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

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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, $\sqrt{s}: \sim 100$ 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, $\sqrt{s}: \sim 100$ TeV)
- Circumference: $\sim 100$ km

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

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Bristol University, 5th Feb 2020
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 $\rightarrow$ High acceleration gradients
  - High luminosity
    - Small beam size and high beam power
    - Beamstrahlung, energy spread
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

| Property          | Unit | FCC-ee (97.8 km) | CEPC (100 km) |
|-------------------|------|------------------|---------------|
| $\sqrt{s}$       | GeV  | Z  | WW | ZH | tt | Z (2T) | WW | ZH |
|                   |      | 91.2 | 160 | 240 | 365 | 91 | 160 | 240 |
| Luminosity        | $10^{34}$/cm$^2$ s | 230 | 28 | 8.5 | 1.55 | 32.1 | 10.1 | 2.93 |
| Bunches/beam      |      | 16 640 | 2 000 | 393 | 48 | 12 000 | 1 524 | 242 |
| Bunch sep.        | ns   | 20 | 163 | 994 | 3396 | 25 | 210 | 680 |
| Beam $\sigma_{xy}$, IP | nm/nm | 6.4/28 | 13/41 | 14/36 | 38/68 | 6/40 | 13.9/49 | 20.9/68 |
| Synch. rad. power | MW   | $\leq$ 50 | $\leq$ 50 | $\leq$ 50 | $\leq$ 50 | 16.5 | 30 | 30 |

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
## LC experimental conditions

| Property          | Unit     | ILC              | CLIC       |
|-------------------|----------|------------------|------------|
| $\sqrt{s}$        | GeV      | 250              | 500        |
| Site length       | km       | 31               | 20.5       |
|                   |          | 20.5/31          | 11.4       |
| Luminosity        | $10^{34}$/cm$^2$ s | 1.35      | 2.7/5.4  |
|                   |          | 1.8/3.6          | 1.5/3      |
| Train rep. rate   | Hz       | 5                | 5/10       |
|                   |          | 5                | 50/100     |
| BX / train        |          | 1312             | 2625       |
|                   |          | 1312/2625        | 356        |
| Duty cycle        |          | 3.6              | 7.2        |
|                   |          | 3.6/7.2          | 0.0089/0.0078 |
| Bunch sep.        | ns       | 544              | 272        |
|                   |          | 544/272          | 0.5        |
| Beam $\sigma_{xy}$, IP | nm/nm | 516/7.7          | 516/7.7   |
|                   |          | 474/5.9          | 149/2.9   |
| Beam $\sigma_z$, IP | µm      | 300              | 300        |
|                   |          | 300              | 70         |

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)

### Property

| Unit  | ILC  | CLIC (Upg.) |
|-------|------|-------------|
| $\sqrt{s}$ | 250 GeV | 500 GeV |
| Site length | 31 km | 20.5 km |
| Luminosity | $10^{34}$/cm$^2$ s | $2.7/5.4 \times 10^{34}$/cm$^2$ s |
| Train rep. rate | 5 Hz | 50 Hz |
| BX / train | 1312 | 2625 |

### Duty cycle

| ns  | ILC | CLIC (Upg.) |
|-----|-----|-------------|
| 3.6 | 7.2 | 3.6/7.2 |
| Bunch sep. | 544 | 544/272 |
| Beam $\sigma_{xy}$, IP | 516/7.7 | 474/5.9 |
| Beam $\sigma_z$, IP | 300 | 300 |

| 0.0089/0.0078 | 0.0078 | 0.0178 |
| 0.5 | 0.5 | 0.5 |

ILC: Crossing angle 14 mrad, electron polarization $\pm$80%, positron polarization $\pm$30%
CLIC: Crossing angle 20 mrad, electron polarization $\pm$80%, upgrade positron polarization
| Property             | Unit | ILC | CLIC |
|---------------------|------|-----|------|
| √s                  | GeV  | 250 | 380  |
| Site length         | km   | 31  | 20.5 |
| Luminosity          | 10^{34}/cm^{2}s | 1.35 | 2.7/5.4 |
| Train rep. rate     | Hz   | 5   | 10/50 |
| BX / train          |      | 1312 | 2625 |
| Duty cycle          |      | 3.6 | 7.2 |
| Bunch sep.          | ns   | 544 | 272 |

| Beam σ_{xy}, IP     | nm/nm | 516/7.7 | 516/7.7 | 474/5.9 | 149/2.9 | -60/1.5 | -40/1 |
| Beam σ_{z}, IP      | µm    | 300     | 300     | 300     | 70      | 44      | 44    |

- ILC: Crossing angle 14 mrad, electron polarization ±80%, positron polarization ±30%.
- CLIC: Crossing angle 20 mrad, electron polarization ±80%, upgrade positron polarization.

**Very small beams and high beam energy → beamstrahlung**

**Incoherent e^+e^- pairs**

**γγ → hadrons**

Example:

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
  - $\sigma_{p_T}/p^2_T \sim 2 \times 10^{-5} \text{GeV}^{-1}$ 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 $\theta = 10 \text{ mrad}$ ($\eta = 5.3$)

Example:
Higgs → $\mu^-\mu^+$ @3TeV

Example:
W/Z separation

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- Impact parameter resolution
  - e.g. b/c-tagging, Higgs couplings
  - $\sigma_{r\phi} \sim a \Theta b / (p[\text{GeV}] \sin^{3/2} \theta) \text{ \mu m}$
    with $a = 5 \text{ \mu m}$, $b = 15 \text{ \mu m}$
- 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: $Higgs \rightarrow \mu^- \mu^+$ @3TeV

Example: W/Z separation
Physics analysis requirements:

- Momentum resolution
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- Impact parameter resolution
  - e.g. b/c-tagging, Higgs couplings
  - $\sigma_{r\phi} \sim a \oplus b / (p[GeV] \sin \theta)^{3/2}$ 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

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

- **Detector technologies:**
  - strong R&D programme

- **Software reconstruction:**
  - flexible and efficient tracking algorithm

- **Computing infrastructure:**
  - computing resources

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

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

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

- **ILC**: SiD
- **ILC**: ILD
- **CEPC**: APIDOS

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

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Proposed $e^+e^-$ collider detectors

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

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

Track reconstruction software:
- Flexible (different geometries, …)
- Robust (different beam-backgrounds, …)
- All-silicon tracker
Conformal Tracking
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 $uv$

$$u = \frac{x}{x^2 + y^2}$$

$$v = \frac{y}{x^2 + y^2}$$
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 \( uv \):

\[
\begin{align*}
    u &= x / (x^2 + y^2) \\
    v &= y / (x^2 + y^2)
\end{align*}
\]

Conformal Tracking (CT)
Cellular Automaton-based track finding in conformal space

Github repo
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

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- Cellular tracks are vectors of cells
- Two steps:
  - Building of cellular track candidates
  - Extension of cellular track candidates

Seed hit

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

- Cell is a segment between two hits with a weight associated
- Cellular tracks are vectors of cells
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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

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  - Building of cellular track candidates
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Cellular tracks reconstruction

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- 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 \((u,v)\) \(\chi^2_{uv}/ndf\)
  - Linear regression fit in \((s,z)\) \(\rightarrow \chi^2_{sz}/ndf\)
    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

Compact Linear Collider

Conformal Tracking for future e+e− colliders
Erica Brondolin (erica.brondolin@cern.ch)
Bristol University, 5th Feb 2020
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 % X₀ per layer
- Silicon Tracker
  - Large pixels/strips
  - Outer R ~ 1.5 m
  - Single point resolution = 7 µm × 90 µm
  - Material budget:
    - Detector: ~1%X₀ per layer
    - Support & cables: ~2.5%X₀
  - Precise timing for background rejection:
    - < 10 ns hit time-stamping in tracking
- Full simulation with DD4hep geometry
The CLICdet tracker

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- Full simulation with DD4hep geometry
How does an “event” look like?

Event display

\[ e^+e^- \rightarrow tt \ @ \ 380 \ GeV \]
+ Background overlay
(10 (20) BX before (after) physics event)
How does an “event” look like?

Event display

{eq}e^+e^- \rightarrow tt \ @ 3 \ TeV\)

+ Background overlay

(10 (20) BX before (after) physics event)
Conformal tracking in CLICdet

| Algorithm     | Hit collection | Configuration          |
|---------------|----------------|------------------------|
| Build tracks  | Vertex barrel  | Standard cuts          |
| Extend tracks | Vertex endcap  | Standard cuts          |
| Build tracks  | Vertex         | Looser cuts (angle x 5) |
| Build tracks  | Vertex         | Looser cuts (angle x 10; $\chi^2$ x 20) |
| Extend tracks | Tracker        | Looser cuts (angle x 10; $\chi^2$ x 20) |
| Build tracks  | Vertex + Tracker | Displaced cuts       |

- **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
Conformal tracking in CLICdet

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
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 \( \geq 4\)

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

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

\[
\text{Fake rate} = \frac{\text{#fake reconstructed tracks}}{\text{#reconstructed tracks}}
\]
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
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 = 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
Performance for complex events

tt events @ 3 TeV

- 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
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 $p_T$

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Performance for complex events

- 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.
### CPU execution time

| Algorithm      | Hit collection | Configuration               |
|----------------|----------------|------------------------------|
| Build tracks   | Vertex barrel  | Standard cuts                |
| Extend tracks  | Vertex endcap  | Standard cuts                |
| Build tracks   | Vertex         | Looser cuts (angle x 5)      |
| Build tracks   | Vertex         | Looser cuts (angle x 10; $\chi^2$ x 20) |
| Extend tracks  | Tracker        | Looser cuts (angle x 10; $\chi^2$ x 20) |
| Build tracks   | Vertex + Tracker | Displaced cuts              |

- 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, $\frac{1}{2}$ of total build tracks process
  - For events with overlay, $\frac{3}{4}$ of total build tracks process

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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
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

arXiv:1911.12230
CLD - A Detector Concept for the FCC-ee
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
  - ...
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: doi:10.1016/j.nima.2019.163304
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:**

  ![Graph showing CLIC stages and physics](image)
# Challenges for Vertex & Tracker

|                         | **Compact Linear Collider** | **(HL-) LHC (ATLAS/CMS)** |
|-------------------------|-----------------------------|---------------------------|
| **Material budget (barrel)** | 1 – 2% X0 (vertex)           | 10 – 15% X0 (vertex)      |
|                         | 8 – 15% X0 (tracker)        | 30 – 40% X0 (tracker)     |
| **Single-point resolution** | 3 µm (vertex)               | 5 µm (vertex)             |
|                         | 7 µm (tracker)              | 30 µm (tracker)           |
| **Time resolution**     | 5 ns                        | 25 ns (1 BX)              |
| **Tracking acceptance** | |                           |
|                         | |                           |
| **Min. granularity (occupancy)** | ≤ 25 µm x 100 µm           | 50 µm x 50 µm             |
| **Active area**         | ~1 m² / ~137 m²             | ~5 - 10 m² / ~200 m²      |
| **Radiation tolerance** | < $10^{11}$ n_{eq} / cm² (vertex) | O($10^{16}$ n_{eq} / cm²) (vertex) |
Pixel detectors technologies

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
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)

| System                          | Cost fraction | Cost [MCHF] |
|---------------------------------|---------------|-------------|
| Vertex                          | 13            | 11          |
| Silicon Tracker                 | 43            | 43          |
| Electromagnetic Calorimeter     | 180           | 180         |
| Hadronic Calorimeter           | 39            | 39          |
| Muon System                     | 16            | 16          |
| Coil and Yoke                   | 95            | 95          |
| Other                           | 11            | 11          |
| **Total**                       | **397**       | **397**     |

| System                          | Cost [MCHF] |
|---------------------------------|-------------|
| Main-Beam Production Injectors  | 175         |
| Main-Beam Production Damping Rings | 309        |
| Main-Beam Production Beam Transport | 409        |
| Drive-Beam Production Injectors | 584         |
| Drive-Beam Production Frequency Multiplication | 379        |
| Drive-Beam Production Beam Transport | 76          |
| Main Linac Modules Main Linac Modules | 1329        |
| Main Linac Modules Post decelerators | 37          |
| Main Linac RF Main Linac Xband RF | 0           |
| Beam Delivery and Post Collision Lines Beam Delivery Systems | 52          |
| Beam Delivery and Post Collision Lines Final focus, Exp. Area | 22          |
| Beam Delivery and Post Collision Lines Post-collision lines/dumps | 47          |
| Civil Engineering Civil Engineering | 1300        |
| Infrastructure and Services Electrical distribution | 243         |
| Infrastructure and Services Survey and Alignment | 194         |
| Infrastructure and Services Cooling and ventilation | 443         |
| Infrastructure and Services Transport / installation | 38          |
| Machine Control, Protection and Safety systems Safety systems | 72          |
| Machine Control, Protection and Safety systems Machine Control Infrastructure | 146         |
| Machine Control, Protection and Safety systems Machine Protection | 14          |
| Machine Control, Protection and Safety systems 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

|                | 2020-2040 | 2040-2060 | 2060-2080 |
|----------------|-----------|-----------|-----------|
| **1st gen technology** |           |           |           |
| CLIC-all       | HL-LHC    | CLIC380-1500 | CLIC3000 / other tech |
| CLIC-FCC       | HL-LHC    | CLIC380   | FCC-h/e/A (Adv HF magnets) / other tech |
| FCC-all        | HL-LHC    | FCC-ee (90-365) | FCC-h/e/A (Adv HF magnets) / other tech |
| LE-to-HE-FCC-h/e/A | HL-LHC   | LE-FCC-h/e/A (low-field magnets) | FCC-h/e/A (Adv HF magnets) / other tech |
| LHeC-FCC-h/e/A | HL-LHC    | + LHeC    | LHeC      | FCC-h/e/A (Adv HF magnets) / other tech |
|                |           |           |           |
| **2nd gen technology** |           |           |           |

- 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 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