The MIMOSIS pixel sensor Design & Measurement

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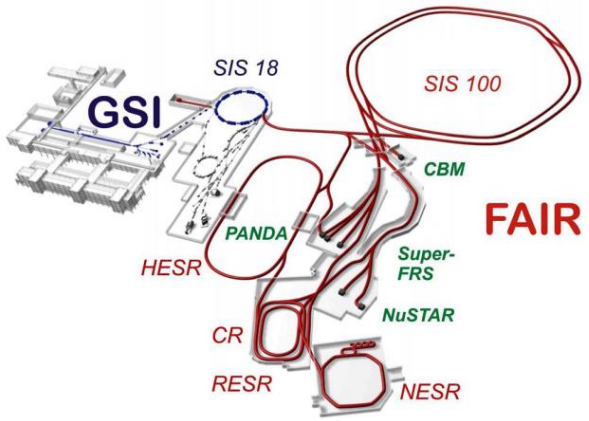
on behalf of IPHC-IKF-GSI collaboration

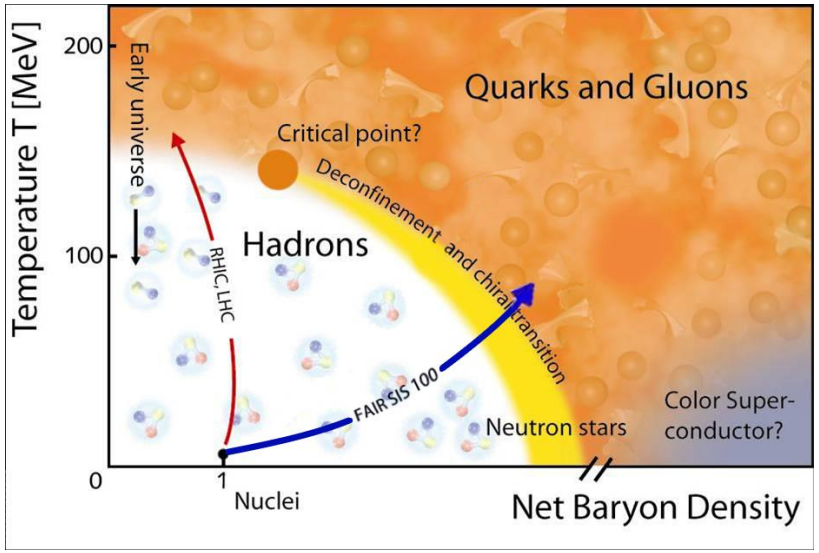
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

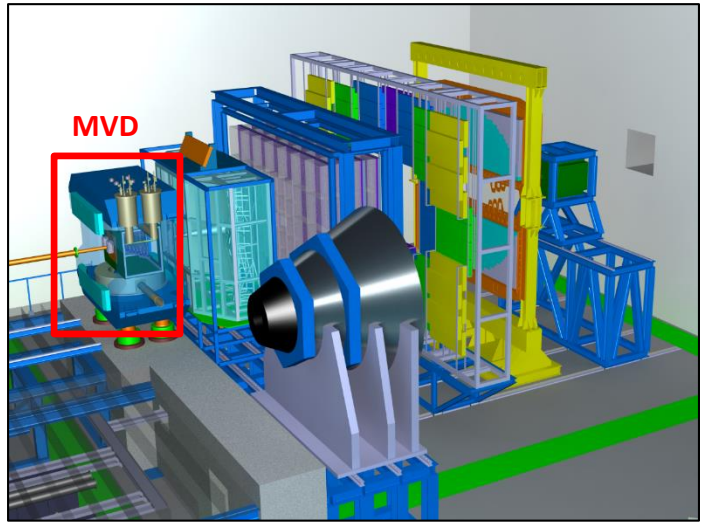
(05P19RFFC1)

The Compressed Baryonic Matter experiment @ FAIR

- Explore phase diagram at region of highest net-baryon density
- Fix target
- Beam start is schedule for end 2024



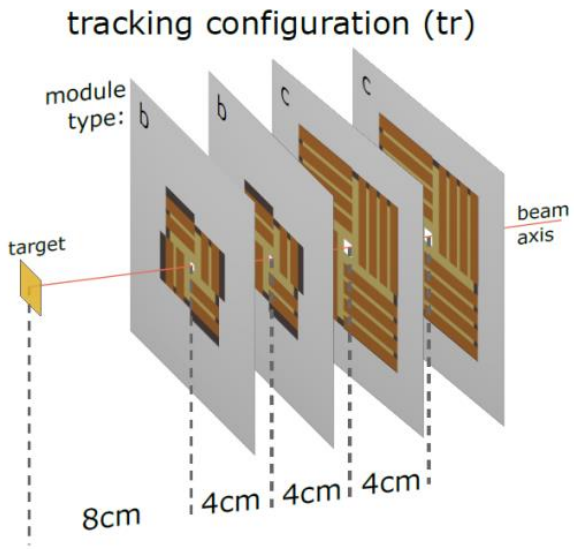


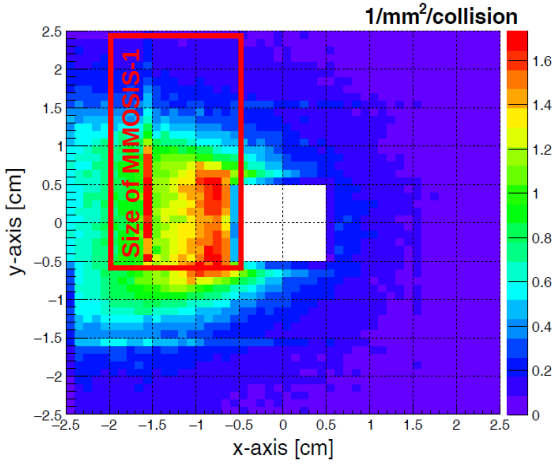


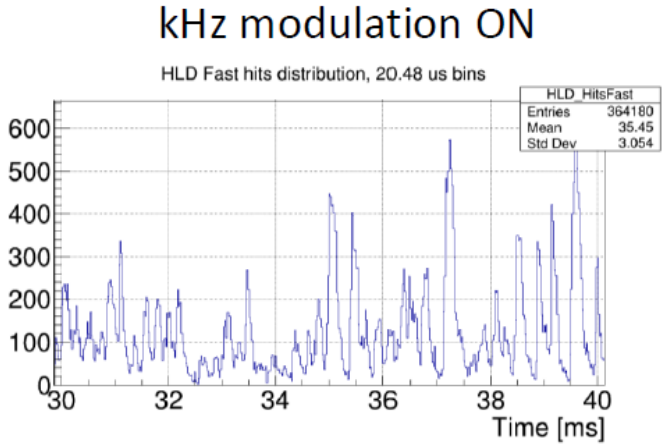
April 2021

Micro Vertex Detector

- Aim for high collision rate capability
  - 100 kHz Au+Au @ 11 AGeV
  - 10 GHz p+Au @ 30 AGeV
- Aim to contribute to tracking
  - 4 planar detector stations
- Aim for good sec. vertex resolution
  - Operate in target vacuum
  - First station 5 cm from target (in vertexing configuration)
  - ~ 5 µm resolution
  - Thin stations
    - ~ 0.3 % X_0 (first station)
    - ~ 0.5 % X_0 (other stations)
- Sensor must handle occupancy gradients in space
- Sensor must handle beam fluctuations in time







MIMOSIS Requirements

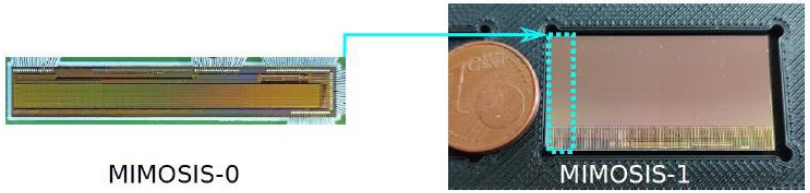
	Requirement
Spatial resolution	~5 µm
Time resolution Triggerless without dead-time	~5 µs
Sensor thickness	~50 µm
Radiation length	~ 0.3 % X_0 (first station) ~ 0.5 % X_0 (other stations)
Power dissipation	<100 - 200 mW/cm²
Operation temperature	- 40°C to +30°C
Temperature gradient on sensor	5 K
Radiation* (non-ionizing)	~ $7x10^{13}$ n_{eq}/cm²
Radiation* (ionizing)	~ 5 Mrad
Radiation gradient on chip	100%
Heavy Ions-tolerance	10 Hz/mm²
Rate (average/50 µs peak)	200/800 kHz/mm²

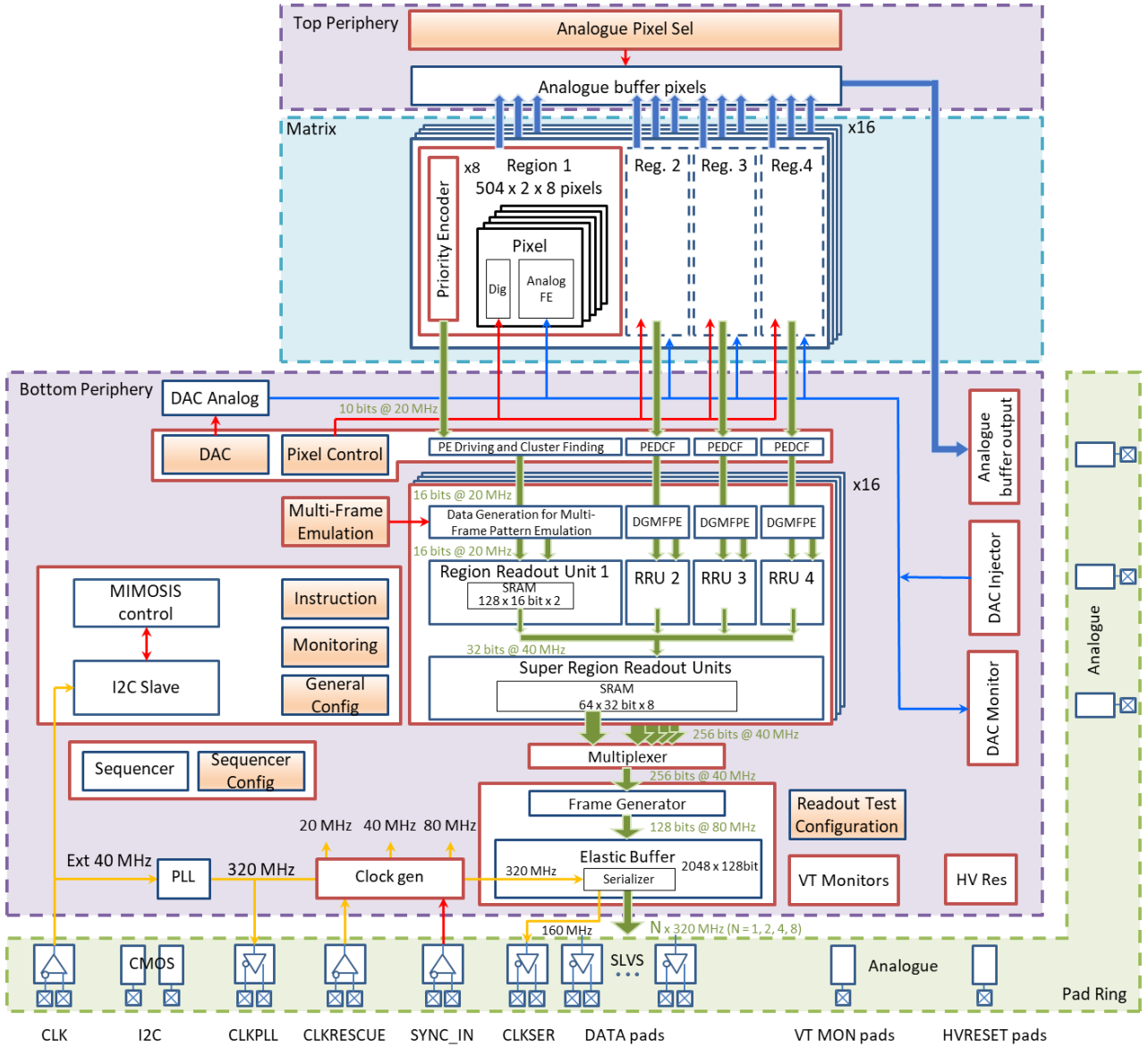
* No safety factor

MIMOSIS diagram

- Matrix dimension: 1024 col. X 504 row
- Pixel dimension: 26.88 µm (height) x 30.24 µm (width)
- Integration time: 5 µs
- Tower Semiconductor 180 nm
- 4 sub-arrays for threshold adjustment
- MIMOSIS chip family:

STAGE	PERIOD	SPECIFICATION
MIMOSIS-0	2018	→ Small size prototype, part of MIMOSIS-1 → Testing/optimization of analogue readout chain → No data buffer structure
MIMOSIS-1	2020-2021	→ 1st full-scale prototype → Fabricated with 9 x CE18 (64x64 pixels) for optimization of in-pixel circuitry → Elastic buffer implemented for high-rate data handling → Removal of double frame counting → SEE hardened by TMR/Hamming design → Tested on beam in June 2021
MIMOSIS-2	2021-2022	→ Clusterization integrated on chip periphery → Full triplicated clock trees to enhanced the SEE hardness → Design tuned basing on CE18 and MIMOSIS-1 test results
MIMOSIS-3	2023	→ Final sensor





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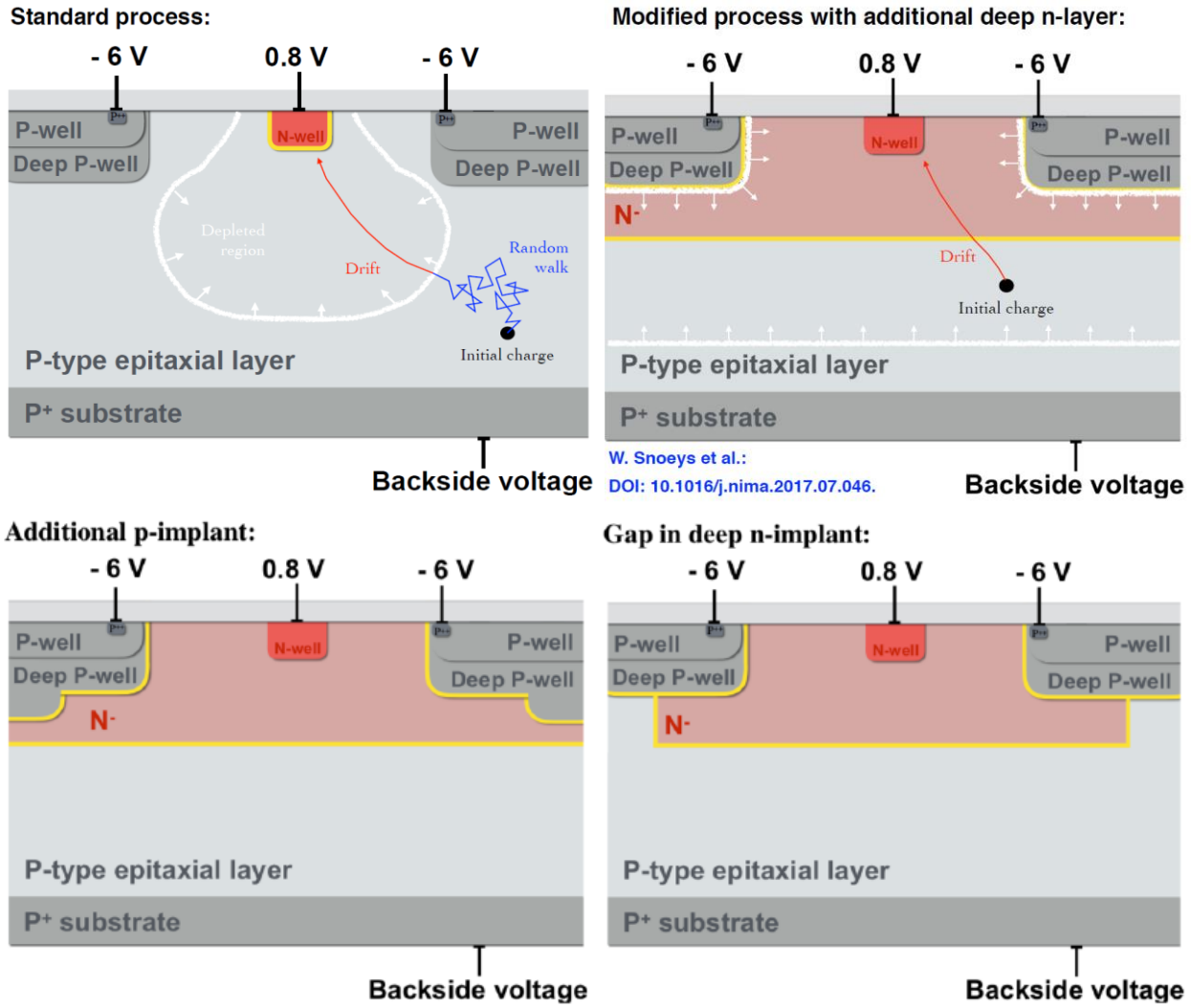
Charge collection

- Tower Semiconductor 180 nm
  - 4 process variants and various epi layer thickness
  - Optimize charge collection
    - efficiency after irradiation
  - Based on the experience accumulated with ALPIDE and MALTA/MONOPIX
- Goals:
  - Increase depletion region with a small collection diode
  - Avoid charge traps due to low lateral electric field on the edges
- Additional degree of freedom for MIMOSIS:
  - AC coupled pixels to increase collection diode voltage

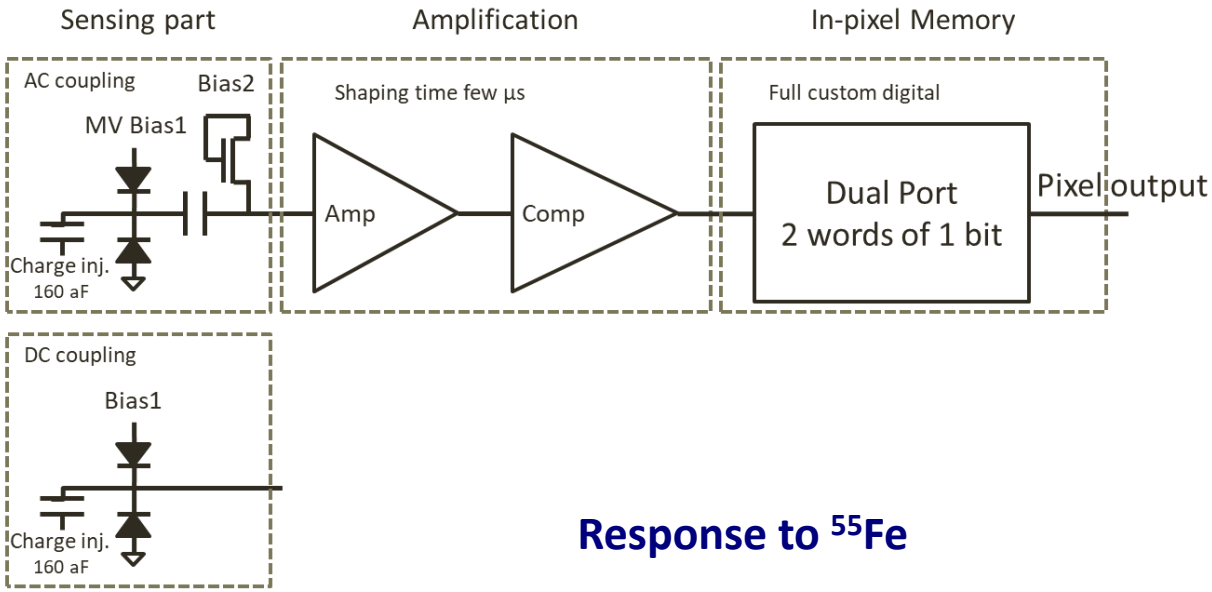


Study of the depletion depth in a frontside biased CMOS pixel sensors
J. Heymes https://doi.org/10.1088/1748-0221/14/01/P01018

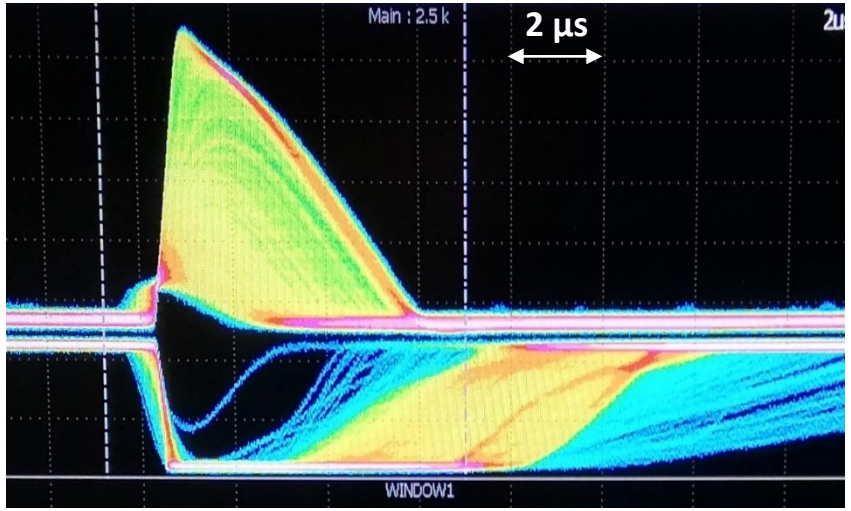
Monolithic CMOS sensors with a small collection electrode
Seminar by M. Munker at Royal Holloway University of London (2019)

Pixel

- 2 versions of sensing part evaluated:
  - DC or AC coupled
    - Polarization of the collecting diode to ~10-20 V in AC
    - Variants are in MIMOSIS0 and MIMOSIS1 prototype
- Amplification:
  - Similar to ALPIDE
  - Non linear and with clipping technique
- In-pixel Memory:
  - Dual ports for triggerless framing (5 µs)
    - One to write the hit (current frame)
    - One to read the hit (previous frame)
  - Avoid multiple counting
    - For impact which spread over several capture windows
  - High density full custom block
- Amplifier and sensing part tested in MIMOSIS0



Response to ^{55}Fe



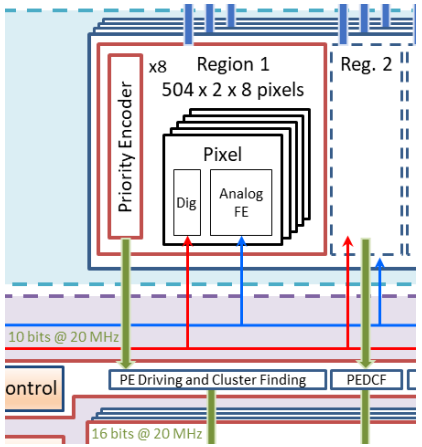
Amplifier output

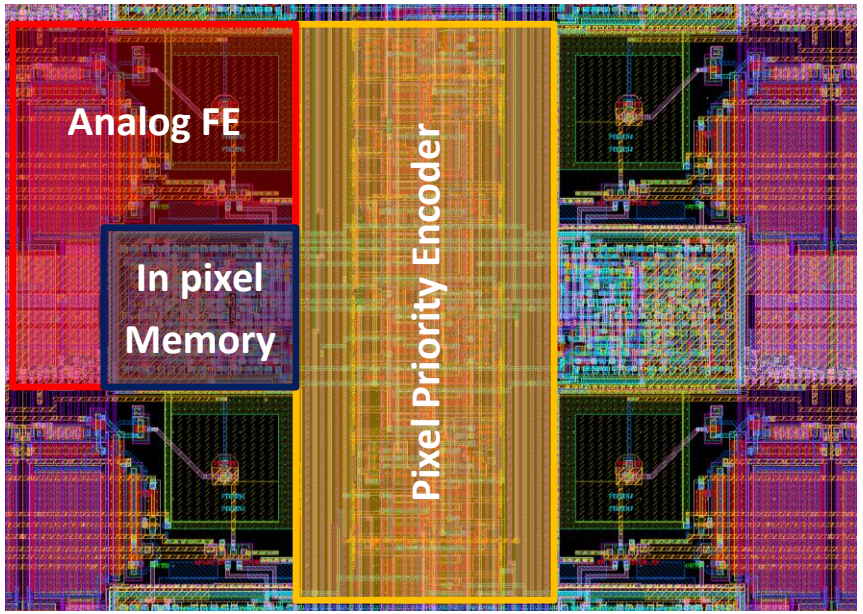
Comparator output

M. Deveaux NIM A 958 (2020) 162653

Matrix readout

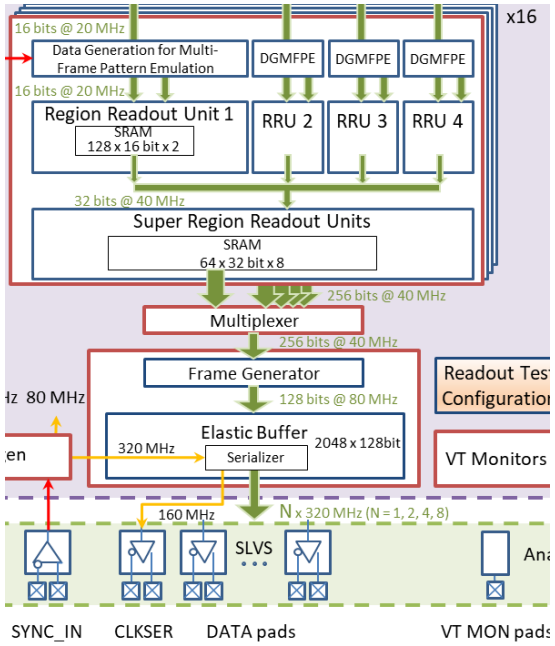
- Priority Encoders Functions:
  - Give the address of the hit pixel with the highest priority
  - Aim the pixel reset signal to the selected pixel
- 2 levels of priority encoders to read a Region:
  - Pixel level
    - inside the pixel array to read 2 columns of 504 pixels
  - Region level
    - at the bottom of the pixel array to read 8 Pixel level Priority encoders
- Characteristics:
  - Reading is done at 20 MHz (100 pixels/frame/region)
    - ~3 MHz/mm² ➔ 1 MHz/mm² (hit multiplicity of 3) > 800 kHz/mm²

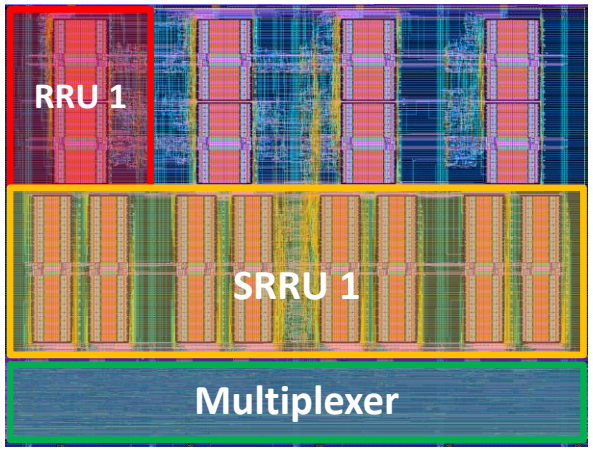


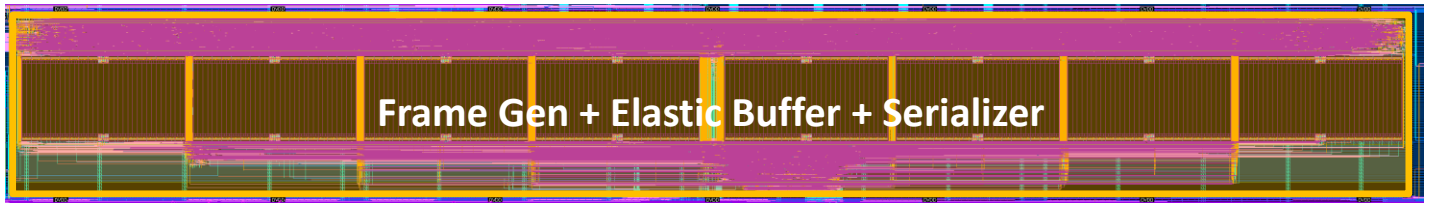


Bottom periphery readout

- Function:
  - Averaging the data fluctuations over the pixel array (gradient in space)
  - Averaging the data fluctuations in time (beam fluctuations)
  - Works like a funnel for the data
    - 20.48 Gb/s (16 bits x 64 regions @ 20 MHz spread over ~3 cm)
    - 2.56 Gb/s (8 serial links @ 320 Mb/s spread over ~3 mm)
- 3 levels of dual port memories
  - 64 Regions and 16 Super-Region (for space averaging)
    - Write frame N in parallel @ low speed
    - Read frame N-1 in serial @ high speed
    - No data loss between matrix readout and Super-Region
  - 1 elastic buffer (for time averaging)
    - Works like a circular buffer
    - Write speed 10.24 Gb/s > Read speed 2.56 Gb/s (for 8 links)
    - Configurable number of serial links (8,4,2 or 1)
    - Can store 3 x nominal beam during 50 µs

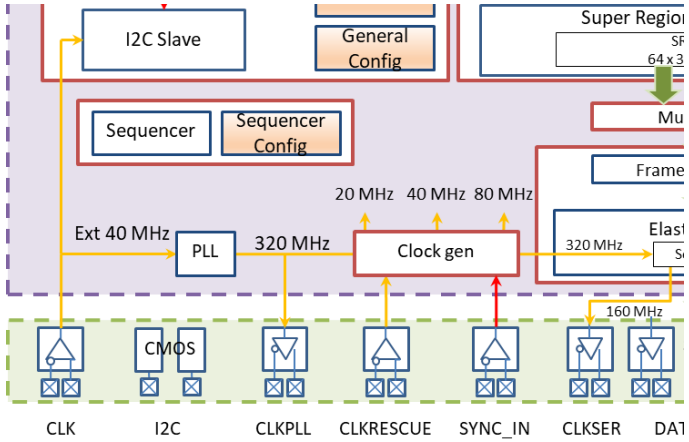






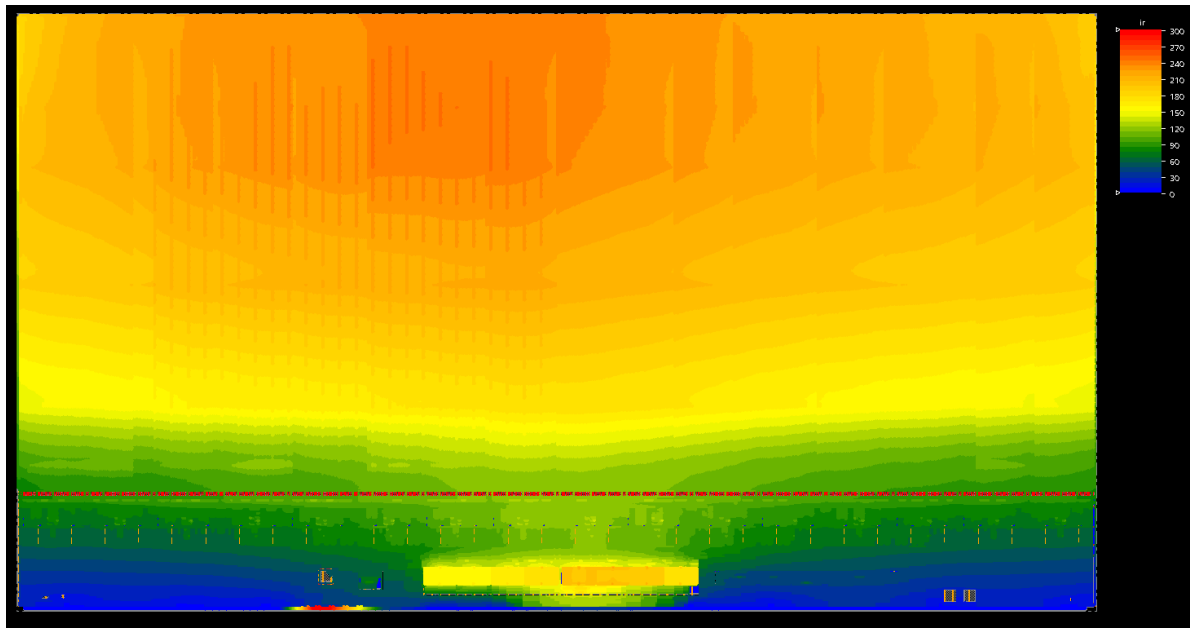
Multi-chips synchronization

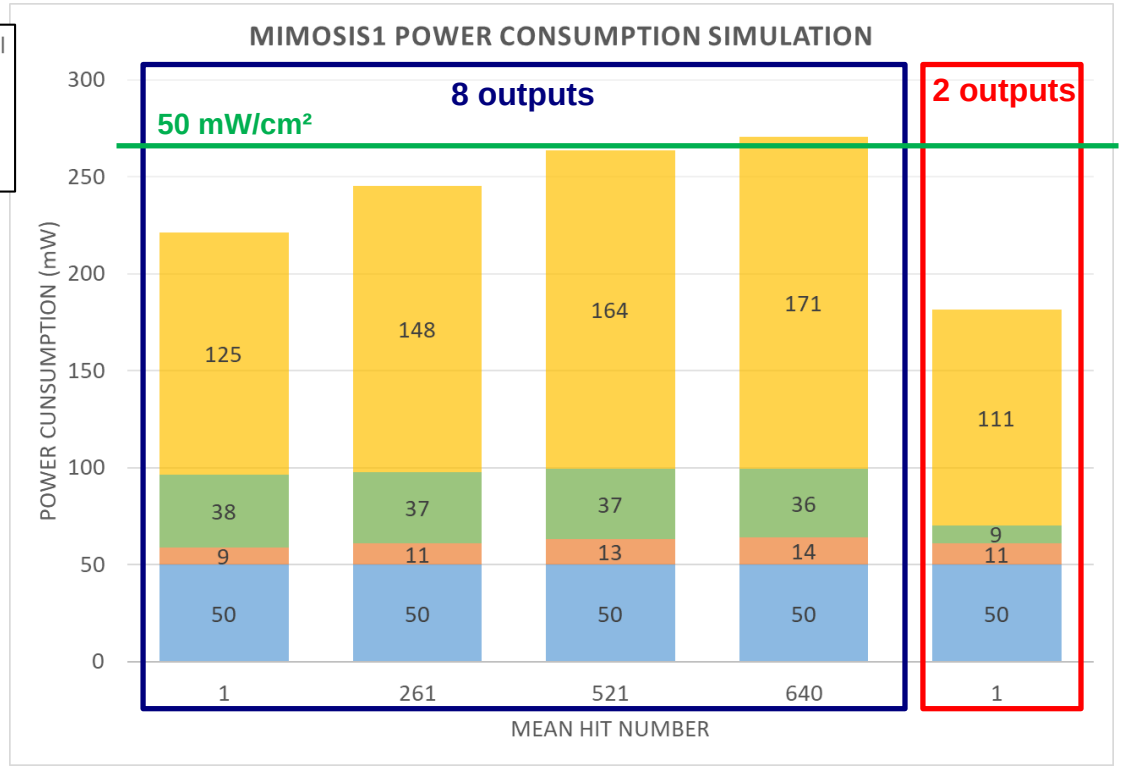
- No trigger available
  - Need a mechanism to synchronize several chips for common base time
- All the clocks derive from the 320 MHz clock from the PLL
  - Synchronisation pad (SYNC_IN) acts like a reset for the clock generator
- Principle
  - Synchronisation signal is latched 2 times
    - With external 40 MHz clock
    - With 320 MHz clock from the PLL
  - Timing constraints for the synchronisation signal over several chips is relax to the 40 MHz clock

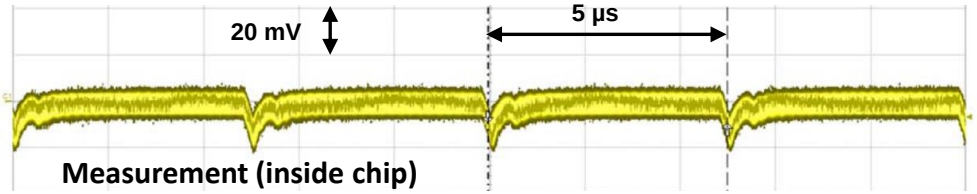


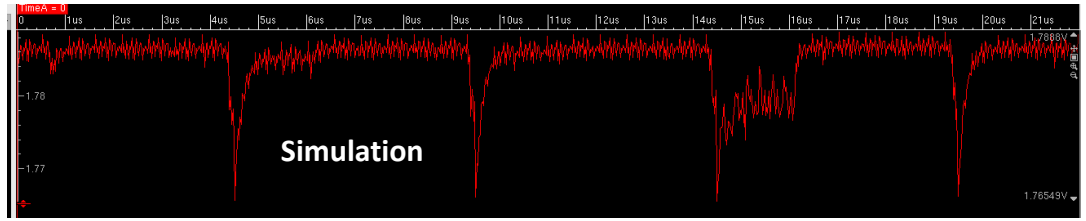
Power consumption

- Well below the requirements:
  - ~50 mW/cm² (for whole chip surface)
  - To be confirmed by measurement
- Dominated by:
  - The number of hits for the bottom periphery
  - The number of outputs in the padring
- Voltage drop will be mitigate in next submission









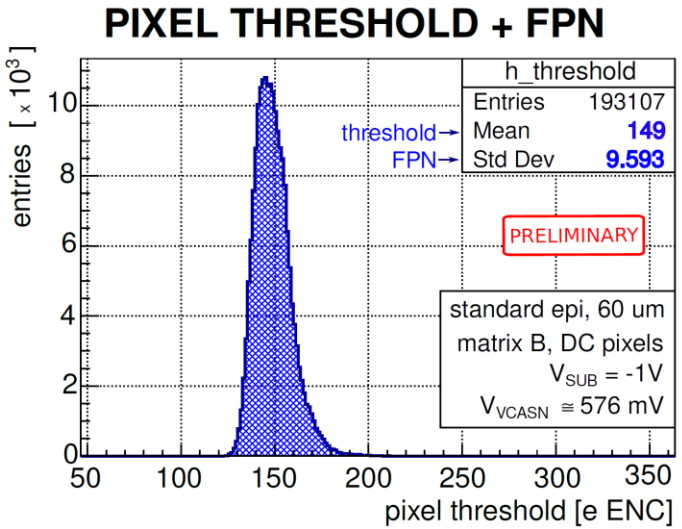
Testability and SEE mitigation

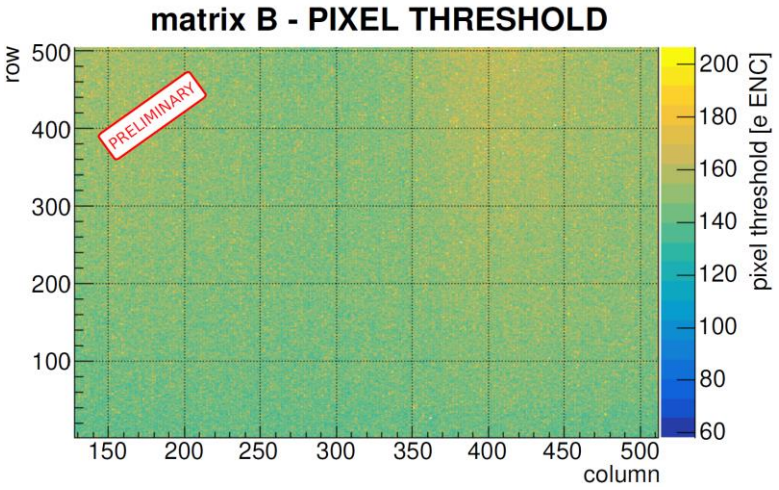
- Several levels of testability
  - Pixel level
    - Analogue and digital pulsing over the whole matrix
    - Output of the amplifier and comparator of the first row is accessible
  - Region level
    - Generates data over several frames for each region
  - Serializer level
    - Serialize a 128 bits words over the 8 serializer
- Single Event Effect mitigation*
  - All FSM are triplicated
  - All configuration registers use a self corrected hamming register
  - Partial triplication of clock and reset trees
    - Full trees in next submission
  - Only a CRC check for data corruption
  - Classic latchup protection

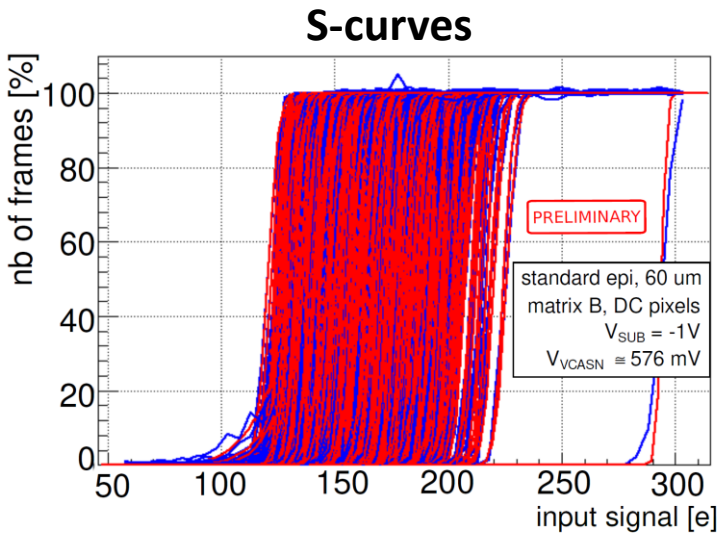
***Y.ZHao PoS(TWEPP2019)131**

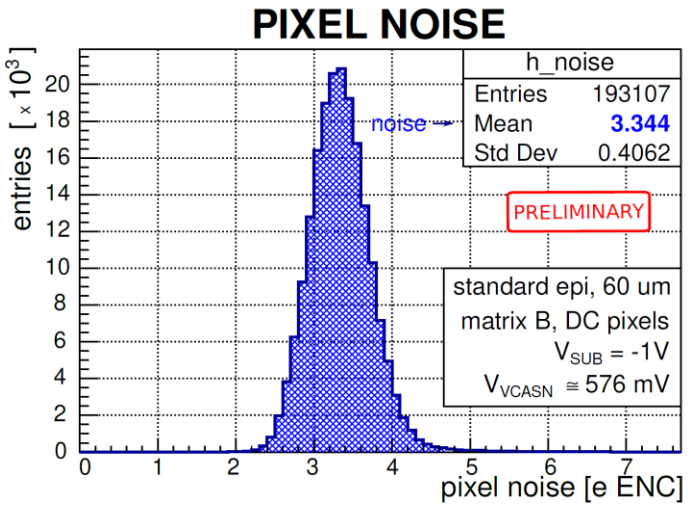
Preliminary Results DC pixel

- Matrix B (DC pixels 24 regions)
  - Vsub=-1 V
  - Threshold scan obtain through charge injection
  - Preliminary conversion factor (mV/e-)
    - 25 % of precision
  - Exemplary Results:
    - Pixel noise: ~3.4 e- ENC
    - Threshold: ~150 e- ENC
    - FPN: ~10 e- ENC





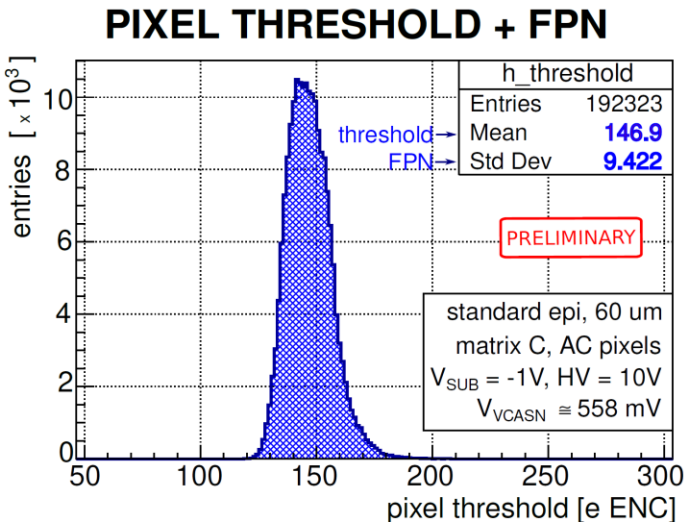


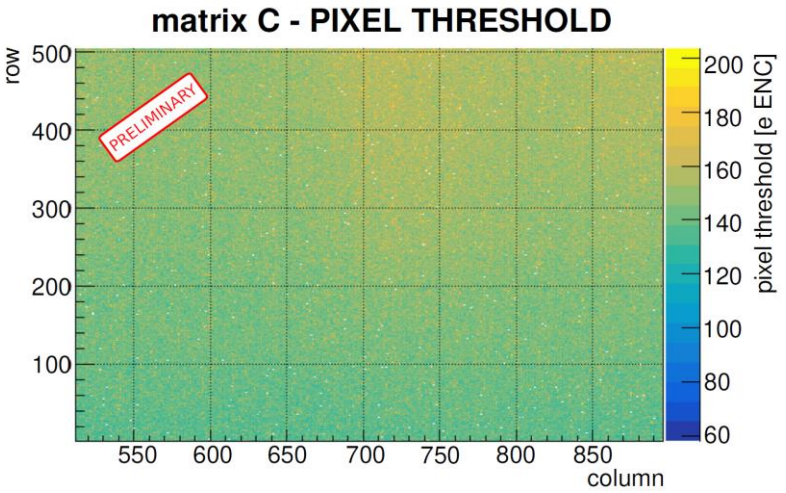


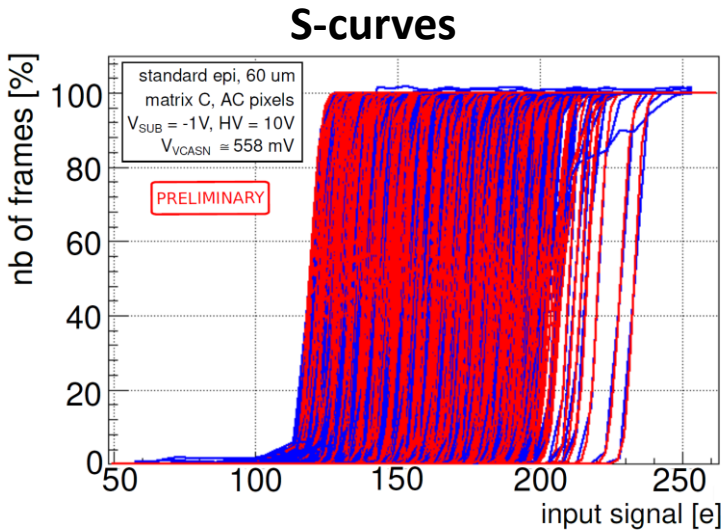
The MIMOSIS-1 pixel sensor for MVD
Roma Bugiel 37th CBM collaboration Meeting

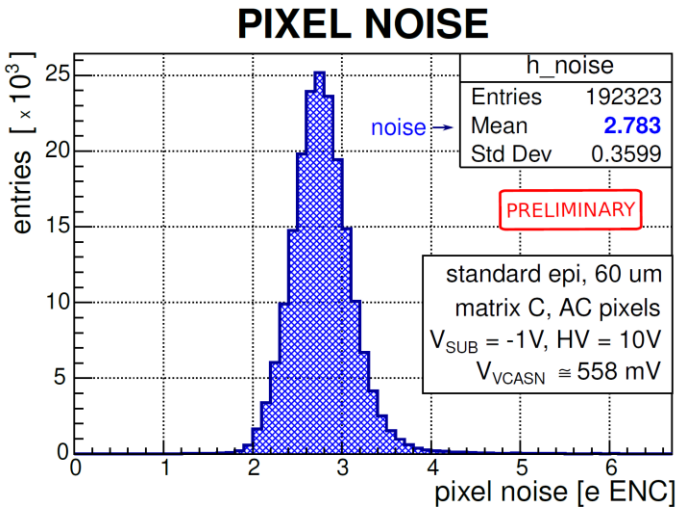
Preliminary Results AC pixels

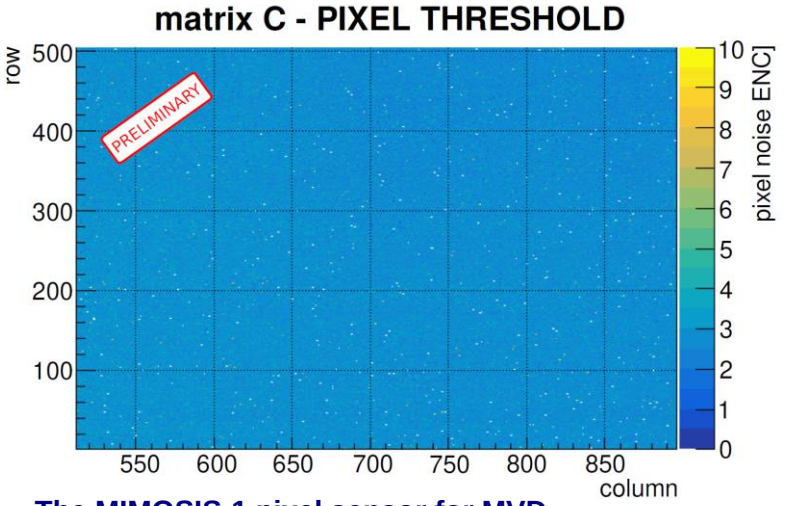
- Matrix C (AC pixels 24 regions)
  - Vsub=-1 V, Diode pol.=10 V
  - Threshold scan obtain through charge injection
  - Preliminary conversion factor (mV/e-)
    - 25 % of precision
  - Exemplary Results:
    - Pixel noise: ~2.8 e- ENC
    - Threshold: ~150 e- ENC
    - FPN: ~10 e- ENC









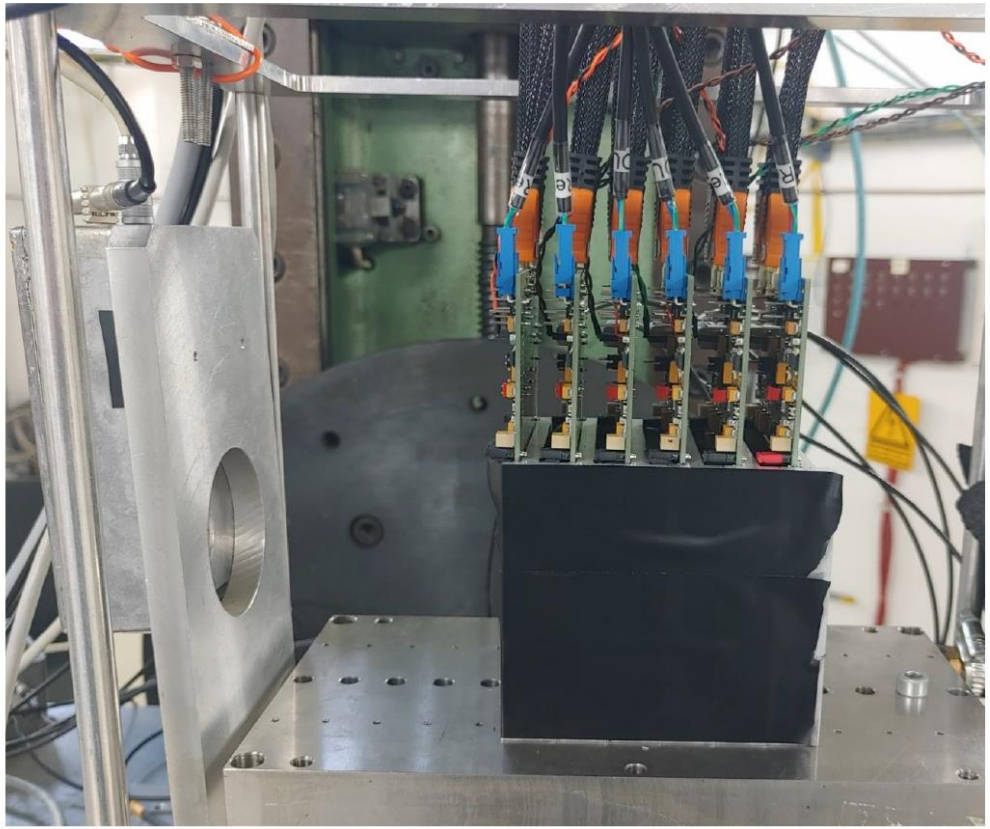


The MIMOSIS-1 pixel sensor for MVD
Roma Bugiel 37th CBM collaboration Meeting

Beam Test results

TEST BEAM – JUNE 2021

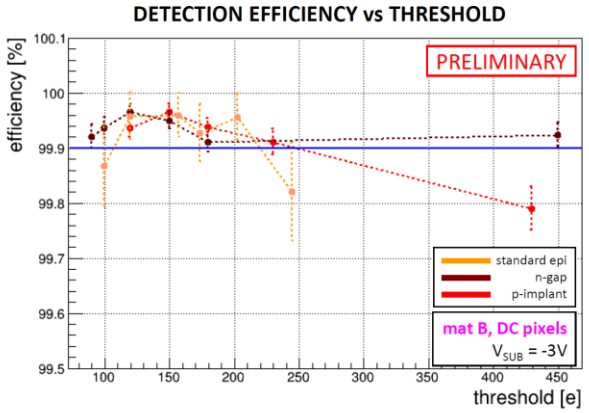
- First MIMOSIS1 test beam in June 2021
  - at DESY
  - ~30 M tracks collected (1.2 M analysed)
    - 182 beam runs + 82 noise runs
    - 4.7 TB of data
- 6 detector planes in stack
  - 15 mm distance between planes
  - 2 DUTs in the middle
- 3 different epi layers tested → standard, n-gap, p-implant
- Various settings:
  - All submatrices (DC and AC pixels)
  - Operating threshold range: 100-200 e
  - Back bias: -1 V, -2 V, -3 V
  - HV for AC pixels: 3 V, 7 V, 10 V
  - Beam energy: 3 GeV, 5 GeV



Beam Test results

DETECTION EFFICIENCY

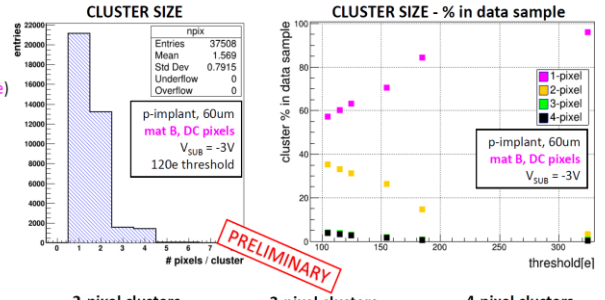
- Excellent efficiency: for most measurements > 99.9%
  observed In wide threshold range (tested up to ~500e
- Homogeneous efficiency over whole matrix



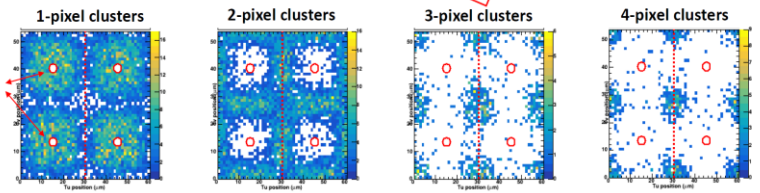
CLUSTER SIZE STUDIES

- Mean cluster size for DC pixels on modified epi (p-implant):
  1.6 @ 120e
- Slightly smaller for AC pixels (1.4 @ 120e)
- Mean cluster size drops with increasing threshold as anticipated
- Dominant fraction of 1-pixel clusters:
  - 1-pixel → > 55 %
  - 2-pixel → < 40 %
  - >= 3-pixel → < 10 %

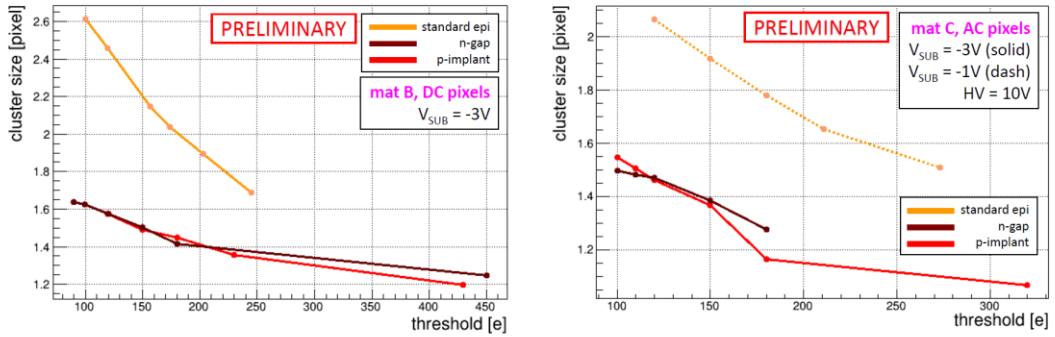
  for < 150 e threshold



- in-pixel hit distribution shown → 4 pixels on plot
- center of electrodes marked symbolically

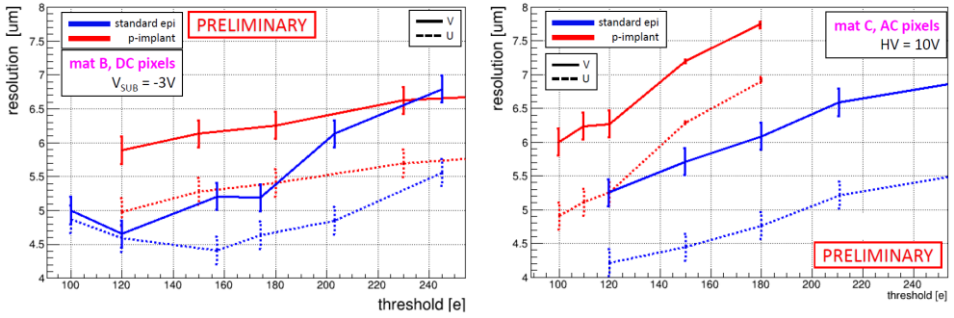


CLUSTER SIZE vs THRESHOLD



- Mean cluster size for n-stop and p-implant epi: 1.2 – 1.6 → DC 1.1 – 1.6 → AC
- Mean cluster for standard epi: 1.8 – 2.6 → DC 1.5 – 2.1 → AC
- Standard epi → significantly larger cluster size → better resolution expected
- AC pixels → smaller cluster size → larger depletion (HV = 10 V)

SPATIAL RESOLUTION (AVERAGED OVER CLUSTER SIZE)



- Hit position → COG
- Pixel dimensions in U (~26.9 µm) and in V (~30.2 µm)
- Binary resolution: ~ 7.8 (U) / 8.3 (V) µm
  - Mean cluster size > 1 → better resolution performance than binary assumption
- Overall satisfying as for preliminary results for spatial ~resolution (as expected from ALPIDE)
  - p-implant epi results shown → n-gap very similar performance → in range of 5-7.5 µm depending on DC/AC pixel type
  - Standard epi ~ 1 µm better spatial resolution → larger cluster size observed

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Conclusion

- MIMOSIS1 is the first full scale prototype for the MVD
  - High peak rate to handle occupancy gradients and beam fluctuations
  - Triggerless without dead time
  - Ultra low power MAPS
  - Single Event Effect hardened for Heavy Ions (fix target)
  - Early results seem promising
  - Sucessfully tested on beam in June 2021 with promising results concerning efficientcy, resolution.
- Next steps:
  - Pursue beam tests
    - Study impact on X-rays & neutron irradiation
  - Submission of MIMOSIS2 this winter 2021
    - Add more features (on-chip clusterization, clock triplication), fix few bugs
    - Focus on promising pixels and processes

Thank You