Test-beam measurements and simulation studies of thin pixel sensors for the CLIC vertex detector

Niloufar Alipour Tehrani

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ETH zürich

CERN

CLIC

Chair:	Prof. Dr. Jérôme Faist
Examiner:	Prof. Dr. Günther Dissertori
Co-examiners:	Prof. Dr. Rainer Wallny
	Dr. Dominik Dannheim

Overview

Introduction

The Compact Linear Collider (CLIC)

The CLIC vertex detector

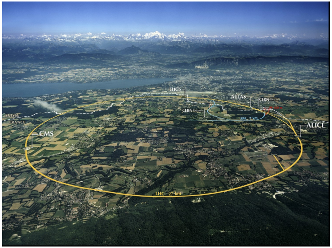
Thin sensors studies

Active edge sensors

Conclusions

Particle physics: its present and future

- The Large Hadron Collider (LHC) is today's largest particle accelerator at CERN (European Organisation for Nuclear Research)
    - Proton-proton collisions
    - Center-of-mass energy: $\sqrt{s} = 13$ TeV
    - Observation of the Higgs boson in 2012

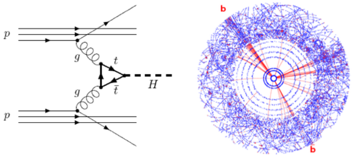


- Still open questions in particles physics remain unanswered:
    - Full understanding of the Higgs boson
    - The origin of matter-antimatter asymmetry
    - Dark matter
    - Many more questions ...
- Several approaches of high-energy particle colliders to address the unanswered questions in the post-LHC era:
    - electron-positron (e^+e^-) colliders
    and/or
    - proton-proton ($p\,p$) colliders

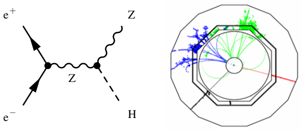
Hadron vs. Lepton colliders

Discovery

$\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ @ LHC



$\mathrm{ZH} \to \mu^+\mu^-\mathrm{b}\bar{\mathrm{b}}$ @ e^+e^-



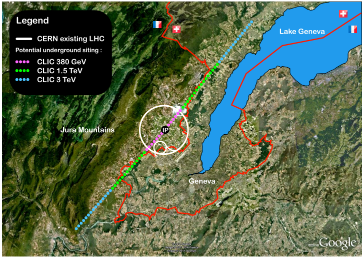
Precision

- Protons ⇒ compound objects
  - Unknown event-by-event initial states
  - Limited achievable precision
- High rates of QCD backgrounds
  - Complex triggering schemes
  - High levels of radiation
- Circular high-energy pp colliders

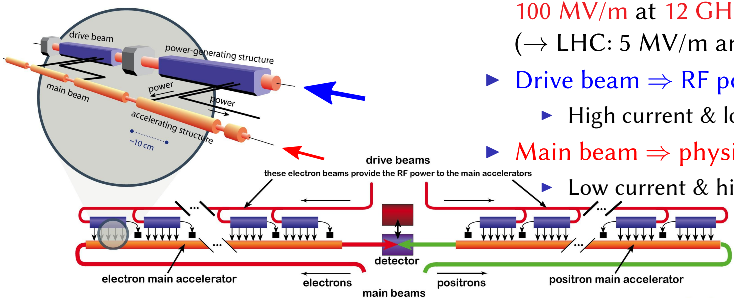
- Electrons/positrons ⇒ point-like
  - Well-defined initial states (energy, polarisation)
  - High-precision measurements
- Cleaner experimental environment
  - Trigger-less readout
  - Low levels of radiation
- Linear or circular high-energy e^+e^- colliders

The Compact Linear Collider (CLIC)

- An e^+e^- linear collider for the post HL-LHC period.
- Energy range $\sqrt{s}$: 380 GeV to 3 TeV
- Precision measurements of:
  - Standard Model processes (Higgs, top).
  - New physics potentially discovered at 13 TeV LHC.
  - Search for new physics
- 50 km tunnel at 3 TeV stage
- Two-beam acceleration scheme



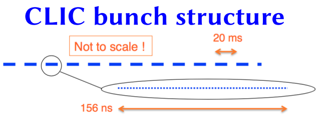
→arXiv:1608.07537



- High-gradient acceleration: 100 MV/m at 12 GHz (→ LHC: 5 MV/m and 400 MHz)
- Drive beam ⇒ RF power
  - High current & low energy
- Main beam ⇒ physics
  - Low current & high energy

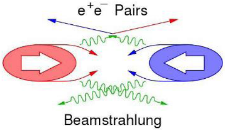
Experimental conditions at CLIC

- Beam profile:
  - Bunch crossings (BX): every 0.5 ns.
  - Train duration: 156 ns (312 bunches).
  - Train repetition: 20 ms (50 Hz).

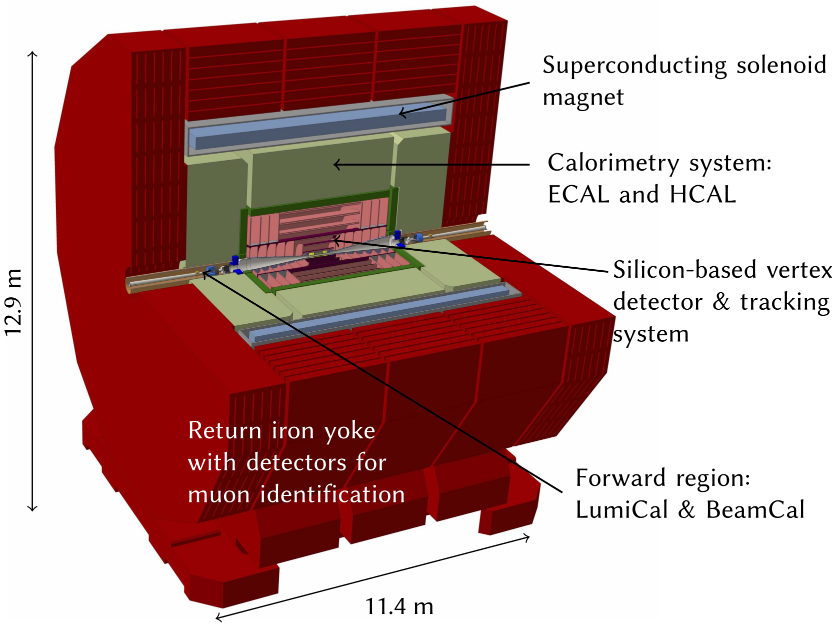


	CLIC at $\sqrt{s} = 3$ TeV	LHC at $\sqrt{s} = 13$ TeV
Instantaneous luminosity $\mathcal{L}$	6×10^{34} cm^{-2}s^{-1}	1×10^{34} cm^{-2}s^{-1}
Bunch-crossing separation	0.5 ns	25 ns
IP size in x / y / z directions	45 nm / 1 nm / 44 µm	15 µm / 15 µm / 5 cm

- Beam-induced backgrounds (small beam sizes):
  - Beamstrahlung: $\gamma\gamma \to e^+e^-$/hadrons
  - Forward direction
  - Timing cuts to reduce the effect
- Each train consists of:
  - At most 1 interesting event
- Moderate exposure to radiation
  - by a factor of 10^4 less than at the LHC



The CLIC detector



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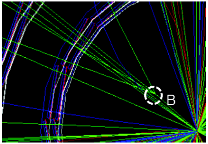
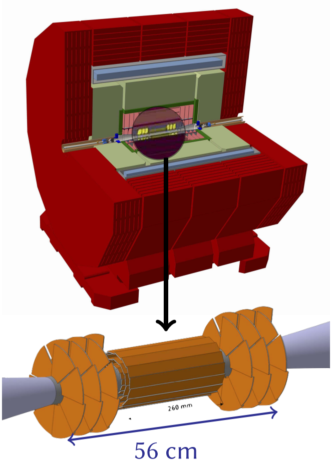
The CLIC vertex detector

Goal: Efficient tagging of heavy quarks through a precise determination of displaced vertices.

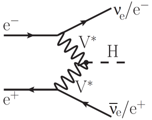


- Requirements:
  - Multi-layer:
    - 6 layers in the barrel and endcap regions
  - Large angular coverage:
    - $\sim$ 30 mm of inner radius and $\theta_{min} \sim 8^{\circ}$
  - B-field: 4 T
  - Hit resolution of $\sim$3 µm
    - Pixel detectors
  - Low material budget:
    - $<$ 0.2% X_0/layer
    - Forced airflow cooling
    - Low-power electronics ($\approx$ 50 mW/cm^2)
  - Time slicing of $\sim$10 ns
    - reject out-of-time background.

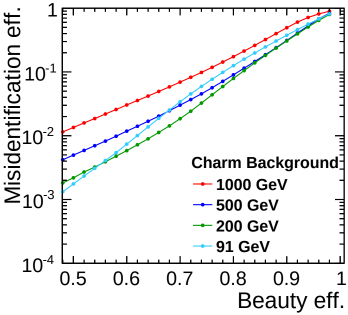


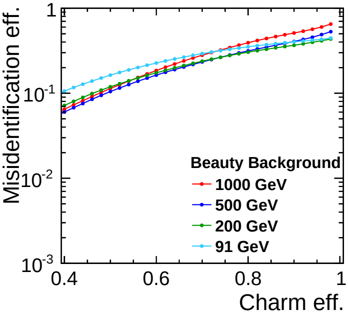
Flavour-tagging at CLIC

- At $\sqrt{s} = 3$ TeV the production of the 126 GeV Higgs boson is dominated by the process: $e^+e^- \rightarrow H\nu\bar{\nu}$



- The Higgs boson preferentially decays to $b\bar{b}$ and $c\bar{c}$ quark pairs.
  - A high-precision vertex detector allows for beauty and charm-tagging and to study such decay modes.

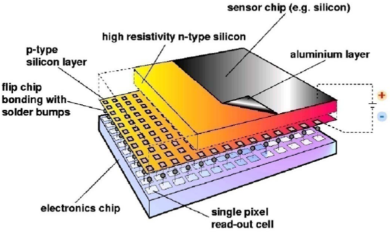


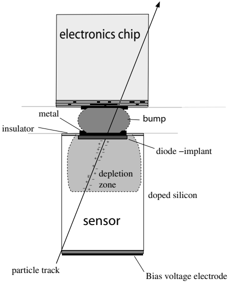


→CLICdp-Note-2014-002

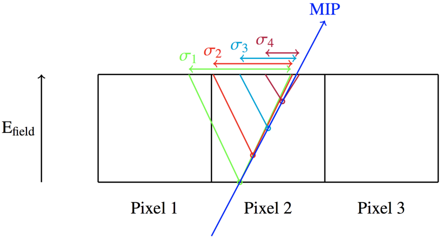
Hybrid pixel detectors

- Sensor and readout electronics are fabricated separately
- Connection via bumps
- Widely used at the LHC experiments



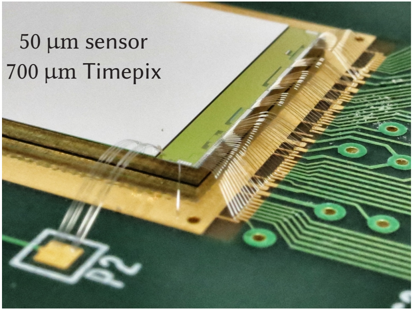


- Planar silicon sensor: reverse-biased pn-junction
  - Drift $\Rightarrow$ external electric field
  - Diffusion $\Rightarrow$ thermal motion
  - Segmentation & diffusion $\Rightarrow$ position information



R&D for planar pixel sensors at CLIC

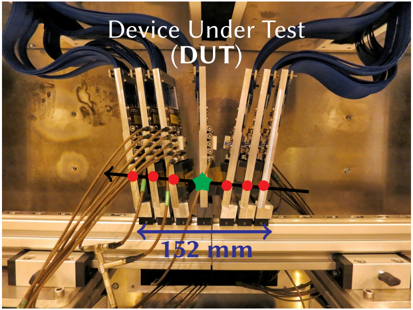
- **Goal**: achieve 3 µm hit resolution with:
  - Low material ⇒ 50 µm-thick sensor & 50 µm-thick ASIC
  - Small pixels ⇒ 25 µm pitch
  - Charge measurement



- Characterisation of thin sensors (Advacam) using the Timepix3 readout ASIC with 55 µm pixel pitch:
  - Sensor thicknesses: 50 µm - 150 µm
  - Spatial resolution
  - Detection efficiency
  - Use simulations to extrapolate to pixels with smaller pitches (i.e. 25 µm).

Test-beam measurements of thin sensors

- Test-beam campaigns at the CERN SPS (Super Proton Synchrotron) with 120 GeV pion beam.
- CLICdp Timepix3 pixel telescope
  - 6 planes of Timepix3 hybrid detectors
  - Track reconstruction.

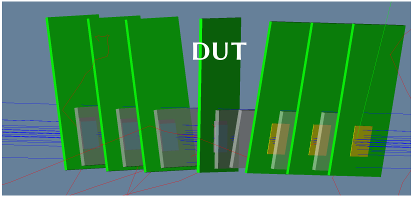


●: measured track position
★: reconstructed track position

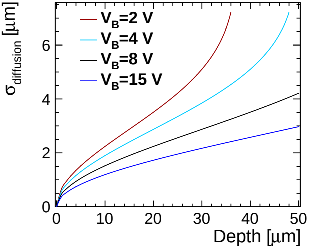
- The resolution on the track prediction
  - $\sim 2\ \mu m$
- Hit resolution for the DUT
  - Measured hit position on the DUT vs. reconstructed track.

AllPix simulation framework

- A general purpose pixel-detector simulation framework (in C/C++) based on GEANT4.
- Fully customisable for detector geometry description:
  - thickness, pixel-pitch, bump geometry, material



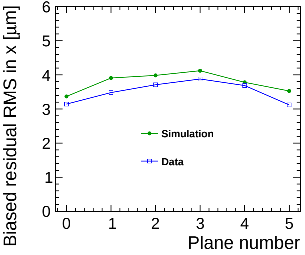
- Digitisation: responsible for the full simulation of the detector
  - Drift and diffusion of the charge carriers in the sensor
  - Functionning of the Timepix3 readout chip



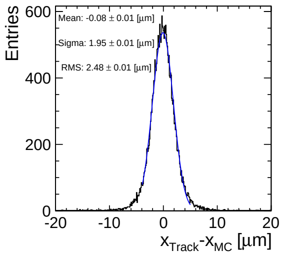
- Goal:
  - Simulation of the test-beam setup.
  - Improve digitisation models for full-detector simulation.

The Timepix3 telescope performance

- In simulation, extract the telescope track prediction resolution on the DUT using the Monte Carlo (MC) hit position



- Residual: reconstructed track vs. measured hit on the telescope planes.
- Agreement between data and simulation ✓

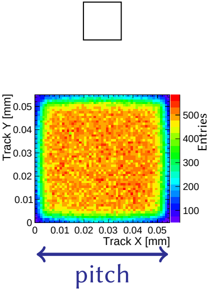


- Track prediction resolution on the DUT: reconstructed track vs. MC hit position
- Excellent tracking resolution of $\sim 2\ \mu m$ on the DUT
  $\Rightarrow$ In agreement with the expectations ✓

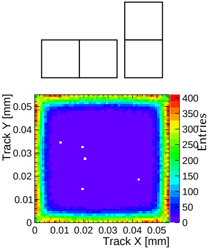
Charge sharing

- Cluster: the group of pixels showing a signal from the same particle due to diffusion

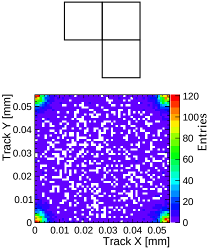
- 1-pixel



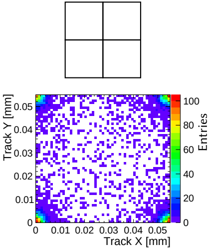
- 2-pixel



- 3-pixel

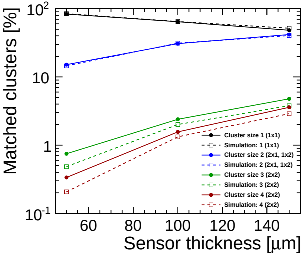


- 4-pixel



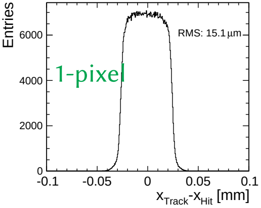
- Factors affecting the charge sharing:
  - Sensor thickness
  - Bias voltage
  - Readout threshold

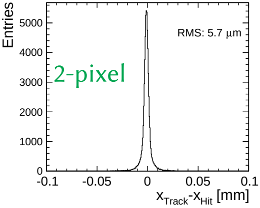
⇒ Simulation in agreement with data

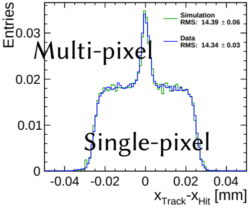


Hit resolution

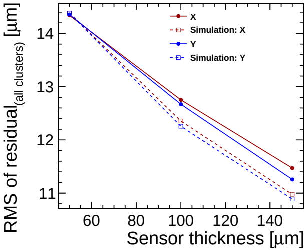
- Reconstructed track position (telescope) vs. hit position on the DUT
  - Single-pixel clusters: hit reconstructed at the geometric center of the pixel
  - Multi-pixel clusters: take advantage of charge sharing for a more accurate hit reconstruction.
- For 50 μm sensors:





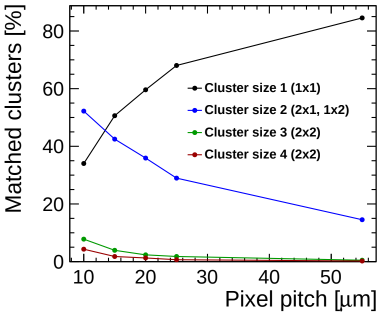


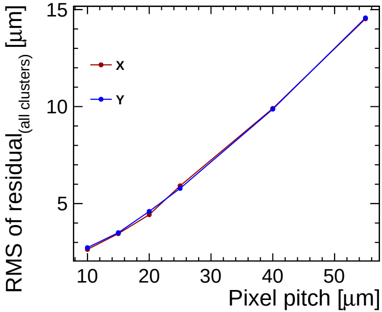
- Simulation in agreement with data



Extrapolation of the simulation to smaller pixels

- CLICpix readout ASIC demonstrator with 25 μm pitch under investigation
- Extrapolation of the simulation to smaller pixels: 10 μm-55 μm pitch
  - For a 50 μm thick sensor and a Timepix3-like readout chip:

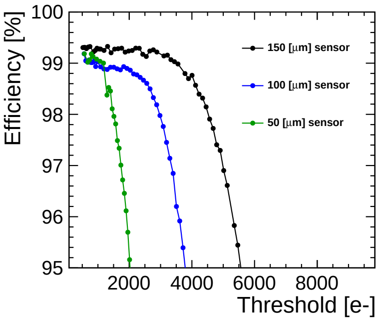




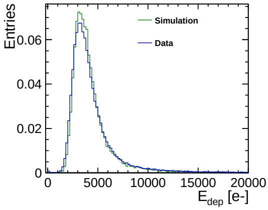
- For 25 μm pitch ⇒ $\sim$ 70% single-pixel clusters, $\sigma \sim 6$ μm
- $\sigma \sim 3$ μm can be achieved with:
  - Smaller pixels ($<$ 15 μm pitch)
  - Enhanced charge sharing solutions

Detection efficiency of thin sensors

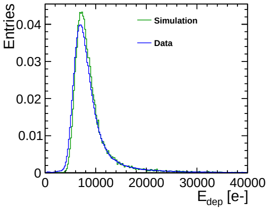
- High detection efficiency (as a function of the readout ASIC threshold):
  - For thinner sensors, the charge deposition is lower ⇒ the efficiency drops more quickly by increasing the threshold.



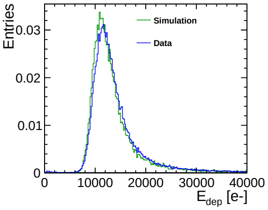
- 50 μm



- 100 μm

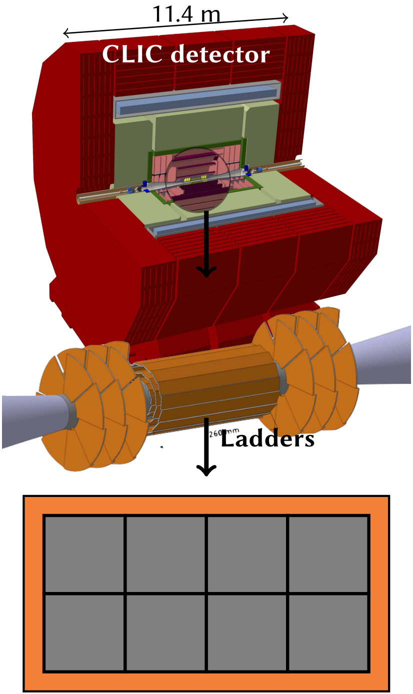


- 150 μm



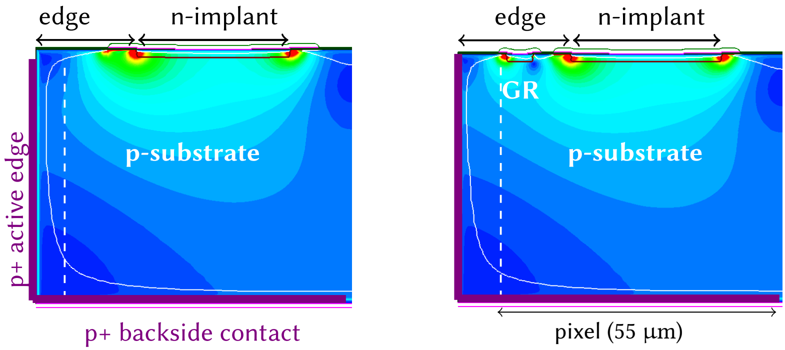
Active edge sensors

- Fabrication of large area detection systems with seamless tiling of pixel sensors:
  - Avoid overlaps between the pixel sensors
  - Reduce the material content in the detector
  - High coverage
- Conventional saw dicing of sensors from a wafer creates inactive regions on the edges.
- Maximise the sensitive region of detectors with active edge sensors



Fabrication process

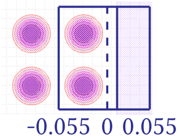
- The DRIE (Deep Reactive-Ion Etching) process is used to cut an active-edge silicon sensor.
- Implantation on the sidewall of the sensor ⇒ control the potential at the edge by creating an extension of the backside electrode on the edge.
- Guard rings (GR) to establish a smooth voltage drop between the edge and the last pixel.



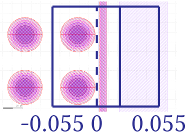
Guard-ring designs and TCAD simulations

- 4 assemblies with 50 µm-thick sensors: No GR, floating and grounded potentials GR.

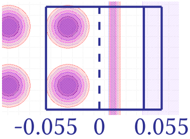
- No GR
  $\Rightarrow$ 20 µm edge



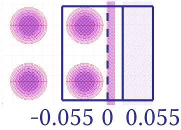
- Grounded GR
  $\Rightarrow$ 28 µm edge



- Grounded GR
  $\Rightarrow$ 55 µm edge



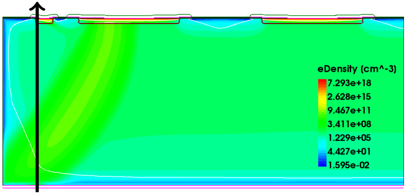
- Floating GR
  $\Rightarrow$ 23 µm edge

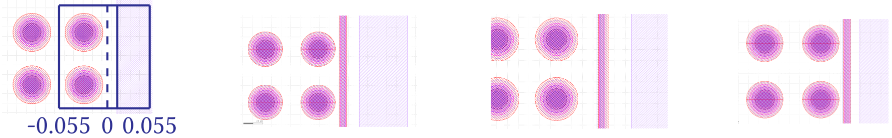


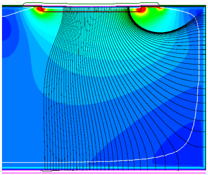
- 2 assemblies with grounded GR: 100 µm and 150 µm thick sensors.
  →**http://dx.doi.org/10.1016/j.nima.2016.05.133**

- TCAD simulations:
  - Finite element methods to numerically solve continuity and diffusion equations in semiconductors.
  - Simulation of semiconductor processing & device operation.

- Transient simulation of a particle track traversing the sensor

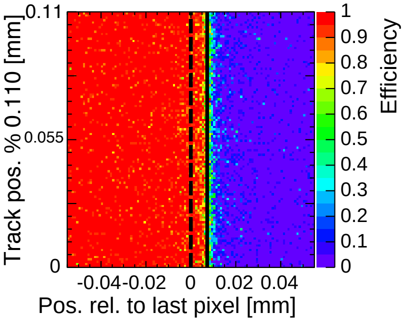




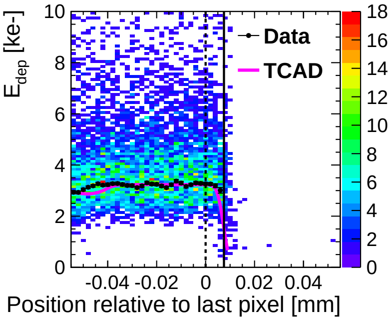


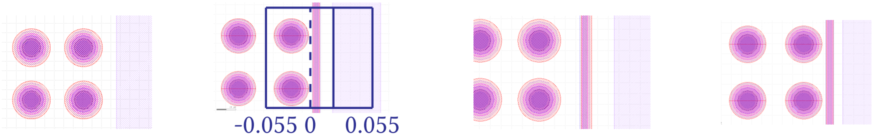
- 50 µm-thick sensor
- No Guard ring
- Edge-to-pixel distance: 20 µm

- Efficiency vs. track position

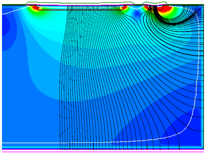


- Energy deposition vs. track position





- 50 μm-thick sensor
- Grounded Guard ring
- Edge-to-pixel distance: 28 μm



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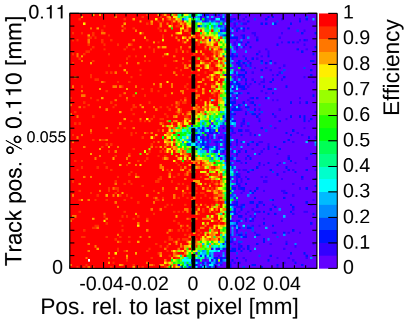
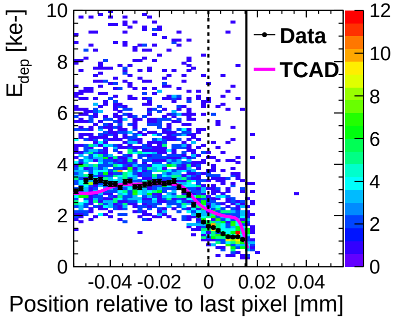
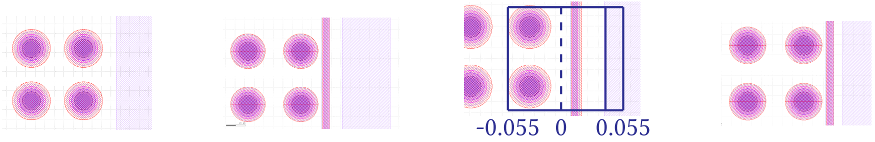
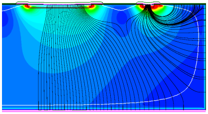


- Energy deposition vs. track position

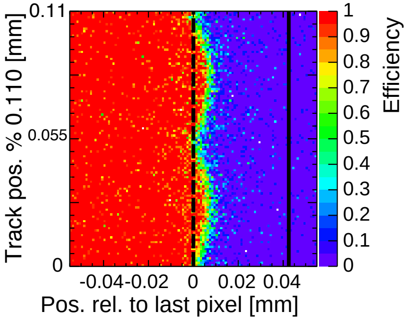




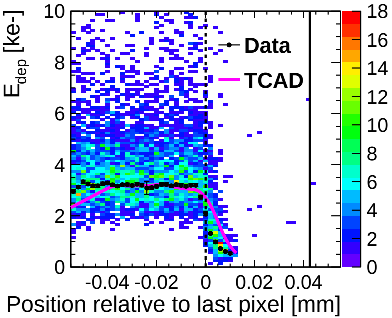
- 50 μm-thick sensor
- Grounded Guard ring
- Edge-to-pixel distance: 55 μm

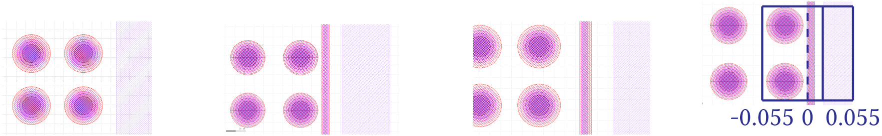


- Efficiency vs. track position

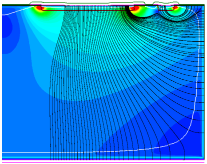


- Energy deposition vs. track position

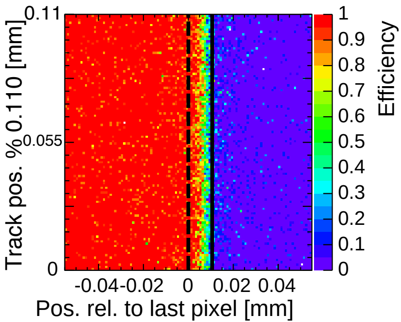




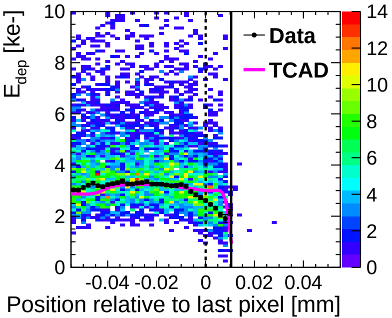
- 50 µm-thick sensor
- Floating Guard ring
- Edge-to-pixel distance: 23 µm



- Efficiency vs. track position

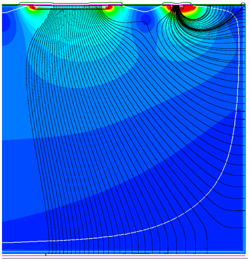


- Energy deposition vs. track position

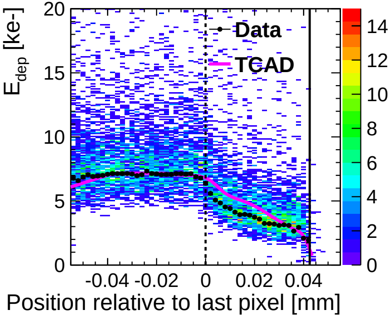


Grounded guard ring for thicker sensors

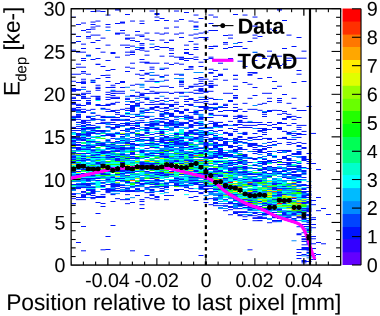
- Assemblies fully efficient up to the physical edge.
- Slight loss of the charge near the edge.



- 100 µm-thick sensor



- 150 µm-thick sensor



Conclusions

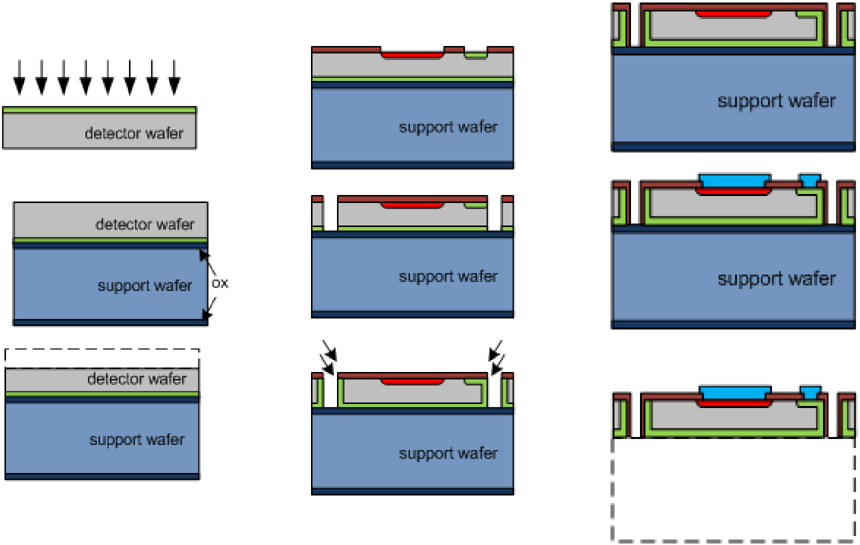
- The vertex detector plays a key role to fully exploit the physics potential at CLIC.
  - High spatial resolution
  - Low material content

    $\Rightarrow$ achieve high flavour-tagging performance
- Characterisation of thin and active-edge planar silicon pixel sensors
  - Test-beam measurements using the Timepix3 telescope with excellent pointing resolution
  - Thin sensors:
    - Study of the charge sharing and hit resolution in test-beam data
    - High detection efficiency
    - Implementation of Timepix3 Geant4-based simulations

      $\Rightarrow$ in agreement with data
  - Thin active edge sensors:
    - Investigation in data and TCAD simulation of different edge and GR configurations.
    - TCAD simulation models implemented are powerful tools to understand data
    - The floating GR is the most suitable solution for thin sensors of 50 μm.

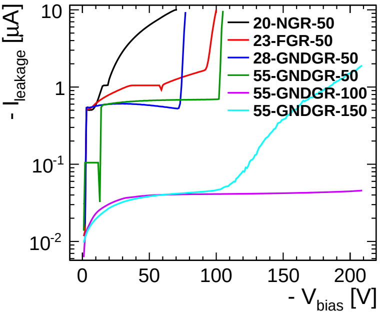
Backup slides

Process-flow for active-edge sensors

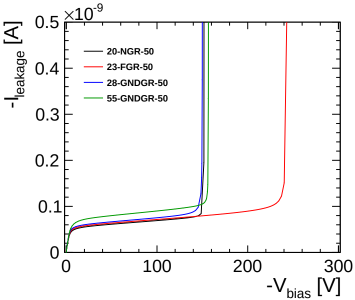


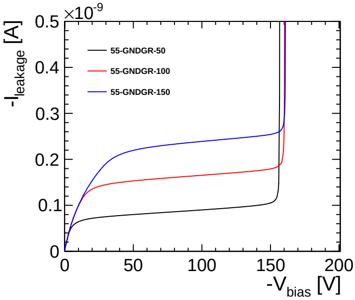
Leakage current in active-edge sensors

- Data



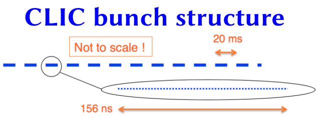
- Simulation





Beam profile for CLIC

- The RF pulse duration limits the number of bunches and the bunch-crossing separation
  - Bunch crossings (BX): every 0.5 ns.
  - Train duration: 156 ns (312 bunches).
  - Train repetition: 20 ms (50 Hz).

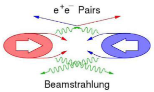


	CLIC at $\sqrt{s} = 3$ TeV	LHC at $\sqrt{s} = 13$ TeV
Instantaneous luminosity $\mathcal{L}$	6×10^{34} cm^{-2}s^{-1}	1×10^{34} cm^{-2}s^{-1}
Bunch-crossing separation	0.5 ns	25 ns
IP size in x / y / z directions	45 nm / 1 nm / 44 µm	15 µm / 15 µm / 50 cm

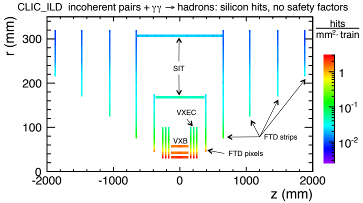
- Bunch separation and train duration drive timing resolution requirements for the detectors
  - Triggerless readout of the detectors.
  - Power pulsing: allows to reduce the average power dissipation.
- Very small beam sizes at the interaction point
  - beam-induced backgrounds

Beam-induced backgrounds

- Backgrounds:
  - e^+e^- pairs: low p_T, forward peaked, limits the inner radius of the VXD.
  - $\gamma\gamma \rightarrow$hadrons: larger p_T particles, main background in the calorimeters and trackers.



- Each train consists of:
  - At most 1 interesting event.
  - > 30000 background particles inside the detector.



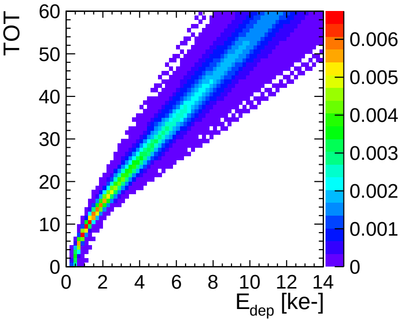
- Occupancy in the pixel detectors for each train (during 156 ns)
  - $\sim 3\%$ for innermost layers.

- Radiation exposure of the vertex detector is moderate:
  - Total ionising dose (TID): 200 Gy/yr
  - Non-ionising energy loss (NIEL): $10^{11} n_{eq}/cm^2/yr$ (for ATLAS phase 1: $10^{15} n_{eq}/cm^2/yr$)

Calibration of the Timepix3 readout chip

- Parametrisation of the measurements done by the readout chip
  - TOT, Threshold DAC $\Longleftrightarrow$ energy deposition in the sensor

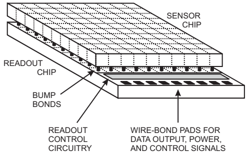
- TOT - energy calibration:
  - Non-linear relationship between the measured TOT and the deposited energy.
  - Internal analogue test pulse generator: $Q = C \cdot \Delta V$



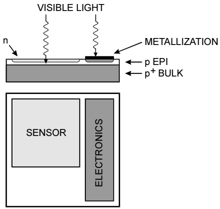
- Preferred operation in the linear regime
  - Clock: 40 MHz
  - I_{krum}: 10

Pixel detectors in high-energy physics

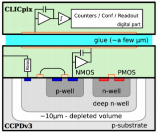
- Hybrid detectors:
  - Planar silicon sensor (High resistive & Full depletion)
  - Mixed-signal readout chip
    - Possibility for complexe signal processing
    - High timing resolution
  - Bump-bonding/flip chip
  - Widely used at the LHC experiments



- Monolithic pixel devices:
  - Integrates sensor and front-end chip
  - Sensitive region: epi-layer
  - Charge collection by diffusion
  - Handles low rates



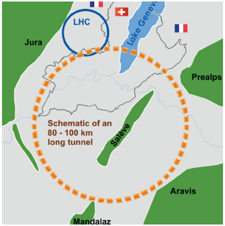
- Capacitive coupled pixel detector (CCPD):
  - Depletion layer with fast signal collection through drift.
  - No bump-bonding $\Rightarrow$ glue



For CLIC, hybrid and CCPD solutions are under investigation.

The Future Circular Collider (FCC-ee)

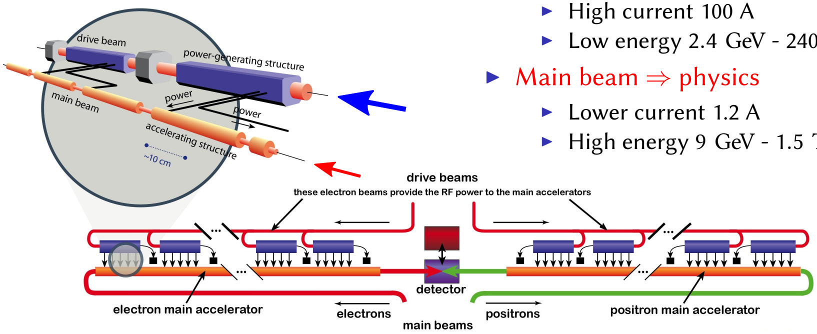
- Lepton collider in a new 80-100 km tunnel around CERN.
- Energy range $\sqrt{s}$: 90 GeV to 350 GeV
  $\Rightarrow$ Z-pole, W pair production threshold, Higgs resonance, $t\bar{t}$ threshold
- FCC-hh: for proton-proton collisions $\sqrt{s}$ is up to 100 TeV.



Two-beam acceleration scheme at CLIC

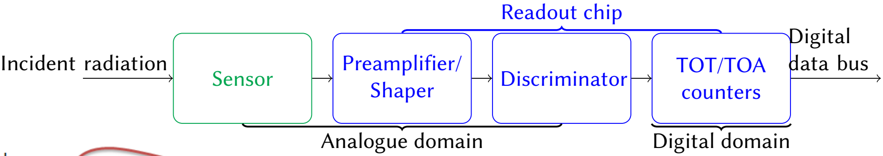
- High-gradient acceleration of 100 MV/m at 12 GHz with copper cavities at room temperature
  (→ LHC: 5 MV/m and 400 MHz)
  - Limit the length of the accelerator
  - Drive beam decelerated and the energy is fed via an RF field in a waveguide to the main beam.

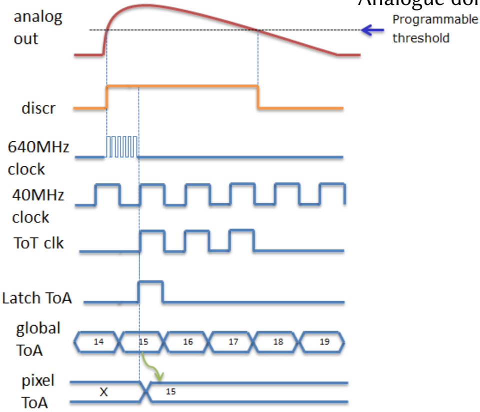
- Drive beam ⇒ RF power
  - 12 GHz bunch structure
  - High current 100 A
  - Low energy 2.4 GeV - 240 GeV
- Main beam ⇒ physics
  - Lower current 1.2 A
  - High energy 9 GeV - 1.5 TeV



The Timepix3 readout chip

- Test vehicle for thin sensors: sensor & Timepix3 readout ASIC





- Matrix of 256 $\times$ 256 pixels
- 55 μm pixel pitch (130 nm CMOS technology)
- Simultaneous measurement:
  - Time-over-threshold (TOT), 10 bit $\Rightarrow$ energy
  - Time-of-arrival (TOA), 18 bit $\Rightarrow$ time
- Electronic noise: $\sim$ 80 e$^-$ RMS
  - Operating threshold: $\sim$ 500 e$^-$