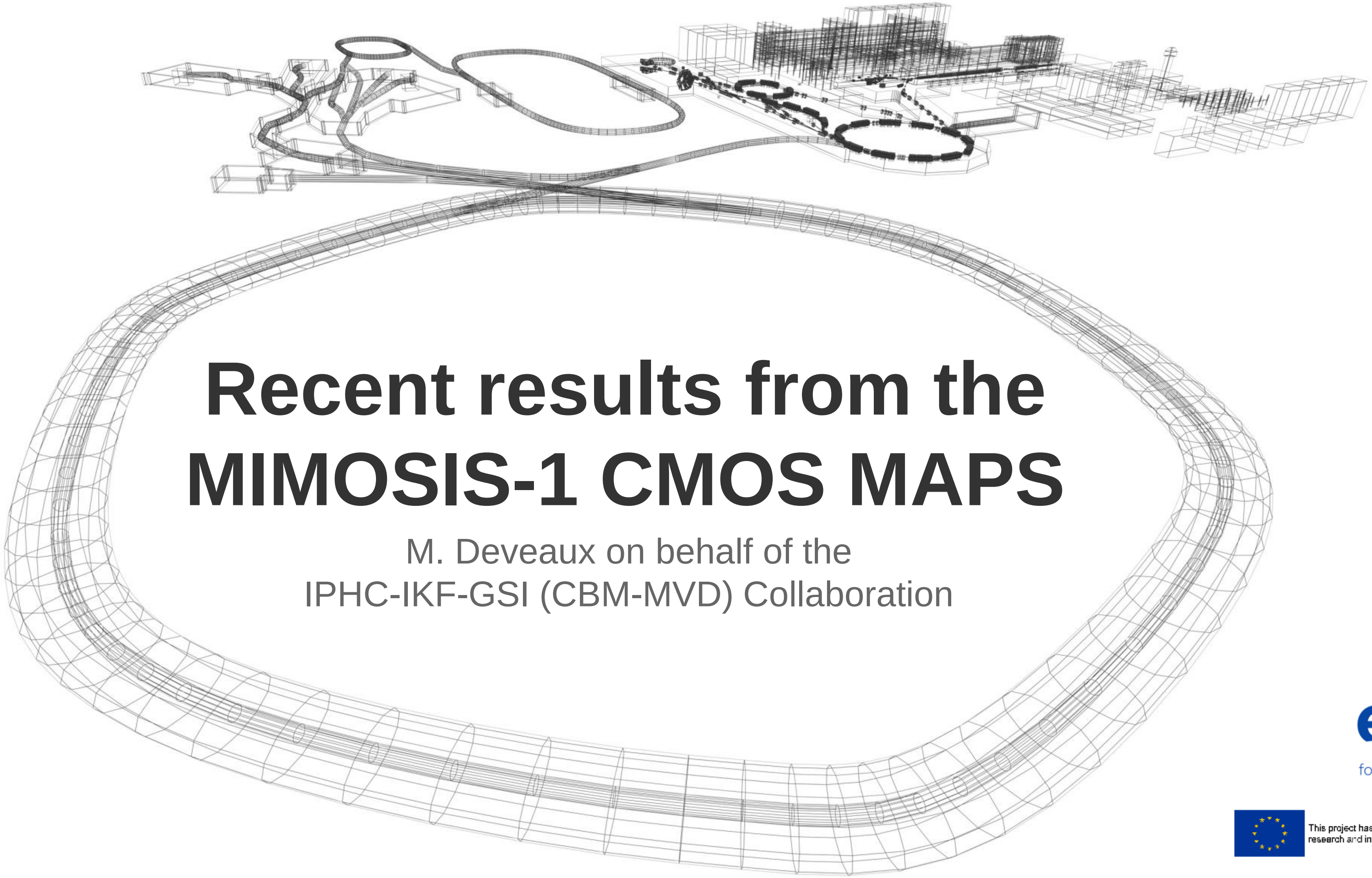


Recent results from the MIMOSIS-1 CMOS MAPS

M. Deveaux on behalf of the
IPHC-IKF-GSI (CBM-MVD) Collaboration

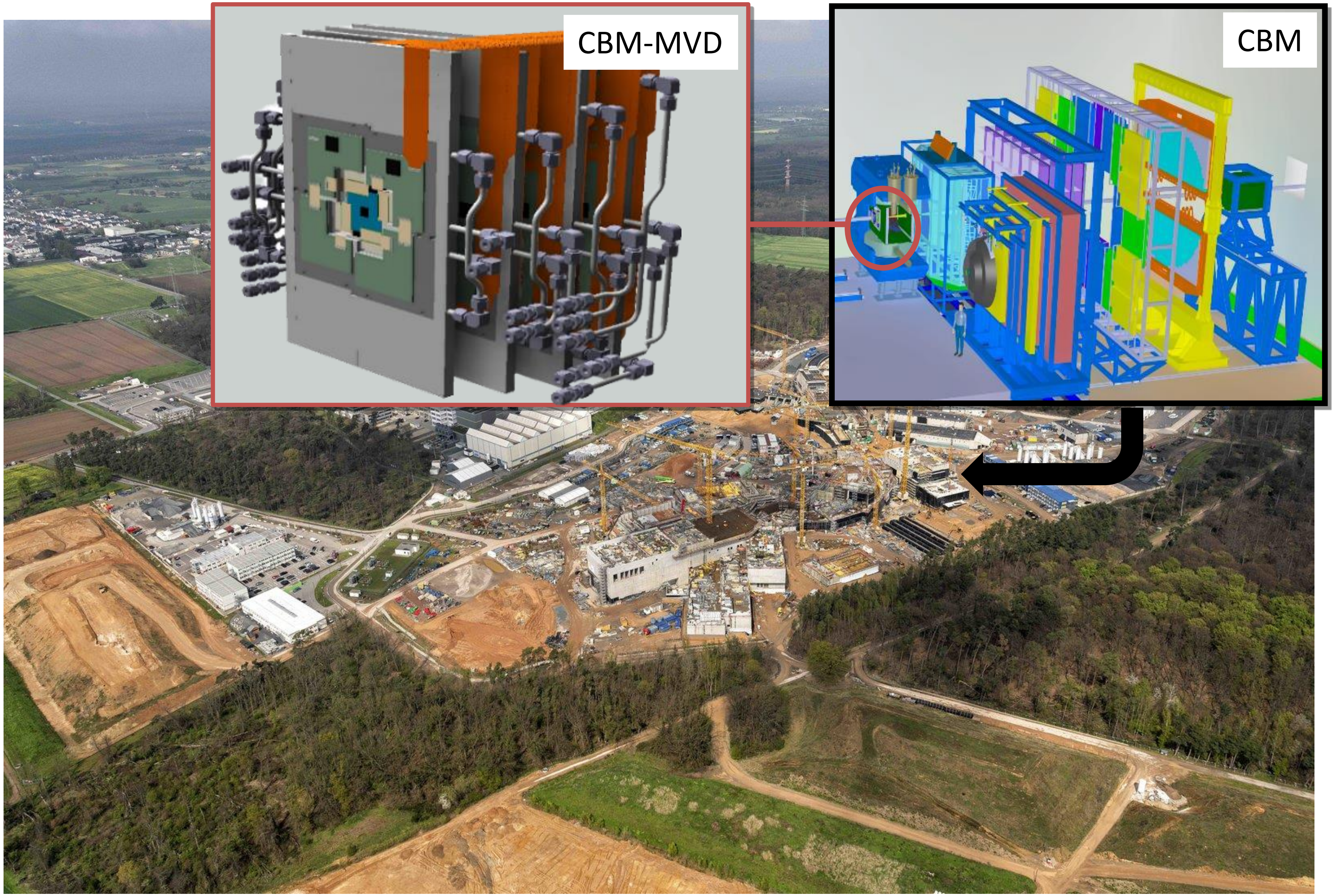
Supported by
Bundesministerium
für Bildung
und Forschung
(05P19RFFC1)

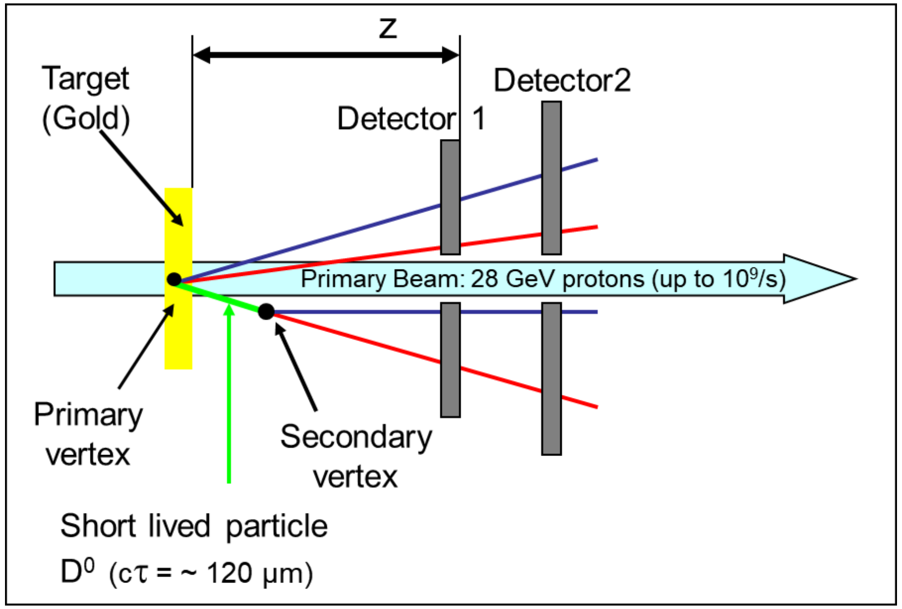
eurizon
European network
for developing new horizons for RIs

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

The CBM Micro Vertex Detector (MVD)

Darmstadt, Germany





Compute mother particle properties by:

- Adding energy + momentum of daughters (invariant mass).

Challenge:

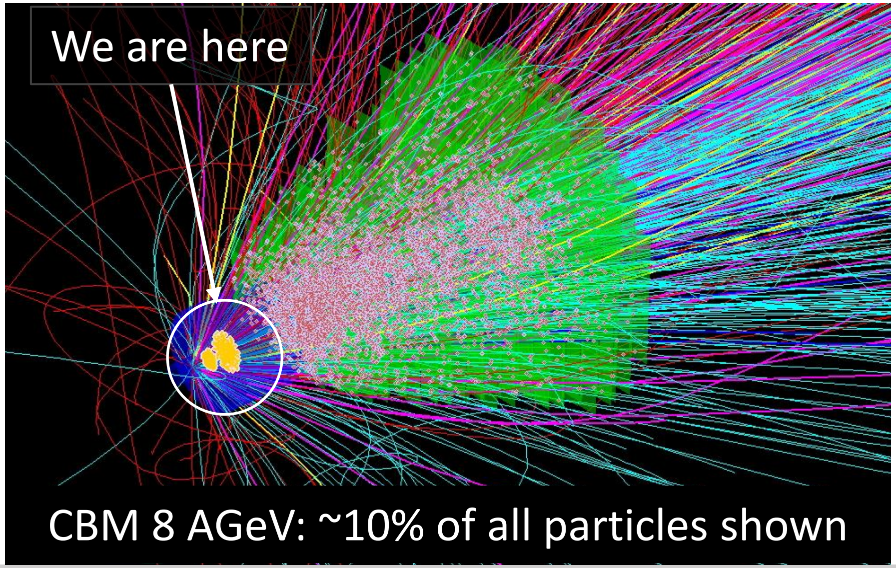
- Select good daughter particles by separating primary and secondary vertex.

⇒ Need 5µm spatial resolution,
⇒ Need 300 - 500 µm Si equivalent material per station (0.3% X_0).
… like ALICE ITS-2…

High rate capability needed:

- 5µs time resolution.
- 20 MHz/cm² (peak 80 MHz/cm²). } ~10 x ALPIDE
- ~10^{14} n_{eq}/cm² radiation tolerance. }
- Tolerance to heavy ion hits (direct beam impacts).

(Find full list of requirements in the backup)



Conclusion (2003, still true today):
Need specifically designed CMOS Monolithic Active Pixel Sensors.

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

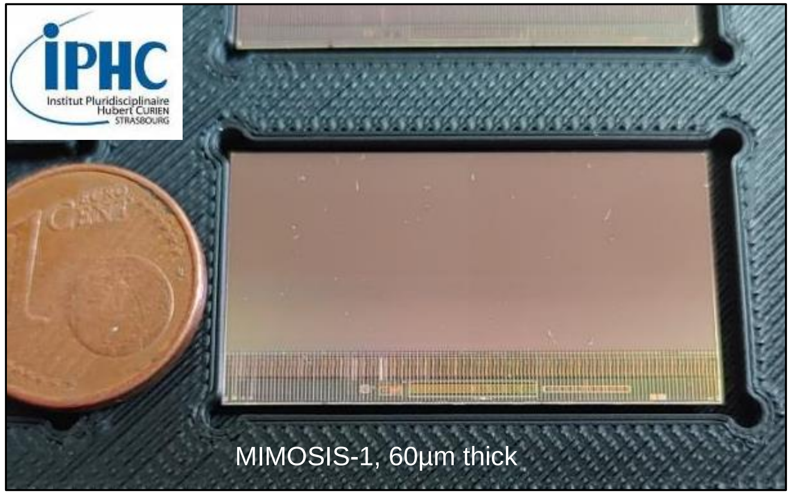
MIMOSIS-1 (2020)
- Full dimension sensor ✓
- Add buffer structure. ✓
- SEE hardening 1/2 ✓

Discussed today

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

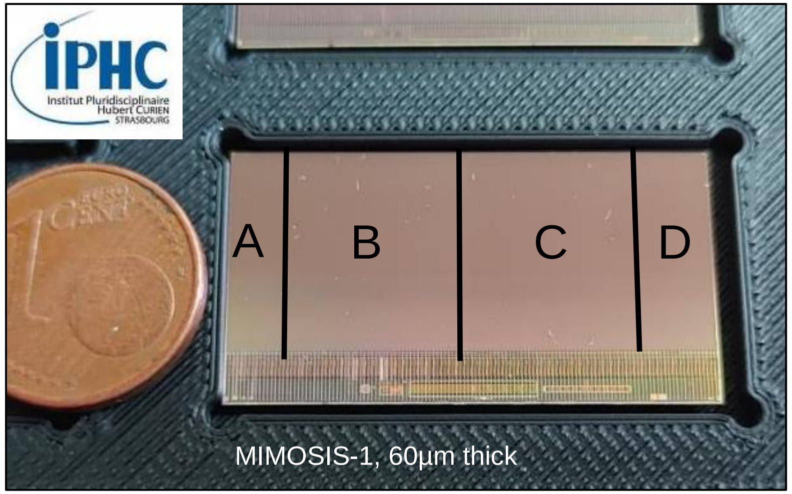
MIMOSIS-3
- Final sensor for mass production

In synergy with:
eurizon
European network for developing new horizons for RIs



MIMOSIS-1

All submissions:
Additional CE18 test structures to study specific design questions.

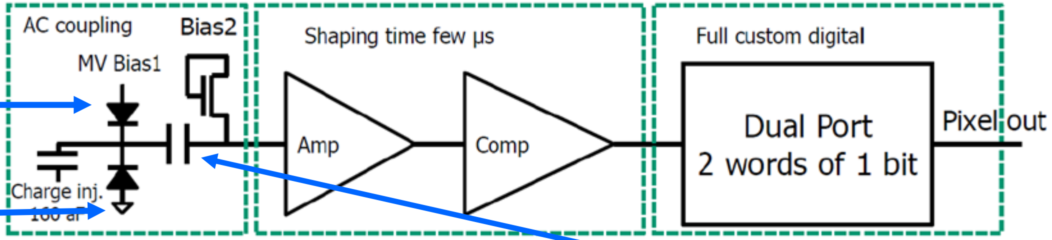


Size: 504 x 1024 pixels (27x30µm²)
FEE integrated.
Pixels types: 2x DC, 2x AC (>20V depletion voltage)

AC-pixel

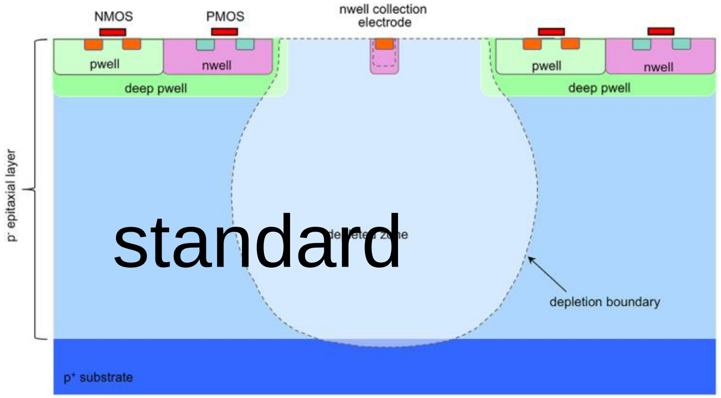
>20V HV top bias

Back bias possible.
P-Well bias (ALPIDE) possible

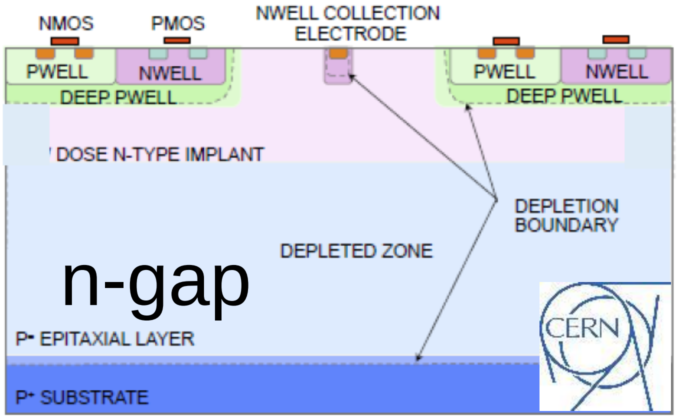


Capacitor blocks HV

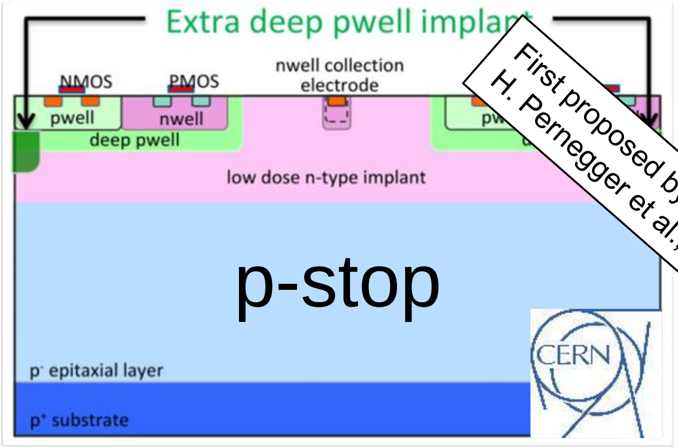
Most likely Fully Depleted



Standard



Rad. hard, candidate 2



Rad. hard, candidate 1

First proposed by W. Snoeys et al.
H. Pernegger et al., 2017 JINST 12 P06008

MIMOSIS-1 beam telescope:

- ✓ 6 MIMOSIS-1 sensors
- ✓ 4 reference sensors (standard epi-layer)
- ✓ 2 device under test
- ✓ Reference Track Uncertainty:
  2.5 µm + 1.5 µm Mult. Scattering (DESY only)

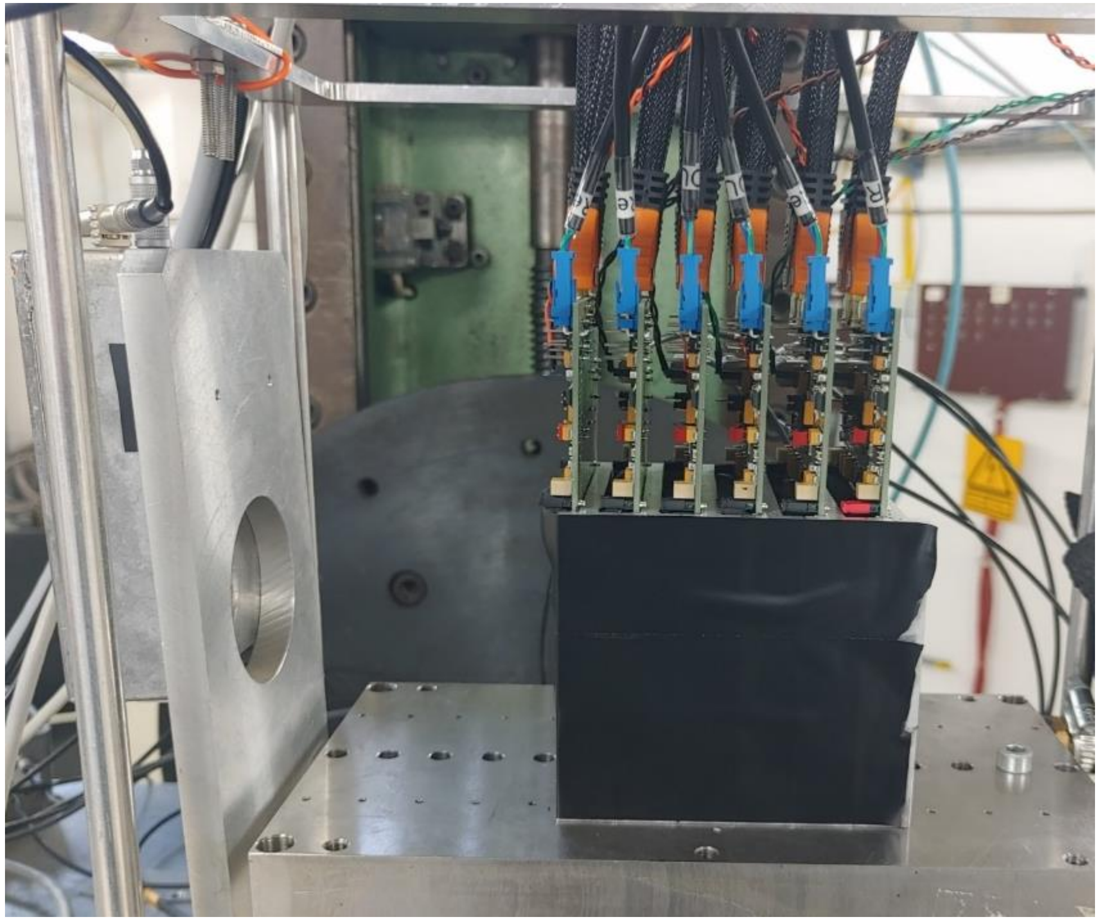
preliminary

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



Sensor performance: New and after 5 MRad + $10^{14} n_{eq}/cm^2$

Best performing pixel: AC P-stop

Efficiency >99% (end of life-time).

Spatial resolution: ~6 µm

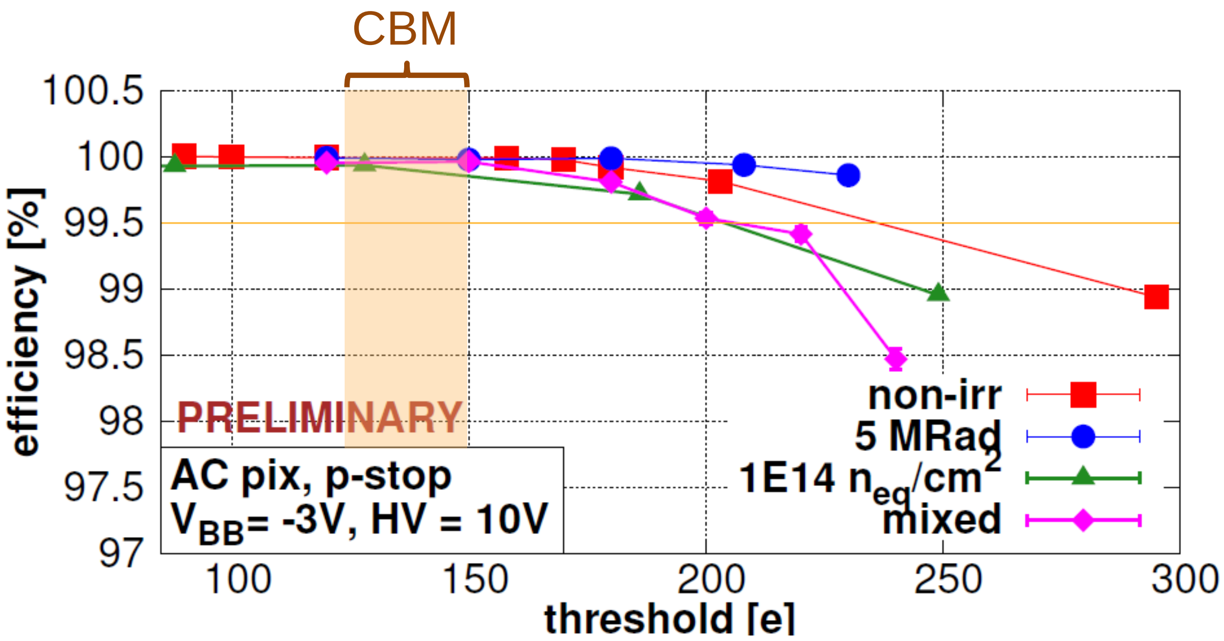
Dark rate (not shown, see backup):

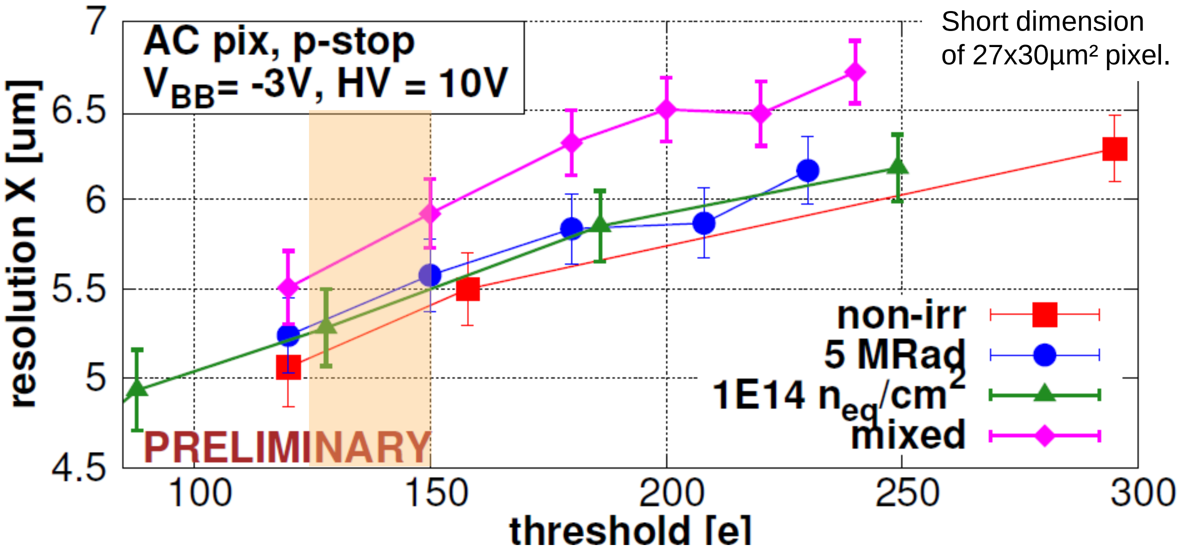
- Marginal before irradiation.
- $<10^{-6}$ after irradiation.

Conclusion on sensor performance:

- All pixels work excellent before irradiation.
- Standard pixels show best spatial resolution.
  (see backup)

- P-stop AC pixel most radiation hard, matches requirements of CBM.



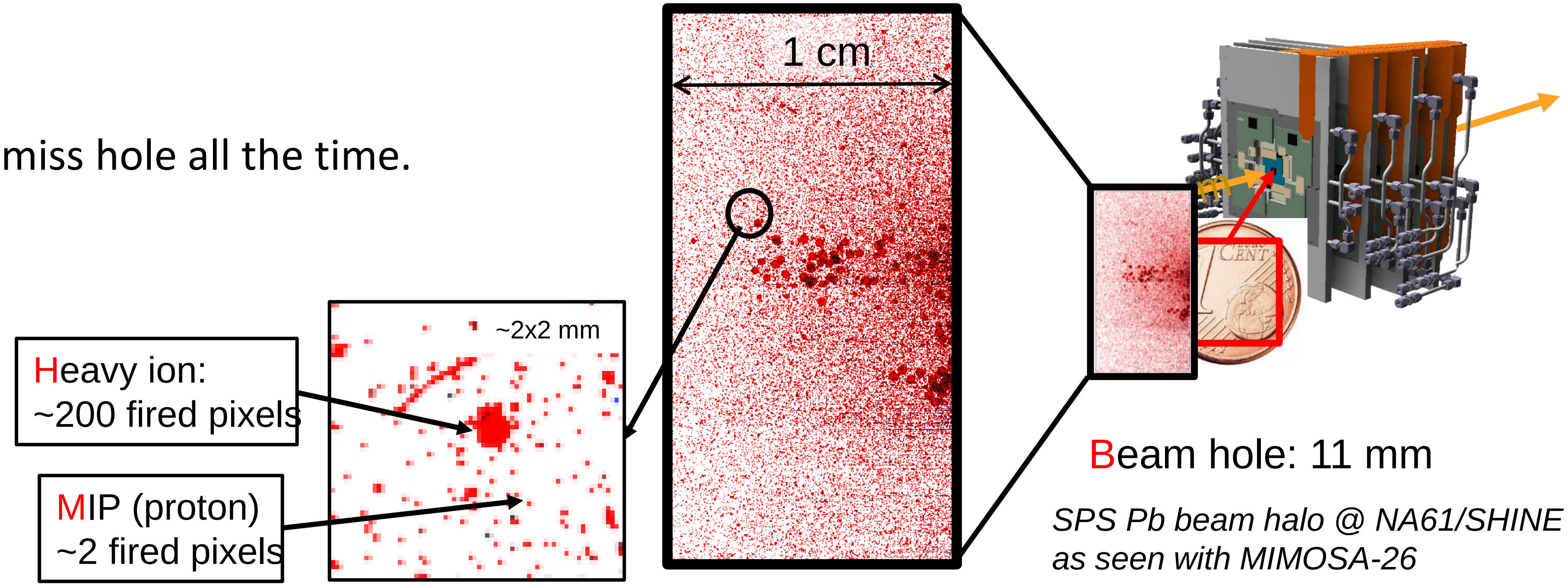


Short dimension of 27x30µm² pixel.

Immunity to heavy ions (Single Event Effects)

Beam halo

Origin:
- Limited focus - few ions miss hole all the time.
- Beam impact.



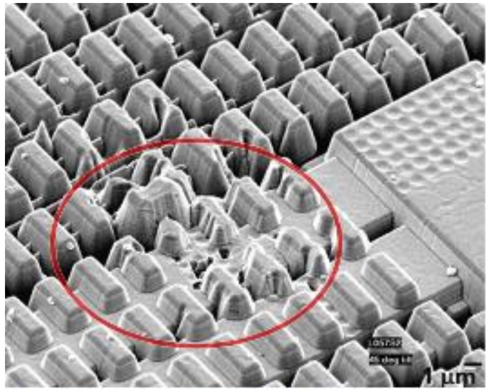
SPS Pb beam halo @ NA61/SHINE as seen with MIMOSA-26

M. Deveaux for NA61/SHINE, SQM 2017

Minority charge carriers excited by ions may:

- Switch digital electronics => Bit flip — Malfunction if ignored
- Open unwanted conduction paths => Latch-up (like short cut, extinguish by power cycle) — Thermal destruction if ignored

Macroscopic damage by individual ion: **Single Event Effect.**



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

Observation on Single Event Effects

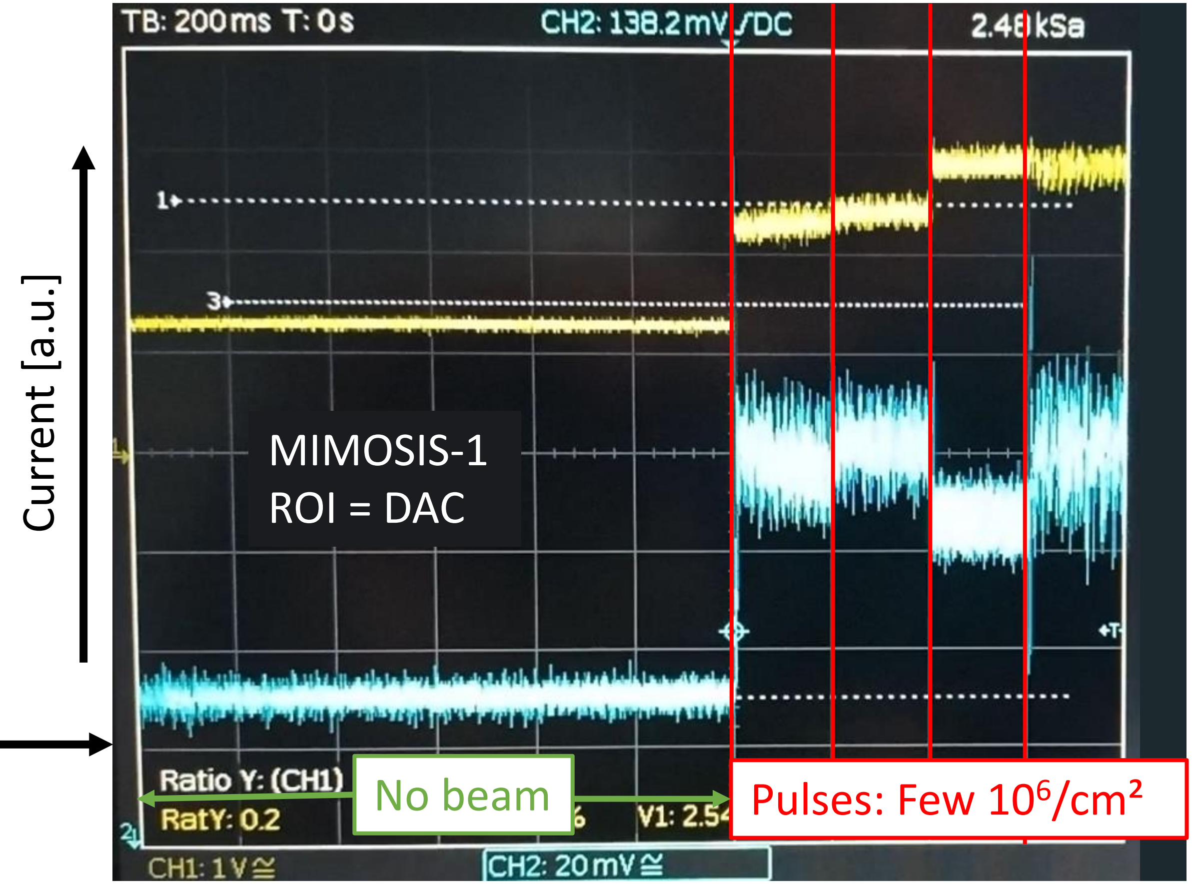
Latch-up (Ion generated short circuit, recover by power cycle):

	GSI - 3.2 *A* MeV Ca 20 MeV cm² / mg
Latch - ups	**0**
ROI (all except DAC)	3.2 cm²
Ions on ROI [1/cm²]	> 3 x 10^{10} / cm²
σ per 5.3cm² sensor	**1.5 x 10^{-10} cm²**

preliminary

No latch-ups observed.

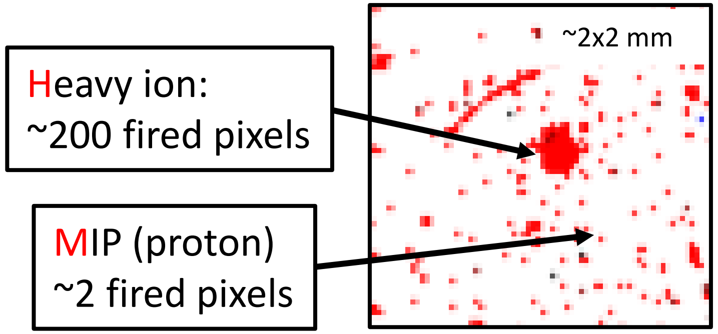
Observation on DAC:
- Bit flips in DAC generate current fluctuation.
  $\Rightarrow$ Bit correction bug to be fixed with MIMOSIS-2.



MIMOSIS-1 seems to tolerate up to 300 MHz/cm² Ions at 20 MeV cm² / mg .
$\Rightarrow$ Latch-up cross-section orders of magnitude better than required (all structurs except DAC) .
$\Rightarrow$ Protection of steering registers to be fixed.
$\Rightarrow$ Data registers not protected – Expect occasional data corruption.

Known for elder sensors:

- Individual pixel is not energy sensitiv but:
- Pixel multiplicity scales with dE/dx [1,2].
- Does this hold for MIMOSIS (dependence on depletion)?

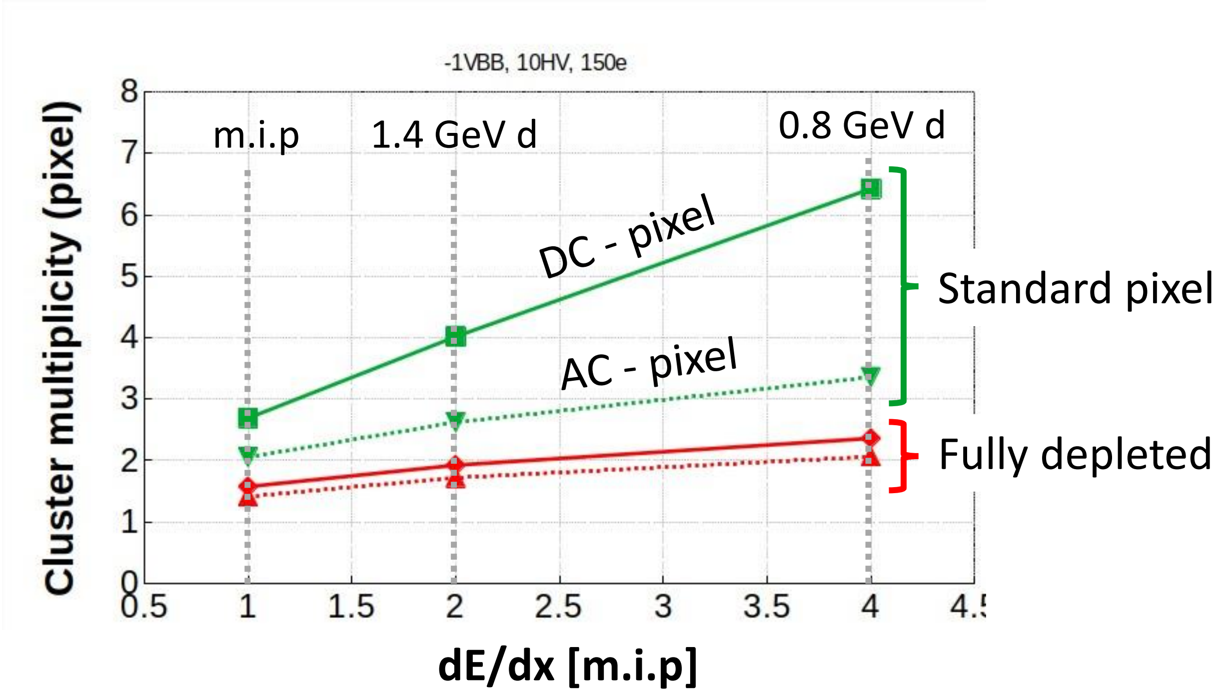


Experimental approach:

- Use deuterium beam of COSY to create dE/dx higher than m.i.p.
- Histogram multiplicity of hits associated to a identified track.

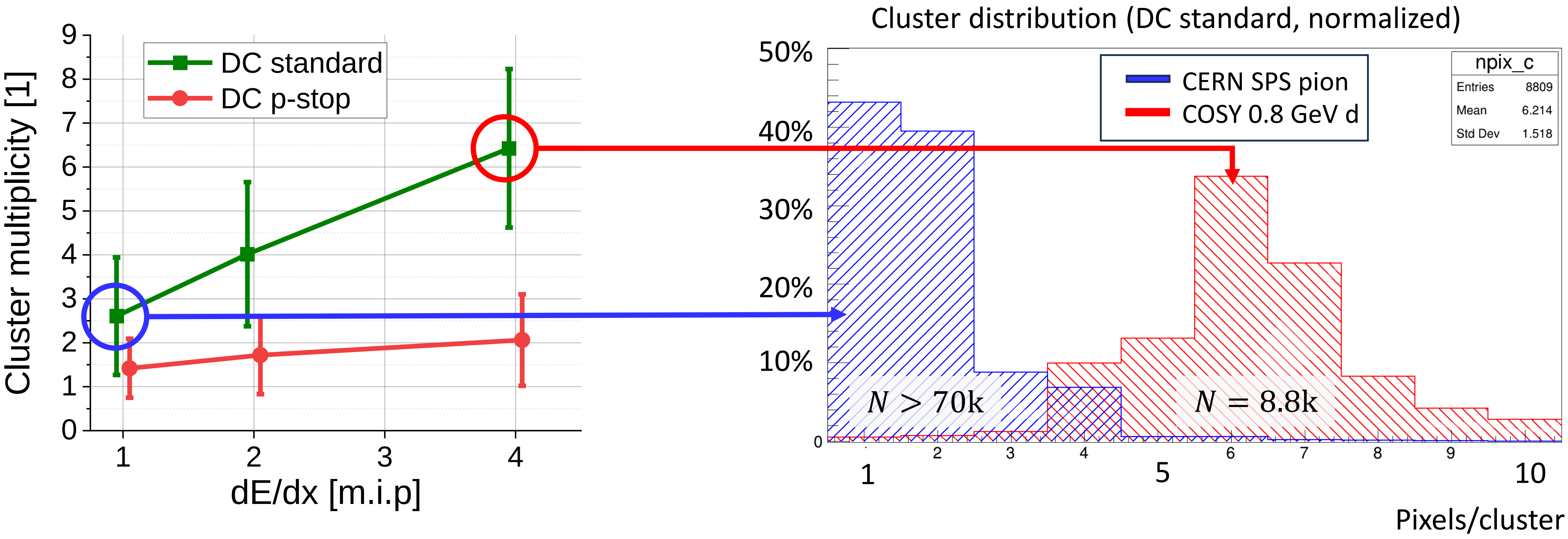
First observation:

- Fully depleted pixels (p-stop) show marginal sensitivity to dE/dx.
- Standard DC-pixel (lowest depletion) shows response. Significant?



[1] C. A. Reidel et al., "Response of the Mimosa-28 pixel sensor to a wi
range of ion species and energies", NIM-A Vol. 1017 (2021) 165807
[2] M. Deveaux for NA61/SHINE, SQM 2017

Response to different dE/dx



Preliminary conclusion:

- Response to increasing dE/dx observed (usefulness for PID to be studied in detail).
- High rad. tolerance configuration with high depletion not compatible with good dE/dx response.

Next step: Reproduce findings in device simulation.

Summary and conclusion

MIMOSIS-1 forms the first full size prototype of the MIMOSIS sensor for the CBM-MVD.

- ✓ 5 µs / 5 µm time/spatial resolution.
- ✓ 80 MHz/cm² peak rate.

MIMOSIS-1 irradiated with up to $3x10^{14}$ n_{eq}/cm² were tested in laboratory and in beam.

- >> 99% detection efficiency after 10^{14} n_{eq}/cm², 5 MRad and a combination of both
- <10^{-6} fake hit rate (after 10^{14} n_{eq}/cm², <0.05% of all pixels masked)
- ~5 µm spatial resolution before and after irradiation => Matches requirement.

- Tolerates HI with up to LET=20 MeV cm² / mg without observed latch-up.
- Response of partially depleted MIMOSIS-1 to different dE/dx may add information to CBM-PID (to be followed up).

MIMOSIS-1 matches the requirements of the CBM-MVD…
… and forms a mile-stone toward a sensor for higgs-factories.

CBM-MVD collaboration members

Julio Andary[1], Benedict Arnoldi-Meadows[1], Ole Artz[1], Jérôme Baudot[2], Grégory Bertolone[2], Auguste Besson[2], Norbert Bialas[1], Roma Bugiel[2], Gilles Claus[2], Claude Colledani[2], Hasan Darwish[1,2,3], Michael Deveaux[1,3,6], Andrei Dorokhov[2], Guy Dozière[2], Ziad El Bitar[2], Ingo Fröhlich[1,3], Mathieu Goffe[2], Benedict Gutsche[1], Fabian Hebermehl[1], Abdelkader Himmi[2], Christine Hu-Guo[2], Kimmo Jaaskelainen[2], Oliver Michael Keller[6], Michal Koziel[1], Franz Matejcek[1], Jan Michel[1], Frédéric Morel[2], Christian Müntz[1], Hung Pham[2], Christian Joachim Schmidt[3], Stefan Schreiber[1], Matthieu Specht[2], Dennis Spicker[1], Joachim Stroth[1,3,4], Isabelle Valin[2], Roland Weirich[1,] Marc Winter[5]and Yue Zhao[2]

[1]Goethe-Universität Frankfurt, Germany
[2]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany
[4]Helmholtz Forschungsakademie Hessen für FAIR, Germany
[5]IJCLab, UMR9012 – CNRS / Université Paris-Saclay / Université de Paris, France
[6]Facility for Antiproton and Ion Research in Europe GmbH,Germany

Supported by:

Bundesministerium für Bildung und Forschung (05P21RFFC2)

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

HFHF Helmholtz Forschungsakademie Hessen für FAIR

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Backup

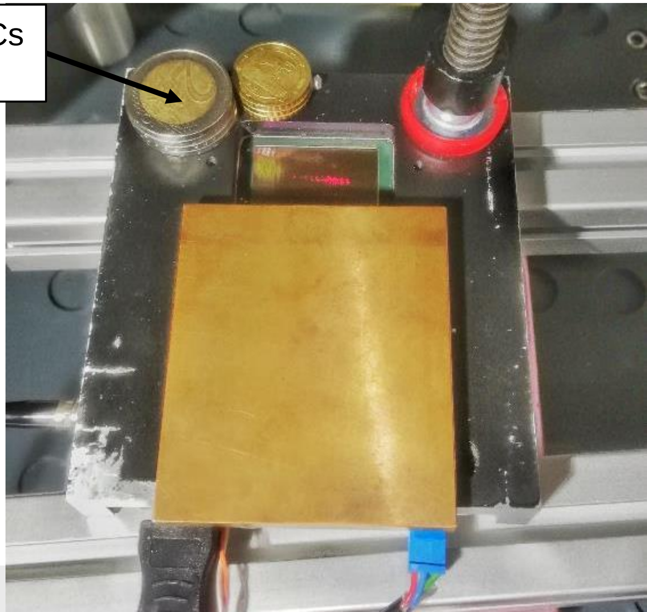
Beam tests (MIMOSIS-1)

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

Shielding for PCB-ICs
(X-rays @ KIT)



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

CBM-MVD Sensor requirements

	Requirement
Time resolution	~5 µs
Spatial resolution	~5 µm
Sensor thickness	~50 µm
Power dissipation	≲200 mW/cm²
Radiation doses (non-ionizing)	> 7×10^{13} n_{eq}/cm^2
Radiation doses (ionizing)	> 5 Mrad
Radiation gradient on chip	100%
HI-tolerance	10 Hz/mm²
Rate (average/peak)	150/700 kHz/mm²

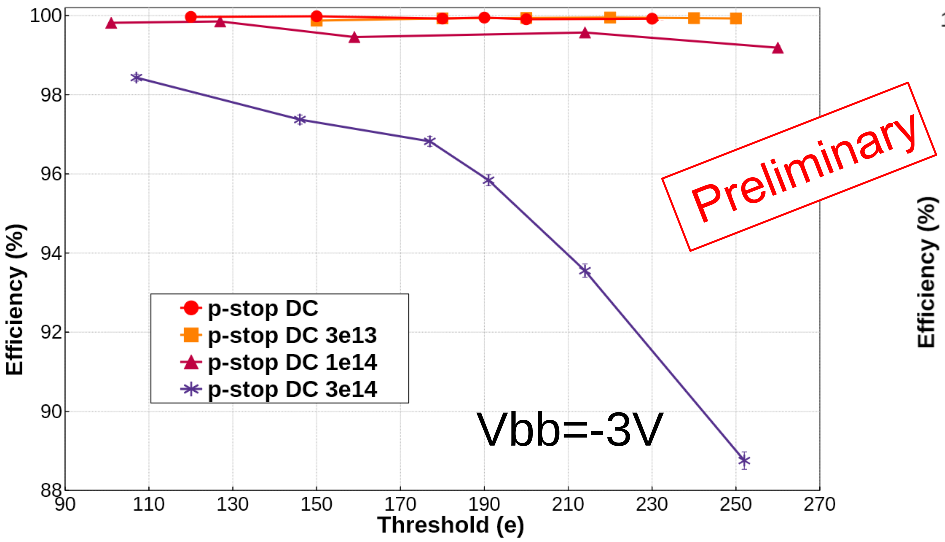
Time resolution, spatial resolution, sensor thickness: Mostly established by ALPIDE (Sensor of ALICE ITS2 upgrade)

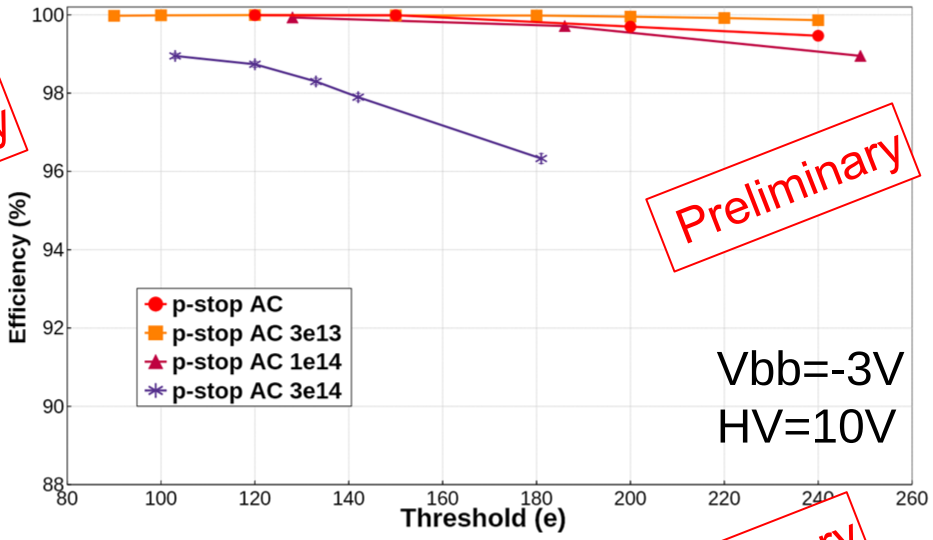
Radiation doses: per year, no safety factor — ≈10 x ALPIDE

Rate: Incompatible with ALPIDE
> 20x internal bandwidth needed

How to arrive there (starting from ALPIDE) based on 180 nm technology?

MIMOSIS-1: Tolerance to non-ionizing radiation

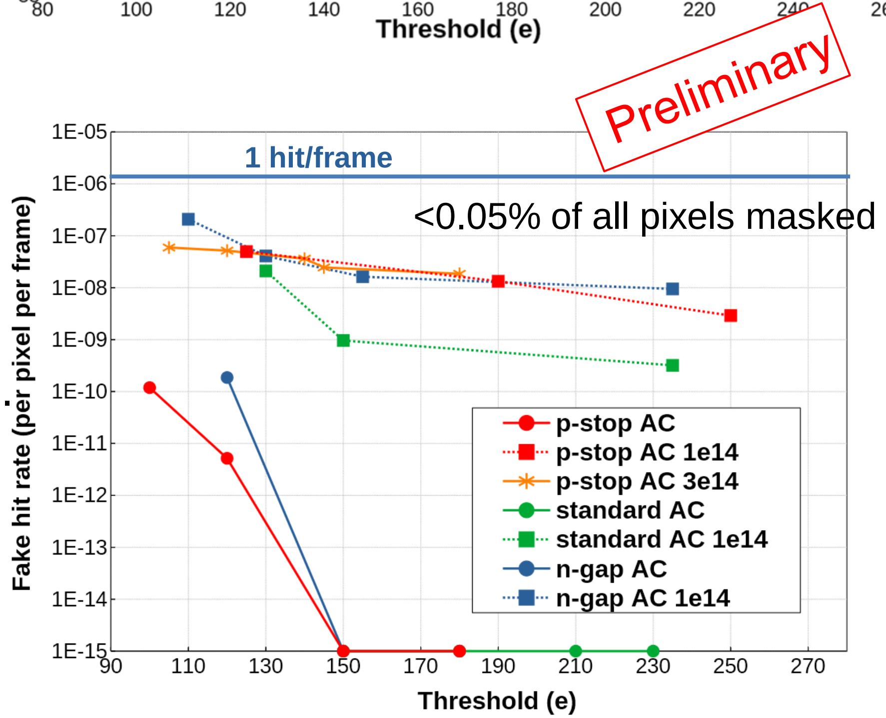




Observation:

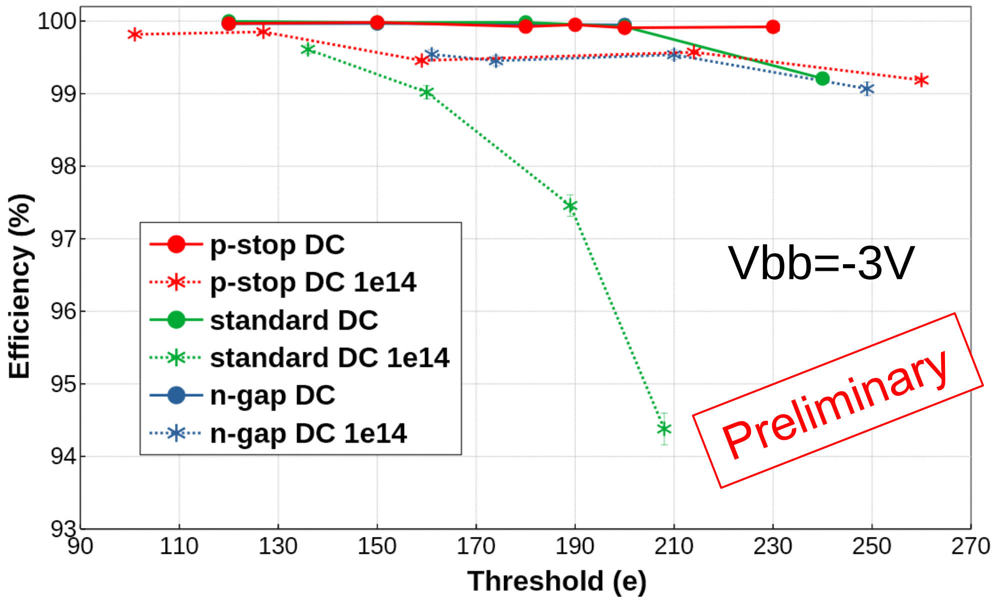
- ✓ Det eff. >> 99% for 10^{14} n_{eq}/cm^2.
- ✓ Resonable performance after 3x 10^{14} n_{eq}/cm^2.
- ✓ AC-pixel shows better efficiency (as expected).

- ✓ Dark rate < 10^{-6} for all pixels tested.
  => Holds for DC-pixels (not shown).
  => Matches requirements.



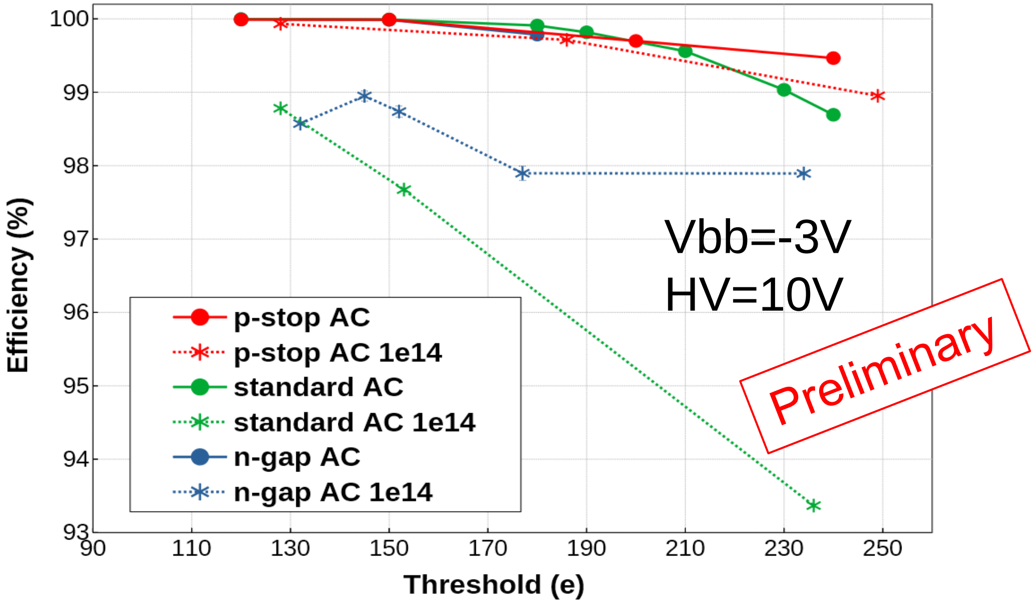
Before irradiation:

- All pixels show excellent performance.



After $10^{14} n_{eq}/cm^2$ (end-of-lifetime):

- Standard epi-layer reaches limits.
- Good performance for p-stop, n-gap.
- Best performance: p-stop AC pixel.
  - n-gap AC worse than n-gap DC => follow up.



MIMOSIS-1 spatial resolution

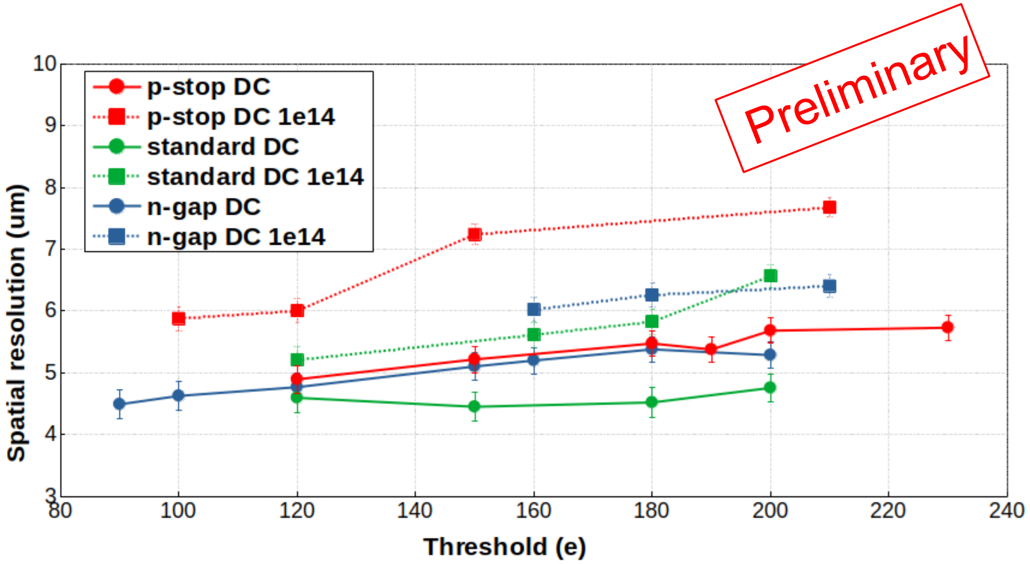
Observation:

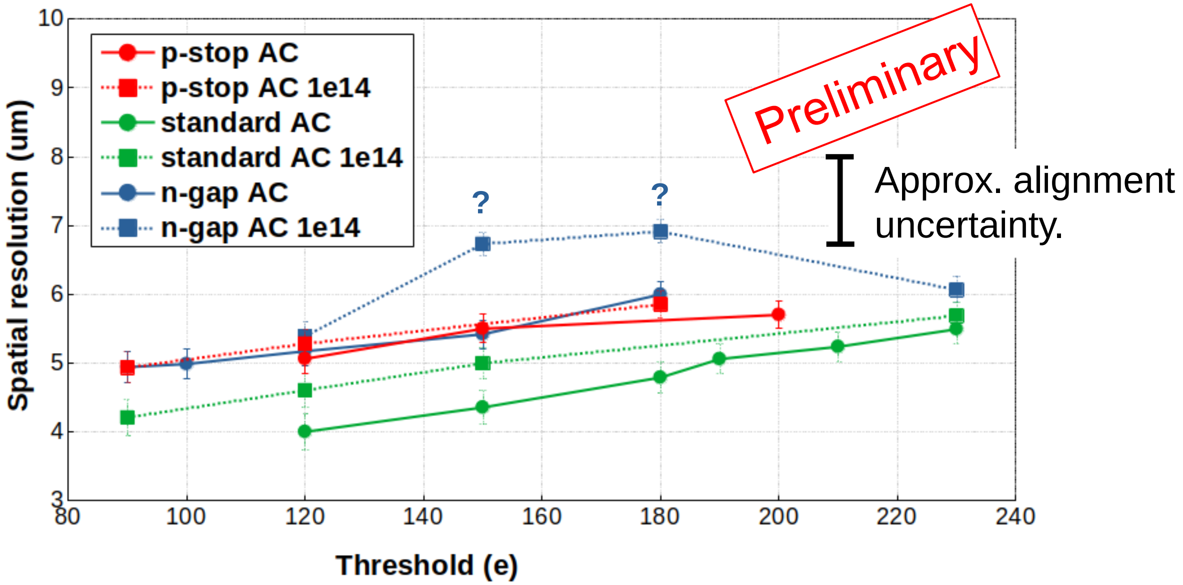
- ✓ Best resolution for standard epi.
  - ⇒ Larger charge sharing (measured, not shown).
- ✓ Resolution mildly worse after irradiation.
  - ⇒ Bulk damage reduces cluster size.
- ✓ Plots hold for small dimensions of pixel
  - ⇒ ~10 % worse resolution for long dimension (not shown).

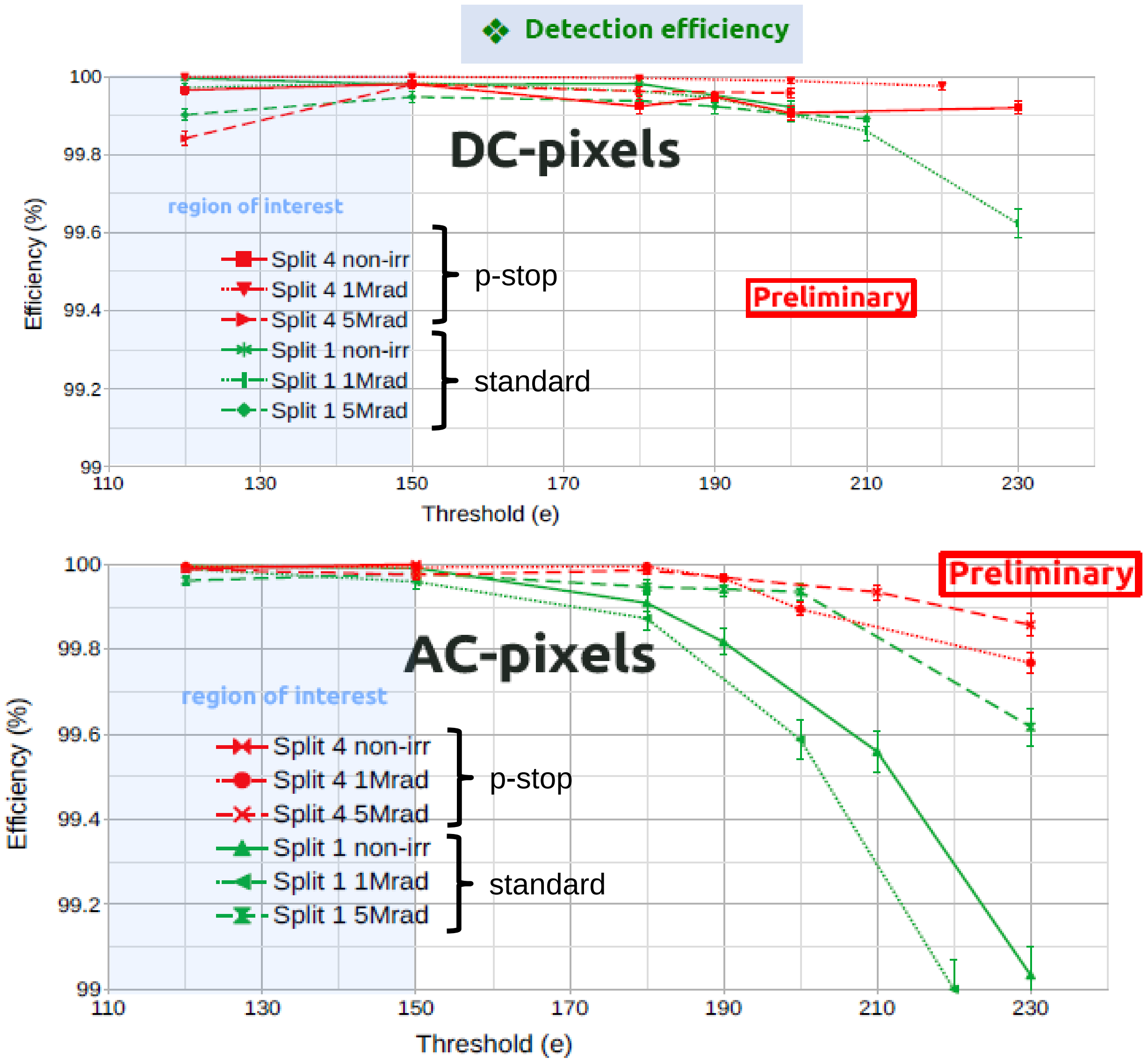
- ✓ Results for all pixels match CBM requirements at default 120 – 150 e threshold.

Note: Preliminary results

- Still preliminary alignment.
  - ⇒ Fixing this may or may not eliminate outlayers (work in progress).





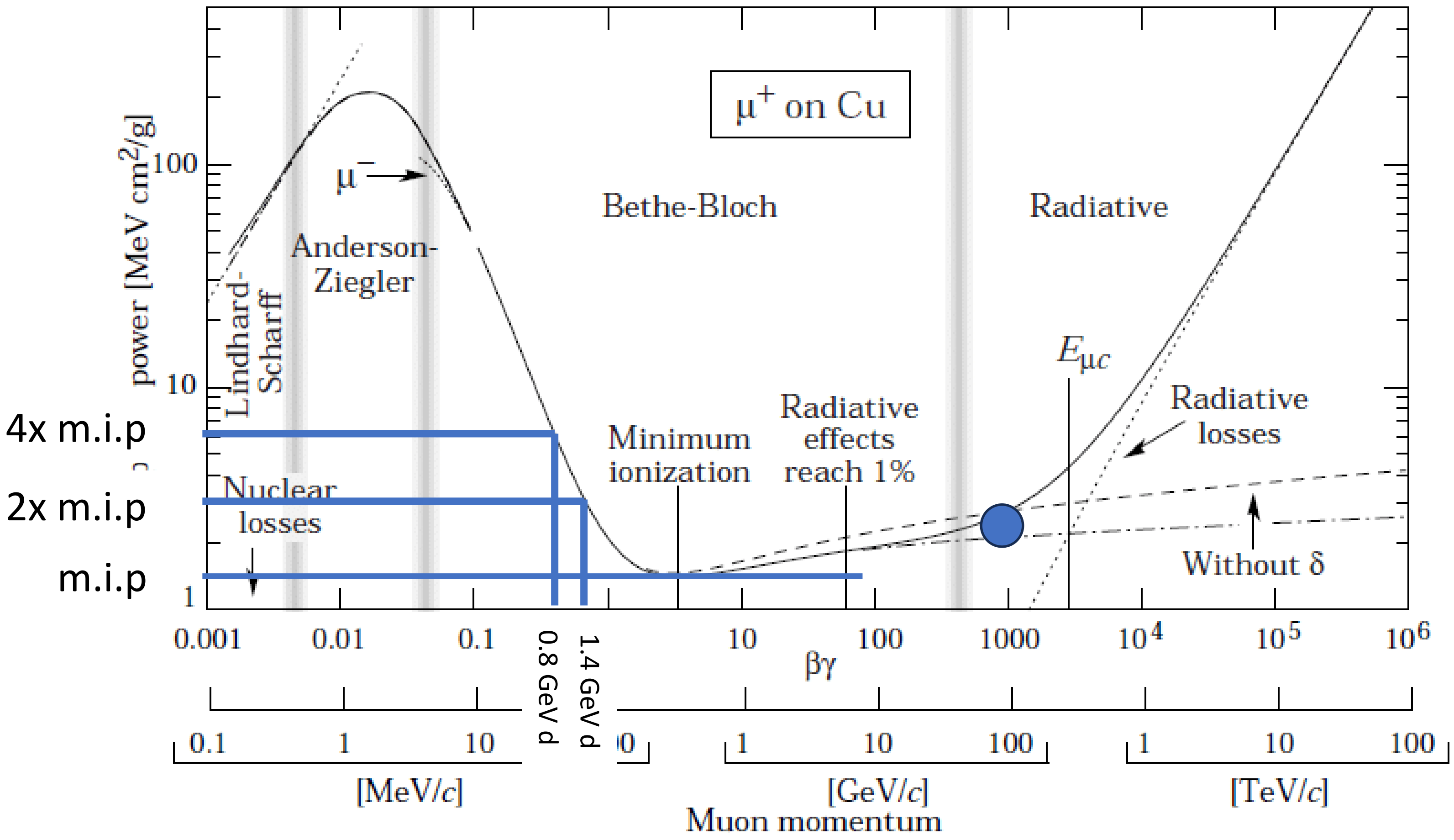


Observation:

- Good detection efficiency also after ionizing doses.
- Radiation seems to improve performance sometimes
  - ⇒ Radiation may modify pixel tuning (7 parameters)
  - ⇒ Probably room for improvement.

Dark rate stays below 10^{-7}

No impact on spatial resolution within uncertainties


μ+ on Cu
power [MeV cm2/g]
100
10
1
4x m.i.p
2x m.i.p
m.i.p
Lindhard-
Scharff
Anderson-
Ziegler
μ−
Bethe-Bloch
Radiative
Nuclear
losses
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
10
100
1000
10^4
10^5
10^6
βγ
0.8 GeV d
1.4 GeV d
0.1
1
10
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum