Test-beam characterisation and simulations for hybrid-pixel readout assemblies with ultra-thin sensors for the CLIC vertex detector

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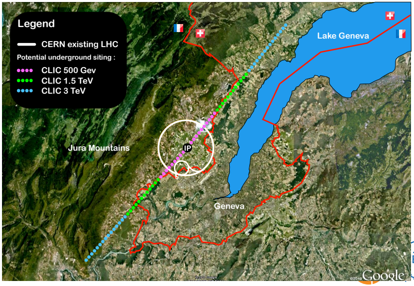
Overview

1. Introduction to CLIC
2. Requirements for the CLIC vertex detector
3. R&D on sensor and readout
4. GEANT4 simulations and digitisation
5. Active-edge sensor optimisation studies
6. Summary

The Compact Linear Collider (CLIC)

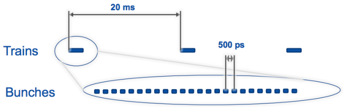
- CLIC is a concept for a future e^+e^- linear collider.
- Energy range: 350 GeV to 3 TeV.
- Provides precision measurements of:
  - Standard Model processes (Higgs, top).
  - new physics potentially discovered at 13-14 TeV LHC.
  - search for new physics: unique sensitivity to particles with electroweak charge.

- A possible staged realisation of CLIC on the CERN site (with a site length of 48 km for 3 TeV):
  - two-beam acceleration scheme to reach high gradients of $\sim$100 MV/m.



Beam profile

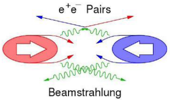
- For CLIC:
  - Bunch crossings (BX): every 0.5 ns.
  - Train duration: 156 ns (312 bunches).
  - Train repetition: 20 ms (50 Hz).



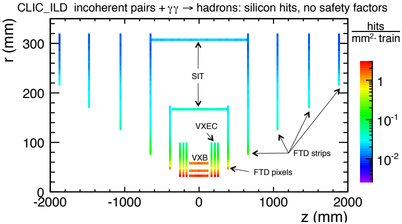
- Short train duration implies:
  1. triggerless readout of the detectors.
  2. power pulsing: allows to reduce the average power dissipation.

	CLIC at 3 TeV	LHC at 14 TeV
BX separation [ns]	0.5	25
Crossing angle	20 mrad	200 μrad
Instantaneous luminosity [$cm^{-2}s^{-1}$]	6×10^{34}	1×10^{34}
1st trigger level [#selected:#total events]	1:1	∼1:400
Data rate after 1st trigger level [GBytes/s]	200	200

Beam-induced backgrounds at CLIC



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



- 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: $10^{15} n_{eq}/cm^2/yr$)

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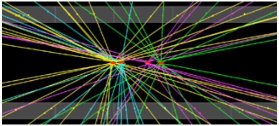
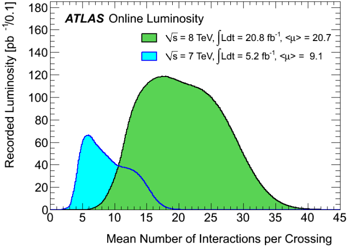
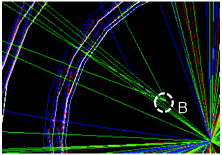
Interaction point (IP)

- For LHC:
  - the IP is smeared over $\sim 5\,\text{cm}$.
  - At current configuration: > 20 vertices per each BX (at 40 MHz).





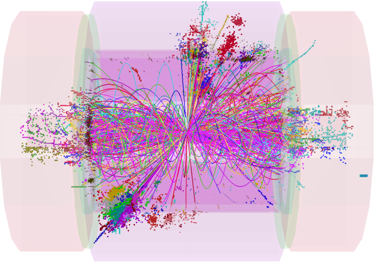
- For CLIC:
  - The IP is point like and can be used as constraint for the track reconstruction.
  - With 312 BXs/train, the beam-induced background overlaps at one interaction point. We are interested in the reconstruction of secondary vertices.

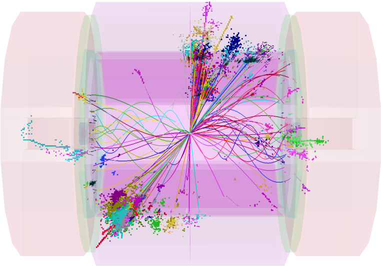


	CLIC at 3 TeV	LHC at 14 TeV
IP size in x/y direction [nm]	45/1	15000/15000
IP size in z direction [μm]	44	50000

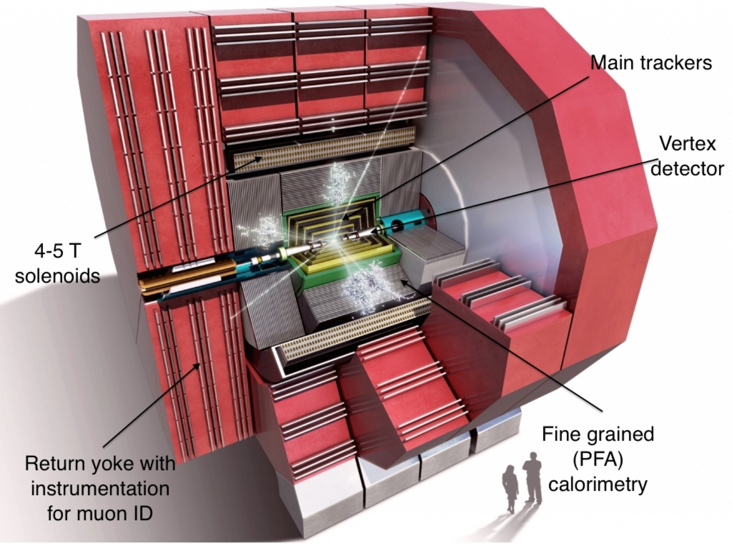
Background rejection

- Time slicing of ∼ 10 ns in the vertex detector and ∼ 1 ns in calorimeters allows to reduce the impact of beam-induced backgrounds on interesting physics events in a bunch of 156 ns.
- The background is suppressed offline.
- Reconstructed particles in a simulated $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$:
  - 60 BX $\gamma\gamma \rightarrow$ hadrons: 1.4 TeV background
  - After tight timing cuts: 0.1 TeV background

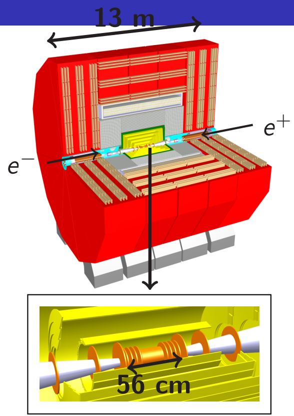




CLIC detector concept

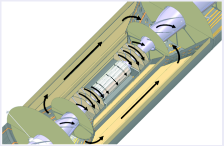


Vertex detector requirements



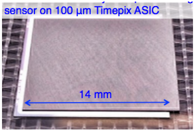
- Efficient tagging of heavy quarks through a precise determination of displaced vertices can be achieved by:
  - multi-layer VXD: 5-6 layers in the barrel and 4-6 disks $\Rightarrow$ ongoing optimisation studies.
  - single point resolution of $\sim 3\,\mu m$ achievable with pixel pitches of $25\,\mu m \times 25\,\mu m$, analog readout (CMS pixels: $100\,\mu m \times 150\,\mu m$).
  - $< 0.2\%$ X_0 for the beam-pipe and each detection layer $\Rightarrow$ implies:
    - no active cooling elements can be placed in the vertex detector ▸ forced airflow cooling
    - power dissipation of the readout electronics $\approx 50\ mW/cm^2$ ▸ power pulsing

airflow cooling

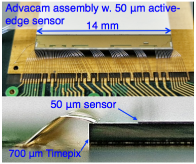


R&D on sensor and readout

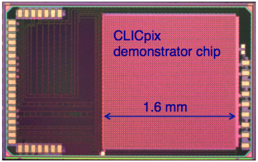
- The ultimate goal for CLIC:
  - low material budget and small pitch: 50 µm sensor on 50 µm ASIC with 25 µm pixel pitch.



- Thin-sensor R&D:
  - Timepix chips (55 µm pixel pitch) are used to study the feasibility of ultra-thin sensors.
  - use simulations to extrapolate to pixels with a pitch of 25 µm.

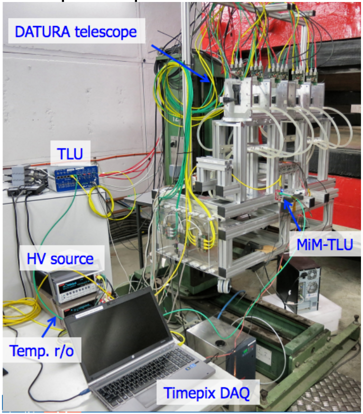


- CLICpix chip demonstrator:
  - matrix of 64 × 64 pixels, 25 µm pixel pitch.
  - 65 nm CMOS technology
  - simultaneous measurement of time of arrival (TOA) and time over threshold (TOT) per pixel.
  - compatible with power pulsing scheme.
  - selectable compression logic.

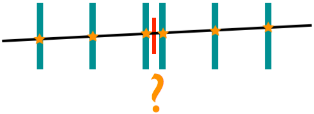


Ultra-thin sensor assemblies and test beams

- Test-beam campaign at DESY in 2013-2014: test assemblies with 50 µm-300 µm sensors on 100 µm-750 µm Timepix chip thickness.



- DESY II beam: 1-6 GeV electron.
- The EUDET telescope is used to reconstruct the tracks and extrapolate them on the device under test (DUT).
- The telescope contains 6 planes of Mimosa26 pixel sensors with a tracking resolution of ∼3 µm at 5.6 GeV.
- The DUT is placed between layer 3 and 4 of the telescope with the possibility of rotation.



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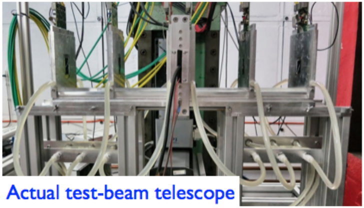
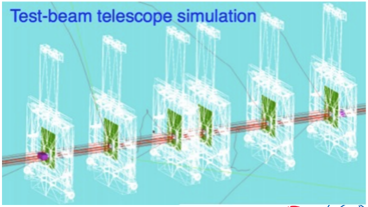
ALLPix simulation framework

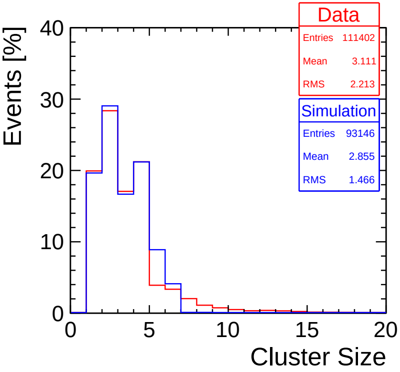
- ALLPix: a general purpose pixel detector simulation framework (in C/C++) based on GEANT4.
- Fully customisable detector geometry:
  - thickness, pitch, bump geometry, material
- Used as a digitiser test bench for ATLAS and CLICdp.
- Digitisers for the test-beam simulation:
  - Mimosa26 digitiser for the telescope planes ⇒ based on data.
  - Timepix digitiser ⇒ based on semiconductor physics.
- Goal:
  - simulate the test-beam setup.
  - extrapolate results for small-pitch pixels.
  - improve digitisation models for full-detector simulation.

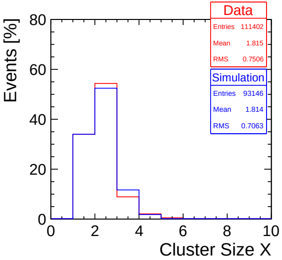

Actual test-beam telescope

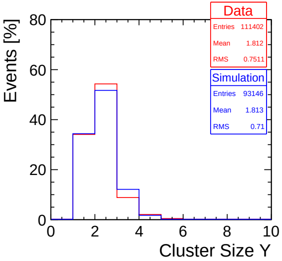

Test-beam telescope simulation

Telescope simulation vs. data: cluster sizes

- Simulation of the telescope (without DUT)
- The digitiser for the telescope sensors (Mimosa26) is tuned to match the data.

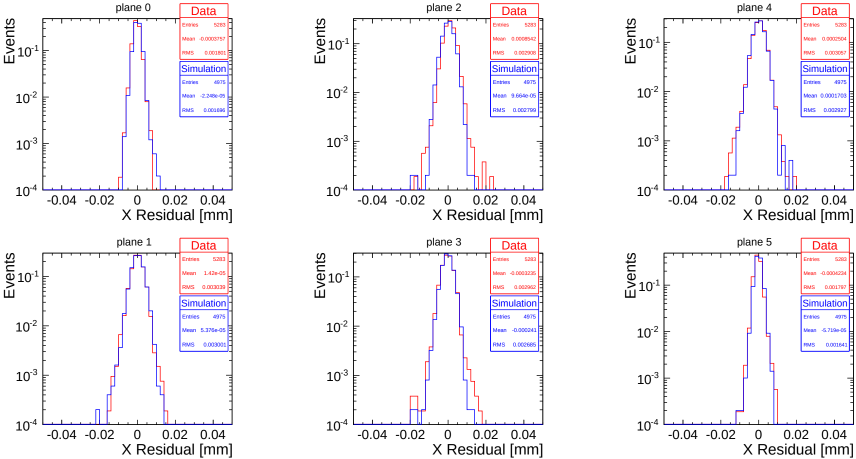






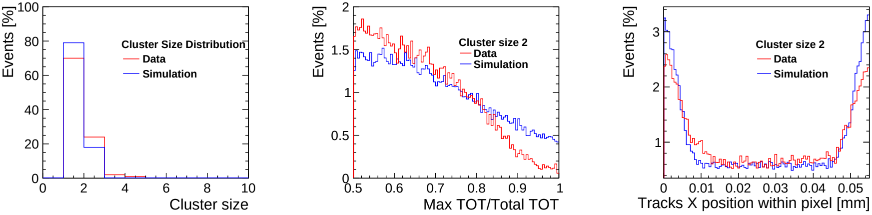
Telescope simulation vs. data: residuals

- The simulation and the data have very similar tracking resolution after the tuning of the simulation.



DUT simulation vs. data

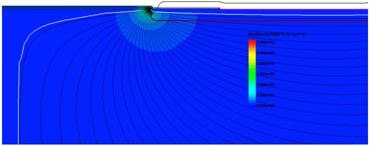
- GEANT4 provides the passing of particles and the energy deposited by ionisation.
- Timepix digitiser simulates:
  - semiconductor physics using theoretical models and TCAD simulations.
  - the Timepix chip (analog and digital parts). ▸ work in progress
  - sensor and ASIC noise. ▸ work in progress
- For 100 µm sensor on 750 µm Timepix (without including noise in simulation) with V_{bias}=35 V (over-depleted sensor) and 5.6 GeV electrons:



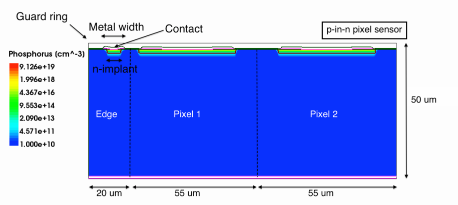
- More tuning is needed for the simulation of the DUT for a better match with data!

Active-edge sensor optimisation studies

- Active edge sensors can reduce significantly the material budget and the dead areas of the detector.
- To control the voltage at the edge, an implantation is done on the sidewall ⇒ the DRIE (deep reaction ion etching) process.
  - extends the backside electrode to the edge.
  - a voltage drop between the edge and the first pixel is created ⇒ early breakdown in silicon for electric fields higher than 3×10^5 V/cm.



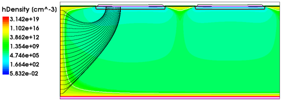
- Guard rings: establish a smooth voltage drop between the edge and the first pixel.

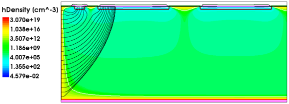


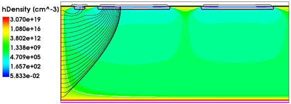
Guard ring solutions

- TCAD simulation tools are used to model semiconductor devices fabrication and device operation.

- No guard ring
- Grounded guard ring
- Floating guard ring







- No guard ring: a break down can occur for $V_{bias} = -50\ V$ on the edge of the first pixel.
- Grounded guard ring: the E-field is significantly reduced on the first pixel but a part of the signal in the edge region is lost (it is collected by the guard ring).
- Floated guard ring: a breakdown risk still exists for very high bias voltages but the inactive region is highly minimised.
- Assemblies with active-edge sensor from Advacam are under process.

Summary

- Challenging demands on the CLIC vertex detector
- Validation of GEANT4 simulation models with test-beam results
- Sensor layout optimisation based on TCAD simulations

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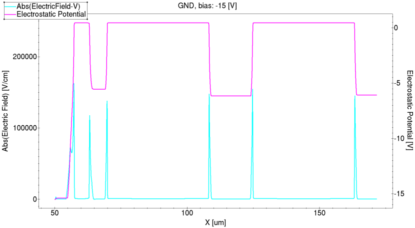
Backup slides

Guard ring solutions: Electric field and potential

- Grounded guard ring increases the depletion region but a part of the signal in the edge region is lost.



- Floated guard ring creates a compromise between the depletion region and the inactive region.