R&D challenges of a CLIC vertex detector

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CERN LCD

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Outline

• Physics at multi-TeV e^+e^-
• Introduction CLIC
  – Multi-TeV e^+e^- collisions
  ➢ Linear collider detector concepts

➢ Vertex detector requirements
  – Time resolution
  – Position resolution
  – Material budget
  – Power pulsing
  – ...

Preliminary
Physics at a few TeV

- Refine LHC physics & explore energy frontier
- What’s different: many interesting channels in forward region
linear collider, producing $e^+e^-$ collisions

ILC

- Based on superconducting RF cavities
- Gradient 32 MV/m
- Energy: 500 GeV, upgradeable to 1 TeV
- (+ lower energies: ttbar resonance,...)
- Detector studies focus mostly on 500 GeV

CLIC

- Based on 2-beam acceleration scheme
- Gradient 100 MV/m
- Energy: 3 TeV, though will probably start at lower energy (~0.5 TeV)
- Detector study focuses on 3 TeV

Luminosities: few $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
CLIC parameters

Train repetition rate 50 Hz

CLIC: 1 train = 312 bunches, 0.5 ns apart  trains at 50 Hz
ILC: 1 train = 2820 bunches, 308 ns apart  trains at 5 Hz
CLIC parameters

Train repetition rate 50 Hz

CLIC: 1 train = 312 bunches, 0.5 ns apart trains at 50 Hz
ILC: 1 train = 2820 bunches, 308 ns apart trains at 5 Hz

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEP 2</th>
<th>ILC 0.5 TeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [cm$^{-2}$s$^{-1}$]</td>
<td>5×10$^{31}$</td>
<td>2×10$^{34}$</td>
<td>6×10$^{34}$</td>
</tr>
<tr>
<td>Crossing angle</td>
<td></td>
<td>14 mrad</td>
<td>20 mrad</td>
</tr>
<tr>
<td>BX separation</td>
<td>~22 µs</td>
<td>308 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>IP size in x / y / z direction [nm]</td>
<td>250 µm / 5 µm / 10 mm</td>
<td>600nm / 6nm / 10mm</td>
<td>45 nm / 1 nm / 40 µm</td>
</tr>
<tr>
<td># ($\gamma\gamma$→hadrons) / BX</td>
<td>negligible</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>#Incoherent pairs / BX</td>
<td>negligible</td>
<td>1 × 10$^5$</td>
<td>3 × 10$^5$</td>
</tr>
</tbody>
</table>

Not to scale
Beamstrahlung at 3 TeV

$\Delta E/E = 29\% \ (10\times\text{ILC}_{\text{value}})$

- **Coherent pairs**
  3.8×$10^8$ per BX
  \~ disappear in beam pipe
- **Incoherent pairs**
  3.0×$10^5$ per BX
  \~ reduced by strong solenoid-field
  *main source of background in vertex detector*

- Large impact on detector concepts:
  - Conical beampipe.
  - Inner radius of vertex detector to be larger at CLIC: 3 cm.

D. Schulte
Based on ILC validated concepts, modified to CLIC requirements

**CLIC_ILD:** International Large Detector

- "Large": tracker radius 1.8 m
- B-field: 4 T solenoid
- Tracker: TPC + Si-strip layer
- Vertex: Si-pixel

**CLIC_SiD:** Silicon Detector

- "Small": tracker radius 1.3 m
- B-field: 5 T solenoid
- Tracker: Silicon
- Vertex: Si-pixel

Both have ECAL+HCAL inside solenoid with high granularity
First design:
5 barrel layers and 7 disks

83 cm
17 cm
20 cm

Double-walled support cylinder and cooling gas distribution manifold
4 pixel inner disks
3 pixel outer disks
2 of 4 beam tube support locations
5-layer pixel barrel
Beam tube

Bill Cooper
‘long barrel’: 25 cm

• Three double-sided barrel ladders
• Interplay between acceptance and amount of material
• short barrel + disks or long barrel?
  – Double/single sided?
• Material for services, cooling options?
Occupancy in vertex detector

- Because of 0.5 ns BX spacing background of several BX will overlap
- Clear separation between direct and back-scattered hits
- 2/3 coming from back-scatters; somewhat reducible with forward region design

➢ Need high granularity in time for read out to reduce background.
➢ Inhomogeneous distribution in azimuthal angle: up to 5x more.

- With for example 20x20 µm pixels, 5-10pix/cluster:
  0.04 hits / mm² / ns in Layer 1 ➔ ~1-2% average occupancy during train.
  x5 for hot spots.
  ➔ Need multi-hit readout electronics

Averaged over φ
Jets at $\sqrt{s} = 3$ TeV

Forward region:
- many interesting physics channels
- worse resolution (more material)
- more background

b-jet angular distribution $\rightarrow$

$0.9 < \cos \theta < 0.995 \sim 6^\circ < \theta < 30^\circ$ or $1.5 < |\eta| < 3$

$e^+e^- \rightarrow \nu\nu H^0 (180) \rightarrow \nu\nu bb$

M. Battaglia
Jets at $\sqrt{s} = 3$ TeV

- Broad range of b-jet energies of interest:
  $\approx 0.05 - 1.5$ TeV.

- Long lived hadrons in b-jets acquire significant flight distance:
  with four jets, over $1/3$ of charged particles with $p > 1$ GeV decay after first vertex detector layer.

$e^+e^- \rightarrow H^0A^0 \rightarrow bbbb$

$e^+e^- \rightarrow H^0A^0 \rightarrow bbbb$

M. Battaglia
Impact parameter Resolution

5-layered barrel VTX with:
• $R_{\text{in}} = 30 \text{ mm}$, $R_{\text{out}} = 60 \text{ mm}$
• $15 \mu\text{m}$ pixels, $3 \mu\text{m}$ single point resolution
• $50 \mu\text{m}$ Silicon, with total layer thickness of $0.12\% X_0$

Material budget in detector concepts:
~$0.1\% X_0$ per layer, to keep contribution of multiple scattering to $\sigma_{\text{IP}}$ low.

<table>
<thead>
<tr>
<th>$\sigma_{\text{point}} = 3\mu\text{m}$</th>
<th>$\sigma_{\text{IP}} = 6.5 \oplus \frac{16.7}{p_t} \mu\text{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{point}} = 5\mu\text{m}$</td>
<td>$\sigma_{\text{IP}} = 9.2 \oplus \frac{18.6}{p_t} \mu\text{m}$</td>
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</tbody>
</table>
Given CLIC constraints this can be achieved with:

- a multi-layered VTX with single point resolution $\approx 3\mu m$, i.e. a $\approx 10\mu m$ binary pixel or a 15-20 $\mu m$ analog pixel with charge interpolation.

- Single-layer material thickness $\approx 0.1\% X_0$ to keep the multiple scattering low.
## R&D issues

<table>
<thead>
<tr>
<th>Technology domains</th>
<th>Issues</th>
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<tbody>
<tr>
<td>Sensor technology &amp; Alignment</td>
<td>Low expected radiation damage. IP size (x/y/z): 45nm / 1nm / 40 μm → Requires high time &amp; position resolution: 3μm point resolution</td>
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<tr>
<td>Readout electronics</td>
<td>Time binning ~10ns, multi-hit capability within 156ns train; high &amp; inhomogeneous occupancy.</td>
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<td>Power dissipation and cooling, Power delivery</td>
<td>readout in less than ~200-400 μs, power pulsing, DC-DC or serial</td>
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<td>Small pitch interconnect and seamless coverage</td>
<td>Hybrid, integrated technologies, 3D/TSV (through-silicon-vias)</td>
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<tr>
<td>Low-mass engineering</td>
<td>~0.1%X₀ per layer</td>
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R&D for CLIC vertex detector will touch upon many technical domains.

- Some issues have overlap with R&D for ILC and R&D for sLHC. However, the combination of (technically conflicting) requirements for CLIC make it a challenging R&D on its own.

- Forward region deserves more attention: expect more of the interesting physics, more background, worse resolution.

- We’re currently still in the phase where we try to understand the extent of the challenge and try to bring it in relation with “what’s on the market”.

  - CLIC CDR to be published April 2011

LCD homepage:  http://lcd.web.cern.ch/lcd/
Indico agenda:  - Track and vertex reconstruction WG
                - Vertex Detector WG
Backup slides
**Tentative long-term CLIC scenario**

Technology evaluation and Physics assessment based on LHC results for a possible decision on Linear Collider with staged construction starting with the lowest energy required by Physics.

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<td>R&amp;D on Feasibility Issues</td>
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<td>Engineering Optimisation &amp; Industrialisation</td>
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<td>Construction (in stages)</td>
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<tr>
<td>Construction Detector</td>
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- **Conceptual Design Report (CDR)**
- **Technical Design Report (TDR)**
- **Project approval?**
- **First Beam?**
The full CLIC scheme

CLIC 3 TeV

Not to scale!
No individual RF power sources

Two Beam Scheme:

Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A
Drive Beam Accelerator

efficient acceleration in fully loaded linac

Drive beam time structure - initial

140 µs total length - 24 × 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 – 100 A – 2.5 cm between bunches

Drive Beam Decelerator Sector (24 in total)

Delay loop × 2
gap creation, pulse compression & frequency multiplication

Combiner ring × 4
pulse compression & frequency multiplication

Combiner ring × 3
pulse compression & frequency multiplication

Transverse RF Deflectors

RF power source
CLIC parameters:

**Accelerating gradient:** 100 MV/m
- RF frequency: 12 GHz
- Basic accelerating structure
  of 23.3 cm active length

Total active length for 1.5 TeV: **15’000 m**

The 12 GHz is a higher frequency than the 0.5 ns between BXs.
- There is time needed between the BXs, not to have them interfere & for the RF to come back to nominal.

The RFs cannot continuously be operated, hence the ‘long’ deadtime between trains.
## CLIC parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ILC 500 GeV</th>
<th>CLIC 500 GeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (Peak 1%) luminosity [\cdot 10^{34}]</td>
<td>2 (1.5)</td>
<td>2.3 (1.4)</td>
<td>5.9 (2.0)</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>5</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Loaded accel. gradient MV/m</td>
<td>32</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Main linac RF frequency GHz</td>
<td>1.3</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Bunch charge [\cdot 10^9]</td>
<td>20</td>
<td>6.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Bunch separation (ns)</td>
<td>370</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Beam pulse duration (ns)</td>
<td>950 $\mu$s</td>
<td>177</td>
<td>156</td>
</tr>
<tr>
<td>Beam power/beam (MWatts)</td>
<td>4.9</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Hor./vert. IP beam size (nm)</td>
<td>600 / 6</td>
<td>200 / 2.3</td>
<td>40 / 1.0</td>
</tr>
<tr>
<td>Hadronic events/crossing at IP</td>
<td>0.12</td>
<td>0.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Incoherent pairs at IP</td>
<td>$1 \cdot 10^5$</td>
<td>$1.7 \cdot 10^5$</td>
<td>$3 \cdot 10^5$</td>
</tr>
<tr>
<td>BDS length (km)</td>
<td>1.87</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>Total site length km</td>
<td>31</td>
<td>13</td>
<td>48</td>
</tr>
<tr>
<td>Total power consumption MW</td>
<td>230</td>
<td>130</td>
<td>415</td>
</tr>
</tbody>
</table>

**Crossing Angle 20 mrad (ILC 14 mrad)**
Parameter drawing of CLIC Detectors

Hubert Gerwig
Occupancy in vertex detector

- Because of 0.5 ns BX spacing background of several BX will overlap
- Clear separation between direct and back-scattered hits
- 2/3 coming from back-scatters; somewhat reducible with forward region design

- Inhomogeneous distribution of hits in phi for the first layer of the VXD
  - Due to 20 mrad crossing angle
  - Intensity ~5x higher at two spots

Vertex 2010, June 10

André Sailer
**Overall detector requirements**

- **momentum:** \((1/10 \times \text{LEP})\)
  
  e.g. Muon momentum
  
  Higgs recoil mass

  \[ \sigma_{1/p} < 5 \times 10^{-5} \text{GeV}^{-1} \]

- **jet energy:** \((1/3 \times \text{LEP/ZEUS})\)
  
  e.g. \(W/Z\) di-jet mass separation
  
  EWSB signals

  \[ \frac{\sigma_E}{E} \approx 3 - 4\% \]

- **impact parameter:** \((1/3 \times \text{SLD})\)
  
  e.g. c/b-tagging, Higgs BR

  \[ \sigma_{r\phi} = 5 \oplus 10/(p \sin^{3/2} \theta) \mu \text{m} \]

- **hermetic:** down to \(\theta = 5\) mrad
  
  e.g. missing energy signatures in SUSY

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*See talk by M. Thomson – CLIC’09*
In a typical jet:
- 60% of jet energy in charged hadrons
- 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10% in neutral hadrons (mainly $n$ and $K_L$)

Traditional calorimetric approach:
- Measure all components of jet energy in ECAL/HCAL!
- ~70% of energy measured in HCAL: $\sigma_E/E \approx 60%/\sqrt{E(\text{GeV})}$
- Intrinsically “poor” HCAL resolution limits jet energy resolution

Particle Flow Calorimetry paradigm:
- Charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E/E < 20%/\sqrt{E(\text{GeV})}$
- Neutral hadrons (ONLY) in HCAL
- Only 10% of jet energy from HCAL → much improved resolution

$$E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}}$$
$$E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n$$
## Physics reach

<table>
<thead>
<tr>
<th></th>
<th>LHC 100 fb(^{-1})</th>
<th>ILC 800 GeV 500 fb(^{-1})</th>
<th>SLHC 1000 fb(^{-1})</th>
<th>CLIC 3 TeV 1000 fb(^{-1})</th>
<th>CLIC 5 TeV 1000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squarks [TeV]</td>
<td>2.5</td>
<td>0.4</td>
<td>3</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Sleptons [TeV]</td>
<td>0.34</td>
<td>0.4</td>
<td>1.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>New gauge boson Z' [TeV]</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Excited quark q(^*) [TeV]</td>
<td>6.5</td>
<td>0.8</td>
<td>7.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Excited lepton l(^*) [TeV]</td>
<td>3.4</td>
<td>0.8</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Two extra space dimensions [TeV]</td>
<td>9</td>
<td>5–8.5</td>
<td>12</td>
<td>20–35</td>
<td>30–55</td>
</tr>
<tr>
<td>Strong W(_LLW(_L) scattering</td>
<td>2(\sigma)</td>
<td>-</td>
<td>4(\sigma)</td>
<td>70(\sigma)</td>
<td>90(\sigma)</td>
</tr>
<tr>
<td>Triple-gauge Coupling (95%)</td>
<td>.0014</td>
<td>0.0004</td>
<td>0.0006</td>
<td>0.00013</td>
<td>0.00008</td>
</tr>
</tbody>
</table>

Integrated luminosities used are 100 fb\(^{-1}\) for the LHC, 500 fb\(^{-1}\) for the 800 GeV LC, and 1000 fb\(^{-1}\) for the SLHC and CLIC. Most numbers given are TeV, but for strong W\(_LLW\(_L\) scattering the numbers of standard deviations, and pure numbers for the triple gauge coupling (TGC).
Example: looking for heavy neutralinos

Gives an excess of events in the $l^+ l^-$ invariant mass distribution. A simultaneous fit of the slepton and $\chi_{1,2}$ mass gives $\sim 2\%$ precision with 1 ab$^{-1}$. The precision is dominated by the correlation between parameters.

Also $\chi_{3,4}$ are accessible in a multi-TeV LC.

\[ \tilde{\chi}_j^0 \rightarrow l^\pm \tilde{l}^\mp \rightarrow l^+ l^- \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_3^0 \rightarrow \tilde{\chi}_{1,2}^0 Z^0 \]
\[ \tilde{\chi}_4^0 \rightarrow \tilde{\chi}_{1,2}^0 h^0 \]

$m_0 = 150$ GeV, $m_{1/2} = 700$ GeV

1 ab$^{-1}$

\[ M_{\tilde{\chi}_2^0} = 540 \text{ GeV}, \quad M_{\tilde{\chi}_1^0} = 290 \text{ GeV}, \quad M_{\ell_L} = 490 \text{ GeV}. \]
Within a SUSY model (CMSSM, NUHM, etc..) we can use low energy measurements, in particular $b \rightarrow s \gamma$, the limit on $M_h$ and $g_\mu - 2$, to evaluate the most probable mass spectra, see for instance arXiv 0808.4128.
After LHC, mass determinations can be improved with CLIC.

- Allows for better identification of susy breaking mechanism.

\[ E_{\text{min,max}} = \frac{\sqrt{s}}{4} \left( 1 - \frac{\tilde{m}_\chi^2}{\tilde{m}_\mu^2} \right) \left( 1 \pm \sqrt{1 - 4 \frac{\tilde{m}_\mu^2}{s}} \right) \]

\[ \tilde{m}_\chi = (652 \pm 22) \text{GeV} \quad 3\% \]
\[ \tilde{m}_\mu = (1145 \pm 25) \text{GeV} \quad 2\% \]
Vertex and Tracking issues:

• With overlapping BX, time stamping might be necessary.
  – For tracker & vertex detector, or only for tracker?

• Narrow jets at high energy
  – 2-track separation is an issue for the tracker/vertex detector
  – Track length may have to increase (fan-out of particles within jet)

Overlapping with $\gamma\gamma \rightarrow \text{hadrons}$

$\sigma(3)$ hadron events per BX