The CLIC detector

Matthias Weber (CERN)
on behalf of the CLIC detector and physics (CLICdp) collaboration
Compact Linear Collider

Proposed $e^+e^-$ linear collider

- Two beam acceleration scheme
- High acceleration gradient (100 MV/m)
- Staged construction up to 3 TeV
  - High precision physics
  - Higgs, top, BSM

<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></td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Detector design driven by physics and experimental constraints

CLIC Accelerator talk #203 by P Skowronski
CLIC beam environment

Low duty cycle → power pulsing
High luminosity
Very small bunch size at IP
Very strong electromagnetic field from opposite beam → Beamstrahlung
- Coherent and trident $e^+e^-$ pairs very forward
- Contribution from incoherent $e^+e^-$ pairs (3x10^5 per BX) in detector region
- Main background in calorimeters and tracker from $\gamma\gamma \rightarrow$ hadrons (3.2 events per BX at 3 TeV)
→ beam background reduced by $p_T$ and timing cuts

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\(\sigma_{x/y}: 40/1\) nm
\(\sigma_z: 44\) \(\mu\)m

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Particles [1/BX]

Coherent Pairs
Incoherent Pairs
Trident Pairs
$\gamma\gamma \rightarrow$ Hadrons

\(\theta\) [rad]
Example: Beamstrahlung background reduction

Forward WW, no background

with background in reconstruction
time window \(\sim 1.2\) TeV

after timing and \(p_T\) cuts: \(\sim 100\) GeV remain
Detectors and data handling session
EPS-HEP 2017, July 8

Matthias Weber
CERN

CLICdet

Return yoke and muon chambers

4T solenoid ($R_{\text{in}} = 3.4$ m)

Fine grain calorimeters (HCAL) and (ECAL) for particle flow reconstruction

Forward EM Calorimeters (LumiCal & BeamCal)

Ultra light Tracker and Vertex

Power pulsed operation (switch off between bunch trains)

Trigger less readout

Final focusing magnet outside of detector

CLICdp-Note-2017-001
**CLICdet: physics requirements**

**Vertex**: excellent identification of secondary vertices for b/c-tagging \(\rightarrow\) excellent impact parameter resolution

**Tracker**: excellent momentum resolution for high \(p_T\) tracks (> 100 GeV), e.g. for Higgs couplings to muons

\[
\frac{\sigma_{p_T}}{p_T^2} \sim 2 \times 10^{-5} \text{ GeV}^{-1}
\]

O(10) better than LHC experiments

**ECAL**: excellent photon resolution below 1% for photons at 1.5 TeV

**Calorimeters (ECAL+HCAL)**: Excellent jet energy resolution O(10-1500 GeV)

\[
\frac{\sigma_E}{E} \sim 5 - 3.5\
\]

Allows separation of W and Z masses in dijets

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Tracker optimization

Tracker design is outcome of optimization studies in fast and full detector simulations

Requirement on momentum resolution for high momentum tracks lead to $B = 4T$, $R = 1.5m$ and single point resolution $r = 7 \mu m$

Good agreement between fast and full simulation

<table>
<thead>
<tr>
<th>$p$ [GeV]</th>
<th>$\sigma(p_{T}/p_{T,true})$ [GeV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>200</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>300</td>
<td>$10^{-5}$</td>
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</table>

Single $\mu$ at $\theta = 90^\circ$

Performance goal

Flavor tagging performance

at least eight recorded hits per track down to polar angles of 8 degrees

Detectors and data handling session
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ECAL optimisation

ECAL optimised to for best performance in isolated photon energy resolution

- Test several configuration of absorber layer thicknesses → uniform 40 layer configuration best at higher photon energies
- Increased number of layers slight improvement on jet energy resolution → 40 SiW layers with 22 $X_0$ and cell size of 5x5 mm$^2$

Jet energy resolution

Photon energy resolution vs layers

Jet energy resolution vs # of layers

Jet energy resolution vs cell size
HCAL optimisation

HCAL optimization using jet observables

- Tungsten and steel show a similar performance → use steel as absorber
- Reduce inner HCAL endcap radius from 36 to 24 cm

Small calorimeter cell size to minimize confusion

ECAL cell size: \(5 \times 5 \text{mm}^2\) → \(20x\) finer than CMS

HCAL cell size: \(30 \times 30 \text{mm}^2\) → \(3000x\) finer than CMS

\[ \Delta \phi \times \Delta \eta = 0.087 \times 0.087 \]

Physics performance for different HCAL EC radii

Overlap of \(m_Z\) and \(m_Z\) measurements

Detectors and data handling session
EPS-HEP 2017, July 8
**Vertex detector R&D**

**Vertex-detector requirements:**
- Ultra-thin (50 μm active silicon)
- High spatial resolution (~3 μm $\rightarrow$ ~25x25 μm$^2$ pitch)
- Precise timing (~10 ns)

- Broad R&D program on sensors, readout, powering, interconnects, mechanical integration and cooling
- Beam tests of 65 nm readout ASICs with ultra-thin fine-pitch active-edge and HV-CMOS sensors
- Prototypes of Light-weight mechanical supports and air cooling
- Second generation of sensors and r/o ASICs with improved performance currently under test
- Most challenging: position-resolution target

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**Glue-assembly metrology**
- 1:1 scale air cooling thermal test setup
- Capacitively coupled assembly
- TCAD simulation
Tracker R&D

Tracker requirements:
- Material budget 1-1.5% X0 / layer
- Spatial resolution ~7 µm
- Fast timing (~10 ns)
- Has to cover ~100 m² surface area
  ⇒ integrated sensors w. large pixels (≤ 30 µm × 1 mm)
- Evaluating prototypes in different technologies:
  SOI; depleted monolithic CMOS
- Collaboration with HL-LHC tracker upgrade projects
- Most challenging: maintain efficiency and good timing, despite large pixel area
- Mechanical integration and cooling concept for full tracker
- Prototypes for support frames constructed

August 2016 test-beam setup in SPS-H6

Prototype of outer barrel tracker support structure

Evaluating prototypes in different technologies:
SOI; depleted monolithic CMOS
Collaboration with HL-LHC tracker upgrade projects
Most challenging: maintain efficiency and good timing, despite large pixel area
Mechanical integration and cooling concept for full tracker
Prototypes for support frames constructed

Prototype of outer barrel tracker support structure
ECAL/HCAL R&D for CLIC performed within the CALICE collaboration with a comprehensive comparison of various technologies

Silicon-Tungsten ECAL
- Finalizing analysis of 1\textsuperscript{st} generation prototypes, 2\textsuperscript{nd} generation under construction with improved r/o technologies

Scintillator sampling analogue HCAL with high granularity, optimized for PFA reconstruction
- easy mass assembly: SiPM-on-tile technology
- integrated readout electronics
- scalable to linear collider detector

Recent developments:
- Construction and testing of large 2\textsuperscript{nd} generation prototypes
- larger ~1m\textsuperscript{3} prototypes under construction with low noise low cross-talk SiPM

good single particle energy resolution, improved by software compensation (SC) techniques

3 GeV electron hits in SiW ECAL
Forward detector R&D

Forward calorimetry R&D for CLIC performed within the FCAL collaboration

- LumiCAL for measurement of luminosity (to a few permille as goal)
- BeamCAL for very forward e or γ tagging

- Evaluating different r/o technologies
  - Radiation hardness
  - Beam tests

LumiCAL prototype
5 GeV electron test beam

LumiCAL module

FCAL talk #1023 by I. Levy
Summary

The CLIC accelerator provides a unique potential for precision measurements and potential of new discoveries at the TeV scale.

New post CDR CLIC detector model CLICdet is proposed, optimised to achieve highest precision over a center of mass energy range from a few hundred GeV up to 3 TeV in a challenging experimental environment.

Broad efforts of ongoing R&D on detector technologies meeting the requirements for linear colliders.
BACKUP
CLIC related contributions at EPS

- P. Skowronski: Lessons from CTF3 (talk #203, accelerator studies)
- J. Roberts: Energy-staging of the Compact Linear Collider (poster #443)
- G. Milutinovic-Dumbelovic: Higgs and BSM physics at CLIC (talk #401)
- M. Weber: Electroweak precision measurements at CLIC (poster #400)
- N. van der Kolk: Toward Precision Top Quark Measurements in e+e- collisions (talk #468)
- G. Grenier: Technological Prototypes and Result Highlights of Highly Granular (talk #779)
- I. Levy: Measurement of shower development and its Molière radius with a four-plane LumiCal test set-up (talk #1023)
CLIC layout at $\sqrt{s} = 380$ GeV

Drive Beam

circumferences delay loop 73 m
CR1 293 m
CR2 439 m

drive beam accelerator
2.0 GeV, 1.0 GHz

446 klystrons
20 MW, 48 $\mu$s

delay loop
decelerator, 4 sectors of 878 m

11 km

TA turnaround
CR combiner ring
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
der

$e^{-}$ main linac, 12 GHz, 72 MV/m, 3.5 km

BDS 1.9 km

IP

BDS 1.9 km

e$^{+}$ main linac

1.9 km

$e^{-}$ DR 427 m

$e^{-}$ injector 2.86 GeV

$e^{+}$ DR 427 m

$e^{+}$ PDR 389 m

$e^{+}$ injector 2.86 GeV

446 klystrons
20 MW, 48 $\mu$s

delay loop
decelerator, 4 sectors of 878 m

11 km

TA turnaround
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CLIC project timeline

**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
Former CDR models of CLIC inspired by ILC detectors (CLIC_SID and CLIC_ILD)
**CLIC inner detector requirements**

**Vertex detector** physics aim: excellent identification of secondary vertices for b/c-tagging → excellent impact parameter resolution

\[
\sigma(d_0) = 5 \oplus 15/(p[GeV] \sin^{\frac{3}{2}}\theta) \mu m
\]

Affected by single point resolution → 3 \(\mu\)m

Affected by multiple scattering → 0.2\% \(X_0\) by detection layer

**Tracker detector** physics aim: excellent momentum resolution for high \(p_T\) tracks (> 100 GeV), e.g. for Higgs couplings to muons

\[
\sigma_{p_T}/p_{T}^{2} \sim 2 \times 10^{-5} \text{GeV}^{-1}
\]

**Position Resolution**

\[
\frac{\delta p_T}{p_T} \propto \frac{\sigma \cdot p_T}{B \cdot L^2} \cdot \frac{1}{\sqrt{N + 4}}
\]

**Multiple Scattering**

\[
\frac{\delta p_T}{p_T} \propto \frac{1}{B \cdot L} \cdot \sqrt{\frac{X_{tot}}{X_0}}
\]

Large and light tracker with good single point resolution, high B Field → \(\sigma_{R_\phi} \sim 7 \mu m, \sim 1-2\% X_0\) per layer

**O(10) better than LHC experiments**

![Graph showing di-muon invariant mass distribution with CLIC]
CLIC calorimeter requirements

Good Photon energy resolution $O(10-1500 \text{ GeV})$

\[
\frac{\sigma E}{E} \sim 4 - 0.4\% \quad \text{Similar to ATLAS}
\]

Excellent jet energy resolution $O(10-1500 \text{ GeV})$

\[
\frac{\sigma E}{E} \sim 5 - 3.5\% \quad \text{ATLAS JER} \lesssim 5\%
\]

for $p_T^{\text{jet}} > 1 \text{ TeV}$

\[\rightarrow\] Allows separation of W and Z masses in dijets

Large Coverage

Detectors and data handling session
EPS-HEP 2017, July 8
Tracker Optimisation

- Tracker overall size and B field
  - Acceptance $|\theta| > 7^\circ \rightarrow |\eta| > 2.8$
  - $B = 4\ T$
  - $4.4\ m \times 3\ m$ tracker

Increasing $B$

\begin{align*}
\text{Precision on luminosity} & \\
\theta_{\text{Max}} [\text{Deg}] & \\
\frac{\Delta L}{L} & \\
\sigma & \\
\end{align*}
Photon Performance

Relative Photon Energy Resolution in different detector regions

Photon phi position resolution in different detector regions as function of true photon energy
Particle flow calorimeters

Classical approach

\[ E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}} \]

Particle flow approach

\[ E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n \]

Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutrons

Always use the best info you have:
- 60% => tracker 😊😊
- 30% => ECAL 😊
- 10% => HCAL 😊

Requires highly granular calorimeters to resolve deposits from different particles and sophisticated software to make correct associations.
Particle flow algorithms: Pandora

“The Pandora Software Development Kit for Pattern Recognition” → EPJC.75.439

1. Multiple tracks associated to single cluster – split cluster.
2. Cluster energy much greater than track momentum – split cluster.

- Exploit calorimeter granularity to gradually build-up picture of events
- More than 70 algorithms to address specific event topologies, with very few mistakes, and to avoid accidental merging of separate particles

Energy of 2 γ in transverse plane to the direction of the flight
• CLICdp collaboration addresses detector and physics issues for CLIC
• CERN acts as host laboratory
• Currently 29 institutes from 18 countries, ~180 members
  http://clicdp.web.cern.ch/
• Close connection to ILC detector concepts, CALICE, FCAL, AIDA-2020
Example: Beamstrahlung background reduction

Forward WW, no background

with background in reconstruction time window ~1.2 TeV

after timing and $p_T$ cuts: ~ 100 GeV remain:
- Remove neutral hadrons with $p_T < 0.5$ GeV
- Remove photons with $p_T < 0.2$ GeV
- For charged hadrons with $p_T < 1$ GeV, cut on cluster time between -0.25 to 1 ns window (tof corrected)
- For neutral hadrons with $p_T < 8$ GeV cut on cluster time window of 0 to 2.5 ns
- For photons with $p_T < 4$ GeV time window of 0 to 1 ns
→ Other particles accepted for default reconstruction time window