The Micro-Vertex Detector (MVD) @The Compressed Baryonic Matter experiment (CBM) & the MIMOSIS program

On behalf of the IPHC-IKF-GSI (CBM-MVD) Collaboration

J. Andary,[a] B. Arnoldi-Meadows,[a] O. Artz,[a] J. Baudot,[b] G. Bertolone,[b] A. Besson,[b] N. Bialas,[a] R. Bugiel,[b] G. Claus,[b] C. Colledani,[b] H. Darwish,[a,b] M. Deveaux,[c] A. Dorokhov,[b] G. Dozière,[b] Z. El Bitar,[b] I. Fröhlich,[a,c] M. Goffe,[b] F. Hebermehl,[a] A. Himmi,[b] C. Hu-Guo,[b] K. Jaaskelainen,[b] O. Keller,[f] M. Koziel,[a] F. Matejcek,[a] J. Michel,[a] F. Morel,[b] C. Müntz,[a] H. Pham,[b] C.J. Schmidt,[c] S. Schreiber,[a] M. Specht,[b] D. Spicker,[a] J. Stroth,[a,c,d] I. Valin,[b] R. Weirich,[a] Y. Zhao[b] and M. Winter[e]

[a] *Goethe-Universität Frankfurt, Germany*
[b] *Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
[c] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany*
[d] *Helmholtz Forschungsakademie Hessen für FAIR, Germany*
[e] *IJCLab, UMR9012 – CNRS / Université Paris-Saclay / France*
[f] *Facility for Antiproton and Ion Research in Europe GmbH, Germany*

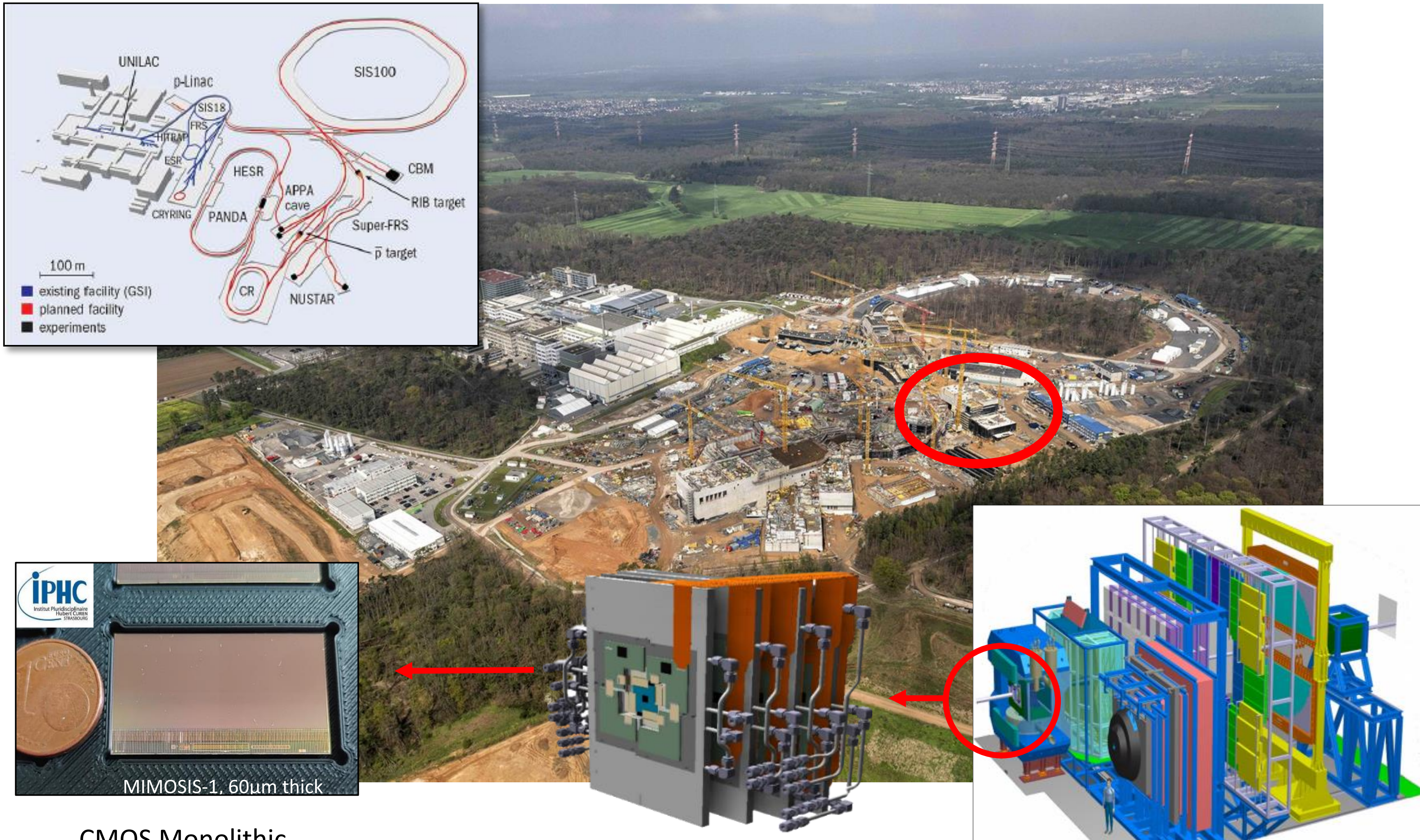
PICSEL

eurizon
European network for developing new horizons for RIs

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)

The MVD @ CBM



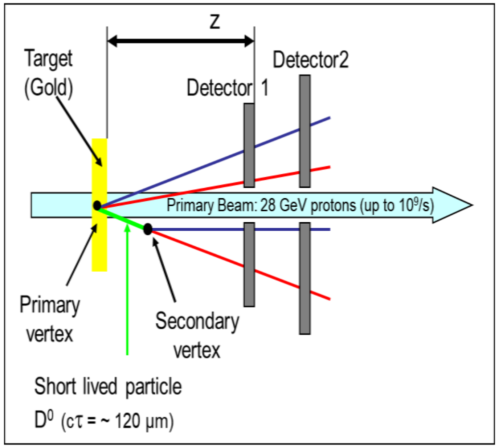
CMOS Monolithic
Active Pixel Sensor
MIMOSIS

CBM Micro Vertex Detector
(MVD)

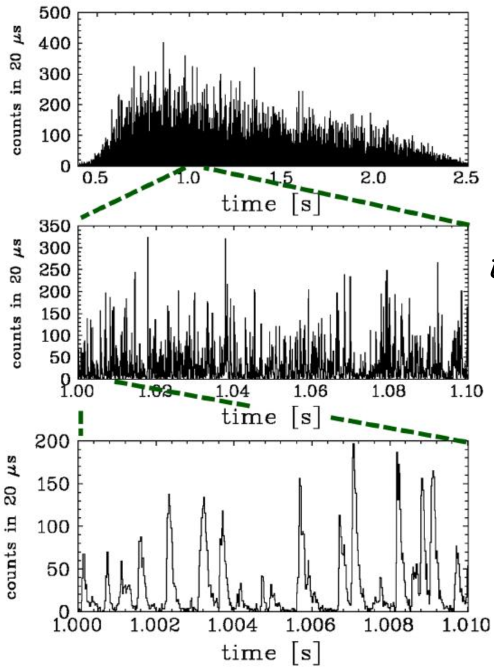
CBM – Experiment @ FAIR

MVD Physics goals

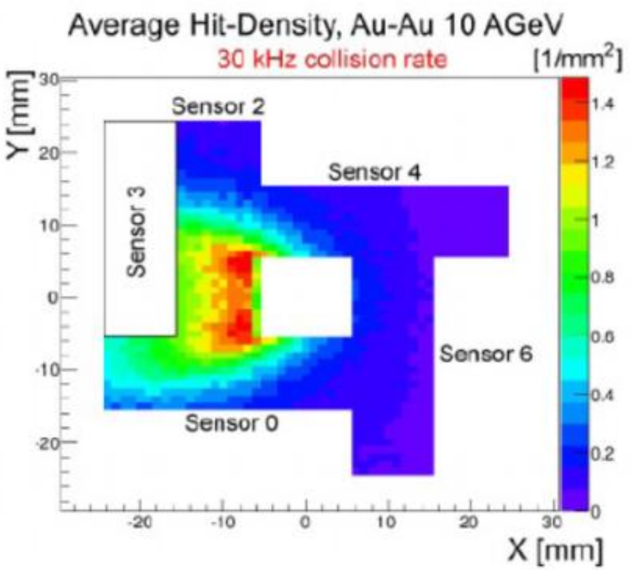
- CBM @ FAIR (GSI)
  - ✓ Fixed target experiment to study the QCD phase diagram in the high baryon density region
- Micro-Vertex Detector (MVD)
  - ✓ High precision reconstruction of secondary vertices
    - e.g. charm mesons ~ 100 μm flying distance
  - ✓ High rate, high irradiation, non homogenous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



Time fluctuations



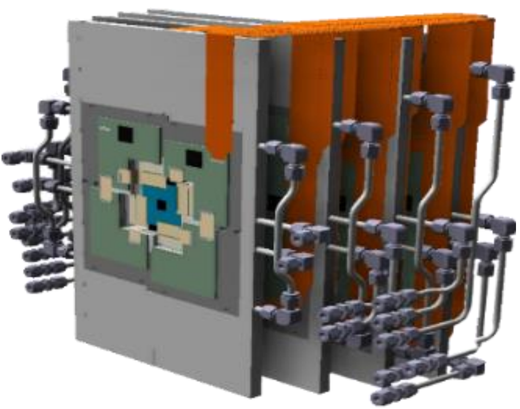
Measured at today's SIS18

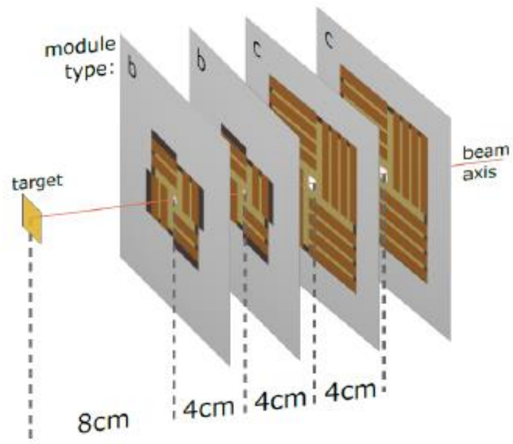


Space inhomogeneity

MVD / MIMOSIS requirements

- Requirements





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 (spatial resolution, time resolution, material budget)

~ x10 ALPIDE (radiation tolerance)

~ x2 ALPIDE (data flow)

- 4 double-sided thin planar detector stations
- 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 chip
  - ✓ Based on ALPIDE architecture
  - ✓ Discriminator on 27x30µm² pixel
  - ✓ Multiple data concentration steps
  - ✓ Elastic output buffer
  - ✓ 8 x 320 Mbps links (switchable)
  - ✓ Triple redundant electronics

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

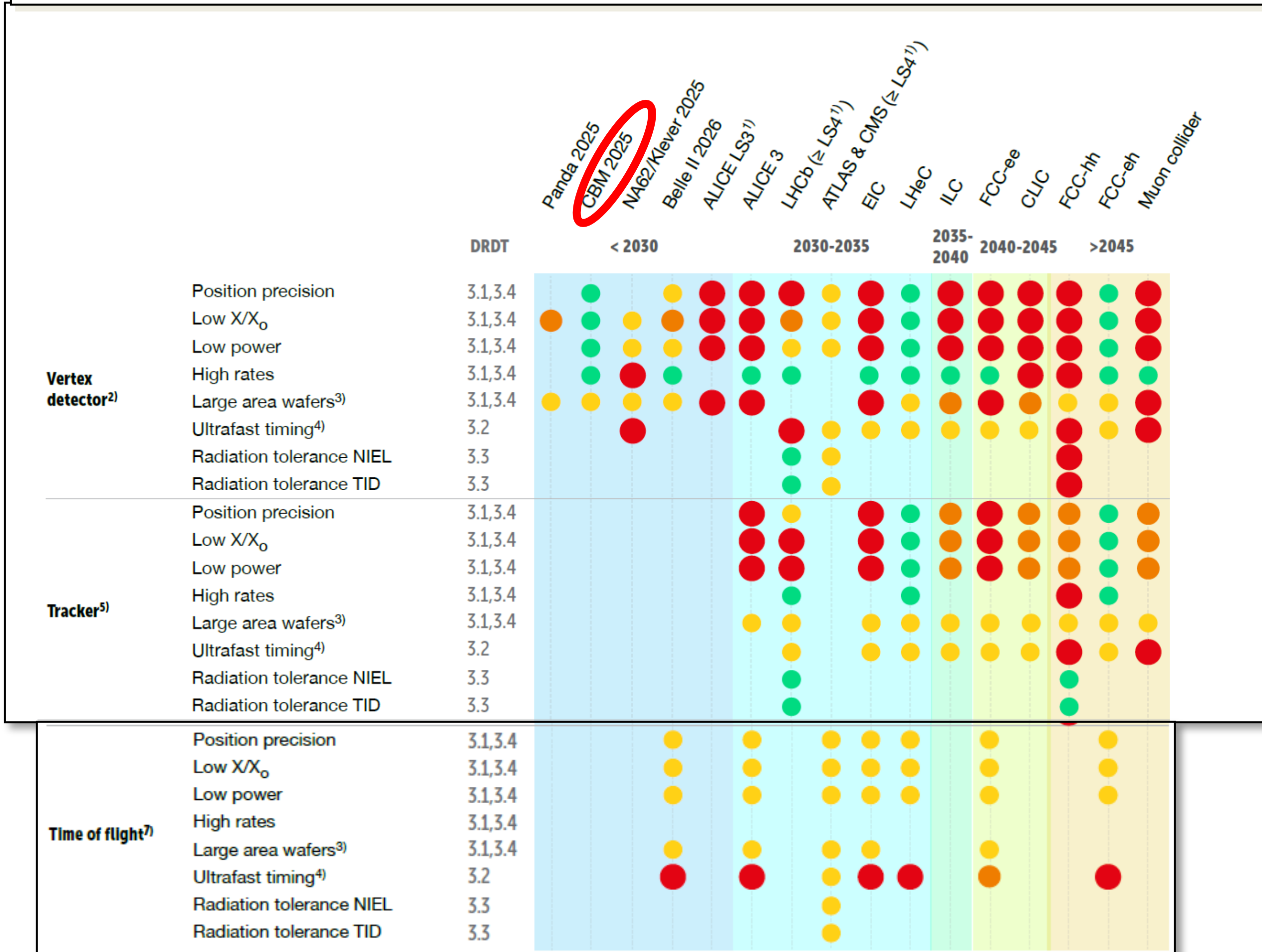
MIMOSIS = a milestone for Higgs factories (5 µm / ≤5 µs)

Synergies

ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather. ***ECFA supports a series of workshops*** *with the aim to* ***share challenges and expertise, to explore synergies in their efforts*** *and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).*

Goal: bring the entire e^+e^- Higgs factory effort together, foster cooperation across various projects; collaborative research programmes are to emerge

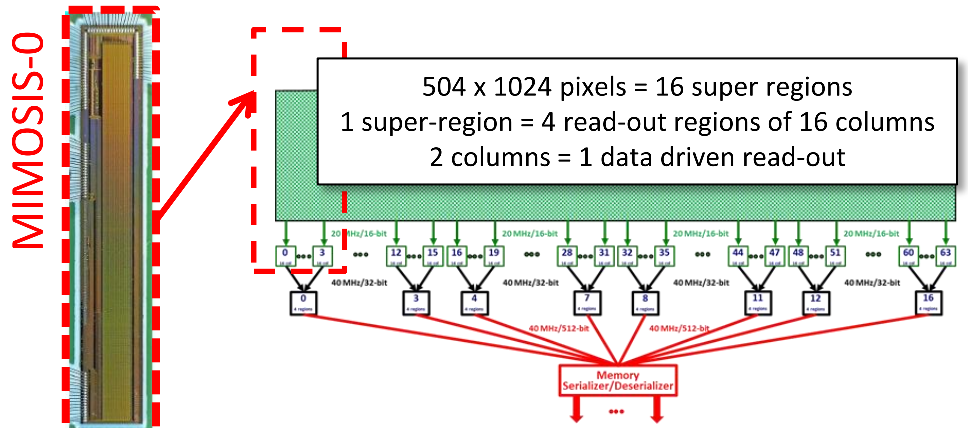
K. Jakobs, FCC Physics Workshop, Feb 2022

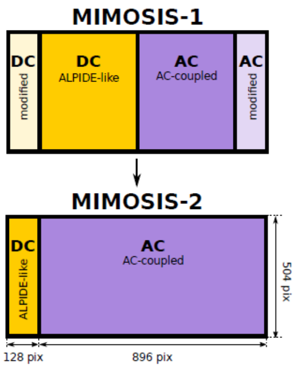


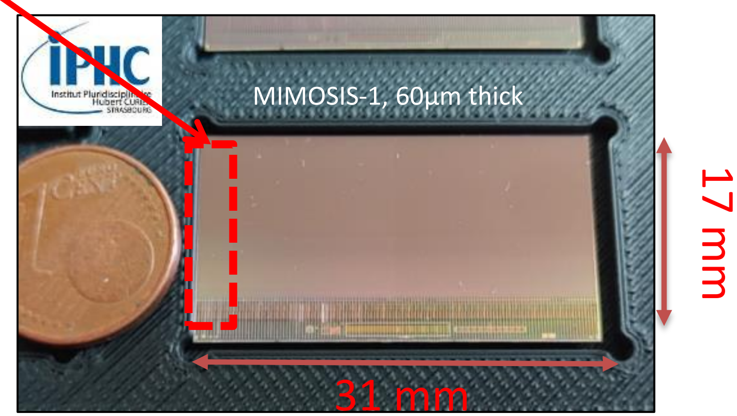
Must happen or main physics goals cannot be met · Important to meet several physics goals · Desirable to enhance physics reach · R&D needs being met

MIMOSIS roadmap

- 4 prototypes:
- MIMOSIS-0: = 2 regions
  - ✓ Tests (2018-2019)
    - Testability
- MIMOSIS-1: 1[st] full size prototype
  - ✓ Elastic buffer, SEE hardened
  - ✓ Fabricated in 2020
  - ✓ Intense test campaign in 2021-22
    - Lab and beam tests
    - Irradiations
    - Latchup tests
- MIMOSIS-2:
  - ✓ On-chip clustering
  - ✓ Triplication added
  - ✓ Back from foundry Q2 2023
- MIMOSIS-3: final pre-production sensor
  - ✓ ≥2025



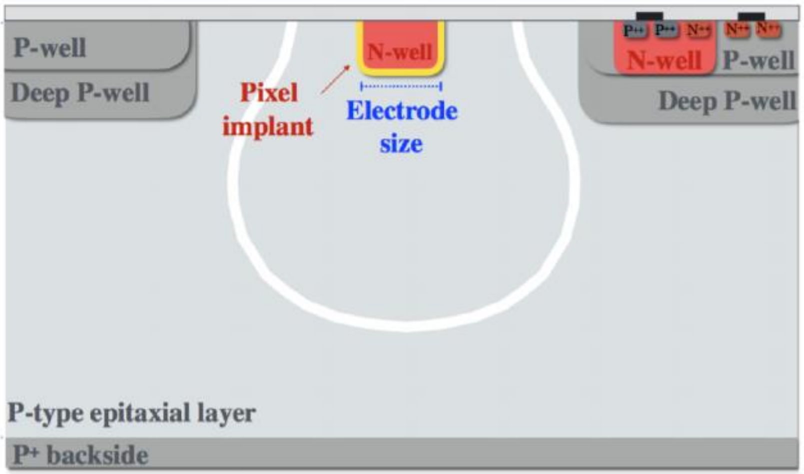




⇨ architecture adaptable to a fast sensor for a future e^+e^- collider vertex detector

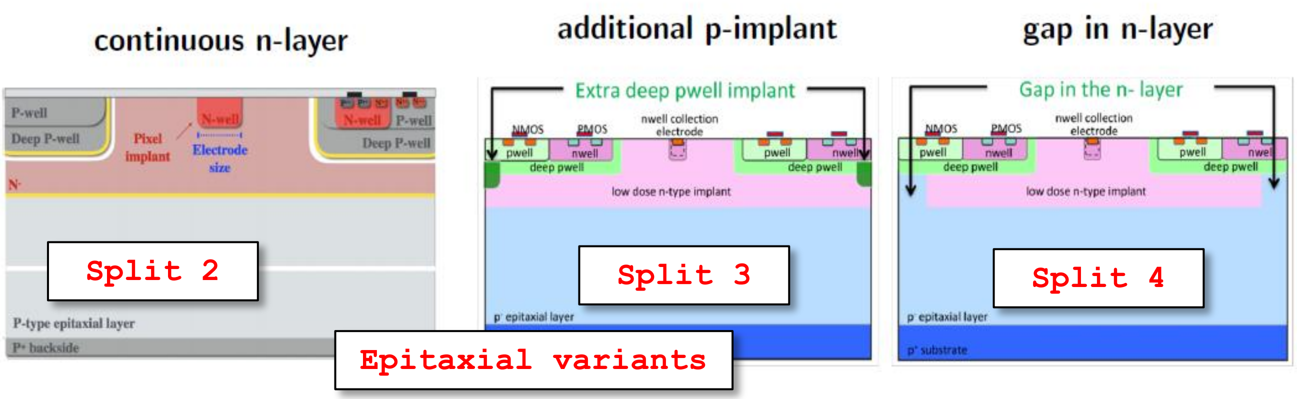
⇨ Opportunity to study different designs/options

Process 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

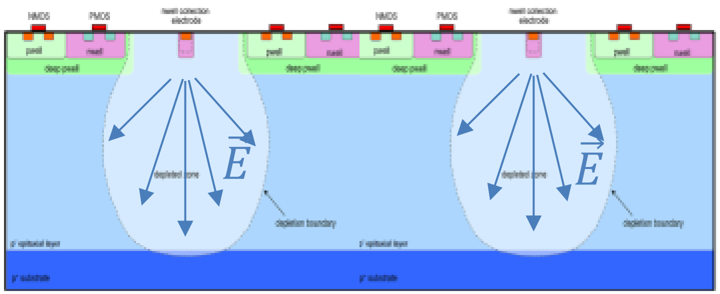
- standard process (3 available wafers)
- continuous n-layer (blanket) (3 wafers)
- additional p-implant (3 wafers)
- gap in n-layer (3 wafers)

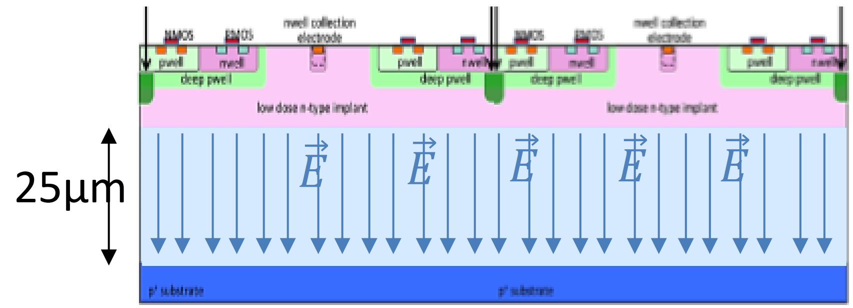


Pic from: Munker, Vertex 2018, Status of silicon detector R&D at CLIC
Carlos, TREDI 2019, Results of the Malta CMOS pixel detector prototype for the ATLAS Pixel ITK

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

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





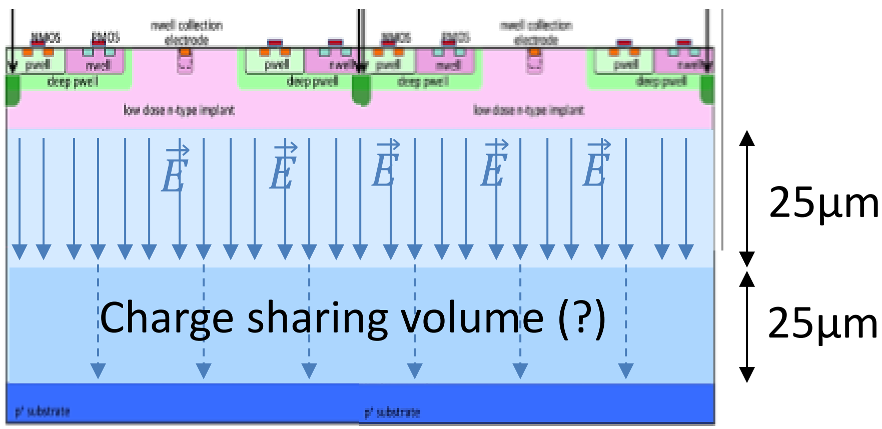
25 or 50 µm epi?

$\sigma = 4-5\ \mu m$
$> 3 \times 10^{13} n_{eq}/cm^2$

Spatial resolution
Rad. hardness

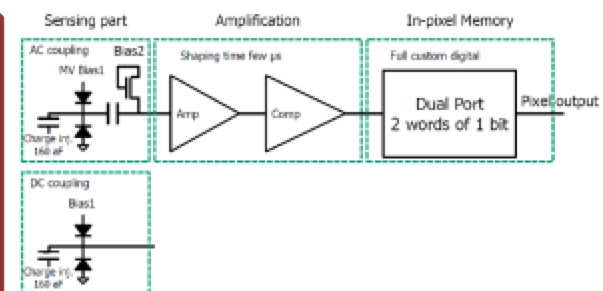
$\sigma = 5-7\ \mu m$
$> 30 \times 10^{13} n_{eq}/cm^2$

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

Lessons learned up to now

Mimosis-1

Lab tests for all different versions (pixels, process)

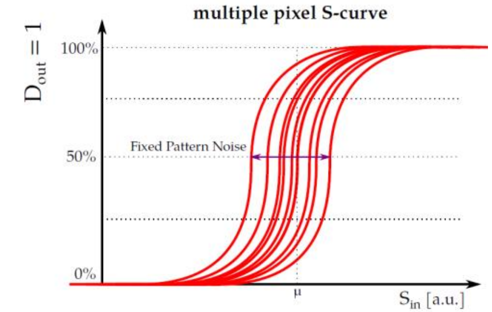
~10 beam test campaigns over 2 years

Single Event Effect studies (not covered here)

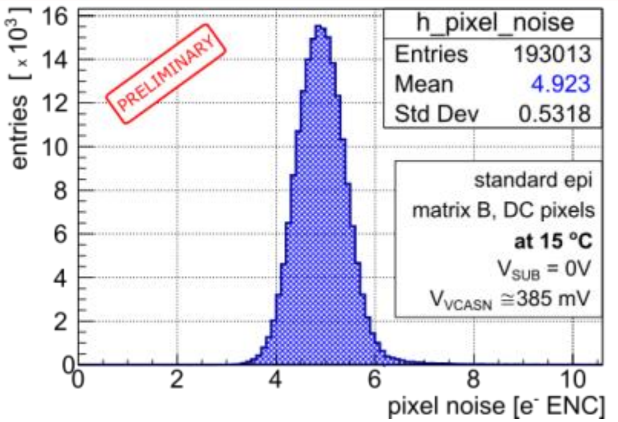
3 irradiations campaigns

Large FTE effort

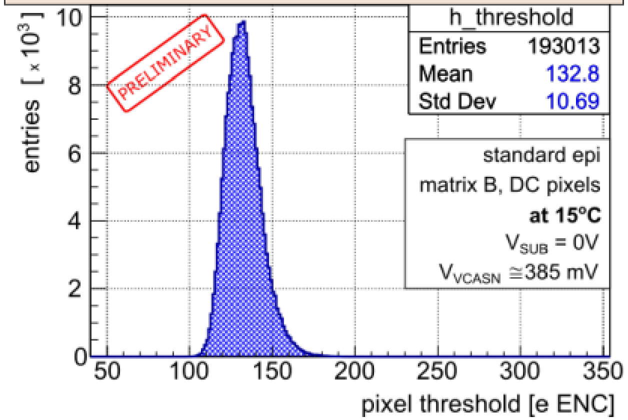
Noise

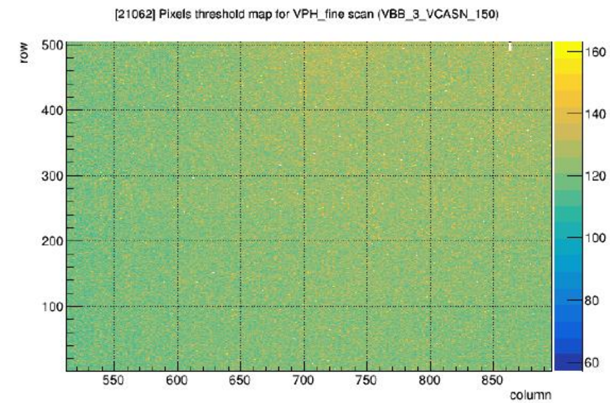


THERMAL NOISE: 3 - 5 e ENC

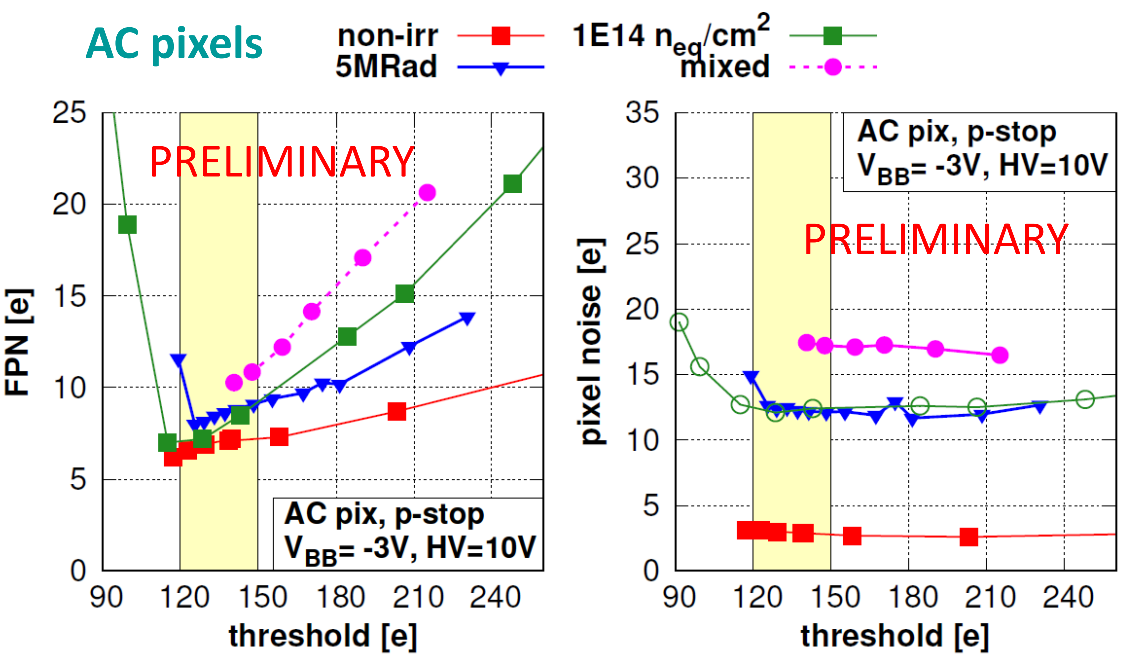


FIX PATTERN NOISE: 5 - 17 e ENC



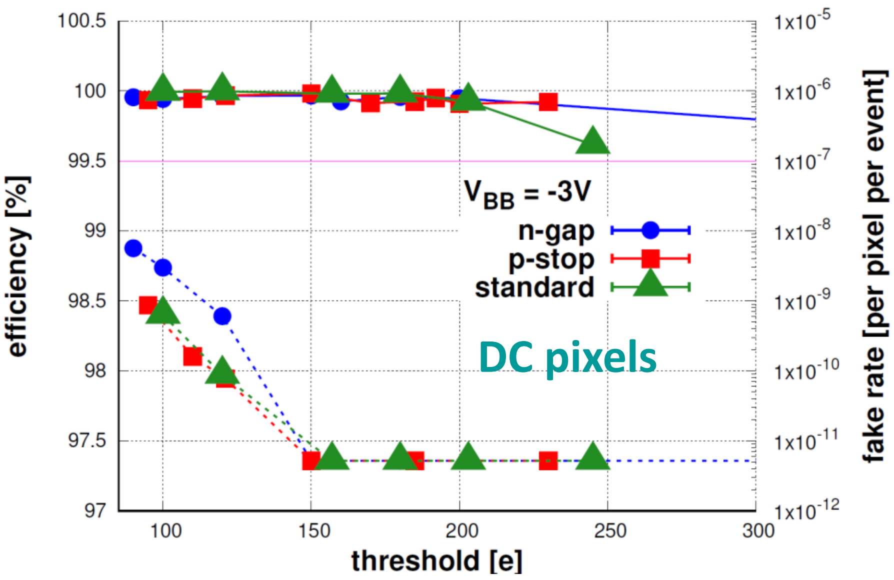


(c) Distribution of the threshold of the pixels over matrix C.

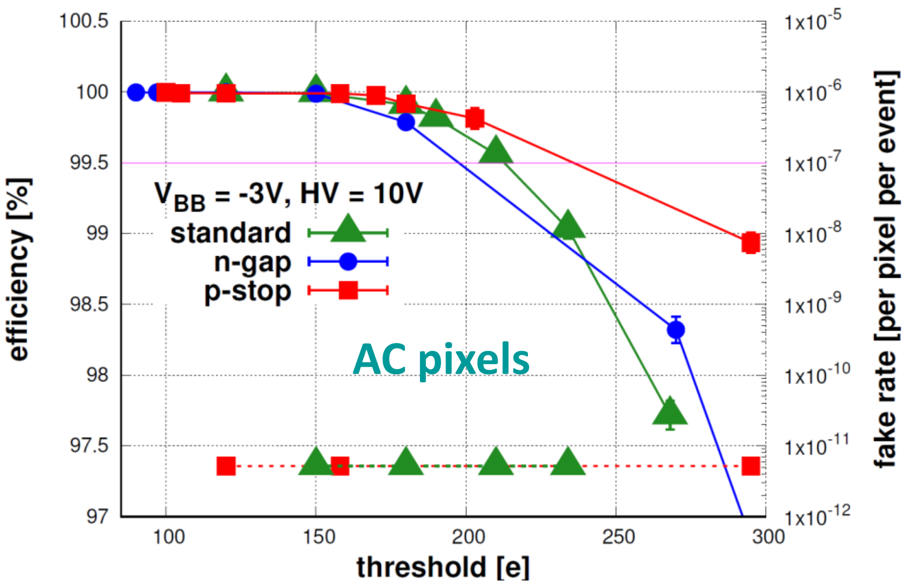


⇨Noise under control,
both for AC / DC & standard/p-stop
even after irradiation:
FPN< 20 ENC ;
Thermal Noise < 20 ENC after Irr.

Efficiency/fake rate: Process comparison



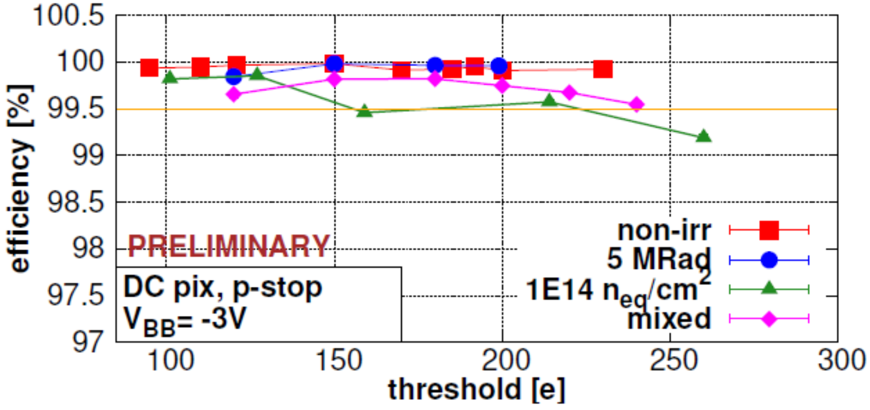
DC pixels



AC pixels

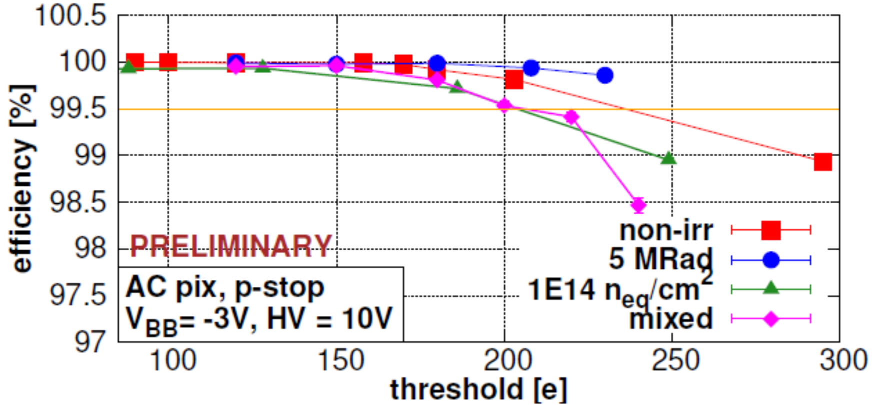
⇨Efficiency / fake rate meets the requirement for all processes / pixel types

Efficiency vs Irradiations type



(a) DC pixels

DC pixels



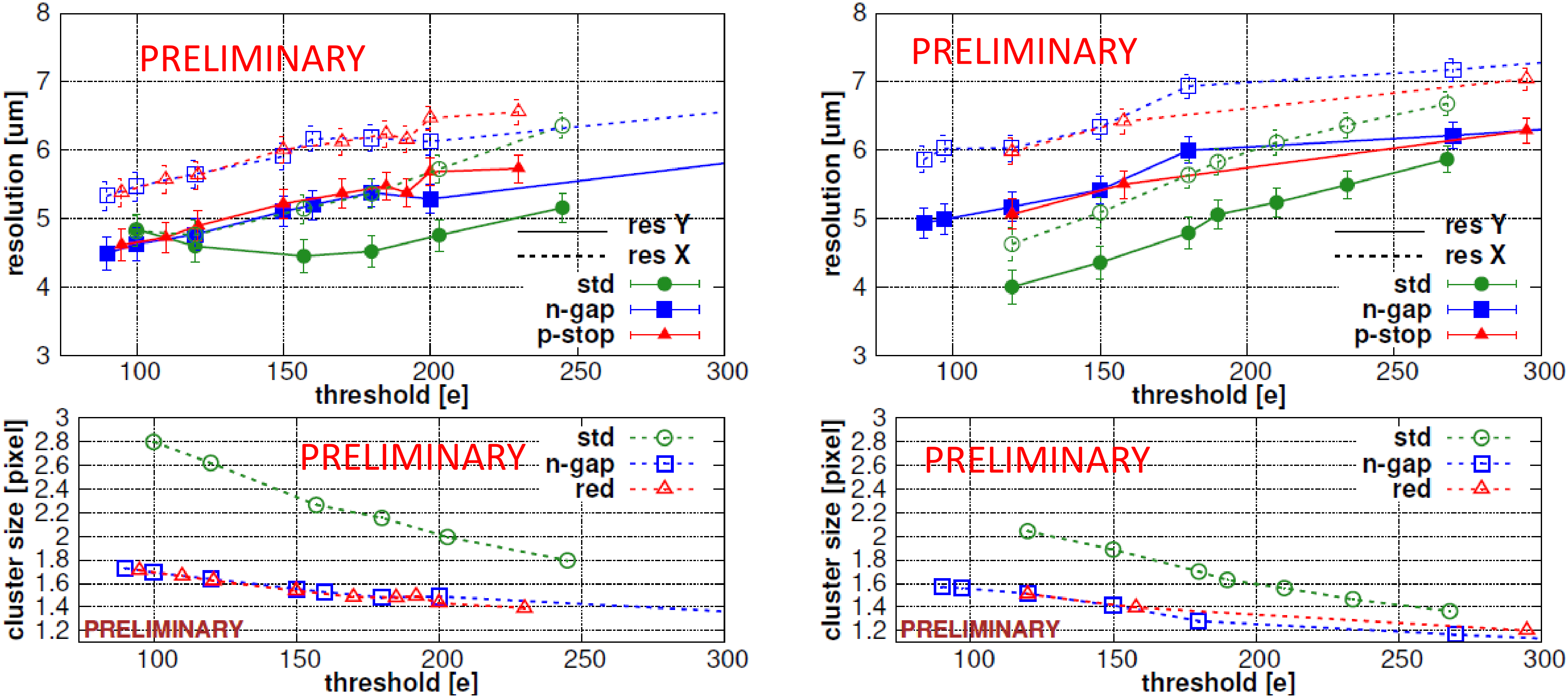
(b) AC pixels

AC pixels

⇨Radiation hardness meets the requirements

Resolution vs process

DC pixels **AC pixels**

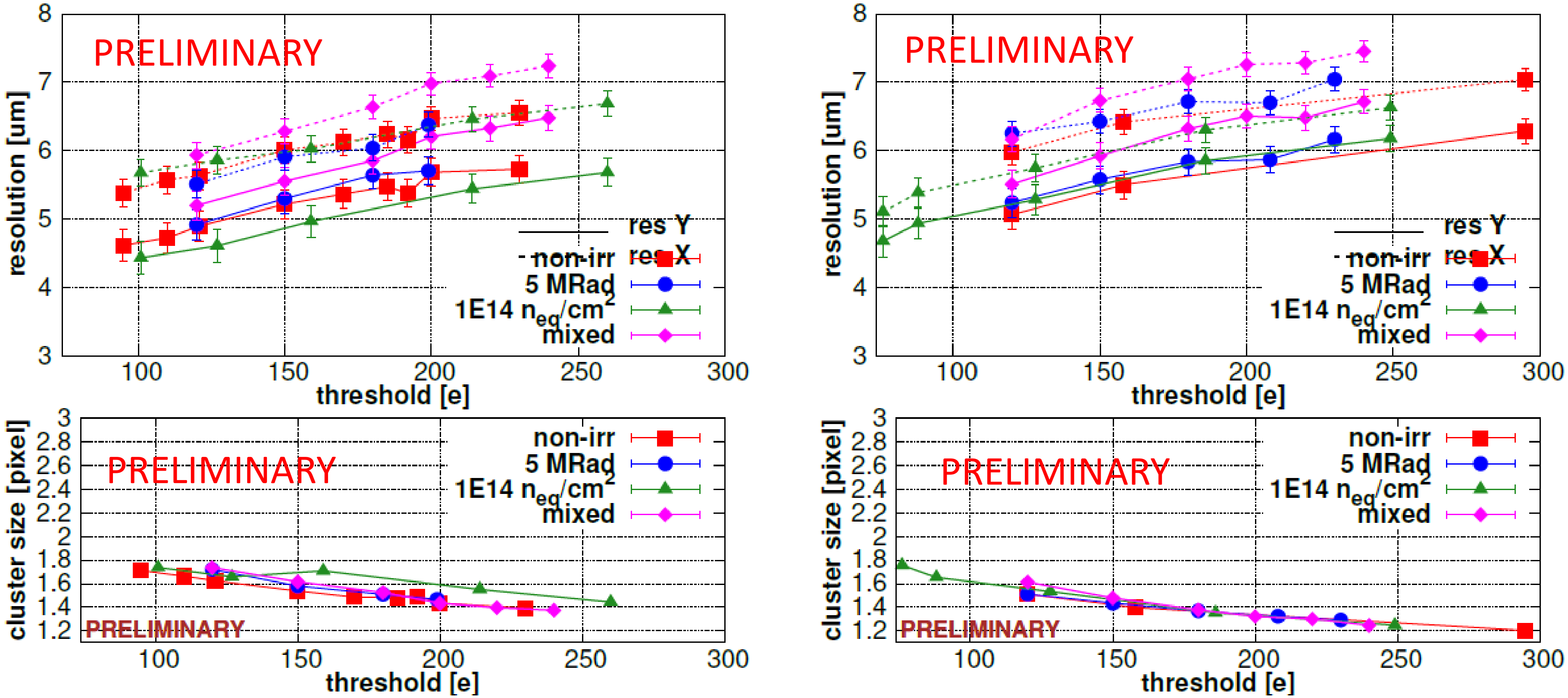


(a) DC pixels (b) AC pixels

⇨ Expected spatial resolution difference between standard / p-stop process

⇨ Spatial resolution meets the requirements

Resolution / cluster size vs irradiation

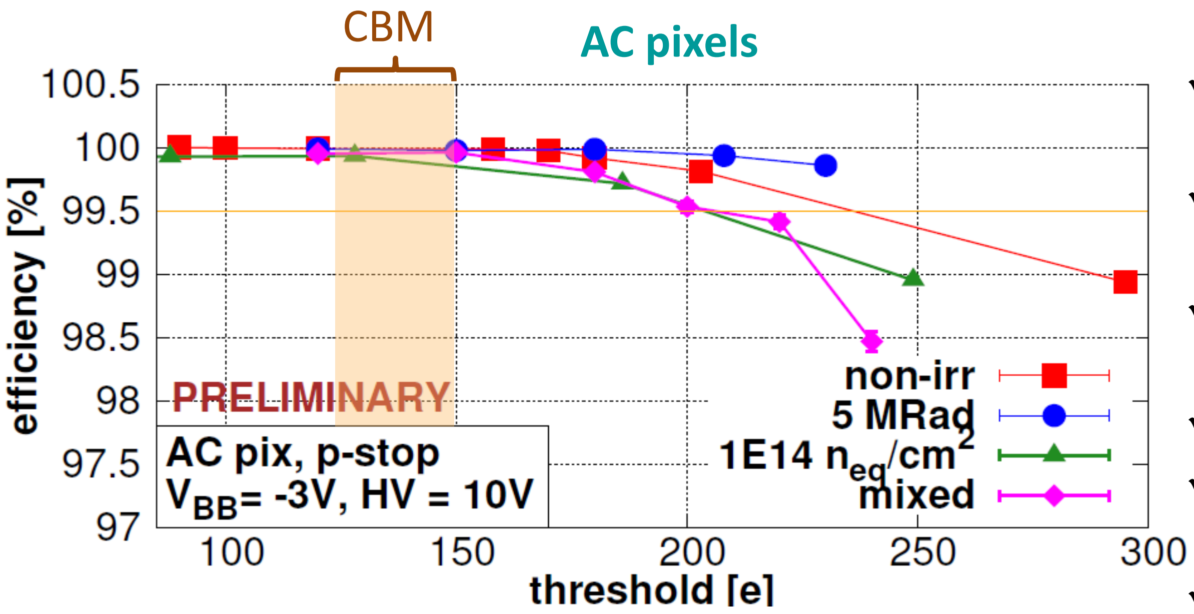


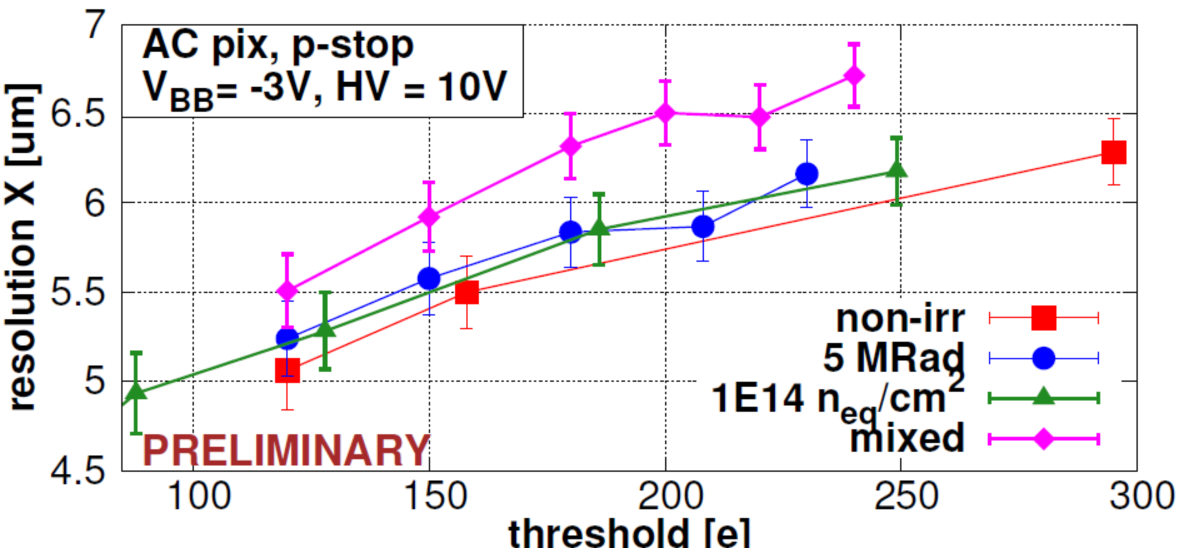
(a) DC pixels (b) AC pixels

Figure 15: Comparison of resolution and cluster size for various irradiation types - p-stop.

⇨ Spatial resolution only slightly degraded with irradiation (10^{14} n_{eq} + 5 Mrad)

Putting all together: Irradiations - efficiency - resolution





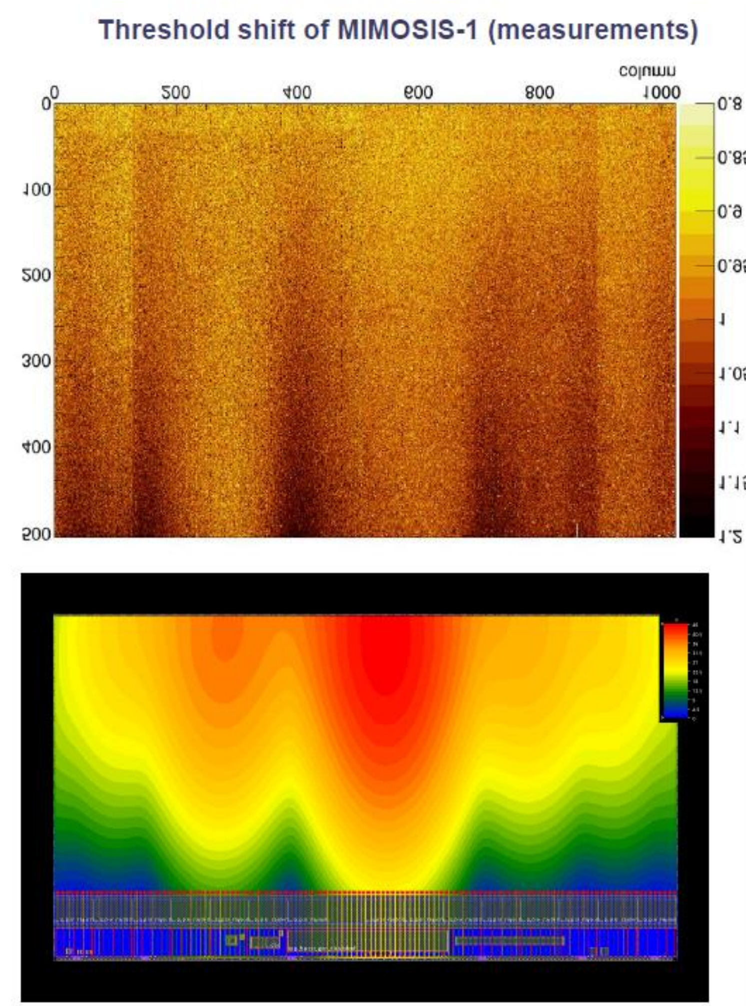
- ✓ Det eff. >> 99% for 10^{14} n_{eq}/cm^2 (p-stop)
- ✓ Reasonable performances after 3x 10^{14} n_{eq}/cm^2.
- ✓ Spatial resolution in the 5-6 µm range for p-stop process
- ✓ Noise under control
- ✓ Fake rate < 10^{-6} for all pixel types tested.
- ✓ "AC pixels + p-stop process" offer a very good compromise efficiency – resolution – radiation hardness
  - ✓ Performances matches requirements

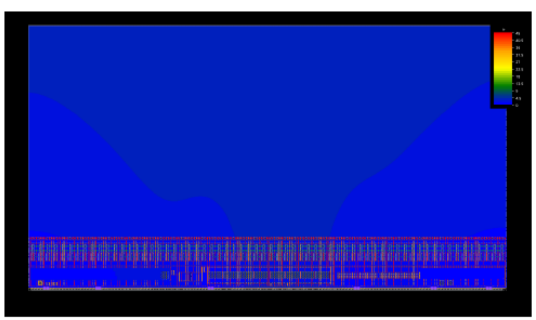
⇨ Working point demonstrated after iraddiation (10^{14} n_{eq} + 5 Mrad)

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]





IR drop on AVDD (simulations)
0-45 mV scale

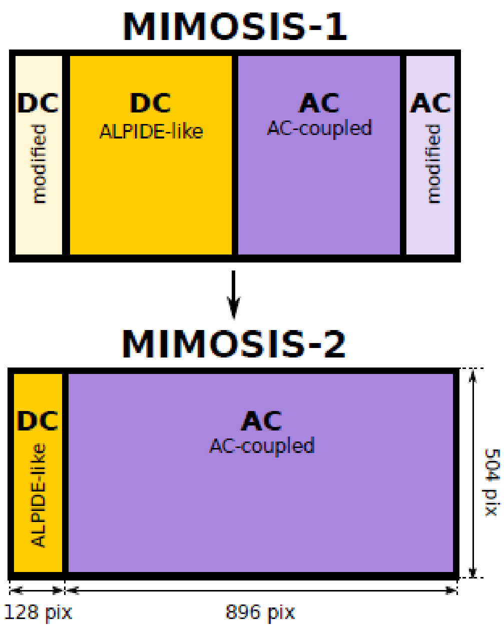
MIMOSIS-1
Mean= 26 mV

MIMOSIS-2
Mean = 3 mV

First look into

Mimosis-2

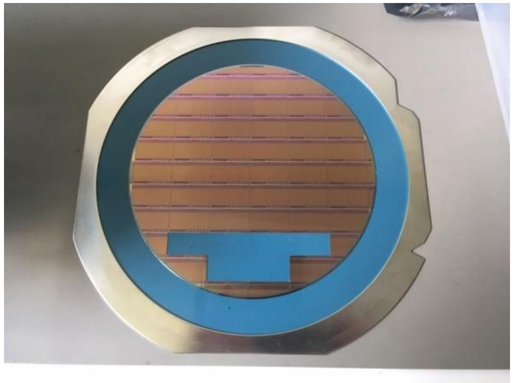
- Evolution of MIMOSIS-1 with
  - ➢ On-chip clustering
  - ➢ Triplication added
  - ➢ Various improvements
- Goal: validate all blocks/functionnalities before final production sensor (Mimosis-3)
- 25 & 50 μm epitaxial thickness versions
- Back from foundry Q2 2023
  - ➢ First tests in June 2023

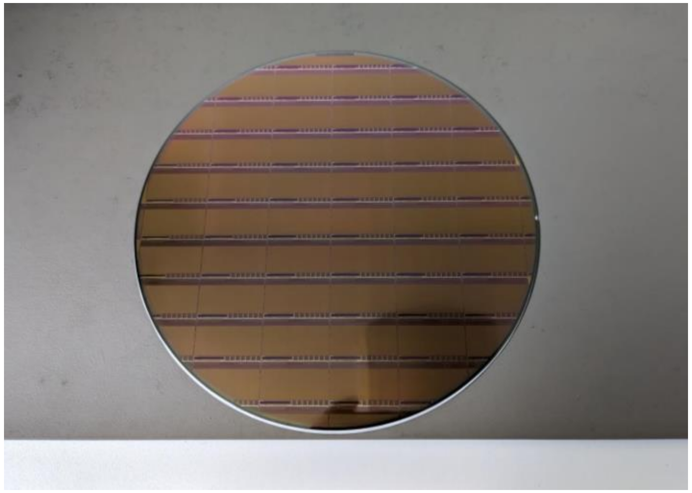


MIMOSIS-2 first tests

- 9 chips diced and tested (from different wafers/process)

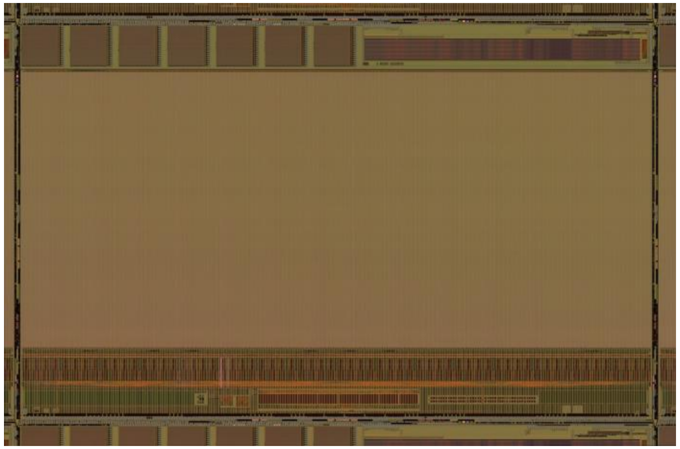
PCB	Process	IA
13	W3 Ngap 25µm	OK
51	W1 Std 25µm	OK
52	W1 Std 25µm	OK
53	W1 Std 25µm	500 mA
54	W1 Std 25µm	OK
55	W1 Std 25µm	OK
56	W1 Std 25µm	OK
57	W6 Pstop 25µm	500 mA
58	W11 Pstop 50µm	OK





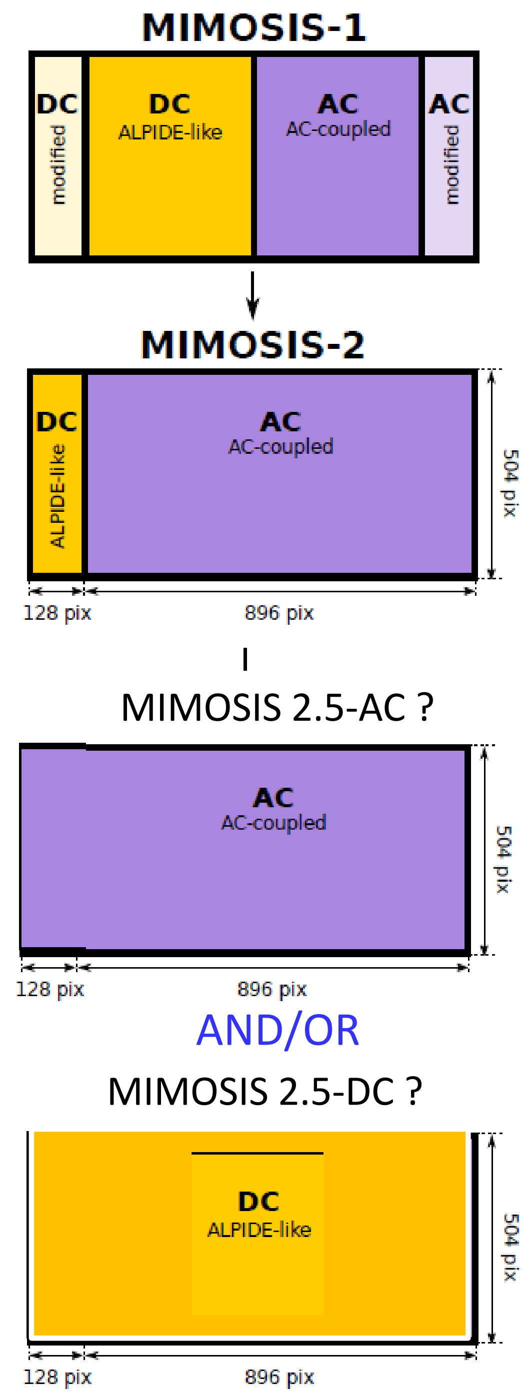
- MIMOSIS-2 does not work properly
  - ✓ **Unexpected issues on the design** (e.g. frequency limitation for some standard cells, reset)
  - ✓ Ongoing discussions with the foundry (NDA)

- Status:
  - ✓ The CBM-MVD collaboration worked hard the last 3 months to identify the sources of the problems.
  - ✓ **The sources of all the identified problems has been understood.**
    - the critical issues can probably be corrected by resubmitting with only 2 modified metal masks
  - ✓ **The current version of MIMOSIS-2 will not allow to fully characterize its performances but we are confident it will allow to validate the additional features with respect to MIMOSIS-1** (on-chip clustering, triplication).



MIMOSIS-2: Action plans

- Focused Ion Beam correction on few chips (FIB)
  - ✓ The Focused Ion Beam process is a circuitry modification protocol that will allow to modify 2 x 2 columns.
  - ✓ It will confirm the problems identification
  - ✓ It will allow to validate the clustering and the triplication.
  - ✓ FIB ongoing ⇨ time before feedback ~1 month
- Lessons learned
  - ✓ Unexpected issues which could have occurred in MIMOSIS-1
  - ✓ Analog simulation tools for the digital part provided valuable input
    - **verification process improvement**
  - ✓ **MIMOSIS-2 will play its role (validation of the final design, verification process optimization)**
- A possible compromise is to resubmit a fabrication with less options :
  - ✓ MIMOSIS 2.5 ?
  - ✓ Less different splits/process, less wafers, perhaps only AC matrix) to optimize costs vs delay vs tests.
  - ✓ Submitting a version closer to the final sensor design (e.g. only one pixel type on the whole matrix) might offer some added value to be estimated.
- Plans
  - ✓ Validate all corrections (in particular thanks to chips corrected with FIBs)
  - ✓ Take an educated decision within 1-2 months



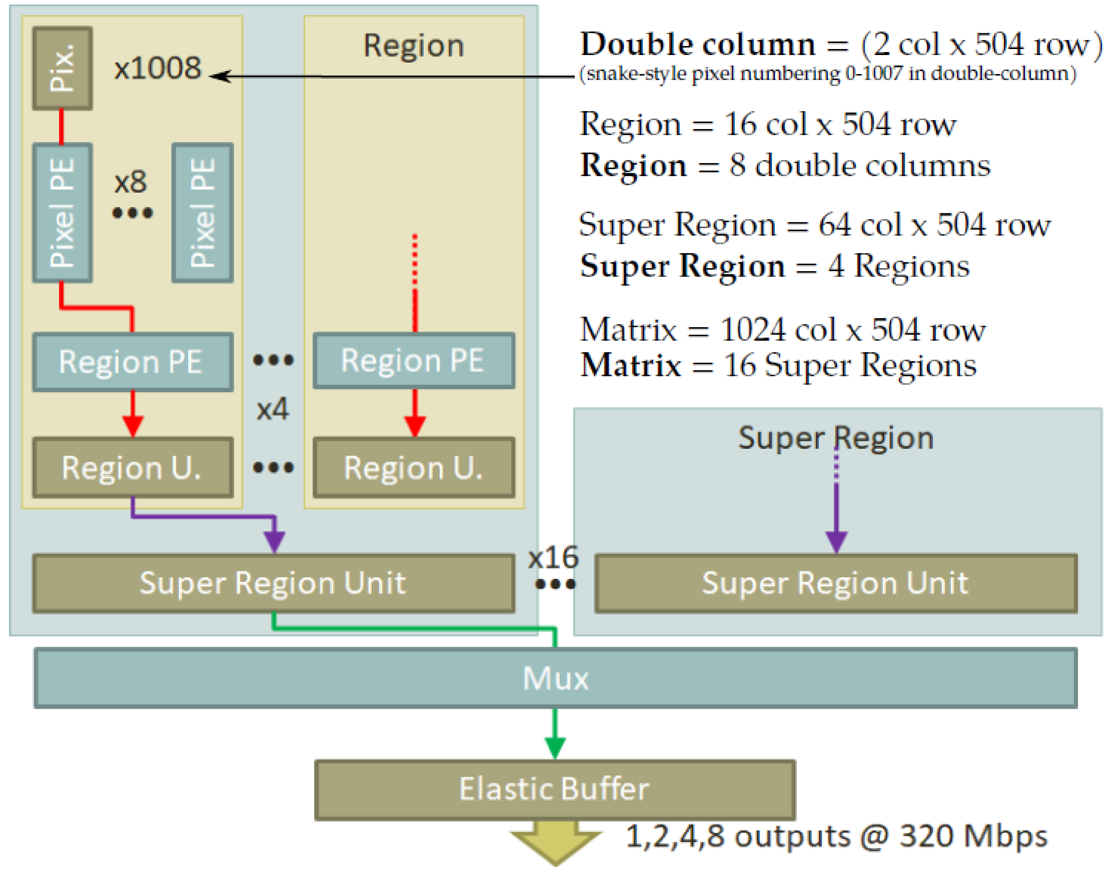
Summary

- MIMOSIS program
  - ✓ Dedicated to equip CBM-MVD
    - Step forward w.r.t ALPIDE performances
    - Demonstrator for future Higgs factories (« 5 μs – 5 μm »)
    - MIMOSIS-1 demonstrated that the requirements can be fulfilled
  - ✓ Intensive test phase mandatory
    - demanding human resources effort by the CBM-MVD collaboration
  - ✓ Very valuable return of experience for the design and tests.
  - ✓ MIMOSIS-2
    - Critical issues met
      - Problems understood
      - Verification process improved
      - MIMOSIS-2 will still allow to validate the final architecture
    - Probable resubmission with cost/delays optimization
- The goal is still to deliver the final sensor (MIMOSIS-3) on time to CBM

Back up

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



Beam tests (MIMOSIS-1)

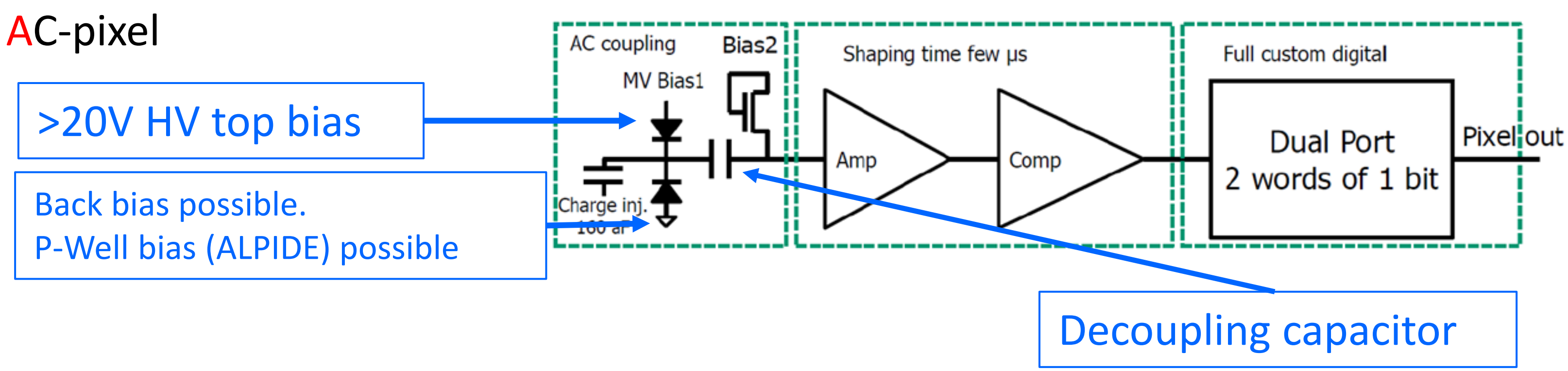
Date	Location	Beam	Goal
13. – 14. Mar 2021	GSI / mCBM	1 AGeV Pb	Single-Event-Effects (SEE)
23. – 24. May 2021	GSI / mCBM	1 AGeV Xe	SEE
07. – 13. Jun 2021	DESY	5 GeV e^-	Performance
19. – 26. Sep 2021	DESY	5 GeV e-	Performance (X-ray irradiated)
05. – 12. Oct 2021	CERN	~100 GeV $\pi^{\pm}$	Performance (neutron irradiated)
14. – 20. Feb 2022	DESY	5 GeV e-	Performance (mixed irradiated) ++
21. – 28. Mar 2022	COSY	0.3 – 3 GeV p	Performance, dE/dx?
23. – 29. May 2022	GSI/UNILAC	~4 MeV Ca	SEE, slow fragments
01. – 07. Sep 2022	CERN	~100 GeV $\pi^{\pm}$	Response to inclined tracks,...

Irradiation campaigns:

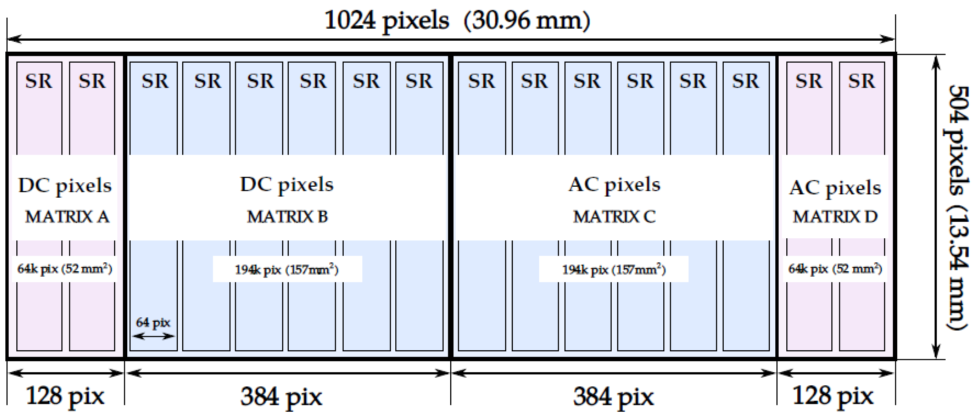
Date	Location	Radiation
Jul – Aug 2021	Ljubjana (TRIGA)	~1 MeV reactor neutrons
Sep 2021	Karlsruhe (KIT)	~10 keV X-rays
Aug 2022	Karlsruhe (KIT)	~10 keV X-rays

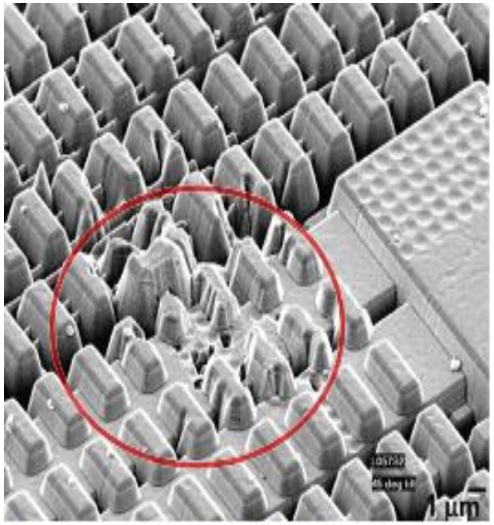
Special thanks to IPHC for massive support in beam time preparation
Meanwhile: 14 IPHC people (9-10 FTE) involved in MIMOSIS.

E. AC / DC pixels

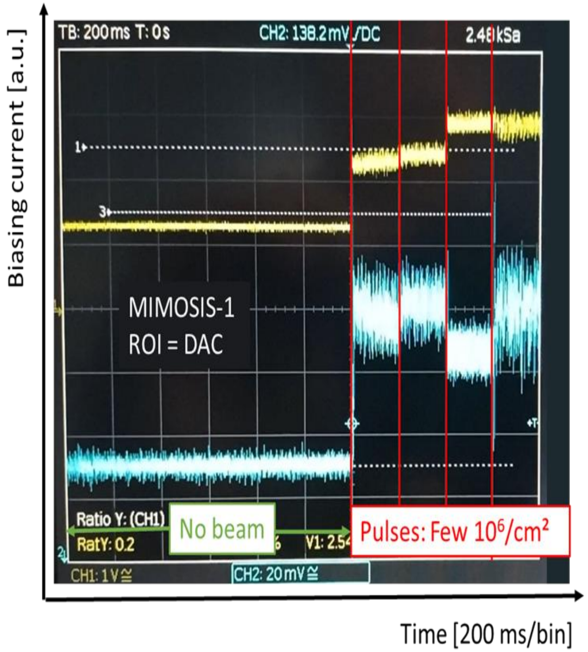


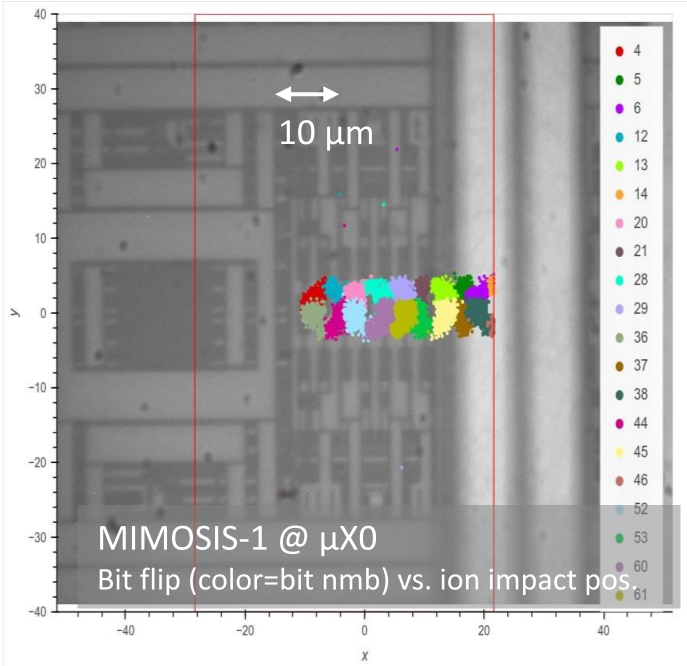
- DC Pixels (~ALPIDE) & AC pixels (top bias up to > 20V)
  - ✓ Amplifier / shaper / discriminator chain similar to ALPIDE in both scheme
  - ✓ Data driven readout
  - ✓ Pulse injection for calibration
  - ✓ Pixel masking options





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





Initial worry:

- Device destruction by latch-up (reversible short cut).
- So far not observed.

Observed with MIMOSIS-1

- Power regulators destabilized by HI-impact => Bit flip.
- Existing protection failed. Bug fixed in MIMOSIS-2.
- Needs checks.

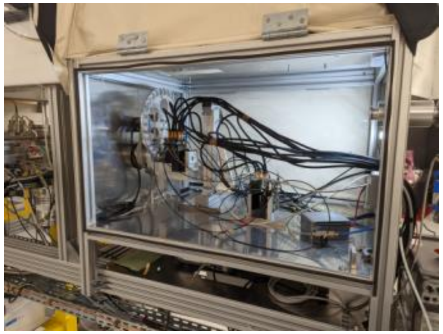
Test plan with with MIMOSIS-2

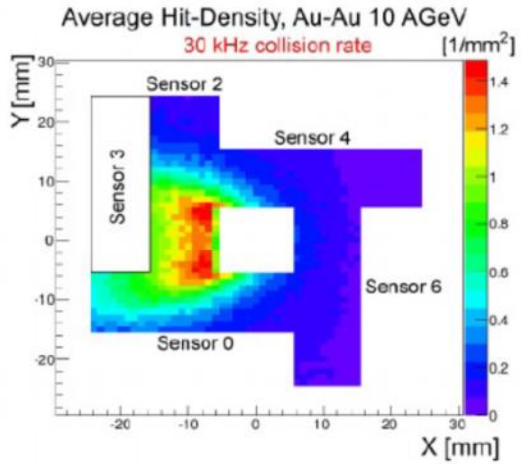
- Repeat test with heavier ions.
- Search for possible additional weak points if existing.

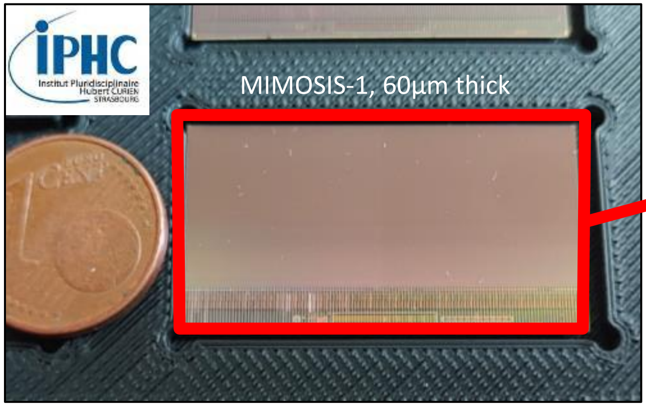
Beam time requested and granted at GSI UNILAC.

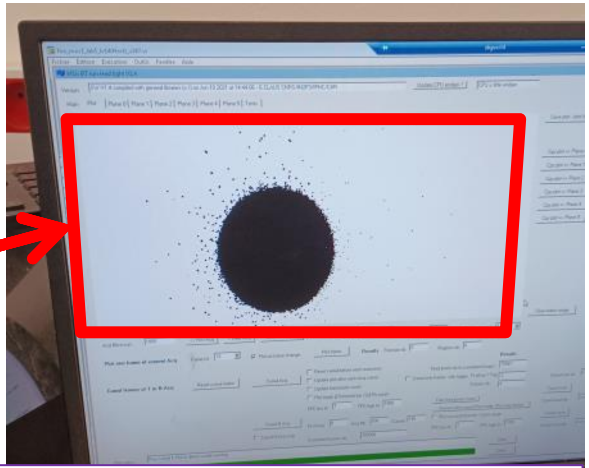
Localized irradiations

- CYRCE platform @IPHC
  - ✓ https://cyrce.fr/
  - ✓ Delivers 25 MeV proton beams
    - Niel factor ~1.8
  - ✓ Can control precisely the dose
    - CYRCE beam characterization
    - High rate tests
    - Localized irradiations
    - Check performances uniformity with non uniform irradiations to mimic the expected MVD irradiation non uniformity
    - First tests performed with MIMOSIS-1 in Q2 2023 ⇨ procedure validated



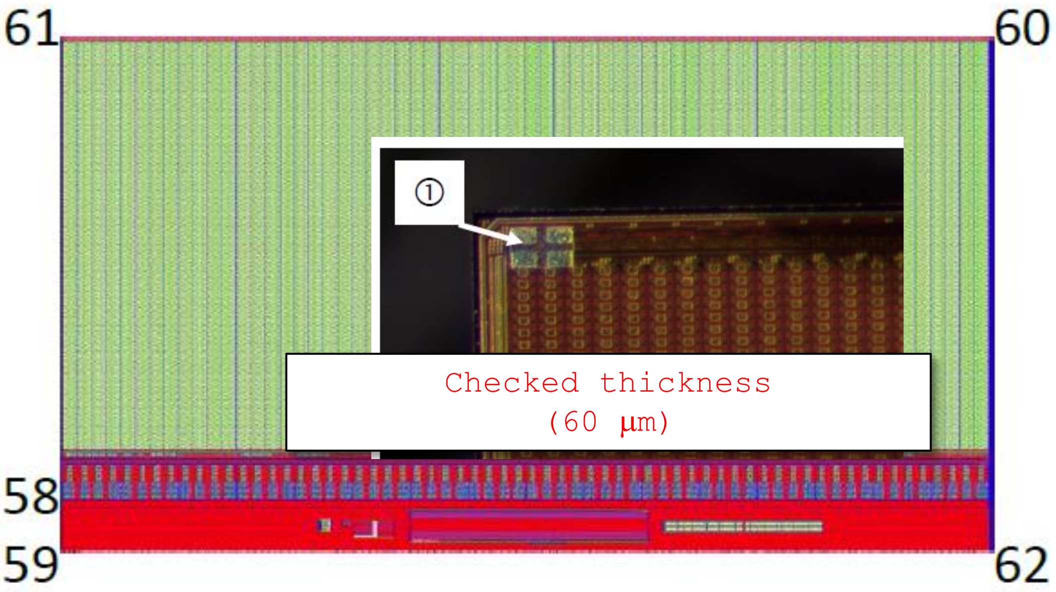






Example of MIMOSIS-1 illuminated with a 8 mm diameter collimation

Thickness homogeneity measurements

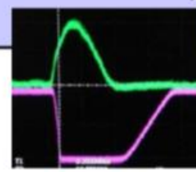


Data Path: from diode up to the output

Analogue | **Pixel array digital** | **Digital** | **Pads**

Diode
- DC
- AC

Analogue Pixel
- Amplifier
- Discriminator



Digital Pixel
- 1-bit word

x1008

Pixel Priority Encoder
- 10-bits address
- 20 MHz

x8

Region Priority Encoder
- 13-bits address
- 20 MHz

Clustering
- 16-bits word
- Not implemented in MIMOSIS1
- 20 MHz

Region Readout
- 16-bits word
- Store 96 words/frame
- 20 MHz write
- 40 MHz read

x4

Super Region Readout
- 16-bits word
- Store 256 words/frame
- 40 MHz

x16

Multiplexer
- 256-bits bus for high bandwidth

Frame Generator
- Reduce bus to 128-bits with higher frequency
- 40 MHz write
- 80 MHz read

Elastic Buffer
- Frame averaging
- 80 MHz write
- 20 MHz read

Serialiser
- 8 parallel serialisers 16→1
- 320 MHz