Silicon pixel-detector R&D for future lepton colliders

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February 24th, 2022

Dominik Dannheim (CERN)
on behalf of the CLICdp collaboration
Outline

- Future Lepton Colliders and pixel-detector requirements

- Pixel-detector R&D examples:
  - Hybrid-detectors
    - CLICpix2 thin-sensor assemblies
    - ACF hybridisation
  - Monolithic sensors
    - CLICTD tracker-technology demonstrator
    - FASTPIX timing demonstrator

- Conclusions
Future Lepton Colliders

- Several proposals for post-LHC future Lepton Colliders:
  - $\sqrt{s} \sim 350 \text{ GeV} - 3 \text{ TeV}$
  - Circular / linear collider designs
  - Physics goals:
    - Precision Higgs / top measurements
    - Measurement of electroweak precision observables
    - Direct/indirect Beyond-the-Standard-Model searches
- Vertex/tracking detector performance needs to match precision-physics goals:
  - Displaced vertices: $\sigma(d_0) \sim 5 \oplus 15/(p[\text{GeV}] \sin^{3/2} \theta) \mu\text{m}$
  - Track-momentum: $\sigma(p_T)/p_T^2 \lesssim 2 \times 10^{-5} \text{ GeV}^{-1}$

**ILC**

**CEPC**

**FCC-ee**

**CLIC**
Lepton Collider vertex/tracker requirements

Vertex detector:
• good single point resolution: $\sigma_{SP} \sim 3 \, \mu m$
• low material budget: $\lesssim 0.2\% \, X_0 / \text{layer}$
  $\rightarrow$ low-power ASICs for air cooling ($\sim 50 \, \text{mW/cm}^2$)

Large-area Tracker:
• 7 $\mu m$ single-point resolution ($\sim 25\text{-}50 \, \mu m$ $R_\phi$ pitch)
  $\rightarrow$ many layers, large outer radius
• $\sim 1\text{-}2\% \, X_0$ per layer
  $\rightarrow$ low-mass supports + services, low power $\sim 150 \, \text{mW/cm}^2$

Both:
• Moderate radiation exposure ($>\sim 10^4$ below LHC!):
  • NIEL: $< 10^{11} \, \text{n}_{eq}/\text{cm}^2/\text{y}$
  • TID: $< 1 \, \text{kGy} / \text{year}$
• few % max. occupancy from beam backgrounds
  $\rightarrow$ sets inner radius and limits cell sizes
• time stamping down to $\sim 5 \, \text{ns}$ accuracy (CLIC 3 TeV)
  $\rightarrow$ depleted sensors, fast frontend
• Benefits of precision timing ($<100 \, \text{ps}$) for PID under study

Linear-Collider specific:
• Low duty cycle: $\sim 20\text{-}200 \, \text{ms}$ gaps between bunch trains
  $\rightarrow$ trigger-less readout, pulsed powering

$\rightarrow$ Emphasis of this talk on technology R&D for 3-TeV CLIC
(most challenging combination of requirements)
CLIC pixel-detector R&D

Hybrid Assemblies

CLICpix2 + planar sensor

| 65 nm CMOS |
| 200 nm SOI |

Timepix3 ACF-bonding

| 130 nm CMOS |
| 65 nm CMOS + 180 nm HV-CMOS |

CLICpix2 + C3PD

| 65 nm CMOS |
| 180 nm CMOS |

Monolithic Sensors

| 180 nm HV-CMOS |
| 180 nm CMOS |

ATLASpix

| 200 nm SOI |
| 180 nm CMOS |

CLICTD

| 180 nm CMOS |
| 65 nm CMOS |

Tools

CLICdp beam telescope

Caribou readout system

MC Simulation framework: Allpix Squared

Analysis & reconstruction framework: Corryvreckan

| Detector technologies for CLIC, CERN-YR-2019-001 |
| Caribou readout system | ap² https://gitlab.cern.ch/allpix-squared/allpix-squared |
| Carbyne | NIM A 901 (2018) 164-172 |
| tools | 2021 JINST 16 P03008 |
| https://gitlab.cern.ch/corryvreckan/corryvreckan |

- Diverse R&D program, focusing on conceptual studies + small technology demonstrators
- Flexible tools developed, to support the R&D and exploit synergies between the various R&D lines
- R&D performed within various collaborative frameworks (CLICdp collaboration, CERN EP R&D, AIDAinnova) and with strong links to HL-LHC developments
Fine-pitch hybrid planar pixel detectors

**CLICpix2 readout ASIC:**
- Targets CLIC vertex-detector requirements
- 65 nm CMOS process
- Pixel pitch 25 µm x 25 µm (128 x 128 pixels)
- Simultaneous 5-bit ToT + 8-bit ToA (10 ns bins) readout
- Used for development of 25 µm-pitch interconnect-process (IZM) and for testing innovative fine-pitch sensor designs (planar active edge, active HV-CMOS, enhanced-lateral-drift sensors)

**SnAg bumps on CLICpix2 (IZM)**

**Cross section of bump bonds by IZM**

- Single-die bump-bonding process with pixel pitch of 25 µm developed by IZM
- Interconnect yield of up to 99.6%

*JINST, 15(03), C03045*
CLICpix2 test-beam results

- Detailed test-beam studies for assemblies with high interconnect yield
- Excellent performance observed for 130 μm sensor thickness, meeting most CLIC requirements:
  - <3 μm intrinsic spatial resolution (mean cluster size ~2.6)
  - Hit-detection efficiency >99.7%
  - Hit-time resolution <5 ns
- However: sensor thickness well above target thickness of 50 μm
  \[ \rightarrow \sim 6.8 \text{ μm} \] spatial resolution for 50 μm sensor thickness (mean cluster size ~1.3)

Efficiency

Spatial residuals

Timing residuals

CERN-THESIS-2020-338
Anisotropic Conductive Film (ACF)

• Adhesive epoxy film with conductive micro particles
  • Compression of particles enables electrical connection between pads

• New prospects for hybridisation and module integration

• Ongoing development / optimisation of two in-house processes:
  • Chemical Electroless Nickel Immersion Gold (ENIG) deposition for Under Bump Metallization (UBM) → uniformity, thickness
  • Semi-automatic flip-chip bonding with ACF layer → ACF material (particle diameter and density), epoxy thickness, lamination procedure, temperature/pressure profile for bonding

CERN-EP-RDET-2021-001

ACF-hybridisation Conductive ACF micro particles ENIG metallisation

https://agenda.linearcollider.org/event/9211/contributions/49469/attachments/37464/58685/ILCX_MVicente_ACF.pdf

Timepix3 ENIG re-processing

Timepix3 pixel matrix with ACF
ACF - Hybridisation Tests

- Bonding tests performed with Timepix3 and CLICpix2 ASICs

- 18 μm film with 3 μm micro particles, 100 kg bonding force

- **Proof-of-concept** for bonding areas up to 1 cm² and 55 μm pitch

- Interconnection for larger areas / smaller pitch more challenging due to the required larger bonding force

**Bonding to Timepix3 sensor**

*Approx. 50% ACF coverage*
ACF for module integration

ACF module integration
Larger bonding pads: 80 µm – few mm diam.
→ Similar to industrial ACF usage
→ Good interconnect results
→ Topology / uniformity of UBM important

Various proof-of-concept projects:
• Beam tests of ALPIDE ACF modules
• Bonding tests with MALTA silicon bridges
• Tests with FCAL LUXE pad sensors

M. Mager, F. Dachs, Y. Benhammou
Small collection electrode monolithic CMOS

- Modified 180 nm CMOS imaging process with small collection electrode (O(fF) capacitance)
  (e.g. ALPIDE, (Mini-)MALTA, CLICTD, FASTPIX …)

- Deep low-dose n-implant for full lateral depletion

- Introduction of lateral doping gradient leads to accelerated charge collection
  - Comparison of various design modification in terms of detector performance

![Diagram of silicon pixel-detector design modifications](Image)

JINST 14 (2019) C05013

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Silicon pixel-detector R&D for future Lepton Colliders
Simulations

- Complex non-uniform field configurations in the small collection-electrode layout require sensor-design optimisations

- Finite-element (3D TCAD) and Monte Carlo (Allpix Squared) simulation to combine accurate sensor modelling with high simulation rates

- Validated against transient 3D TCAD and data

Electrostatic potential + streamlines

NIM A 1016 (2020) 0163784

NIM A 901 (2018) 164172

CLICdp-Pub-2021-003
https://arxiv.org/abs/2202.03221
CLICTD Technology Demonstrator

CLICTD 180nm monolithic sensor
• Channel pitch: 300 µm x 30 µm (16x128 channels)
• Sub-pixel pitch: 37.5 µm x 30.0 µm
• Analogue front-end of 8 sub-pixels grouped in one digital front-end (= readout channel)
• 8-bit ToA (10 ns ToA bins) + 5-bit ToT (combined ToA/ToT for every 8 sub-pixels in 300µm dimension)
• Sensors produced with different substrate materials (epitaxial, high-resistivity Cz) and thicknesses (40-300 µm)


Excellent performance observed in test-beam measurements:
• Threshold: ~100 - 180 e (occupancy < 10^{-3} hits/sec)
• Single pixel noise : < 15 e
• Hit-detection efficiency : > 99.7 %
• Spatial resolution : 4.6 µm
• Time resolution : 5.2 ns
(Limited by front-end time resolution)

• Reduced charge sharing for pixel flavour with segmented n-implant leads to higher concentration of charge in one pixel cell → Improved efficiency at high thresholds
Advanced sensor materials

- Production using high-resistivity Czochralski (few kΩcm) wafers allowing for larger depleted volume → Larger active sensor volume

- Improved efficiency at high thresholds due to higher signal
- High-resistivity Czochralski sample enables combination of small collection electrode with large depleted volume → Improvement for all performance parameters (though limited by front-end)

NIM A 986 (2021) 164381

- Improved efficiency at high thresholds due to higher signal
- High-resistivity Czochralski sample enables combination of small collection electrode with large depleted volume → Improvement for all performance parameters (though limited by front-end)
FASTPIX technology demonstrator for sub-ns timing

- Modified 180 nm CMOS imaging process
- 32 mini matrices of hexagonal pixels (8.66 to 20 μm pitch)
- 4 analogue outputs + 4x16 pixels with ToT/ToA
- Various sensor designs and process options
- Position and ToT encoding via delay lines (asynchr. r/o)

W. Snoeys, T. Kugathasan

On-chip readout circuit

Simulated chip parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor capacitance</td>
<td>1 fF</td>
</tr>
<tr>
<td>Equivalent Noise Charge</td>
<td>11 e-3</td>
</tr>
<tr>
<td>Jitter (for Q_m = 1000 e-)</td>
<td>20 ps</td>
</tr>
<tr>
<td>In pixel source follower</td>
<td>18 μW</td>
</tr>
<tr>
<td>Periphery discriminator</td>
<td>150 μW</td>
</tr>
<tr>
<td>Analog monitoring buffer</td>
<td>20 mW</td>
</tr>
</tbody>
</table>

- Optimised for precise sensor timing in 3D TCAD simulation studies
- Hexagonal pixel layout:
  - Improved charge collection at pixel edges
  - Reduced number of neighbouring pixels
    - Less charge sharing
ATTRACTION FASTPIX: Test-beam measurements (I)

→ Fully efficient operation (for ~43 e threshold, ~5 e noise)

Intrinsic position resolution ~4 μm (for 20 μm pitch), significantly below binary resolution of 5.8 μm

Charge sharing mostly at the pixel edges
→ increased cluster size
→ Reduced seed charge
Test-beam timing results:

- Strong time-walk effects in particular at matrix edge due to charge sharing
- Time resolution of ~500 ps w/o time-walk correction
- Time resolution of ~120 ps after offline time-walk correction

Conclusions

• **Stringent requirements** for Lepton Collider vertex and tracking detectors have inspired broad and integrated technology R&D program

• Innovative sensor + readout technologies under study
  • Combination of **vertex-detector** requirements remains challenging (**CLICpix2**)
  • **Tracker** requirements met by monolithic technologies (**CLICTD**)
  • **Sub-nanosecond sensor timing** demonstrated in monolithic technology (**FASTPIX**)

• Innovative **interconnect technology** under development for hybridisation and module building (**ACF**)

• Advanced tools for characterization (**Caribou**), simulation (**Allpix2**) and analysis (**Corryvreckan**) support the detector R&D

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Additional Material
Caribou DAQ

Versatile data acquisition system based on programmable hardware

System-on-Chip (SoC) board

- Embedded CPU for DAQ, user interface, operating system (Linux)
- Field programmable gate array (FPGA) for detector control and data processing

Control and Readout (CaR) interface board

- Physical interface from SoC board to detector chip
- Voltage regulators, ADCs, pulse/clock generator

Application-specific detector carrier board

- Only detector chip and passiv components
- Successfully used for ATLASPix, ATLASPix2, ATLASPix3, CLICpix2/C3PD, H35Demo/FEI4, RD50-MPW1

https://iopscience.iop.org/article/10.1088/1748-0221/12/01/P01008

https://gitlab.cern.ch/Caribou
Allpix-Squared simulation toolkit

Selected Applications

- **Detectors for HEP**
  - MAPS (CLICTD, ALICE, ARCADIA,...), RD53, ATLAS ITk Strips, ...
- **NASA / Space Radiation Analysis**
- **ISS radiation monitor simulations**
- **Germanium X-ray detector (Synchrotron SOLEIL)**
- **Education / Outreach activities**
  - EDIT Detector School, Beamline for Schools 2019,...

Publications

- NIM A 901 (2018) 164-172
- NIM A 964 (2020) 163784

Website
https://cern.ch/allpix-squared

Repository
https://gitlab.cern.ch/allpix-squared/allpix-squared

User Forum
https://cern.ch/allpix-squared-forum/

User Manual

Mailing list
https://e-groups.cern.ch/e-groups/Egroup.do?egroupld=10262858
Corryvreckan test-beam analysis framework

**Reconstruction and analysis software for test-beam data**

- Highly flexible/configurable by using separate modules for each reconstruction/analysis step

- Wide user base e.g. CLICdp, ALICE ITS3, ATLAS ITk, LHCb Ib/Ii, Mu3e, etc.

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**Corryvreckan**

2021 JINST 16 P03008

- Visit the website for the manual, tutorials and more
  [https://cern.ch/corryvreckan](https://cern.ch/corryvreckan)

- Check out the repository
  [https://gitlab.cern.ch/corryvreckan/corryvreckan](https://gitlab.cern.ch/corryvreckan/corryvreckan)

- Join the discussion in the forum
  [https://corryvreckan-forum.web.cern.ch/](https://corryvreckan-forum.web.cern.ch/)

- Contact us
corryvreckan.info@cern.ch
CLIC (Compact Linear Collider): linear $e^+e^-$ collider concept for post HL-LHC phase

- $\sqrt{s}$ from few hundred GeV up to 3 TeV (two-beam acceleration with $\sim 100$ MV/m)
- Precision and discovery physics at the TeV scale
- Detector and physics studies within the CLICdp collaboration of 30 institutes

CLIC detector model

- **Solenoidal Magnet**: Superconducting magnet at 4 Tesla
- **Tracking Detector**: Silicon pixel detector, outer radius 1.5 metres
- **Vertex Detector**: Ultra-low mass silicon pixel detector, inner radius 31 millimetres
- **Return Yoke**: Iron return yoke with detectors for muon ID
- **Fine-grained Calorimeters**: Electromagnetic and hadronic calorimeters used for particle flow analysis
- **Forward Region**: Electromagnetic calorimeters for luminosity measurement and extended angular coverage

Staged CLIC implementation

CLICdp collaboration institutes

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**Tracking detector**
- Material: 1-2% $X_0$ / layer
- Single-point resolution: 7 micrometres

**Vertex detector**
- 25 micrometre pixels
- Material: 0.2% $X_0$ / layer
- Single-point resolution: 3 micrometres
- Forced air-flow cooling

**Electromagnetic calorimeter**
- 40 layers (silicon sensors, tungsten plates)
- Material: 22 $X_0$, $+1\lambda$

**Hadronic calorimeter**
- 60 layers (plastic scintillators, steel plates)
- Material: 7.5 $\lambda$

Learn more about the CLIC detector at clic.cern

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Silicon pixel-detector R&D for future Lepton Colliders
Experimental conditions at CLIC

- CLIC operates with bunch trains, 50 Hz repetition rate
  - Low duty cycle
  - Trigger-less readout between trains
  - Allows for power-pulsed operation of detector, to reduce average power consumption

- Collisions within 156 ns bunch trains
- High E-fields lead to Beamstrahlung
  - High rates of beam-induced background particles
  - Drives detector design (layout, granularity, timing)

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Main backgrounds in detector

- **Incoherent e+e- pairs**
  - 19k particles / bunch train at 3 TeV
  - Constrains beam pipe radius, granularity

- **γ γ →hadrons events**
  - 17k particles / bunch train at 3 TeV
  - Constrains granularity, layout, impacts physics

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High instantaneous hit rates (up to 6 GHz/cm²), however: very low readout rate (50 Hz)
• Study impact of technology parameters (pixel size, material budget) on detector performance
• Optimization of detector geometry (# layers, placement) for given technology assumptions
• Using fast simulations (LiC detector toy) and Geant-4 based full detector simulations including beam-induced backgrounds
• Main benchmark parameters: impact-parameter and momentum resolution, flavor-tagging performance, reconstruction efficiency
Sensor and readout R&D

Hybrid planar sensors

ELAD planar sensors

CCPD sensors

Hybrid detectors:
- Factorise r/o and sensor R&D
- Smallest feature-size ASICs
- Advanced sensor concepts
- Small pixels, highest performance → for inner layers

SOI CMOS sensors

Monolithic CMOS sensors:
- Lowest material budget
- Medium feature-size
- Simplified construction → for large-area tracker
- Recent developments target also inner layers

Large fill-factor CMOS sensors

Small fill-factor CMOS sensors
CLICpix2 r/o ASIC

• CLICpix2 in same 65 nm process as CLICpix:
  • Increased matrix size to 128 × 128 pixels
  • Longer counters for charge (5-bit) and timing (8-bit) measurements
  • Improved noise isolation and removal of cross-talk issue observed in first CLICpix
  • More sophisticated I/O with parallel column readout and 8/10 bit encoding
  • Integrated test pulse DACs and band gap

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Power dissipation</td>
<td>≤ 12 µW</td>
</tr>
<tr>
<td>Area</td>
<td>≤ 12.5x25 µm²</td>
</tr>
<tr>
<td>Input charge, $Q_{in}$</td>
<td>nominal 4 ke-, max. 40 ke-</td>
</tr>
<tr>
<td>Minimum threshold, $Q_{th,min}$</td>
<td>≤ 600 e-</td>
</tr>
<tr>
<td>Equivalent input-referred noise, $Q_{n,in}$</td>
<td>≤ 70 e-</td>
</tr>
<tr>
<td>ToT dynamic range</td>
<td>≥ 40 ke-</td>
</tr>
<tr>
<td>ToA accuracy</td>
<td>≤ 10 ns</td>
</tr>
<tr>
<td>Total ionizing dose (for 10 yr)</td>
<td>1 Mrad</td>
</tr>
<tr>
<td>Input charge types</td>
<td>e-, h+</td>
</tr>
<tr>
<td>Testability</td>
<td>in-pixel test pulse (i.e. $Q_{test}$) injection</td>
</tr>
</tbody>
</table>
CLICpix2 50-um test-beam results

Size distribution of associated clusters

Residual in X

Residual in Y

Sensor bias voltage -60V, device without guard ring
CLICTD monolithic HR-CMOS tracker chip

Good performance of studied 180 nm HR-CMOS technology with respect to requirements of CLIC tracker

Technology used for ongoing design of a fully integrated chip for the CLIC tracker

CLIC Tracker Detector (CLICTD) – monolithic HR-CMOS sensor with 30 μm x 300 μm pixels

Segmented macro-pixel structures to maintain advantages of small collection diode (prompt and fully efficient charge collection) while reducing digital logic:

Discriminator output of 8 collection diodes combined in logical OR

Output of logical OR passed to digital circuitry:

- Simultaneous 8-bit ToA and 5-bit ToT measurements
- Expect $\sigma_{SP} \sim 7$ μm in short direction (charge sharing)
- Hit bit pattern → maintain good resolution also in long direction
- 100 MHz clock to achieve 10 ns time binning