Status and Performance of the MIMOSIS CMOS Sensor for the Micro-Vertex Detector of CBM Experiment

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For the CBM-MVD collaboration

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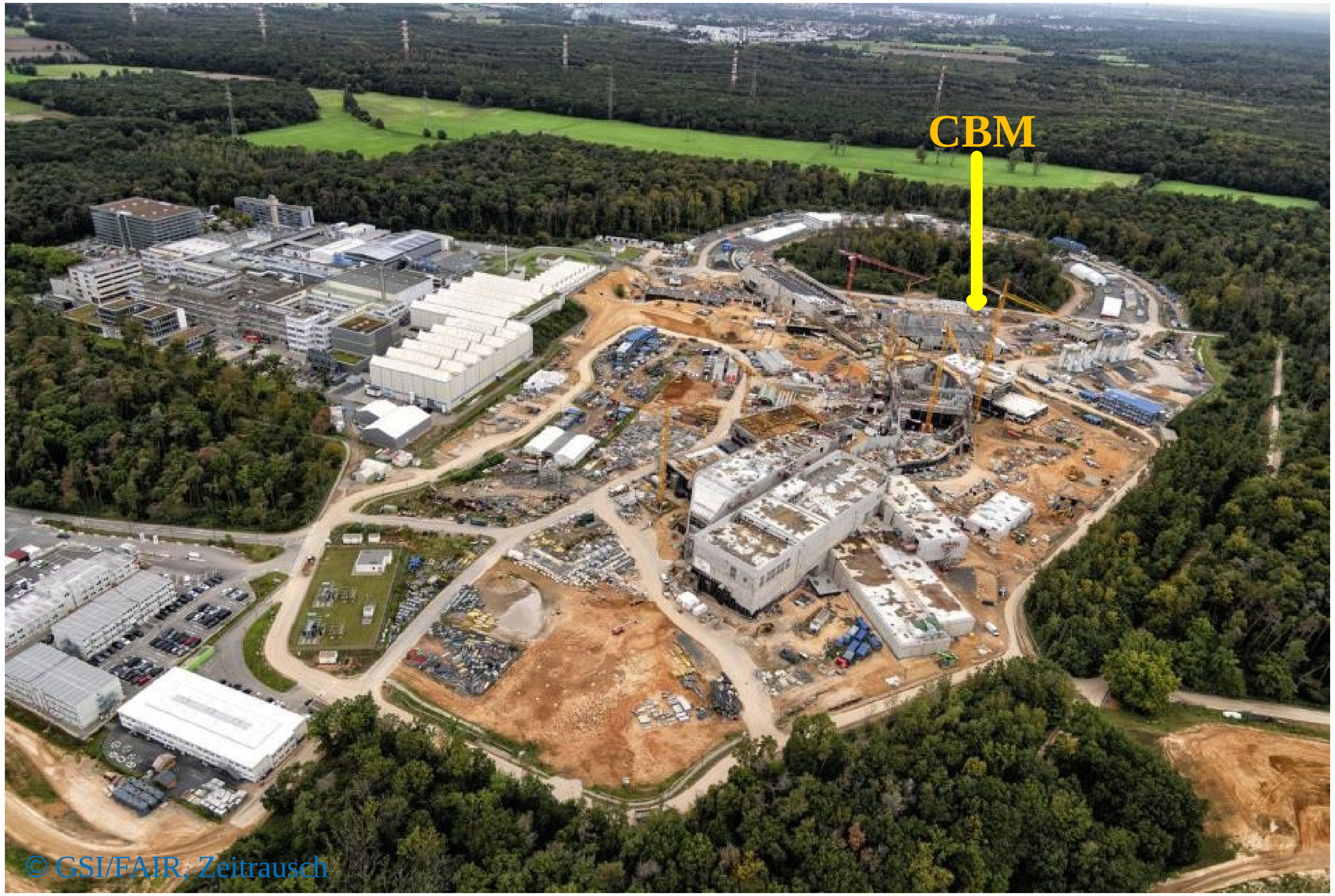
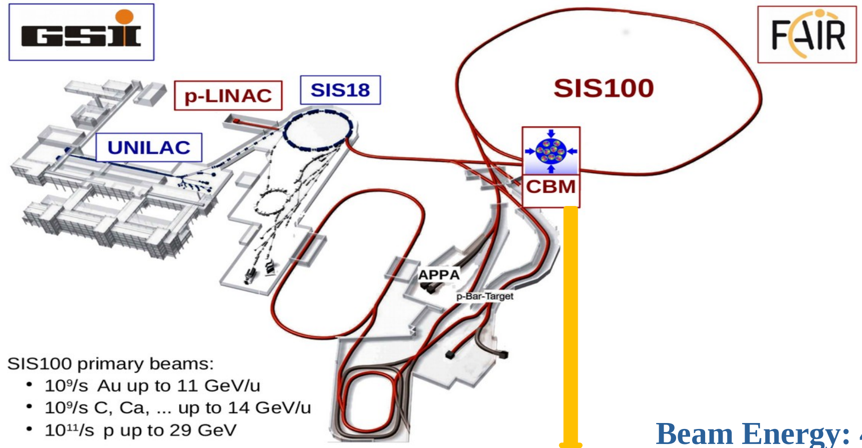
Outline

- Introduction to CBM experiment
- Overview of CBM-MVD
- MIMOSIS sensors for MVD
- System integration
- Testing sensors in the mini-CBM experiment
- Summary

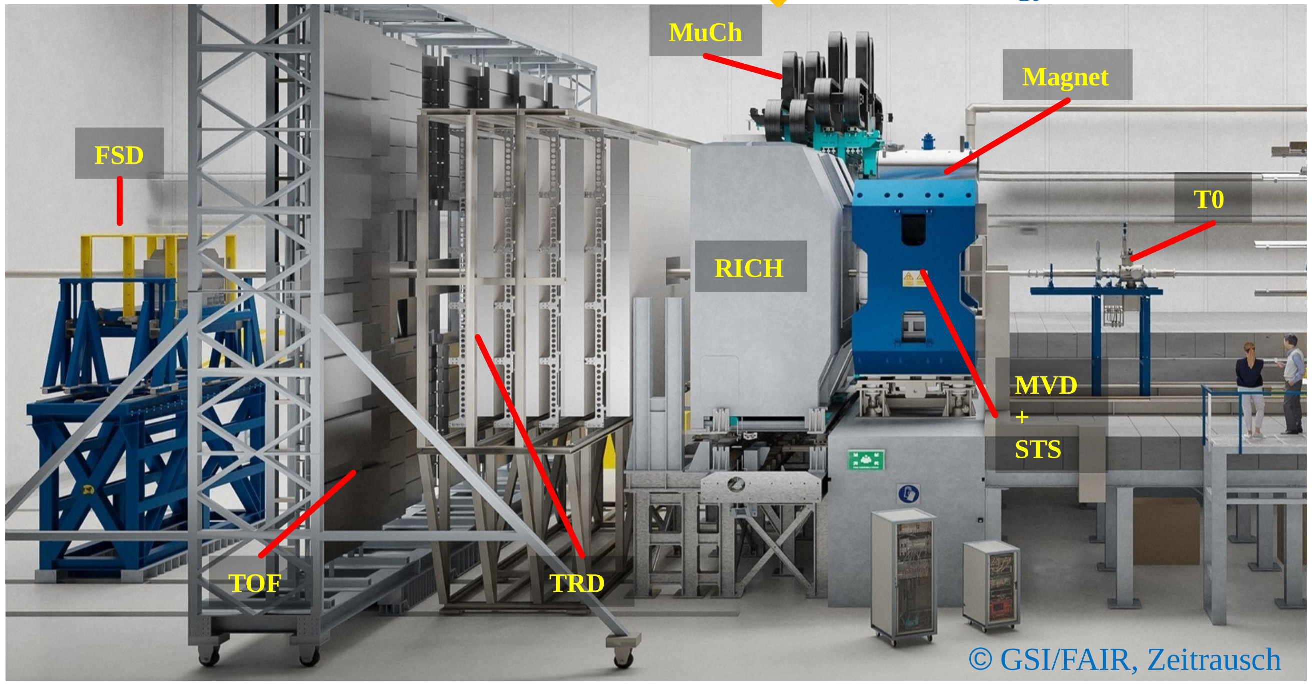


CBM Experiment @ FAIR

- Fixed target heavy ion experiment
- Explore properties of nuclear matter at high net baryon density and understanding the Equation of State (EoS)
- Investigate rare probes:
  - Multi-strange hyperons, hypernuclei, dileptons
  - Aiming to identify signature of first order phase transition
- Goal is to measure precisely low- and high-momentum tracks in high multiplicity and radiation environment
- To achieve this:
  - High interaction rates
  - CBM employs free-streaming, self-triggered readout
  - Radiation hard detectors and components



Beam Energy: 4-10AGeV Au+Au

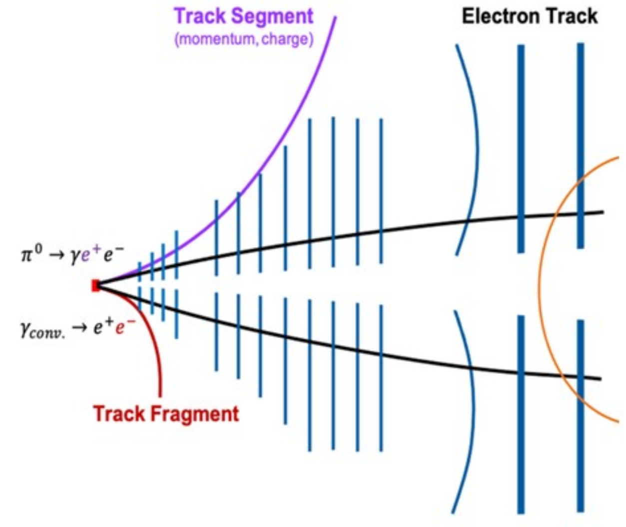


Schematics of the CBM experimental setup with its subdetectors (arXiv:2506.20545)

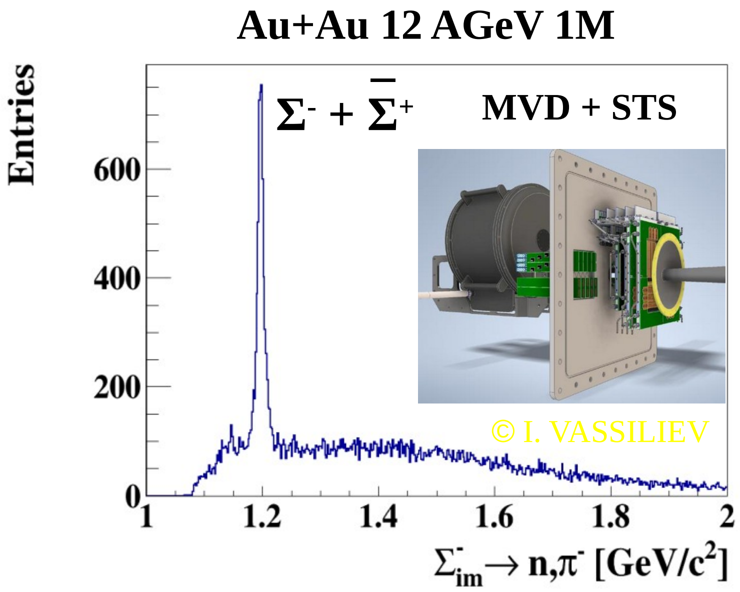
T0: Time Zero and Beam Diagnostic
STS: Silicon Tracking System
RICH: Ring Imaging Cherenkov Detector
TOF: Time of Flight

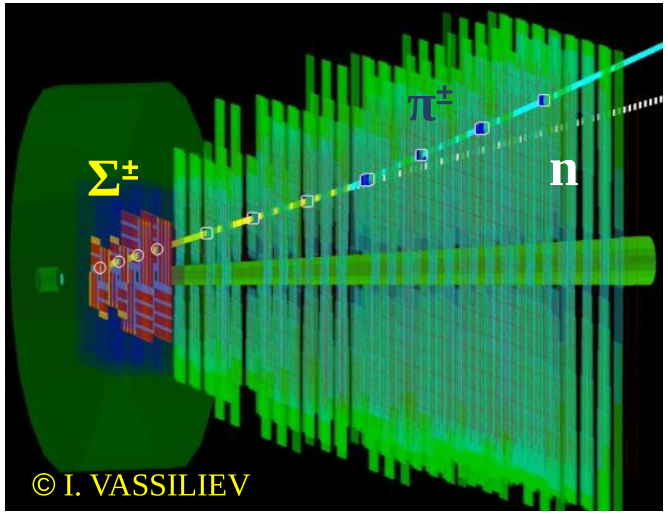
MVD: Micro-Vertex Detector
MuCh: Muon Chamber
TRD: Transition Radiation Detector
FSD: Forward Spectator Detector

- Key component of CBM tracking system
- Precise reconstruction of secondary decay vertices
- Suppression of combinatorial background (di-electron)
  - Conversion
  - π^0 Dalitz pairs
- Reconstruction of short lived particles
  - Λ, Ξ, and open charm hadrons
- Low momentum tracking



- together with STS
  - enables reconstruction of Σ baryons (which decay with neutral daughter)



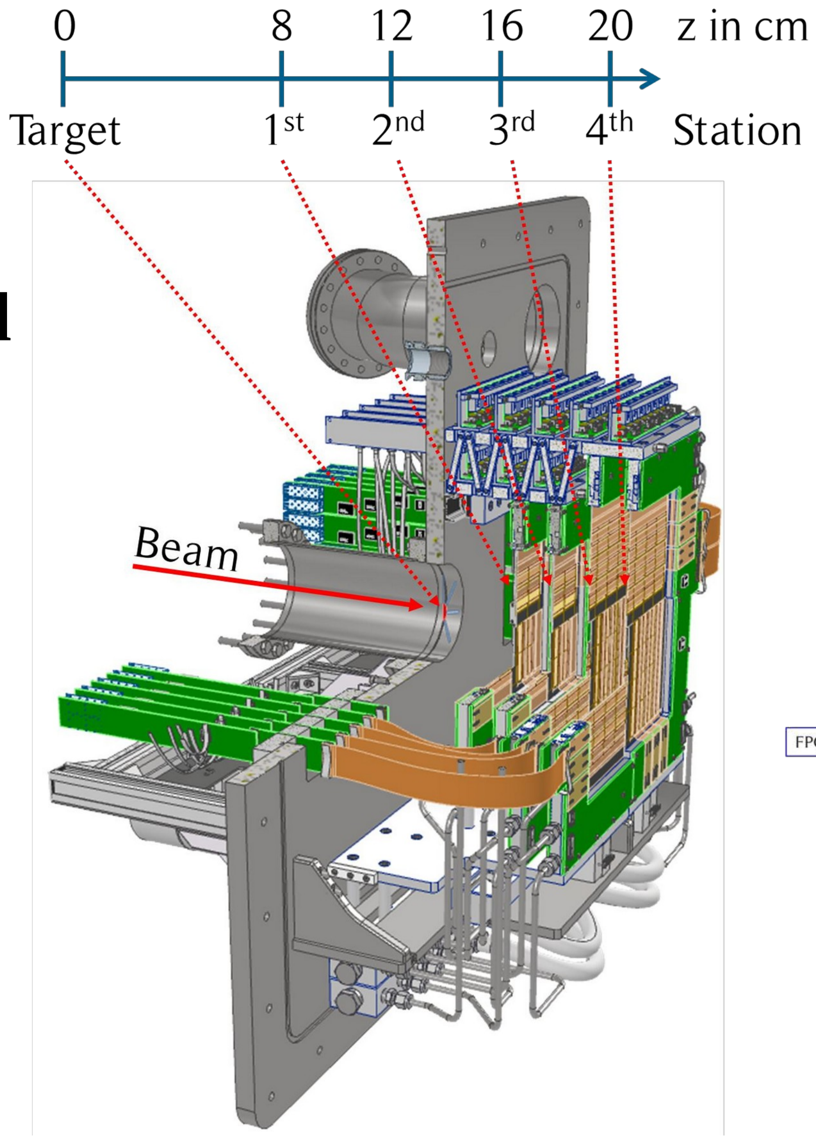


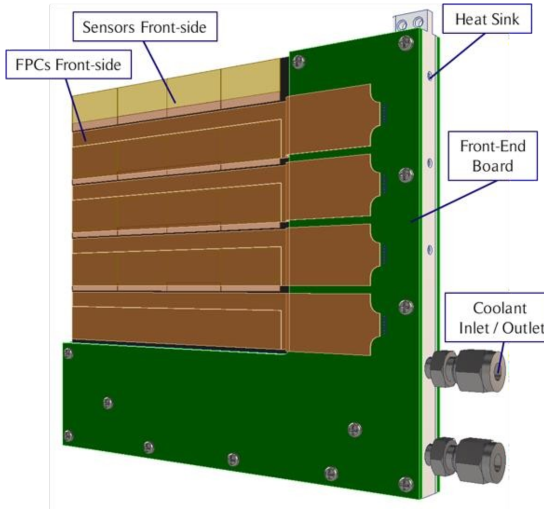
Overview of CBM-MVD

- Four planar tracking stations
  - ~300 CMOS MAPS
  - Placed inside **vacuum**, **magnetic field**
  - 1 Tm magnetic field

- σ = 5μm and < 0.5 % X_0/layer
- 100 kHz — 10 AGeV Au+Au collisions
- 10 MHz — 30 GeV p+Au collisions

- Two detector geometries
  - **Tracking (8-20 cm) → Start Setup**
  - Vertexing (5-20 cm)

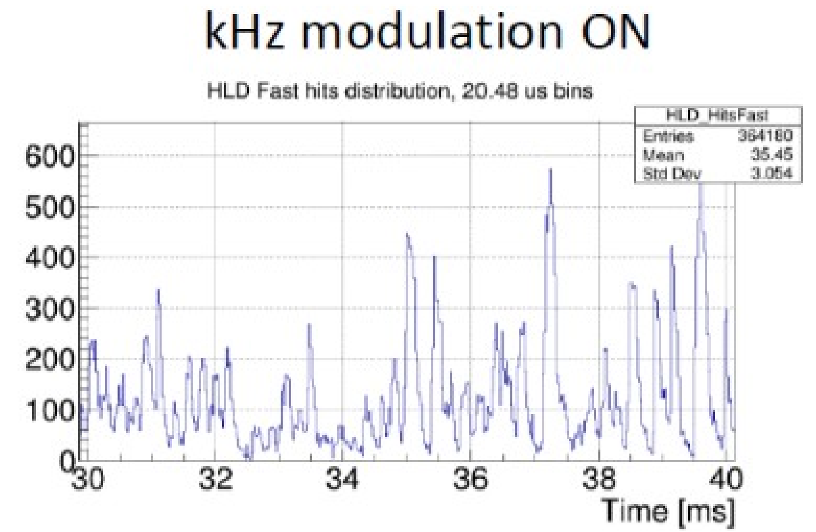


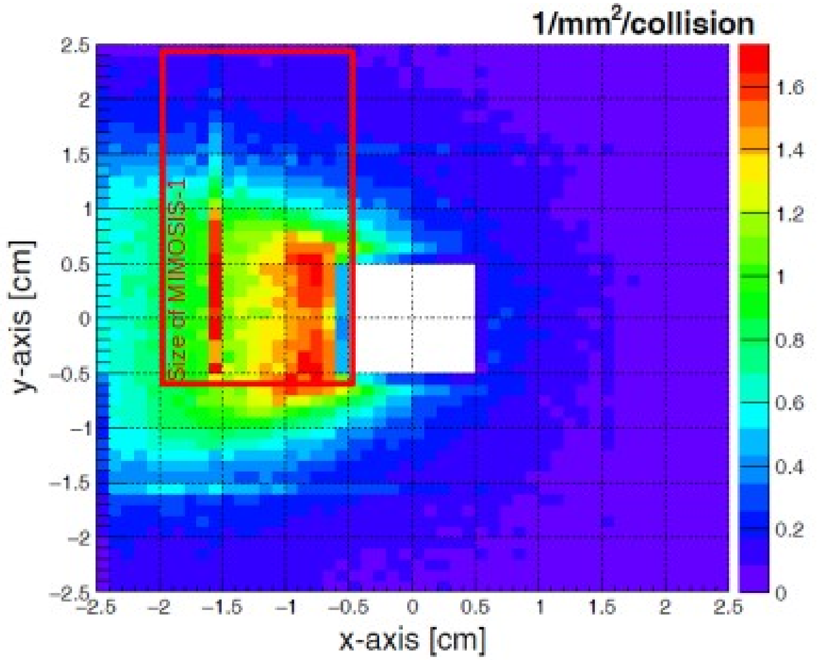


Requirement on the Sensor

	Requirement	
Spatial & Time Resolution	5 µm & 5 µs	
Sensor thickness	~70 µm (50µm EPI)	
Power dissipation	< 100 mW/cm^2	
NIEL	7 x 10^{13} n$_{eq}$/cm^2	~10 x ALPIDE
TID	~5 MRad	
Radiation gradient over sensor	~100%	
Heavy ion tolerance	1 kHz/cm^2	
Rate (Average / 35 µs peak)	20/80 MHz/cm^2	~20 x ALPIDE

beam intensity fluctuations (SIS-18)





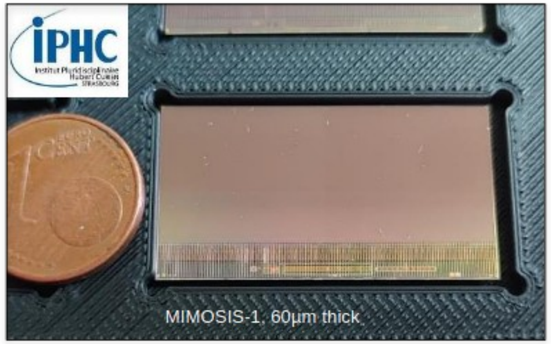
Customized sensor for CBM MVD: MIMOSIS

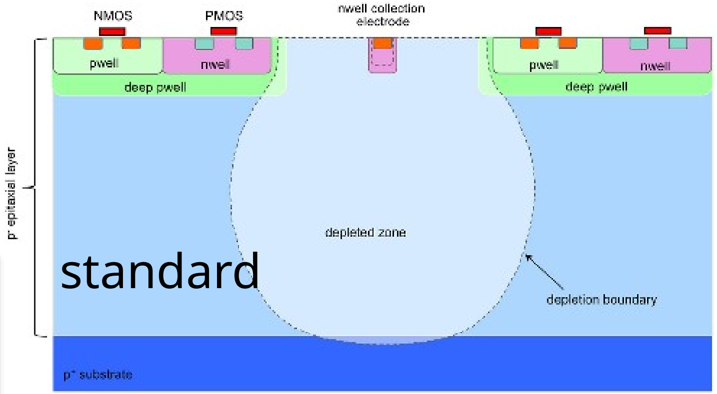
- Derived from ALPIDE (TJ 180 nm process)
- Fully depleted sensing node
- Re-designed digital front- and back-end (higher bandwidth, elastic buffer...)

MIMOSIS for MVD

Technical features of MIMOSIS

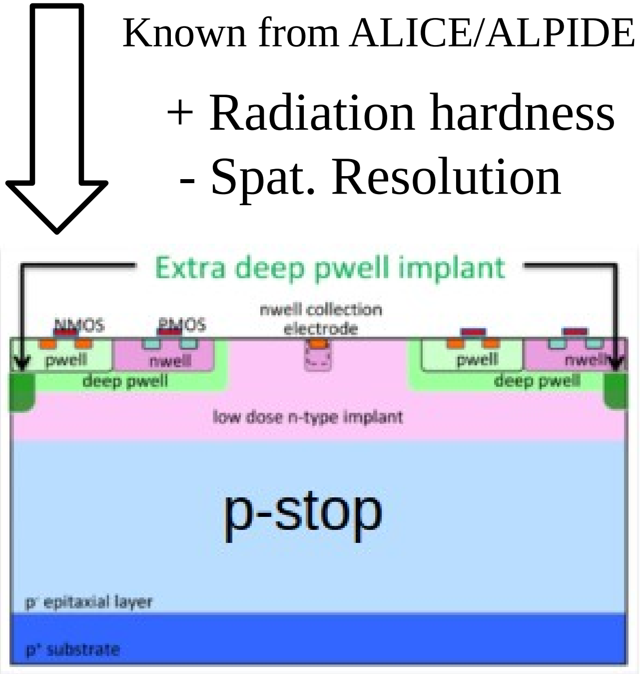
Category	Specification
Pixel Matrix	1024 × 504 pixels; ~30 µm × ~27 µm pitch
Active Area	≈ 31.15 × 17.25 mm²
Epitaxial Layer options	25 µm and 50 µm
Sensing node	DC (ALPIDE-like) and AC pixels
Biasing	Back bias up to 6 V; top HV (AC pixels) up to 20 V
Frame	5 µs integration time
Output Bandwidth	Up to 8 × 320 Mb/s differential links (switchable)
Power density	< 100 mW/cm²
Special Features	On-matrix pixel grouping





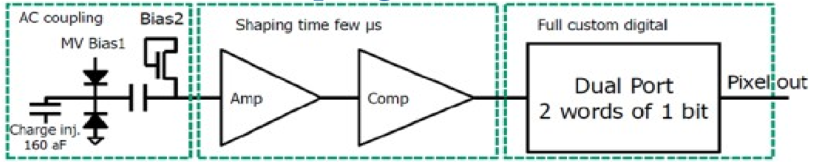
Known from ALICE/ALPIDE

+ Radiation hardness
- Spat. Resolution

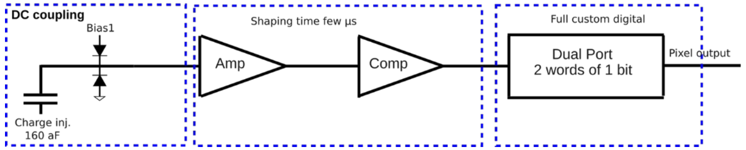


H. Pernegger et al., 2017 JINST 12 P06008

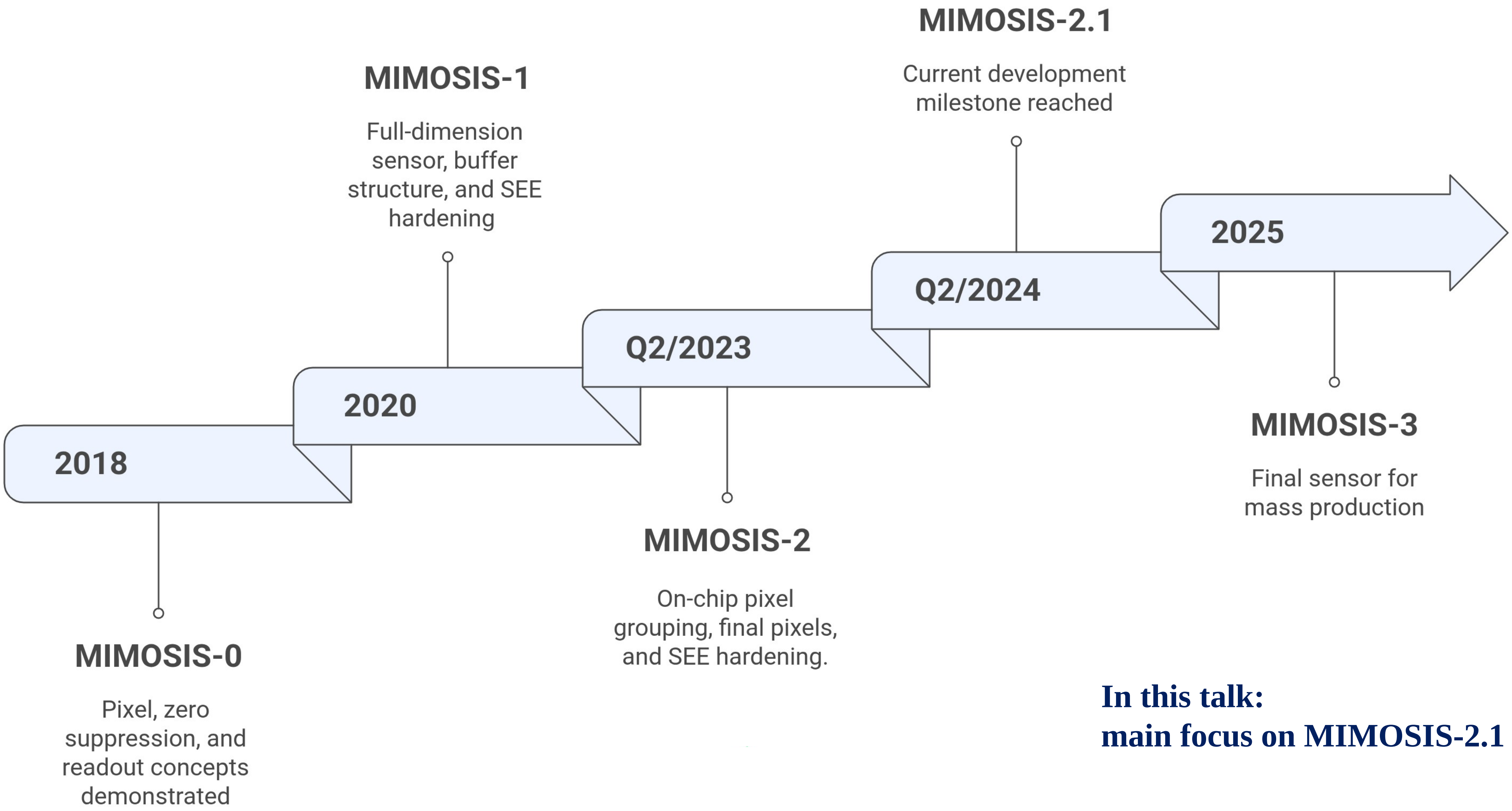
AC coupling



DC coupling



MIMOSIS Sensor development



In this talk:
main focus on MIMOSIS-2.1

Test of MIMOSIS sensors: Setup

MIMOSIS - beam telescope:

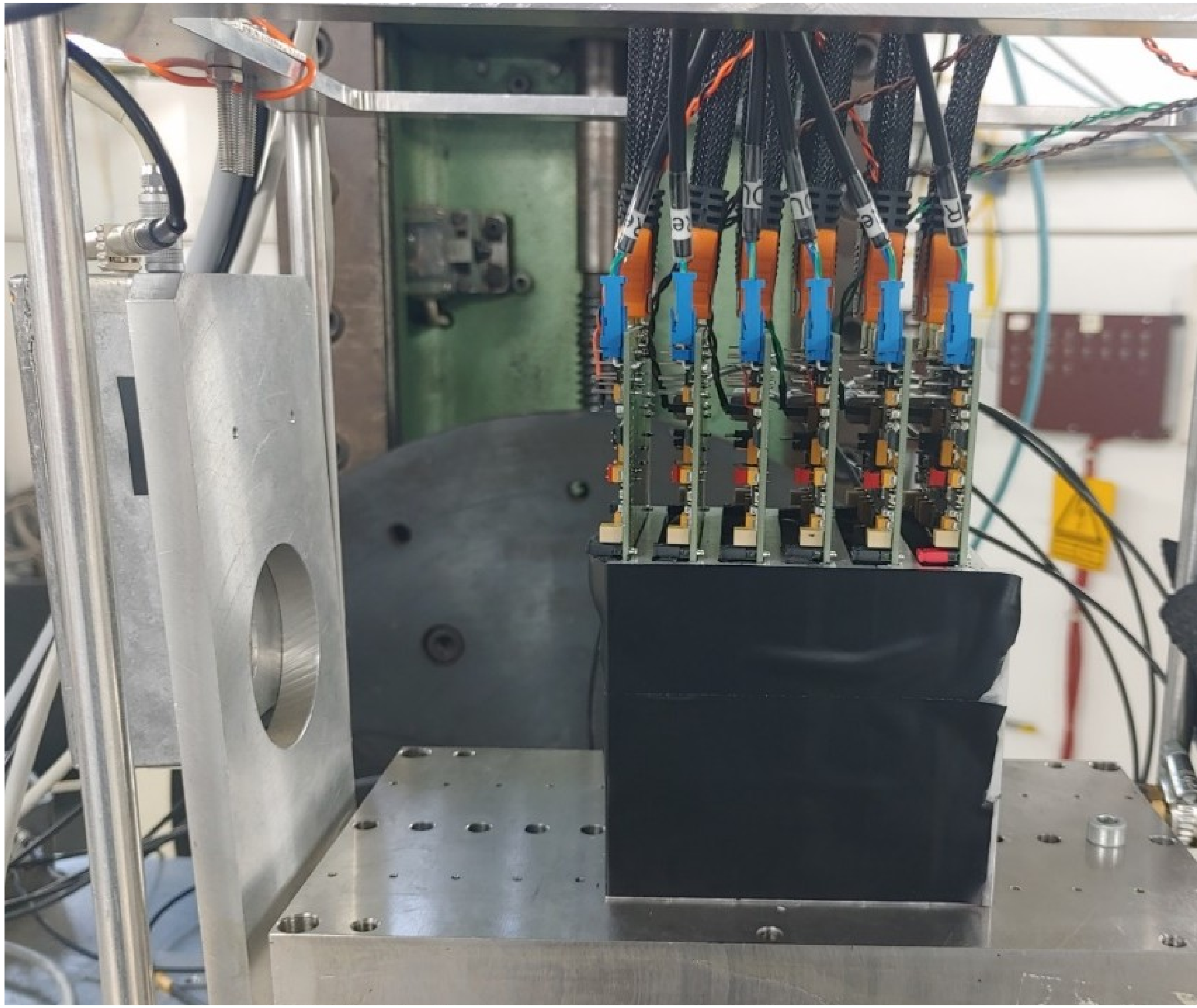
- 6 MIMOSIS-1 or 2.1 sensors
- 4 reference sensors (standard epi-layer)
- 2 devices under test
- Reference Track Uncertainty:
  - 2.5 µm + 1.5 µm multiple scattering (DESY only)

Irradiation:

- 1 MeV reactor neutrons (TRIGA, Ljubjana).
- Few 10 keV X-rays (KIT)
- Storage at room temperature.

Beam test:

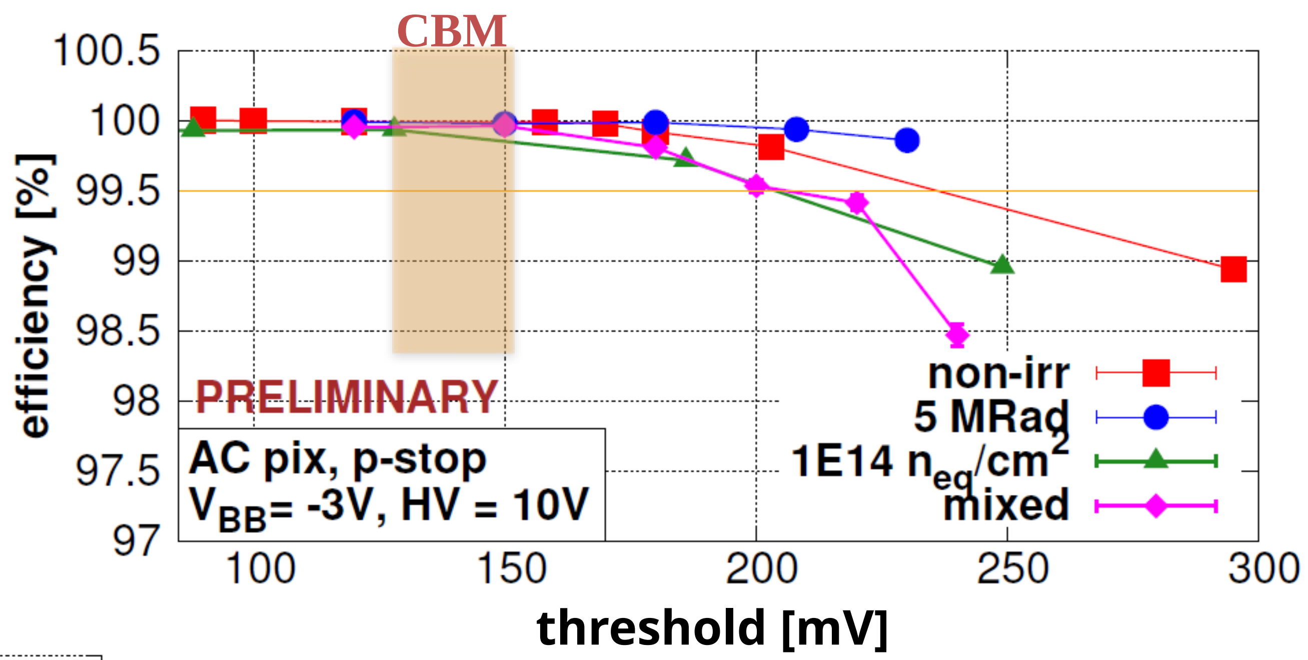
- 5 GeV e- Beam @ DESY
- 120 GeV Pion Beam @SPS-CERN
- ~ 1 GeV d – beam @ COSY
  (Stabilized room temperature)

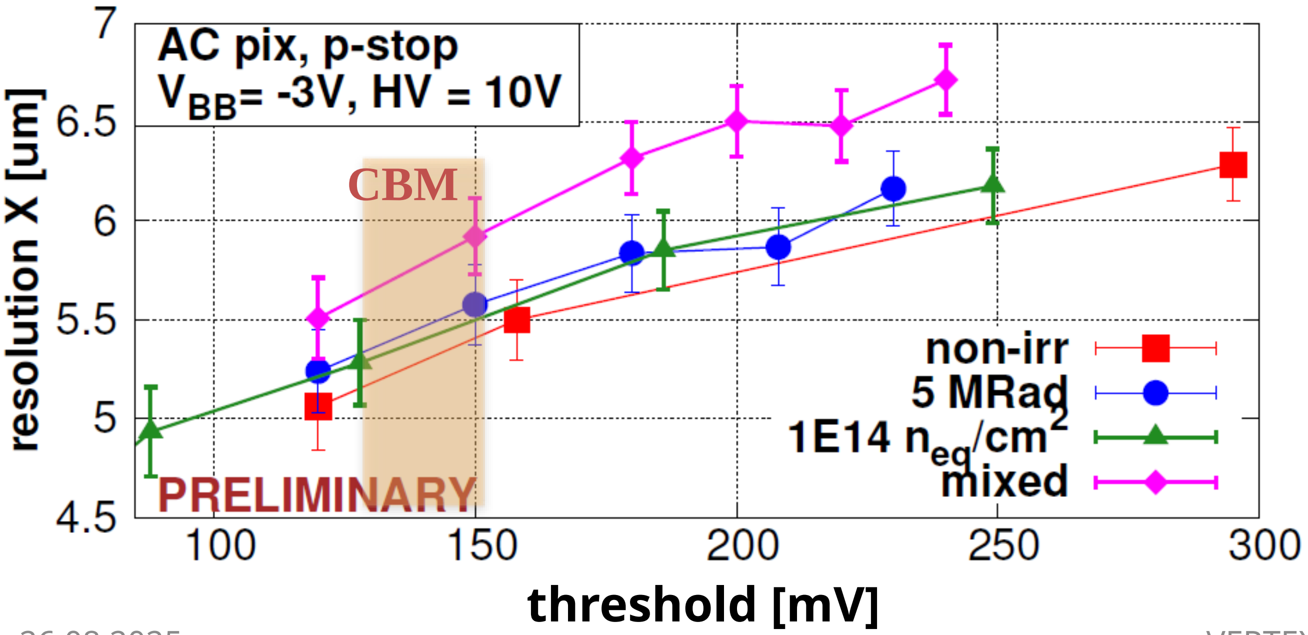


MIMOSIS-1 performance: After 5 MRad + 10^{14} n_{eq}/cm^2

Before and after irradiation

- Best performance: AC P-stop
- Efficiency > 99% (end of lifetime)
- Dark rate:
  - Marginal before irradiation
  - < 10^{-6} after irradiation

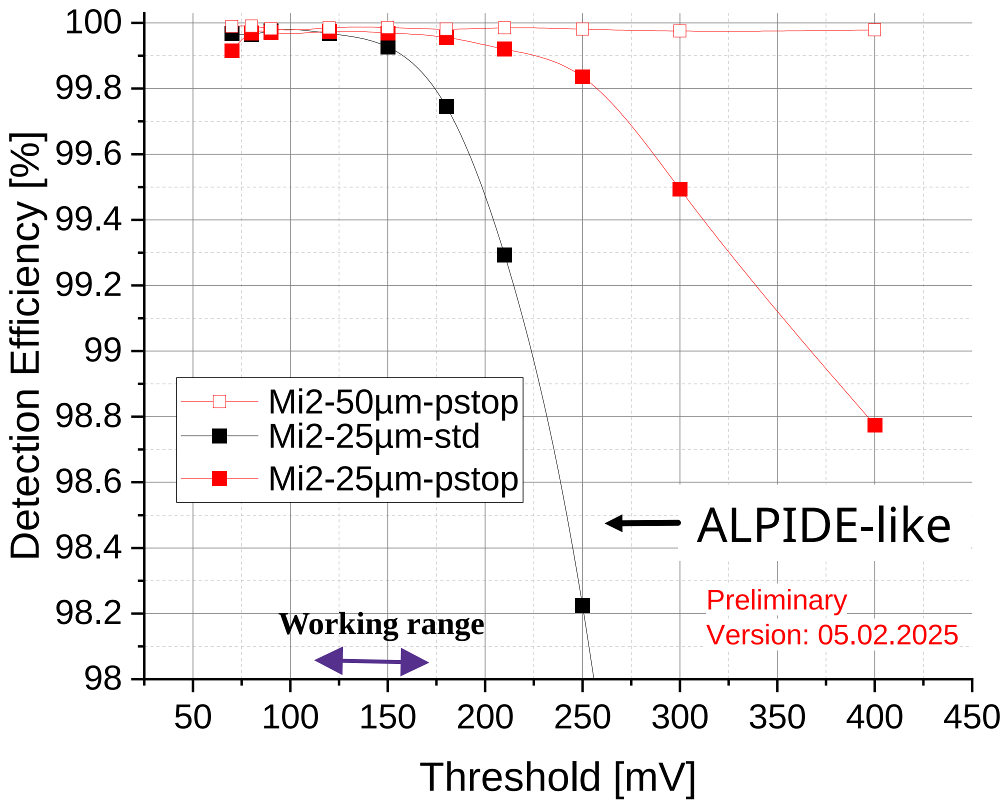


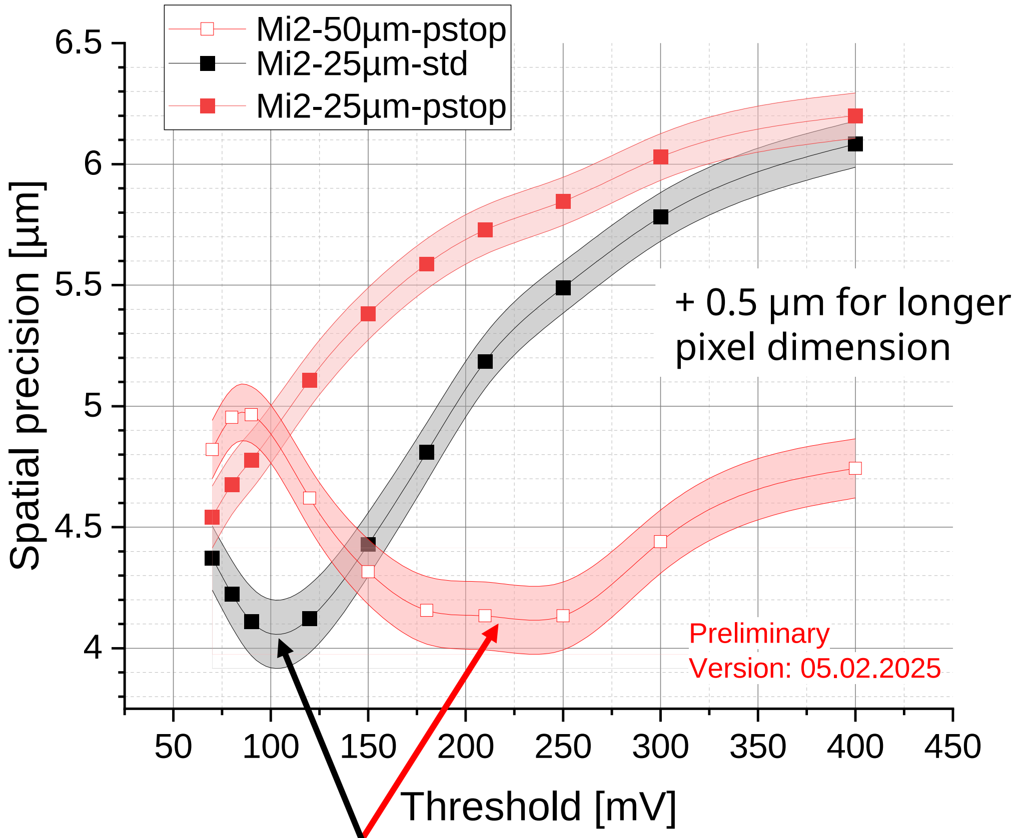


Conclusion:

- All pixels work excellently before irradiation
- STD pixels show better spatial resolution
- P-stop AC pixel: most radiation hard — matches CBM requirements

Sensor Performance: 25 µm vs. 50 µm



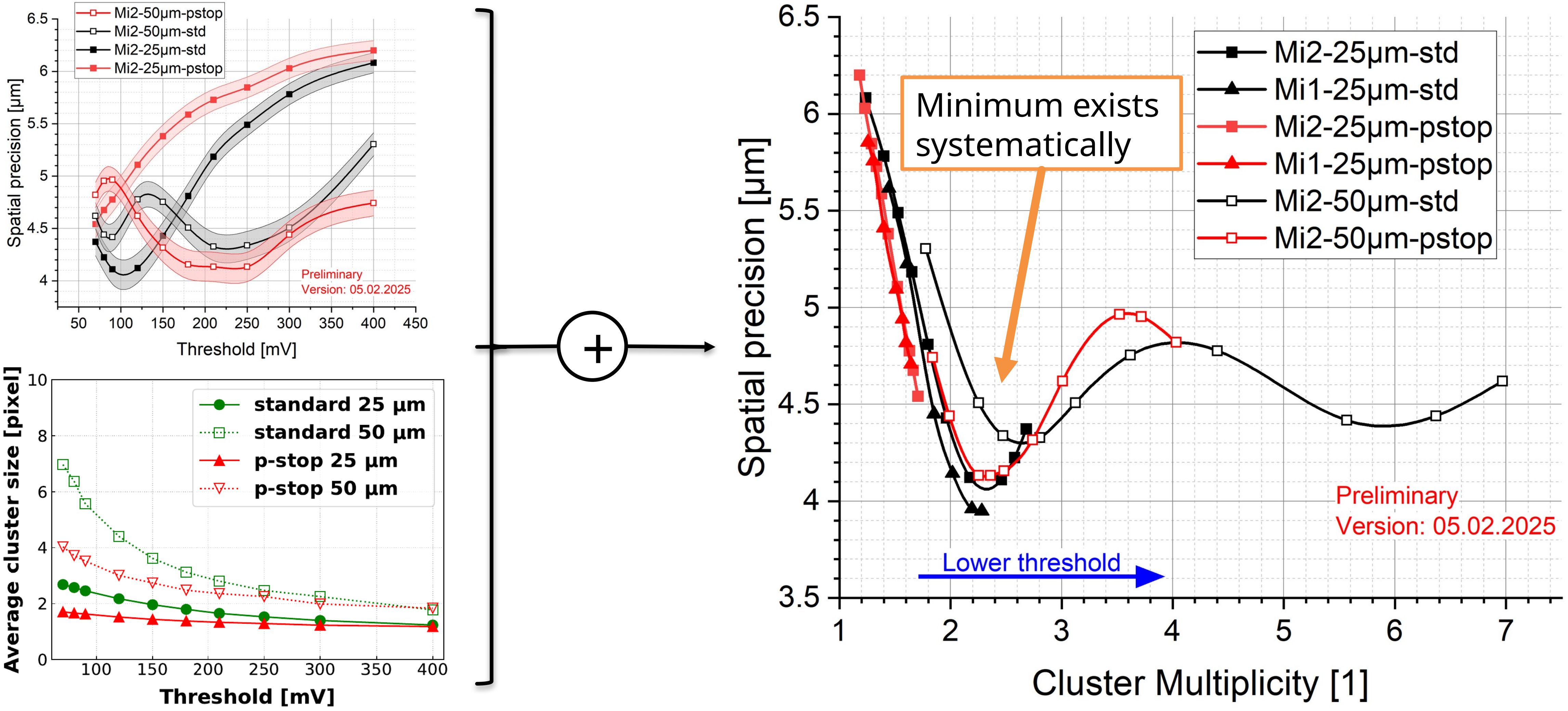


Optimal number of fired pixels/particle (about 2.5)

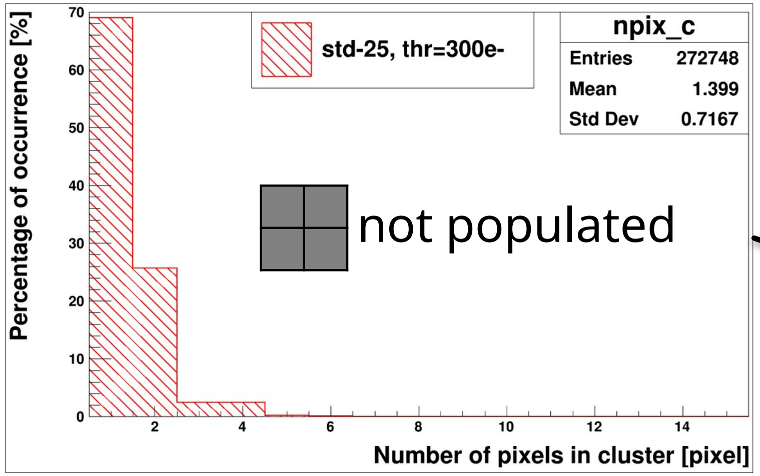
Dark rate typically <10^{-10}/pixel (2 Hz/cm^2) driven by individual hot pixels.

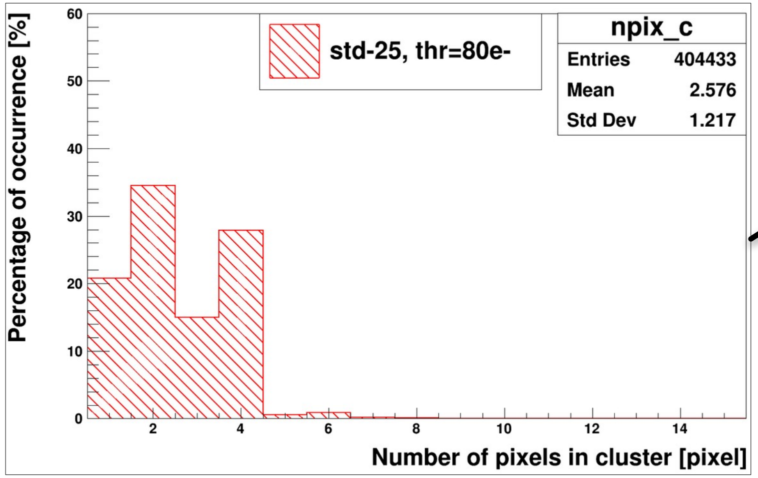
P-stop 50 µm shows superior working range and spat. precision w.r.t p-stop 25 µm.

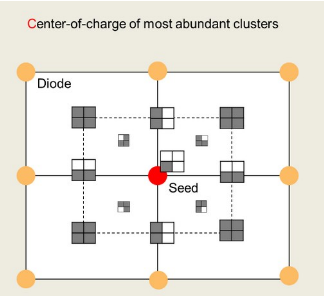
AC-pixel

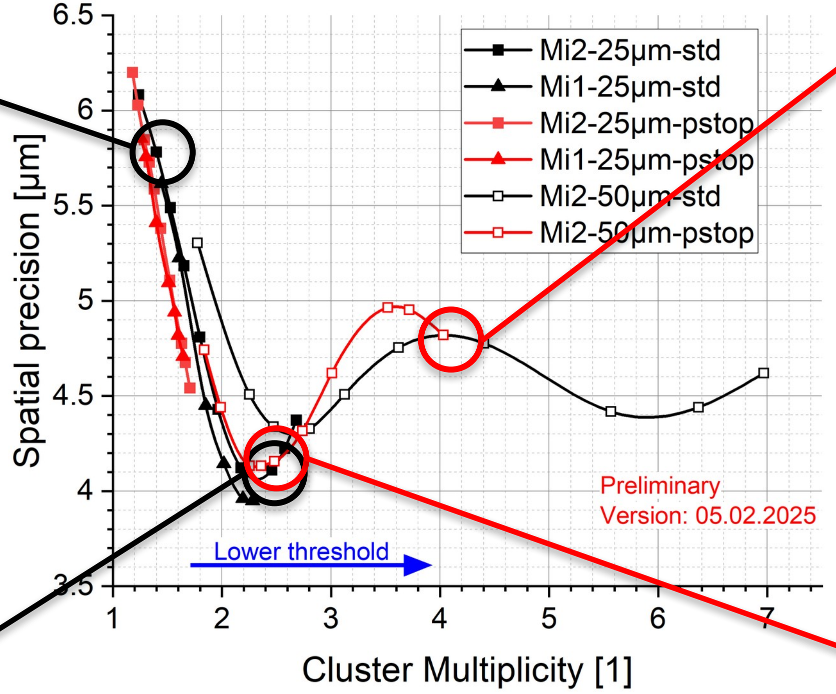

Mi2-50µm-pstop
Mi2-50µm-std
Mi2-25µm-std
Mi2-25µm-pstop
Spatial precision [µm]
Threshold [mV]
Preliminary
Version: 05.02.2025
standard 25 µm
standard 50 µm
p-stop 25 µm
p-stop 50 µm
Average cluster size [pixel]
Threshold [mV]
Minimum exists systematically
Mi2-25µm-std
Mi1-25µm-std
Mi2-25µm-pstop
Mi1-25µm-pstop
Mi2-50µm-std
Mi2-50µm-pstop
Spatial precision [µm]
Preliminary
Version: 05.02.2025
Lower threshold
Cluster Multiplicity [1]

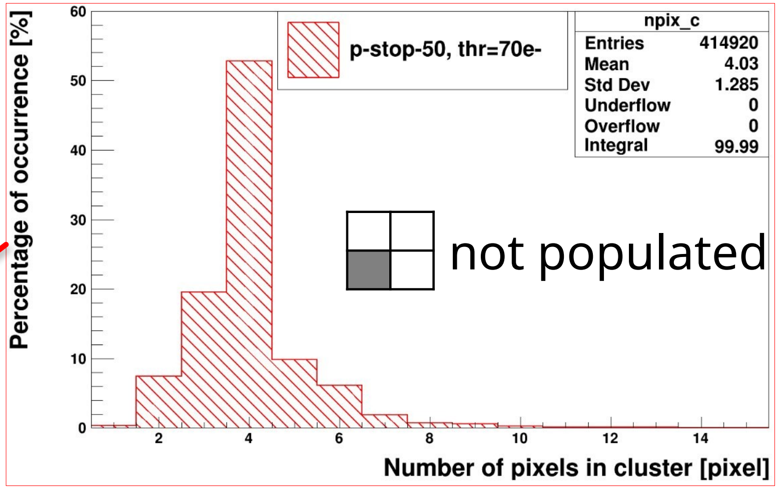
Sensor Performance: Optimal cluster multiplicity

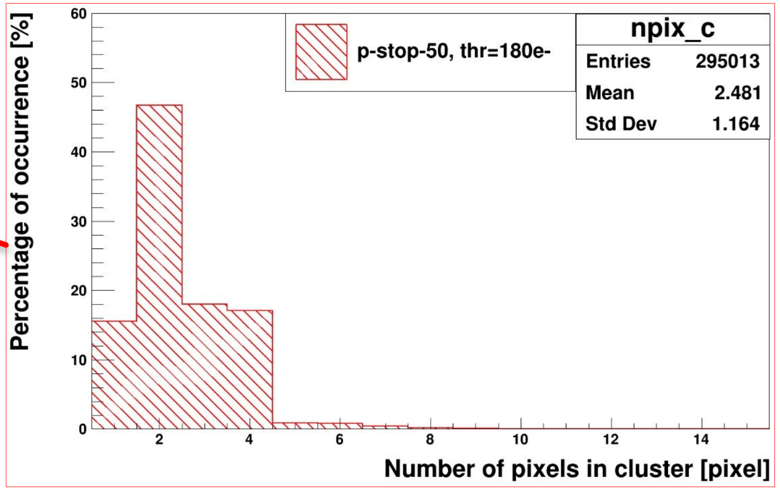






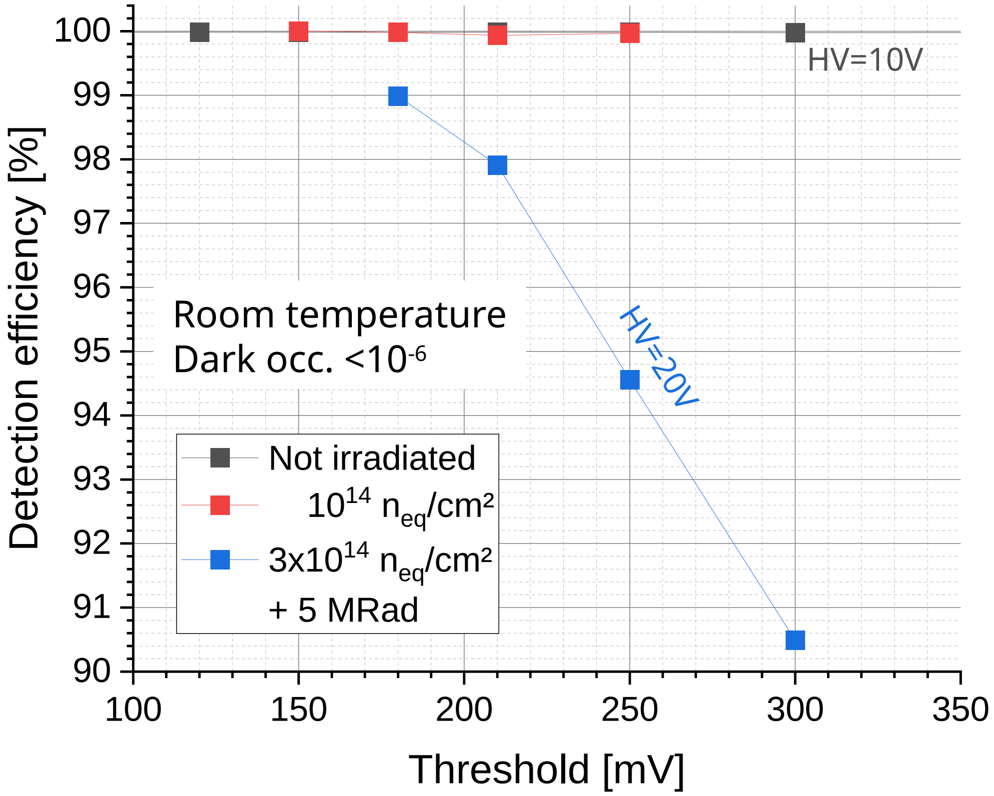




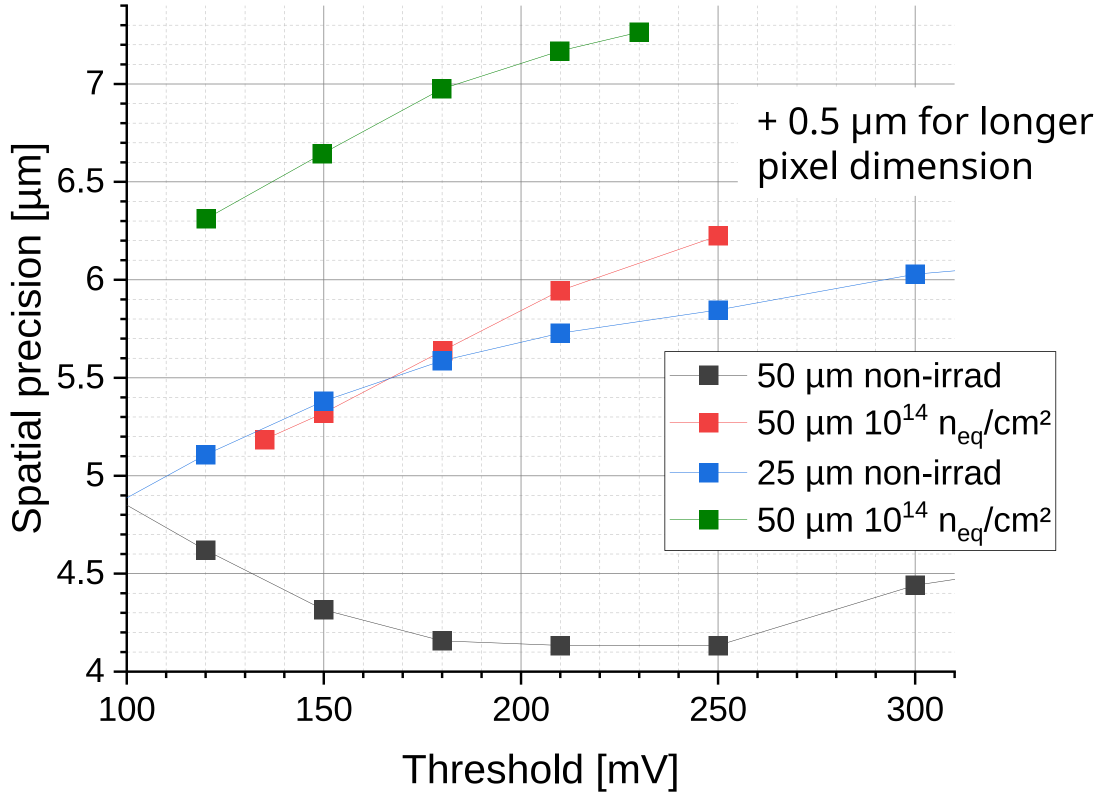


Broadest distribution of cluster shapes
⇒ Most different center – of – charge.
⇒ Best spatial precision.

Detection efficiency MIMOSIS-2.1
p-stop 50 µm



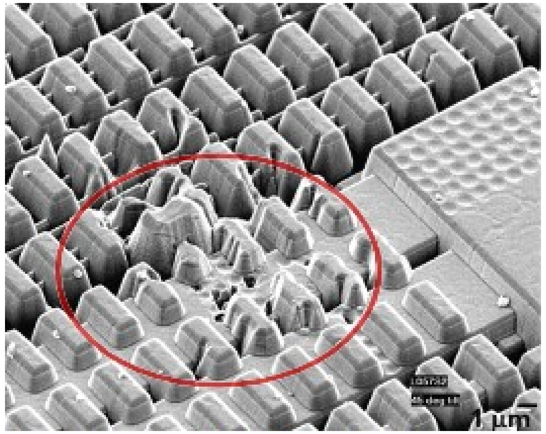
Spat. precision MIMOSIS-2.1
p-stop 25 µm vs. 50 µm



P-stop 50µm matches rad. tolerance of P-stop 25 µm (not shown).
P-stop 50µm keeps its advantages in terms of spat. precision after $10^{14} n_{eq}/cm^2$

Sensor Performance – tolerance to heavy ion impacts

Initial worry: Single-Event Latch up
- Ions create meta-stable short circuit in the ASIC.
- Must power cycle to avoid device burn out.

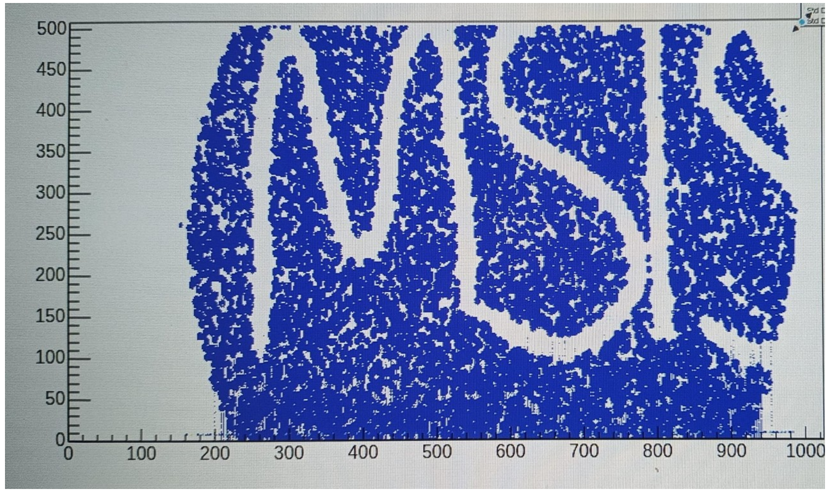


Latch-up in ULTIMATE sensor
G. Contin, JINST 11 C12068 (2016)

Test of MIMOSIS with ~5 AMeV heavy ions at GSI:
- No latch-ups to LET (dE/dx) > 35 MeV cm² / mg.
- No destruction after >100 MHz/cm² pulses for >1 ms.

- ~~Sensor resumes operation if exposed to ~20 MeV cm²/mg.~~

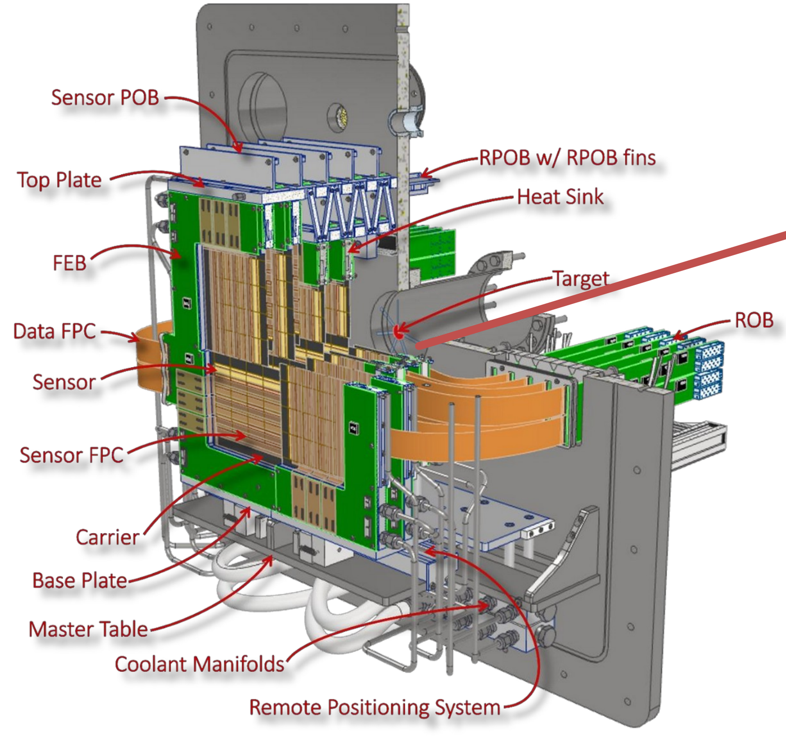
Work in progress



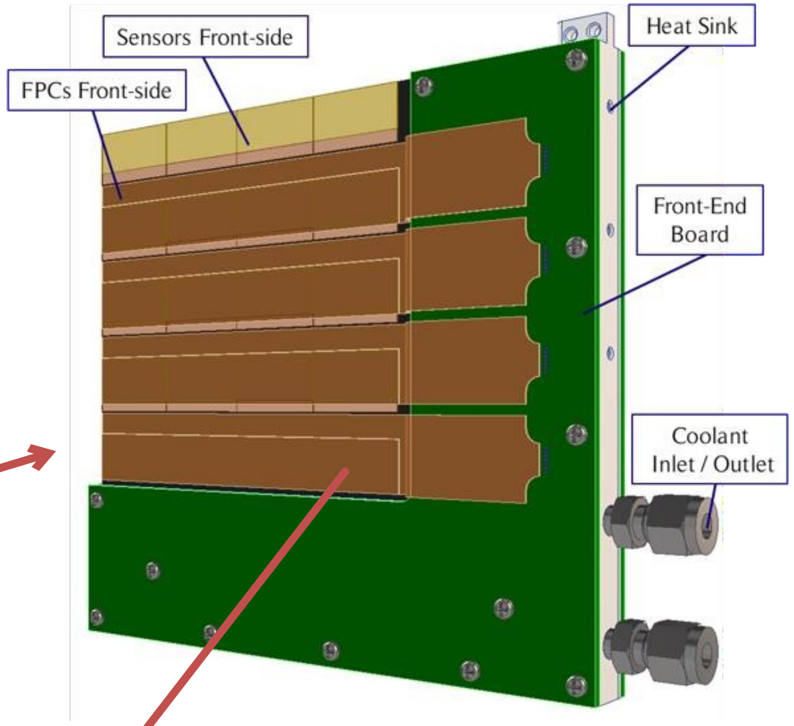
MVD Integration

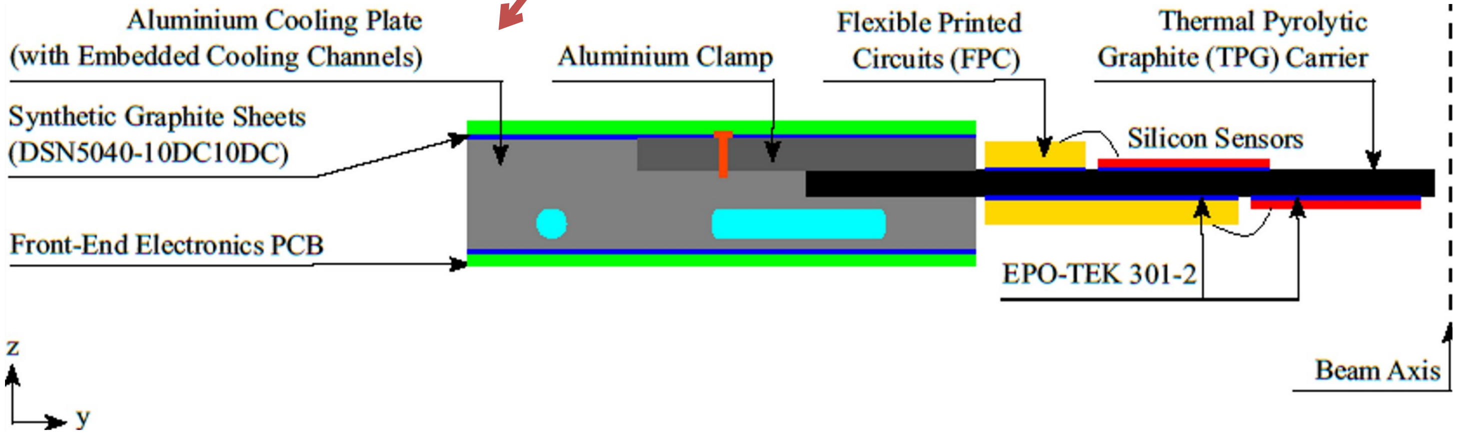
Four planar tracking stations

- ~300 CMOS MAPS
- 5 - 20 cm downstream
- Placed inside Vacuum
- 1Tm Magnetic field
- 0.3 - 0.5 % X_0



Credits: F. Matejcek

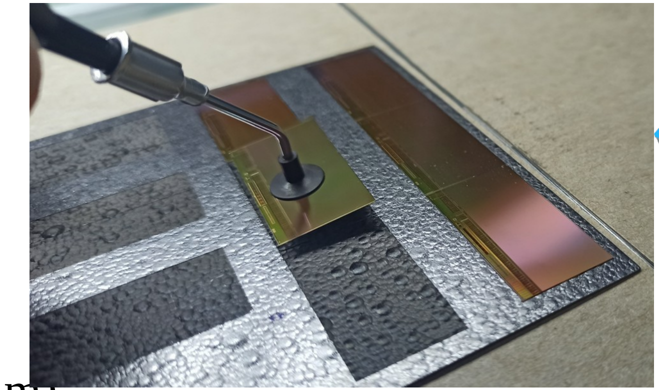


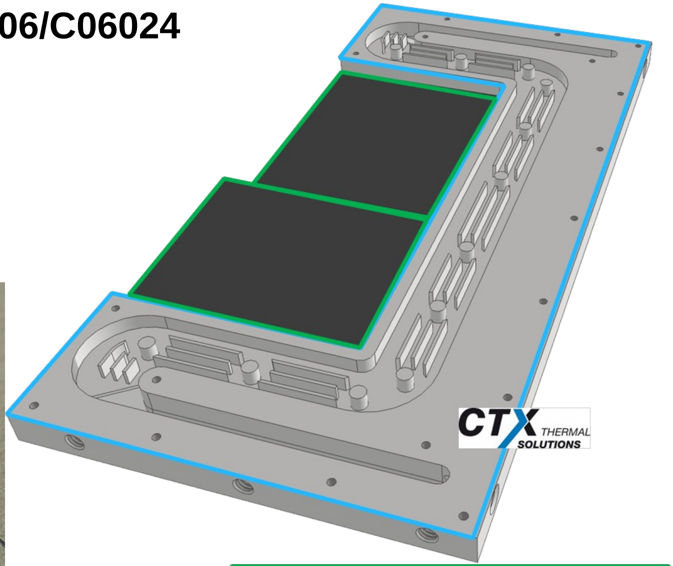


MVD Integration

- **Cooling:**
  - Heat conduction inside geometrical acceptance
  - Glycol/water based active cooling outside
  - Using **Thermal Pyrolytic Graphite (TPG)** Carrier
    - Mechanically stable
    - Low material budget (< 0.2% X_0)
    - Highly thermally conductive
    - Large (~150 x 150 mm²)
    - Laser cutting

Ref: 10.1088/1748-0221/20/06/C06024



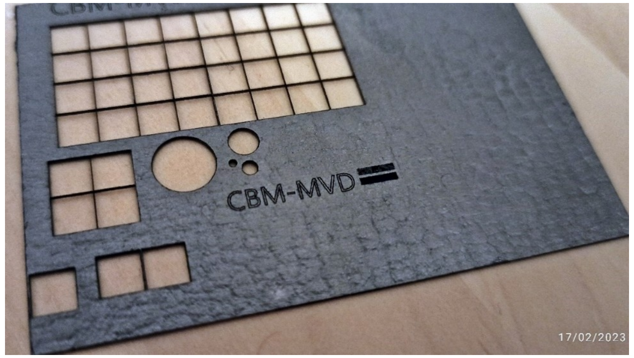


Passive, conductive cooling

Active, liquid cooling

- **Double-sided Integration:**
  - Integration (double-sided) **TPG sheets** (250 µm and 380 µm)

- **Probe testing at IKF – inspired by ALPIDE**
  - Quality assurance (QA) of sensors
  - Automatic test procedure for monitoring: analog, digital, biasing currents, threshold measurement, etc...
  - Yield: ~55% (First measurements) → main issue is powering

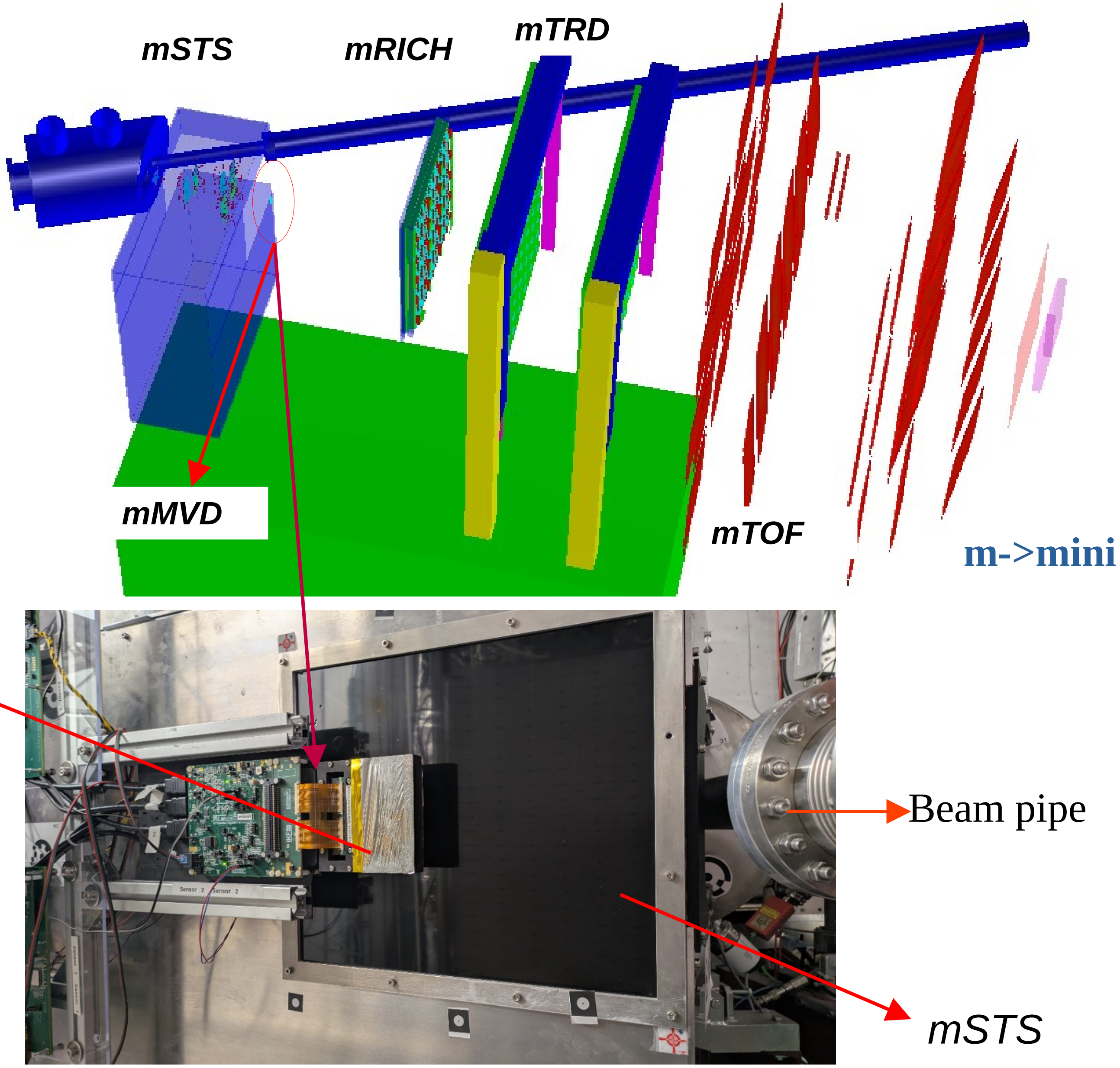


Testing mMVD in mCBM experiment

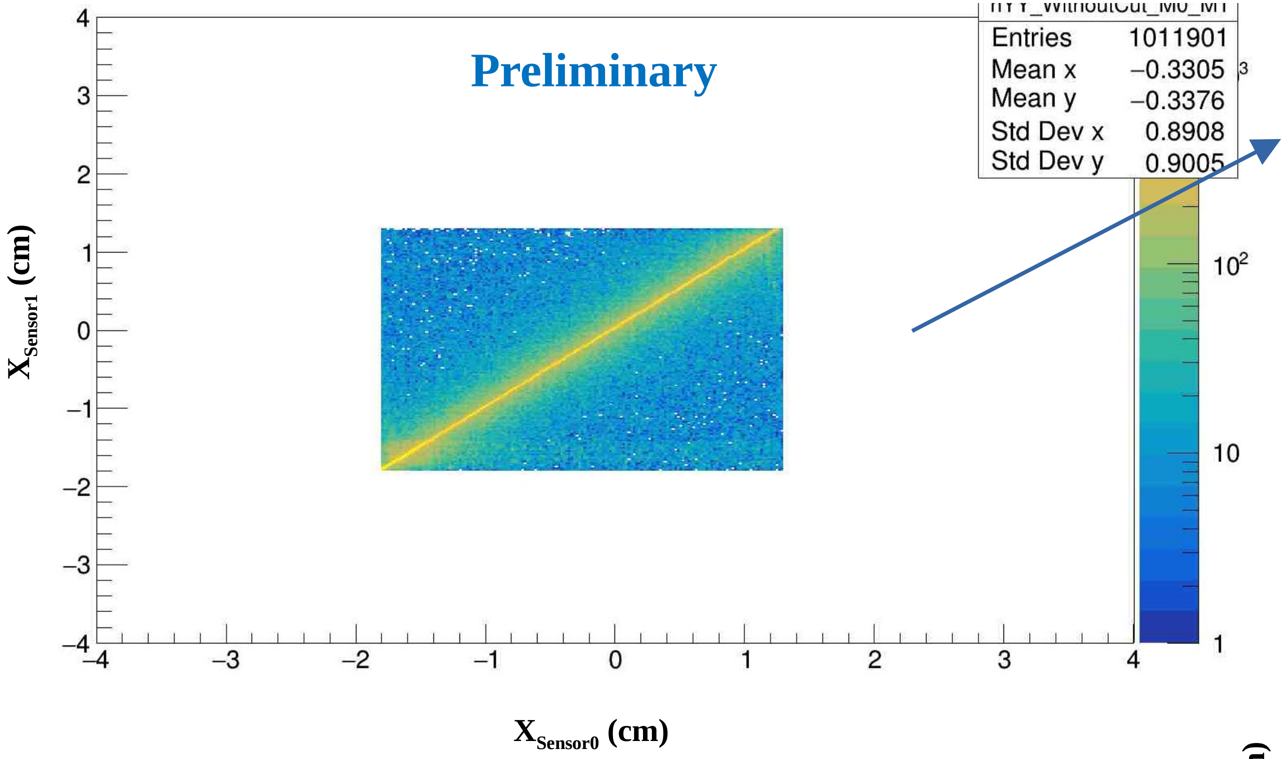
- **System demonstrator** of CBM in real beam conditions
- **Demonstrate triggerless, free-streaming readout** at high rates
- **Commission & integrate** sub-detectors

- **mMVD**
  - consists of **2 MIMOSIS-2.1 sensors**
  - first time tested in mCBM experiment together others (STS...)

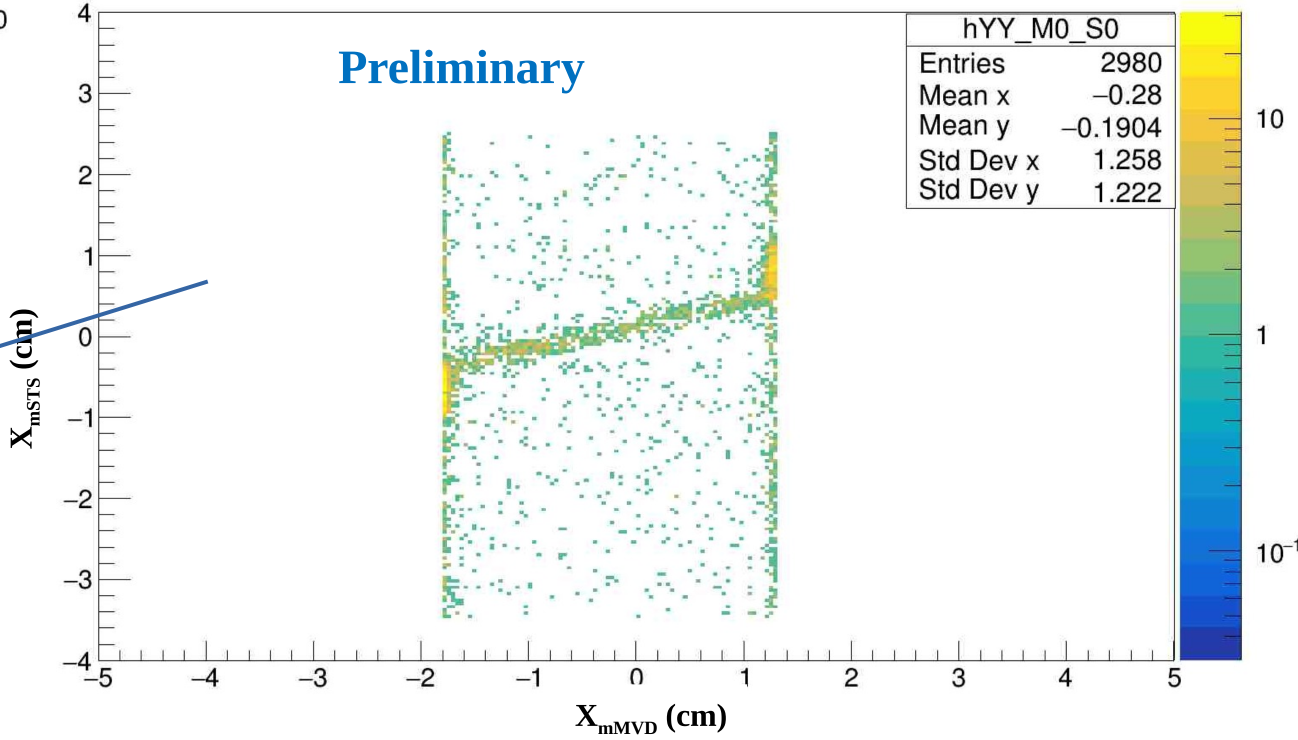
- **Goal:**
  - Test and validate readout
  - Test Synchronisation with others
    - Spa. correlation amongst both sensors
    - Spa. correlation between mMVD and mSTS



Spatial Correlation: mCBM



Spatial Correlation between two MIMOSIS sensors



Spatial Correlation between mMVD and mSTS

Successful operation of **MIMOSIS** sensors in **CBM-like** environment

- free streaming DAQ, Self-triggered common readout

Summary and Future Outlook

- ✓ **MVD role & specs:** four planar stations (~300 MAPS) in vacuum
  - target **σ ≈ 5 µm**, **0.3–0.5 % X_0/layer**
- ✓ **Performance (MIMOSIS-2.1 focus): 50 µm p-stop** gives the best overall performance
  - efficiency > **99 %** with **marginal dark rate,** spatial resolution around **5–6 µm**
  - even after irradiation (up to **5 MRad + 10^{14} n_{eq} cm^{-2}**)
  - Also provide higher operational margin
- ✓ **SEE robustness: no latch-up** observed for **LET > 35 MeV.cm^2 mg^{-1}** meets CBM heavy-ion tolerance requirements
- ✓ **Integration status:** double-sided modules on **TPG carriers** (≈0.2 % X_0), automatic bonding, Probe testing for QA of sensors
  - Mass testing setup ready and running with MIMOSIS-2.1
- ✓ **System demo (mCBM):** first **mMVD** with two MIMOSIS-2.1 sensors operated with other subsystems
  - **Time synchronization and spatial correlations** demonstrated

- ➢ **MIMOSIS-3** submission: end of 2025

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Measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

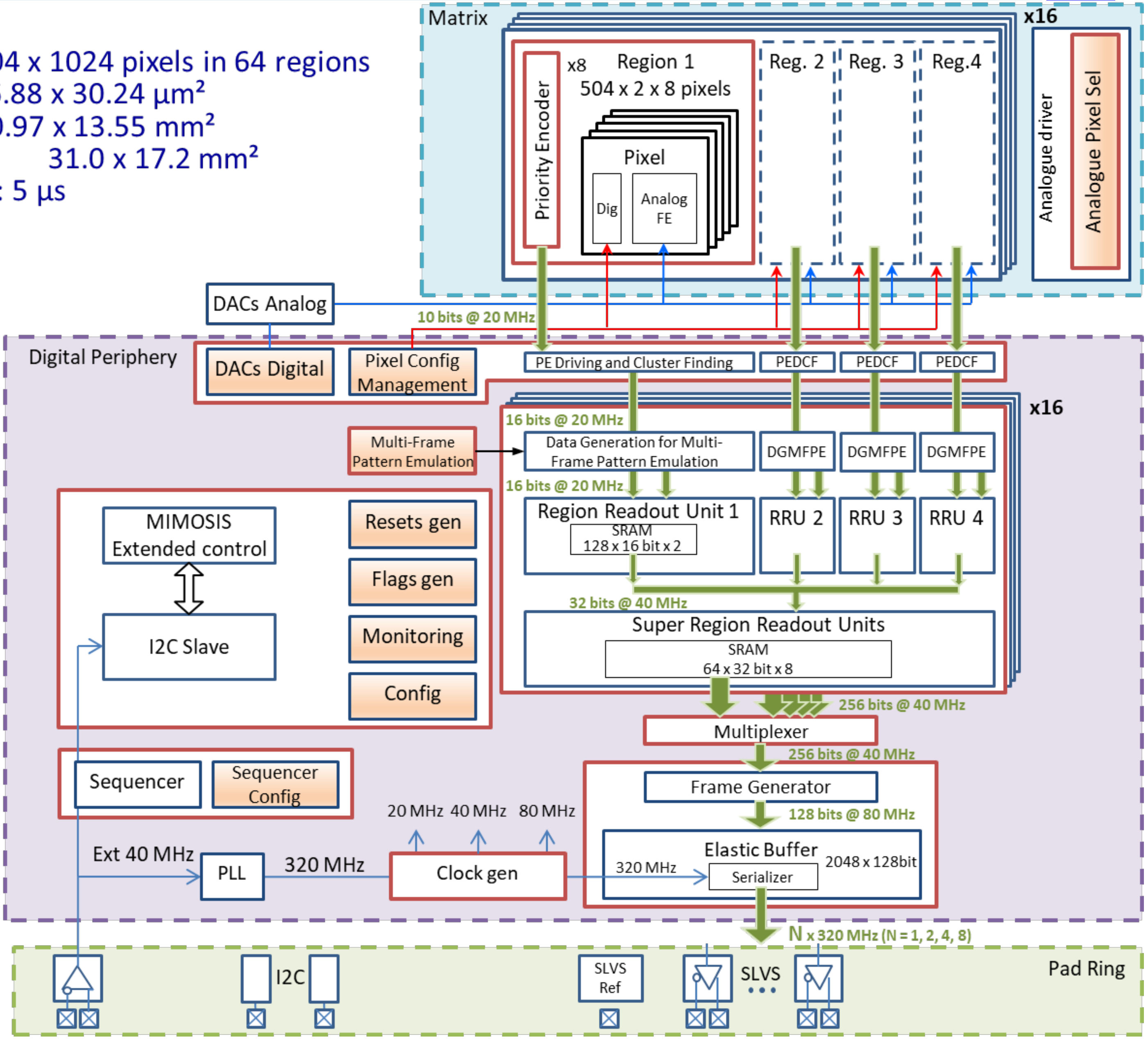
Thank You!

Backup

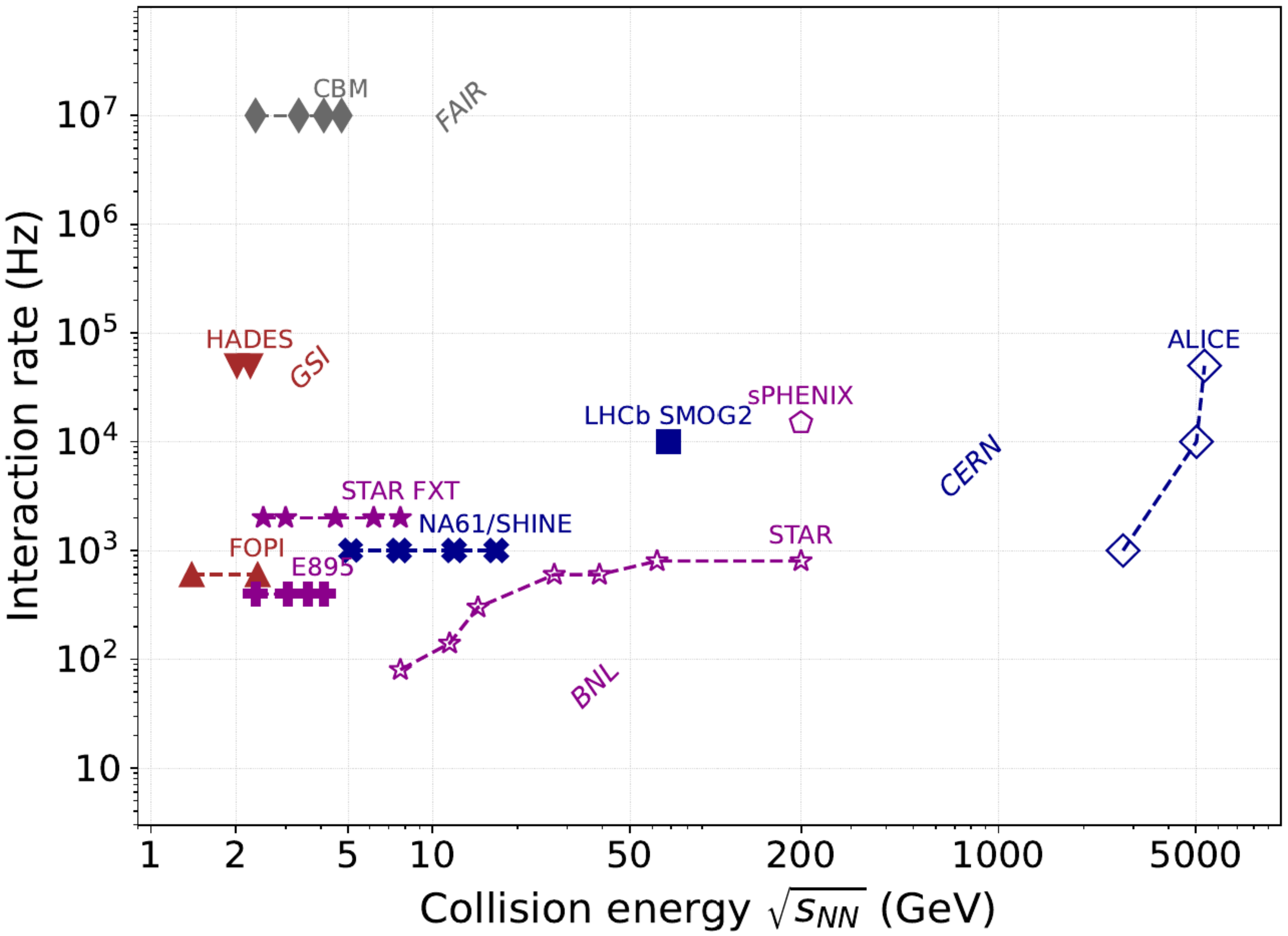
MIMOSIS schematic

- Pixel array: 504 x 1024 pixels in 64 regions
- Pixel pitch: 26.88 x 30.24 μm^2
- Active area: 30.97 x 13.55 mm^2
- Chip dimension: 31.0 x 17.2 mm^2
- Integration time: 5 µs

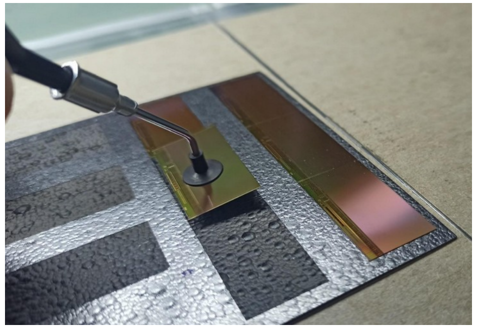
- Pixel array:
  - Analog part of pixel similar to ALPIDE, but 2 versions
  - Digital part of pixel redesigned
  - Priority encoder: same
- Fully reworked digital part

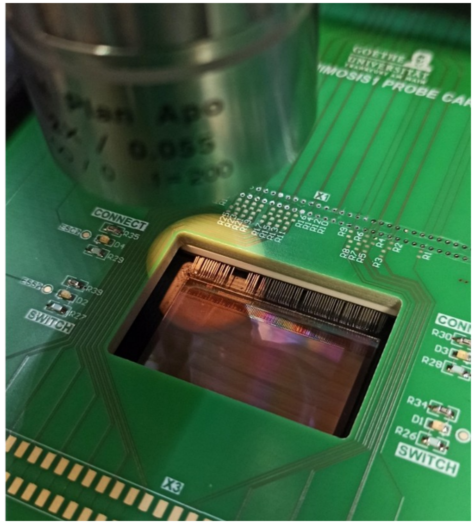


Interaction rate



Pre-production roadmap





Detection System Functionality

Ensuring proper operation of detection system

Thermal Management

Implementing cooling system for optimal temperature

Structural Support

Integrating carrier for overall structural integrity

Electrical Connections

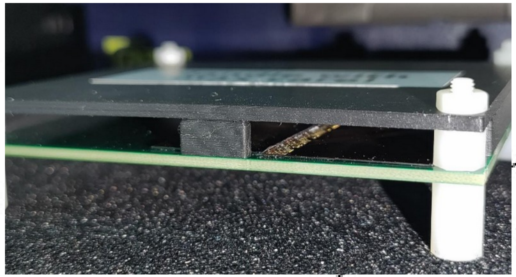
Establishing electrical connections between components

Flexible Printed Circuit Assembly

Assembling the flexible circuit board

Quality Assurance

Ensuring sensor functionality and quality



Detector Mechanics

Cooling

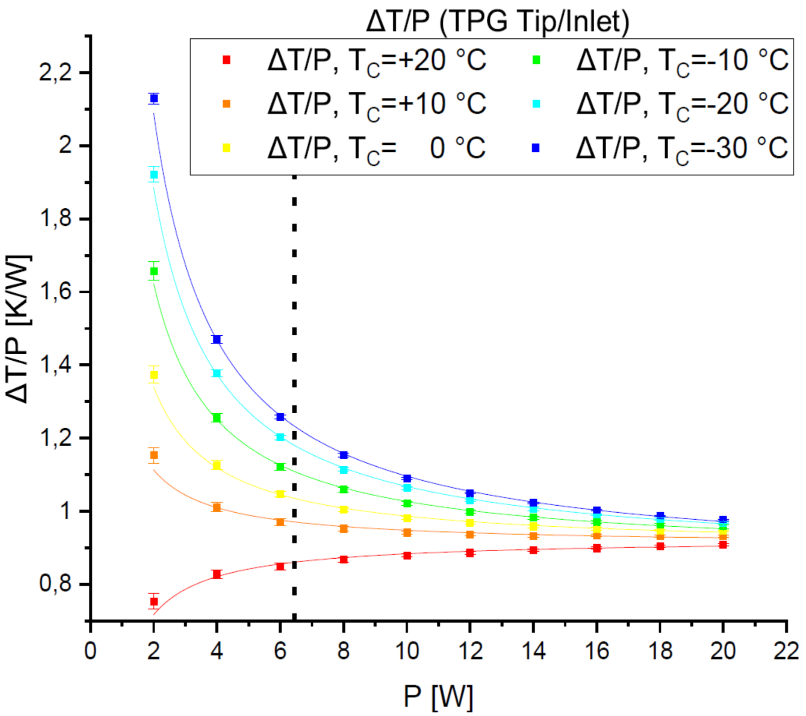
Carrier

Wire-Bonding

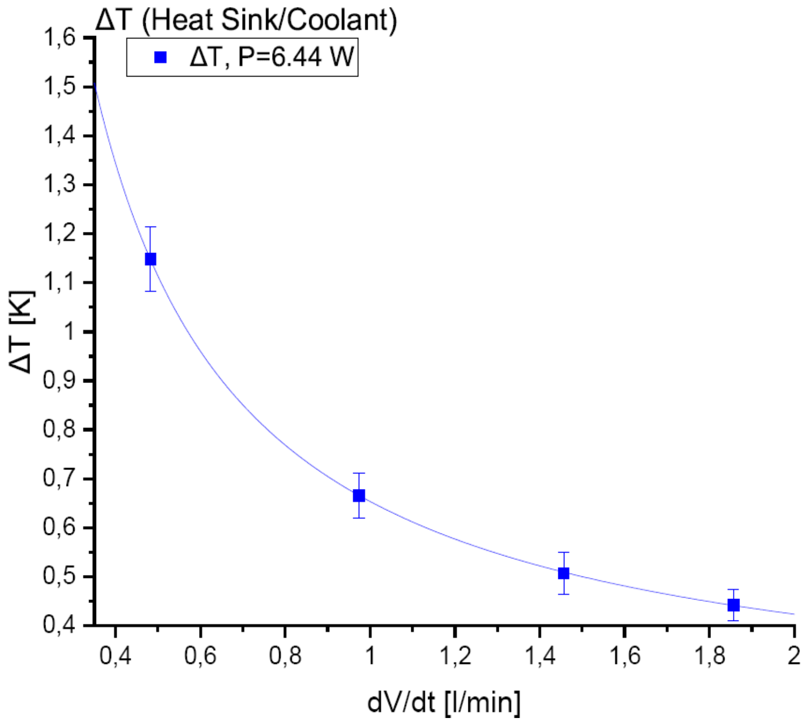
FPC

Sensor QA

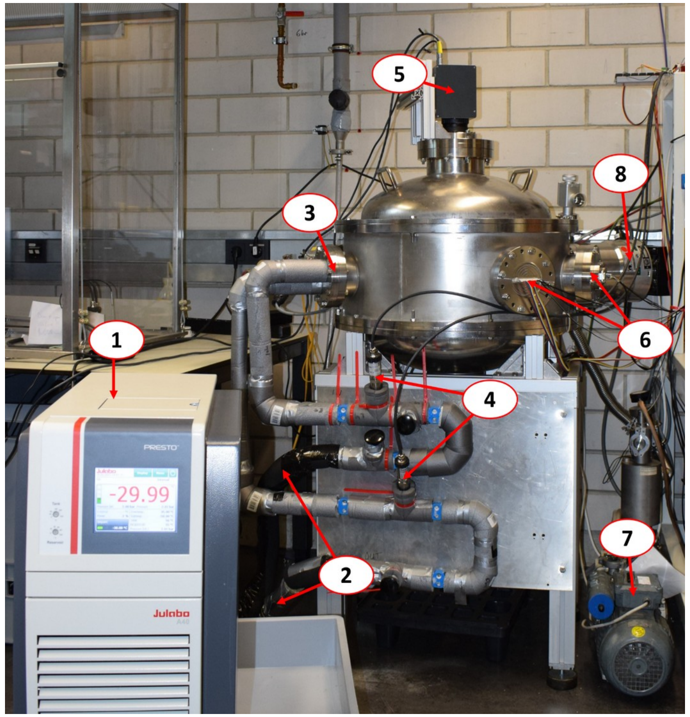
MVD Thermal Performance



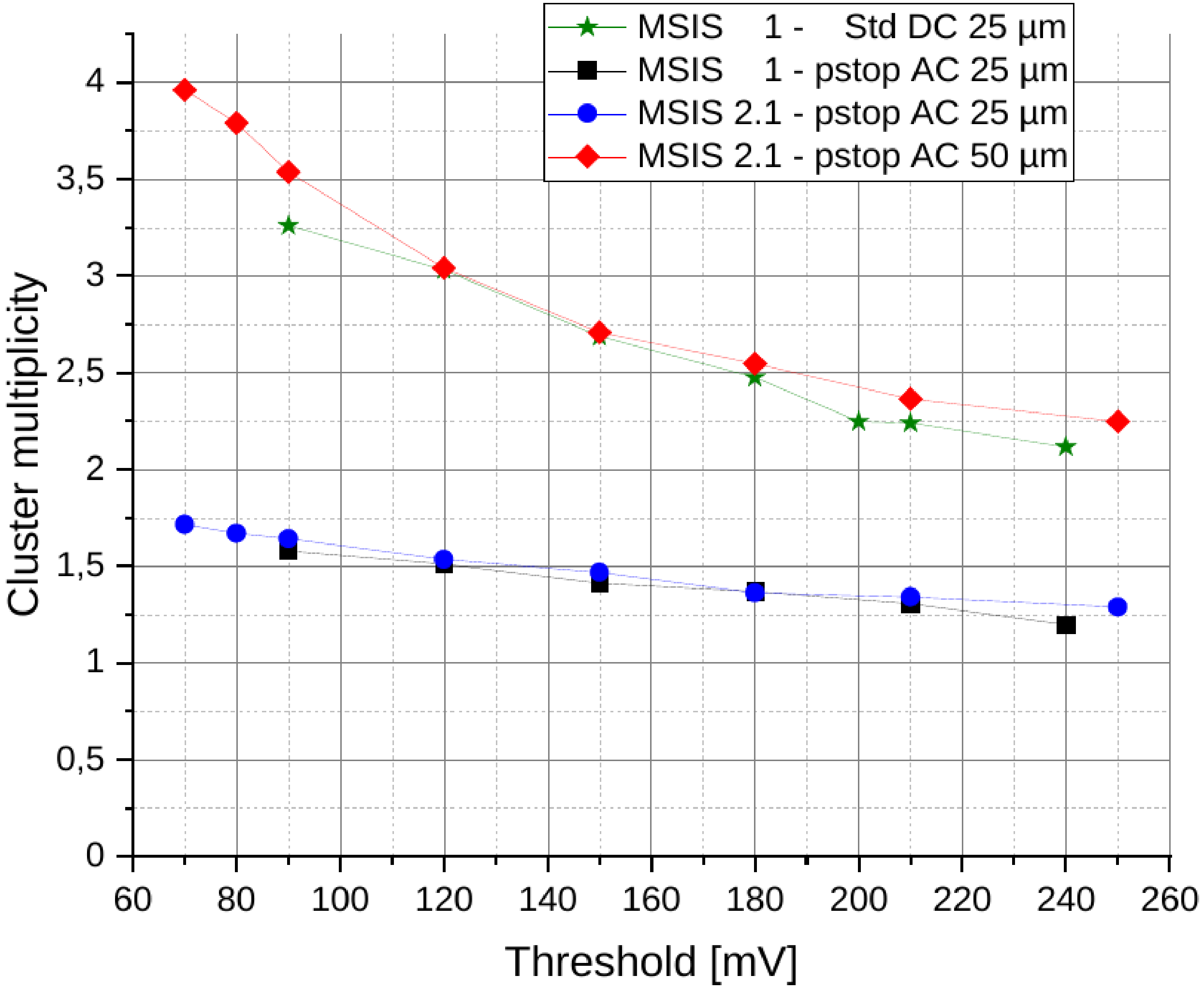
Influence of thermal radiation in testing setup

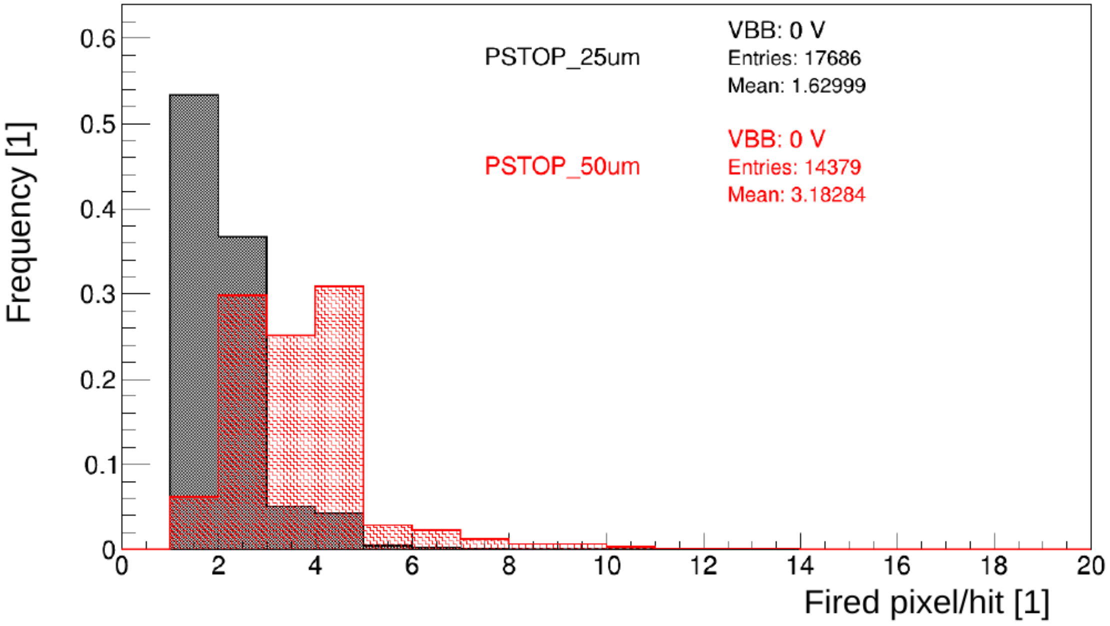


Influence of coolant flow in testing setup



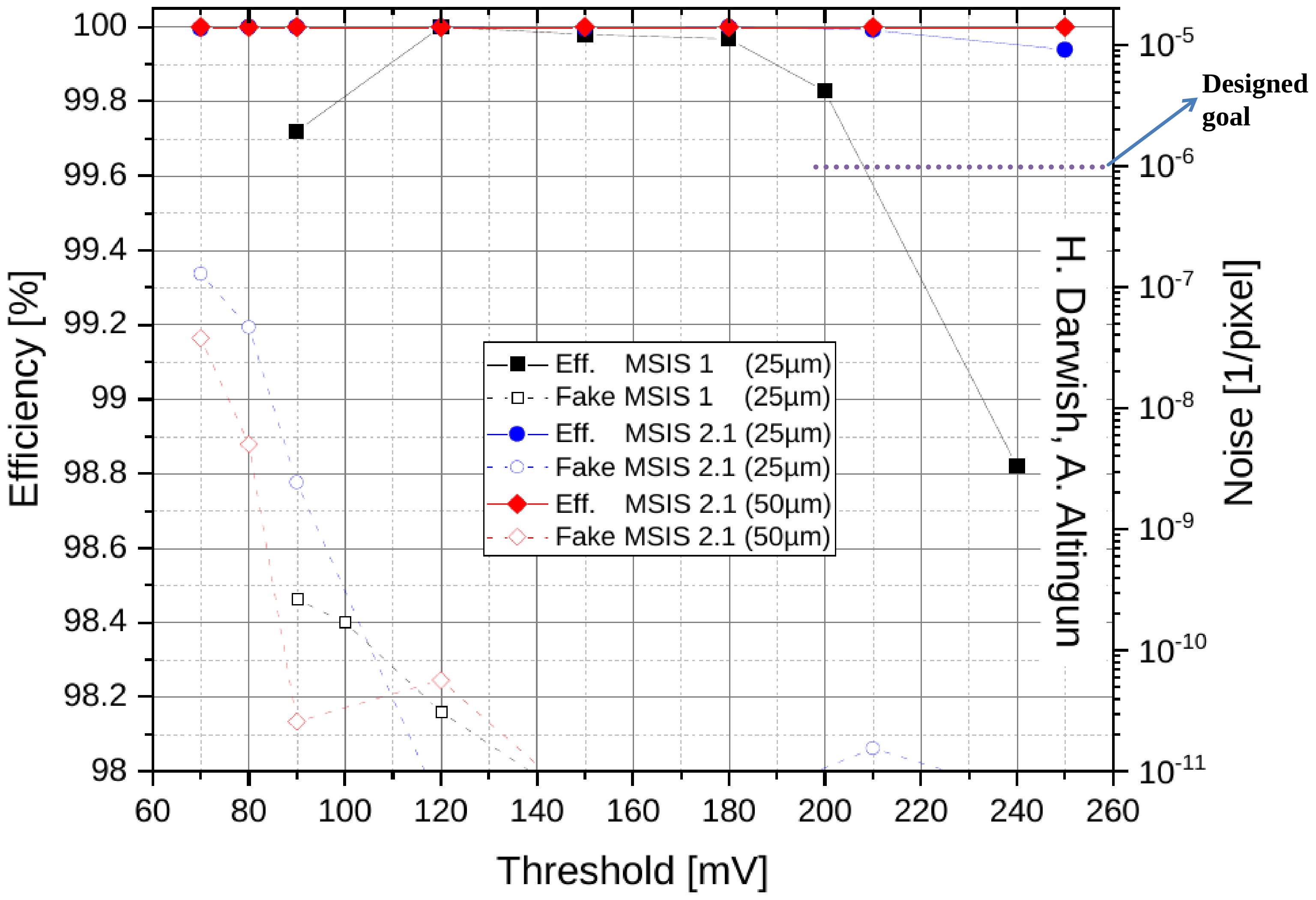
MIMOSIS-2.1: Cluster Multiplicity





Sensor Performance: MIMOSIS-1 vs MIMOSIS-2.1

- MIMOSIS-2.1 shows even better efficiency at lower threshold than MIMOSIS-1.
- Large operation range for MIMOSIS-2.1.
- Dark rate bellow the designed goal (noisy pixels NOT masked)
- Best performance for 50µm epitaxial layer with p-stop.



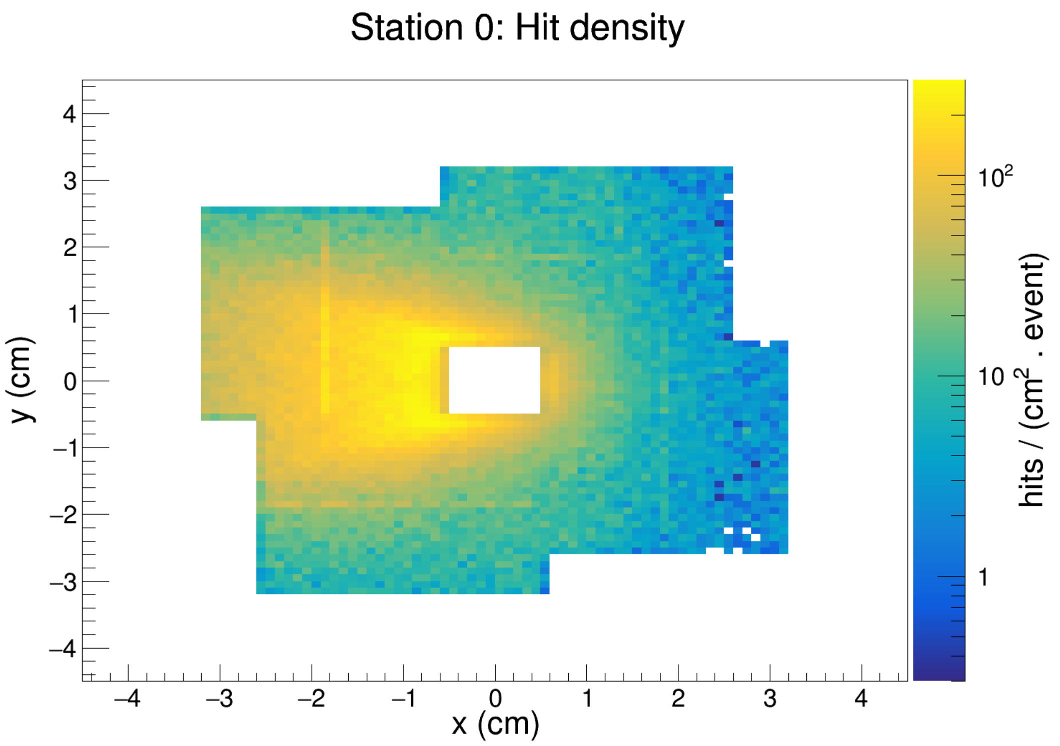
Challenges for Vertex Detector at CBM

- High density track environment
  - Forward-boosted cone near target —> very high local hit rates
  - Mitigate with 5 μs frames, on-chip clustering, elastic buffers, multi-link readout

- δ-electrons & beam-induced backgrounds
  - Knock-out e-, halo scraping, back-scatter

- Anisotropic radiation environment
  - Dose/Fluence gradient across acceptance
  - Fully depleted pixels, cool operation

- Stringent material budget (0.3-0.5% X_0 per layer)
  - Minimize multiple scattering for low momentum tracks, reduce secondary production
  - 50-70 μm sensors, TPG carriers, light FPCs



Au+Au, 12AGeV