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AIDA-2020

Advanced European Infrastructures for Detectors at Accelerators

Presentation

Silicon pixel-detector R&D for CLIC

Nurnberg, Andreas (CERN)

06 September 2016

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This work is part of AIDA-2020 Work Package **7: Advanced hybrid pixel detectors**.

Silicon pixel-detector R&D for CLIC

Andreas Nürnberg
on behalf of the CLICdp collaboration

8th International Workshop on
Semiconductor Pixel Detectors for Particles and Imaging
Sestri Levante, Italy
5.-9. September 2016

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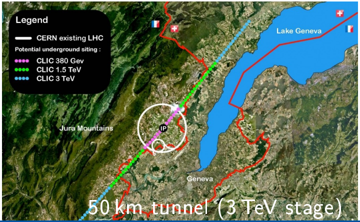
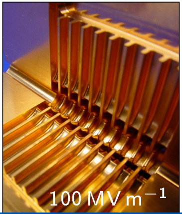
CLIC

- CLIC (Compact LInear Collider): linear e^+e^- collider proposed for the post HL-LHC phase
- Energy range from a few hundred GeV up to 3 TeV, staged construction
- Physics goals:
  - Precision measurements of SM processes (Higgs, top)
  - Precision measurements of new physics potentially discovered at 14 TeV LHC
  - Search for new physics: unique sensitivity to particles with electroweak charge

Possible layout near Geneva

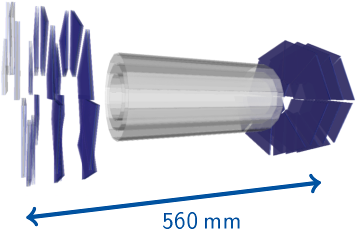


CLIC accelerating structure



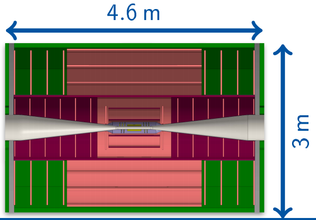
CLIC vertex and tracker detector

- Vertex detector
  - Efficient tagging of heavy quarks → precise determination of displaced vertices
  - 3 µm single point resolution, fine pitch, ≤ 25 µm × 25 µm pixel size,
  - Limited material budget, 0.2 %X_0 per detection layer, 50 µm sensor + 50 µm ASIC
  - Hybrid concept under study with either planar or active sensor
- Tracker
- Both



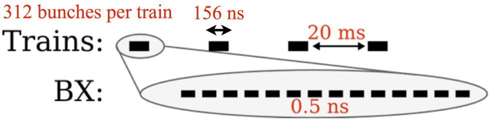
CLIC vertex and tracker detector

- Vertex detector
- Tracker
  - Good momentum resolution, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}\,\text{GeV}^{-1}$, 7 μm single point resolution
  - 4 T field, large radius, large sensitive area
  - 1 %X_0 to 2 %X_0 per detection layer
  - Larger cell sizes, $\sim 50\,\mu\text{m} \times 1 - 10\text{mm}$, limited by occupancy from beam induced background particles
  - Pursue also monolithic solution
- Both



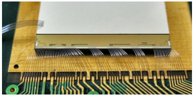
CLIC vertex and tracker detector

- Vertex detector
- Tracker
- Both
  - 20 ms gaps between bunch trains
  - Trigger-less readout
  - Pulsed power operation
  - 10 ns time slicing
  - moderate radiation exposure: 10^{-4} LHC

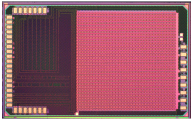


Technology R&D programme

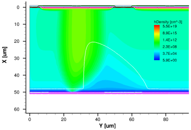
Sensors



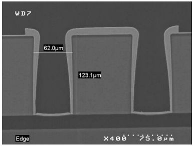
Readout ASICs



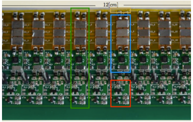
Simulations



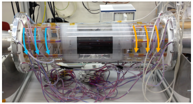
Interconnects



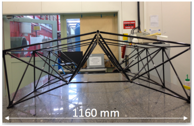
Powering



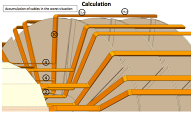
Cooling

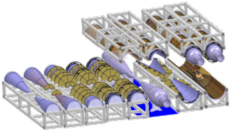


Light-weight supports



Detector integration

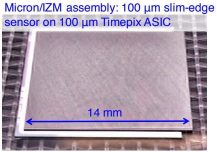


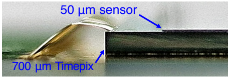


→ Integrated R&D effort addressing CLIC vertex and tracker detector

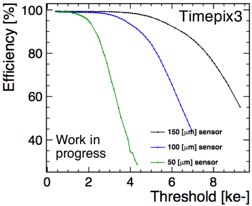
Today: focus on sensor and readout technology

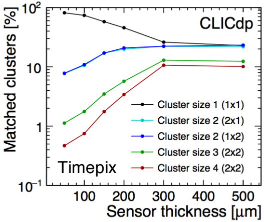
Thin sensor test beam results

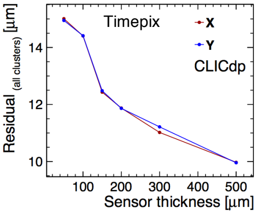




- Test beam studies on sensor assemblies with different thickness (Micron, Advacam) using Timepix(3) readout ASICs, 55 µm pitch
- Thinnest assembly: 100 µm sensor on 100 µm Timepix ASIC
- Study performance of thin planar sensors
  - High detection efficiency even for 50 µm thin sensor under normal operating conditions
  - Resolution limited by cluster size in thin sensors



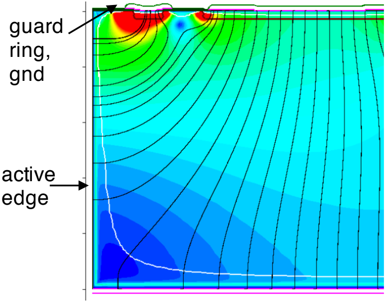




Active edge sensors

- Study feasibility of thin sensors with active edge using Timepix3 readout ASICs
- Advacam MPW with 50 μm to 150 μm thick n-in-p sensors
- The DRIE (Deep Reactive-Ion Etching) process is used to cut an active edge silicon sensor
- Implantation on the sidewall of the sensor ⇒ extension of the backside electrode on the edge

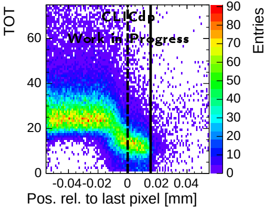
T-CAD simulation of electric field in the edge region



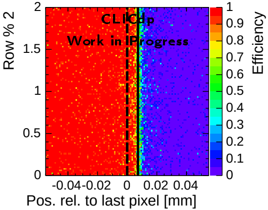
Active edge sensors: results

- Comparing different edge layouts: without guard ring (GR), floating GR and grounded GR
- Signal loss to grounded GR
- Device without GR and with floating GR is fully efficient up to the physical edge of the sensor
- Efficiency loss in thin sensors with grounded GR, in agreement with TCAD simulations

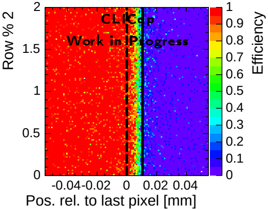
50 µm thick, grounded guard ring



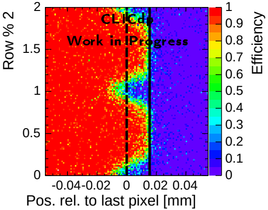
50 µm thick, no guard ring



50 µm thick, floating guard ring

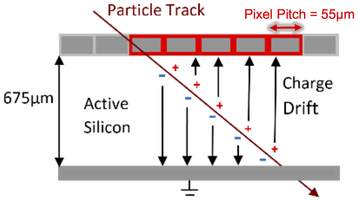


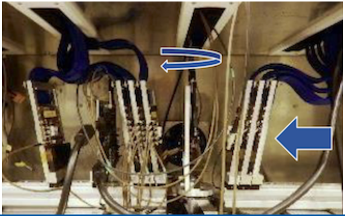
50 µm thick, grounded guard ring



Single layer track reconstruction using drift-time

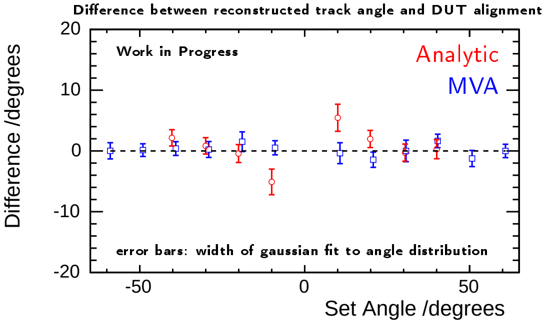
- Idea: use good time binning of Timepix3 (1.5 ns) to extract depth of charge deposit from measured drift-time
- Track reconstruction like in a time projection chamber using a single detection layer
- Proof-of-principle using angle scan on 675 µm thick p-in-n sensor in CLIC Timepix3 telescope
- Possible applications in CLIC tracker
  - rejection of background from back-scattered and low-momentum particles
  - improvement of pattern recognition / track reconstruction





Single layer track reconstruction using drift-time

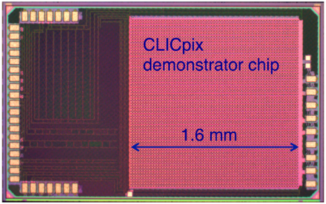
- Two analysis methods
  - Analytic: using mobility parameterization to extract drift distance
  - Machine learning: use known track angle from alignment to train neuronal network. Use as much available information as possible (time gradient, cluster size, cluster energy). Not yet fully optimized



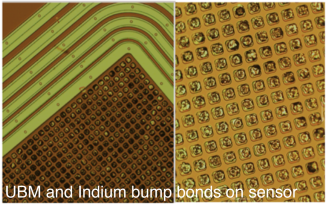
- Use case for CLIC tracker currently under study: test thinner sensors

CLICpix planar sensor assemblies

- CLICpix
  - Timepix/Medipix chip family
  - 65 nm technology
  - Demonstrator chip with 64x64 pixels
  - Pitch of 25 µm
  - Simultaneous 4-bit ToT and ToA

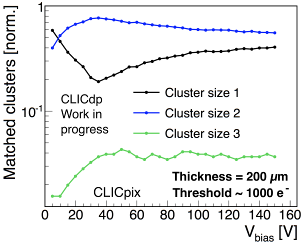


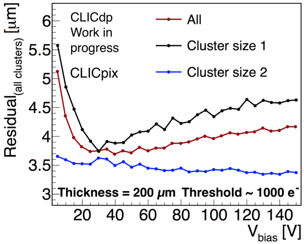
- Test assemblies produced with 200 µm, 150 µm and 50 µm n-in-p CLICpix sensors
  - Single-chip bump-bonding process for 25 µm pitch developed at SLAC
  - 200 µm assembly tested in AIDA telescope at SPS
  - Data taking on 50 µm assembly in Timepix3 telescope took place last week



CLICpix planar sensor assemblies

- Results for 3 test assemblies with 200 μm Micron sensors:
  - 0.2 % to 3 % unconnected channels
  - 1 % to 2 % shorted channels
- Test-beam measurements:
  - Operation threshold ∼ 1000 e^-, Vdep ∼ 35 V
  - High detection efficiency (>99.5 %)
  - ∼ 20 % single-pixel clusters at Vdep
  - ∼ 4 μm single-point resolution
- Characterization of assembly with 50 μm thin Advacam active-edge sensor ongoing

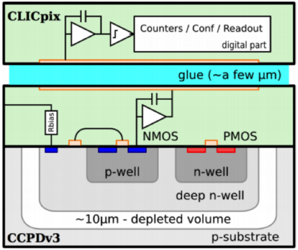




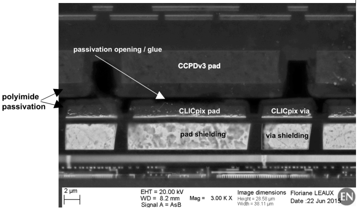
HV-CMOS active sensor with capacitive coupling

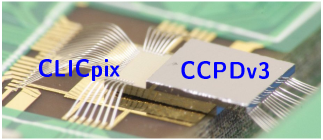
Capacitive coupled pixel detector (CCPDv3) used as active sensor

- CCPDv3 chip is capacitively coupled to the CLICpix readout ASIC via a thin layer of glue ⇒ no bump-bonding
- 180 nm HV-CMOS process
- Deep n-well shields electronics from substrate bias
- Two-stage amplifier in each pixel, 120 ns rise time
- 60 V reverse bias ⇒ create a depletion layer, fast signal collection by drift



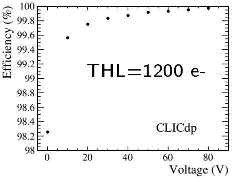
SEM picture CCPDv3-CLICpix assembly

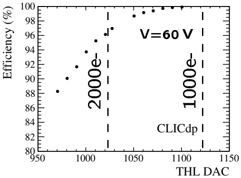


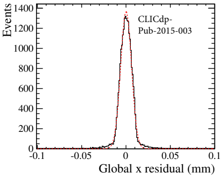


CCPDv3-CLICpix test-beam results

- High detection efficiency even without bias and 1000 e- threshold
- 6.1 μm single-point resolution ($\sim$ 1.6 μm telescope resolution unfolded)



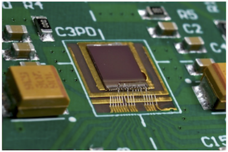




- Proof of principle for feasibility of capacitively coupled hybrid pixel detectors

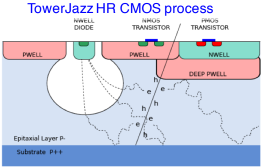
- Improved CLICpix2 readout ASIC (128 × 128 matrix) and matching HV-CMOS sensor (C3PD) are being produced
- First standalone characterization of new active sensor shows expected performance
  - Measured amplifier rise time: 20 ns

Thinned (50 μm) C3PD chip



Integrated CMOS pixel detectors: HR CMOS

- TowerJazz 180 nm High-Resistivity CMOS
  - Quadruple well process with full CMOS: n-wells shielded by deep p-wells
  - 15 µm to 40 µm / 1 kΩ cm to 8 kΩ cm epitaxial layer, not fully depleted (Vbias $\leq$ 6 V)
- ALICE Investigator analog test chip
  - Pixel sizes: 20x20 μm^2 to 50x50 μm^2
  - Optimization of collection-diode geometry to minimize capacitance ($\sim$ 2 fF)
  - Readout with external sampling ADCs



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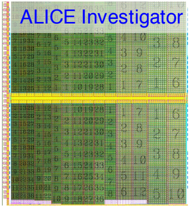

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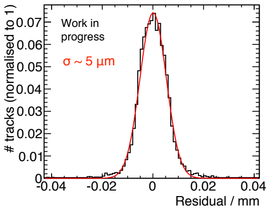
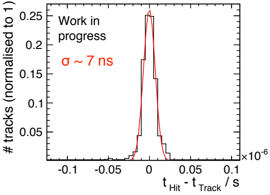
  - Pixel sizes: 20x20 µm^2 to 50x50 µm^2
  - Optimization of collection-diode geometry to minimize capacitance ($\sim$ 2 fF)
  - Readout with external sampling ADCs
  - Integration in CLIC Timepix3 test-beam setup
    - good spatial resolution: $\sim$ 5 µm at 28 µm pixel pitch
    - good time resolution: few ns

Spatial residual:

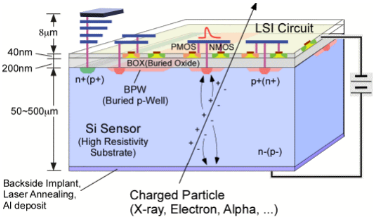


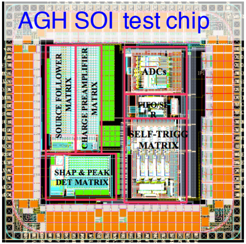
Hit time with respect to time of telescope track:



Integrated CMOS pixel detectors: SOI

- Lapis 200 nm SOI
  - CMOS sensor on Silicon On Insulator (SOI) wafers
  - Electronics on low resistivity wafer, separated by buried oxide from fully depleted high-resistivity sensing layer
- Test-chip from AGH Cracow
  - Different pixel sizes ($\geq$ 30 x 30 μm^2) and readout techniques (source follower, charge preamp., self-triggering, ...)
  - Targeted towards CLIC requirements (position, amplitude and few ns timing)
  - Integration in CLIC test-beam setup. Chip functional, first data taking finished last week, analysis ongoing





Summary

- CLIC accelerator provides
  - unique potential for discoveries and precision physics at the TeV scale
  - challenging requirements for vertex and tracker detector
- Integrated R&D effort for the CLIC vertex and tracking detector on sensors and readout chips
  - Hybrid readout with planar sensors
  - Capacitively coupled pixel detector with active sensors
  - Integrated CMOS sensors
- Not shown today: (T-CAD) simulations, mechanical integration, powering, cooling, ...

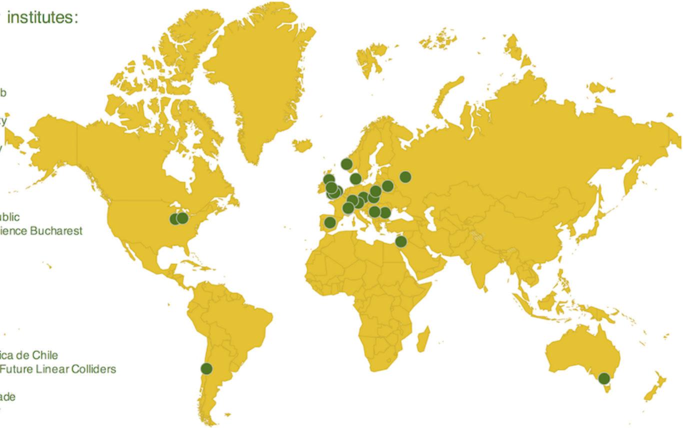
Thanks to everyone who provided material for this talk! Thank you for your attention!

Additional Material

CLIC detector and physics collaboration

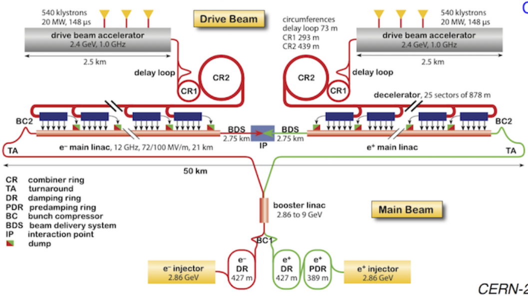
CLICdp member institutes:

- Aarhus University
- ACAS Australia
- AGH-UST Cracow
- Argonne National Lab
- Bergen University
- Birmingham University
- Bristol University
- Cambridge University
- CERN
- DPNC Geneva
- Glasgow University
- IFJPAN Cracow
- IPASCR Czech Republic
- Institute of Space Science Bucharest
- JINR Dubna
- KIT IPE Karlsruhe
- LAPP Annecy
- Liverpool University
- Michigan University
- MPI Munich
- NC PHEP Belarus
- Oxford University
- Pontificia Univ. Catolica de Chile
- Spanish Network for Future Linear Colliders
- Tel Aviv University
- Vinca Institute Belgrade
- University of Warsaw

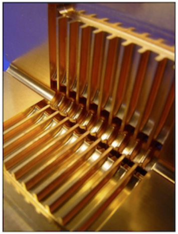


CLIC accelerator

CLIC layout at 3 TeV



CLIC accelerating structure

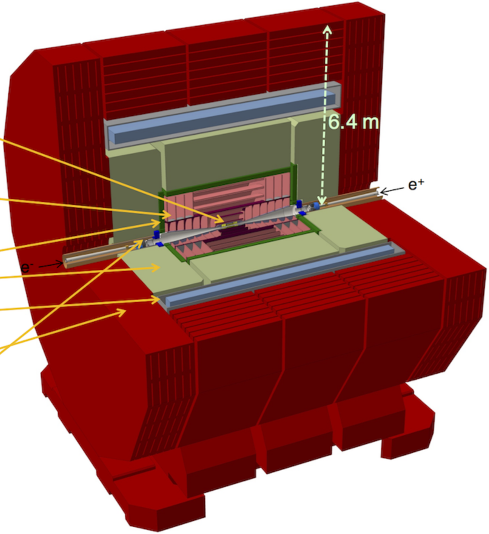


CERN-2012-007

- Linear e+e- collider
- 2-beam acceleration scheme, operated at room temperature
- Gradient: 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Luminosity: $6 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (at 3 TeV)
- Physics + Detector studies for 350 GeV - 3 TeV

CLIC detector concept

- low-mass **vertex detector** with ~25x25 µm^2 pixels
- **silicon tracker**
- fine-grained **PFA calorimetry**, 1+7.5 Λ_i W-ECAL + Fe-HCAL
- 4 T **solenoid**
- **return yoke** with muon ID
- Complex instrumented **forward region**



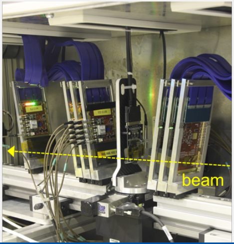
Test beam infrastructure

EUDET/AIDA telescope

- Used for initial test-beam studies at DESY II, CERN PS and CERN SPS
- Rolling-shutter readout over $\sim 230\,\mu s \rightarrow$ limited rate and timing capabilities

CERN LCD Timepix3 telescope

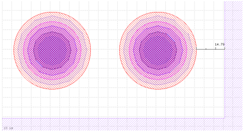
- High rate (up to 10M particles/s)
- Good tracking resolution on DUT in space ($<2\,\mu m$) and time ($\sim 1\,ns$)
- Motion and rotation stages for automatic scans



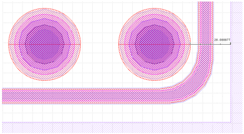
Guard ring layouts

- 4 different guard ring layouts implemented
- Edge distance is defined as the distance between the last n-implant and the cut edge

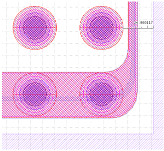
- 20 µm edge, no guard-ring



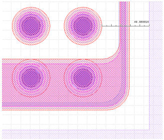
- 23 µm edge, floating guard-ring



- 28 µm edge, GND guard-ring

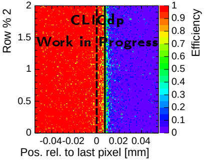


- 55 µm edge, GND guard-ring

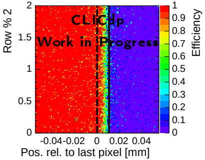


Efficiency and signal in the edge

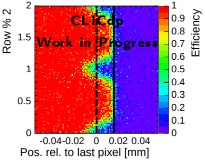
- 50 μm thick, 20-noGR



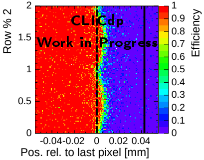
- 50 μm thick, 23-floatGR



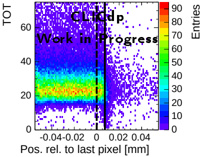
- 50 μm thick, 28-groundGR



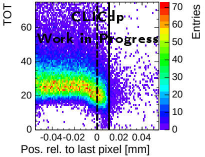
- 50 μm thick, 55-groundGR



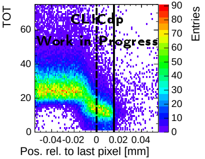
- 50 μm thick, 20-noGR



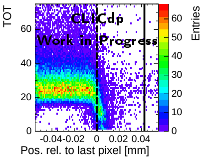
- 50 μm thick, 23-floatGR



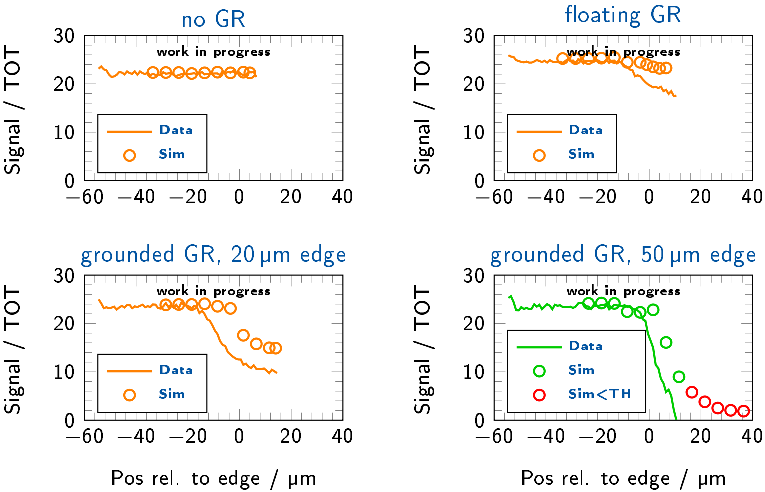
- 50 μm thick, 28-groundGR



- 50 μm thick, 55-groundGR

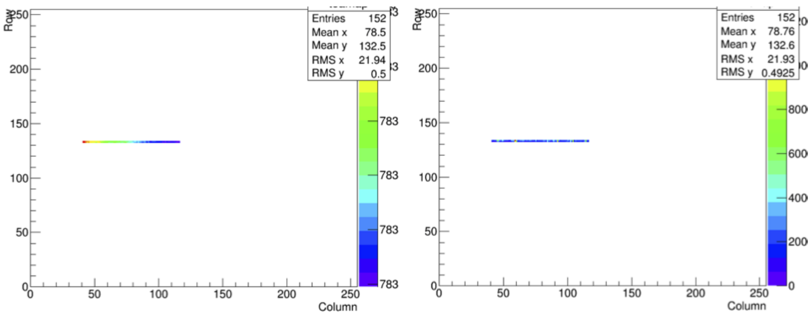


Signal in the edge - T-CAD transient simulation

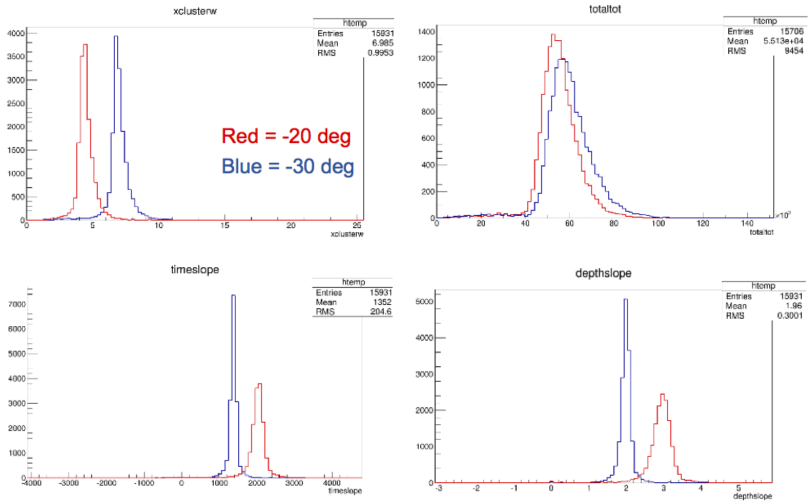


- Arbitratry signal normalization, qualitative agreement

Example: TOA and TOT at 80 degree incident

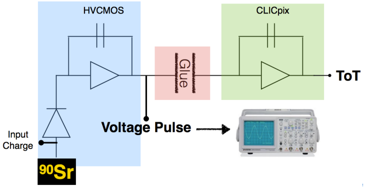


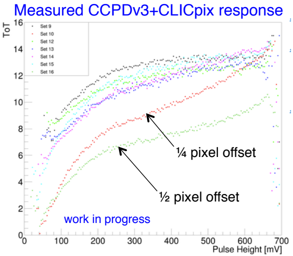
MLP input

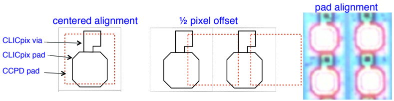

xclusterw
htemp
Entries 15931
Mean 6.985
RMS 0.9953
Red = -20 deg
Blue = -30 deg
xclusterw
totaltot
htemp
Entries 15706
Mean 5.513e+04
RMS 9454
totaltot
timeslope
htemp
Entries 15931
Mean 1352
RMS 204.6
timeslope
depthslope
htemp
Entries 15931
Mean 1.96
RMS 0.3001
depthslope

Alignment and calibration

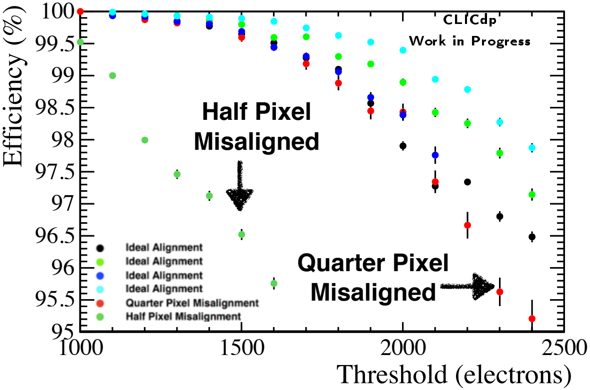
- Laboratory and test-beam measurements
- Correlate performance with glue parameters (alignment, coupling strength, uniformity)
- Dedicated test pixels: direct access to CCPDv3 output signal
- Used to calibrate CLICpix ToT response







CCPDv3-CLICpix test-beam results



- High detection efficiency at 1000 e^- threshold
- Faster degradation with threshold for misaligned assemblies shows reduced coupling capacitance and hence lower induced signal