator 100 MV/m
- accelerator 72 MV/m

Year

Luminosity per year [fb\(^{-1}\)]

- 0.38 TeV
- 1.5 TeV
- 3 TeV

L = 1.87 km
L = 2.75 km
Unused arcs
Developed optimised first energy stage
Upgrade to higher energies included
# Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>380</td>
<td>1500</td>
<td>3000</td>
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<tr>
<td>Repetition frequency</td>
<td>$f_{\text{rep}}$</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>$n_b$</td>
<td></td>
<td>352</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>$\Delta t$</td>
<td>ns</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>$G$</td>
<td>MV/m</td>
<td>72</td>
<td>72/100</td>
<td>72/100</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>$\mathcal{L}$</td>
<td>$10^3$ cm$^{-2}$ s$^{-1}$</td>
<td>1.5</td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity above 99% of $\sqrt{s}$</td>
<td>$\mathcal{L}_{0.01}$</td>
<td>$10^3$ cm$^{-2}$ s$^{-1}$</td>
<td>0.9</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>Main tunnel length</td>
<td></td>
<td>km</td>
<td>11.4</td>
<td>29.0</td>
<td>50.1</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>$N$</td>
<td>$10^9$</td>
<td>5.2</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$</td>
<td>$\mu$m</td>
<td>70</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>IP beam size</td>
<td>$\sigma_x/\sigma_y$</td>
<td>nm</td>
<td>149/2.9</td>
<td>$\sim 60/1.5$</td>
<td>$\sim 40/1$</td>
</tr>
<tr>
<td>Normalised emittance (end of linac)</td>
<td>$\varepsilon_x/\varepsilon_y$</td>
<td>nm</td>
<td>—</td>
<td>660/20</td>
<td>660/20</td>
</tr>
<tr>
<td>Normalised emittance</td>
<td>$\varepsilon_x/\varepsilon_y$</td>
<td>nm</td>
<td>950/30</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Estimated power consumption</td>
<td>$P_{\text{wall}}$</td>
<td>MW</td>
<td>252</td>
<td>364</td>
<td>389</td>
</tr>
</tbody>
</table>
Accelerating Structure

380 GeV / 3 TeV

12 GHz
27 / 23 cm long
72 / 100 MV/m
59.5 / 61.3 MW input power
244 ns RF pulses

20600 / 140,000 structures 380 GeV / 3 TeV

Total peak RF power:
1.6 TW (380 GeV) 8.5 TW (3 TeV)

But only $10^{-5}$ duty factor
• 50 RF bursts per second
• 244 ns long (312 bunches)
• = 12.2 μs / s

Production of peak power is a challenge
Typical 12 GHz klystrons produces O(50 MW)

Solution is drive beam
Breakdowns (discharges during the RF pulse)
- Require \( p \leq 3 \times 10^{-7} \text{ m}^{-1}\text{pulse}^{-1} \)

Structure design based on empirical constraints, not first principle
- Maximum surface field
- Maximum temperature rise
- Maximum power flow

R&D established gradient \( O(100 \text{ MV/m}) \)

Structure for 380 GeV optimised for cost of first energy stage
\( \Rightarrow 72 \text{ MV/m} \)
Drive beam power:
$446 \times 19.5 \text{ MW} \times 0.95 = 8.2 \text{ GW}$

Pulse length: 48 $\mu$S
Drive Beam Combination Concept

48 μs x 8.2 GW

8 x 244 ns x 197 GW
Each pulse feeds one decelerator

$8 \times 244 \times 200 \text{ GW} \Rightarrow 244 \text{ ns} \times 1.6 \text{ TW}$
Two-beam Module Concept

100 A drive beam

1.7 A

Straight references

1.7 A drive beam

2.2 m

3 dB E-plane HYBRID

LOAD

CHOKE-MODE FLANGE

time: 0 0.0 ns

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CLIC Two-beam Module

80% filling with accelerating structures
11 km for 380 GeV cms
50 km for 3 TeV
CLIC Test Facility (CTF3)
Drive Beam Scheme Performance

CTF3 measurements:
• RF to drive beam efficiency > 95%
• Current multiplication factor 8
• Most of beam quality
• 145 MV/m X-band acceleration

Detailed simulations of drive beam performance in CLIC

Arrival time with feedback

Current stability affected by very low CTF3 energy, 3 x larger beam and delay loop design different from CLIC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CLIC goal</th>
<th>CTF3 measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival time</td>
<td>50 fs</td>
<td>50 fs</td>
</tr>
<tr>
<td>Current after linac</td>
<td>0.75 x 10^{-3}</td>
<td>0.2-0.4 x 10^{-3}</td>
</tr>
<tr>
<td>Current at end</td>
<td>0.75 x 10^{-3}</td>
<td>2-18 x 10^{-3}</td>
</tr>
<tr>
<td>Energy</td>
<td>1.0 x 10^{-3}</td>
<td>0.7 x 10^{-3}</td>
</tr>
</tbody>
</table>
From CTF3 to CLEAR

CTF3 has demonstrated drive beam production and main beam acceleration
- Technology
- Beam quality
- Operation

Now stopped

New facility is coming online: CLEAR
CERN Linear Electron Accelerator for Research

Figure 1: The current CALIFES beam line. The length of the facility (as shown) is ~20m.
Can re-write normal luminosity formula

\[ \mathcal{L} = H_D \frac{N^2}{4\pi \sigma_x \sigma_y} n_b f_r \]

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y} \]

Luminosity spectrum
Beam current
Beam Quality (+bunch length)

Need to ensure that we can achieve each parameter
Luminosity and Parameter Drivers

Can re-write normal luminosity formula

\[ \mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r \]

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} n_b f_r \frac{1}{\sigma_y} \]

The limit is the beam stability in the main linac

Need to ensure that we can achieve each parameter.

Luminosity spectrum

Beam current

Beam Quality (+bunch length)
Goal: maximise beam current
⇒ Maximise bunch charge
⇒ Minimise distance between bunches

Limits are given by wakefields:
With an offset particles produce transverse wakefields
⇒ The head kicks the tail, force is defocusing
⇒ Can render beam unstable

RF team loves small $a$
Less power
easier to reach gradient

Beam team hates small $a$
More wakefields
Beam less stable

Multi-bunch wakefields minimised by damping and detuning
Tricks of the Beam Physics

Make the focus strong again
- Use $O(10\%)$ of the linac for magnets
- Leads to small beta-function
- Makes the beam stable (strong spring for an oscillator)

For single bunch use BNS damping (Balakin, Novokhatsky and Smirnov)
- Introduce energy chirp that compensates transverse wakefields
Beam Stability, With BNS

No BNS damping

Offset beam centre at injection

With BNS damping

Offset beam centre at injection

Direction of motion
No BNS damping

Simple betatron oscillation

Direction of motion

Tail and centre flap quite a lot

With BNS damping

Simple betatron oscillation

Direction of motion

Tail still flaps a little bit

Centre of bunch is much more stable
Luminosity and Beam Quality

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} \frac{N n_b f_r}{\sigma_y} \frac{1}{\sigma_y} \]

\[ \sigma_y = \sqrt{\beta_y \epsilon_y / \gamma} \]

Damping ring main source of horizontal emittance
But value is OK, as we will see

<table>
<thead>
<tr>
<th></th>
<th>( \Delta \epsilon_x ) [nm]</th>
<th>( \Delta \epsilon_y ) [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total contribution</td>
<td>( \text{Design limits} )</td>
<td>( \text{Static imperf.} )</td>
</tr>
<tr>
<td>Damping ring exit</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td>End of RTML</td>
<td>150</td>
<td>1</td>
</tr>
<tr>
<td>End of main linac</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Interaction point</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>sum</td>
<td>950</td>
<td>6</td>
</tr>
</tbody>
</table>

Imperfections are the main source of final vertical emittance
Require 90% likelihood to meet static emittance growth target
Damping Rings

Cool the beams from the sources

- energy loss
- re-acceleration

Important progress in collaboration with light source community

Studies of lattice and collective effects show that emittance targets can be reached for 3TeV

Currently optimising for 380 GeV
1) Align components accurately on the supporting girders

2) Establish reference system with overlapping wires, has some error but is not critical

3) Align modules remotely to the wires using their sensors and movers

The error for this is most critical misalignment of components is of the order $O(10\mu m)$

4) Use sophisticated beam-based alignment such as dispersion free steering (DFS, i.e. different energy beams) to align components
   In particular to align BPMs
RF Alignment

Structures scattered on girder ⇒ Wakefield kick

5) Measure beam offset with wakefield monitor
Move girder to remove mean offset ⇒ No net wakefield kick

Limit mainly from
• wakefield monitor accuracy (3.5 μm)
• reproducibility of wakefield
• tiny variation of betatron phase along girder

Wakefield monitor: Measure wakefield in damping waveguide
Main Linac Emittance Growth (3 TeV)

<table>
<thead>
<tr>
<th>imperfection</th>
<th>with respect to</th>
<th>symbol</th>
<th>value</th>
<th>emitt. growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM offset</td>
<td>wire reference</td>
<td>$\sigma_{\text{BPM}}$</td>
<td>14 $\mu$m</td>
<td>0.367 nm</td>
</tr>
<tr>
<td>BPM resolution</td>
<td></td>
<td>$\sigma_{\text{res}}$</td>
<td>0.1 $\mu$m</td>
<td>0.04 nm</td>
</tr>
<tr>
<td>accelerating structure offset</td>
<td>girder axis</td>
<td>$\sigma_4$</td>
<td>10 $\mu$m</td>
<td>0.03 nm</td>
</tr>
<tr>
<td>accelerating structure tilt</td>
<td>girder axis</td>
<td>$\sigma_t$</td>
<td>200 $\mu$radian</td>
<td>0.38 nm</td>
</tr>
<tr>
<td>articulation point offset</td>
<td>wire reference</td>
<td>$\sigma_5$</td>
<td>12 $\mu$m</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>girder end point</td>
<td>articulation point</td>
<td>$\sigma_6$</td>
<td>5 $\mu$m</td>
<td>0.02 nm</td>
</tr>
<tr>
<td>wake monitor</td>
<td>structure centre</td>
<td>$\sigma_7$</td>
<td>3.5 $\mu$m</td>
<td>0.54 nm</td>
</tr>
<tr>
<td>quadrupole roll</td>
<td>longitudinal axis</td>
<td>$\sigma_r$</td>
<td>100 $\mu$radian</td>
<td>$\approx$ 0.12 nm</td>
</tr>
</tbody>
</table>

Emittance growth for different imperfections

Using sophisticated beam-based methods

Note: The tight tolerances are the price for the strong focusing, Which allowed high beam current

Goal: less than 10% above $\Delta\varepsilon_y = 5$ nm

Further improvement using tuning bumps
CLIC Beam-Based Alignment Tests at FACET

DFS applied to 500 meters of SLC linac
- System identification algorithms to construct model
- DFS correction with GUI
- Emittance growth is measured
Beam Delivery System

Removes longitudinal tails
Protection from RF failures
Cleaning transverse halo
Protection from transverse jitter

Squeezing beam to minimum size

Goal 143 nm x 2.9 nm

$\beta_x = 8 \text{ mm}, \beta_y = 0.1 \text{ mm}$
First magnet has been at $L^* = 3.5$ m from the interaction point, inside of detector

Short $L^*$ limits chromaticity, the main challenge
First magnet has been at $L^* = 3.5$ m from the interaction point, inside of detector

Limited angular coverage of detector

Magnet is put on cantilever from tunnel

Magnet needed to be shielded from detector solenoid
Beam Delivery System

New design with $L^* = 6$ places magnet outside of detector and mitigates high chromaticity

Better for physics

Also easier for equipment:
No shielding solenoid
Final quadrupole can be attached to tunnel floor
Beam-beam Effect

\[ \mathcal{L} \propto H_D \left( \frac{N}{\sigma_y} \right) N n_b f_r \frac{1}{\sigma_y} \]

Dense beams to reach high luminosity
Beam focus each other

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

\[ \sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x \]
Beam-beam Effect

\[ \mathcal{L} \propto H_D \left( \frac{N}{\sigma_y} \right) N n_b f r \frac{1}{\sigma_y} \]

Emittance beamstrahlung
Develop luminosity spectrum

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

\[ n_{\gamma} \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y} \]

\[ \sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x \]

Aim for O(1) at 380 GeV
The total luminosity $L$ varies strongly with beta-function.

But $L_{0.01}$ does not change so much.

Hard to push beta-functions that low.

Use $L_{0.01}/L=60\%$ as criterion.
Reasonable compromise for most physics studies.
Including pinch effect

\[ L = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r \]

Geometric luminosity
No beam-beam forces

Somewhat above optimum because small beta-functions because it is easier for the machine

CLIC choice 100 \( \mu \text{m} \), reached by beam delivery system
Realistic imperfections in BDS

Beam-based alignment and beam size tuning is used

Aim to reach 110% of promised luminosity with 90% likelihood (10% is budget for dynamic imperfections)

Single beam tuning 85% reach 110% of promised luminosity

Two-beam study ongoing

Small difference in performance

Luminosity is still increasing

Simulation is very slow (much slower than reality)

Try to improve speed
ATF 2 Results

Beam size (41 nm) is close to target (37 nm)

Much learned on instrumentation, tuning, design, …
Many practical issues from reused equipment, long bunches, …

Beam jitter: 0.2 / 0.1 σ
No feedback / with feedback

Summary of the IP vertical beam size measurement
Dynamic Imperfection Example: Ground Motion

Ground motion can impact beam trajectory

Beam-trajectory feedback corrects pulse-to-pulse (20 ms)
⇒ Cures low frequency ground motion
⇒ But not higher frequencies

LEP tunnel
Want to be able to cope with this (Model B10 similar to CMS hall)

Beam-trajectory feedback: Example transfer curve (recursive filter)
Beam Motion with Beam Feedback Only

Time: 0.02 s
- Beam motion

ML, $e^-$
Jitter at IP

Time: 0.00s

B10, no PRE
IPFB, OFB
no STAB

x offset

y offset
The Stabilisation System

K. Artoos et al.
Beam Trajectory Jitter

Time: 0.02 s

- GM: B10
- Beam motion
- Beam motion, STAB, OFB

position [km]

ground/beam motion [μm]
Beam Jitter at IP
Beam Jitter at IP

Target achieved
Well within budget
Tests at ATF 2
Goals bring cost and power consumption down: “reasonable cost”: O(6 GCHF) 
Power < O(200 MW)

CERN energy consumption 2012: 1.35 TWh

Preliminary value for 380 GeV (MCHF of Dec 2010)

<table>
<thead>
<tr>
<th>Category</th>
<th>Value (in TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main beam production</td>
<td>1245</td>
</tr>
<tr>
<td>Drive beam production</td>
<td>974</td>
</tr>
<tr>
<td>Two-beam accelerator</td>
<td>2038</td>
</tr>
<tr>
<td>Interaction region</td>
<td>132</td>
</tr>
<tr>
<td>Civil engineering etc.</td>
<td>2112</td>
</tr>
<tr>
<td>Control &amp; operation</td>
<td>216</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>6690</strong></td>
</tr>
</tbody>
</table>

Improvement of cost and power is ongoing
Detailed bottom up estimate
Already savings
Develop klystron-based alternative
Expect comparable cost for first energy stage
But increases faster for high energies

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Can re-use previous systems and components

Just add more linac and drive beam pulse length

At 3 TeV add one drive beam
Site Near Geneva

Compact Linear Collider (CLIC)
- 380 GeV - 11.4 km (CLIC380)
- 1.5 TeV - 29.0 km (CLIC1500)
- 3.0 TeV - 50.1 km (CLIC3000)
Exploration of novel acceleration methods for lepton collider has started
- Dielectric accelerating structures
- Laser driven plasma
- Beam driven plasma

Plasma-based acceleration demonstrated gradients of 50 GV/m

Application of novel technologies to colliders
- Started a working group for CLIC to understand potential
- Plasma community started a working group on colliders

Main challenge
- Beam quality preservation has to be explored theoretically and experimentally
Conclusion

A staged design for CLIC has been developed

- First energy stage at 380 GeV optimised for performance, cost and power
  - Meet the physics performance targets
  - Cost roughly comparable to LHC
  - Power $O(200 \text{ MW})$
- Further energy stages can reuse components
  - Site available for 3 TeV
- In the long run novel acceleration methods may become available

High gradients and high peak power are key to CLIC

Great control of imperfections is second key

- Technical solutions have been demonstrated, see tomorrow
- Beam-based methods have been established
Vol 1: The CLIC accelerator and site facilities
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- https://edms.cern.ch/document/1234244/

Vol 2: Physics and detectors at CLIC
- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- http://arxiv.org/pdf/1202.5940v1

Vol 3: “CLIC study summary”
- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

Input documents to Snowmass 2013 has also been submitted:
Scan 1.7 billion cases:

Fix structure design parameters: $a_1, a_2, d_1, d_2, N_c, f, G$

$\Rightarrow$ key beam parameters

$\Rightarrow$ Luminosity, cost and power (including other systems)

Resulting designs:
Colors indicate luminosities

This is the one that we picked
Reserve
Goal set as “reasonable cost”: 6 GCHF

Preliminary cost estimate from rebaselining

Performing bottom-up cost estimate

Also optimise the cost

- Module design is being improved
- Injector cost has been relatively high, is being reduced substantially by about halving number of klystrons
- Drive beam injector has already been optimised
- Civil engineering is being reviewed
- ...

Preliminary value for 380 GeV
(MCHF of Dec 2010)

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</table>
Goal set as “reasonable power”: 200 MW

Preliminary power estimate from rebaselining

Performing bottom-up power estimate

Also optimise the power

• Use of permanent magnets
• Reduction of injector power
• More efficient klystrons
• Use of green power: Ability to switch on and off to follow electricity availability
• …

Preliminary Estimate 252 MW

CERN energy consumption 2012: 1.35 TWh
Systems
Damping ring makes flat beams

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_x$ [nm]</th>
<th>$\varepsilon_y$ [nm]</th>
<th>$\sigma_z$ [$\mu$m]</th>
<th>$N$ [$10^9$]</th>
<th>$E$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ring exit</td>
<td>700</td>
<td>5</td>
<td>1600</td>
<td>5.2</td>
<td>2.86</td>
</tr>
<tr>
<td>End of RTML</td>
<td>850</td>
<td>10</td>
<td>70</td>
<td>5.2</td>
<td>9.0</td>
</tr>
<tr>
<td>End of main linac</td>
<td>920</td>
<td>20</td>
<td>70</td>
<td>5.2</td>
<td>190.0</td>
</tr>
<tr>
<td>Interaction point</td>
<td>950</td>
<td>30</td>
<td>70</td>
<td>5.2</td>
<td>190.0</td>
</tr>
</tbody>
</table>

Bunch energy defined by main linac

Final bunch length defined by main linac

Bunch charge defined by main linac

All systems contribute to vertical emittance
Transports the beam from the damping rings to the main linacs

Shortens the long bunch from the damping ring
Beam-beam Feedback

Strong deflection allows to easily measure and correct offset

10 ns from IP to BPM
13 ns to apply correction kick
10 ns from kicker to IP
= 33 ns latency vs. 170 ns beam pulse

\[ \Delta_y = 0.1 \sigma_y = 0.3 \text{nm} \]

40 mm beam offset
3m downstream of IP

FONT system (Oxford) tested in ATF 2: 13 ns
Note: Klystron

Beam is not relativistic
So that it can be bunched
Performances
Emittance $\varepsilon_{x,y} \leq 150\mu$m

Transverse jitter $\leq 0.3\sigma$

Current stability $0.75 \times 10^{-3}$

Phase stability $0.2^\circ @ 12\text{GHz}$ (with feedforward)

Bunch length stability 1%

Phase stability $0.2^\circ @ 1\text{GHz} = 2.5^\circ @ 12\text{GHz}$

Correlated energy spread $\sim 1\% \text{ RMS}$

RF power stability 0.2% (CTF3)

RF phase stability 0.05° (CTF3)
Drive Beam Combination in CTF3

RF to drive beam efficiency > 95%

Measured accelerating gradient

Maximum gradient 145 MV/m
Current stability and phase stability are key

Errors lead to wrong main beam energy

Arrival time with feedback

Losses in the delay loop, different design than in CLIC due to space
3 x smaller beam in CLIC should help

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CLIC goal</th>
<th>CTF3 measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival time</td>
<td>50 fs</td>
<td>50 fs</td>
</tr>
<tr>
<td>Current after linac</td>
<td>$0.75 \times 10^{-3}$</td>
<td>$0.54 \times 10^{-3}$</td>
</tr>
<tr>
<td>Current at end</td>
<td>$0.75 \times 10^{-3}$</td>
<td>$2 - 18 \times 10^{-3}$</td>
</tr>
<tr>
<td>Energy</td>
<td>$1.0 \times 10^{-3}$</td>
<td>$0.7 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Availability

Aim for 80% availability during scheduled physics runs
- Identifying the most important failures
- Mitigation concepts
- Repair time
- Operation schedule to optimise timing of stops
Longitudinal Wakefields and Energy Spread

Loaded gradient along bunch

On-crest acceleration:
- more than 2% full gradient spread
- 0.7% RMS energy spread

Off-crest acceleration (12°):
- 1% full gradient spread
- 0.35% RMS gradient spread
- Loose about 2% in gradient
Beam stability
• incoming beam can jitter (have small offsets) and become unstable
• lattice design, choice of beam parameters

Static imperfections
• errors of reference line, elements to reference line, elements.
• excellent pre-alignment, beam-based alignment, beam-based tuning

Dynamic imperfections
• Ground motion, cooling water induced jitter, RF jitter, electronic noise.
• lattice design, BNS damping, component stabilisation, feedback, re-tuning, re-alignment

• Combination of dynamic and static imperfections can be severe
• Lattice design needs to balance dynamic and static effects
Main Linac: Dispersion-free Steering

Method reduces dispersion

Use beams of **different energy** to identify offset BPMs

Compromise between offset and difference

Offset BPM produces bump

Off-energy beam has different bump

DFS finds new solution with smaller bump

Adjust BPM reference to be on new trajectory

**Dispersion:** Different energy particles take different trajectories
Reference line error with given wavelength

Betatron wavelengths of the different sectors
Ground Motion Summary

Luminosity achieved/lost [%]

<table>
<thead>
<tr>
<th>Code</th>
<th>B10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No stab.</td>
<td>53%/68%</td>
</tr>
<tr>
<td>Current stab.</td>
<td>108%/13%</td>
</tr>
<tr>
<td>Future stab.</td>
<td>118%/3%</td>
</tr>
</tbody>
</table>

Close to/better than target

Machine model
Beam-based feedback
Aim to reach 110% of promised value (10% is budget for dynamic imperfections)

Single beam study

85% reach 110% of promised luminosity

Two-beam study ongoing

Small difference in performance
Beam Delivery System Tuning

Most demanding case: Full two-beam tuning at 3 TeV

90% of machines achieve more than 97% of promised luminosity

Working on pushing this to 110% of promised luminosity

15000 luminosity measurements required

Luminosity is still increasing
Simulation is very slow (much slower than reality)
Good luminosity
Taking into account hourglass effect

\[ \beta(s) = \sqrt{\beta(0) + \frac{s^2}{\beta(0)}} \]

Luminosity does not improve much below \( \beta_y < \sigma_z \)

For flat beams, the optimum is around \( \beta_y = 0.25 \times \sigma_z \)

Note: This is different for round beams
Upgrade
The Approach

Build a linac that can be extended for further energy stages

- Detector
- BDS
- Accelerator 100 MV/m
- Accelerator 72 MV/m

Higher gradient will be beneficial for upgrade.
CLIC Staged Design

Optimised first energy stage 380 GeV: HZ, WW fusion, top, ...
Further stages re-use infrastructure and equipment

Preliminary value of first stage 6690 MCHF
Further optimisation ongoing

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\mathcal{L}_{\text{int}}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Compact Linear Collider (CLIC)

D. Schulte
Future Accelerator Machines, EPS 2017

11-50 km
Hardware will be modified, but try to minimise changes
At high energy smaller number of bunches and bunch charge
• Should be acceptable in most systems
But have to allow for longer pulses
• Upgrade of injector and RTML RF systems

Example: BDS takes energy stages into account

CLIC 3 TeV ($L^* = 3.5$ m)
$c,a = 20$ mrad

CLIC 380 GeV ($L^* = 4.3$ m)
$c,a = 18.3$ mrad