Detector Systems at CLIC

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Outline

- Experimental Conditions at CLIC

- CLIC Detector Designs
  - General detector philosophy
  - Vertex detectors
  - Calorimetry
  - Engineering Studies

- Event reconstruction
  - Coping with backgrounds

- Summary/Outlook
Experimental Conditions at CLIC
CLIC: The Compact Linear Collider

- 3 TeV center of mass energy (staged construction possible: ~ 500 GeV initially)
- 2-beam acceleration using warm cavities: 100 MV/m gradient
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- 2-beam acceleration using warm cavities: 100 MV/m gradient

Luminosity at 3 TeV: $5.9 \times 10^{34}$ cm$^{-2}$s$^{-1}$

\[ (2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ in top 1\%}) \]
Conditions at CLIC

• The bunch structure at CLIC

- 20 ms
- 156 ns long bunch trains
- 0.5 ns bunch to bunch spacing
- 312 bunches per train
- 50 Hz repetition rate

- precise time-stamping required
- power pulsing of electronics possible
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Beamstrahlung driven by energy and focusing:
mean bunch $\Delta E/E \sim 29\%$

- coherent $e^+e^-$ pairs: $3.8 \times 10^8$ / bunch crossing
- incoherent $e^+e^-$ pairs: $3.0 \times 10^5$ / bunch crossing
- $\gamma\gamma \rightarrow$ hadrons interactions: 3.2 / bunch crossing
Conditions at CLIC: Beamstrahlung Details

- Coherent $e^+e^-$ pairs with angles $< 10$ mrad
  - Crossing angle at CLIC: 20 mrad
  - Beam pipe opening angle $\pm 10$ mrad
  - For outgoing beam:
    - Coherent pairs disappear in beampipe
- Incoherent pairs: swept away by solenoidal field,
  - Constrain innermost radius of vertex detector
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- $\gamma\gamma \rightarrow$ hadrons: $\sim 3.2$ events / bx,
  - $\sim 28$ ch. particles in detector acceptance
  - $\sim 60$ GeV energy
  - $\sim 15$ TeV dumped in detector during bunch train, forward peaked
  - Requires precise time stamping and clever event reconstruction
CLIC Detector Design

- General Considerations
- Vertex Detectors
- Calorimetry
- Engineering Studies
General Considerations

• Requirements for CLIC detectors driven by physics:
  • Excellent resolution for multi-jet final states
  • Hermetic coverage for missing energy measurements
  • Precise track reconstruction
  • Excellent flavor tagging: b & c identification and separation

• These requirements are satisfied by the validated ILC detector concepts ILD and SID
  • Detector systems with large solenoid, event reconstruction based on Particle Flow

• Modifications are necessary to account for CLIC-specific issues:
  • Higher energy: Jets up to the TeV region
  • Higher backgrounds due to high energy and small beam size, combined with high bunch crossing rate
CLIC Detectors - Main Features

- **highly granular calorimeters for PFA**
- **low-mass, high precision vertex detector**
- **forward calorimeters for luminosity measurements and overall detector hermeticity**
- **stabilized final focusing elements**
- **potential compensation coils to limit stray field**
- **precision tracking**
- **magnet yoke with muon detector / tail catcher**
- **high-field solenoid**
Overview: The CLIC Detector Concepts

- Two detectors, following the ILC designs: CLIC_ILD and CLIC_SID

  - Si pixel vertex detector
  - Si strip inner tracker
  - CLIC_ILD: TPC main tracker
  - CLIC_SID: Si strip main tracker
  - SiW electromagnetic calorimeter
  - Hadronic calorimeter with tungsten absorbers in barrel, steel in endcaps
  - Active medium: Scintillator tiles with SiPM readout currently studied, digital calorimeter with gas detectors also an option

All inside large solenoid
Changes to ILC Detector Concepts

- The overall detector philosophy, and the general design remains unchanged with respect to the ILC concepts
- Still, many changes to address CLIC-specific issues in both CLIC_ILD and CLIC_SID:
  - redesigned yoke,
  - changed instrumentation
  - added compensation coils
  - Solenoid dimensions roughly the same, CLIC_ILD at 4 T, CLIC_SID at 5 T
  - Hadron calorimeter increased in depth: $7.5 \lambda_I$
  - Significant redesign of forward region
  - Vertex/inner detector: increased radius, changed beam pipe
  - Modified forward tracking
  - Main tracker unchanged
  - both CLIC concepts: same outer dimensions
The Vertex Detector - Design Considerations

- Performance goal: Excellent secondary vertex resolution to identify heavy flavors, to discriminate between charm and bottom and tag $\tau$ decays.

Resolution goal:

$$\sigma_{IP}(p_T) = \sqrt{a^2 + \frac{b^2}{p_T^2}}, \text{ with } a = 5 \, \mu m \text{ and } b = 15 \, \mu m GeV$$

- Move innermost layer of detector as close as possible to the interaction point — limited by background!

3 TeV, inc. pairs, $p_T > 8$ MeV, $\theta > 2^\circ$: charged particles / mm$^2$ / bx (cylindrical projection)

Study for CLIC_ILD
The Vertex Detector - Design Considerations

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, with $a = 5\, \mu m$ and $b = 15\, \mu m GeV$

• Move innermost layer of detector as close as possible to the interaction point

$\Rightarrow$ limited by background!

Study for CLIC_ILD

At innermost layer of vertex detector:

total of

0.04 hits / mm$^2$ / ns

For a low-energy CLIC option at 500 GeV, the inner layer can move in by about 6 mm
Pixel Vertex Detector Design

Resulting designs for CLIC_ILD / CLIC_SiD:

- **ILD:**
  - Be beam pipe at 29.4 mm, 0.6 mm thick

- **SID:**
  - Be beam pipe at 25 mm, 0.5 mm thick

- **ILD:** 3 double layers, 3 forward DL discs

- **SID:** 5 single layers, 8 forward discs
Pixel Vertex Detector - Technology

• Resolution goals require ~ 3 µm single hit resolution:
  20 x 20 µm² pixels with analog readout

• Requirements for technology:
  • Low mass: 0 0.1% X₀ per detector layer (corresponds to just 100 µm Si!)
    CLIC_ILD: 0.18% X₀ per DL 2 x 50 µm Si, 134 µm carbon support)
    CLIC_SID: 0.12% X₀ per SL ( 50 µm Si, 130 µm carbon support)
  • Only achievable with low power: Powerpulsing at 50 Hz
  • Forced gas-flow cooling wherever possible - Barrel layers
  • Integrated liquid cooling solutions: micro-channel cooling in support structures
  • Time stamping on the few ns level
    • “Classical” solution: thinned hybrid pixels with 3D interconnects,
      small feature size for readout chips
    • Alternatives: Semi-integrated CMOS active pixel sensors, SOI, ...
  • Rad-hardness not a critical issue:
    NIEL ~10¹⁰ nₑq / cm² / year, TID ~ 100 Gy / year
The Calorimeters

- Based on the Particle Flow concept: Highly granular to provide shower separation within hadronic jets
- CLIC-specific: Increased depth to contain higher energies

Simulation study of PFA performance in CLIC_ILD

Performance goal of 3.5% jet energy resolution over full energy range requires 7.5 $\lambda_I$ thick HCAL

For reference:
ILD: 5.5 $\lambda_I$
SID: 4.8 $\lambda_I$
The Hadron Calorimeter: Dense Absorbers

- No dead material between tracker and calorimeters for optimal PFA performance: Calorimeter has to be inside solenoid - Compactness required!
- Promising absorber material: Tungsten

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<th>W</th>
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<td>9.95</td>
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<td>$X_0$ [cm]</td>
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- Significantly reduced interaction length
- Reduced sampling for electromagnetic subshowers due to short interaction length
- Heavy nucleus: Richer time structure of shower?
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Heavy nucleus: Richer time structure of shower?

Test beam required:
CALICE analog HCAL active layers
Tungsten absorber plates

• Validation of Geant4 simulations used to evaluate full detector performance
• Study of energy resolution, shower shapes, time structure
Tungsten HCAL - First Beam Tests

- First beam campaign at CERN PS in 2010
  Muon, hadron, electron beams up to 10 GeV

More data coming:
Tests at SPS starting next week!
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Measurements of time structure of hadronic showers in Tungsten HCAL:
Calo Session, Ontario, 15:00 today
Magnet Systems

- Large solenoids for CLIC detectors push the technological limits
  - CLIC_SID most challenging: 5 T field - Extreme pressure on SC cable
    - Free bore 5.5 m, Length 6.2 m, Stored energy ~ 2.3 GJ, Energy/Mass ~14 kJ/kg
    - (CMS: 6 m, 12.5 m, 2.6 GJ, 11.6 kJ/kg)

Inspired by CMS design:
3 modules, 5 layers
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    (CMS: 6 m, 12.5 m, 2.6 GJ, 11.6 kJ/kg)

Conductor options under investigation - Cooperation between CERN, KEK and Swiss industry
Mechanical Stability

- Final focusing magnets need extreme stabilization:
  Vertical position of final quadrupole better than 0.15 nm RMS for $f > 4$ Hz
  Required because of small beam size: vertical 1 nm, horizontal 40 nm, longitudinal 45 µm
- Permanent magnets + warm magnet for QD0 to reduce vibrations
- Supported from active stabilization, decoupled from detector
- Passive high-mass low stiffness spring system to suppress high frequencies from ground
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Damping system under development, simulations validated with mechanical experiment
Two Detectors: Push-Pull

- Two detectors share one IR: Push-pull scheme also adopted by ILC
- CLIC Detector designs: Both detectors have equal outer dimensions: facilitates push-pull operations
Event Reconstruction
CLIC Event Reconstruction

- Event reconstruction technique: Particle Flow
  - Key challenge: Backgrounds from two-photon processes
    - $e^+e^-$ pairs in the vertex detectors
    - hadrons in the main tracker and in the calorimeters

- The way to reject backgrounds: Timing
  - Match the time of all reconstructed physics objects with the time of the event
  - Assume ~10 ns timing in vertex detectors and Si trackers
  - Key detectors: Calorimeters with ~1 ns cluster timing
    - Long integration time in the HCAL to account for shower time structure
  - More stringent cut on low $p_t$ particles (more likely to be background)
Background Removal

• Beam related background from $\gamma\gamma \rightarrow$ hadrons processes adds significant energy to events, in particular in the forward region - simulation chain fully validated

$1\text{ TeV } Z \rightarrow uds$
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$1\ \text{TeV } Z \rightarrow \text{uds } + \gamma\gamma \rightarrow \text{hadrons background}$

$\sim 60\ \text{BX}, 1.4\ \text{TeV}$
Background Removal

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  \[ 1 \text{ TeV} \ Z \rightarrow \text{uds} \ + \ \gamma\gamma \rightarrow \text{hadrons background} \]

- Timing cuts reduce the impact of background significantly

\[ \sim 60 \text{ BX, 1.4 TeV} \]

\[ \text{realistic timing assumptions: 200 GeV} \]
Impact of Timing Cuts

- Tight timing cuts in particular on low momentum particles affect jet energy resolution for low-energy jets
- For jets in the region of interest for a 3 TeV machine, the impact is small

<table>
<thead>
<tr>
<th>Jet Energy Resolution (RMS₂₀) in %</th>
<th>E_j</th>
<th>45GeV</th>
<th>100GeV</th>
<th>250GeV</th>
<th>500GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIC_ILD_CDR, v01-11, new config</td>
<td>3.74 ± 0.05</td>
<td>3.02 ± 0.04</td>
<td>3.00 ± 0.04</td>
<td>3.20 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>CLICTrackSelector, 50ns cut</td>
<td>3.90 ± 0.05</td>
<td>3.13 ± 0.04</td>
<td>3.03 ± 0.04</td>
<td>3.21 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>CLICPfoSelection, loose</td>
<td>4.40 ± 0.06</td>
<td>3.34 ± 0.04</td>
<td>3.12 ± 0.04</td>
<td>3.27 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>CLICPfoSelection, default</td>
<td>5.18 ± 0.07</td>
<td>3.65 ± 0.05</td>
<td>3.20 ± 0.04</td>
<td>3.30 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>CLICPfoSelection, tight</td>
<td>6.00 ± 0.08</td>
<td>3.99 ± 0.05</td>
<td>3.35 ± 0.04</td>
<td>3.37 ± 0.06</td>
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</tr>
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</table>

- For lower energy operation (500 GeV), relaxed cuts will be used to recover performance also for lower energy jets
Background Reduction in Physics Analysis

- Use of specific jet algorithms, momentum and geometry cuts, ...
  are studied to obtain best possible precision - Depends on physics channel

Example: Squark pair production
Signature: 2 jets + missing energy
- susceptible to hadronic background!
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Example: Squark pair production

Signature: 2 jets + missing energy

- susceptible to hadronic background!

Jet finding can reduce background effects considerably: Choose the right finder / metric!

\[ k_t, \text{angular distance} \]

\[ k_t, \Delta \eta \Delta \varphi \]

\[ \approx 1.3 \text{ TeV} \]
Summary / Outlook
Summary: Detector Concepts and Challenges at CLIC

• Experimental conditions at CLIC put stringent demands on the detector systems:
  • Highly precise jet energy reconstruction up to TeV energies, precision tracking and powerful flavor tagging to meet the physics goals
  • Time stamping in all detector systems to handle high background levels

• The starting point: ILC detector designs - Optimized for Particle Flow: Meet already most of the performance requirements (with the exception of high energy jets) - Specific modifications:
  • Increased depth of calorimeters - More compact absorbers
  • Changed vertex detector geometry
  • Increased mechanical stabilization of final focusing elements - small beam size!
  • Redesigned forward region - not discussed here
  • Time stamping on the few ns level in all detector systems to reduce background
  • Use of time information in Particle Flow Algorithms to reduce background
Outlook: R&D Challenges for CLIC Detector Systems

• Vertex detector:
  Combine extremely low mass and low power with time stamping
  Power pulsing very likely indispensable to achieve the mass and power goals

• Calorimeters:
  Explore tungsten as absorber material for the barrel HCAL
  Time stamping in the calorimeters - Coming with the new generation of CALICE Electronics

• Mechanics:
  Active and passive stabilization of beam focusing elements

• Magnets:
  Develop conductors suited for a compact large-bore 5T solenoid
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... several talks on some of these issues at this conference!