Recent results with HV-CMOS and planar sensors for the CLIC vertex detector

Niloufar Alipour Tehrani (CERN, ETH Zürich)
On behalf of the CLICdp collaboration

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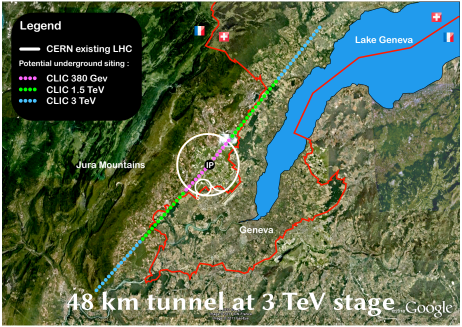
Overview

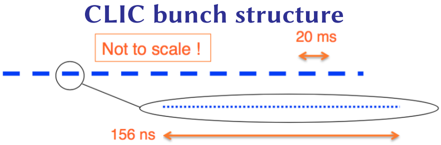
The Compact Linear Collider (CLIC)

- A concept for an e^+e^- linear collider for the post HL-LHC period.
- Energy range $\sqrt{s}$: 380 GeV to 3 TeV
  - Two-beam acceleration scheme with gradients of ∼100 MV/m.

- Precision measurements of:
  - Standard Model processes (Higgs, top).
  - New physics potentially discovered at 13 TeV LHC.
  - Search for new physics: unique sensitivity to particles with electroweak charge.



CLIC beam profile



- 1 train consists of 312 bunches with 0.5 ns spacing.

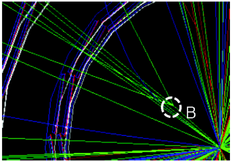
	LHC at 13 TeV	CLIC at 3 TeV
$\mathcal{L}$ $[cm^{-2}s^{-1}]$	1×10^{34}	6×10^{34}
BX separation [ns]	25	0.5
#BX/train	2808	312
Train duration	90 μs	156 ns
Train repetition	11 kHz	50 Hz
σ_x / σ_y [nm]	15000/15000	$\approx$ 45/1
σ_z [nm]	$\sim$50000	44

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

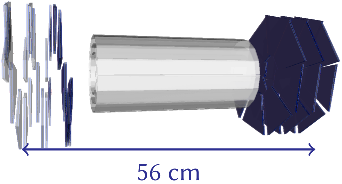
- Bunch separation and train duration: drive timing resolution and stamping requirements for the detectors.
- Very small beam sizes at the interaction point $\Rightarrow$ beam-induced backgrounds:
  - e^+e^- pairs: low p_T, forward peaked, limits the inner radius of the VXD.
  - $\gamma\gamma \rightarrow$hadrons: larger p_T particles.

CLIC vertex-detector requirements

- Efficient tagging of heavy quarks through a precise determination of displaced vertices can be achieved by:
  - Multi-layer VXD: 6 layers in the barrel and 6 disks
  - B-field: 4 T.
  - Single point resolution of ∼3 µm: 25 µm pixel pitch & analog readout.
  - Low material budget: $< 0.2\%$ X_0/layer and beam-pipe
    - forced airflow cooling & low-power electronics ($\approx$ 50 mW/cm^2)



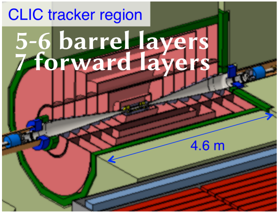
- Time slicing of ∼10 ns to reduce the impact of beam-induced backgrounds.
  ⇒ high-resistive & depleted sensors, readout with precise timing.



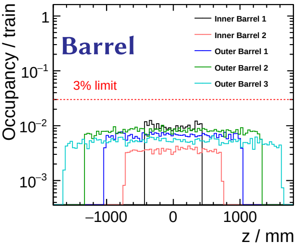
- Moderate radiation exposure of the vertex detector:
  - Total ionising dose (TID): <1 kGy/yr
  - Non-ionising energy loss (NIEL): 10^{11} $n_{eq}/cm^2/yr$ (ATLAS phase 1: 10^{15} $n_{eq}/cm^2/yr$)

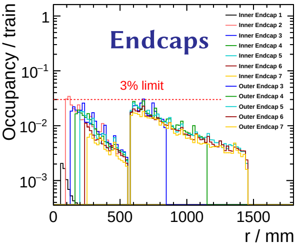
CLIC outer tracker requirements

- Momentum resolution (Higgs recoil mass, H$\rightarrow \mu\mu$, BSM leptons): $\sigma(p_\mathrm{T})/p_\mathrm{T}^2 \sim 2\times10^{-5}\ \mathrm{GeV}^{-1}$
  - 7 μm single-point resolution
  - $\sim$ 1.5 – 2%X_0/layer (low-mass supports, cabling and cooling)
- Time stamping with $\sim$10 ns accuracy to reject background.



- Beam-induced background hits from $\gamma\gamma\rightarrow$hadrons and incoherent pairs:



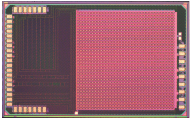


- Readout granularity defined by the backgrounds occupancy of $\sim$ 3%
  $\Rightarrow$ 50 μm pitch and 1-10 mm strip lengths.

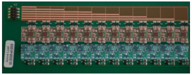
CLIC vertex-detector R&D programme

- Wide range of R&D activities for the CLIC VXD

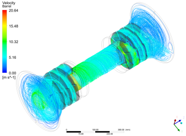
- Readout ASICs



- Powering

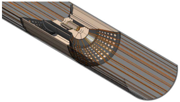


- Cooling

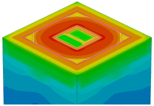


- Sensors

- Mechanical integration



- Simulations

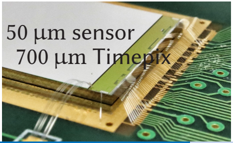


- Light-weight supports

Next slides focus on recent developments on the sensor, readout R&D and simulations.

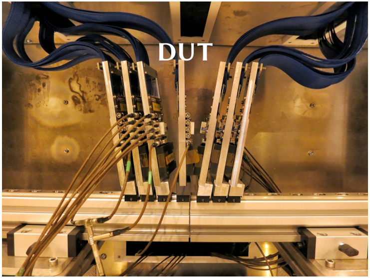
Thin planar sensor R&D

- The ultimate goal for CLIC:
  - 50 µm sensor on 50 µm readout ASIC with 25 µm pixel-pitch.
- Feasibility of thin sensors tested with Timepix/Timepix3 readout chips:
  - 55 µm pixel-pitch.
  - Simultaneous measurement of time (TOA) and energy (TOT).
- Sensor thicknesses: 50 µm to 300 µm.
- Test-beam campaigns with:
  - EUDET/AIDA telescope at DESY and CERN PS/SPS.
  - CLICpix Timepix3 telescope at CERN SPS.

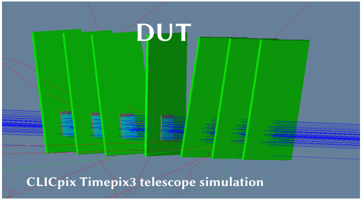


- Test-beam data is used to validate simulations and to extrapolate to pixels with a pitch of 25 µm.

- The CLICpix Timepix3 telescope for reference tracking:
  - $\sim$ 2 µm pointing resolution on the device under test (DUT) for 120 GeV pions.
  - $\sim$1 ns time resolution per plane.

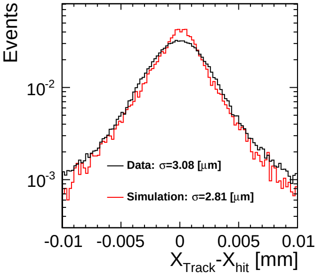


ALLPix: a GEANT4-based simulation framework



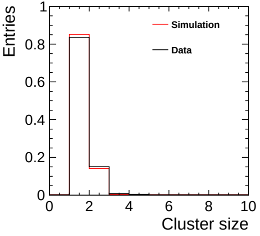
- ALLPix: a general purpose pixel-detector simulation framework (in C/C++) based on GEANT4.
- Fully customisable for detector geometry description:
  - thickness, pixel-pitch, bump geometry, material
- Digitiser test-bench for ATLAS and CLICdp.
- **Goal**:
  - Simulate the test-beam setup.
  - Extrapolate results for small-pitch pixels (e.g. CLICpix with 25 μm pitch).
  - Improve digitisation models for full-detector simulation.
- Good agreement between the Timepix3 telescope digitiser and the data.

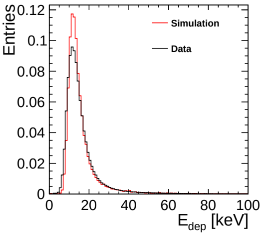
- Biased residual on the first telescope plane in x-direction:

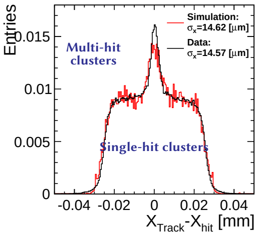


Thin sensors test-beam results & simulation

- Validation of the ALLPix simulation with test-beam results for 50 μm-thick sensor, 55 μm pitch and THL∼ 500 e- (noise RMS for simulations: 90 e-).

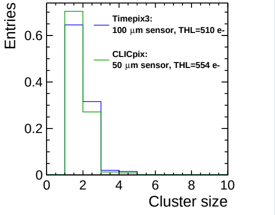


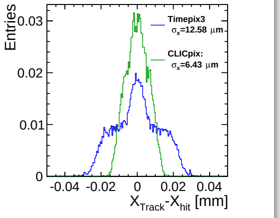




Prediction for a 50 μm sensor and 25 μm pitch in simulation:

- Including the telescope tracking resolution: $\sigma \sim 6.4$ μm
- New solutions needed to achieve the required single-point resolution of $\sigma \sim 3$ μm.

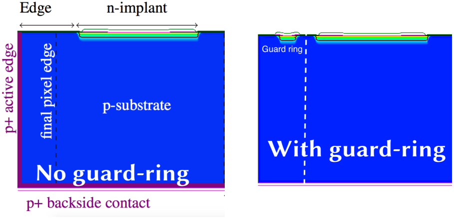




Active-edge sensors

The DRIE (Deep Reactive-Ion Etching) process is used to cut an active-edge silicon sensor.

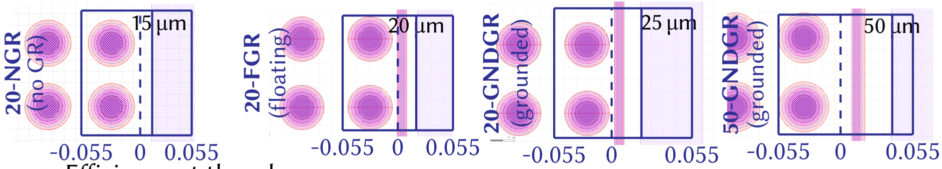
- Implantation on the sidewall of the sensor ⇒ control the potential at the edge by creating an extension of the backside electrode on the edge.
- Guard-rings: metal and n-implants to establish a smooth voltage drop between the edge and the last pixel.



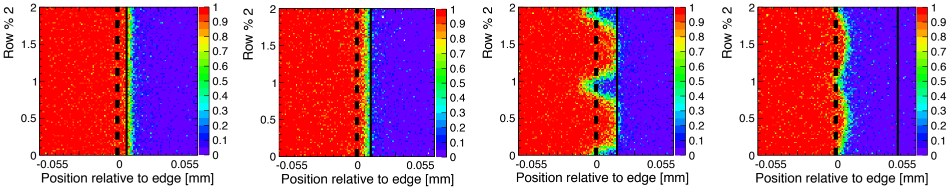
- Advacam active-edge devices (n-in-p) bump-bonded to the Timepix3 ASICs:

Assembly	Sensor thickness [μm]	Edge width [μm]	Edge type
20-NGR	50	20	No guard-ring
20-FGR	50	20	Floating guard-ring
20-GNDGR	50	20	Grounded guard-ring
50-GNDGR	50	50	Grounded guard-ring

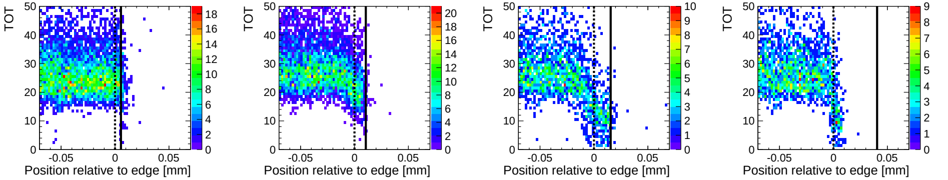
Active-edge planar sensors (50 μm): efficiency & signal



- Efficiency at the edge:

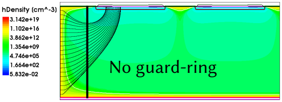


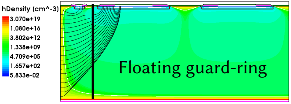
- Signal at the edge:

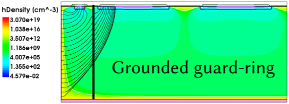


Conclusions on thin active-edge planar sensors

- Devices without guard-ring and with floating guard-ring are efficient up to the physical edge of the sensor.
- The grounded guard-ring is not suitable for thin sensors: for 20-GNDGR, the efficiency drops before the last pixel and in-between the pixels.
- For thin sensors, the floating guard-ring shows a compromise between the signal lost in the guard-ring and an acceptable breakdown behavior (leakage current).
- Ongoing TCAD simulation studies for different guard-ring solutions:

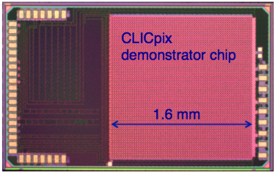






CLICpix readout ASICs demonstrator

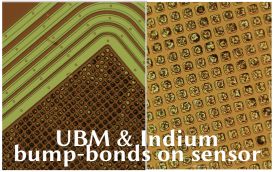
- Hybrid readout chip: 65 nm CMOS technology
- Based on Timepix3/Medipix chip family
- Intended for the CLIC vertex detector:
  - Demonstrator chip with 64×64 matrix
  - 25 μm pixel pitch
  - 4-bit time (TOA) & energy (TOT) measurement
  - Front-end time slicing < 10 ns
  - Data compression: pixel, cluster & column-based
  - Full chip readout in < 800 μs: at 10% occupancy, < 320 MHz readout clock
  - Power-pulsing scheme: $P_{avg} < 50$ mW/cm^2



- Tested with:
  - bump-bonded planar sensors
  - active HV-CMOS sensors

CLICpix: planar sensor assemblies

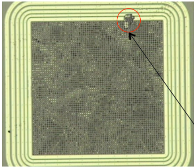
- Single-chip bump-bonding process for 25 µm pitch ⇒ developed at SLAC (C. Kenney, A. Tomada).
- 3 test assemblies produced with 200 µm n-in-p CLICpix sensors from Micron Velopix wafer.



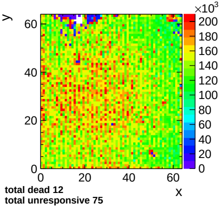
- Process flow:
  - Spin photoresist
  - Expose with contact aligner
  - Evaporator: 4 µm Indium
  - Lift-off
  - bumping

- Defects due to the indium solder bumps (did not stick everywhere):
  - 0.2-3% unconnected channels
  - 1-2% shorted channels

- Correlation between unconnected and shorted pixels with defects visible before flipping.

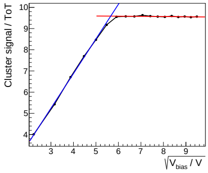


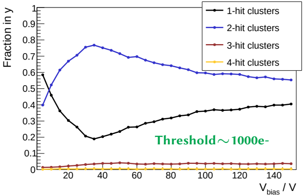
- Laboratory measurements with the ^{90}Sr source:

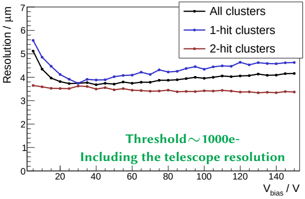


CLICpix: planar sensor test-beam results

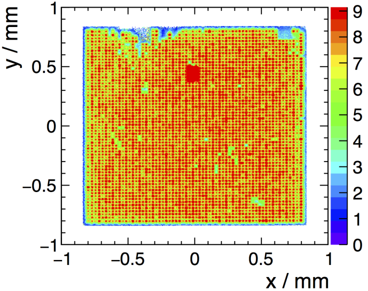
- Beam-tests with the EUDET/AIDA telescope at CERN SPS H6B
- Depletion voltage at 35 V with maximal charge sharing and best resolution of 4 μm (including the telescope resolution of 1.6 μm).





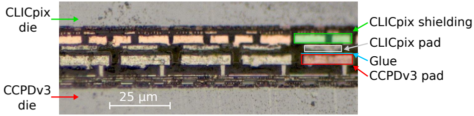


- High detection efficiency: > 99%
- Average signal of leading pixel in cluster in test-beam
  - Identification of dead and shorted pixels
  - In shorted pixels, the charge is shared ⇒ reduced.

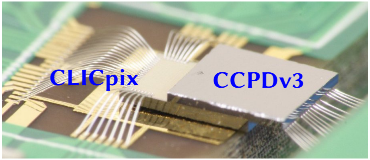


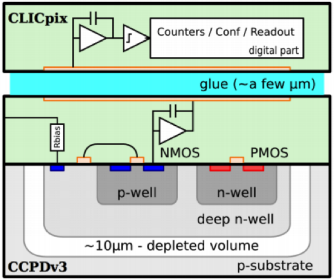
HV-CMOS active sensor with capacitive coupling

- Capacitive coupled pixel detector (CCPDv3) used as active sensor integrating sensor & amplifier
  - Commercial 180 nm HV-CMOS process.
  - Two-stage amplifier in each pixel: t_{peak}=120 ns.
  - Deep n-well shield electronics from substrate bias ⇒ prevents charge loss to electronics wells
  - Biased at 60 V ⇒ create a depletion layer with fast signal collection through drift.
  - Through a layer of glue, the CCPDv3 chip is capacitively coupled from its amplifier output to the CLICpix readout ASIC ⇒ no bump-bonding.



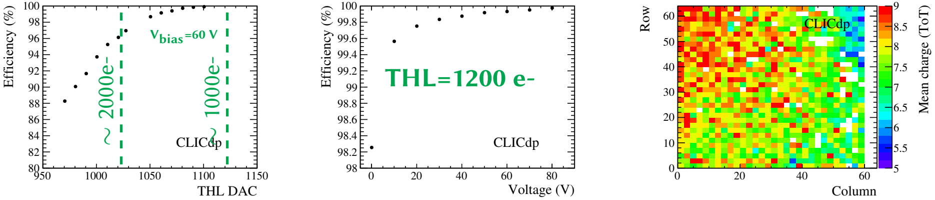
- 250 µm-thick sensor





CCPDv3-CLICpix test-beam results

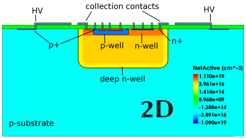
- Test-beam at CERN SPS with EUDET/AIDA telescope:
  - High detection efficiency even without bias
  - Non-uniformity of the glue thickness can be seen in the variation of the measured mean charge (TOT) across matrix
  - $\sim 6\ \mu m$ single-point resolution.

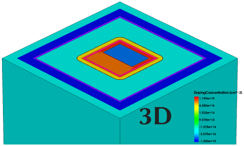


- Proof of principle for HV-CMOS sensors achieved
- Updated CLICpix2 readout ASIC (128 × 128 matrix) and HV-CMOS sensors are being produced based on the results obtained from CCPDv3 and bump-bonded planar sensors.

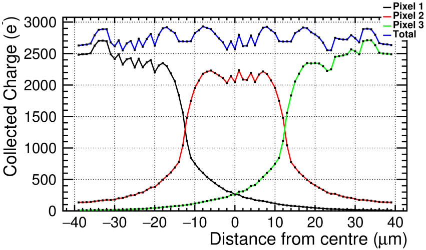
TCAD simulation of CCPDv3

- n-in-p CCPDv3 pixel layout implemented in TCAD:

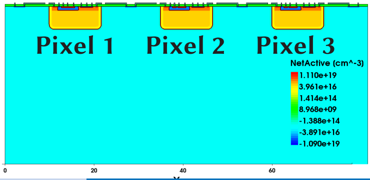




- 3D simulations used to prove 2D simulation



- MIP scan and charge collected by the neighbouring pixels after a timing integration of 100 ns:
  - Uniform charge collection
  - Diffusion to neighbouring pixels



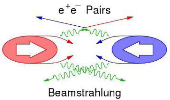
Conclusions

- Challenging requirements for the CLIC vertex detector and tracker.
- A very active R&D on sensor and readout ASICs
  - Thin planar sensors with Timepix3 readout, validation of simulations and prediction of resolution for the final CLIC requirements.
  - Different guard-ring solutions for thin active-edge sensors tested.
  - CLICpix ASICs
    - ★ Planar sensors bump-bonded successfully to fine 25 μm pitch.
    - ★ Proof of principle for the HV-CMOS active sensors achieved

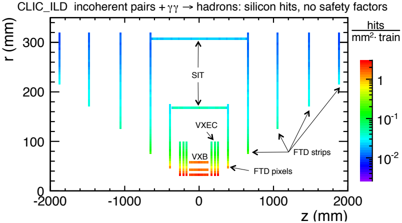
Backup slides

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

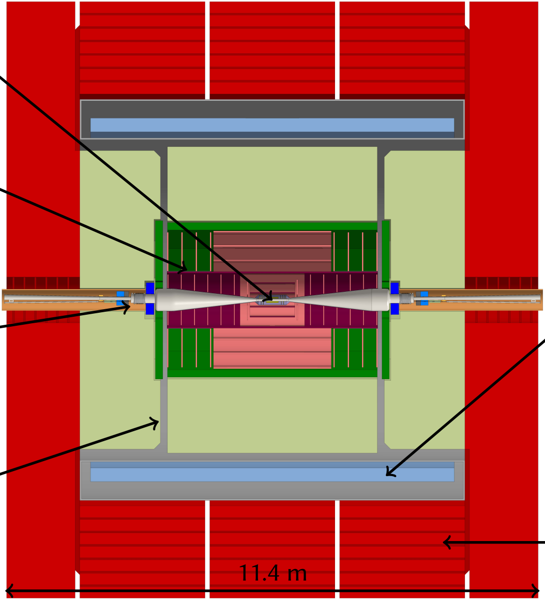
CLIC detector concept

Ultra low-mass vertex detector

Main tracker, silicon based

Forward region with LumiCal & BeamCal

Fine grained calorimetry used in Particle Flow (PFA)



Solenoid magnet: B=4 T

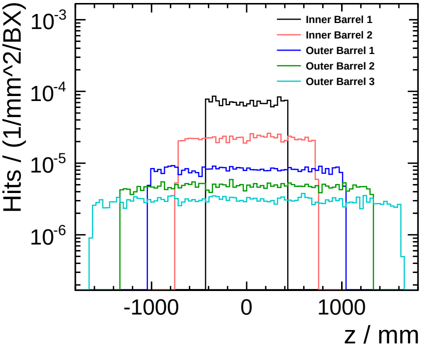
Return yoke (Fe) with detectors for muon ID

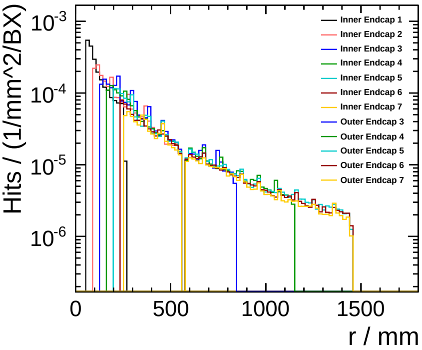
Occupancy in the tracker

- B=4 T
- 50 μm pitch in the tracker

- Barrel strip lengths:
  - Layers 1 & 2: 1 mm
  - Layer 3: 5 mm
  - Layers 4 & 5: 10 mm

- Endcap strip lengths:
  - Inner discs: 1 mm
  - Outer discs: 10 mm





Leakage current in active-edge sensors

- Sensor type: n-in-p
- IV-curve measurement for all the tested assemblies:
  - The sensor without any guard-ring (20-NGR) has the highest leakage current and the break-down occurs earlier.