The Compact Linear Collider (CLIC)

Outline

• A CLIC project overview
• CLIC at 380 GeV
• Multi-TeV studies
• Summary

Plenary ECFA
Nov. 19th, 2021
Proposed $e^+e^-$ linear colliders – CLIC

The Compact Linear Collider (CLIC)

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- **CDR in 2012.** Updated project overview documents in 2018 (Project Implementation Plan). See resource slide.
- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

- Comprehensive **Detector and Physics** studies
Collaborations

CLIC accelerator
- ~50 institutes from 28 countries
- CLIC accelerator studies
- CLIC accelerator design and development
- Construction and operation of CLIC Test Facility, CTF3

CLIC detector and physics (CLICdp)
- 30 institutes from 18 countries
- Physics prospects & simulations studies
- Detector optimisation + R&D for CLIC

+ strong participation in the CALICE and FCAL Collaborations and in AIDA-2020/AIDAinnova
### CLIC 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>$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</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>$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>0.9</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>Total integrated luminosity per year</td>
<td>$\mathcal{L}_{\text{int}}$</td>
<td>fb$^{-1}$</td>
<td>180</td>
<td>444</td>
<td>708</td>
</tr>
<tr>
<td>Main linac 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>900/20</td>
<td>660/20</td>
<td>660/20</td>
</tr>
<tr>
<td>Final RMS energy spread</td>
<td></td>
<td>%</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Crossing angle (at IP)</td>
<td></td>
<td>mrad</td>
<td>16.5</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
CLIC is a mature design/study

The CLIC accelerator studies are mature:

- Optimised design for cost and power
- Many tests in CTF3, FELs, light sources and test-stands
- Technical developments of “all” items
Resources

3-volume CDR 2012

Updated Staging Baseline 2016

4 CERN Yellow Reports 2018

Two formal submissions to the ESPPU 2018

Several LoIs have been submitted on behalf of CLIC and CLICdp to the Snowmass process:

The CLIC accelerator study: Link
Beam-dynamics focused on very high energies: Link
The physics potential: Link
The detector: Link

Details about the accelerator, detector R&D, physics studies for Higgs/top and BSM

Available at: clic.cern/european-strategy
Updates since 2019

• After ESU
  • Immediate study of luminosity performance margins, gamma-gamma and Z-pole operation
  • Timeline for further studies changed (slower implementation)

Accelerator
  • Resources too limited to move into TDR “proper”
  • External projects using X-band technology very important and much increased
  • Prioritise R&D type of studies and development of core technologies (will show later)

Physics and Detector:
  • Less resources for dedicated CLIC studies, more “Higgs-factory” approach (i.e. CLIC, ILC, FCC-ee, CEPC) and continue linking to detector R&D collaborations
CLIC timeline

Technology Driven Schedule from start of construction shown above.

A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)
CLIC Project Readiness Report (PRR)

Project Readiness Report as a step toward a TDR – for next ESPP
Assuming ESPP in 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

Focusing on:
- The X-band technology readiness for the 380 GeV CLIC initial phase
- Optimizing the luminosity at 380 GeV
- Improving the power efficiency for both the initial phase and at high energies

More details:
- X-band studies: Structure manufacturability and optimized conditioning, interfaces to all connecting systems for large scale production, designs for and support of use in applications, e.g. for FEL linacs, ICS and medical linacs, possible future improvements for power/cost
- Luminosity: beamdynamics studies and related hardware optimisation for nano beams from damping rings to final focus (mechanical and thermal stability, alignment, instrumentation, vacuum systems, stray field control, magnet stability, etc)
- Improving damping ring and drive beam RF efficiency, study parameters and potential hardware changes to reduce power, from 380 GeV to multi-TeV energies with high luminosities
CLIC Project Readiness Report (PRR)

X-band studies: For CLIC and applications in smaller linacs

Luminosity: Beam-dynamics studies and related hardware optimisation for nano beams

RF efficiency and sustainability studies

Goals for these studies:

- Improved 380 GeV parameters/performance/project plan
- Push multi-TeV options/parameters
Industrial questionnaire:
Based on the companies feedback, the preparation phase to the mass production could take about five years. Capacity clearly available.

Structures and components production programme to study designs, operation/conditioning, manufacturing, industry qualification/experience

EU projects: ARIES, I-FAST, new TNA

PECFA / CLIC / Stapnes
Use in smaller linacs (C and X-band)

SwissFEL: C-band linac

- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar μm-level tolerance
- Length ~ 800 CLIC structures
- Being commissioned
- X-band structures from PSI perform well

26 academic and industrial partners: [http://www.compactlight.eu/Main/HomePage](http://www.compactlight.eu/Main/HomePage)

CompactLight Design Studies 2018-21 ([link](http://www.compactlight.eu/Main/HomePage))
Compact FEL based on X-band technologies
Applications – injector, X-band modules, RF

- CompactLight Design Studies 2018-21 (right)
- INFN 1 GeV linac
- Flash RT CDR, next build it at CHUV
- “Design Studies” for ICS
- AERES, IFAST and TNA project
Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma

- Z pole performance, $2.3 \times 10^{32} - 0.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma spectrum (example)
- Luminosity margins and increases
  - Baseline includes estimates static and dynamic degradations from damping ring to IP: $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, a “perfect” machine will give: $4.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, so significant upside
  - In addition: doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of +50 MW and ~5% cost increase
- Studies cover from beam-dynamics to technical studies of the required performances of stability, alignment, instrumentation, magnets, BDS, final focus, injectors including positrons, damping rings – priority for next ESU

- CLIC note and paper about these studies
High Efficiency implementations:
- New small X-band klystron, ordered
- Large with CPI, work with INFN
- L-band two stage, design done, prototyping for FCC

Also important, redesign of damping ring RF system (well underway) – no klystron development foreseen
CLIC Detector

**CLICdet:**
- High-performing detector optimized for CLIC beam environment
- Full GEANT-based simulation, including beam-induced backgrounds, available for optimization and physics studies
- Mature reconstruction chain allows detailed performance characterisation
  - e.g. for tracking: effect of busy environment; displaced track reconstruction

**Software framework:**
- Originally in iLCSof, the simulation/reconstruction is now fully embedded in the Key4HEP ecosystem — a common target for all future collider options
  - existing reconstruction algorithms “wrappered” for the new framework

NIM A956 (2020) 163304
Detector R&D for CLICdet

Calorimeter R&D => within CALICE and FCAL
Silicon vertex/tracker R&D:
• Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
• Now integrated in the CERN EP detector R&D programme

A few examples:

Hybrid assemblies:
• Development of bump bonding process for CLICpix2 hybrid assemblies with 25 μm pitch
  https://cds.cern.ch/record/2766510

• Successful sensor+ASIC bonding using Anisotropic Conductive Film (ACF), e.g. with CLICpix2, Timepix3 ASICS.
  ACF now also used for module integration with monolithic sensors.
  https://agenda.linearcollider.org/event/9211/contributions/49469/

Monolithic sensors:
• Exploring sub-nanosecond pixel timing with ATTRACT FASTPIX demonstrator in 180 nm monolithic CMOS
  https://agenda.linearcollider.org/event/9211/contributions/49445/

• Now performing qualification of modified 65 nm CMOS imaging process for further improved performance

CLICTD monolithic tracking sensor:
Detailed simulations, Allpix² transient Monte Carlo combined with electrostatic 3D TCAD.

Beam tests at DESY, e.g. 5.8 ns CLICTD time resolution achieved
https://agenda.linearcollider.org/event/9211/contributions/49443/
Physics Potential recent highlights 1: Initial energy stage

- Ongoing studies on Higgs and top-quark precision physics potential

**Higgs coupling sensitivity:**
- Sensitivities under different integrated luminosity scenarios to complement accelerator luminosity studies

### Increased integrated luminosity at 380 GeV

- **Baseline:** 380 GeV ($1\text{ab}^{-1}$)
- + 1.5 TeV

### Top-quark threshold scan

- Optimisation of scan points including beam spectrum; here optimising on mass and Yukawa coupling.
- Expected top-quark mass precision of 25 MeV can be improved by 25% without losing precision on width or Yukawa.

https://arxiv.org/abs/2103.00522

---

**Table:**

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>HL-LHC</th>
<th>HL-LHC + CLIC</th>
<th>HL-LHC + FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.6</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>11.</td>
<td>9.3</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>3.1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>4.3</td>
<td>4.1</td>
</tr>
</tbody>
</table>


other sensitivities from Briefing Book https://arxiv.org/abs/1910.11775
Power and Energy
(for cost see backup slides)

Design Optimisation:
The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost but also increasingly focussing on reducing power consumption.

Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons, and super conducting and permanents magnets for damping rings and linacs.

Running when energy is cheap:
CLIC is normal conduction, single pass, can change off-on-off quickly, at low power when not pulsed. Specify state-change (off-standby-on) times and power uses for each – see if clever scheduling using low cost periods, can reduce the energy bill.

Renewable energy (carbon footprint):
Is it possible to fully supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost)

---

Power estimate bottom up (concentrating on 380 GeV systems)
- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, etc

Further savings possible, main target damping ring RF, L-band klystron (target 140-150 MW)

Energy consumption ~0.8 TWh yearly (target 0.7)
CERN is currently (when) running at 1.2 TWh (~90% in accelerators)
CLIC can easily be extended

What are the critical elements:
- Physics
- Gradient and power efficiency
- Costs

1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides

Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV
Physics Potential recent highlights 2: Multi-TeV stages

◆ Ongoing studies on new physics searches

Search for heavy neutrinos
◆ $e^+e^- \rightarrow N\nu \rightarrow q\bar{q}l\nu$ signature allows full reconstruction of $N$
◆ BDT separates signal from SM; beam backgrounds included.
◆ cross-section limits converted to mass ($m_N$) coupling ($V_{ln}$) plane

Dark matter using mono-photon signature at 3TeV, $e^+e^- \rightarrow XX\gamma$
◆ New study using ratio of electron beam polarisations to reduce systematics
◆ Exclusions for simplified model with mediator Y and DM particle X
◆ For benchmark mediator of 3.5TeV, photon energy spectrum discriminates different DM mediators & allows 1TeV DM particle mass measurement to ~1% 

Higgs $V_{sr}(\phi)$ =

iller,


CLIC core studies:

Normal conducting accelerating structures are limited in gradient by three main effects (setting aside input power):

- Field emission
- Vacuum arcing (breakdown)
- Fatigue due to pulsed surface heating

Studying these processes gives important input into:

- RF design – Optimizing structures also coupled with beam dynamics
- Technology – Material choice, process optimization
- Operation – Conditioning and recovery from breakdown

Designs for CLIC steadily improving, but also RFQ, Muon collider, XFEL, ICS, etc

Important experimental support

Multi-TeV energies:
High gradient, high wall-plug to beam efficiency, nanobeam parameters increasingly demanding

Cryogenics systems extended: Combining high-gradwnts in cryo-copper and high-temperature superconductors for high-efficiency and reduced peak RF power requirements.
Connecting - the collaborative cloud

The LC studies at CERN also contains work for ILC, and common working groups have been active for many years. Many collaborating institutes work on both.

The physics and detector community, including software, also in many cases do common studies or work on both.

Good participation in ECFA H/t/etc working groups and Detector Roadmap processes.

LDG report covers both NCRF and SFR cavities and a lot of common interest on gradient/efficiency challenges and work on RF sources. Compact and efficient RF in general very nicely pushed forward by a variety of smaller machines, in many cases outside HEP.

CLIC in particular, with a drivebeam, very high alignment/stability requirements and multi-TeV studies also connect into novel RF technology studies as plasma (and a general focus on compact linacs for “applications”).

Links also to muon cooling RF challenges.
Summary and thanks

• CLIC studies focused on core technologies, X-band and nanobeam, for next ESU, well underway.

• Keep focus on both 380 GeV and multi-TeV performance and R&D

• Greatly helped by studies of smaller linacs and systems using X-band technology

• Detector and physics studies continue at lower pace, also in many areas integrated or connected with "Higgs-factory" studies, and wider Detector R&D efforts

• Thanks to many CLIC accelerator colleagues for slides and input, and the CLICdp slides in particular compiled by Aidan Robson
Machine has been re-costed bottom-up in 2017-18
- Methods and costings validated at review on 7 November 2018
  – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated

<table>
<thead>
<tr>
<th>Domain</th>
<th>Sub-Domain</th>
<th>Cost [MCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Beam Production</td>
<td>Injectors</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>Damping Rings</td>
<td>309</td>
</tr>
<tr>
<td></td>
<td>Beam Transport</td>
<td>409</td>
</tr>
<tr>
<td>Drive Beam Production</td>
<td>Injectors</td>
<td>584</td>
</tr>
<tr>
<td></td>
<td>Frequency Multiplication</td>
<td>379</td>
</tr>
<tr>
<td></td>
<td>Beam Transport</td>
<td>76</td>
</tr>
<tr>
<td>Main Linac Modules</td>
<td>Main Linac Modules</td>
<td>1329</td>
</tr>
<tr>
<td></td>
<td>Post decelerators</td>
<td>37</td>
</tr>
<tr>
<td>Main Linac RF</td>
<td>Main Linac Xband RF</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2788</td>
</tr>
<tr>
<td>Beam Delivery and Post Collision Lines</td>
<td>Beam Delivery Systems</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Final focus, Exp. Area</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Post-collision lines/dumps</td>
<td>47</td>
</tr>
<tr>
<td>Civil Engineering</td>
<td>Civil Engineering</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1479</td>
</tr>
<tr>
<td>Infrastructure and Services</td>
<td>Electrical distribution</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>Survey and Alignment</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td>Cooling and ventilation</td>
<td>443</td>
</tr>
<tr>
<td></td>
<td>Transport / installation</td>
<td>38</td>
</tr>
<tr>
<td>Machine Control, Protection and Safety systems</td>
<td>Safety system</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Machine Control Infrastructure</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>Machine Protection</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Access Safety &amp; Control System</td>
<td>23</td>
</tr>
<tr>
<td>Total (rounded)</td>
<td></td>
<td>5890</td>
</tr>
</tbody>
</table>

CLIC 380 GeV Drive-Beam based: \(5890^{+1470}_{-1270}\) MCHF;

CLIC 380 GeV Klystron based: \(7290^{+1800}_{-1540}\) MCHF.
Cost - II

Other cost estimates:

Construction:
• From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
• From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
• Labour estimate: ~11500 FTE for the 380 GeV construction

Operation:
• 116 MCHF (see assumptions in box below)
• Energy costs

  − 1% for accelerator hardware parts (e.g. modules).
  − 3% for the RF systems, taking the limited lifetime of these parts into account.
  − 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.