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
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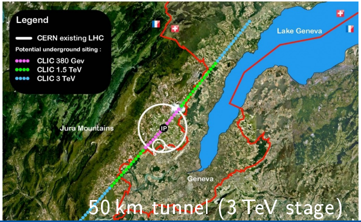
CLIC

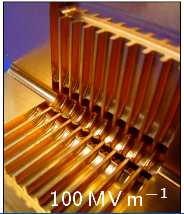
- CLIC (Compact LInear Collider): linear e^+e^- collider proposed for the post HL-LHC phase
- Energy range from a few hundred GeV up to 3 TeV, staged construction
- Physics goals:
  - Precision measurements of SM processes (Higgs, top)
  - Precision measurements of new physics potentially discovered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

Possible layout near Geneva



50 km tunnel (3 TeV stage)

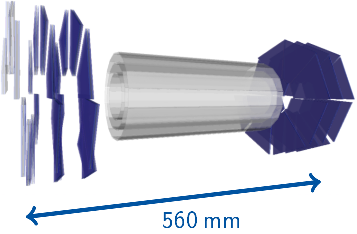
CLIC accelerating structure



$100\,\mathrm{MV\,m^{-1}}$

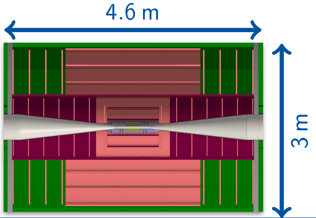
CLIC vertex and tracker detector

- Vertex detector
  - Efficient tagging of heavy quarks → precise determination of displaced vertices
  - 3 μm single point resolution, fine pitch, $\leq 25\,\mu m \times 25\,\mu m$ 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



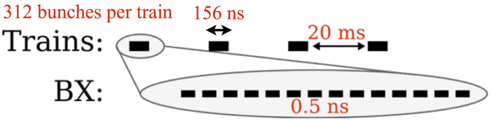
CLIC vertex and tracker detector

- Vertex detector
- Tracker
  - Good momentum resolution, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$, 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, $\sim 50\,\mu\mathrm{m} \times 1 - 10\mathrm{mm}$, limited by occupancy from beam induced background particles
  - Pursue also monolithic solution
- Both



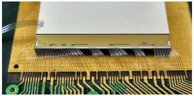
CLIC vertex and tracker detector

- 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

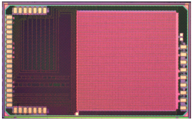


Technology R&D programme

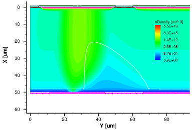
Sensors



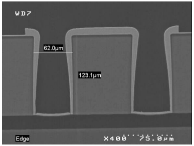
Readout ASICs



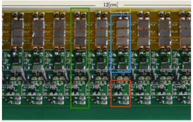
Simulations



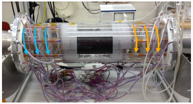
Interconnects



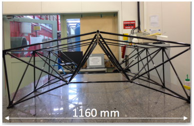
Powering



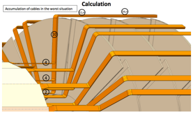
Cooling

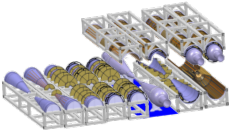


Light-weight supports



Detector integration

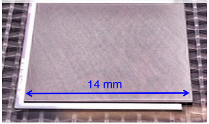


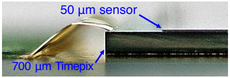


→ Integrated R&D effort addressing CLIC vertex and tracker detector
Today: focus on sensor and readout technology

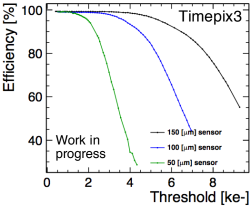
Thin sensor test beam results

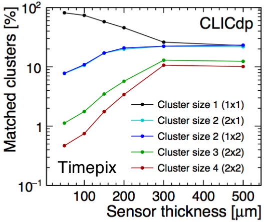
Micron/IZM assembly: 100 µm slim-edge sensor on 100 µm Timepix ASIC

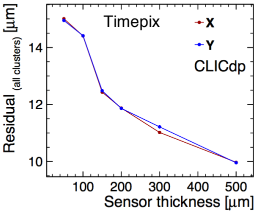




- Test beam studies on sensor assemblies with different thickness (Micron, Advacam) using Timepix(3) readout ASICs, 55 µm pitch
- Thinnest assembly: 100 µm sensor on 100 µm Timepix ASIC
- Study performance of thin planar sensors
  - High detection efficiency even for 50 µm thin sensor under normal operating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



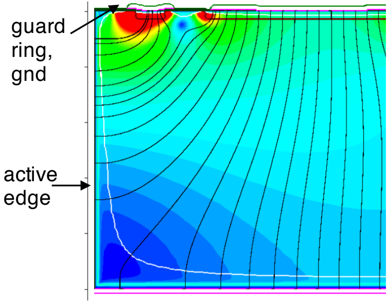




Active edge sensors

- 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

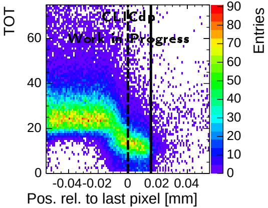
T-CAD simulation of electric field in the edge region



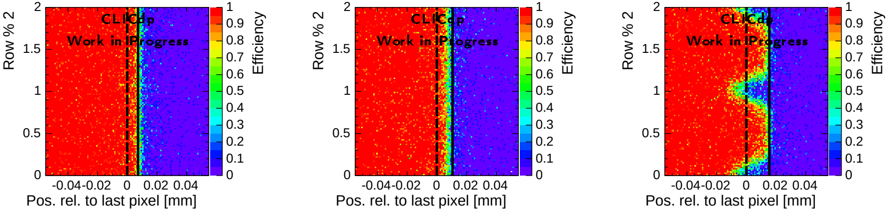
Active edge sensors: results

- 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

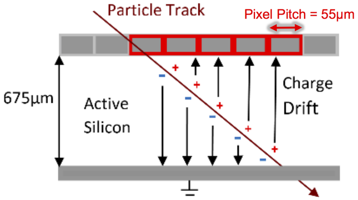


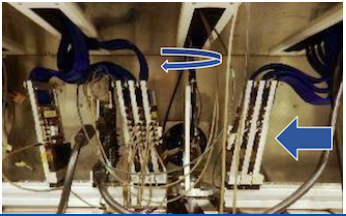
50 µm thick, no guard ring **50 µm thick, floating guard ring** **50 µm thick, grounded guard ring**



Single layer track reconstruction using drift-time

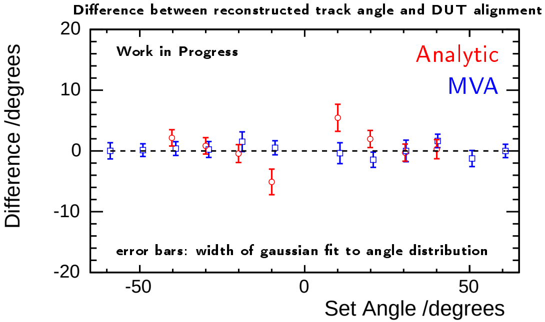
- Idea: use good time binning of Timepix3 (1.5 ns) to extract depth of charge deposit from measured drift-time
- Track reconstruction like in a time projection chamber using a single detection layer
- Proof-of-principle using angle scan on 675 µm thick p-in-n sensor in CLIC Timepix3 telescope
- Possible 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

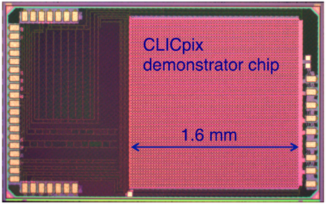
- Two analysis methods
  - Analytic: using mobility parameterization to extract drift distance
  - Machine learning: use known track angle from alignment to train neuronal network. Use as much available information as possible (time gradient, cluster size, cluster energy). Not yet fully optimized



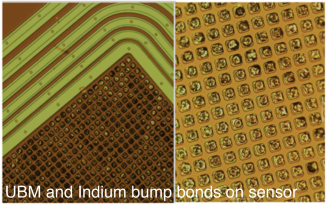
- Use case for CLIC tracker currently under study: test thinner sensors

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

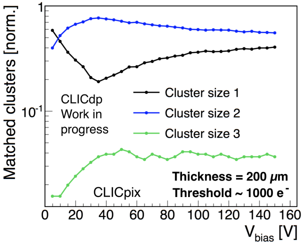


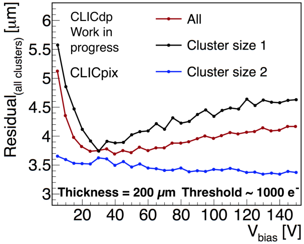
- Test assemblies produced with 200 µm, 150 µm and 50 µm n-in-p CLICpix sensors
  - Single-chip bump-bonding process for 25 µm pitch developed at SLAC
  - 200 µm assembly tested in AIDA telescope at SPS
  - Data taking on 50 µm assembly in Timepix3 telescope took place last week



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

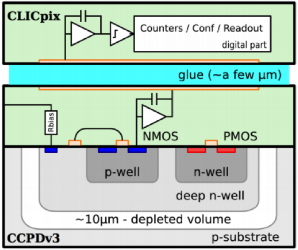


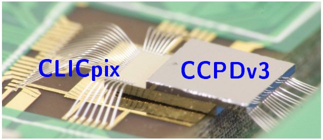


HV-CMOS active sensor with capacitive coupling

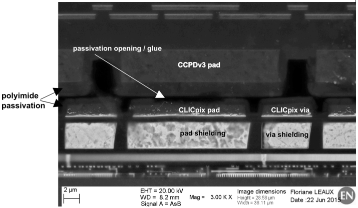
Capacitive coupled pixel detector (CCPDv3) used as active sensor

- 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



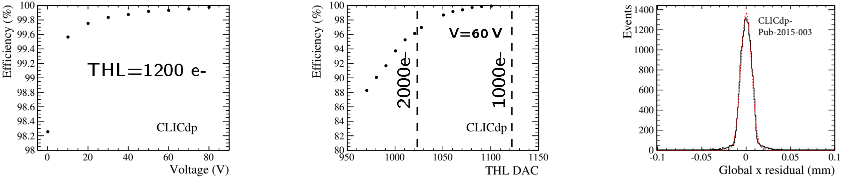


SEM picture CCPDv3-CLICpix assembly



CCPDv3-CLICpix test-beam results

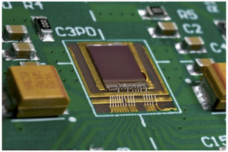
- High detection efficiency even without bias and 1000 e- threshold
- 6.1 µm single-point resolution ($\sim$ 1.6 µm telescope resolution unfolded)



- 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

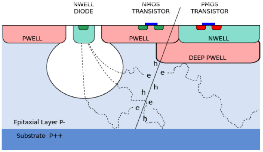
Thinned (50 µm) C3PD chip



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

TowerJazz HR CMOS process



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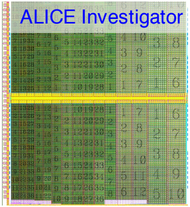

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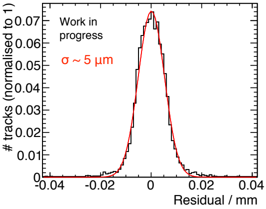
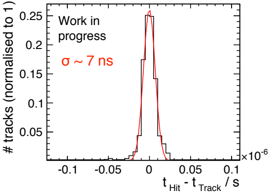
  - Pixel sizes: 20x20 µm^2 to 50x50 µm^2
  - Optimization of collection-diode geometry to minimize capacitance ($\sim$ 2 fF)
  - Readout with external sampling ADCs
  - Integration in CLIC Timepix3 test-beam setup
    - good spatial resolution: $\sim$ 5 µm at 28 µm pixel pitch
    - good time resolution: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

Spatial residual:

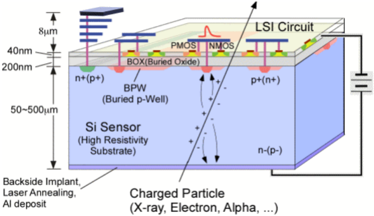


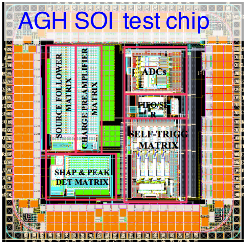
Hit time with respect to time of telescope track:



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, ...

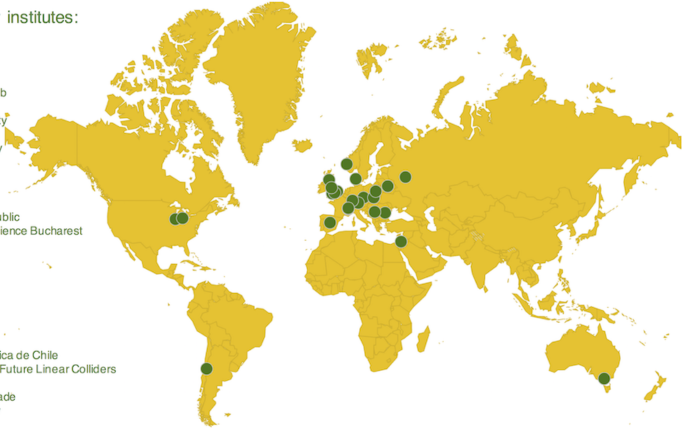
Thanks to everyone who provided material for this talk! Thank you for your attention!

Additional Material

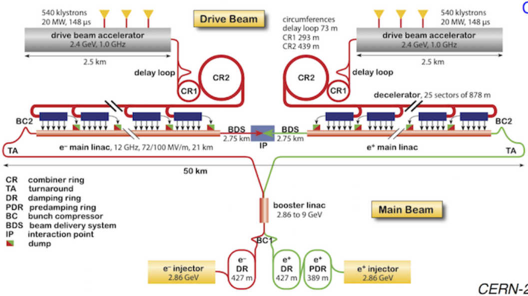
CLIC detector and physics collaboration

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

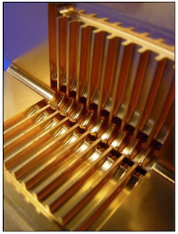


CLIC accelerator



CLIC layout at 3 TeV

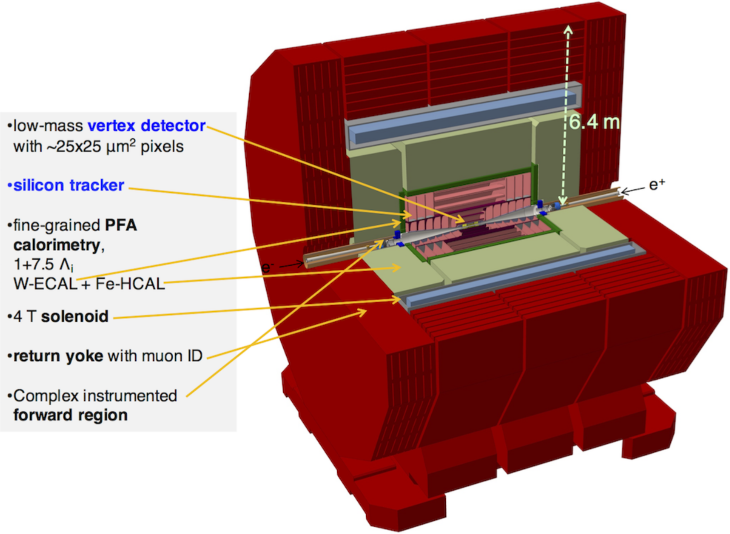
CLIC accelerating structure



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**, $1+7.5\ \Lambda_i$ W-ECAL + Fe-HCAL
- 4 T **solenoid**
- **return yoke** with muon ID
- Complex instrumented **forward region**

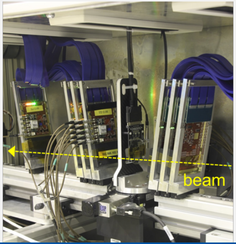
Test beam infrastructure

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

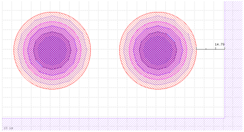
- High rate (up to 10M particles/s)
- Good tracking resolution on DUT in space ($<2\,\mu m$) and time ($\sim 1\,ns$)
- Motion and rotation stages for automatic scans



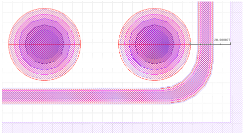
Guard ring layouts

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

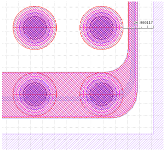
- 20 µm edge, no guard-ring



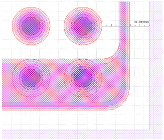
- 23 µm edge, floating guard-ring



- 28 µm edge, GND guard-ring

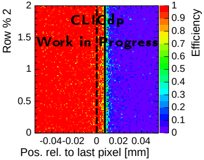


- 55 µm edge, GND guard-ring

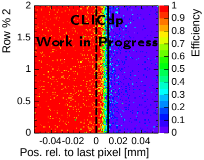


Efficiency and signal in the edge

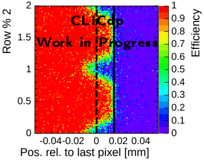
- 50 µm thick, 20-noGR



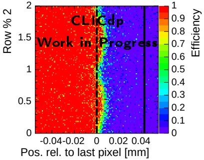
- 50 µm thick, 23-floatGR



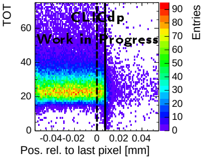
- 50 µm thick, 28-groundGR



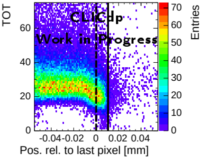
- 50 µm thick, 55-groundGR



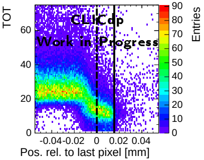
- 50 µm thick, 20-noGR



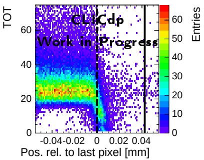
- 50 µm thick, 23-floatGR



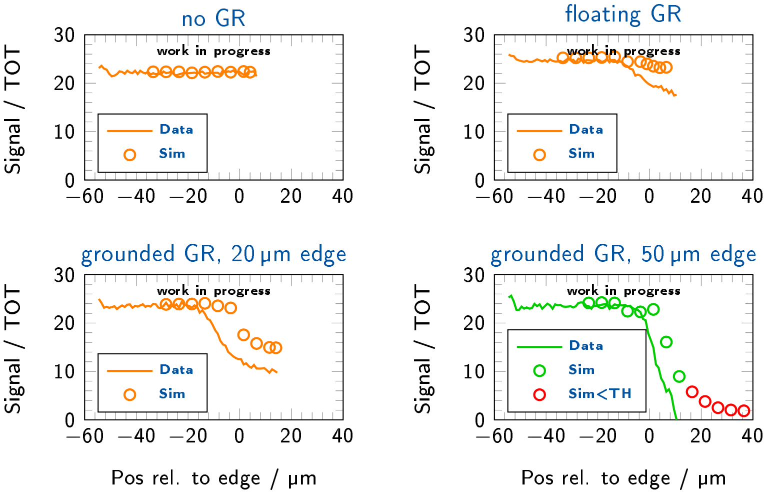
- 50 µm thick, 28-groundGR



- 50 µm thick, 55-groundGR

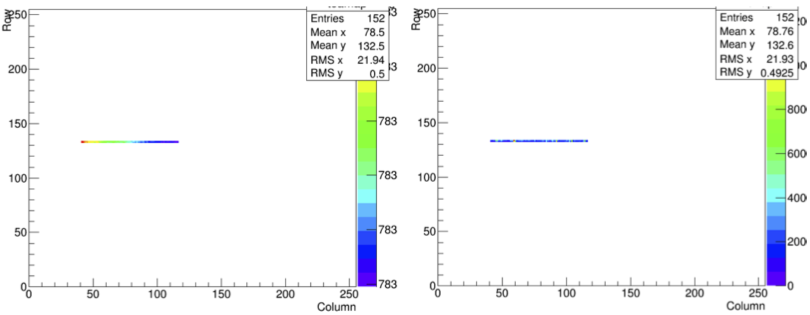


Signal in the edge - T-CAD transient simulation

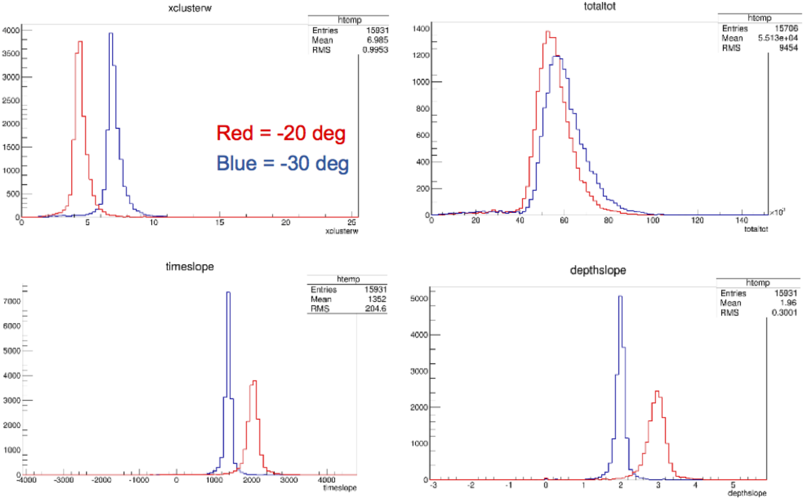


- Arbitratry signal normalization, qualitative agreement

Example: TOA and TOT at 80 degree incident

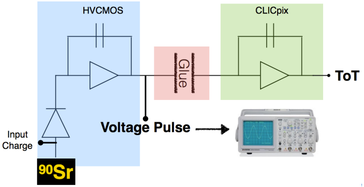


MLP input

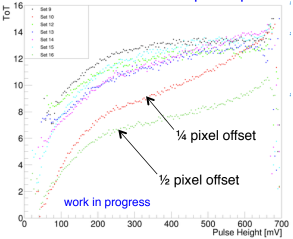

xclusterw
htemp
Entries 15931
Mean 6.985
RMS 0.9953
Red = -20 deg
Blue = -30 deg
0
500
1000
1500
2000
2500
3000
3500
4000
0
5
10
15
20
25
xclusterw
totaltot
htemp
Entries 15706
Mean 5.513e+04
RMS 9454
0
200
400
600
800
1000
1200
1400
0
20
40
60
80
100
120
140
×10³
totaltot
timeslope
htemp
Entries 15931
Mean 1352
RMS 204.6
0
1000
2000
3000
4000
5000
6000
7000
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
timeslope
depthslope
htemp
Entries 15931
Mean 1.96
RMS 0.3001
0
1000
2000
3000
4000
5000
-3
-2
-1
0
1
2
3
4
5
depthslope

Alignment and calibration

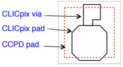
- Laboratory and test-beam measurements
- Correlate performance with glue parameters (alignment, coupling strength, uniformity)
- Dedicated test pixels: direct access to CCPDv3 output signal
- Used to calibrate CLICpix ToT response



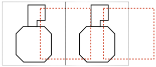
Measured CCPDv3+CLICpix response



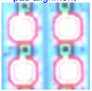
centered alignment



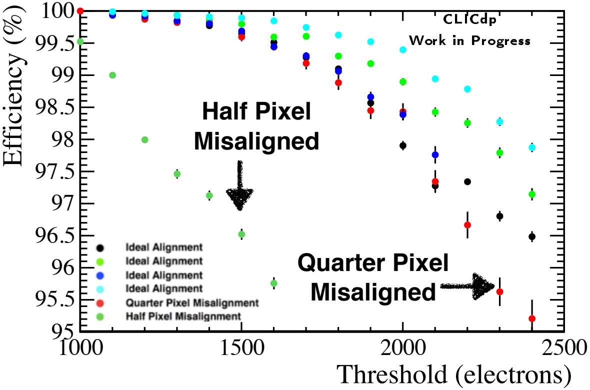
½ pixel offset



pad alignment



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