Characterizing of MIMOSIS-1 CMOS Monolithic Active Pixel Sensor Using a 25 MeV Proton Beam at CYRCé

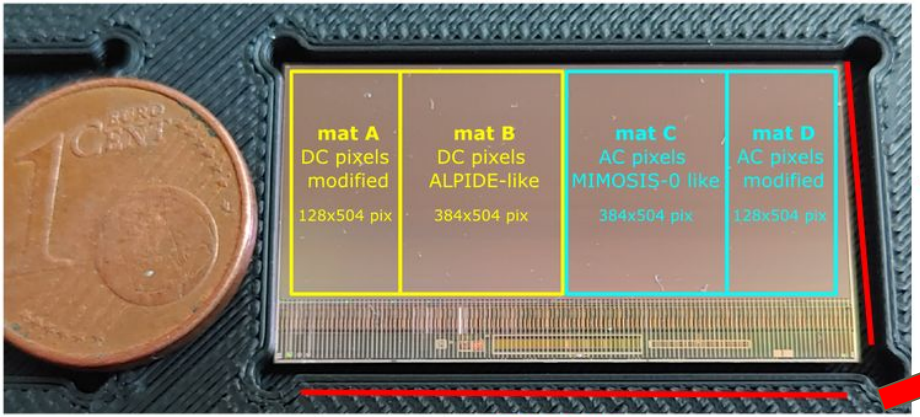
Ali Murteza Altingun - IPHC Strasbourg

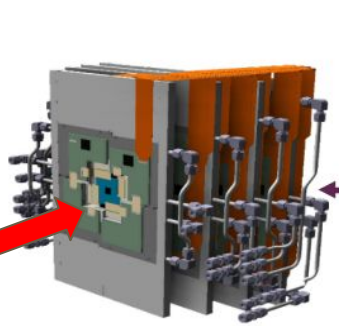
On behalf of the IPHC-IKF-GSI (CBM-MVD) Collaboration

19th Apr, 2024 - 12th BTTB

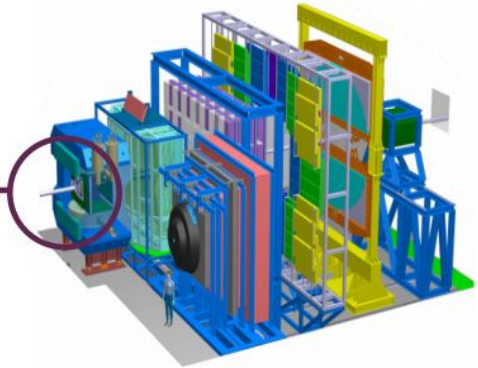
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
Université de Strasbourg
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
GSI Helmholtzzentrum für Schwerionenforschung

MIMOSIS - A CMOS Sensor for CMB-MVD





CBM Micro Vertex Detector (MVD)



CBM – Experiment @ FAIR

- For Micro Vertex Detector (MVD)-CBM (Compress Baryonic Matter) experiment at FAIR [1]
- MIMOSIS-1 - first full size prototype
- 1024 x 504 pixel array - size 31 x 27 μm^2

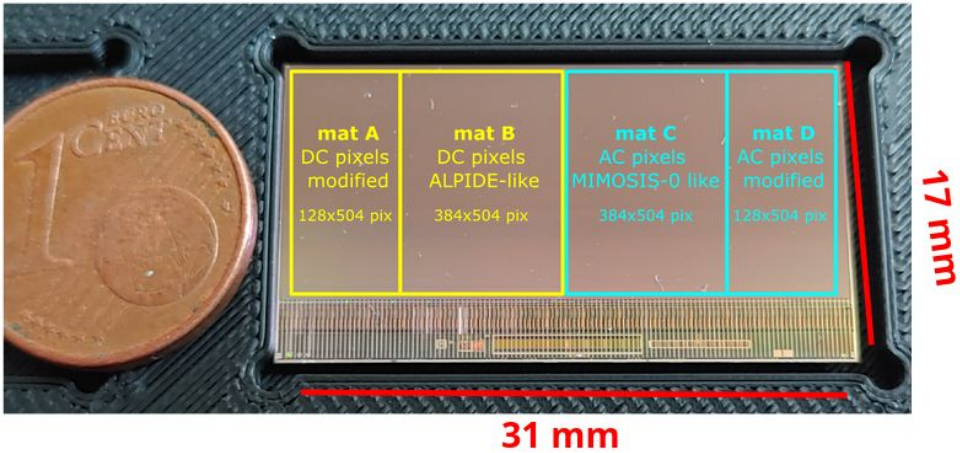
The CBM – MVD will operate at:

100 kHz Au+Au collisions @
10 MHz p+Au collisions @

(up to 100x higher rates in absence of MVD)

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG — cnrs — UNIVERSITÉ DE STRASBOURG — GOETHE UNIVERSITÄT FRANKFURT AM MAIN — GSI Helmholtzzentrum für Schwerionenforschung

MIMOSIS - A CMOS Sensor for CMB-MVD



Parameters	Requirements
Spatial/Time Res.	~ 5 µm/5 µs
Sensor Thickness	~ 60 µm
Rad. Tolerance (non-ionizing)	~ 10^{13} neq/cm2
Rad. Tolerance (ionizing)	~ 5 MRad
Data Flow (peak hit rate)	~ 70 MHz/cm2

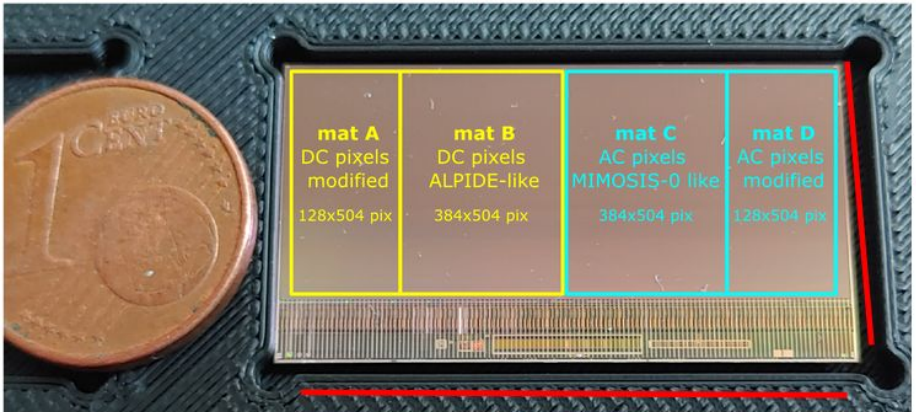
MIMOSIS pixels:

- DC-pixels ⟶ Derived from ALPIDE sensor (ALICE ITS)
- AC-pixels ⟶ foreseen improved radiation hardness with top bias possibility > 20V

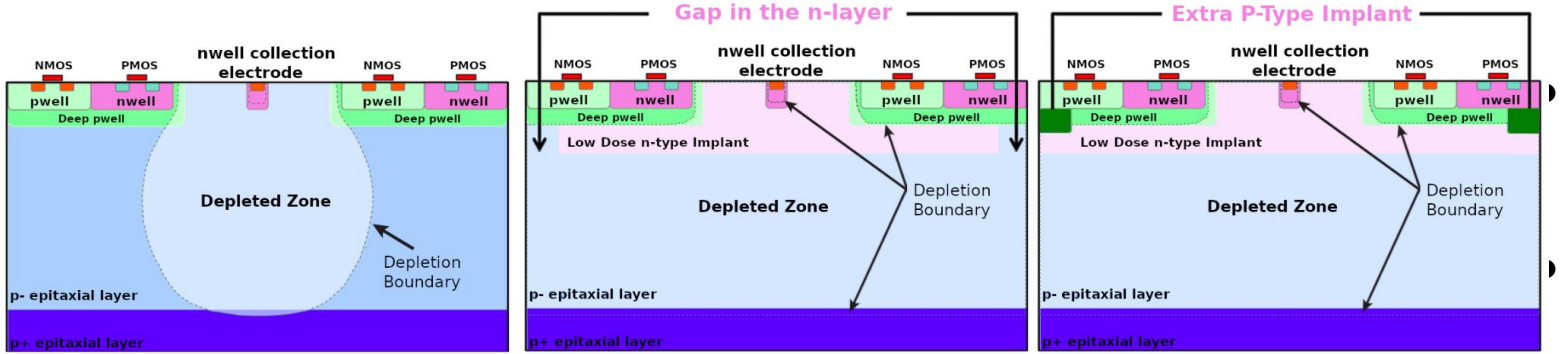
4 submatrices with various pixel circuitry:

- B, C ⟶ basic pixels architectures
- A, D ⟶ 128-column matrices for analog pixel circuitry optimization

MIMOSIS - A CMOS Sensor for CMB-MVD



Parameters	Requirements
Spatial/Time Res.	~ 5 µm/5 µs
Sensor Thickness	~ 60 µm
Rad. Tolerance (non-ionizing)	~ 10^{13} neq/cm2
Rad. Tolerance (ionizing)	~ 5 MRad
Data Flow (peak hit rate)	~ 80 MHz/cm2



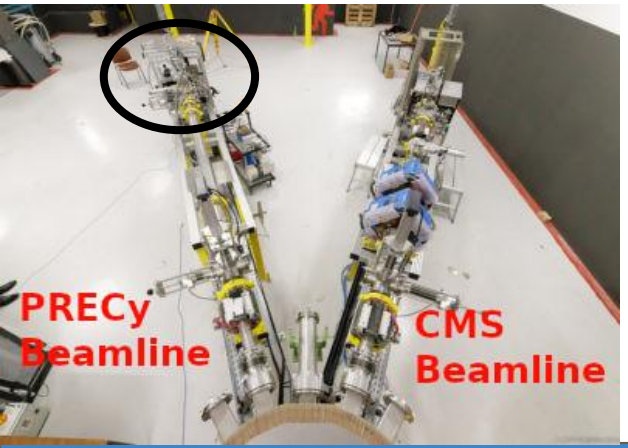
Standart Process "Split-1"

Modified Process Low dose n-implant "Split-3"

Modified Process Low dose n-implant + p-type implant "Split-4"

- 3 MIMOSIS-1 sensor type available [2]
- Standard and split-3 were investigated.

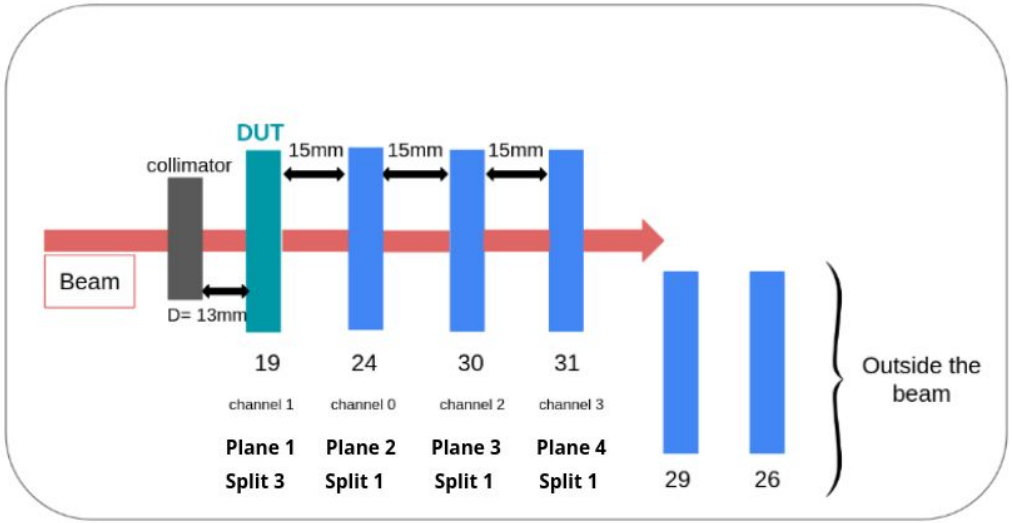
CYRCé platform



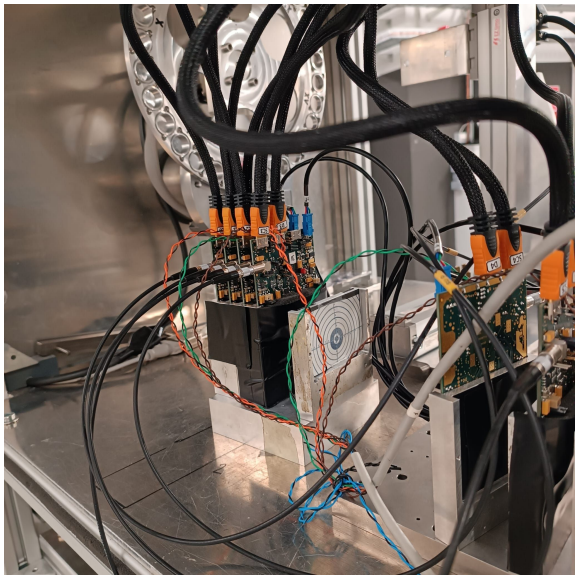
- Radiobiology platform (PRECy Line)
  - a few keV to 25 MeV proton beams

- High particle rate capability (Intensities from 100 aA to 10 nA)
- Localized irradiations
- Testing MIMOSIS 1 chips and Cyrcé proton beam characterization
- 25 MeV proton beams used (Niel factor ~1.8)
- Tested Split 1-3 chips with 60 µm thickness:
  - **Different collimator sizes** (beam characterization)
  - **Threshold Scan** (study the cluster sizes and sensor efficiency)
  - **Beam Intensity Scan** (determine the limitations on data bandwidth)
  - **Testing Localized Irradiation Capability**

Different Collimator Dimensions

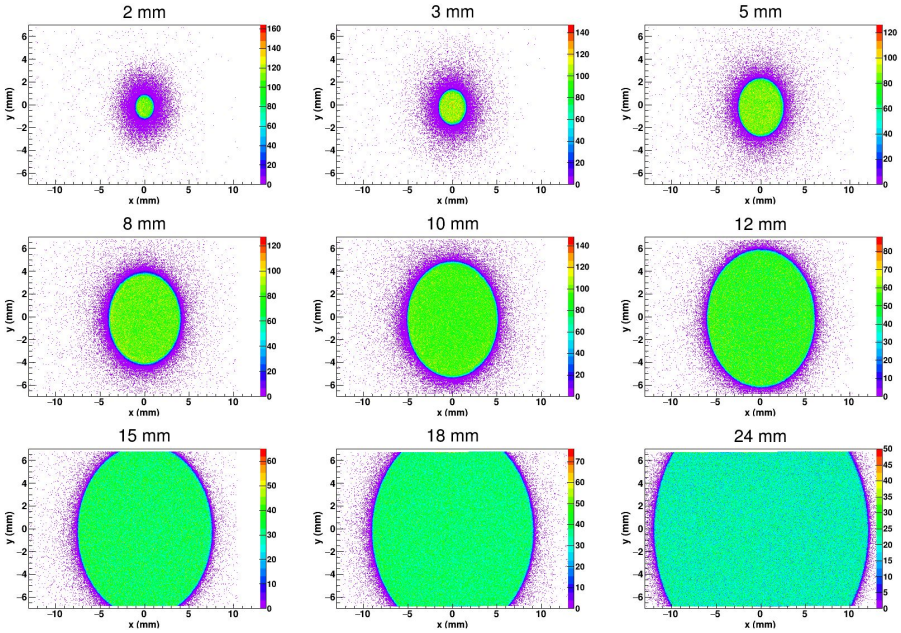


- The tests for different collimators with 2-24 mm diameter
- Using a telescope of 4 planes for tracking:



Thresh e- (DUT/Ref): 240/120
Collimator (mm): 2-24
Back Bias (DUT/Ref): -3 / -1 V
High Voltage (DUT/Ref): 10 / 10 V
Chip 19 - Split 3

Different Collimator Dimensions - Beam Profile



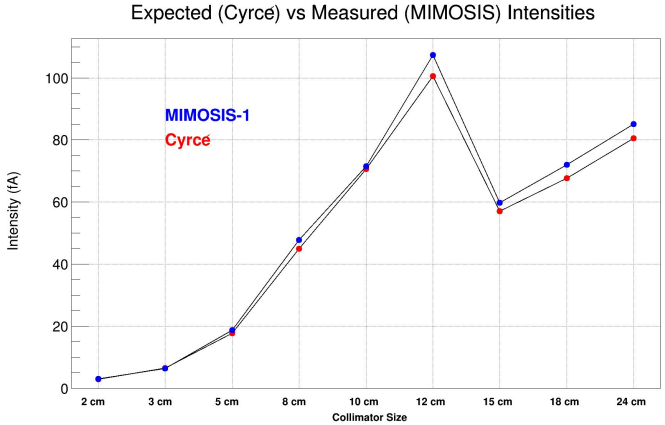
- Intensity from Cyrcé (I_C):

$$I_C = I_F \times a$$

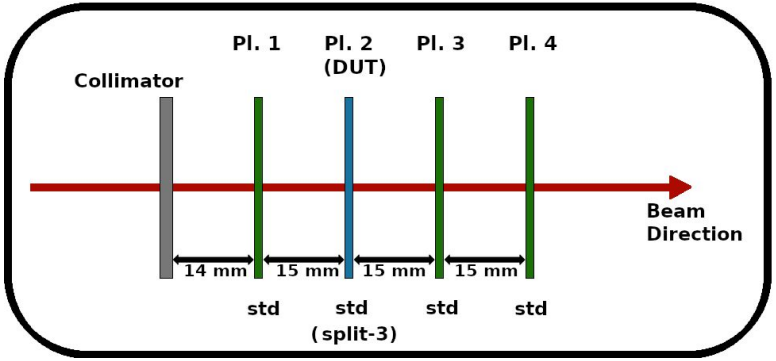
(I_F :Faraday cup intensity, a: geometrical factor)

- MIMOSIS intensity

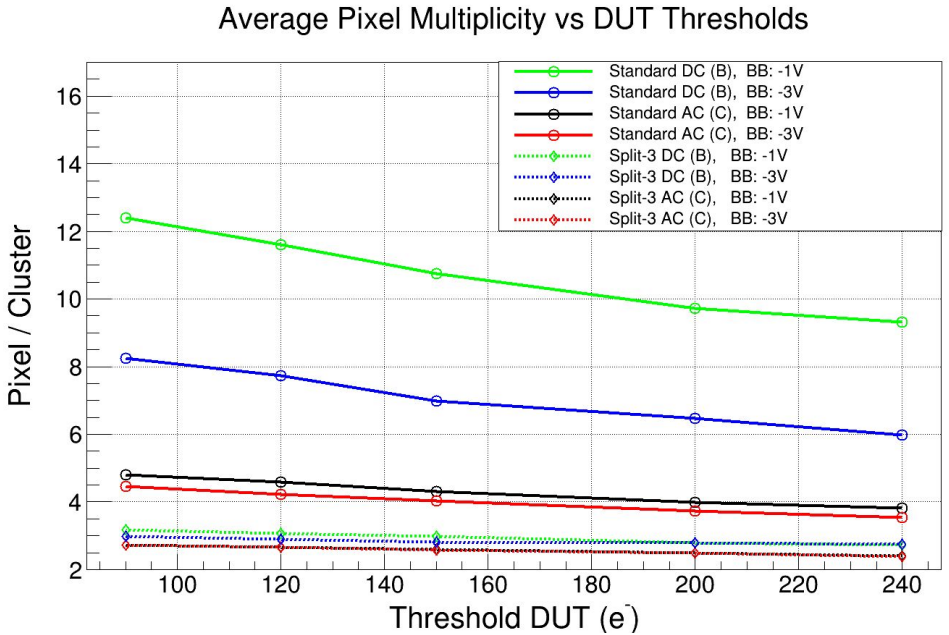
$$I_M = \frac{N \times q}{T}$$



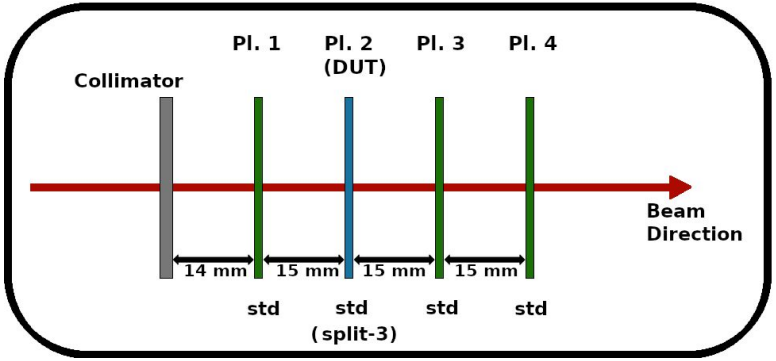
Threshold Scan



- **Threshold (e-) - (DUT):** 90 - 120 - 150 - 200 - 240, **(Ref):**120
- **Collimator (mm):** 10
- **DUT BB:** -3 V and -1 V, **Ref Planes BB:** -1 V,
- **HV:** 10 V

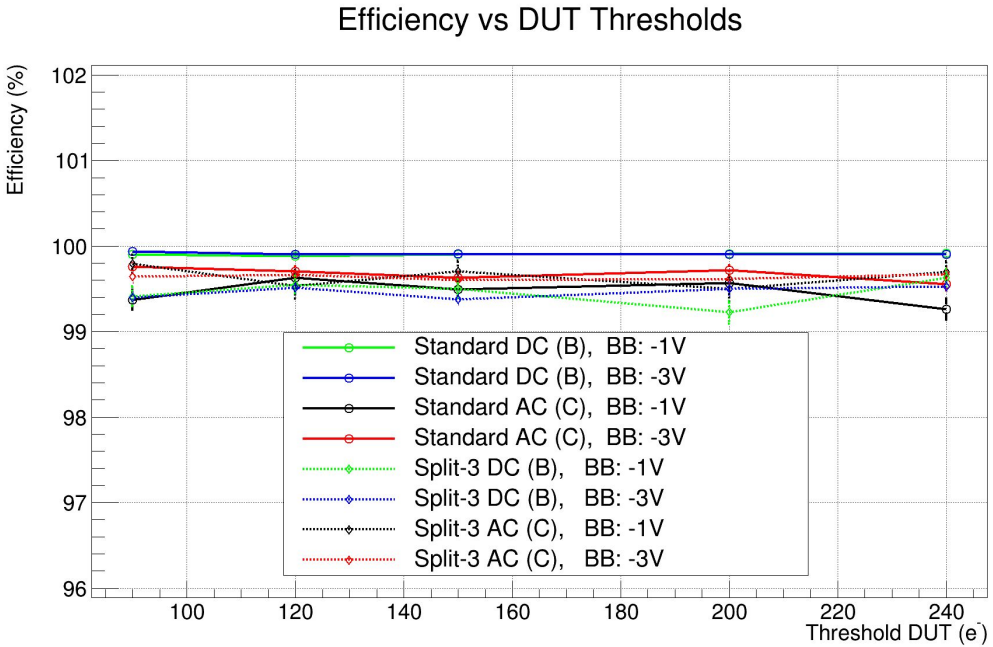


Threshold Scan



Track selection quality determines efficiency performance:

$$Eff = N_{Track-DUT} / N_{Total-Track}$$

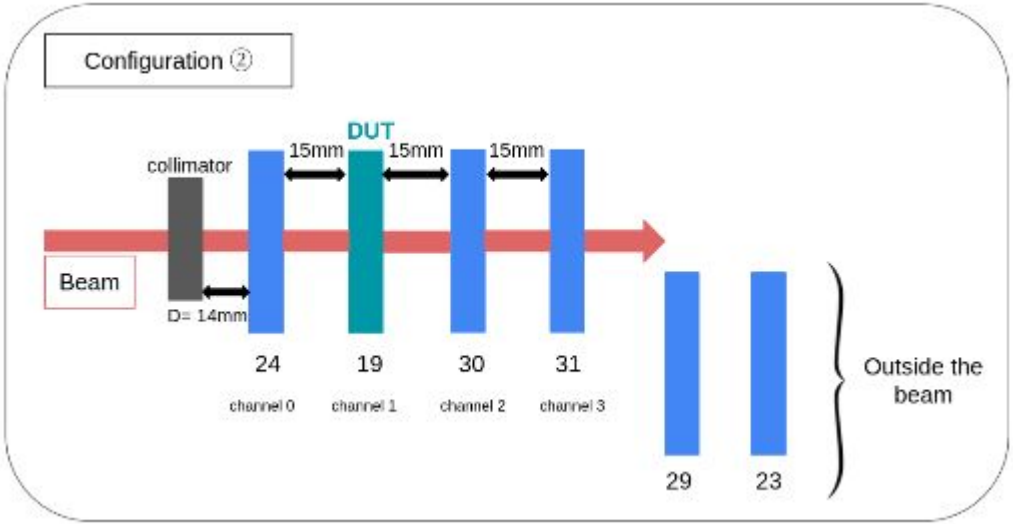


- **Threshold (e-) - (DUT):** 90 - 120 - 150 - 200 - 240, **(Ref):**120
- **Collimator (mm):** 10
- **DUT BB:** -3 V and -1 V, **Ref Planes BB:** -1 V,
- **HV:** 10 V

Beam Intensity Scan

Standard

I_{AC}(pA)	I_{DC}(pA)
0.04	0.04
0.07	0.07
0.30	0.29
0.59	0.59
1.16	1.15
1.74	1.72
2.32	2.31
2.88	2.88



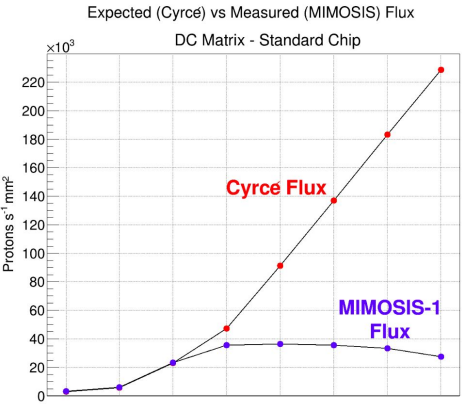
Thresh e- (DUT/Ref): 240/120
Collimator (mm): 10
Back Bias (DUT/Ref): -3 / -1 V
High Voltage (DUT/Ref): 10 / 10 V

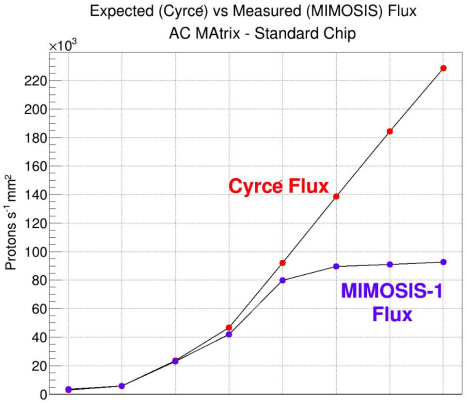
Split-3

I_{AC}(pA)	I_{DC}(pA)
0.04	0.04
0.07	0.07
0.30	0.29
0.58	0.58
1.15	1.16
1.74	1.73
2.30	2.30
2.88	2.91

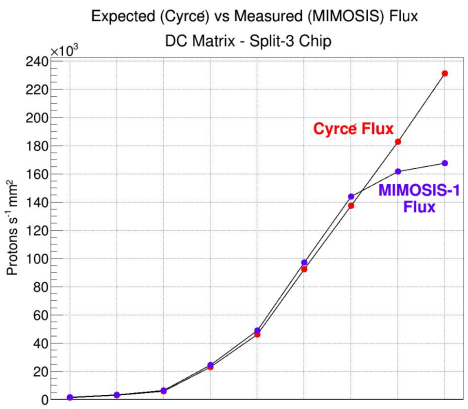
Beam Intensity Scan

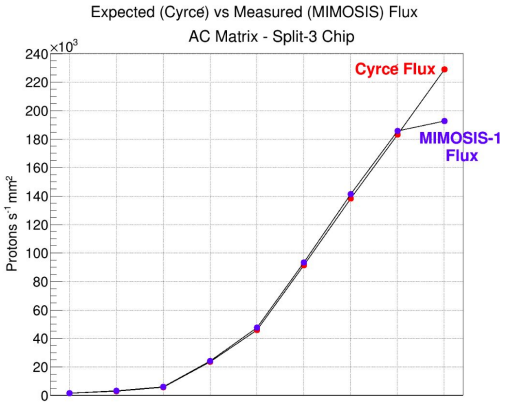
Standard Chip



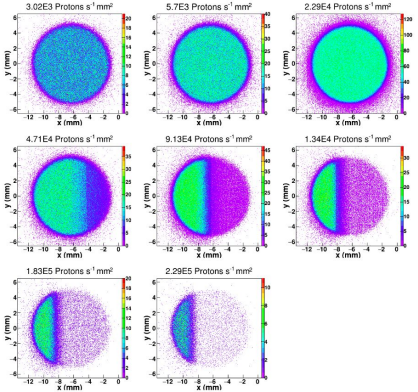


Split-3

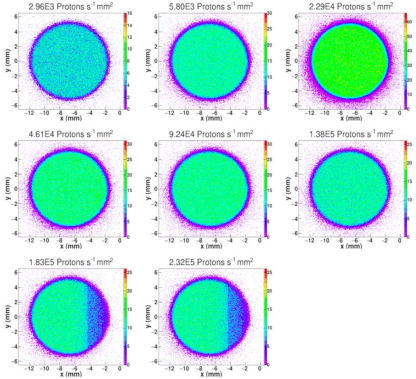




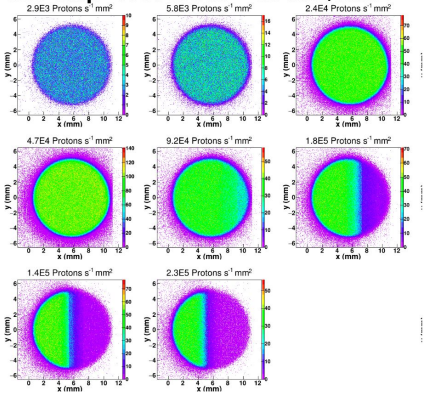
Std Chip - DC Matrix ~ 23 kHz/mm2



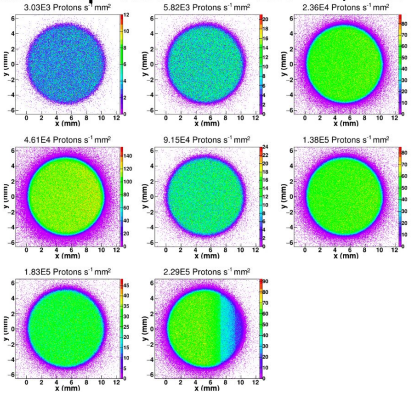
Split-3 Chip - DC Matrix ~140 kHz/mm2



Std Chip - AC Matrix ~ 80 kHz/mm2

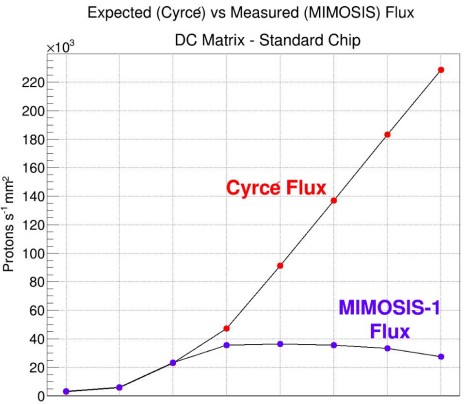


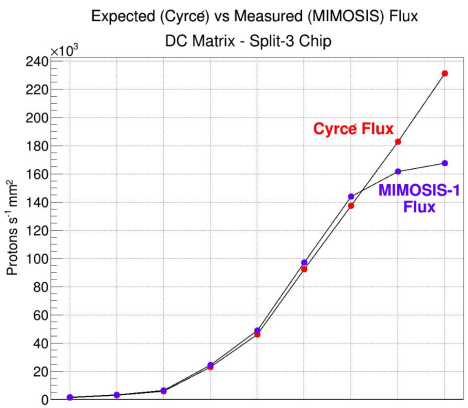
Split-3 Chip - AC Matrix ~180 kHz/mm2

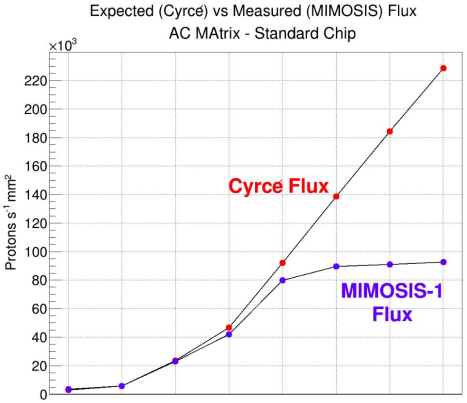


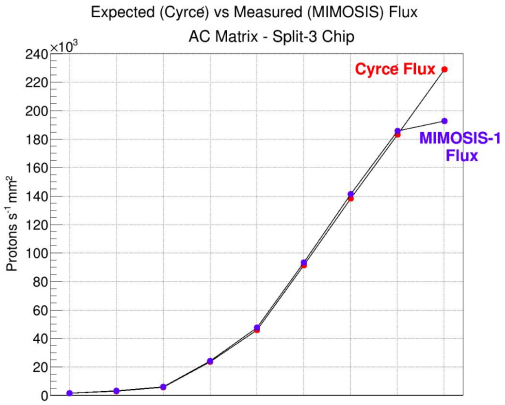
Beam Intensity Scan

Standard Chip | **Split-3**



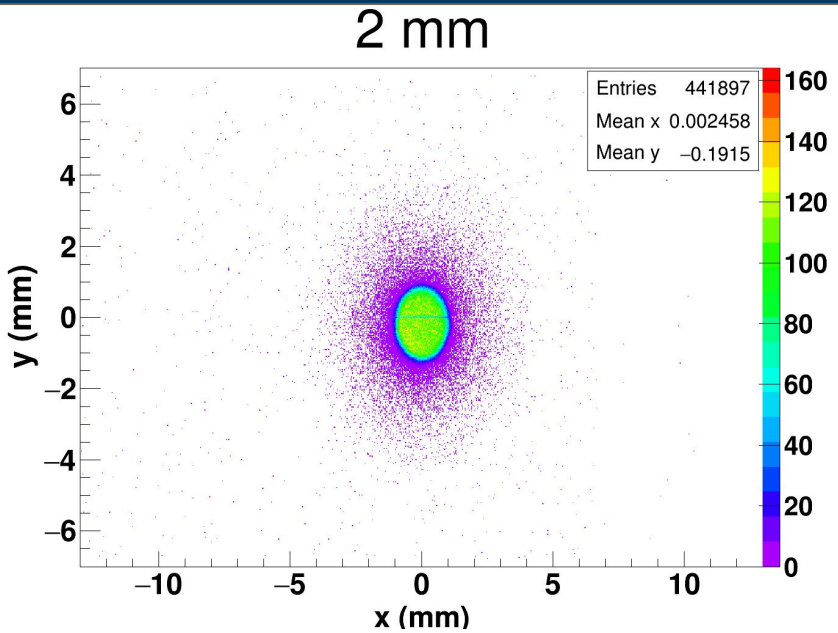


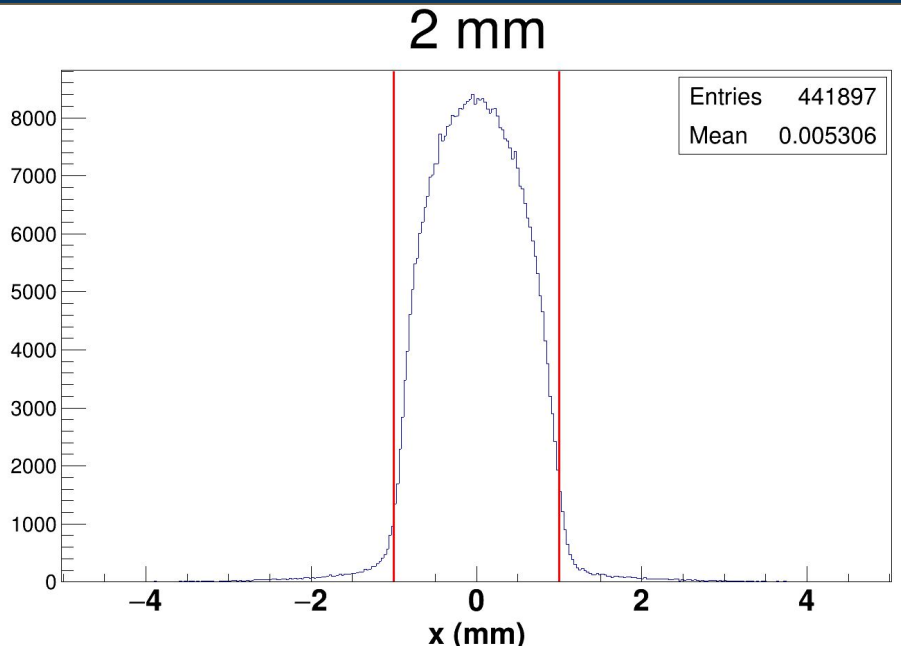




- Saturation level depends on the cluster multiplicity (size) as expected.
- Max bandwidth at around **18 MHz/cm^2**
- There is 2 outputs out of 8 used on the chips.
  → Max: 18 MHz/cm^2 X 4 = **72 MHz/cm^2**
- Standard:
  - DC matrix ~ 10 MHz/cm^2
  - AC matrix ~ 32 MHz/cm^2
- Split-3:
  - DC matrix ~ 56 MHz/cm^2
  - AC matrix ~ 72 MHz/cm^2
  - Requirement ~ 70 MHz/cm^2[1]

Localized Radiation at Cyrcé - Proton beam with 2 mm





- Proton beam (2.9 fA - 5761.5 protons/s/cm^2)
- Localized irradiation verified.

- Radiation hardness and inhomogeneous radiation field experiments for the future tests (for MIMOSIS-2)

Summary

- The measured intensity values from sensors and the intensities from CYRCé in a good agreement.
- Further analysis ongoing for beam dispersion and fluence profile studies.
- Sensor shows expected response to high particle rates up to its data bandwidth limit. Preliminary bandwidth limit as observed for 25 MeV protons (upscaled to 8 outputs):
- Split 1 (Standard):
  DC matrix 12 MHz/cm2
  AC matric 16 MHz/cm2

  Split 3:
  DC matric 56 MHz/cm2
  AC matrix 72 MHz/cm2 - Requirement 70 MHz/cm2
- As threshold increases, cluster multiplicity decreases slightly
- Efficiency > 99 for all thresholds
- The cluster size basically depends on the depletion.
- 25 MeV protons create larger clusters than that of MIPs
- Localized irradiation validated at CYRCé.
- Bandwidth studies can be performed at CYRCé.
- CYRCé facility is very flexible and proficient to test our sensors.

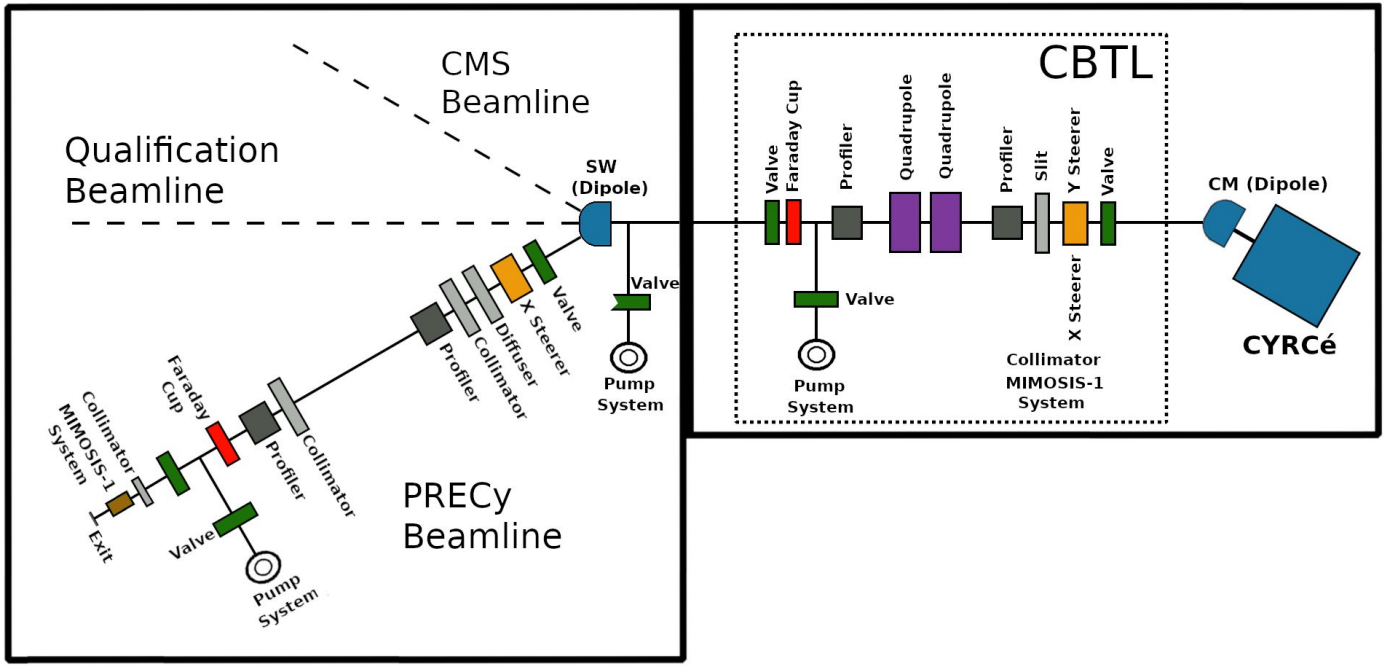
THANK YOU!

References

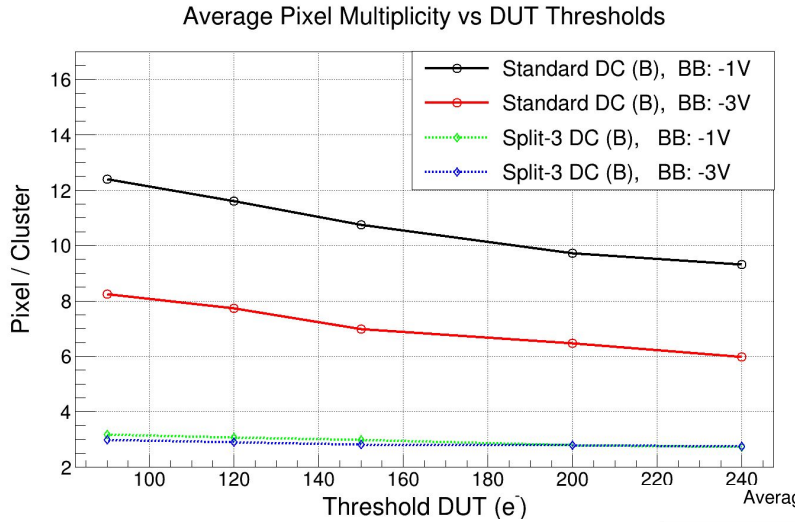
1 - P. Klaus, M. Koziel, J. Michel, C. Muentz, J. Stroth, M. Deveaux, Technical Design Report for the CBM: Micro Vertex Detector (MVD),310 Technical Report GSI-2022-00549, CBM Collaboration, 2022.
https://repository.gsi.de/record/246516/
2. W. Snoeys, “FASTPIX: sub-nanosecond radiation tolerant CMOS pixel sensors”,
ATTRACT

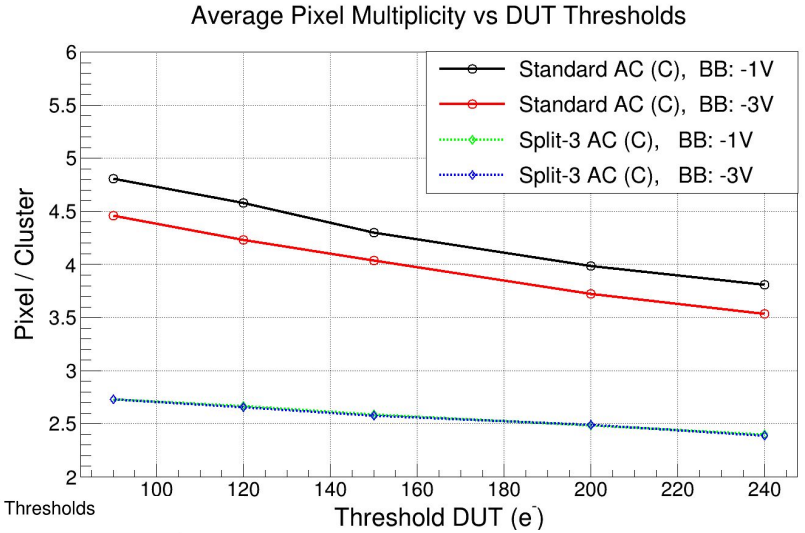
Backup

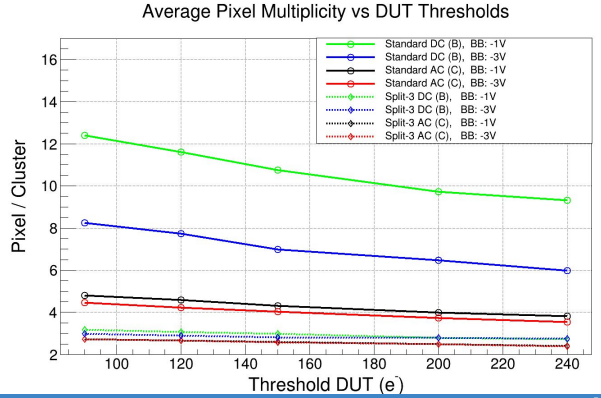
CYRCé



Backup


Average Pixel Multiplicity vs DUT Thresholds
Standard DC (B), BB: -1V
Standard DC (B), BB: -3V
Split-3 DC (B), BB: -1V
Split-3 DC (B), BB: -3V
Pixel / Cluster
Threshold DUT (e⁻)

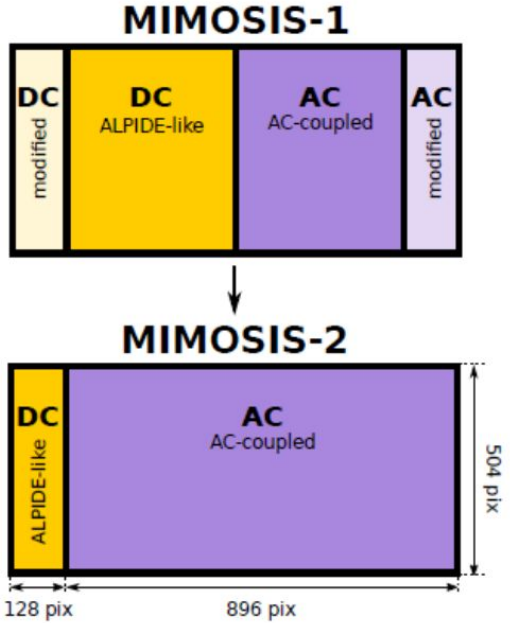

Average Pixel Multiplicity vs DUT Thresholds
Standard AC (C), BB: -1V
Standard AC (C), BB: -3V
Split-3 AC (C), BB: -1V
Split-3 AC (C), BB: -3V
Pixel / Cluster
Threshold DUT (e⁻)


Average Pixel Multiplicity vs DUT Thresholds
Standard DC (B), BB: -1V
Standard DC (B), BB: -3V
Standard AC (C), BB: -1V
Standard AC (C), BB: -3V
Split-3 DC (B), BB: -1V
Split-3 DC (B), BB: -3V
Split-3 AC (C), BB: -1V
Split-3 AC (C), BB: -3V
Pixel / Cluster
Threshold DUT (e⁻)

Backup

MIMOSIS-2:

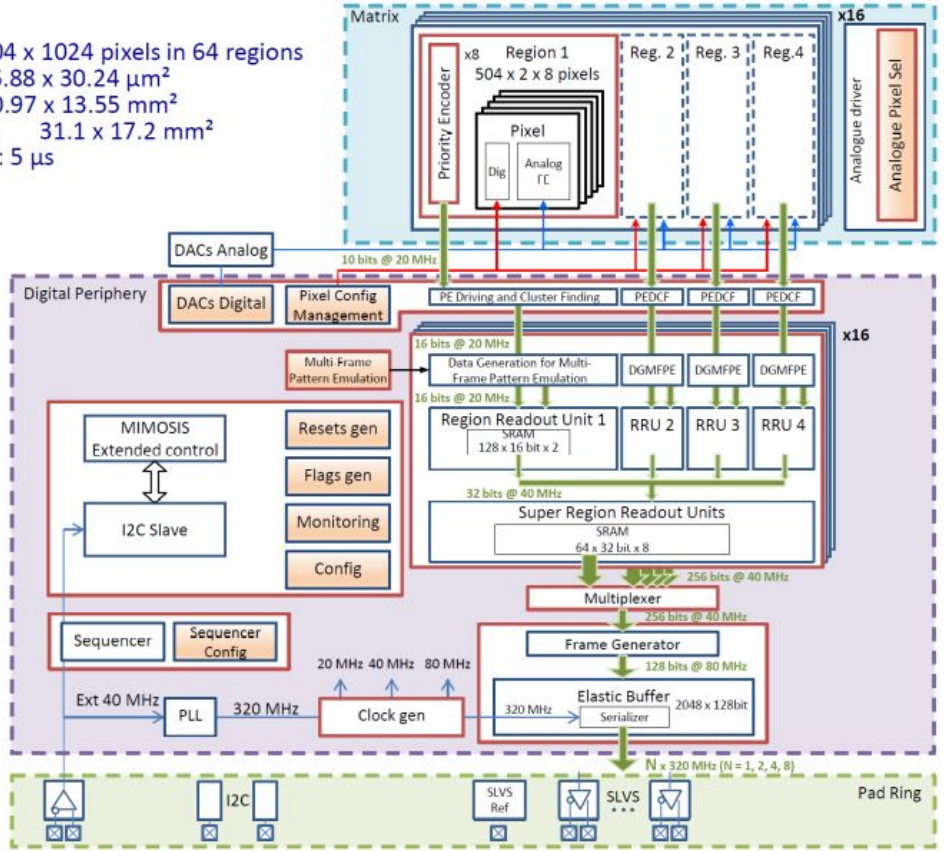
- On-chip clustering
- Additional features for SEE correction
- Various bug fixes and improvements



Backup

- Pixel array: 504 x 1024 pixels in 64 regions
- Pixel pitch: 26.88 x 30.24 µm²
- Active area: 30.97 x 13.55 mm²
- Chip dimension: 31.1 x 17.2 mm²
- 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



Backup

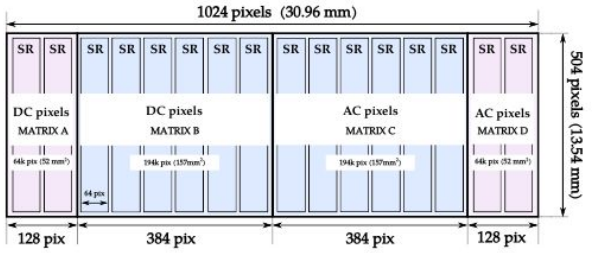
Parameter	Value
Technology	TowerJazz CIS 180 nm
Epitaxial layer	$\sim 25\,\mu m$, $> 1 k\Omega \cdot cm$
Sensor thickness	$300\,\mu m$ or $60\,\mu m$
Pixel size	$26.9\,\mu m \times 30.2\,\mu m$
Pixel array	1024×504 pixels
Sensitive area	$\approx 4.2\,cm^2$
Array readout time	$\approx 5\,\mu s$
Power consumption	$< 100\ mW/cm^2$

MIMOSIS pixels:

- DC-pixels → ALPIDE-like
- **AC-pixels** → foreseen improved radiation hardness with top bias possibility $> 20V$

4 submatrices with various pixel circuitry:

- B, C → basic pixels architectures
- A, D → 128-column matrices for analog pixel circuitry optimization

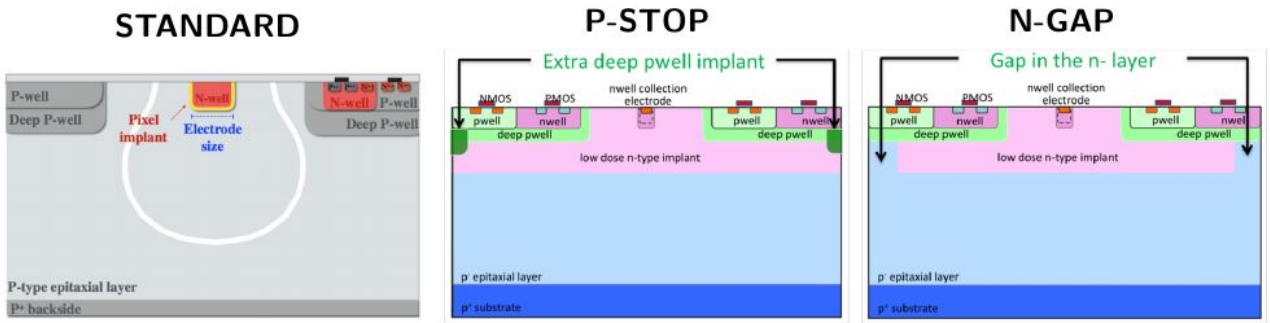


MIMOSIS-1 fabrication reticules

Backup

- 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)

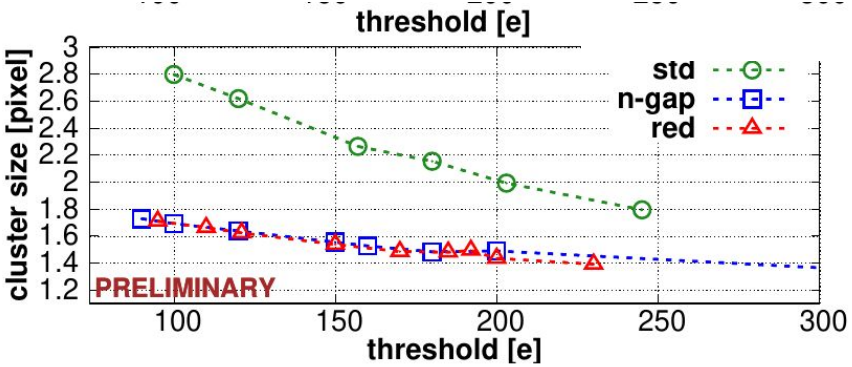
  → expected improved radiation tolerance
- sensors 300 µm, also thinned to ≈ 60 µm

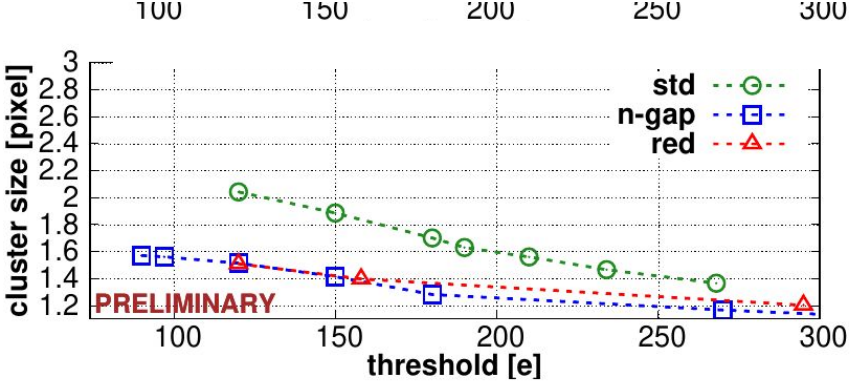


W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

Backup

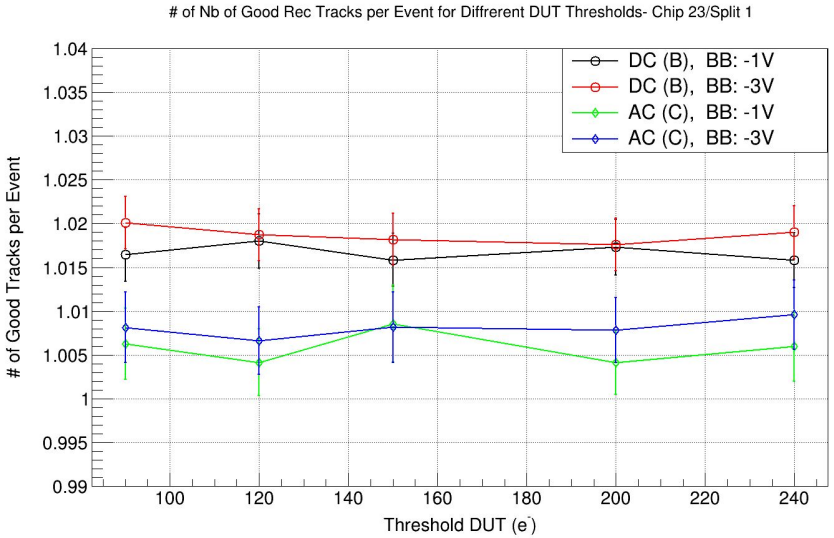
DESY -> 5 GeV e-

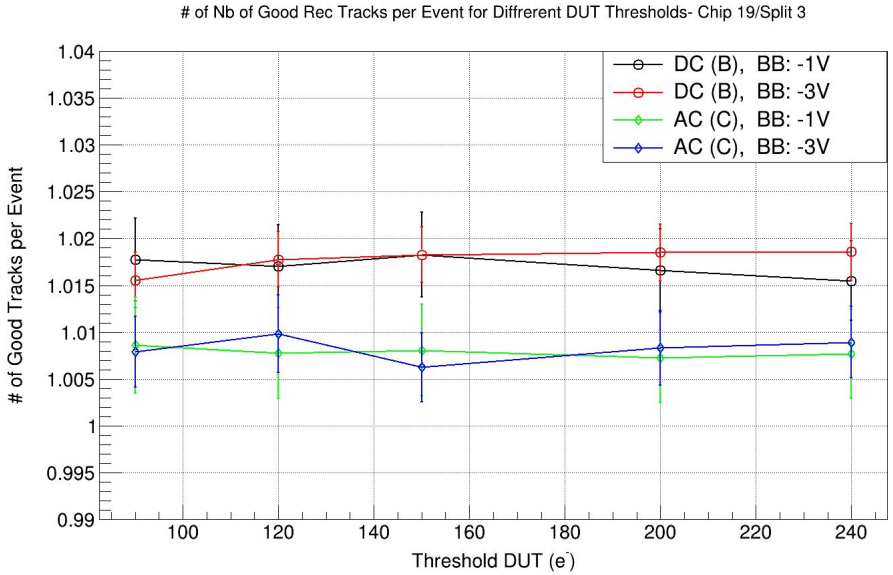




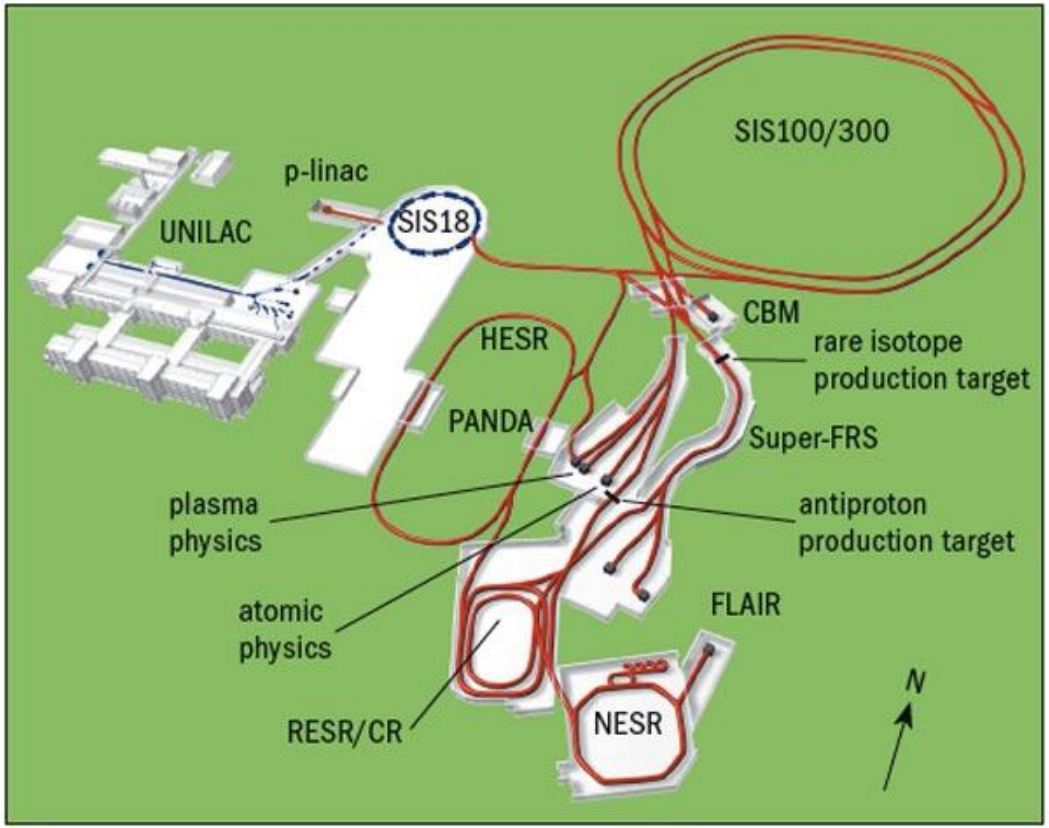
Backup

Track per event for Std and Split 3 chips



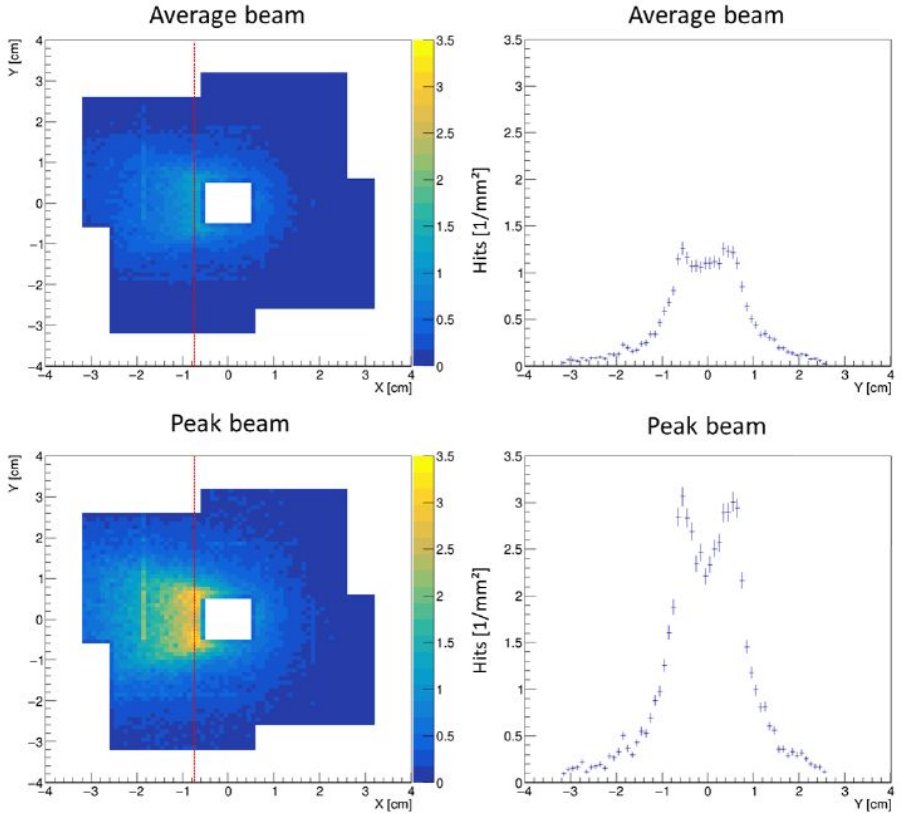


Backup



SIS100:
1 GeV/u Au beam
29 GeV proton beam

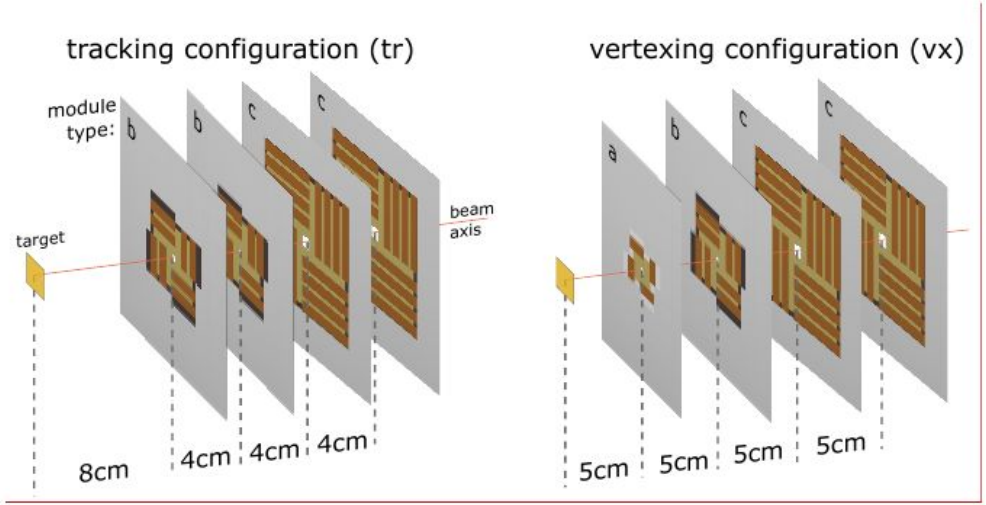
Backup



Hit Occupancy of the first station of the MVD assuming 100 kHz Au-Au collisions
at 12 AGeV beam energy and a sensor integration time of 5 µs.

The upper panels: Values for the average occupancy,
the lower panels: anticipate peak beam intensities

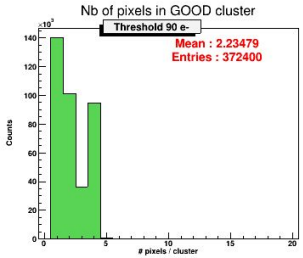
Backup

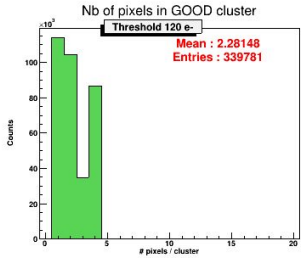


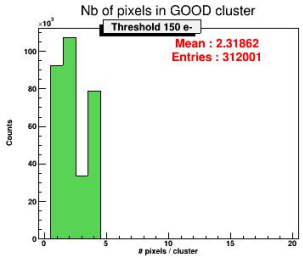
VX: This geometry focuses on the identification of secondary vertices of decaying open charm D mesons

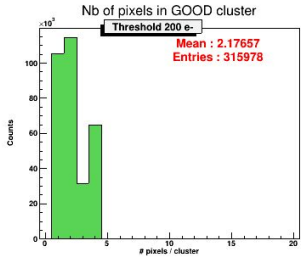
TR: This geometry focuses on track reconstruction of mainly low-momentum particles

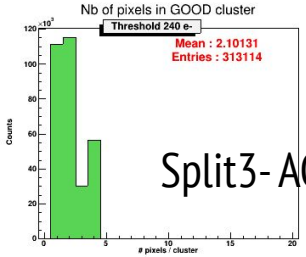
Backup



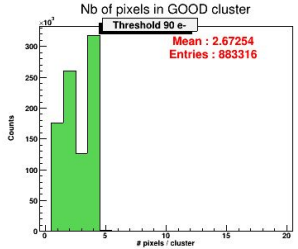


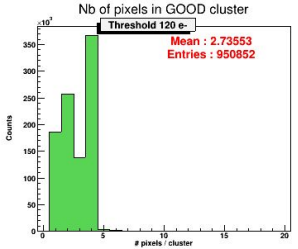


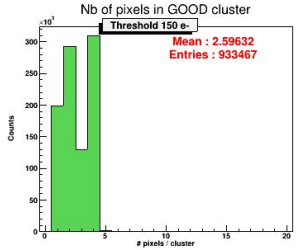


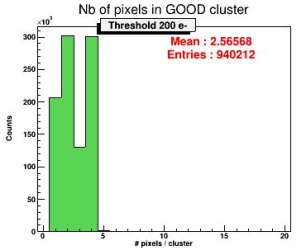


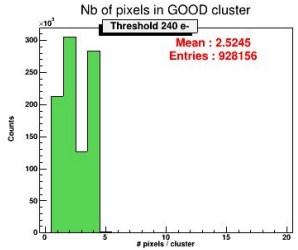
Split3- AC matrix, -1 V





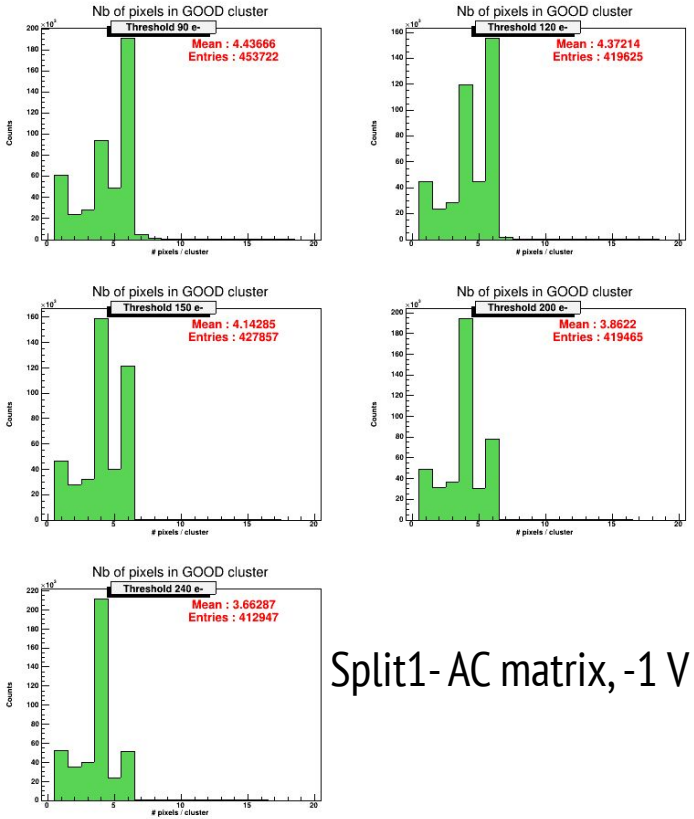




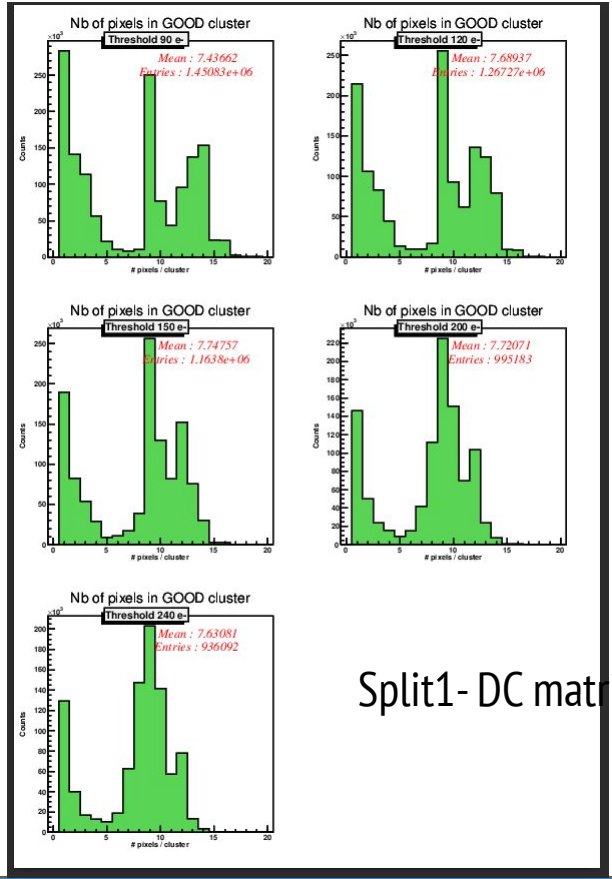


Split3- DC matrix, -1 V

Backup



Split1- AC matrix, -1 V



Split1- DC matrix, -1 V