Latest results from MIMOSIS-1

Roma Bugiel

postdoc at Hubert Curien Pluridisciplinary Institute in Strasbourg (IPHC)
(on behalf GSI-IKF-IPHC (CBM-MVD) Collaboration)

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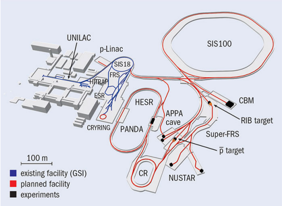
EURIZON

Overview

CBM experiment at FAIR - introduction

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



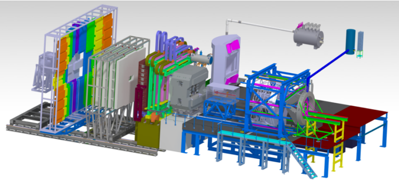
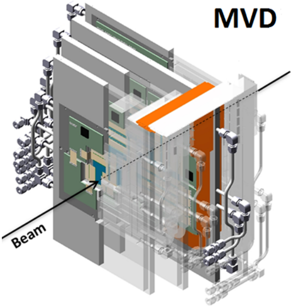


Figure: Left: CBM, right: HADES experiments @ FAIR

- 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

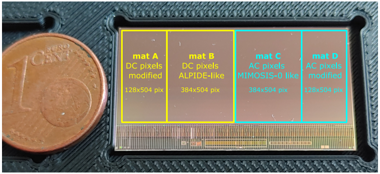


MIMOSIS – sensor for MVD

MIMOSIS – **CMOS Monolithic Active Pixel Sensor**

→ for CBM Micro Vertex Detector.
→ also milestone for Future Higgs factories (5 μs, 5 μm, $< 100\,\frac{mW}{cm^2}$, $< 100\,\frac{mHz}{cm^2}$, 50 μm thickness)

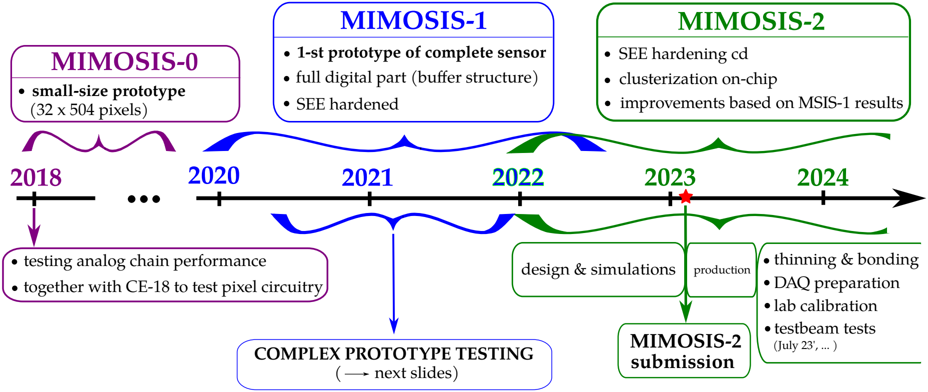
- based on ALPIDE sensor (ALICE ITS [1])
- major modifications made to comply with MVD requirements → physics or beam- structure driven.
  - 100 kHz Au+Au
  - occupancy gradient in space (almost 100%)
  - beam fluctuations in time
- **major challenge** → high non-homogeneous data rate and radiation hardness



Physics parameter	**Requirements**
Spatial resolution	$\approx 5\,\mu m$
Time resolution	$\approx 5\,\mu s$
Power consumption	$< 100\text{-}200\,mW/cm^2$
Material budget	$0.05\%\,X_0$
Radiation (non-ion)	$\approx 7 \times 10^{13}\,n_{eq}/cm^2$
Radiation (ionizing)	$\approx 5\,Mrad$
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)

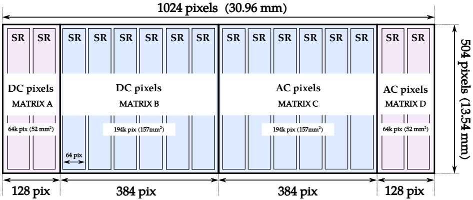
MIMOSIS timeline



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

MIMOSIS-1 – detector 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** → foreseen improved radiation hardness with top bias possibility $> 20\,V$

4 submatrices with various pixel circuitry:

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

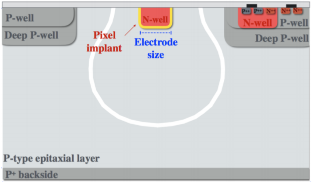
MIMOSIS-1 fabrication reticules

MIMOSIS-1 – technology

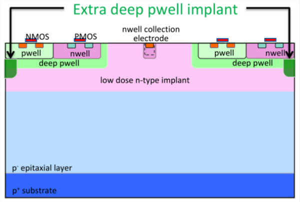
- TowerJazz CIS 180 nm technology → providing several process modifications and some flexibility on epitaxial layer thickness.
- MIMOSIS-1 available on:
  - **standard process** (3 available wafers)
  - modified process [continuous n+ layer] (3 wafers)
  - **gap in n-layer** [n-gap] (3 wafers)
  - **additional p-implant** [p-stop] (3 wafers)

  → expected improved radiation tolerance
- sensors 300 μm, also thinned to ≈ 60 μm

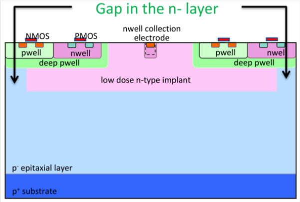
STANDARD



P-STOP

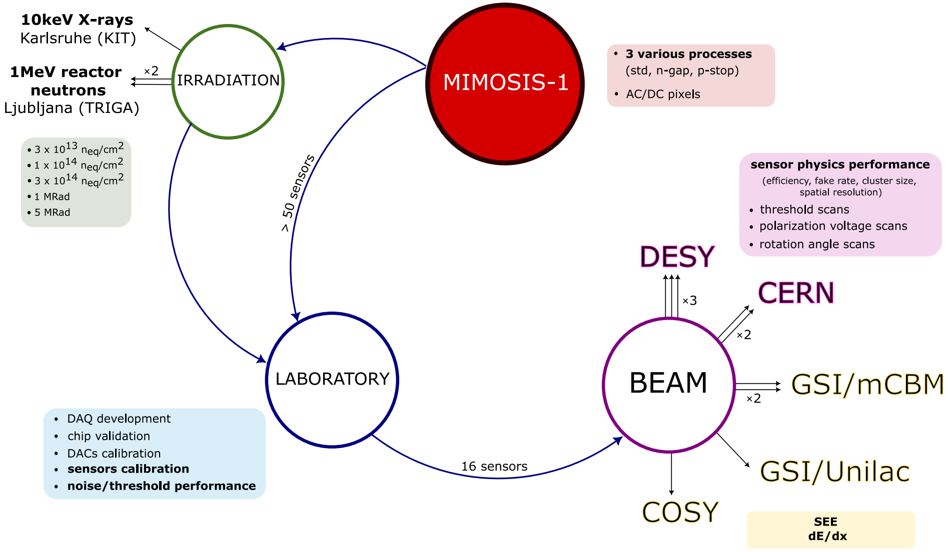


N-GAP



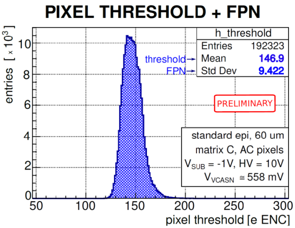
W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

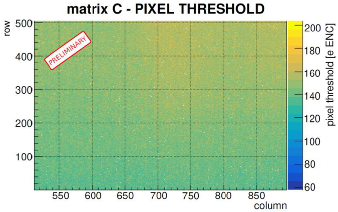
MIMOSIS-1 activities

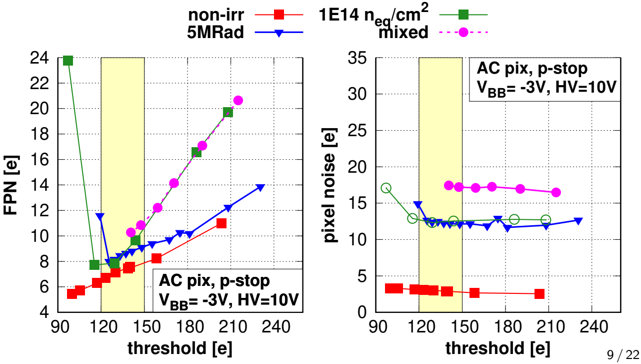


Laboratory measurements. Noise and threshold performance

- complex phase space of MIMOSIS → tuning parameters needed
- characterization by pulse injection (room temperature)
  - threshold (from S-curves)
  - Fixed Pattern Noise (FPN)
  - pixel noise (dominant thermal noise TN)
- **before irradiation:**
  - FPN: 7-10 e ENC
  - TN: 3-5 e ENC
- **after irradiation:**
  - FPN: $<$ 25 e ENC
  - TN: 10-20 e ENC
- 1 mV → 1 e^- charge-to-voltage conversion gain assumed for all proccesess/irradiation (WIP)
- very similar performance of AC/DC and various epi layers







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:

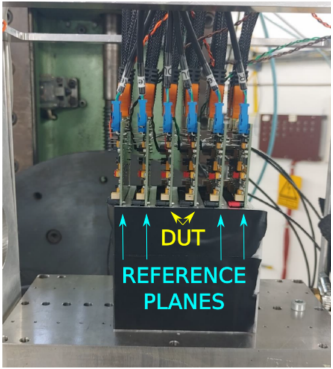
- std, p-stop, n-gap process
- non-irradiated, X-ray irradiated, neutron irradiated, combined

SETUP :

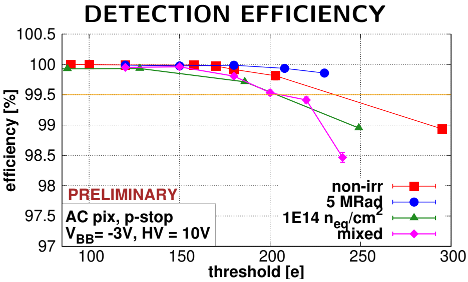
- 6 MIMOSIS planes in stack (4 for tracking, 2 DUT)
- 15 mm distance between planes

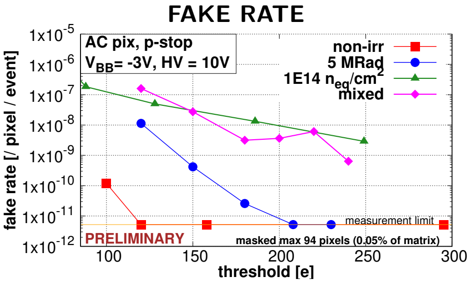
ANALYSIS:

- 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 - illustrative results





- AC pixels, p-stop process, all irradiation types
- 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
- similar results achieved for n-stop process

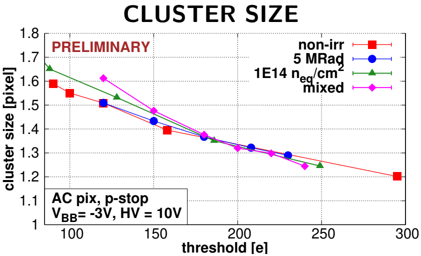
Cluster size and spatial resolution

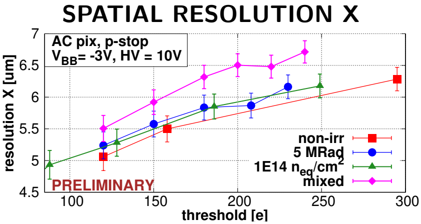
spatial resolution → **preliminary** results

work in progress, not all issues solved yet, alignment to be improved

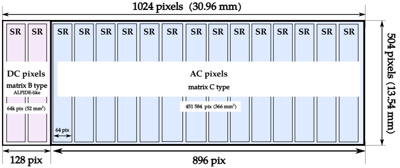
- no major influence of radiation on cluster size (nominal doses)
- mean cluster size 1.2 – 1.7 pixel for studied discriminator thresholds, modified p-stop process

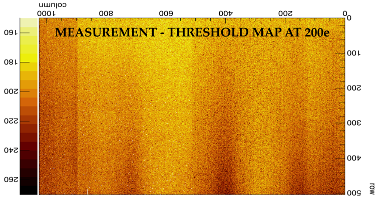
- pixel size: ≈ 27 µm × 30 µm
- spatial resolution for shorter edge shown
- almost no difference after X-Ray and neutron irradiation → **resolution typically** 5 - 5.5 µm **for thresholds** 150 e−
- about 0.5 µm larger after combined irradiation
- longer pixel edge → ≈ 0.5 – 1 µm more

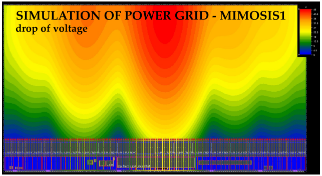


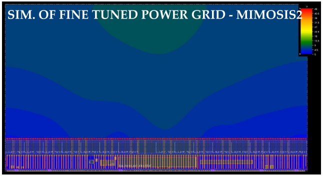


MIMOSIS-2 – highlights









- submitted in January '23, expected in 4-5 months
- validation of MSIS-1 – a crucial milestone for its successor $\rightarrow$ 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) $\rightarrow$ for radiation hardness vs spatial resolution optimization studies

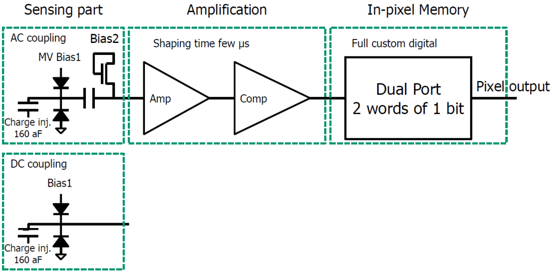
Conclusions and plans

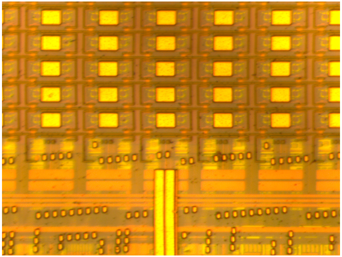
MIMOSIS-1 – 1st full scale prototype for MVD detector
→ its performance being validated by set of complex tests and measurements
→ milestone for MIMOSIS-2 development

1. **9 test-beam campaigns in 2021/2022** → for SEE tests and essential detector performance validation
2. **3 various processes** (std, n-gap, p-stop) tested and two pixel types **(DC, AC)** → to find **variants 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
   - above 99.5 % of detection efficiency after irradiation for AC pixels on p-stop [up to combined 5 MRad and 10^{14} n_{eq}/cm^2]
   - around 5 µm spatial resolution estimated up to 150 e^- discriminator threshold
4. **MIMOSIS-2 → final prototype incorporating all functionalities of final sensor and benefiting from corrected shortcomings observed with MIMOSIS-1**
5. MIMOSIS-2 expected back from foundry in middle of 2023

BACKUP

Front-end scheme





MIMOSIS-1 pixel matrix microscope photography

- there are two types of pixels: DC ($\rightarrow$ ALPIDE) and AC (top bias up to $> 20\,$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 has 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

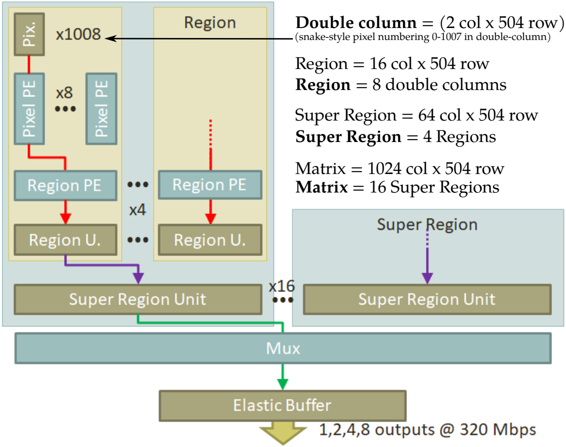
- 3-stage buffering → to cope with in-homogeneous hit density
- Region readout out @ 20 MHz → 5 μs time of full matrix readout
- Elastic buffer → can store variable-size frames → required because of the data rate fluctuations
- Variable number of outputs → lower bandwidth but lower power consumption

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

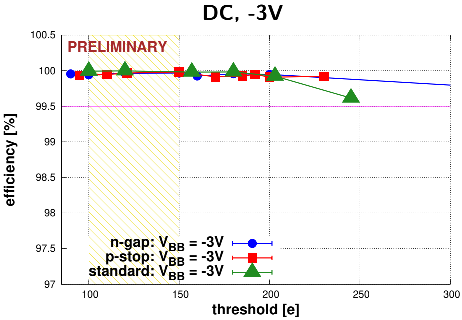
Matrix = 1024 col x 504 row
Matrix = 16 Super Regions

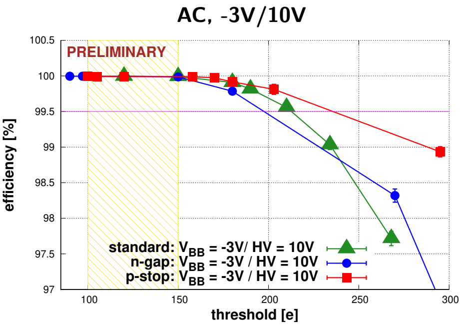


MIMOSIS-1 has 8 outputs each 320 Mb/s providing a required data throughput for MVD

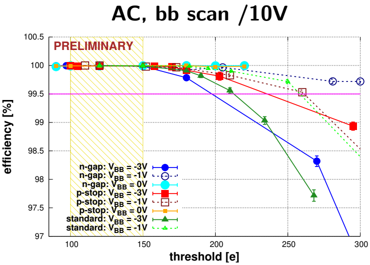
more details: F. Morel, "The MIMOSIS pixel sensor", TIPP 2021

Efficiency for non-irradiated sensors – DC vs AS all processes

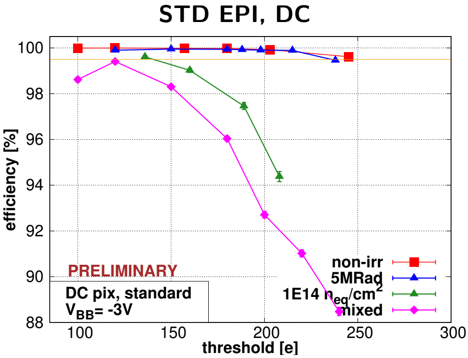


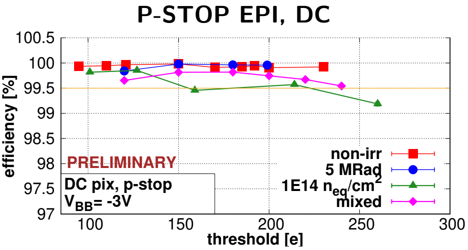


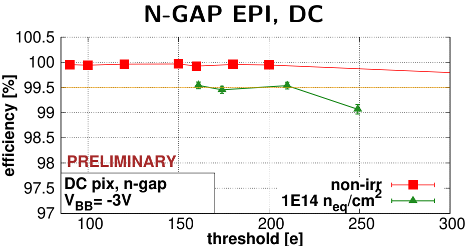
- DC excellent detection efficiency at least up to 250 e-
- for AC pixels efficiency starts to drop for about 200 e- for V_{bb} = -3V
  $\rightarrow$ V_{bb} = -1V shows again very good performance for higher thresholds.



Efficiency after various doses irradiation – DC pixels all processes

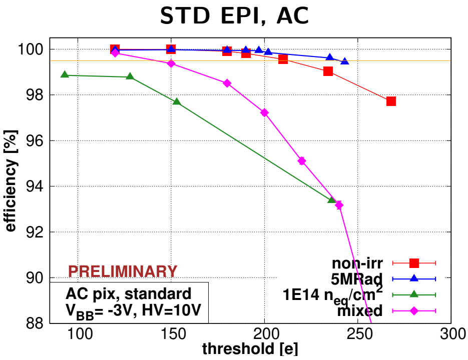


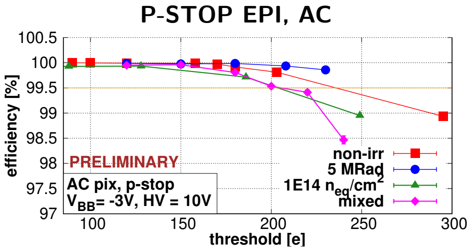


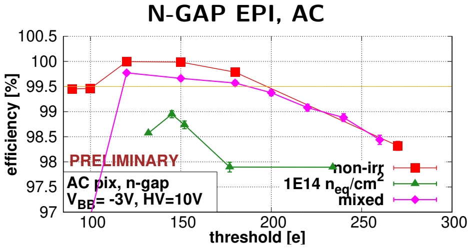


- ngap: 5 MRad → chip not available
  mixed → data available, character. not done
- **std epi** → drop of efficiency after neutron and mixed → as for AC
- **p-stop epi** → neutron slightly worse than mixed → to be investigated → still > 99.5 %
- **n-gap epi** → drop of efficiency after neutron → still > 99.5 %

Efficiency after various doses irradiation – AC pixels all processes



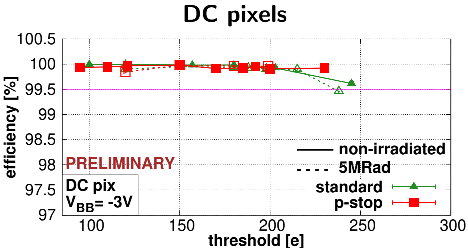


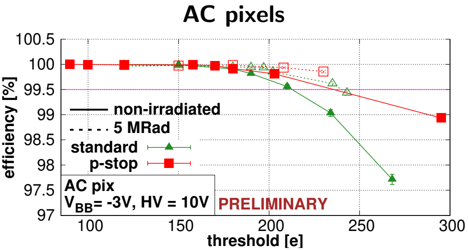


- **std and n-gap epi** → to be investigated because after mixed irradiation results not expected to be better than after only neutron irradiation (the same chip!)

- **p-gap epi** → efficiency detection $> 99.5\,\%$ → coherent results for this process

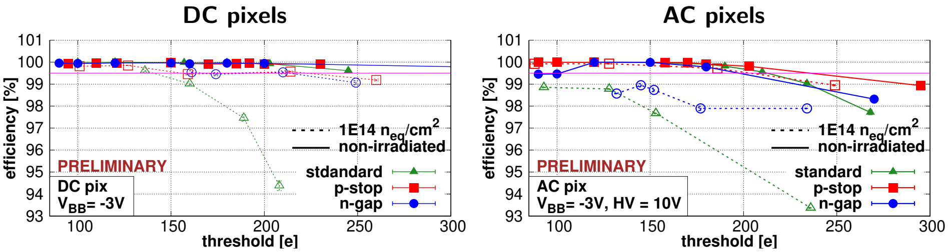
Efficiency after X-Ray irradiation – all processes





- comparison of different epi layers only after ionizing irradiation 5 MRad
- both matrices shown excellent efficiency
- some degradation is observed for standard epi only, especially AC

Efficiency after neutron irradiation – all processes



- comparison of different epi layers only after neutron $10^{14}\ n_{eq}/cm^2$ fluence
- standard epi doping profiles shows degradation of efficiency for both pixel types
- for AC pixels only p-stop epi keeps the performance as for non-irradiated sensor
- one chip statistic → highly probable that conclusions might change