Performance of the MIMOSIS – Monolithic Active Pixel Sensor for CBM MVD and beyond

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on behalf GSI-IKF-IPHC (CBM-MVD) Collaboration

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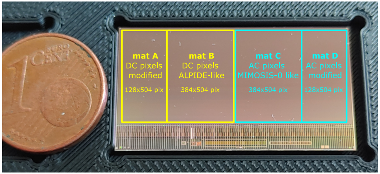
Overview

MIMOSIS – sensor for MVD

MIMOSIS **CMOS Monolithic Active Pixel Sensor**

→ for the CBM Micro Vertex Detector.
→ also milestone for Future Higgs factories ($5\,\mu s$, $5\,\mu m$, $< 100\,\frac{mW}{cm^2}$, $< 100\,\frac{mHz}{cm^2}$, $50\,\mu m$ thickness)
→ as a beam telescope unit for EURIZON projects

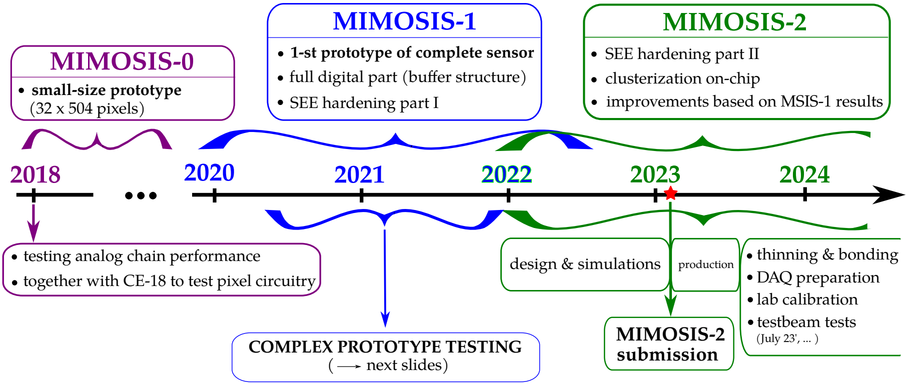
- based on ALPIDE sensor (ALICE ITS2 [1])
- major modifications made to comply with MVD requirements → physics or beam- structure driven.
  - 100 kHz Au+Au
  - occupancy gradient in space (almost 100%)
  - beam fluctuations in time
- **major challenge** → high non-homogeneous data rate and radiation hardness



Physics parameter	**Requirements**
Spatial resolution	$\approx 5\,\mu m$
Time resolution	$\approx 5\,\mu s$
Power consumption	$<$ 100-200 mW/cm^2
Material budget	0.05% X_0
Radiation (non-ion)	$\approx 7 \times 10^{13}\ n_{eq}/cm^2$
Radiation (ionizing)	≈ 5 MRad
Data flow (peak hit rate)	$7 \times 10^5\ /(mm^2 s)$ (> 2 Gbit/s)

[1] M. Suljic. "ALPIDE: the Monolithic Active Pixel Sensor for the ALICE ITS upgrade", JINST C11025 (2016)

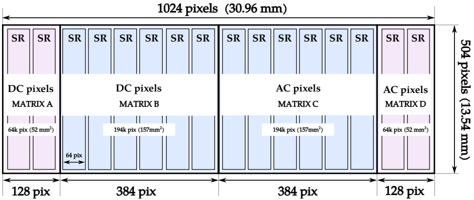
MIMOSIS timeline



⟶ **MIMOSIS-3** – final sensor production (around 2025)

MIMOSIS-1 – sensor overview

Parameter	Value
Technology	TowerJazz CIS 180 nm
Epitaxial layer	$\sim 25\,\mu m$, $> 1k\Omega{\cdot}cm$
Sensor thickness	300 μm or 60 μm
Pixel size	$26.9\,\mu m \times 30.2\,\mu m$
Pixel array	1024×504 pixels
Sensitive area	$\approx 4.2\,cm^2$
Array readout time	$\approx 5\,\mu s$
Power consumption	$< 100\ mW/cm^2$



MIMOSIS pixels:

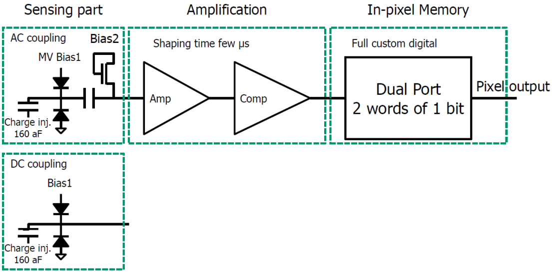
- DC-pixels → ALPIDE-like
- **AC-pixels** → possible improved radiation hardness with top bias possibility $> 20V$

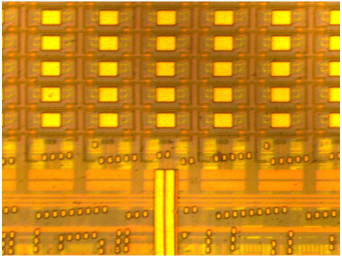
4 submatrices with various pixel circuitry:

- B, C → basic pixels architectures
- A, D → 128-column matrices for analog pixel circuitry optimization (also C18 prototypes) – not shown here

MIMOSIS-1 fabrication reticules

Front-end scheme





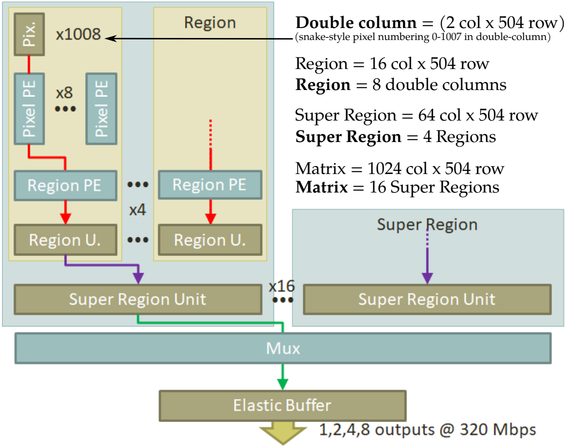
MIMOSIS-1 pixel matrix microscope photography

- there are two types of pixels: DC ($\rightarrow$ ALPIDE) and AC (top bias up to $> 20\,\mathrm{V}$)
- each pixel has a full amplifier – shaper – discriminator chain similar to ALPIDE
- in-pixel digital part is non-triggered, frame based readout (global shutter)
- each pixel hosts a pulse injection for calibration
- each pixel masking possibility

more details: A. Dorokhov, "The MIMOSIS pixel sensor for the CBM MicroVertex Detector and beyond", VCI 2022

Data path

- 3-stage buffering → to cope with in-homogeneous hit density
- Region readout out @ 20 MHz → 5 μs time of full matrix readout
- Elastic buffer → can store variable-size frames → required because of the data rate fluctuations
- Variable number of outputs → lower bandwidth but lower power consumption



Double column = (2 col x 504 row)
(snake-style pixel numbering 0-1007 in double-column)

Region = 16 col x 504 row
Region = 8 double columns

Super Region = 64 col x 504 row
Super Region = 4 Regions

Matrix = 1024 col x 504 row
Matrix = 16 Super Regions

MIMOSIS-1 has 8 outputs each 320 Mb/s providing a required data throughput for MVD

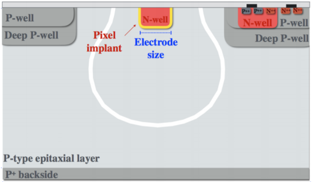
more details: F. Morel, "The MIMOSIS pixel sensor", TIPP 2021

MIMOSIS-1 – technology

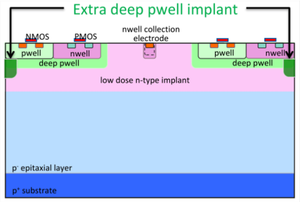
- TowerJazz CIS 180 nm technology → providing several process modifications and some flexibility on epitaxial layer thickness.
- MIMOSIS-1 available on:
  - **standard process**
  - **gap in n-layer** [n-gap]
  - **additional p-implant** [p-stop]

  → expected improved radiation tolerance (better depletion development)
- sensors 300 μm, also thinned to ≈ 60 μm

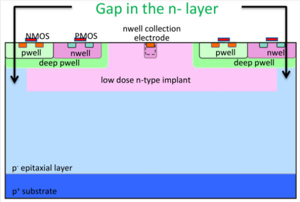
STANDARD



P-STOP

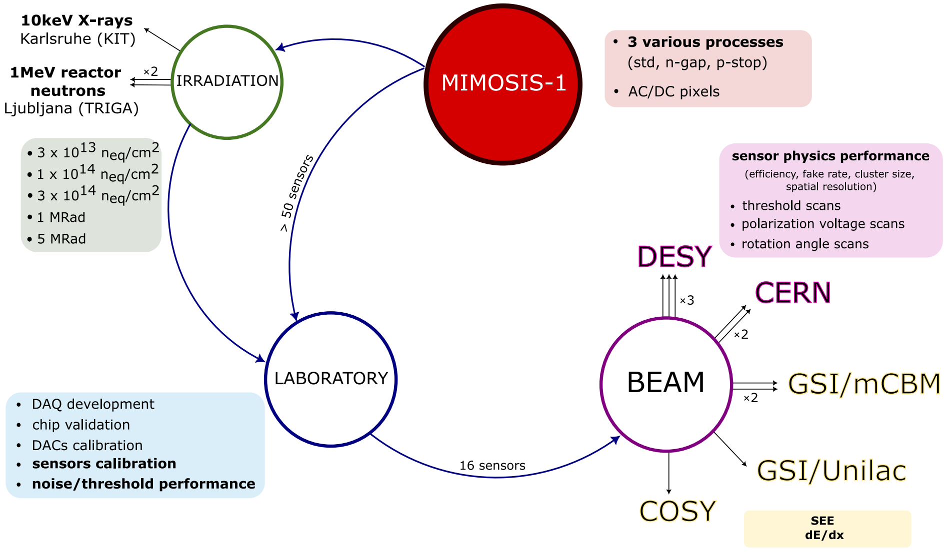


N-GAP



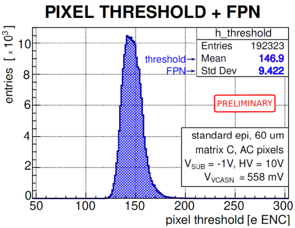
W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

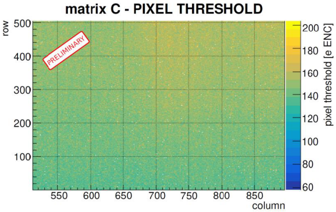
MIMOSIS-1 activities



Laboratory measurements. Noise and threshold performance

- complex phase space of MIMOSIS → tuning parameters needed
- characterization by pulse injection (room temperature)
    - threshold (from S-curves)
    - Fixed Pattern Noise
    - pixel noise (thermal dominant)





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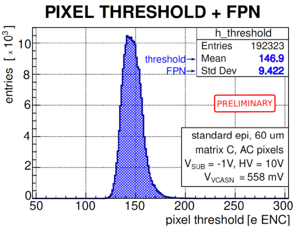
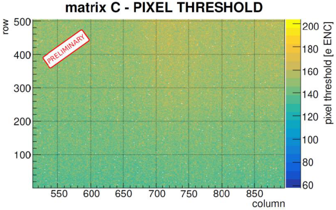
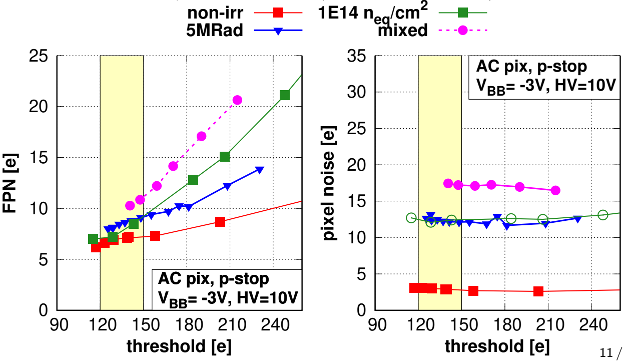
- complex phase space of MIMOSIS → tuning parameters needed
- characterization by pulse injection (room temperature)
  - threshold (from S-curves)
  - Fixed Pattern Noise
  - pixel noise (thermal dominant)
- **before irradiation:**
  - FPN: 7-10 e ENC
  - TN: 3-5 e ENC
- **after irradiation:**
  - FPN: < 25 e ENC
  - TN: 10-20 e ENC
- now: 1 mV → 1 e^- charge-to-voltage conversion gain used. Ongoing tests indicate **1 mV → ∼ 2 e^- → update soon**
- very similar performance of AC/DC and various epi layers





1/3 of the matrix results (full → ∼ 15% higher FPN)



Test-beams and analysis strategy

TEST BEAMS

- DESY – 5 GeV e^-
- CERN – 100 GeV $\pi^\pm$
- measurements:
  - DC and AC pixels
  - back bias (0 V, −1 V, −3 V)
  - top bias (3 V, 7 V, 10 V, 15 V)
  - discriminator thresholds (100-250 e)
  - rotation angles (0, 30, 45, 60)

SENSORS:

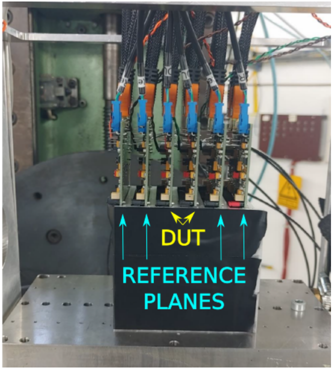
- std, p-stop, n-gap process
- non-irradiated, X-Ray irradiated, neutron irradiated, combined

SETUP :

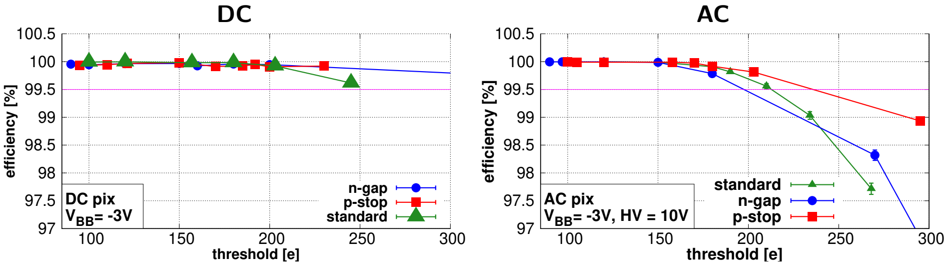
- 6 MIMOSIS planes in stack (4 for tracking, 2 DUT)
- 15 mm distance between planes

ANALYSIS:

- TAF software, Corryvreckan foreseen
- one plane as DUT in time
- $\sigma_{tel} = 2.5\mu m$, $\sigma_{ms}^{DESY} = 1.5\mu m$
  $\sigma_{ms}^{CERN} = 0\mu m$

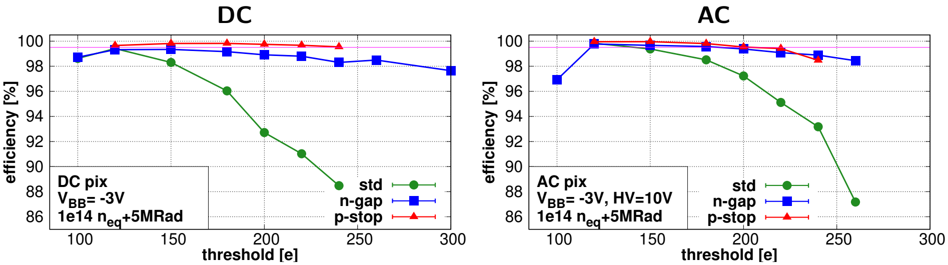


Detection efficiency - non-irradiated sensors – process comparison



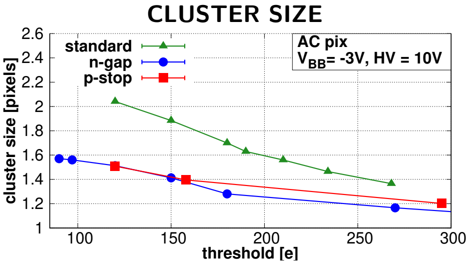
- detection performance barely sensitive to processes
- detection efficiency $> 99.5\,\%$ for both AC and DC $\rightarrow$ the operational values of the discrimination thresholds around $100\ e^-$ – operation point fulfilling requirements
- $V_{BB} = -1V$ extends better efficiency for AC pixels towards higher thresholds
- fake rate $\rightarrow < 10^{-6}$ / pixel / frame
- chip-to-chip variation to be studied

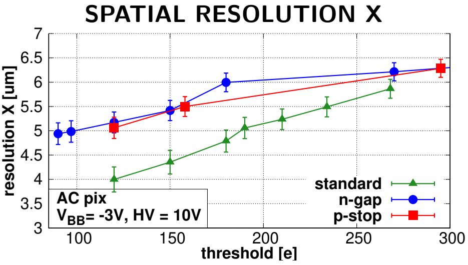
Detection efficiency – combined irradiation – process comparison



- visible better performance of modified processes over standard
- DC and AC pixels exhibit similar

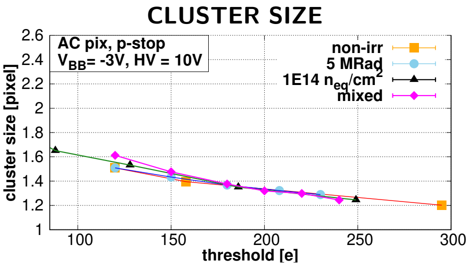
Cluster size and spatial resolution – process comparison, AC, non-irradiated

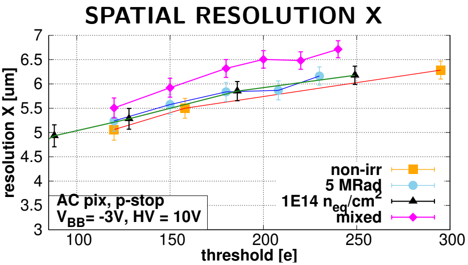




- pixel size: $\approx$ 27 µm $\times$ 30 µm, spatial resolution for shorter edge shown
- standard process exhibits larger cluster size than modified $\rightarrow$ cluster size translated to spatial resolution
- spatial resolution around 4.5 µm at 150 e− for standard and 1 µm worse for modified
- longer pixel edge about 0.5 µm larger resolution

Cluster size and spatial resolution – irradiated, p-stop, AC pixels





- no major influence of radiation on cluster size
- spatial resolution: no difference after X-Ray and neutron irradiation → **typically 5 - 5.5 µm at 150 e−**
- about 6 µm larger after combined irradiation at 150 e−
- larger pixel edge → ≈ 0.5 – 1 µm more
- DC pixels → larger cluster size (but below 2) and spatial resolution 5.5 µm at 150 e−

Conclusions and plans

MIMOSIS-1 – 1st full scale prototype for MVD detector and beyond (beam telescopes, future linear colliders, neutron detectors)

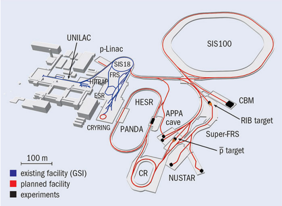
→ performance being validated by set of complex tests and measurements
→ milestone for MIMOSIS-2 development

1. **9 test-beam campaigns in 2021/2022** → for SEE tests and essential detector performance validation
2. **3 various processes [EPI variants]** (std, n-gap, p-stop) tested and two pixel types **(DC, AC)** → to validate **designs complying with** the radiation tolerance and spatial resolution required for **the MVD**
3. required radiation tolerance verified with nominal loads expected by experiment, but also beyond
   - around 99.5 % of detection efficiency after combined irradiation for AC and DC pixels on modified processes (keeping fake rate below 10^{-6} per pixel per frame)
   - spatial resolution around 5.5 µm before irradiation and around 6 µm after estimated up to 150 e^- discriminator threshold
4. MIMOSIS-1 fulfils experiment requirements and the project goals were reached
5. MIMOSIS-2 (improved and complete design) expected back from foundry in mid of 2023

BACKUP

CBM experiment at FAIR - introduction

- The **Compressed Baryonic Matter** (CBM) – fixed target experiment at **FAIR in GSI**
  $\rightarrow$ to explore physics in high-energy heavy-ion collisions (QCD phase diagram at high baryon densities)



- The **Micro-Vertex-Detector** (MVD) – vertex for CBM
  - built of four layers silicon MAPS
  - micro-tracking for e+e- pairs coming from light meson decays
  - exposed to high-rate non-homogeneous irradiation

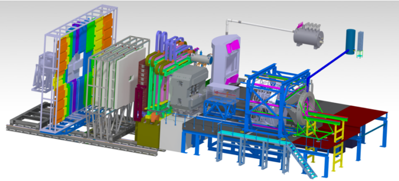
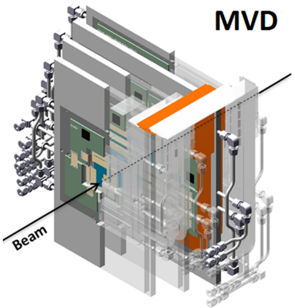
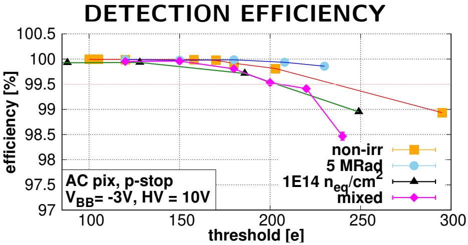
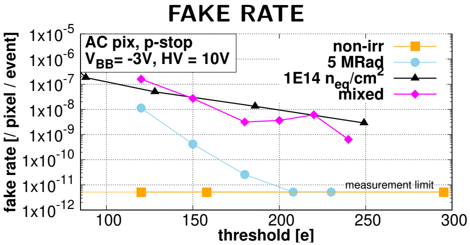


Figure: Left: CBM, right: HADES experiments @ FAIR



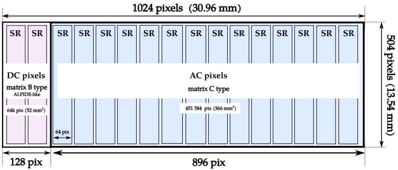
Detection efficiency – irradiation type – AC, p-stop

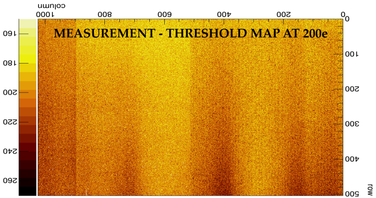


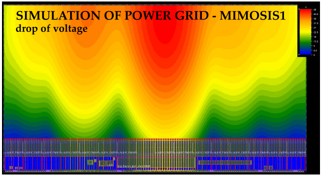


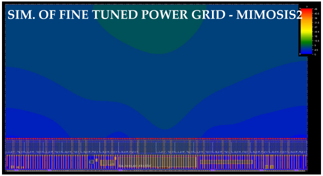
- AC pixels, p-stop process, all irradiation types shown
- similar results for DC, n-gap
- detection efficiency $> 99.5\,\%$ up to $\approx 200\,e^{-}$ $\rightarrow$ the operational values of the discrimination thresholds around $100\,e^{-}$ – operation point fulfilling requirements
- fake rate $\rightarrow$ $< 10^{-6}$ per pixel per event $\rightarrow$ work in progress

MIMOSIS-2 – highlights



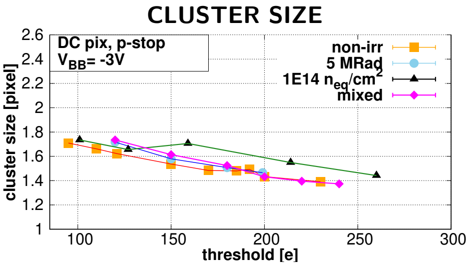


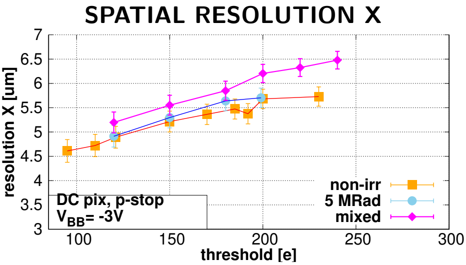




- submitted in January '23, expected in 4-5 months
- validation of MSIS-1 – a crucial milestone for its successor → spotted shortcomings improved (PLL PSRR, DACs, analog power grid enhancement, several others)
- new/other features finished: SEE hardening, on-chip clustering
- mostly based on the **AC-coupled pixels**: 896 × 504
- on **3 different processes** (std, p-stop, n-nap) and **2 different EPI layer thickness** (25 µm and 50 µm) → for radiation hardness vs spatial resolution optimization studies

Cluster size and spatial resolution – irradiated, p-stop, DC pixels





- slightly better spatial resolution than AC
- neutron - work in progress
- about 5.5 μm for combined irradiation at 150 e−
- longer pixel edge → ≈ 0.5 – 1 μm more