All-silicon tracker concepts for future e+e- colliders - focus on CLD at FCC-ee -

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Introduction

- **Detector designs** for future e+e- colliders driven by **physics requirements** and experimental conditions

- **Physics requirements** depend on the *energy* and *luminosity* of the accelerator but in all future e+e- colliders they are similar in terms of outstanding precision
  - excellent momentum resolution, impact parameter resolution, jet energy resolution, flavour tagging, lepton identification
  - particle-flow-based designs push the tracking requirements to the limit

- **Experimental conditions** are based on the collider
  - general goal from a detector point of view: background rejection, limit occupancy
  - timing and $p_T$ information fundamental to reject background
All-silicon trackers

The challenges

- occupancy
- segmentation
- power consumption
- cooling

The guarantees

- compactness
- validated technology
- stability
- calibration
- redundancy

material budget

single point resolution

thick sensors (charge sharing)

“I suppose I’ll be the one to mention the elephant in the room.”
Content of this talk

1. CLD Tracker Concept
   - tracker design and optimization
   - tracker performance with low-level observables
   - cooling considerations
   - beam-background and data rate
   - tracking (detector and algorithm) performance with complex events

2. FST Tracker Concept
   - CEPC experimental conditions
   - tracking design and performance

3. Tracker Concepts at Linear Colliders
   - LC experimental conditions
   - CLICdet concept and performance
   - SiD concept and performance
CLD at FCC-ee

CLD is the all-silicon-tracker detector concept developed for FCC-ee

- adapted to B=2T, driven by 30 mrad beam crossing angle and vertical emittance
- respecting 150 mrad forward cone reserved for MDI elements
- built upon a 15 mm radius beam pipe

CLD Vertex Detector

3 double barrel layers + 3 double-layer disks per side
- radius of innermost layer = 17 mm
  - as low material budget as possible
  - sensitive thickness: 50 μm per layer
  - 0.6% $X_0$ per double layer
- pixel size 25 x 25 μm
- total sensitive area = 0.35 m$^2$

CLD Tracker

- Inner Tracker: 3 barrel layers + 7 forward disks per side
- Outer Tracker: 3 barrel layers + 4 forward disks per side
- outer radius = 2.1 m
- microstrips size (50 μm x 1-10 mm)
  - first inner tracker disk pixelated like vertex detector
- total sensitive area = 195.6 m²

- lightweight tracker:
  - sensitive thickness: 200 μm per layer
  - 1% $X_0$ per layer (sensitive + liquid cooling + connectivity) + 2.5% $X_0$ main support, cooling pipes, cabling routes

CLD Tracker Performance

all studies done in full simulation

Transverse impact parameter

Achieved desired transverse impact parameter resolutions for high-energy muons well below the high-momentum goal of 5 μm

Transverse momentum

Achieved transverse momentum resolution of ~7x10^-5 GeV^-1 for 45 GeV muons at normal incidence (corresponding to required accuracy for Z width measurements)

- curves do not saturate at high momenta => resolution affected by multiple scattering

CLD Tracker Optimization

Current CLD design straightforwardly adapted by rescaling the CLICdet from B=4T to B=2T.

Transverse momentum variation with outer tracker size:
- fast detector simulation and track reconstruction in LicToy
- reduced outermost layer radius and rescaled other layers

\[ R_{\text{max}} = 2.1 \text{ m (default)} \]

\[ R_{\text{max}} = 1.8 \text{ m} \]

With outer tracker radius of 1.8 m, achieved transverse momentum resolution \(~8 \times 10^{-5} \text{ GeV}^{-1}\) for 45 GeV muons at normal incidence (still within 100-200 MeV accuracy on muon momentum) required for point-to-point energy error in Z width measurements in Z scan.

Next step: study material budget reduction in the tracker in terms of best number of layers and location
CLD Tracker Occupancies

Once the beam pipe is shielded, the impact of SR photons on the detector is drastically reduced. The main source of background is the incoherent pairs produced in beamsstrahlung processes.

Impact on the vertex barrel at 365 GeV

Assumptions to calculate the occupancy:
- pixel (strip) size 25x25 $\mu$m$^2$ (0.05x1mm$^2$)
- cluster size = 5
- safety factor = 3

Worst scenario: using 10 $\mu$s integration time as from ALICE ITS Upgrade Technology

More on G. Voutsinas’ talk > https://indico.cern.ch/event/932973/contributions/4075874/

CLD Tracker Cooling Considerations

- In FCC-ee: continuous operation does not allow for power pulsing
- Impact of cooling and material depends on the technology choices
- ALICE ITS Upgrade technology
  => current amount of material in the vertex detector 0.3% $X_0$ per single layer

In case current amount of material is too optimistic, $d_0$ resolution probed with an additional 50% to the current thickness

Resolution for low-energy muons worsened only by ~15-20%

Figure 31: Impact parameter resolution as a function of polar angle (a) in the transverse and (b) in the longitudinal plane, for muon tracks with momenta of 1, 10 and 100 GeV. Empty markers refer to the baseline CLD vertex detector. Results shown with full markers are obtained with a detector model with the material budget in the vertex increased by 50% with respect to CLD.

Figure 32: (a) Polar and (b) azimuthal angular resolution as a function of polar angle for muon tracks with momenta of 1, 10 and 100 GeV. Both resolutions improve while moving from the forward to the transition region and then level up in the barrel. The only exception is the trend of the $\theta$ resolution for high energy muons, as it increases in the barrel region, where the single point resolution becomes dominant. For the high energy muons, the $\phi$ resolution reaches a minimum of 0.023 mrad in the barrel and the $\theta$ resolution reaches the same value in the transition region.

The $p_T$ resolution $\sigma(\Delta p_T/p_T^2)$ for single muons is determined from a single Gaussian fit of the distribution $(p_T^{MC} - p_T^{rec})/p_T^{2}$ and is shown in Figure 33 as a function of the momentum.
CLD Read-out Data Rate

- Current estimate of the data rate is based on several technology assumptions.

- At the Z pole:
  - Event rate to be read-out in the tracking system is dominated by Z production (~100 kHz)
  - For the vertex detector:
    - 160 hits on average from hadronic Z decays * 5 (cluster size) = 800 channels / evt
    - 50 hits/BX from incoherent pairs * 3 (safety factor) * 5 (cluster size) = 750 channels / BX
    - Assuming 1 μs integration time (~50 BXs) and 13 bits: 1 kB (physics) + 60 kB (bkgd) / evt
    - With 100 kHz trigger rate: ~6 GB/s
  - For the tracker:
    - 200 hits on average for hadronic Z decays * 2.5 (cluster size) = 500 channels / evt
    - 90 hits/BX from incoherent pairs * 3 (safety factor) * 2.5 (cluster size) = 675 channels / BX
    - Assuming 1 μs integration time (~50 BXs) and 22 bits: 1.4 kB (physics) + 93 kB (bkgd) / evt
    - With 100 kHz trigger rate: ~10 GB/s

- For comparison:
  - CLIC 3 TeV *tracking system*~900 MB/s, ATLAS/CMS pp *full detector* ~100 GB/s (L1)
Full simulation of incoherent pairs background, integrated in a 10 µs window to probe worse scenario: tracking algorithm performance barely affected by background.
FST at CEPC

FST is the version of the baseline detector for CEPC, where the TPC is replaced by an all-silicon tracking system

- adapted to $B=3T$
- built upon a 14.5 mm radius beam pipe

FST Tracker

VXD
- 6 pixel layers, radius first layer = 16 mm
- 3 $\mu$m single point res
- 0.15% $X_0$ per layer

EIT
- 2 pixel disks

SOT
- 6 double-strip layers
- outer radius = 1.8 m
- 50 $\mu$m pitch

EOT
- 5 double-strip disks
- 50 $\mu$m pitch

Total sensitive area = 140 m$^2$

Total radiation length = 5-8% (barrel - endcap)

NB: FST2 version exists with single layers replacing the double layers. Not discussed in this talk.
FST at CEPC: Tracking Performance

Figure 4.28: The track $p_T$, $d_0$, and $z_0$ resolutions are as functions of $p_T$ measured using single muons in the barrel region (left) and endcap region (right), comparing the performance of the CEPC baseline and the FST options. The FST option shows slightly worse resolutions at low momentum due to its extra material.

NB: no occupancy and background studies available for this version of the detector.

d0 resolution below 5μm
pT resolution 5×10⁻⁵ GeV⁻¹
efficiency 100% for pT > 45 GeV, > 95% otherwise

Linear Colliders experimental conditions

Beam structure:

- allows for power pulsing
  => air cooling possible
  [CLICdet only for vertex detector, SiD both for vertex and tracker]

Beam backgrounds:

- incoherent pairs -> for 3 TeV CLIC defines the beam pipe radius, thus the position of the innermost vertex detector layer
- $\gamma\gamma$ -> hadrons -> main source of background in detectors
CLICdet at CLIC

CLICdet is the all-silicon-tracker detector concept developed for CLIC

- designed for B=4T
- built upon a 30 mm radius beam pipe

CLICdet Vertex Detector

- 3 double-layer barrels + 3 double-layer disks
- pixel sizes 25x25 μm²
  - with analog readout
  => single point resolution 3 μm
- time resolution ~5 ns
- max desired occupancy of 3%

- low material budget: 0.4% $X_0$ per double layer
  - 50 μm-thick sensors
  - 50 μm-thick ASICs
  - ~100 μm ‘equivalent thickness’ for cooling, cabling, support
- total sensitive area = 0.84 m²

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<th>CLICdet</th>
<th>CLD</th>
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<tr>
<td>Vertex inner radius [mm]</td>
<td>31</td>
<td>17</td>
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<td>Tracker half length [m]</td>
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<tr>
<td>Tracker outer radius [m]</td>
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<td>ECAL absorber</td>
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<td>ECAL $X_0$</td>
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<td>HCAL absorber</td>
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<td>HCAL $\lambda_1$</td>
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<td>Solenoid field [T]</td>
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<td>Overall height [m]</td>
<td>12.9</td>
<td>12.0</td>
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<tr>
<td>Overall length [m]</td>
<td>11.4</td>
<td>10.6</td>
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</table>
CLICdet Tracker

- inner tracker: 3 barrel layers + 7 disks
- outer tracker: 3 barrel layers + 4 disks
- carbon fibre support structure
- total sensitive area = 137 m²

- first inner tracker disk pixelated for pattern recognition needs
- strixels (short strips/long pixels)
  - with analog readout => single point resolution in (R, \( \varphi \)) 7 \( \mu \)m
  - time resolution of ~5 ns

- material budget
  - 200 \( \mu \)m-thick silicon layers (shared between sensor and ASICs)
  - 1\% \( X_0 \) per tracker layer (sensitive + cooling + cabling)
  - 2.5\% \( X_0 \) main support tube + supports per layer+ cooling pipes + cable routes

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CLICdet Tracking Performance

Achieved desired transverse impact parameter resolutions for high-energy muons well below the high-momentum goal of 5 µm

Achieved transverse momentum resolution goal of 2x10^{-5} GeV^{-1} for high-energy muons in the barrel

- curves saturate at high momenta => no multiple scattering, only effect of single point resolution

CLICdet Tracking Performance

all studies done in full simulation


Displaced single muons

Tracking efficiency 100% for $p > 1$ GeV
• all-silicon tracker no showstopper for V0 decays, secondary vertices, ...

Complex events - w/wo background

Tracking efficiency 100% for $p_T > 500$ MeV
• background does not affect performances for $p_T > 1$ GeV
SiD at ILC

SiD is the all-silicon-tracker detector concept developed for ILC

- designed for B=5T
- built upon a 10 mm radius beam pipe

SiD Vertex Detector and Tracker

Vertex detector:
- 5 barrel layers, radius first layer = 14 mm
- 4 disks + 3 additional forward disks
- 20 μm pixel pitch up to 50 μm
- 0.1% $X_0$ per layer
- single BX time stamp: ~300ns
- coverage down to $\cos(\theta) \approx 0.984$

Tracker:
- 5 barrel layers, 0.9 % $X_0$ per layer
- outer radius = 1.25m
- 4 conical disks, 1.3 % $X_0$ per layer
- 25 μm sensor pitch
- 6 hits down to 8°

Total material budget: < 20% $X_0$ within 10° of the beam direction

https://indico.cern.ch/event/868940/contributions/3814064/attachments/2081543/3496370/SiD_ICHEP_2020_A_White.pdf
SiD Tracking Performance

all studies done in full simulation


Average 98% tracking efficiency with 1BX of beam backgrounds overlaid, except low momenta and very forward tracks.

Exceeded transverse momentum resolution goal of 2x10^{-5} GeV^{-1} for high-energy muons in the barrel
- 100-200GeV tracks still affected by multiple scattering
- very forward tracks limited by shorter lever arm

Transverse momentum

![Graph showing transverse momentum](image)

Tracking efficiency

![Graph showing tracking efficiency](image)

\[ \sigma(p_T) / p_T^2 \text{ [GeV}^{-1} \]
Summary

- **Detector concepts with all-silicon trackers** for future e+e- colliders comply with experimental constraints and meet physics requirements.
- **All-silicon trackers** designs result from a balanced compromise between low occupancy/small single point resolution and material budget.

- **R&D in silicon sensors, read-out, cooling and infrastructure** *
  *Not discussed in this talk*
  - has already achieved promising results in proving feasible to meet the challenging requirements.
  - is paving the way to the future of ultra-thin bendable sensors with low power consumptions and minimal cooling.

Thank you for your attention.
Extra