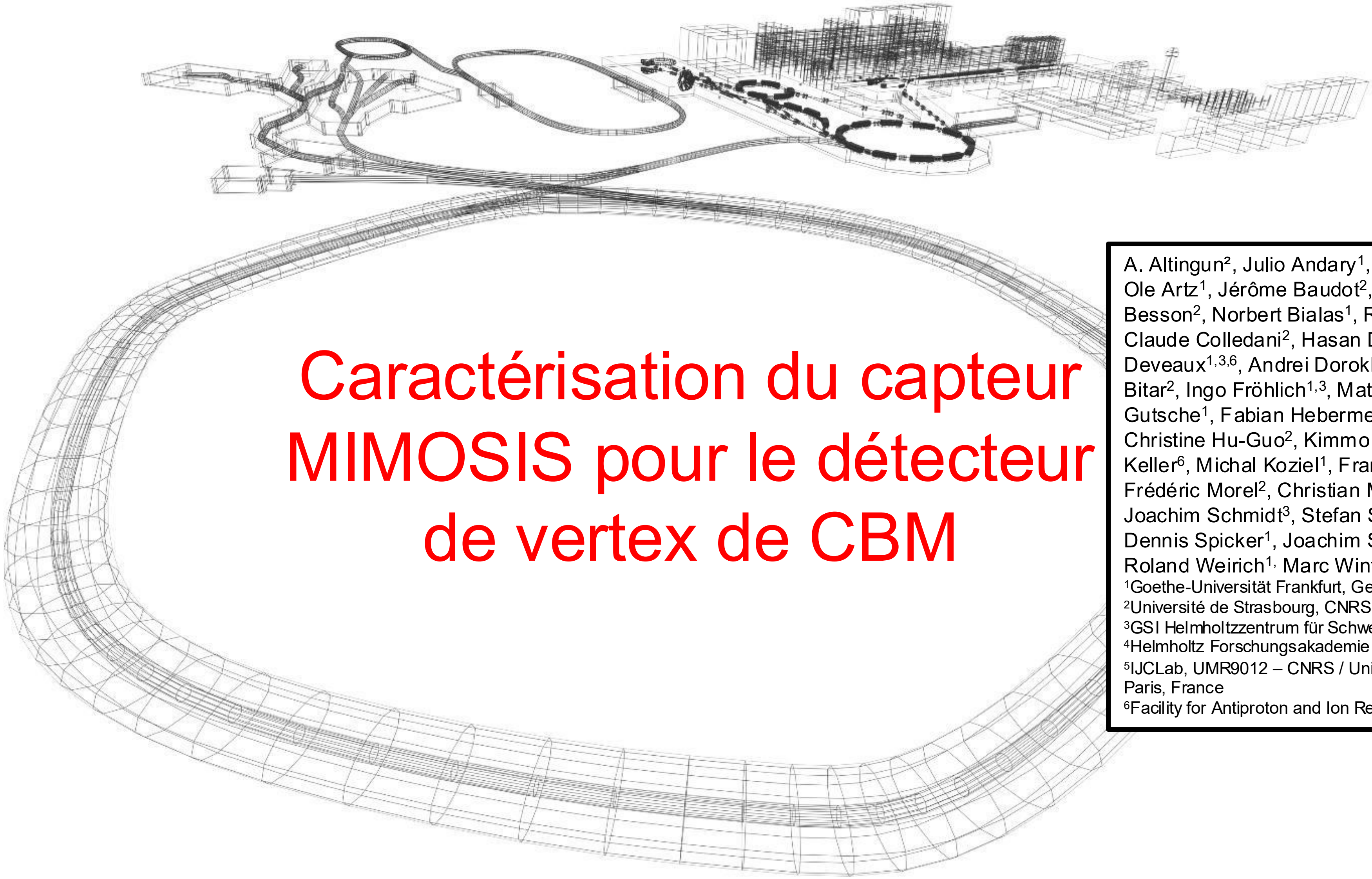
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

Supported by Bundesministerium für Bildung und Forschung (05P19RFFC1)



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

Caractérisation du capteur MIMOSIS pour le détecteur de vertex de CBM

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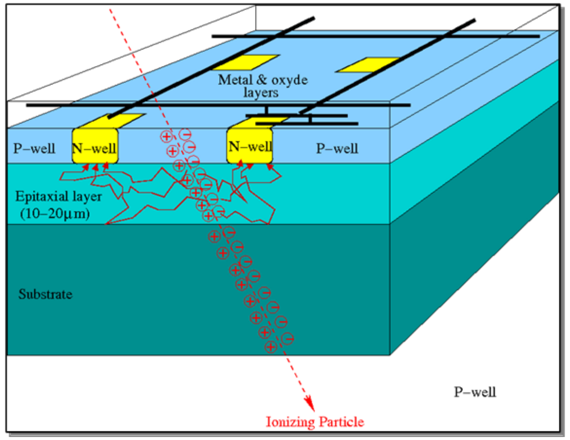
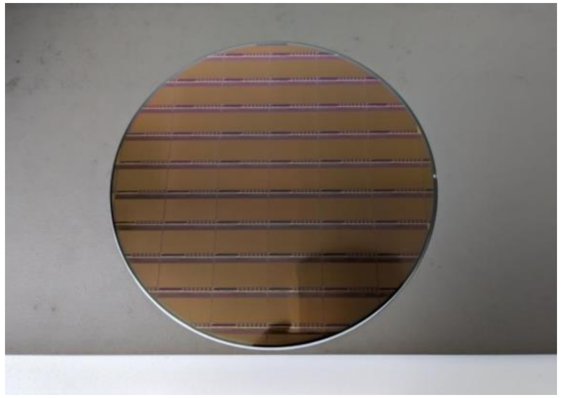
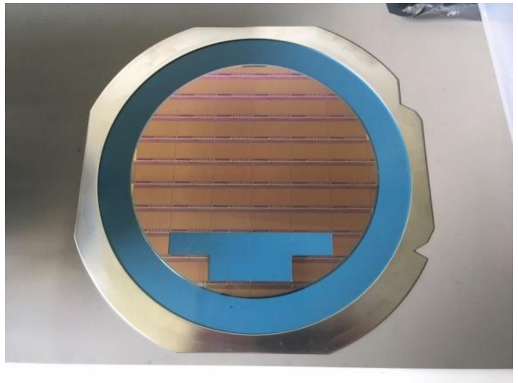
[6]Facility for Antiproton and Ion Research in Europe GmbH,Germany

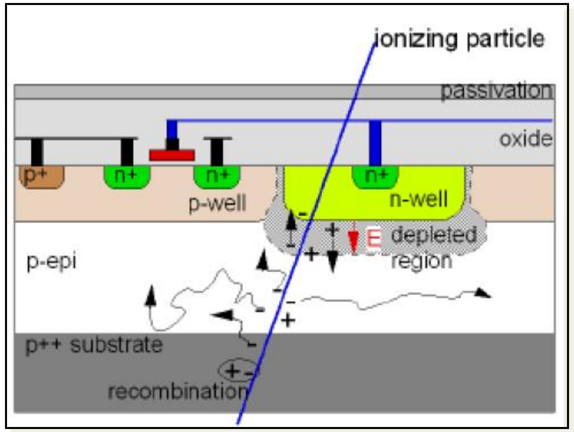
CMOS pixel sensors for charged particle detection

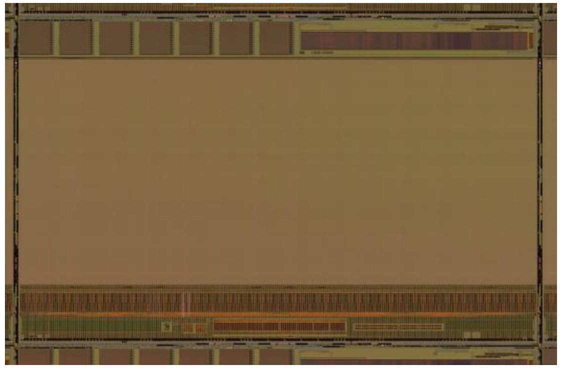
- Main features
  - ✓ Monolithic, p-type Si
    - Signal created in low doped thin epitaxial layer ~10-30 μm
  - ✓ Thermal diffusion of e-
    - Limited depleted region (can be enhanced)
  - ✓ Charge collection: N-Well diodes
    - Charge sharing => resolution
  - ✓ Continuous charge collection
    - No dead time
- Main advantages
  - ✓ Granularity
    - Pixel pitch down to 10 x 10 μm^2 spatial resolution down to ~ few μm)
  - ✓ Material budget
    - whole sensor routinely thinned down to 50 μm
  - ✓ Signal processing integrated in the sensor
    - Flexible running conditions
    - From ~ 0°C up to 30-40°C if necessary
  - ✓ Low power dissipation (~ 100 mW/cm^2) => material budget
  - ✓ Radiation tolerance: > MRad and O(10^{14} neq) f(T,pitch)
  - ✓ Industrial mass production
    - Advantages on costs, yields, fast evolution of the technology,
    - Possible frequent submissions
  - ✓ Evolving technology: new accessible processes:
    - Smaller feature size, adapted epitaxial layer
    - Open the door for new applications
- Main limitations
  - ✓ Industry adresses applications far from HEP experiments concerns
    - Different optimisations on the parameters on the technologies



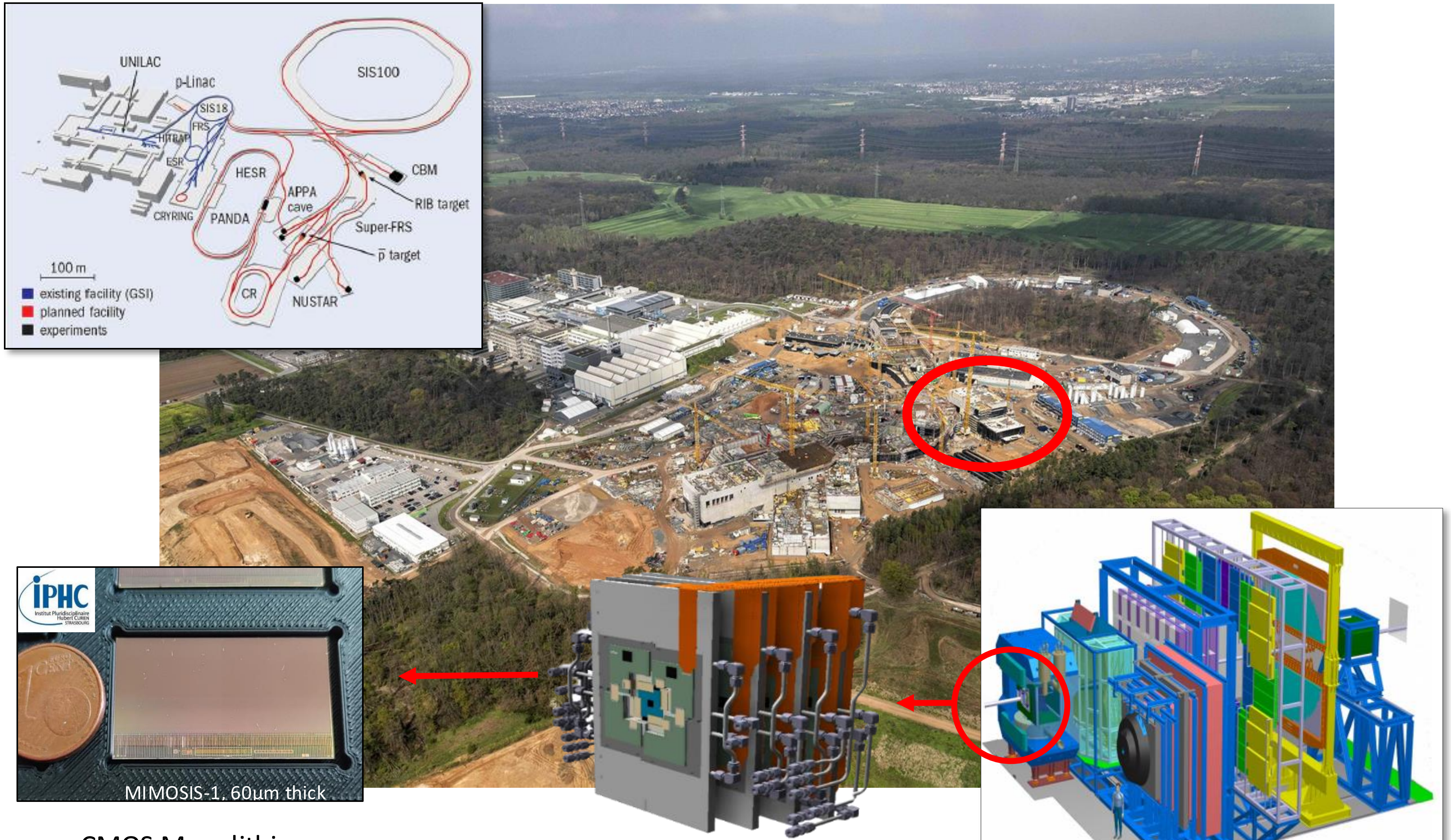








The MVD @ CBM @ FAIR - GSI



CMOS Monolithic
Active Pixel Sensor
MIMOSIS

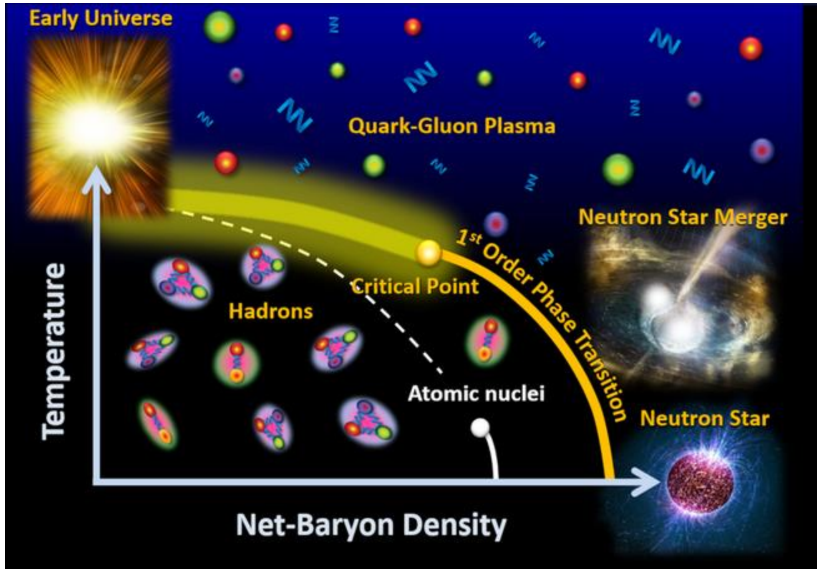
CBM Micro Vertex Detector
(MVD)

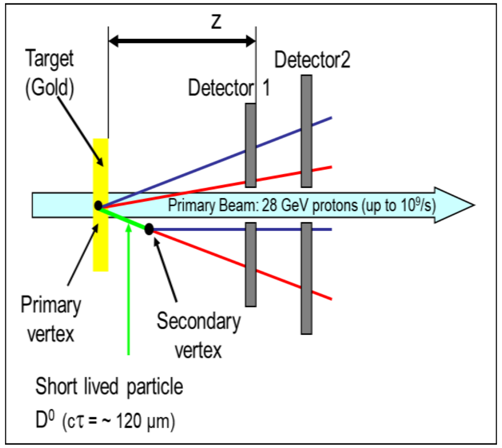
CBM – Experiment @ FAIR

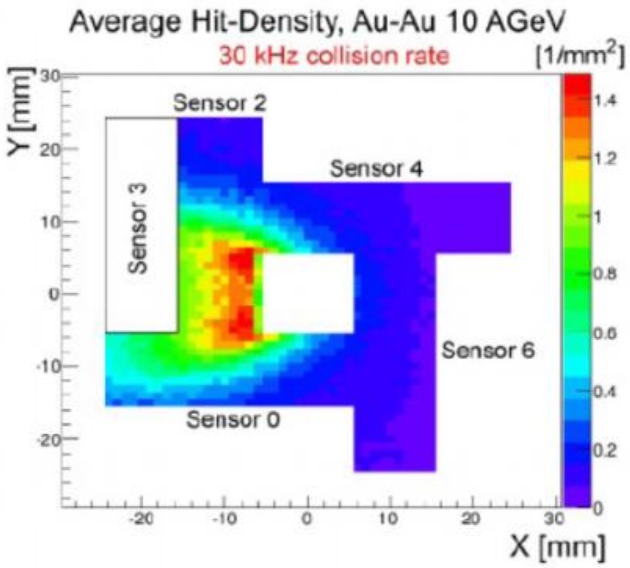
A.Besson, G. Bertolone, Z. El Bitar

MVD Physics goals

- CBM @ FAIR (GSI)
  - ✓ Fixed target experiment to study the QCD phase diagram in the high baryon density region
- Micro-Vertex Detector (MVD)
  - ✓ High precision reconstruction of secondary vertices
    - e.g. charm mesons ~ 100 μm flying distance
  - ✓ High rate, high irradiation, non homogenous in time and space

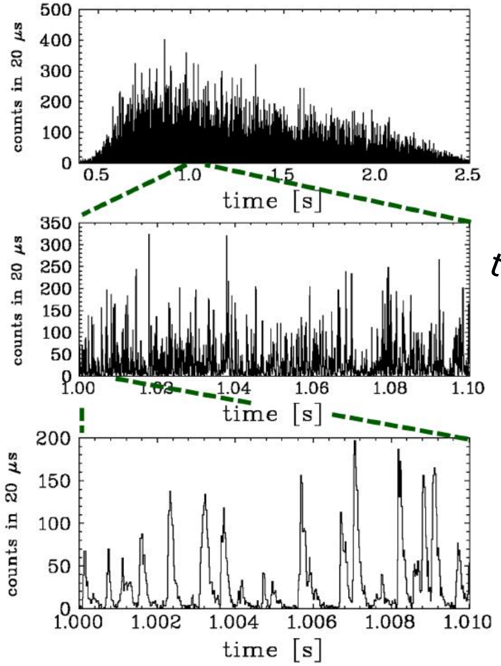






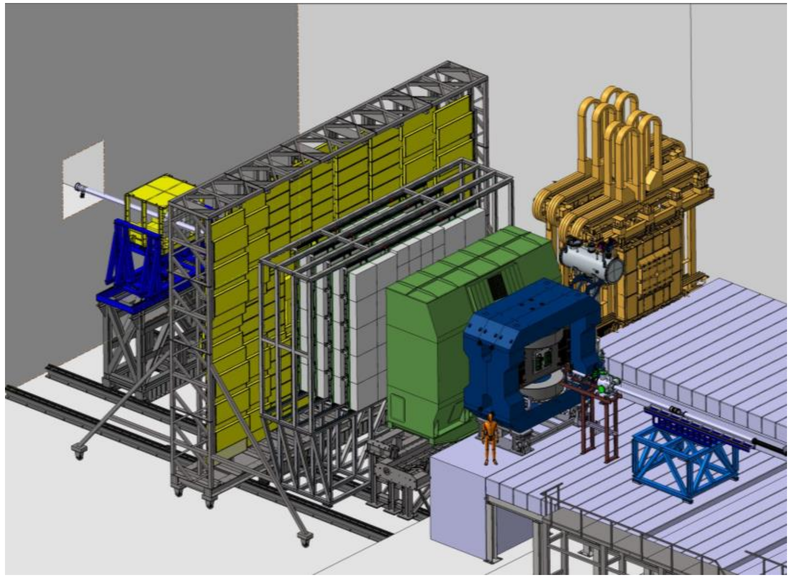
Space inhomogeneity

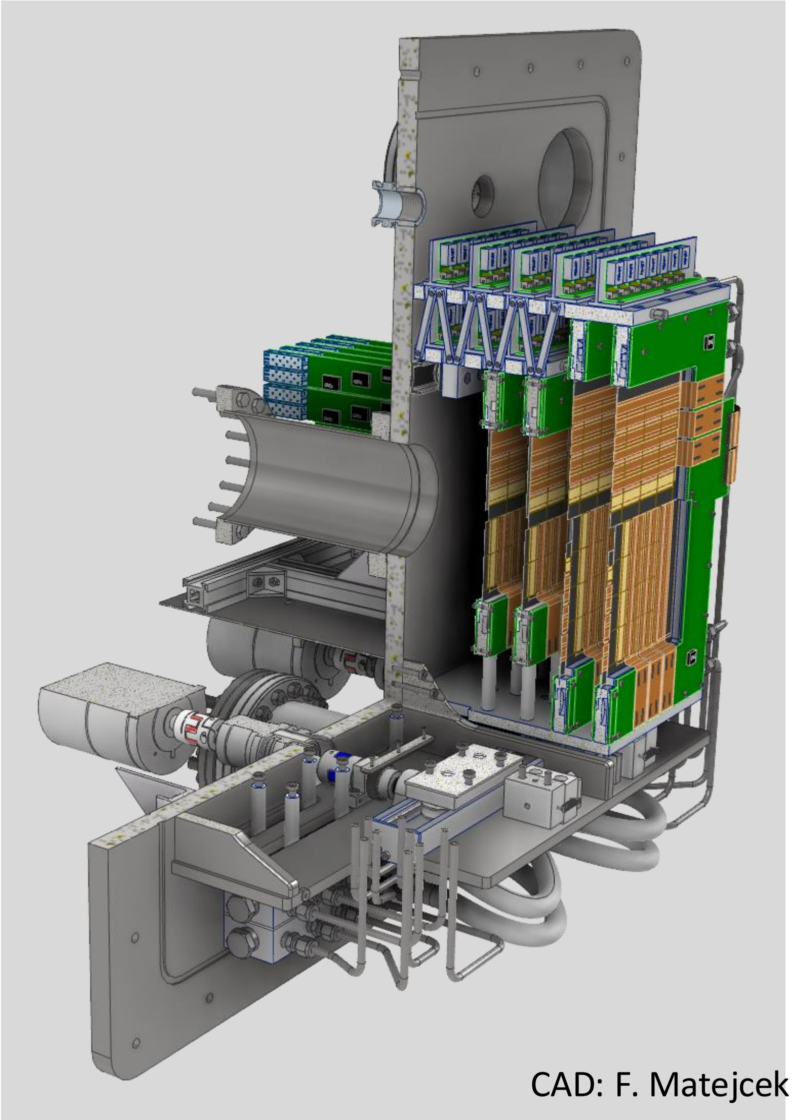
Time fluctuations



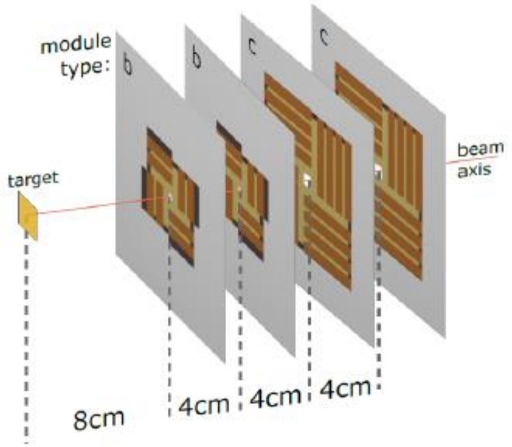
Measured at today's SIS18

CBM experiment at FAIR





CAD: F. Matejcek



- 4 double-sided thin planar detector stations
- ~300 sensors needed
- 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
- Non uniform hit density in time and space
- High radiation environment, operating in vacuum

MIMOSIS Sensor in 1 slide

- MIMOSIS sensor for CBM-MVD @ FAIR
  - ✓ Based on ALPIDE architecture
    - Multiple data concentration steps
    - Elastic output buffer
    - 8 x 320 Mbps links (switchable)
    - Triple redundant electronics
  - ✓ A milestone for Higgs factories
    - « 5 μm / 5 μs » + enhanced bandwidth
    - Improve radiation hardness

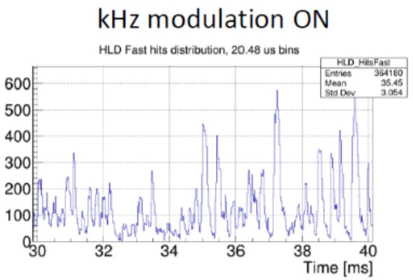
Requirements already achieved with MIMOSIS-1

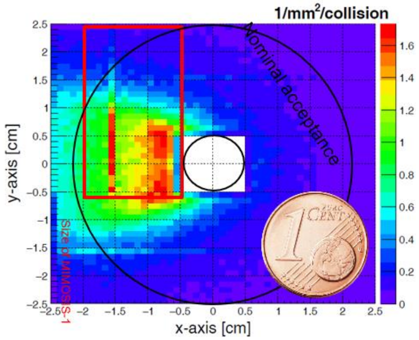
Physics parameter	Requirements
Spatial resolution	~ 5 um
Time resolution	~ 5 us
Material budget	0.05% X_0
Power consumption	< 100 – 200 mW/cm^2
Operation temperature	- 40 °C to 30 °C
Temp gradient on sensor	< 5K
Radiation tol* (non-ion)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation tol* (ionizing)	~ 5 MRad
Data flow (peak hit rate)	@ 7 x 10^5 / (mm^{2}s) > 2 Gbit/s

Similar to ALPIDE

~ x10 ALPIDE

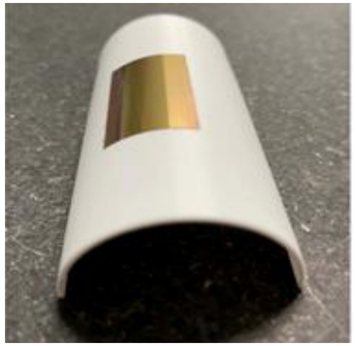
~ x2 ALPIDE





Parameter	Value
Technology	TowerJazz 180 nm
Epi layer	~ 25 µm
Epi layer resistivity	$> 1k\Omega cm$
Sensor thickness	60 µm
Pixel size	26.88 µm × 30.24 µm
Matrix size	1024 × 504 (516096 pix)
Matrix area	≈ 4.2 cm^2
Matrix readout time	5 µs (event driven)
Power consumption	40-70 mW / cm^2

Bent MIMOSIS-2 (R= 15mm) For e+e- collider VTX demonstrator



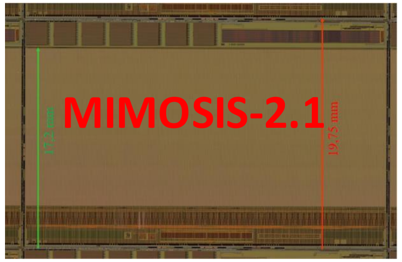
MIMOSIS-0 (2018)
- Demonstrate pixel concept.
- Demonstrate zero suppression.
- Demonstrate readout concept.

MIMOSIS-1 (2020)
- Full dimension sensor
- Add buffer structure.
- SEE hardening 1/2

MIMOSIS-2 (Q2/2023) Major issues
- On-chip pixel grouping.
- Final pixels.
- SEE hardening 2/2
- MIMOSIS-2.1

MIMOSIS-2.1 (Q4 2023)
- = M-2 corrected
- Delivered May 2024
- Tested in beam in July-September 2024

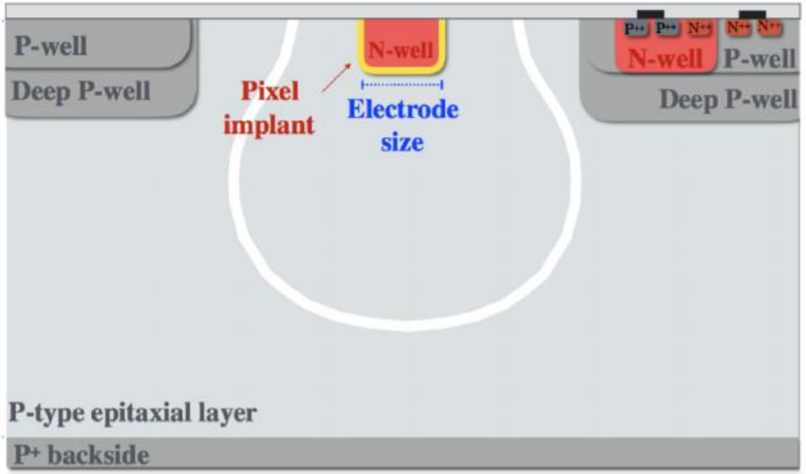
Excellent performances of MIMOSIS-2.1



MIMOSIS-3
- Final sensor for mass production
- Submission in 2025

Design & variants

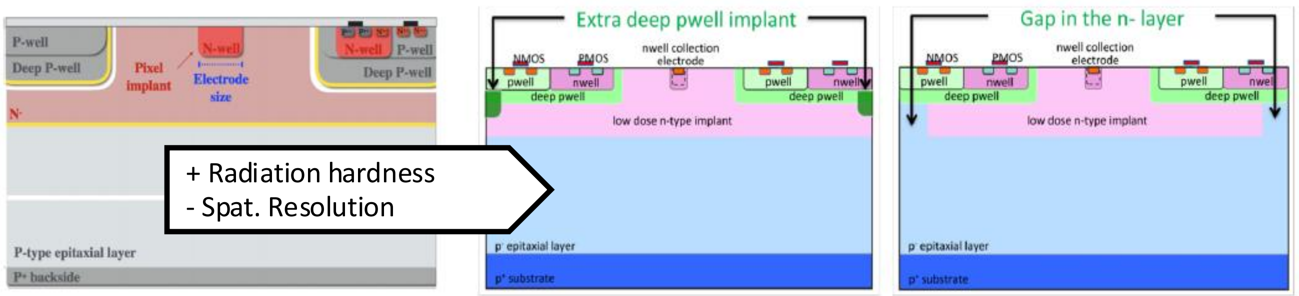
MIMOSIS and process options/modifications



Pic from: Munker, Vertex 2018, Status of silicon detector R&D at CLIC
Carlos, TREDI 2019, Results of the Malta CMOS pixel detector prototype for the ATLAS Pixel ITK

- standard process (3 available wafers)
- continuous n-layer (blanket) (3 wafers)
- additional p-implant (3 wafers)
- gap in n-layer (3 wafers)

continuous n-layer | additional p-implant | gap in n-layer

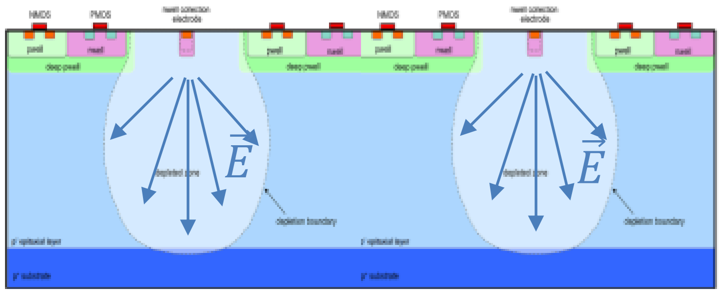


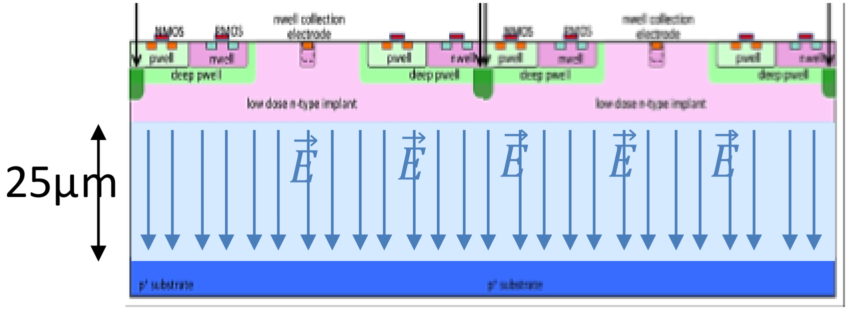
Pic from: Munker, Vertex 2018, Status of silicon detector R&D at CLIC
Carlos, TREDI 2019, Results of the Malta CMOS pixel detector prototype for the ATLAS Pixel ITK

Example: MIMOSIS (CBM-MVD) & Decision on options for sensing elements

Process modification: Standard? P-stop? N-Gap?

25 or 50 µm epi?



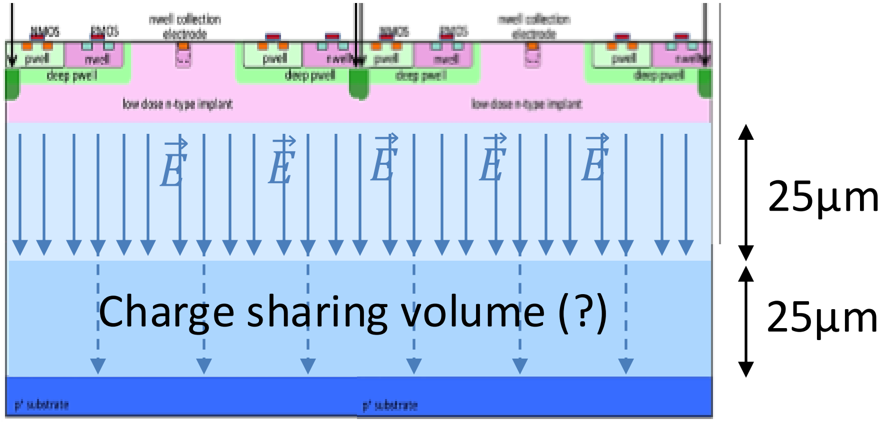


$\sigma = 4 - 5$ µm
> 3 x $10^{13} n_{eq}/cm^2$

Spatial resolution
Rad. hardness

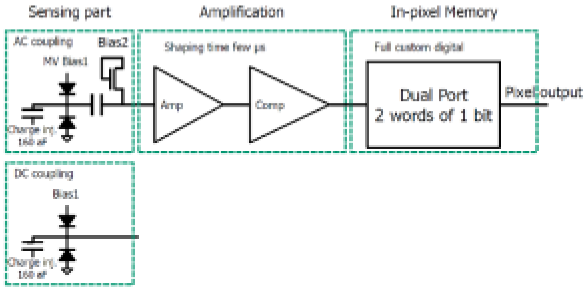
$\sigma = 5 - 7$ µm
> 30 x $10^{13} n_{eq}/cm^2$

Process options inherited from ALPIDE



- Better spatial res. at given rad. tolerance?
- Higher S/N => Robustness to external noise?
- Nuclear fragment ID by dE/dx?

AC? DC? pixel

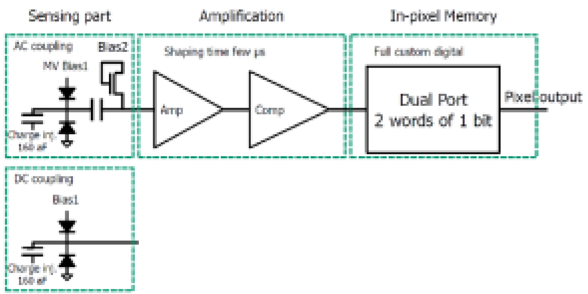


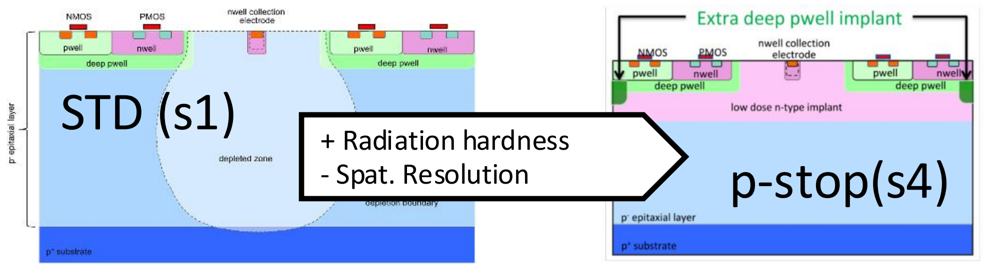
- DC pixel – limited rad. hardness.
- AC Pixel – more biasing lines.

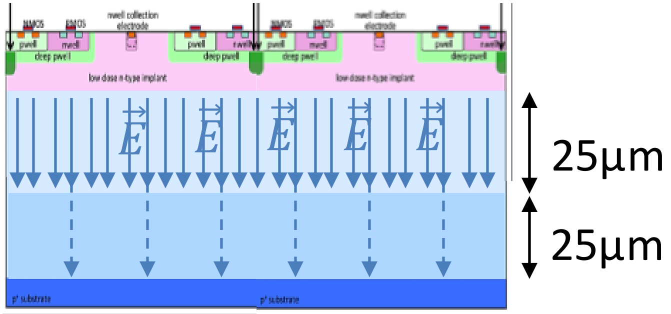
W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

Variants

- Pixel structure:
  - ✓DC pixels (substrate bias applied up to 6V)
  - ✓AC pixels (substrate + top bias up to 6V + 20V)
- Doping profile:
  - ✓Standard process (partially depleted)
  - ✓"p-stop" (fully depleted)
- Epitaxial layer thickness:
  - ✓25 µm thick
  - ✓50 µm thick
- 8 pixel variants in total

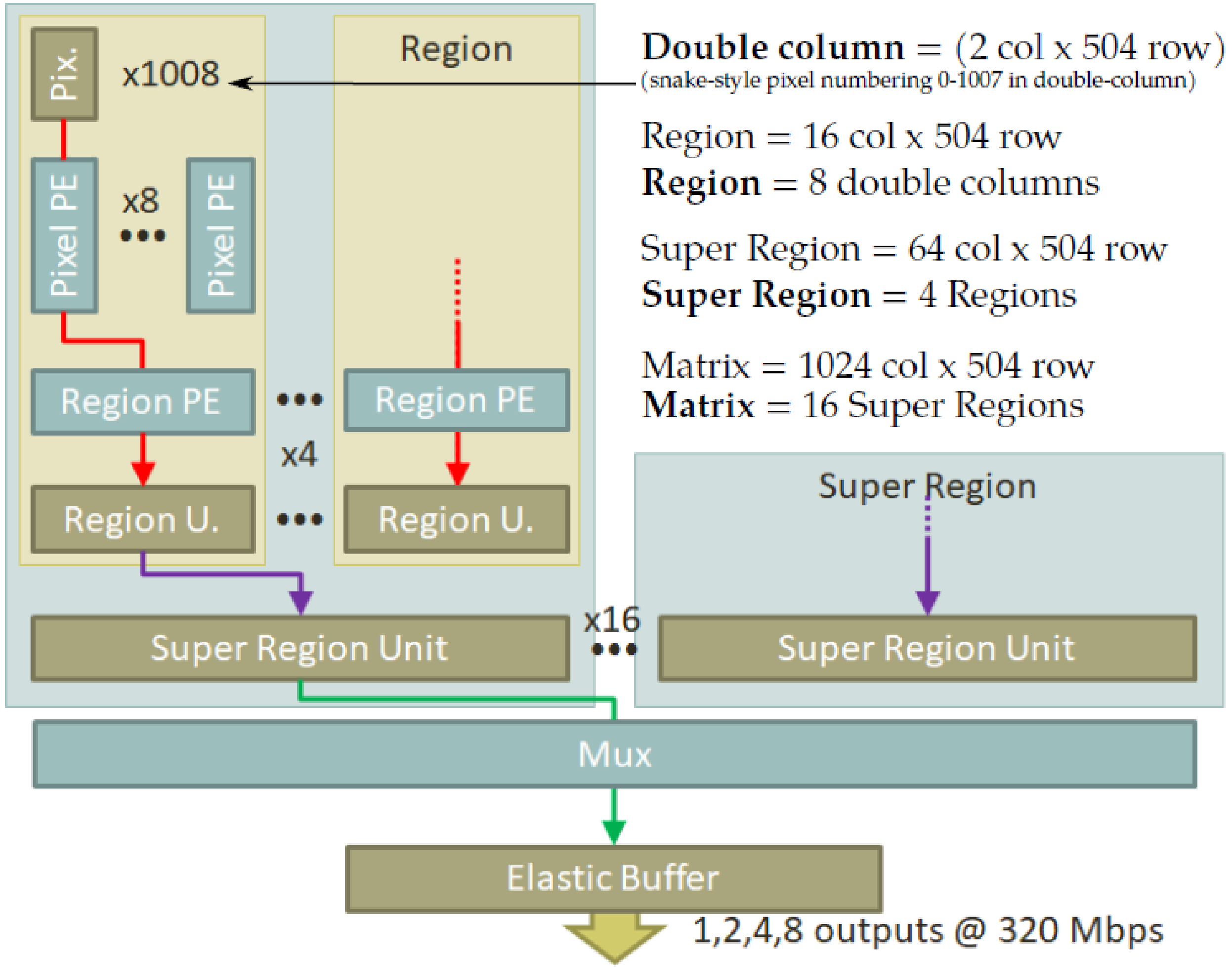




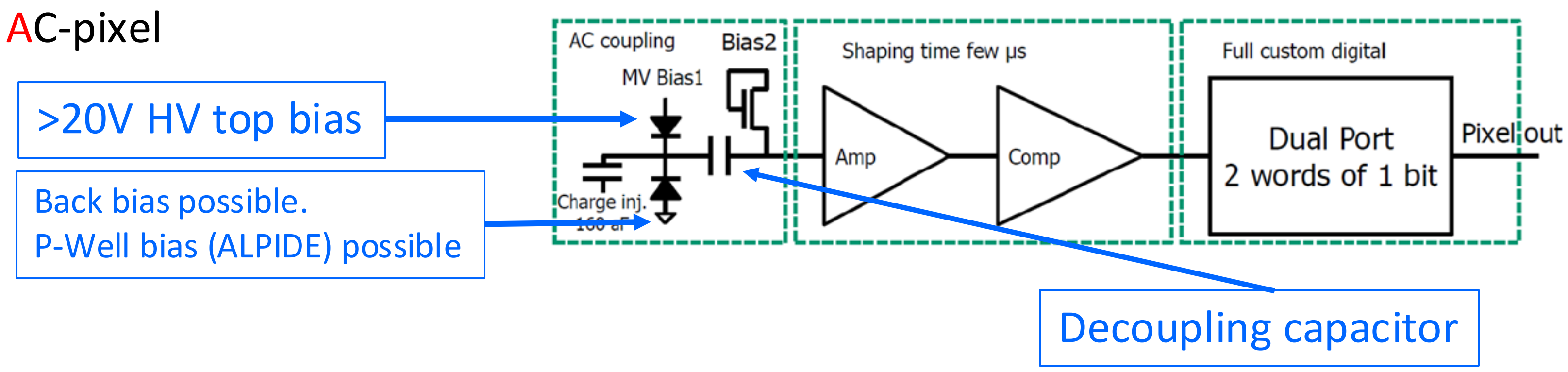


MIMOSIS read-out architecture

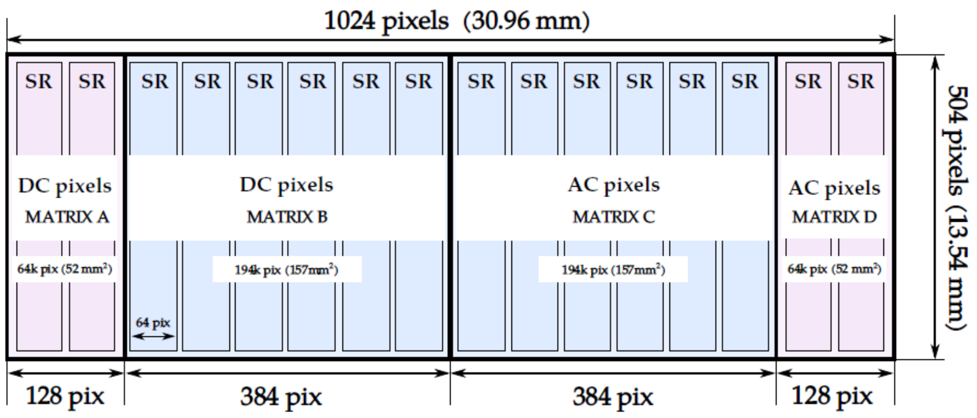
- 3-stage buffering → to cope with in-homogeneous hit density
- Region readout out @ 20 MHz → 5 µs time of full matrix readout
- Elastic buffer → can store variable-size frames → required because of the data rate fluctuations
- Variable number of outputs → lower bandwidth but lower power consumption



E. AC / DC pixels



- DC Pixels (~ALPIDE) & AC pixels (top bias up to > 20V)
  - ✓ Amplifier / shaper / discriminator chain similar to ALPIDE in both scheme
  - ✓ Data driven readout
  - ✓ Pulse injection for calibration
  - ✓ Pixel masking options

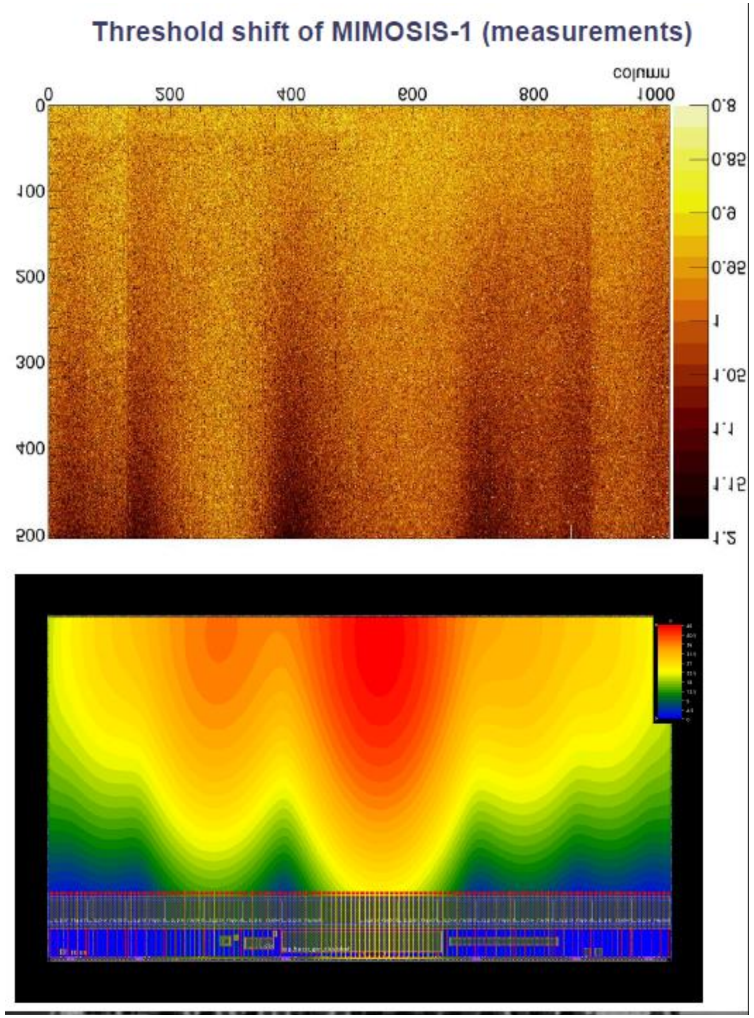


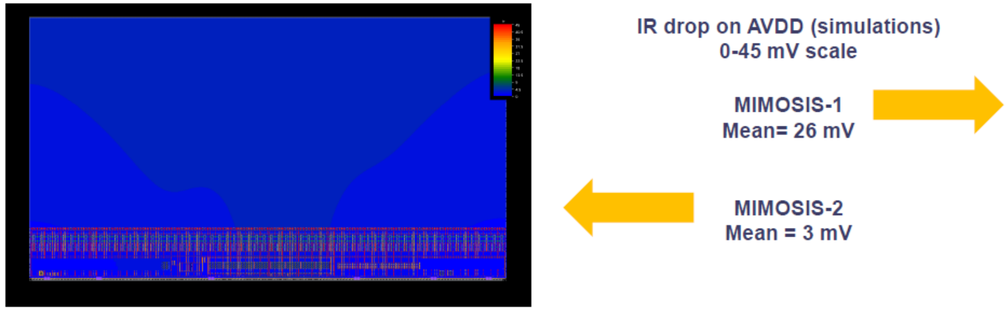
A.Besson, G. Bertolone, Z. El Bitar

Mimosis-1 Verification tools example

- Large and complex designs need
  - ✓ A hierarchy in the work flow to keep submission on schedule
  - ✓ Verification tools that can be run in a reasonable time
  - ✓ Knowledge of these tools is crucial
- Example Power-grid problem observed in MIMOSIS-1
  - ✓ Threshold shifts
  - ✓ Problem fixed quickly thanks to the verification tools

[F. Morel DRD7 kick-off meeting]



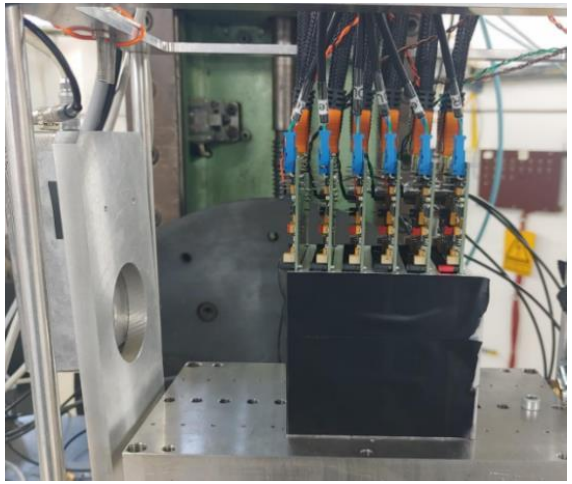


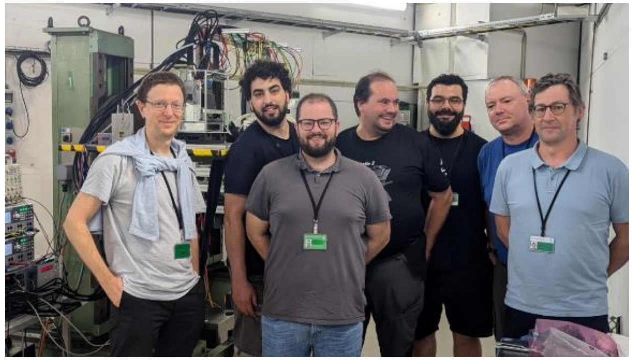
Performances

Mimosis-1/2

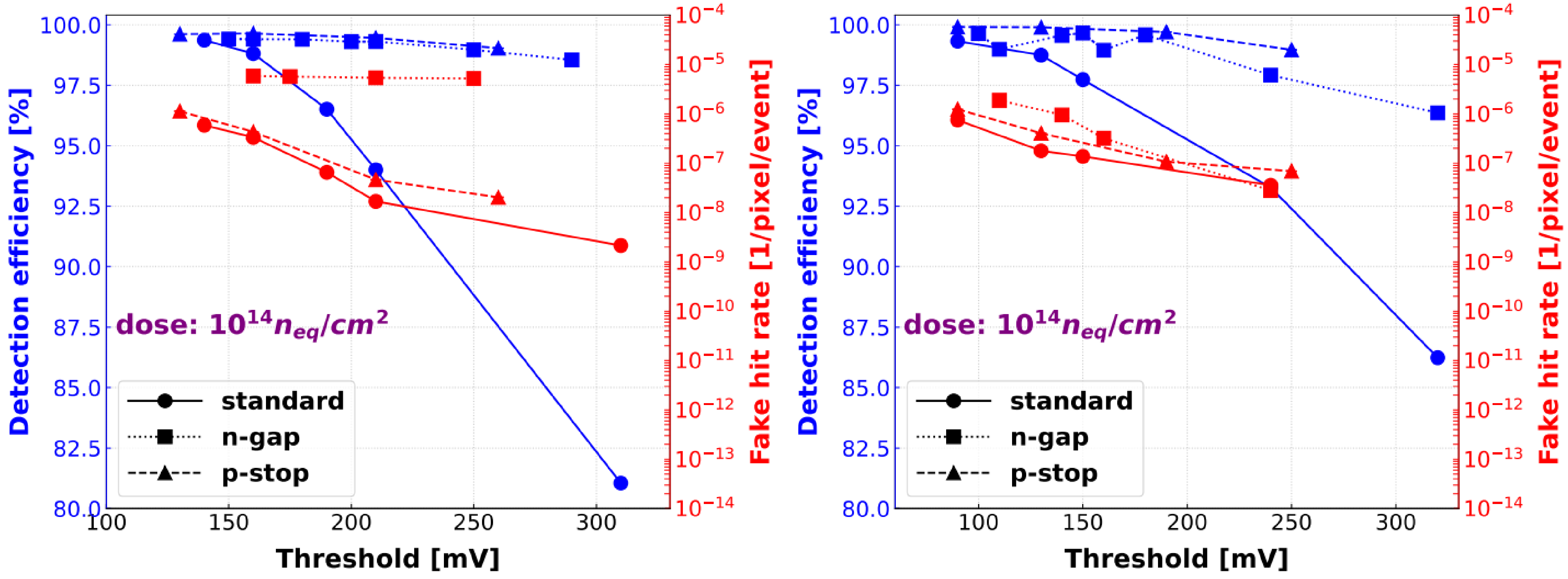
Lab tests for all different versions (pixels, process)
~15 beam test campaigns over 4 years (DESY, CERN, CYRCE, etc.)
Single Event Effect studies (not covered here)
Irradiations campaigns
Large FTE effort

[In beam performances of the MIMOSIS-2.1 CMOS Monolithic Active Pixel Sensor (PIXEL 2024)]
20th Anniversary Trento Workshop on Advanced Silicon Radiation Detectors February 2025,Trento, Italy





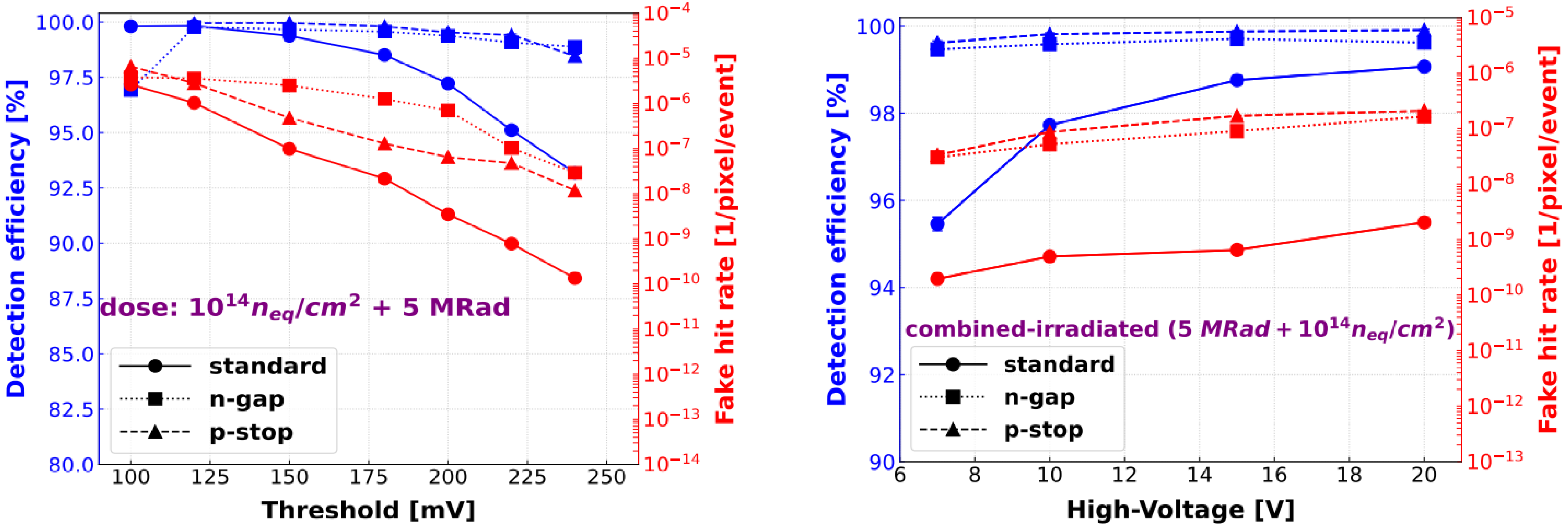
MIMOSIS-1



(a) DC-pixels. (b) AC-pixels.

Figure 5: Detection efficiency (blue) and fake hit rate (red) as function of threshold for DC-pixels (left) and AC-pixels (right). The three different pixel types (standard, "n-gap" and "p-stop") are shown in different line styles.

MIMOSIS-1

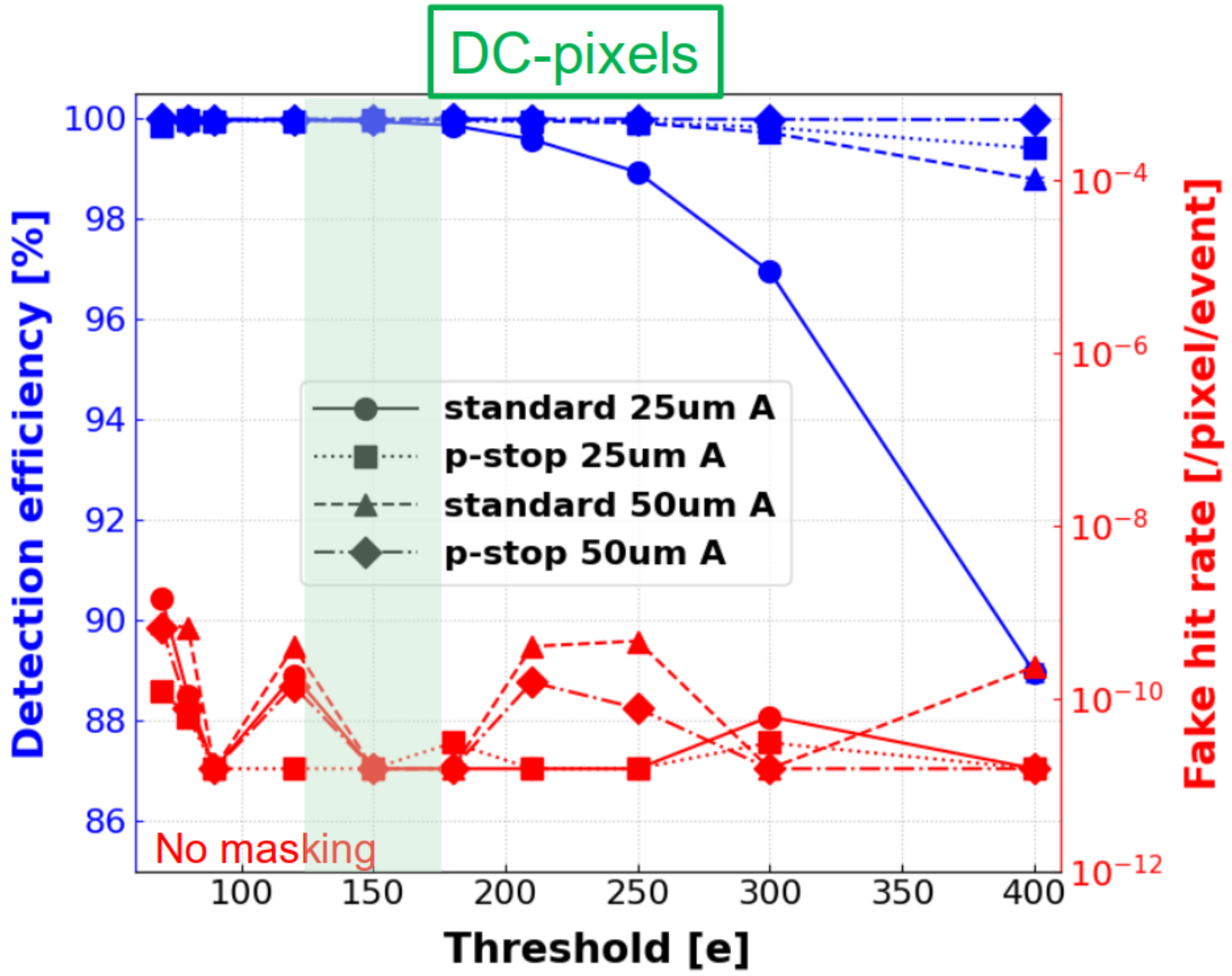


(a) Detection efficiency and fake hit rate as function of the threshold of AC-pixels for combined-irradiated chips.

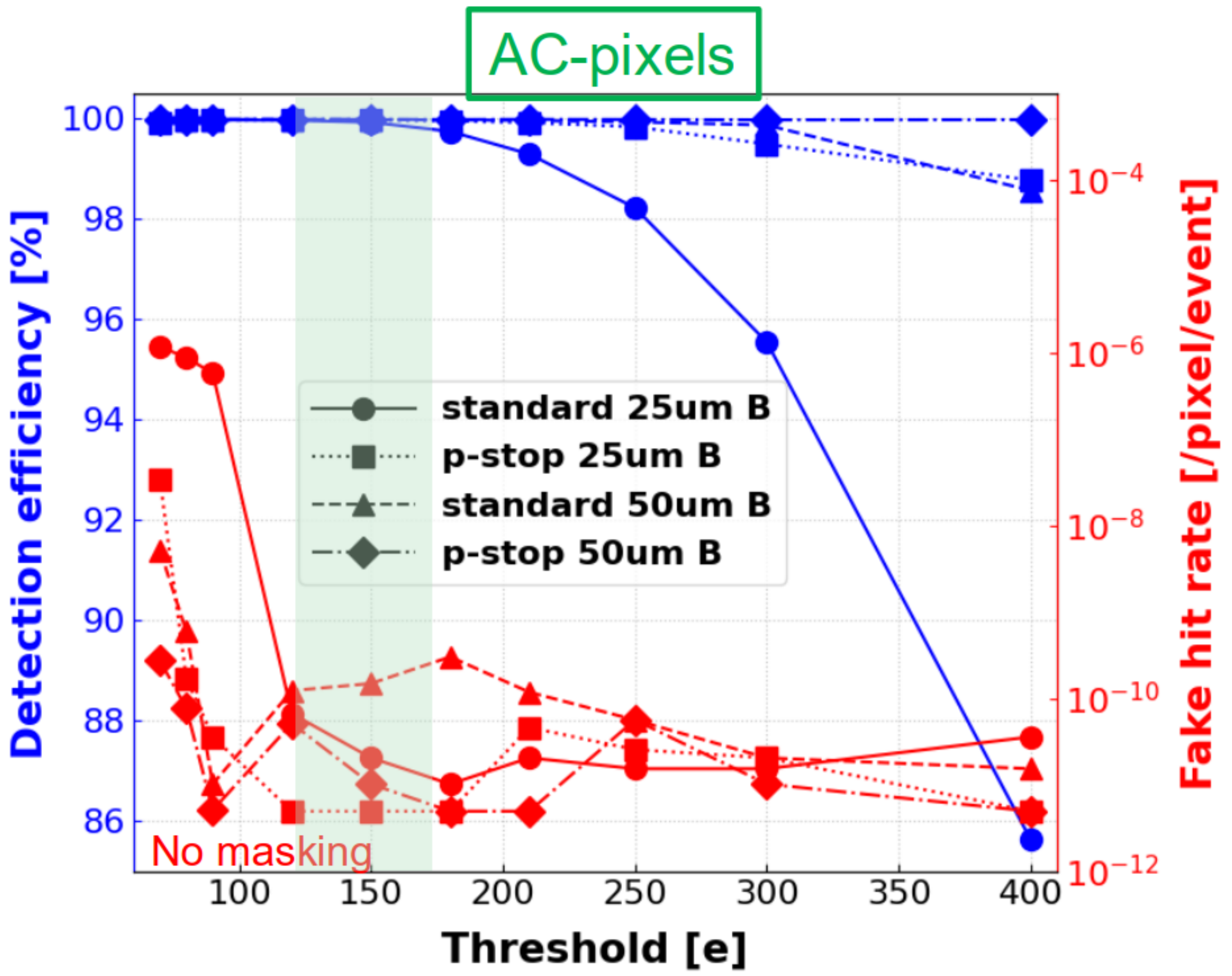
(b) Detection efficiency and fake hit rate as function of the applied HV of AC-pixels for combined-irradiated chips at 200 e^- threshold and -1V BB.

Figure 8: Detection efficiency and fake hit rate for the 3 pixel options after a combined-irradiated dose (~5 MRad TID and ~10^{14} n_{eq}/cm^2 NIEL fluences).

MIMOSIS-2.1



DC-pixels
Detection efficiency [%]
Fake hit rate [/pixel/event]
standard 25um A
p-stop 25um A
standard 50um A
p-stop 50um A
No masking
Threshold [e]
100
98
96
94
92
90
88
86
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
100
150
200
250
300
350
400



AC-pixels
Detection efficiency [%]
Fake hit rate [/pixel/event]
standard 25um B
p-stop 25um B
standard 50um B
p-stop 50um B
No masking
Threshold [e]
100
98
96
94
92
90
88
86
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
100
150
200
250
300
350
400

MIMOSIS1 and MIMOSIS-2.1

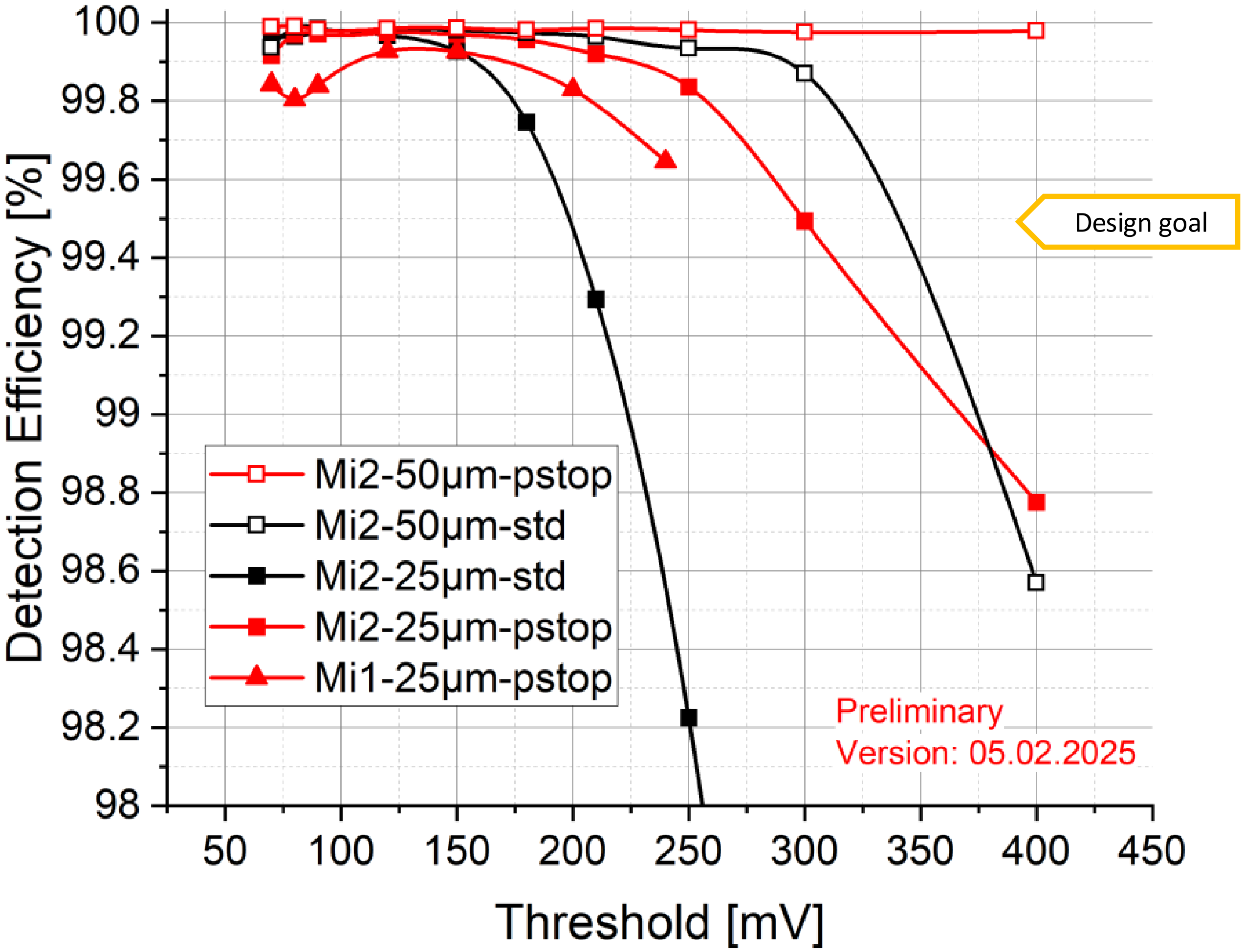
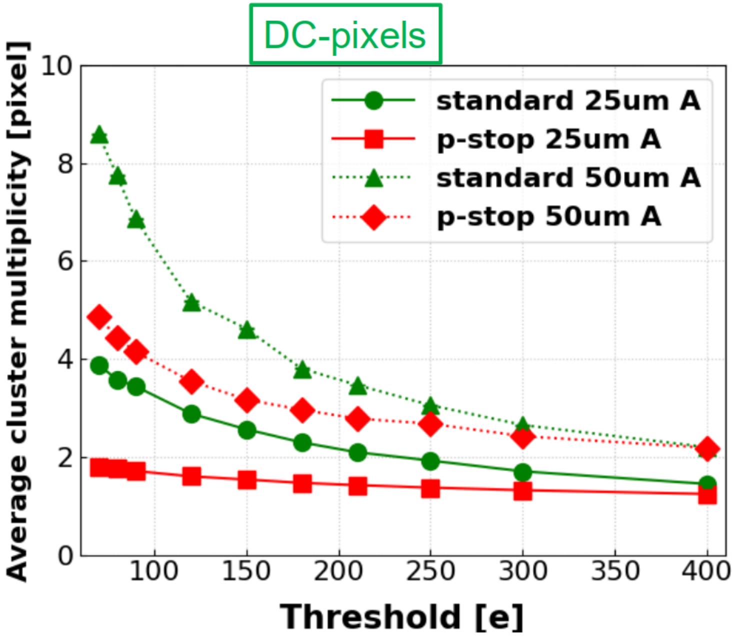


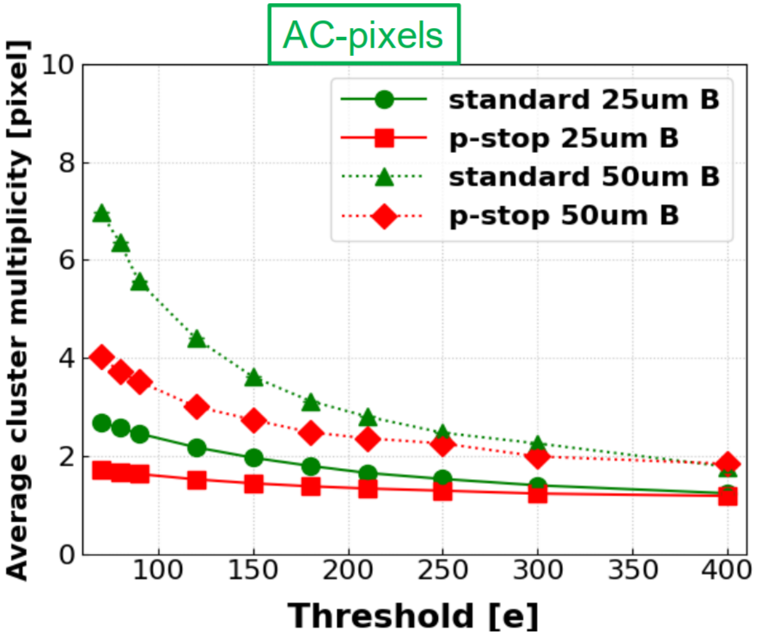
Figure 4: Detection efficiency of the pixels of MIMOSIS-2.1 as compared to the p-stop pixel of MIMOSIS-1. Lines to guide the eye. The (statistical) uncertainties are not shown for clarity and remain below 0.02%. Note the color/symbol code:

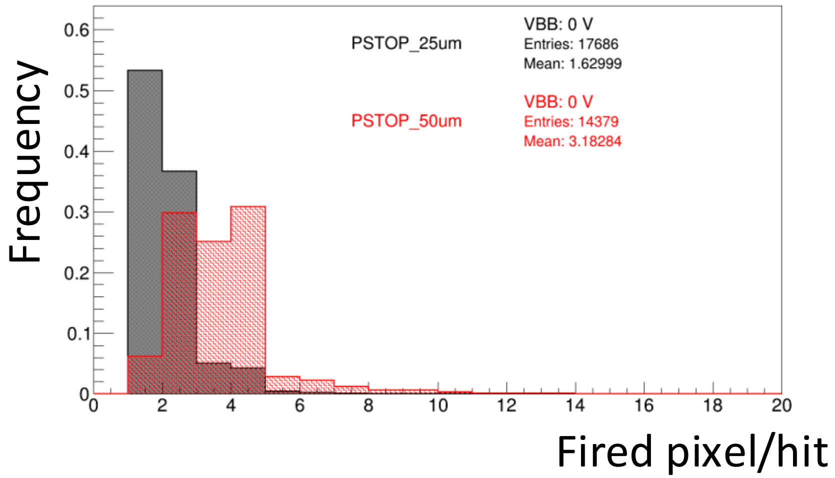
standard pixel	p-stop pixel
■▲ 25 µm epi	□△ 50 µm epi
△▲ MiSIS-1	□■ MiSIS-2.1

Fake rate below 10^{-7} hit/pixel/read-out

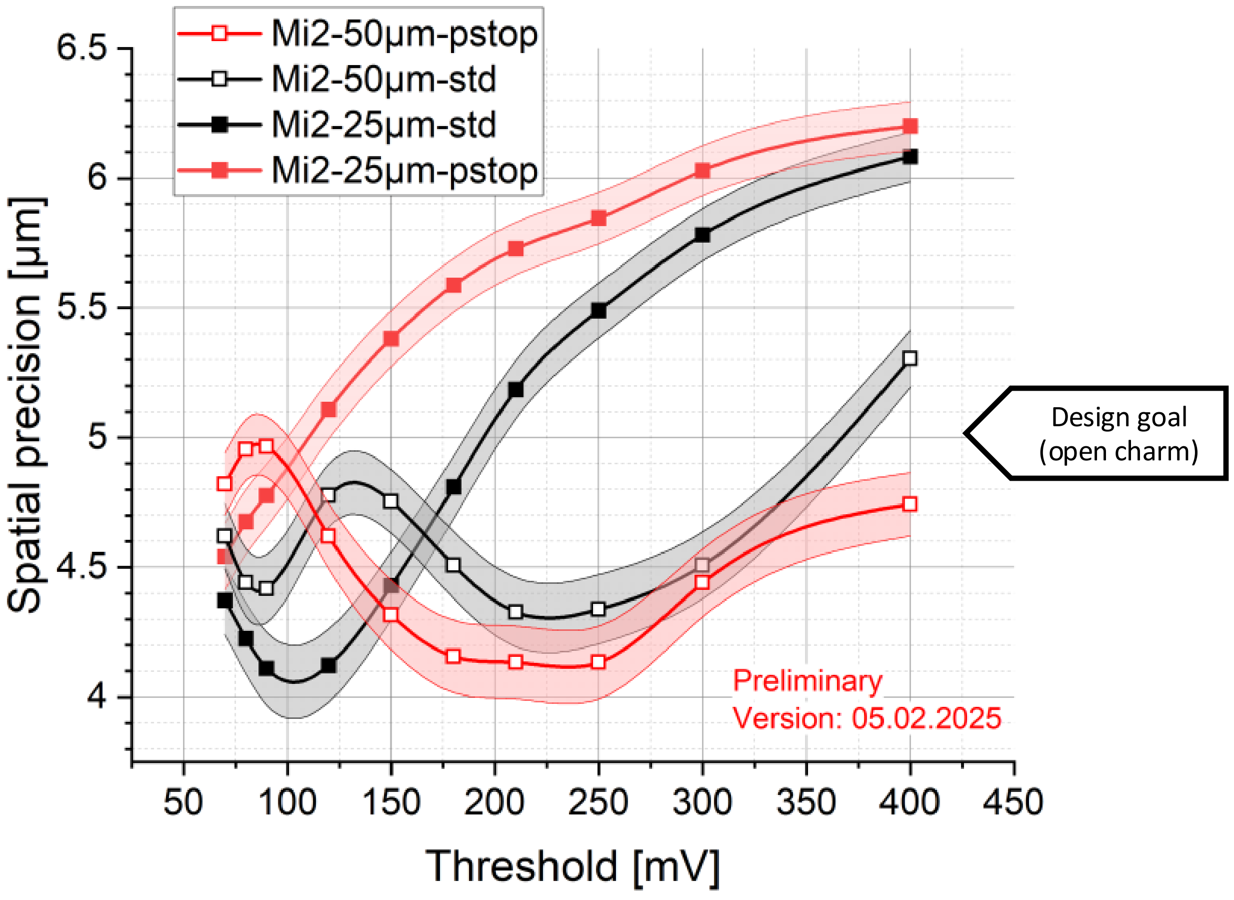
MIMOSIS-2.1: Cluster mulitiplicity with MIPS



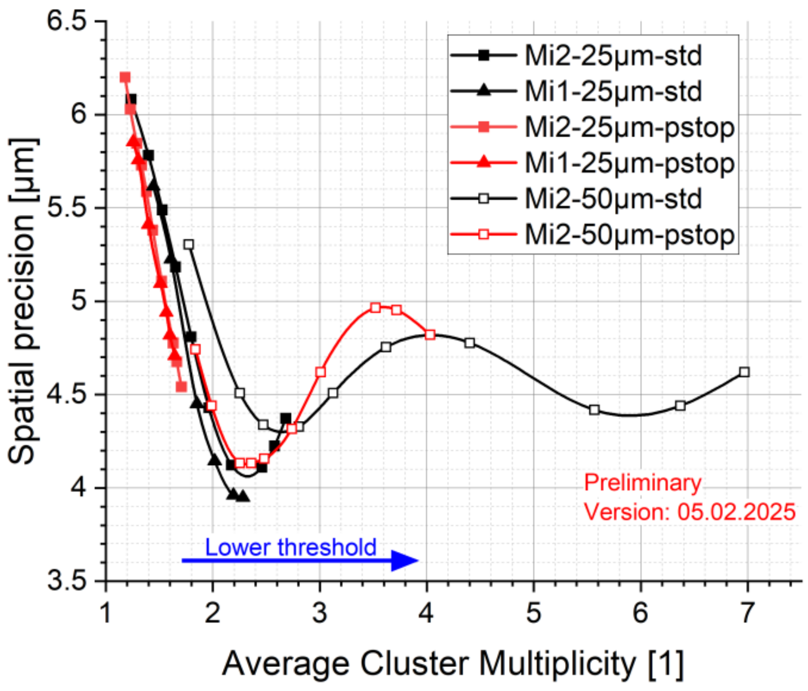




Spatial resolution and cluster multiplicity (MIPS)



(a) Spatial precision vs. threshold.

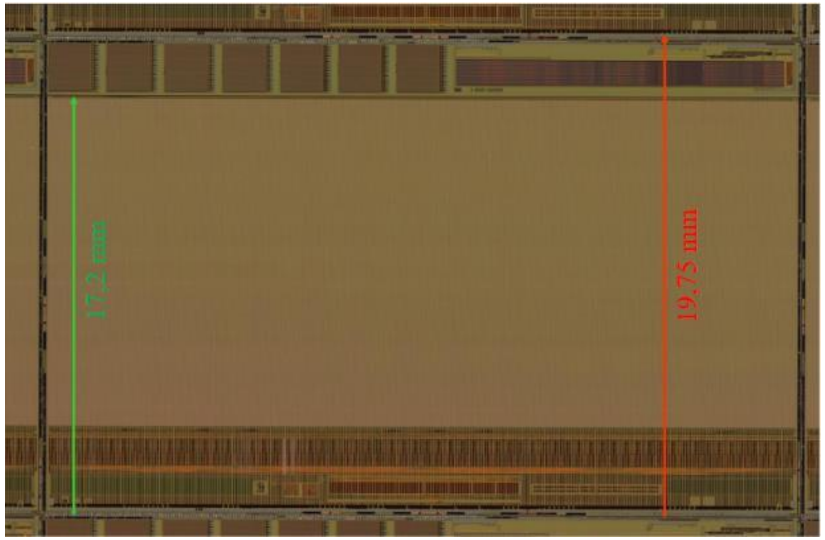


(b) Spatial precision vs. cluster multiplicity.

standard pixel	p-stop pixel
■▲ 25 µm epi	□△ 50 µm epi
△▲ MiSIS-1	□■ MiSIS-2.1

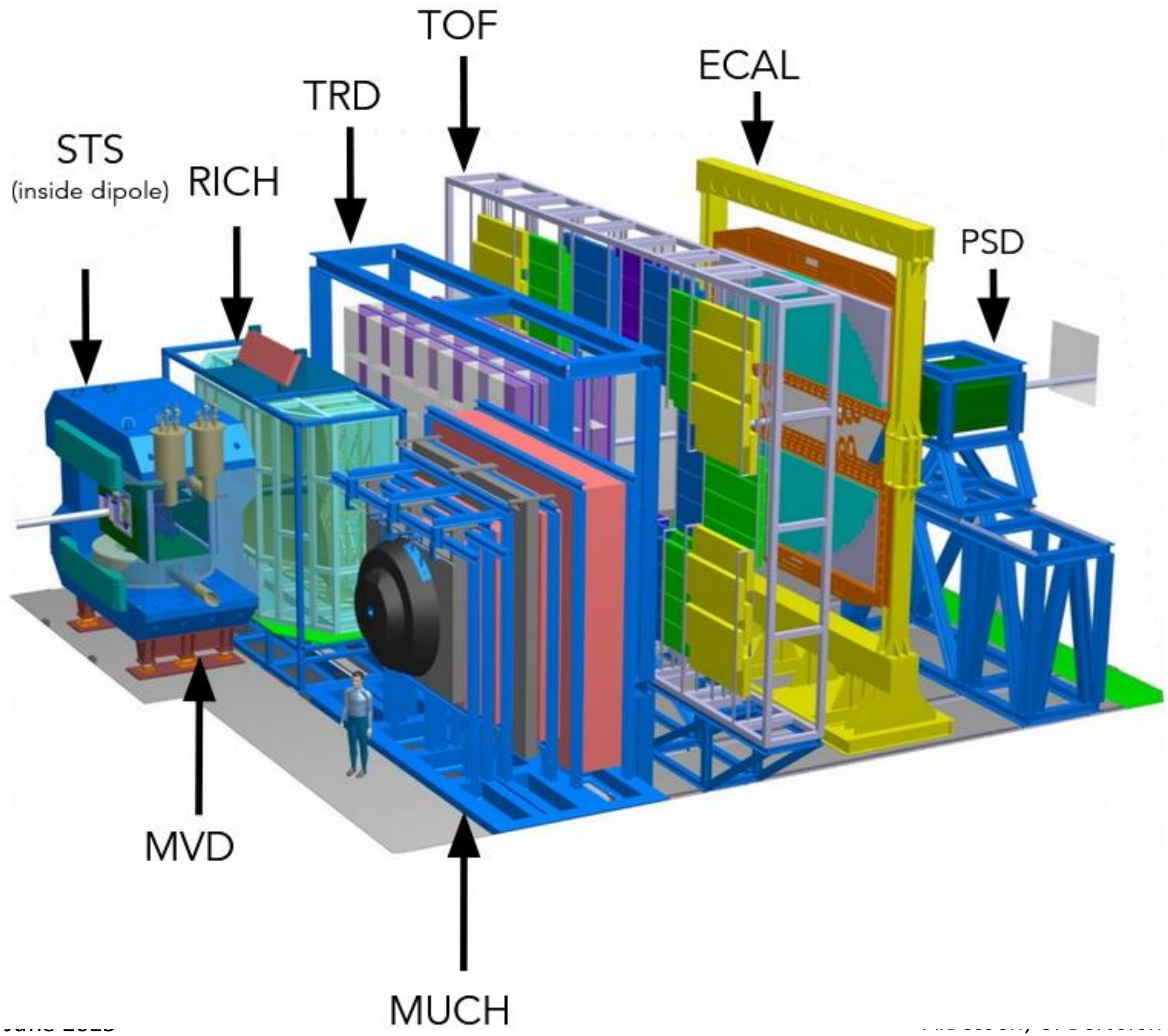
Summary

- MIMOSIS CMOS sensor is a versatile sensor for many subatomic applications
  - ✓ 5 µs / ~5 µm time/spatial resolution.
  - ✓ 80 MHz/cm² peak rate
  - ✓ Radiation hardness
  - ✓ High efficiency, low fake rate
- Final version (MIMOSIS-3) to be submitted in 2025



Back up

CBM detector subsystem



- Tracking acceptance: $2.5^{o} < \theta_{Lab} < 25^{o}$
- Peak R_{int} is 10 MHz for Au+Au (300 kHz for MVD)
- Fast & radiation hard detectors
- Free-streaming DAQ
- 4D tracking (space, time)
- Online event reconstruction and selection
- Data rate: 1 TB/sec

GSI GreenITCube
High performance computing farm for data processing

Requirement for MVD:

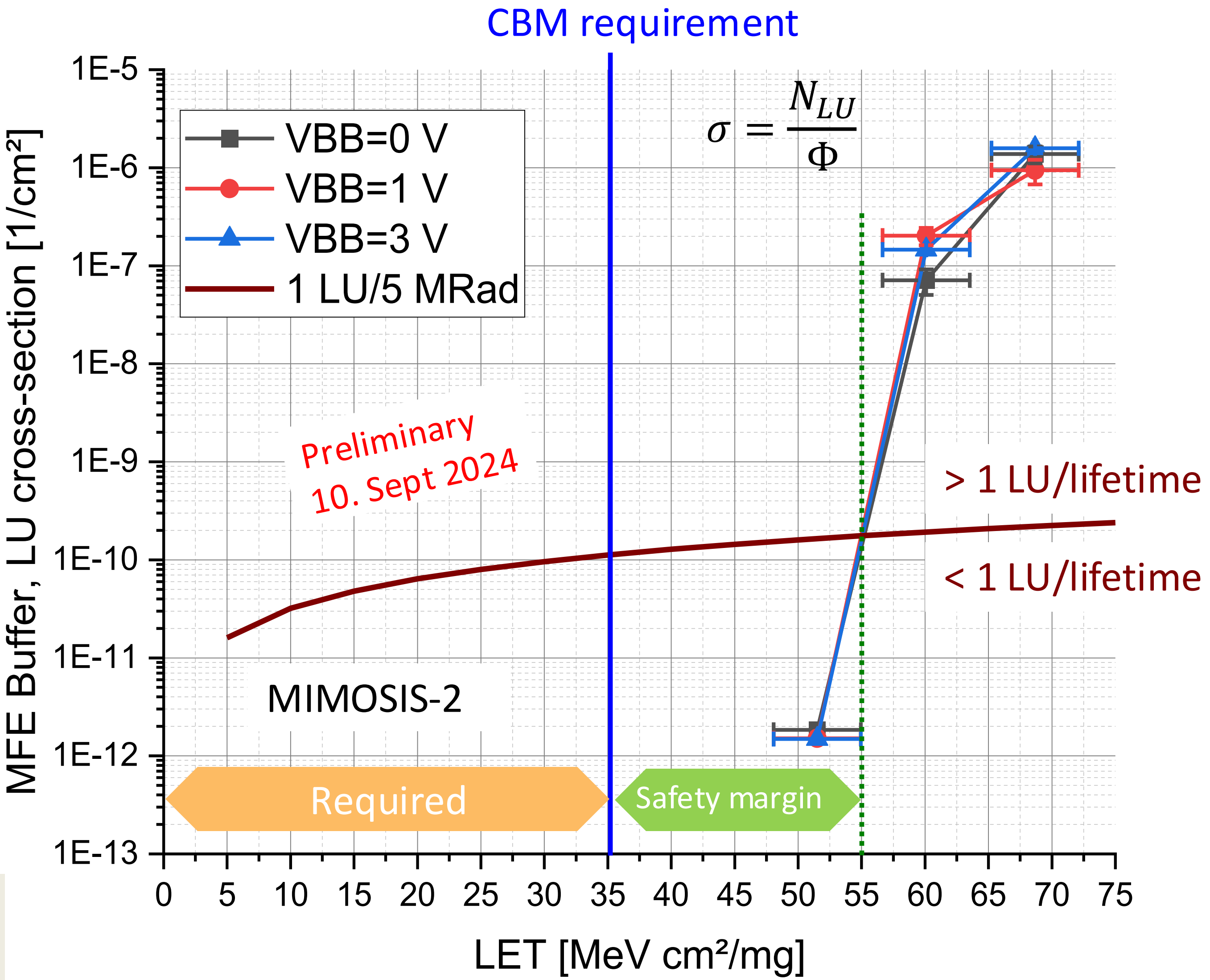
- Must withstand 1kHz/cm² ions with LET< 35 MeV cm²/mg.
  (H. Darwish, PhD under preparation)

Preliminary test results (Bit flips):

- Frequent single bit errors seen.
- Correction in status registers works…
  … but may be overwhelmed by simultaneous to 2-bit flips (at unrealistically high ion fluxes).
- Data registers not protected.

Preliminary test results (Latch-up):

- No LU for LET≲50 MeV cm²/mg.
- Some LU seen above.



Preliminary conclusion: Sensor matches requirements – no LU protection system needed.

T.b.d: Bit flip tolerance of data chain.

Sensor performance: MIMOSIS-1 vs. MIMOSIS 2.1

Observations:

- MIMOSIS-2.1 reaches lower threshold than MIMOSIS-1.
- MIMOSIS-2.1 reaches even(!) higher efficiency than MiSIS-1.
- Best performance: Novel 50µm epitaxial layer with p-stop.

- Dark occupancy marginal for all sensors (noisy pixels NOT masked).