The Compact Linear Collider (CLIC): High Precision Physics beyond the HL-LHC

SPS Annual Meeting 2018, EPFL Lausanne

Konrad Elsener, CERN
Outline

• The CLIC accelerator: status and plans
• A detector for CLIC
• Precision physics beyond HL-LHC
• Summary
The CLIC project

Multi-TeV electron-positron collisions with high luminosity

To be built and operated in stages (total time: 25-30 years)

N.B. recently updated -> Europ. Strat. Update (previous scenario: CERN-2016-004)

<table>
<thead>
<tr>
<th>Stage</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( \mathcal{L}_{\text{int}} ) (ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>5</td>
</tr>
</tbody>
</table>

Top physics above threshold; Higgs via ZH and WW-fusion
study top at threshold

New Physics, Higgs self coupling, \( ttH \), ...

E / lumi to be updated with input from LHC and/or stage 1 of CLIC
**CLIC accelerating structure** – normal cond. technology

RF frequency 12 GHz; 244 ns pulses @ 50 Hz

<table>
<thead>
<tr>
<th></th>
<th>380 GeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [cm]</td>
<td>27</td>
<td>24</td>
</tr>
<tr>
<td>Gradient [MV/m]</td>
<td>72</td>
<td>100</td>
</tr>
<tr>
<td>Number of structures</td>
<td>20600</td>
<td>143000</td>
</tr>
</tbody>
</table>

Vacuum flange

Vacuum tube

CC waveguide

Bonded discs stack
# CLIC 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>
</tr>
<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>Pulse length</td>
<td>$\tau_{\text{RF}}$</td>
<td>ns</td>
<td>244</td>
<td>244</td>
<td>244</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>$10^{34}$ 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>$10^{34}$ 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>Number of particles 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>920/20</td>
<td>660/20</td>
<td>660/20</td>
</tr>
<tr>
<td>Normalised emittance (at IP)</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>589</td>
</tr>
</tbody>
</table>
Two-beam acceleration
drive beam (12 GHz) → main beam

(2.4 GeV -> 0.24 GeV)
100 A drive beam

1.7 A main beam
CLIC at 380 GeV

Drive Beam

Main Beam

80% polarised
unpolarised

80% polarised
unpolarised

CERN

30 August 2018
SPS Annual Meeting
Konrad.Elsener@cern.ch
CLIC at 380 GeV

Compact Linear Collider (CLIC)
- **380 GeV - 11.4 km (CLIC380)**
- Drive/main beam injector
- LHC - existing infrastructure
Key technical challenges for CLIC

- High-current drive beam bunched at 12 GHz
- Power transfer + main-beam acceleration
- 100 MV/m gradient in main-beam accel. cavities
- Produce, transport + collide low-emittance beams
- System integration, engineering, cost, power …
Status (CLIC Test Facility / CTF3 result)

- Produced high-current drive beam bunched at 12 GHz
Status (CLIC Test Facility / CTF3 result)

- Produced high-current drive beam bunched at 12 GHz

Arrival time stabilised to 50 fs

PFF – “phase feed forward” (0.2 deg. <-> 50 fs)
Status (CTF3 result)

- Demonstrated two-beam acceleration

![Experimental setup and data analysis graphs showing energy at screen center values of 215.33 MeV and 212.25 MeV with and without drive beam.]

31 MeV = 145 MV/m
**Status** (high power tests around the world)

- Achieved 100 MV/m gradient in main-beam RF cavities
Key technical challenges for CLIC

- High-current drive beam bunched at 12 GHz
- Power transfer + main-beam acceleration
- 100 MV/m gradient in main-beam cavities

→ Industrialisation of 12 GHz RF/structure technologies

→ Application to medium- and large-scale systems
on-going: detailed bottom-up estimate of **cost** and **power**

Present estimate: **$O(6 \text{ GCHF})$** for 380 GeV stage, power **$O(200 \text{ MW})$**

Considerable savings w.r.t. CERN-2016-004 estimate identified
(2016 estimates were extrapolated from 500 GeV CLIC (CDR 2012) – **6.7 GCHF**)

CLIC cost and power (380 GeV)

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**380 GeV**

- **Main beam production**
- **Drive beam production**
- **Interaction region (w/o detector)**
- **Civil Engineering and Services**
- **Accelerator control & op. infrastructure**
CLIC site and upgrade to 3 TeV

- re-use systems / components
- add more tunnel, linac and drive pulse length
- at 3 TeV, add 2nd drive beam
CLIC collaborations

CLIC/CTF3 accelerator collaboration
~70 institutes from ~30 countries
(incl. PSI, ETHZ)
http://clic-study.web.cern.ch/

CLIC detector and physics (CLICdp)
30 institutes from 18 countries
(incl. Uni GE)
http://clicdp.web.cern.ch/

CLIC accelerator studies:
• CLIC accelerator design and development
• Construction and operation of CTF3

Focus of CLIC-specific studies on:
• Physics prospects and simulation studies
• Detector optimisation + R&D for CLIC
Detector for CLIC

- return yoke (Fe) with muon-ID detectors
- Superconducting solenoid, 4 Tesla
- fine grained (PFA) calorimetry, $1 + 7.5 \Lambda$, Si-W ECAL, Sc-FE HCAL
- silicon tracker, (large pixels / short strips)
- forward region with compact forward calorimeters
- ultra low-mass vertex detector, ~25 \( \mu \)m pixels
CLIC detector R&D (examples)

Vertex & Tracker

- CLICpix2 + C3PD glue assembly
  - 3.2 mm

- Hybrid
  - (with UniGE)

- Monolithic

Calorimetry

- CALICE silicon PIN diodes
  - 1 \times 1 \text{ cm}^2 \text{ in } 6 \times 6 \text{ matrices}

- Wafer

- Positioning grid

- Calibrated dot of glue

- CALICE scint. tiles + SiPMs
  - 3 \times 3 \text{ cm}^2
Full detector simulations

- Geant4 detector simulations including overlay of beam induced backgrounds
- reconstruction chain including reconstruction of tracks and clusters → particle flow objects → jets → flavour tagging

\[e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b \tau\bar{\nu}b \bar{b}\]

CLIC 1.4 TeV
N.B.
CLIC Detector model (and software) adapted and used for FCC-ee studies
CLIC detector performance: Example (1)
(full detector simulations)

Vertexing and Tracking

**impact parameter**

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**momentum resolution**

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dotted lines: performance goal, $a = 5 \, \mu m$, $b = 15 \, \mu m$

performance goal: $2 \times 10^{-5}$
CLIC detector performance: Example (2)
(full detector simulations)

Tracking efficiency and fake rate in complex events: $b\bar{b}$ at 3 TeV
(impact of beam-induced background)

100% efficiency $> 1$ GeV

N.B. fake tracks $\leftrightarrow$ purity $< 75%$

$purity = \frac{N_{\text{hits\_MC\ particle}}}{N_{\text{hits\_total}}}$
CLIC detector performance: Example (3)
(full detector simulations)

Calorimetry, using PANDORA Particle Flow Algorithms
beam-induced background included)

Jet energy resolution

W/Z separation
(Example: di-jet mass distribution of 250 GeV c.m. WW and ZZ events)
Physics at CLIC

e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\bar{W}bH \rightarrow q\bar{q}b \tau\bar{\nu}b \bar{b}b
Higgs Physics at CLIC


Dominant processes:

- Higgsstrahlung
  \( \sigma \sim 1/s \)
  Higgs id. from Z recoil

- WW(ZZ) - fusion
  \( \sigma \sim \log(s) \)
  Large stat. at high E

<table>
<thead>
<tr>
<th>( \sqrt{s} ) [GeV]</th>
<th>380 GeV</th>
<th>1.5 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(e^+e^- \rightarrow HX) ) [fb]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H\nu_e\bar{\nu}_e )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZHH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H\nu_e\bar{\nu}_e )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **\( L_{\text{int}} \)**
  - 1 ab\(^{-1}\)
  - 2.5 ab\(^{-1}\)
  - 5 ab\(^{-1}\)

- **\# \( ZH \) events**
  - 120k
  - 30k
  - 30k

- **\# \( H\nu_e\bar{\nu}_e \) events**
  - 40k
  - 650k
  - 1.6M

- **\# \( He^+e^- \) events**
  - 7k
  - 70k
  - 160k

**N.B.** high selection efficiencies
Higgs couplings (model-dependent)

Model dependent fit:

\[ \kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{\text{SM}}} \]

\( \text{BR}_i \): SM branching fractions (prediction)

Only SM Higgs decays:

\[ \frac{\Gamma_{H,\text{md}}}{\Gamma_H^{\text{SM}}} = \sum_i \kappa_i^2 \text{BR}_i \]

- **first CLIC stage** significantly more precise than HL-LHC for several of the couplings

- **full CLIC program** → still higher precision + access to rare events

ATLAS-PHYS-PUB-2014-016
Higgs couplings – model independent

unique at lepton colliders

Model-independent:

- Higgs width is a free parameter, allows for additional non-SM decays

Full CLIC program, ~7-8 yrs of running at each stage

- Model-independent: down to and below ±1% for most couplings
- Model-dependent: ±1% down to ± few % for most couplings
- Accuracy on Higgs width: ±2.5% (model-independent)
Double Higgs production

- Cross section sensitive to $g_{HHH}$ and $g_{WWHH}$
- Small cross section
  (about 700/6000 evts @ 1.5/3 TeV)
- Large backgrounds

⇒ Requires high energy and high luminosity

⇒ $\Delta g_{HHH}/g_{HHH} \approx \pm 10\%$
  for operation at 3 TeV
Double Higgs production and New Physics

**Strong sensitivity to BSM**

\[ \frac{\Delta g_{hhh}/g_{hhh}}{g_{hhh}} \approx \pm 10\% \]

for operation at 3 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>( \Delta g_{hhh}/g_{hhh}^{SM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>(-18% )</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>tens of %</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>(-2%^a) (-15%^b)</td>
</tr>
<tr>
<td>NMSSM</td>
<td>(-25% )</td>
</tr>
</tbody>
</table>

Motivation:
So far top quark only measured at hadron colliders
Precision top physics in $e^+e^-$:
- sensitive to many BSM scenarios
- understanding EWSB
- testing ground of QCD

Top physics programme:
- Top quark **mass**
  - $tt$ threshold scan at 350 GeV;
  - reconstructed mass above threshold
- **Electroweak couplings** to the top quark
  - At 380 GeV, and above 1 TeV (boosted top)
- **Yukawa coupling** through $ttH$ production
- **Rare decays** (strongly suppressed in SM)
  ... ...
CLIC 1\textsuperscript{st} stage: threshold scan of top pair production

- Top pair production cross section around the $t\bar{t}$ threshold
- Resonant-like structure, very sensitive to $m_{\text{top}}$, and $\alpha_s$

\[
\begin{align*}
\text{e}^+ & \rightarrow t \bar{t} \\
\text{e}^- & \rightarrow Z/\gamma^* \\
t & \rightarrow \text{hadrons}
\end{align*}
\]

- Measurement at 10 different $\sqrt{s}$, 10 fb\textsuperscript{-1} each
- **Expected precision on mass:** $\approx 50$ MeV
- Error currently dominated by theory uncertainties
Top quark pairs are produced via Z/γ
New physics would modify the ttV vertex

At a linear collider the **y and Z form factors** can be disentangled using **beam polarization** by measuring:
- production cross section
- forward-backward asymmetry
- helicity angle distribution (in leptonic decays)
top quark couplings to $Z$ and $\gamma$

expected precision at LHC, ILC (500 GeV) and CLIC (380 GeV / 3 TeV)

example: CP-violating form factors
68% C.L. limits
a sensitive probe of BSM physics

ILC: $e^-$ and $e^+$ polarized (80% / 30%)

CLIC: $e^-$ polarized (80%)

NB. old staging scenario, CERN-2016-004

Summary

- **CLIC** – an excellent option for a future $e^+e^-$ collider: 380 GeV, upgrade stages of 1.5 TeV and 3 TeV

- key technological challenges: demonstrated feasibility at test benches / facilities

- great potential for precision physics (Higgs, top) beyond HL-LHC (studied in detail, using full simulation incl. backgrounds): $< 1\%$ accuracies on Higgs couplings already at the 1$^{\text{st}}$ stage

- New Physics - direct discovery in the TeV range, or indirect observation: 1$\%$ precision on top quark couplings to $Z$ and $\gamma$; Higgs self-coupling measured to 10$\%$ precision

- could be ready for physics by 2035 – at “affordable” cost ($\approx 6$ GCHF)

Thank you!
additional material
Exploration of Future Upgrades

Started exploration of novel acceleration methods for high-energy upgrades
- Make sure CLIC is consistent with this

Plasma-based acceleration demonstrated gradients of 50 GV/m
Dielectric structures could lead to reduced cost

Main challenges
- Preservation of beam quality has to be explored theoretically and experimentally
- Efficiency and beam stability
- Many technical challenges

Might be possible to reuse drive beam
CERN Academic Training lectures on CLIC

- Physics potential of a high-energy electron-positron collider
- Detector technology R&D for CLIC
- The CLIC accelerator design and performance
- Key technology developments for the CLIC accelerator
- Overview of applications using high-gradient acceleration, from photon sources to medical physics
CLIC at 380 GeV

Drive beam time structure - initial

240 ns
140 μs train length - 24 x 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

240 ns
5.8 μs
24 pulses - 101 A - 2.5 cm between bunches

BC2

e⁻ main linac, 12 GHz, 72 MV/m, 3.5 km

BDS

1.9 km

IP

1.9 km

e⁺ main linac

11 km

CR
combiner ring

TA
turnaround

DR
damping ring

PDR
predamping ring

BC
bunch compressor

BDS
beam delivery system

IP
interaction point

dump

booster linac
2.86 to 9 GeV

e⁻ injector
2.86 GeV

e⁻ DR
427 m

e⁺ DR
427 m

e⁺ PDR
389 m

e⁺ injector
2.86 GeV
CLIC drive beam performance
Synchronisation of arrival time of drive / main beam

Arrival time with “phase feed forward” (PFF) system

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

<table>
<thead>
<tr>
<th>Parameter (jitter)</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>0.2-0.4 (\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>

one PFF system per turn-around loop; prototype tested at CTF3

Time jitter \(<->\) phase jitter at 12 GHz:

50 fs \(<->\) 0.2 degree

(phase monitors, low latency digitizer/feedforward, fast kickers)
Beam quality for luminosity
Small beam spot – tests at ATF2 (KEK)

Summary of the IP vertical beam size measurement

NB. achieved 41 nm - close to target (37 nm)
Beam quality for luminosity

Innovative beam-based alignment – “dispersion-free steering”: tests over 500 m at FACET (SLAC)
The rich exchange between different projects in the high-gradient community is typified by PSI and in particular the SwissFEL. Many essential features of the SwissFEL have a linear-collider heritage, such as the micron-precision diamond machining of the accelerating structures, and SwissFEL is now returning the favour. For example, a pair of CLIC X-band test accelerating structures are being tested at CERN to examine the high-gradient potential of PSI’s fabrication technology, showing excellent results: both structures can operate at more than 115 MV/m and demonstrate potential cost savings for CLIC. In addition, the SwissFEL structures have been successfully manufactured to micron precision in a large production series – a level of tolerance that has always been an important concern for CLIC. Now that the PSI fabrication technology is established, the laboratory is building high-gradient structures for other projects such as Elettra, which wishes to increase its X-ray energy and flux but has performance limitations with its 3 GHz linac.
X-band (12 GHz) radio-frequency (RF) accelerating structures are under consideration for future free electron lasers, medical linacs and linear colliders. Two such structures, built by PSI in the framework of a CERN/PSI collaboration, are currently being tested at high power at CERN. They are reported to have reached an accelerating gradient in excess of 115 MV/m, making them among the best X-band structures to have been tested by the CERN Linear Collider project group. The structures have benefitted from the fabrication protocols used for the SwissFEL C-band structures. The gradient continues to improve with further “conditioning” at CERN.
PSI News

![Graph showing accelerating gradient vs. pulses](image)

- **Xbox 3D T24PSI1**
- **Xbox 2 T24PSI1**
- **Xbox 3D T24PSI2**

**Axes:**
- Y-axis: Accelerating Gradient (MV/m)
- X-axis: Pulses (millions)
New Physics: rare FCNC* top-quark decays

* Flavour-changing Neutral Current

**FCNC top-quark decays are strongly suppressed in SM (CKM+GIM):**

\[
\begin{align*}
BR(t \rightarrow c \gamma) & \sim 5 \cdot 10^{-14} \\
BR(t \rightarrow c H) & \sim 3 \cdot 10^{-15} \\
BR(t \rightarrow c Z) & \sim 1 \cdot 10^{-14} \\
BR(t \rightarrow c g) & \sim 5 \cdot 10^{-12}
\end{align*}
\]

**Significant enhancement possible in many BSM scenarios**

**Maximum branching fractions possible:**

<table>
<thead>
<tr>
<th>Model</th>
<th>2HDM</th>
<th>MSSM</th>
<th>RS SUSY</th>
<th>LH</th>
<th>Q singlet</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(BR(t \rightarrow c \gamma))</td>
<td>(10^{-6})</td>
<td>(10^{-6})</td>
<td>(10^{-5})</td>
<td>(10^{-7})</td>
<td>(8 \cdot 10^{-9})</td>
<td>(10^{-9})</td>
</tr>
<tr>
<td>(BR(t \rightarrow c H))</td>
<td>(10^{-2})</td>
<td>(10^{-4})</td>
<td>(10^{-6})</td>
<td>(10^{-5})</td>
<td>(4 \cdot 10^{-5})</td>
<td>(10^{-4})</td>
</tr>
</tbody>
</table>
New Physics: rare FCNC\(^*$\) top-quark decays
\(^*$\) Flavour-changing Neutral Current

Expected limits for 500 fb\(^{-1}\) collected luminosity at 380 GeV:
(significant improvement for 1 ab\(^{-1}\))

\[
\begin{align*}
\text{BR}(t \rightarrow c\gamma) & < 4.7 \cdot 10^{-5} \rightarrow 2.6 \cdot 10^{-5} \\
\text{BR}(t \rightarrow cH) \times \text{BR}(H \rightarrow b\bar{b}) & < 1.2 \cdot 10^{-4} \rightarrow 7.1 \cdot 10^{-5} \\
\text{BR}(t \rightarrow c\Xi) & < 1.2 - 4.1 \cdot 10^{-4} \\
\end{align*}
\]
(work in progress)