Conformal Tracking for all-silicon trackers at future electron-positron colliders

Erica Brondolin (CERN)
erica.brondolin@cern.ch

Seminar at Bristol University - 5th February 2020
Outline

- **Overview**
  Future $e^+e^-$ colliders, detector requirements, tracking challenges

- **Conformal Tracking**
  Conformal mapping, cellular track building and extension

- **Track reconstruction at CLIC**
  CLICdet tracker, event simulation, performance

- **Next steps and conclusions**
Future high-energy $e^+e^-$ colliders

**Future Circular Collider (FCC-ee)**
- CERN
- $e^-e^+$, $\sqrt{s}$: 90 - 365 GeV (followed by pp, $\sqrt{s}$: ~100 TeV)
- Circumference: 97.75 km

**International Linear Collider (ILC)**
- Japan (Kitakami)
- $e^-e^+$, $\sqrt{s}$: 250 GeV (500 GeV)
- Length: 17 km (31 km)

**Compact Linear Collider (CLIC)**
- CERN
- $e^-e^+$, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
- Length: 11 km, 29 km, 50 km

**Circular Electron Positron Collider (CEPC)**
- China
- $e^-e^+$, $\sqrt{s}$: 90 – 240 GeV (followed by pp, $\sqrt{s}$: ~100 TeV)
- Circumference: ~100 km
Circular vs. linear $e^+e^-$ colliders

**Circular colliders**
- Can accelerate beam in many turns
- Can collide beam many times
- Possibility of **several interaction regions**
- Limited energy due to **synchrotron radiation**
  - $m_p/m_e \approx 2000$
  - Synchrotron radiation $\sim E^4/(m^4 \cdot \text{Radius})$
- **Beam strahlung**

**Linear colliders**
- One interaction region
- Operation in bunch trains
- **Very little synchrotron radiation**
- Can reach high energies
- Have to achieve energy in a **single pass**
  - High energy -> High acceleration gradients
  - High luminosity
    - Small beam size and high beam power
    - Beamstrahlung, energy spread

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Conformal Tracking for future $e^+e^-$ colliders

Bristol University, 5th Feb 2020
Future high-energy $e^+e^-$ colliders

- **Circular colliders:**
  - Large luminosity at lower energies
  - Luminosity decreases with energy

- **Linear colliders:**
  - Can reach the highest energies
  - Luminosity rises with energy
  - Beam polarisation at all energies

- **Circular & linear $e^+e^-$ colliders**
  - Comparable luminosities in overlap region (ZH, $tt$)

- **NB.** Peak luminosity at LEP2 (209 GeV) was $\approx 10^{32}\text{cm}^{-2}\text{s}^{-1}$
## CC experimental conditions

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>FCC-ee (97.8 km)</th>
<th>CEPC (100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>91.2</td>
<td>160</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{34}$/cm²·s</td>
<td>230</td>
<td>28</td>
</tr>
<tr>
<td>Bunches/beam</td>
<td></td>
<td>16 640</td>
<td>2 000</td>
</tr>
<tr>
<td>Bunch sep.</td>
<td>ns</td>
<td>20</td>
<td>163</td>
</tr>
<tr>
<td>Beam $\sigma_{xy}$, IP</td>
<td>nm/nm</td>
<td>6.4/28</td>
<td>13/41</td>
</tr>
<tr>
<td>Synch. rad. power</td>
<td>MW</td>
<td>$\leq 50$</td>
<td>$\leq 50$</td>
</tr>
</tbody>
</table>

### At $Z$ peak, high luminosity combined with high $e^+e^-$ cross section
- Achieve very low statistical uncertainties ($\sim 10^{-4} - 10^{-5}$)
  - Drives detector performance req. to match systematic uncertainties
- High number of bunches and small distance between bunches
- Very high data rates (physics rates 100 kHz)
  - Triggerless readout can still be possible

### Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Mitigated through machine-detector interface design and detector design

### Properties and Units

<table>
<thead>
<tr>
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<th>CEPC (100 km)</th>
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<tbody>
<tr>
<td>Z</td>
<td></td>
<td>Z (2T)</td>
<td>WW</td>
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<tr>
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<td>WW</td>
<td>ZH</td>
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<tr>
<td>ZH</td>
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<td>ZH</td>
<td></td>
</tr>
<tr>
<td>tt</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $\sqrt{s}$: Energy in GeV
- Luminosity: $10^{34}$/cm²·s
- Bunches/beam: Number of bunches in a beam
- Bunch sep.: Bunch separation in ns
- Beam $\sigma_{xy}$, IP: Beam size in nm/nm
- Synch. rad. power: Synchrotron radiation power in MW
## LC experimental conditions

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>ILC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s</td>
<td>GeV</td>
<td>250</td>
<td>250(Upg.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>380(Upg.)</td>
</tr>
<tr>
<td>Site length</td>
<td>km</td>
<td>31</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.5/31</td>
<td>11.4</td>
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<tr>
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<td>11.4</td>
<td>29.0</td>
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<td></td>
<td>29.0</td>
<td>50.1</td>
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<tr>
<td>Luminosity</td>
<td>10^{34}/cm^{2} s</td>
<td>1.35</td>
<td>2.7/5.4</td>
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<td></td>
<td></td>
<td>1.8/3.6</td>
<td>1.5/3</td>
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<td></td>
<td></td>
<td>1.5/3</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Train rep. rate</td>
<td>Hz</td>
<td>5</td>
<td>5/10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>50/100</td>
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<td></td>
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<td>50</td>
</tr>
<tr>
<td>BX / train</td>
<td></td>
<td>1312</td>
<td>2625</td>
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<td></td>
<td></td>
<td>1312/2625</td>
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<td>0.0089/0.0078</td>
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<tr>
<td></td>
<td></td>
<td>0.0078</td>
<td>0.0178</td>
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<td></td>
<td></td>
<td>544/272</td>
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<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Beam σ_{xy}, IP</td>
<td>nm/nm</td>
<td>516/7.7</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>474/5.9</td>
<td>149/2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>149/2.9</td>
<td>-60/1.5</td>
</tr>
<tr>
<td></td>
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<td>-60/1.5</td>
<td>-40/1</td>
</tr>
<tr>
<td>Beam σ_{z}, IP</td>
<td>µm</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>70</td>
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<tr>
<td></td>
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<td>70</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>44</td>
<td>44</td>
</tr>
</tbody>
</table>

ILC: Crossing angle 14 mrad, electron polarization ±80%, positron polarization ±30%,
CLIC: Crossing angle 20 mrad, electron polarization ±80%, upgrade positron polarization
Linear colliders operate in **bunch trains**: 

- Low duty cycle
- Possibility of power pulsing of detectors and triggerless readout
- Bunch separation → Impact on detector design (timing, granularity)

**Example: CLIC@3TeV**

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<table>
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<th>Bunch sep.</th>
<th>Beam $\sigma_{xy}$, IP</th>
<th>Beam $\sigma_z$, IP</th>
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<tr>
<td></td>
<td>ns</td>
<td>nm/nm</td>
<td>µm</td>
</tr>
<tr>
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<td>3.6</td>
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<td>300</td>
</tr>
<tr>
<td>CLIC</td>
<td>7.2</td>
<td>516/7.7</td>
<td>300</td>
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<tr>
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<td>3.6/7.2</td>
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<td>300</td>
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<td>ns</td>
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<td>Beam σₓᵧ, IP</td>
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<tr>
<td>Beam σ², IP</td>
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#### Example

**Incoherent e⁺e⁻ pairs** → beamstrahlung

\[ \gamma \gamma \rightarrow \text{hadrons} \]

- CLICcap: 3 TeV
- γγ → hadrons

![Beamstrahlung Diagram](image)

#### Detector Requirements for Future High-Energy Collider Experiments

- Eva Sicking - 27th Jan 2020
Detector requirements

Physics analysis requirements:

- Momentum resolution
  - e.g. Higgs coupling to muons, leptons from BSM
  - $\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1}$ above 100 GeV
- Jet energy resolution
  - e.g. separation of W/Z/H di-jets
  - $\sigma_E/E \sim 5\% - 3.5\%$ for jets at 50 GeV – 1000 GeV
- Impact parameter resolution
  - e.g. b/c-tagging, Higgs couplings
  - $\sigma_{r\phi} \sim a \oplus b / (p[\text{GeV}] \sin^{3/2} \theta) \mu\text{m}$
    - with $a = 5 \mu\text{m}$, $b = 15 \mu\text{m}$
- Angular coverage
  - Very forward electron and photon tagging
  - Down to $\theta = 10$ mrad ($\eta = 5.3$)
Detector requirements

Physics analysis requirements:

- Momentum resolution
  - e.g. Higgs coupling to muons, leptons from BSM
  - $\sigma_{p_T}/p^2_T \sim 2 \times 10^{-5}$ GeV$^{-1}$ above 100 GeV

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    with $a = 5 \text{ \(\mu\text{m}\)}$, $b = 15 \text{ \(\mu\text{m}\)}$

- Angular coverage
  - Very forward electron and photon tagging
  - Down to $\theta = 10 \text{ mrad}$ ($\eta = 5.3$)

+ Requirements from beam structure and beam-induced background

Example: Higgs $\rightarrow \mu^\pm\mu^\mp$ @3TeV

Example: W/Z separation
Detector requirements

Physics analysis requirements:
- Momentum resolution
  - e.g. Higgs coupling to muons, leptons from BSM
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  - $\sigma_{r\phi} \sim a \oplus b / (p[GeV] \sin \theta/2)$ μm
  - with $a = 5$ μm, $b = 15$ μm
- Angular coverage
  - Very forward electron and photon tagging
  - Down to $\theta = 10$ mrad ($\eta = 5.3$)

+ Requirements from beam structure and beam-induced background

Differences between ILC, CLIC, FCC-ee, CEPC requirements rather small

Impact on detector designs:
- Shielding
- Granularity
- Timing
- Cooling

Example: Higgs → $\mu^-\mu^+$ @3TeV

Example: W/Z separation
Tracking challenges

- #reco tracks without (with) background ~ $O(100)$ $O(500-1000)$

- **Physics requirements:**
  - Momentum resolution
  - Impact parameter resolution
  - Best possible angular coverage
  - Beam structure
  - Background rejection

- **Tracker requirement:**
  - Low material budget tracker
  - High spatial resolution
  - Low occupancy ~3% → High granularity
  - No or $O(1\text{ ns})$ timing requirement
Tracking challenges

- #reco tracks without (with) background ~ $O(100)$ $O(500-1000)$

- Physics requirements:
  - Momentum resolution
  - Impact parameter resolution
  - Best possible angular coverage
  - Beam structure
  - Background rejection

- Detector technologies:
  - strong R&D programme

- Software reconstruction:
  - flexible and efficient tracking algorithm

- Computing infrastructure:
  - computing resources

- Tracker requirements:
  - Low material budget
  - High spatial resolution
  - Low occupancy ~3% → High granularity
  - No or $O(1\text{ ns})$ timing requirement

Example: CLIC@3TeV
Proposed $e^+e^-$ collider detectors

$E_{CM}$ up to 3 TeV
3.5 - 5 T solenoids

CLIC: CLICdet

CLIC: CLICdet

$E_{CM}$ up to 365 GeV
2 - 3 T solenoids

FCC-ee: CLD

FCC-ee & CEPC: IDEA

ILC: SiD

ILC: ILD

CEPC: APIDOS

E CM up to 3 TeV
3.5 - 5 T solenoids

$E_{CM}$ up to 365 GeV
2 - 3 T solenoids
Proposed $e^+e^-$ collider detectors

- **E_{CM} up to 3 TeV**
  - 3.5 - 5 T solenoids
  - CLIC: CLICdet
  - ILC: SiD
  - ILC: ILD

- **E_{CM} up to 365 GeV**
  - 2 - 3 T solenoids
  - FCC-ee: CLD
  - CEPC: APIDOS

Track reconstruction software:
- Flexible (different geometries, ...)
- Robust (different beam-backgrounds, ...)
- All-silicon tracker
Conformal Tracking for future e⁺e⁻ colliders

Erica Brondolin (erica.brondolin@cern.ch)

Bristol University, 5th Feb 2020
Conformal Mapping

- The conformal mapping method is based on the fact that circles passing through the origin of a coordinate system xy can be translated onto straight lines in a new coordinate system uv

\[ u = \frac{x}{x^2 + y^2} \quad v = \frac{y}{x^2 + y^2} \]
The conformal mapping method is based on the fact that circles passing through the origin of a coordinate system xy can be translated onto straight lines in a new coordinate system uv

\[ u = \frac{x}{x^2 + y^2} \quad v = \frac{y}{x^2 + y^2} \]
Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
  - Extension of cellular track candidates
Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
- Two steps:
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1) Define seed hits
Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
  - Extension of cellular track candidates

2) Create cellular track candidate
- Define hit neighbour \((\Delta \theta, \Delta z)\)
Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
  - Extension of cellular track candidates

2) Create cellular track candidate

- Define hit neighbour ($\Delta \theta, \Delta z$)
- Seed cell is created if hit neighbour:
  - not lie in same det layer
  - located at smaller conf radius
  - hit not used already in other cellular track
- Cell is created with associated weight
  - subsequent link increments the weight by 1
- Cell can be discarded, if too long in uv
Cellular tracks reconstruction

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- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
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  - subsequent link increments the weight by 1
- Cell can be discarded, if too long in uv
- Seed cell is extrapolated along seed direction
Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
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- Two steps:
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Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
  - Extension of cellular track candidates

3) Select best candidates
- Starting from higher weight back to the seed cell
  - For all cellular tracks stemming from the seed hit
    - Hits progressively removed one by one
    - Linear regression fit in (u,v) $\chi^2_{uv}/\text{ndf}$
    - Linear regression fit in (s,z) $\rightarrow \chi^2_{sz}/\text{ndf}$
    - Where s is arc segment along the helix
    - Reject or accept hit according to total $\chi^2_{tot}$
- Clone treatment
  - Clones if #overlapping hits >= 2
  - Longest track is kept
  - If same length, small $\chi^2_{tot}$

4) Mark hits in cellular track as used
Cellular tracks reconstruction

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
  - Extension of cellular track candidates

1) Estimation of $p_T$ with conformal formulas
2) Tracks with higher-$p_T$ are extended first
   - Similar process than building (search for neighbours layer by layer)
   - Best hit is chosen based on smallest $\chi^2_{\text{tot}}$
   - Mark hits as used
3) Tracks with lower $p_T$
   - All hits are used (no cut in $\theta$)
   - Quadratic terms in $\chi^2_{uv}$ fit added
Track reconstruction at CLIC
The CLICdet tracker

- Superconducting solenoid with 4T magnetic field
- Vertex detector
  - 25 × 25 µm² pixels
  - 3 double layers in barrel
  - Spiral arrangement in forward region
  - Air cooling
  - Extremely accurate and light:
    - Single point resolution = 3 µm
    - Material Budget < 0.2 % $X_0$ per layer
- Silicon Tracker
  - Large pixels/strips
  - Outer R ~ 1.5 m
  - Single point resolution = 7 µm × 90 µm
  - Material budget:
    - Detector: ~1%$X_0$ per layer
    - Support & cables: ~2.5%$X_0$
  - Precise timing for background rejection:
    - < 10 ns hit time-stamping in tracking
- Full simulation with DD4hep geometry
The CLICdet tracker

- Superconducting solenoid with 4T magnetic field
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- Full simulation with DD4hep geometry
How does an “event” look like?

Event display

\[ e^+e^- \rightarrow tt \text{ at } 380 \text{ GeV} \]

+ Background overlay

(10 (20) BX before (after) physics event)
How does an “event” look like?

Event display
\(e^+e^- \rightarrow tt \ @ \ 3 \ TeV\)
+ Background overlay
(10 (20) BX before (after) physics event)
Conformal tracking in CLICdet

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Hit collection</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build tracks</td>
<td>Vertex barrel</td>
<td>Standard cuts</td>
</tr>
<tr>
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- **5 steps targeting prompt-tracks:**
  - From vertex detector to silicon tracker
  - Min number of hits = 4
  - Standard or looser (angle or \(\chi^2\)) cuts
- **1 step targeting displaced tracks:**
  - Quadratic terms in conformal space fit added
  - Inverted order search: from silicon tracker to vertex detector
  - Broader search angle than for prompt tracks
  - Min number of hits = 5

---

Erica Brondolin (erica.brondolin@cern.ch)  
Conformal Tracking for future e^+e^- colliders  
Bristol University, 5th Feb 2020
Conformal tracking in CLICdet

<table>
<thead>
<tr>
<th>Algorithm</th>
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Conformal Tracking for future $e^+e^-$ colliders

Bristol University, 5th Feb 2020
Track fitting and selection

- **Track fit**
  - It consists of a Kalman filter (KF) and smoother in global coordinate space
  - **Pre-fit step:**
    - Helix prefit with three hits (first, middle, last) gives track state to initialize fit
  - KF fit proceeds forward
    - Hits added one by one
    - Hit is acceptance/rejected based on a $\chi^2$ cut
    - Only in the case of failed fit, the KF is tried again in a backward fashion
  - Packages used:
    - KalTest: iterative Kalman filter
    - DDKalTest: DD4hep - KalTest = interface to provide surfaces

- **Track selection**
  - Clone treatment is repeated one last time
  - Minimum number of hits = 4
Performance
Performance (some definitions)

**Associated** particle = Simulated MC particle from which the majority of track hits are originated

**Reconstructable** particle = stable MC particle with following requirements:
- $p_T > 0.1$ GeV
- $|\cos\theta| < 0.99$
- unique hits ≥ 4

**Purity** = Number of track hits associated to the same MC particle
- **Pure track** if purity ≥ 75 %
- **Fake track** if purity < 75%

**Efficiency** = $\frac{\text{#pure tracks associated to MC particle}}{\text{#reconstructable MC particles}}$

**Fake rate** = $\frac{\text{#fake reconstructed tracks}}{\text{#reconstructed tracks}}$
Performance for isolated particles

Isolated muons

- Tracking fully efficient in the entire tracker volume and at any transverse momentum more than 0.1 GeV
Performance for isolated particles

Isolated electrons

- Tracking fully efficient in the entire tracker volume and at any transverse momentum more than 0.1 GeV

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Conformal Tracking for future $e^+e^-$ colliders

Bristol University, 5th Feb 2020
Performance for isolated particles

**Isolated pions**

- Tracking fully efficient in the entire tracker volume and at any transverse momentum more than 0.1 GeV
**Isolated muons, displaced**

Tracks generated uniformly along y-axis with given opening angle

- Tracking fully efficient down to 340 mm
- Sharp drop expected due to the requirement on the number of hits
- Full coverage for b-decay

vertex $R = \text{particle production vertex radius}$
Performance for isolated particles

Isolated muons

- Very good agreement with target values of required physics performance
Performance for isolated particles

Isolated muons, detector optimisation

Conformal Tracking for future e+e− colliders

Erica Brondolin (erica.brondolin@cern.ch)

Bristol University, 5th Feb 2020
Performance for complex events

- Similar performance w/ and w/o background
- Efficiency > 98% in the entire tracker volume
- Fully efficient for simulated MC particles with $p_T > 1$ GeV
- Efficiency > 90% down to 200 MeV
Performance for complex events

**tt events @ 3 TeV**

- Similar performance w/ and w/o background
- Fully efficient in vertex region
- 1% inefficiency for very small distance between particles

\[ \Delta_{MC} \text{ [rad]} \]

\[ \text{vertex } R = \text{ particle production vertex radius} \]

\[ \Delta_{MC} = \text{ minimum distance between particle associated to the track and any other} \]
Performance for complex events

**tt events @ 3 TeV**

- Similar performance w/ and w/o background
- Fake rate about per-cent level
- Small increase for tracks with low $p_T$
Performance for complex events

di-jet events @ 500 GeV

- Reconstructed tracks and Pandora Particle Flow Objects (PFOs) are used as input to the vertex reconstruction and jet clustering.
- For CLICdet, LCFIPlus software package is used for the vertex fitting, jet clustering and flavor tagging.

Erica Brondolin (erica.brondolin@cern.ch)

Conformal Tracking for future $e^+e^-$ colliders

Bristol University, 5th Feb 2020
## CPU execution time

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</tr>
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</table>

One core used with 27.5 DB12 machine

Average of 25 event of single tt without (with) overlay:
- #reco tracks = ~ 90 (550)
- ~10 sec (~340 sec) for single tt event without (with) overlay

- For events **without** overlay, the **KF filter** is the most time consuming part
- For events **with** overlay, the **build tracks** step is the most time consuming part
- **Step 5** is the most time consuming part:
  - For events without overlay, ½ of total build tracks process
  - For events with overlay, ¾ of total build tracks process
Conformal tracking @ CLD

- CLD detector configuration
  - Smaller magnetic field 4 T → 2 T
  - Larger tracker 1.5 m → 2.15 m
  - Smaller beam-pipe 29 mm → 15 mm
- Tuning pattern recognition parameters
- Using DD4hep detector description
Next steps

- Conformal tracking completed its **initial phase**

- Further developments and ideas:
  - Non-homogeneous magnetic field
  - Soft hit-to-track assignment
  - Test performance w/ other backgrounds
  - Further CPU time optimisation
    - Multi-core usage mode
    - Tuning of parameters for displaced and low $p_T$ particles
  - Hit time information in pattern recognition
  - ...

Erica Brondolin (erica.brondolin@cern.ch)

Conformal Tracking for future e$^+e^-$ colliders

Bristol University, 5$^{th}$ Feb 2020
Summary & conclusions

- Future $e^+e^-$ colliders tracking challenges are fertile ground for new ideas:
  - Physics requirements are interesting
  - Beam-induced background not negligible
  - Moreover, detector is available in full simulation

- The conformal tracking provides robust solution for pattern recognition
  - Works in single particle as well as complex events
  - Performs well with displaced tracks
  - Can cope successfully with beam induced backgrounds

- The conformal tracking is flexible
  - Successfully handles different detector geometries
  - Possible to include new iteration easily

- Comprehensive article published recently:
Backup

“My own visions of CLIC”, artwork by Natasha de Heney, 2010
The CLIC project

- **CLIC = Compact Linear Collider**
- **High-energy linear e^+e^- collider**
- **CLIC would be implemented in three energy stages (7-8 years each)**
  - Centre-of-mass energy from 380 GeV up to 3 TeV
  - Constructing next stage while taking data with current stage

- **Physics programme extends over 25–30 years:**
  - Precision measurement of Higgs boson and top quark
  - Precision measurement of new physics (discovered at LHC, CLIC, ...)
  - Search for physics Beyond Standard Model (BSM)

Possibility to adapt the stages to new LHC discovery!
CLIC staging

- **Electron polarisation:**
  - ±80% longitudinal polarization for the electron beam
  - Enhances Higgs production at high-energy stages
  - Helps to characterise new particles in case of discovery

- **Luminosity spectrum:**
  - Effect is dependent on $\sqrt{s}$
  - Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
  - Most of the analyses use the entire lumi spectrum

- **Baseline scenario:**

  ![Baseline scenario diagram](image-url)
## Challenges for Vertex & Tracker

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Compact Linear Collider</th>
<th>(HL-) LHC (ATLAS/CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material budget (barrel)</td>
<td>1 – 2% X0 (vertex)</td>
<td>10 – 15% X0 (vertex)</td>
</tr>
<tr>
<td></td>
<td>8 – 15% X0 (tracker)</td>
<td>30 – 40% X0 (tracker)</td>
</tr>
<tr>
<td>Single-point resolution</td>
<td>3 µm (vertex)</td>
<td>5 µm (vertex)</td>
</tr>
<tr>
<td></td>
<td>7 µm (tracker)</td>
<td>30 µm (tracker)</td>
</tr>
<tr>
<td>Time resolution</td>
<td>5 ns</td>
<td>25 ns (1 BX)</td>
</tr>
<tr>
<td>Tracking acceptance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. granularity (occupancy)</td>
<td>≤ 25 µm x 100 µm</td>
<td>50 µm x 50 µm</td>
</tr>
<tr>
<td>Active area</td>
<td>~1 m² / ~137 m²</td>
<td>~5 - 10 m² / ~200 m²</td>
</tr>
<tr>
<td>Radiation tolerance</td>
<td>&lt; 10¹¹ n_{eq} / cm² (vertex)</td>
<td>O(10¹⁶ n_{eq} / cm²) (vertex)</td>
</tr>
</tbody>
</table>
Hybrid pixel detectors

- Sensor and readout chip developed independently
- Small pixel cell sizes achievable down to 25μm
- Extensive functionality w/ mixed CMOS circuits
- Bump bonding
  - Cost-driving factor on detector production
  - Limiting factor for the pixel pitch
  - Limiting factor for device thickness: stability

Monolithic pixel detectors

- Sensor and readout produced together
- Example shown here: “High-Resistivity CMOS Sensors”
- Suitable for large-scale systems
- Low material budget, no bump-bonding
  - Facilitated production and reduced cost
- Additional engineering required to separate bias voltage from CMOS voltage
The CLICpix2 prototype

- Example of hybrid pixel detector
- Readout ASIC to meet CLIC vertex requirements
- Timepix/Medipix chip family
  - 128 x 128 pixels (3.2 x 3.2 mm² active area)
  - 65nm CMOS, 25μm x 25μm pitch
  - Per-pixel 5-bit ToT and 8-bit ToA

- Challenge: single-chip bonding of sensors with 25μm pitch
- Promising results from first beam tests
  - Spatial resolution $\sigma_x \sim 5$ μm (130 μm sensor thickness), characterization ongoing
- However, with thin sensors (50 μm) target resolution of 3 μm not achievable at 25 μm pitch
The CLICTD prototype

- Example of monolithic pixel detector
- Fully-integrated sensor for CLIC Tracking Detector
- 180 nm CMOS + High-Resistivity (HR) epitaxial layer
  - 16 x 128 pixels (4.8 x 3.84 mm$^2$ active area)
  - Geometry with 8 sub-pixels with 30 μm x 37.5 μm pitch each
  - Per-pixel 5-bit ToT and 8-bit ToA
- Just finished first test beam campaign at DESY
  - Very successful – correlations (space and time) from day 1
  - Currently analyzing data

Online DQM
Power and energy

- Power estimate redone bottom-up for 380GeV CLIC
- Total power: **168 MW**
- Much reduced compared with CDR, from optimised drive-beam complex, more efficient klystrons and injectors, and better estimates of nominal conditions

- CERN’s current energy consumption is approximately 1.2 TWh per year (LHC accounts for 90%)
Cost

- Machine recosted bottom-up in 2017–18
- Total cost for 380 GeV stage: **5.9 BCHF**
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of main linac)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of main linac)

<table>
<thead>
<tr>
<th>System</th>
<th>Cost fraction</th>
<th>Cost[MCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Silicon Tracker</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>Electromagnetic Calorimeter</td>
<td></td>
<td>180</td>
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<tr>
<td>Hadronic Calorimeter</td>
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<td>39</td>
</tr>
<tr>
<td>Muon System</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Coil and Yoke</td>
<td></td>
<td>95</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>397</strong></td>
</tr>
</tbody>
</table>

| Main-Beam Production          |               |            |
| Injectors                     |               | 175        |
| Damping Rings                 |               | 309        |
| Beam Transport                |               | 409        |
| Drive-Beam Production         |               |            |
| Injectors                     |               | 584        |
| Frequency Multiplication      |               | 379        |
| Beam Transport                |               | 76         |
| Main Linac Modules            |               |            |
| Main Linac Modules            |               | 1329       |
| Post decelerators             |               | 37         |
| Main Linac RF                 |               |            |
| Main Linac Xband RF           |               |            |
| Beam Delivery and Post        |               |            |
| Delivery Systems              |               | 52         |
| Final focus, Exp. Area        |               | 22         |
| Post-collision lines/dumps    |               | 47         |
| Civil Engineering             |               |            |
| Electrical distribution       |               | 243        |
| Survey and Alignment          |               | 194        |
| Cooling and ventilation       |               | 443        |
| Transport / installation      |               | 38         |
| Machine Control, Protection   |               |            |
| and Safety systems            |               |            |
| Safety systems                |               | 72         |
| Machine Control Infrastructure|               | 146        |
| Machine Protection            |               | 14         |
| Access Safety & Control System|               | 23         |
| **Total (rounded)**           |               | **5890**   |
Schedule

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, pre-series and system optimisation studies, 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

2020
Update of the European Strategy for Particle Physics

2026
Ready for construction

2035
First collisions
A landscape for colliders in Europe

<table>
<thead>
<tr>
<th></th>
<th>2020-2040</th>
<th>2040-2060</th>
<th>2060-2080</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>1st gen technology</strong></td>
<td><strong>2nd gen technology</strong></td>
</tr>
<tr>
<td>CLIC-all</td>
<td>HL-LHC</td>
<td>CLIC380-1500</td>
<td>CLIC3000 / other tech</td>
</tr>
<tr>
<td>CLIC-FCC</td>
<td>HL-LHC</td>
<td>CLIC380</td>
<td>FCC-h/e/A (Adv HF magnets) / other tech</td>
</tr>
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<td>FCC-all</td>
<td>HL-LHC</td>
<td>FCC-ee (90-365)</td>
<td>FCC-h/e/A (Adv HF magnets) / other tech</td>
</tr>
<tr>
<td>LE-to-HE-FCC-h/e/A</td>
<td>HL-LHC</td>
<td>LE-FCC-h/e/A (low-field magnets)</td>
<td>FCC-h/e/A (Adv HF magnets) / other tech</td>
</tr>
<tr>
<td>LHeC-FCC-h/e/A</td>
<td>HL-LHC + LHeC</td>
<td>LHeC</td>
<td>FCC-h/e/A (Adv HF magnets) / other tech</td>
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- All elements related to the CLIC, FCC and LHeC proposals are discussed in their CDRs.
- The LE-to-HE-FCC-h/e/A scenario moves from initially lower-field magnets to higher-field magnets, potentially HTS magnets.
- The LHeC+FCC-h/e/A scenario includes the LHeC and foresees FCC-h/e/A at a later stage directly with high-field magnets.
CLIC input to European Strategy Update

- Yellow Reports:
  - CLIC 2018 Summary Report
  - CLIC Project Implementation Plan
  - The CLIC Potential for New Physics
  - Detector technologies for CLIC

- Two formal ESU submissions:
  - Physics Potential
  - Accelerator and Detector

- Many more Journal publications and CLICdp Notes

- Full list can be found in: [http://clic.cern/european-strategy](http://clic.cern/european-strategy)