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Results from Single Event Effect Tests with MIMOSIS-1

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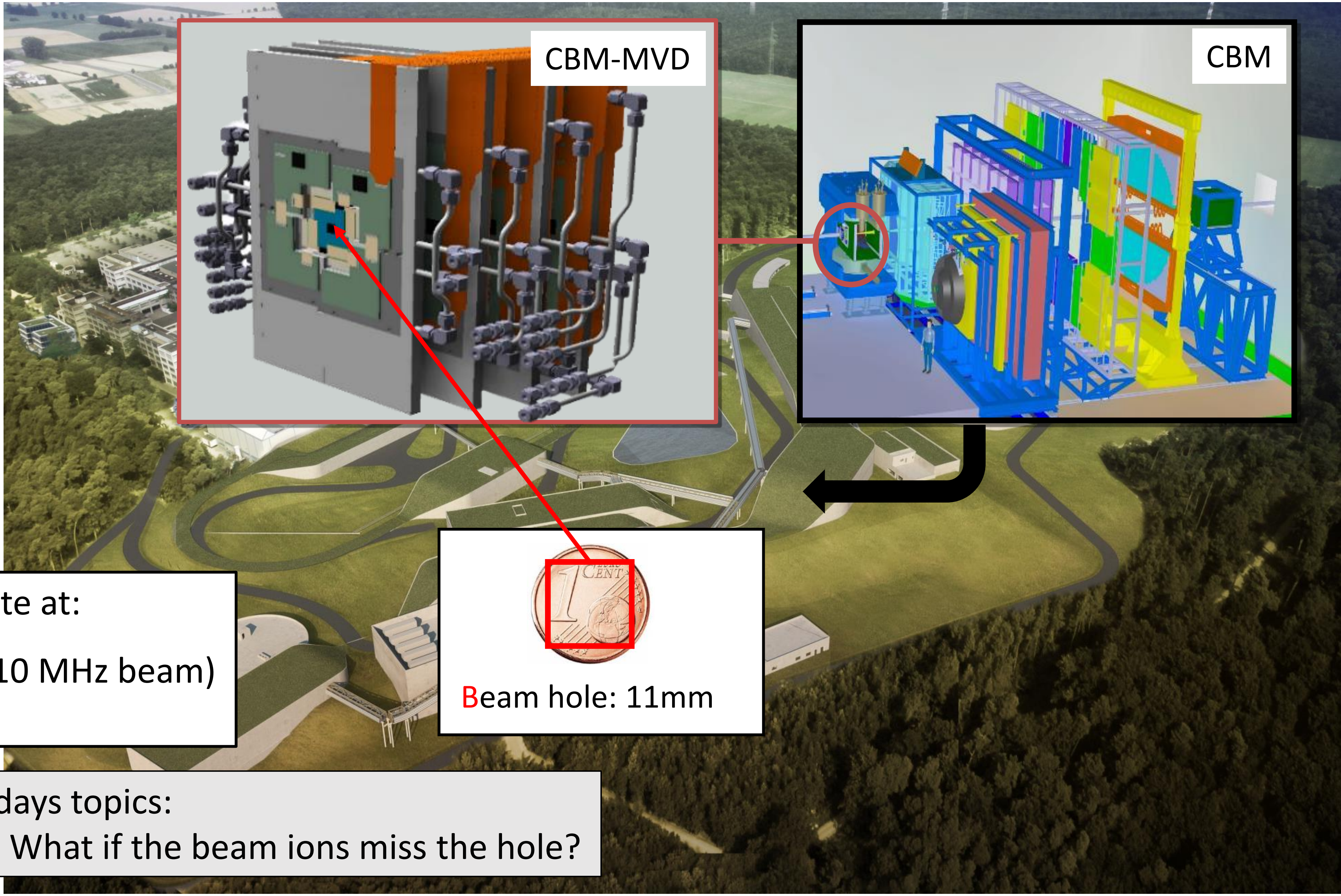
for the CBM-MVD Collaboration

IWORID2022, June 28th, 2022.

The CBM Micro Vertex Detector (MVD)



The CBM – MVD will operate at:

100 kHz Au+Au collisions (10 MHz beam)
10 MHz p + Au collisions

Todays topics:

- What if the beam ions miss the hole?

Requirements on the MIMOSIS sensors

	Requirement
Spatial / time resolution	~5 µm / 5 µs
Sensor thickness	~50 µm
Radiation doses (non-ionizing)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation doses (ionizing)	~ 5 MRad
Rate capability (mean/peak)	(20/80) MHz/cm²
Readout mode	Continuous

Spatial / time resolution and sensor thickness: Established by ALPIDE (Sensor of ALICE ITS2 upgrade)

Radiation doses: ~10 x ALPIDE

Rate capability and readout mode: Incompatible with ALPIDE
> 20x internal bandwidth needed

Idea:

Get inspiration from ALPIDE:
- Re-use pixel analog front-end.
- Re-use priority encoder.

Complement design with:
- High bandwidth internal DAQ.
- Fully depleted pixels (> 20 V top bias).
- …

MIMOSIS-0 (2018)
- Confirm (depleted) pixels and priority encoder

MIMOSIS-1 (2020)
- **Full size prototype, this work**

MIMOSIS-2 (2022)
- Advanced rad. hardening, data compression…

MIMOSIS-3 (2023/24)
- Final sensor

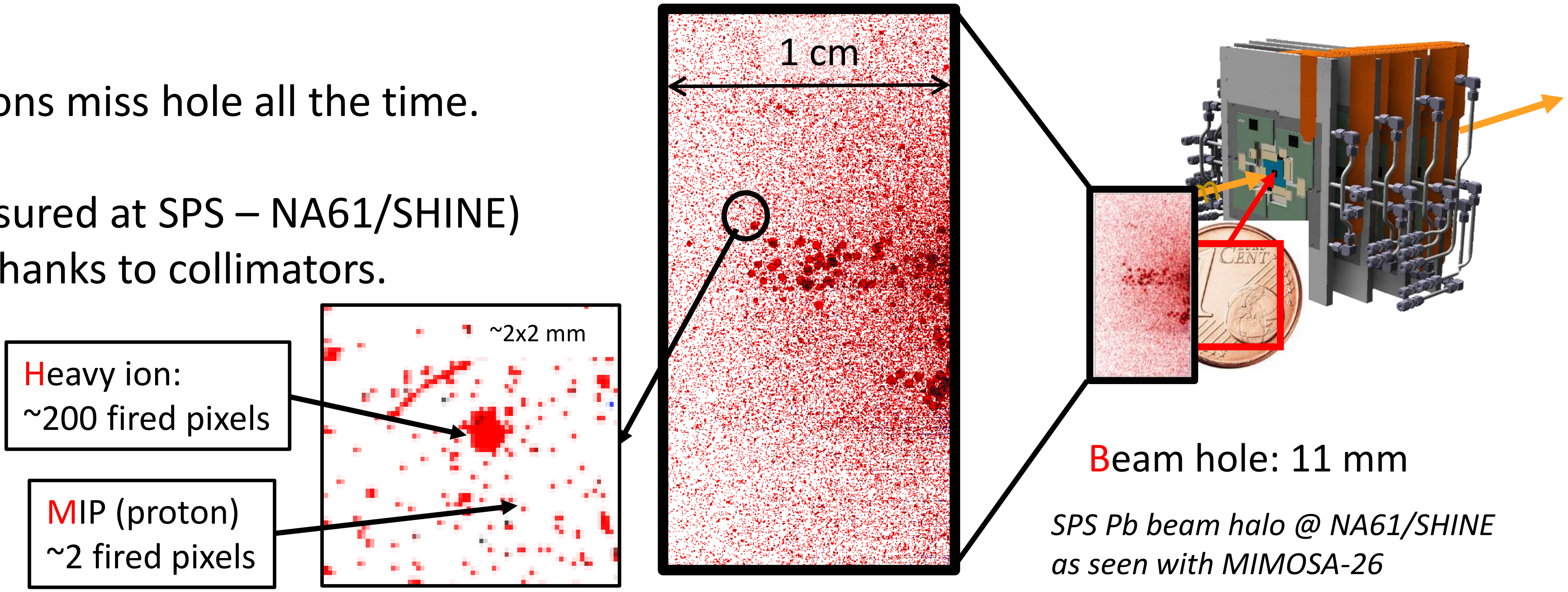
Origin of heavy ion impacts

Beam halo

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

Our assumptions:

- Geometry still (measured at SPS – NA61/SHINE)
- Assume 1 kHz/cm² thanks to collimators.



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

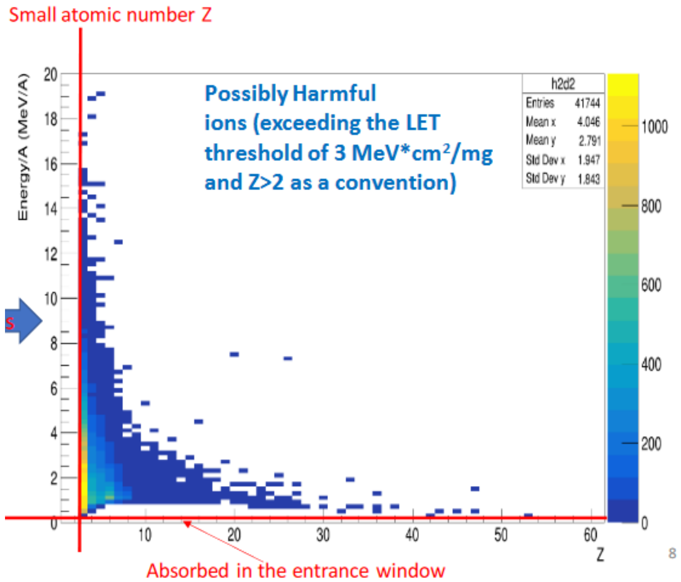
M. Deveaux for NA61/SHINE, SQM 2017

Beam loss

- Direct beam impact to MVD due to steering fail.
- Highest rate: ~300 MHz/cm² Au ions in MVD

Target fragments

- Nuclear fragments kicked out of target by beam.
- Very slow: Absorbed by first station.
- Highest energy transfer: 35 MeV cm²/mg



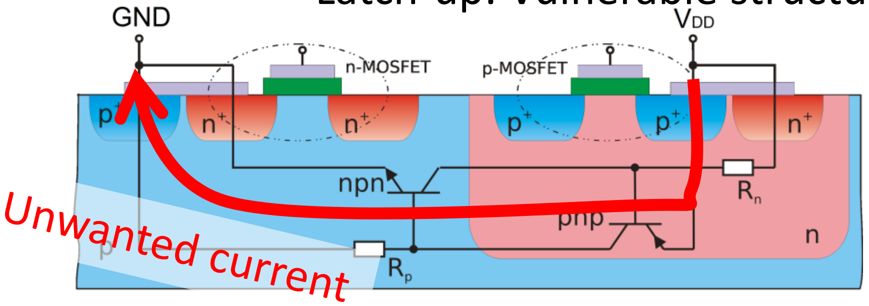
More information on simulation:
H. Darwish, CBM Progress Report 2020

Effect of heavy ion hits on electronics

Heavy ions show high dE/dx or LET:

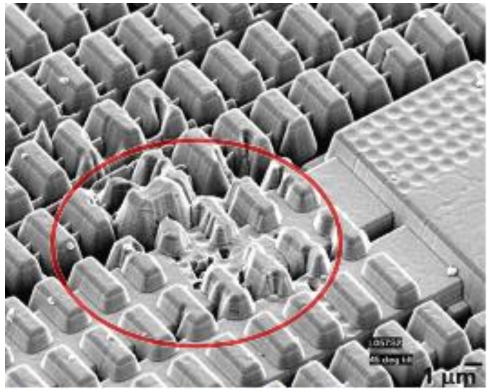
- Scales with z^2 of the projectile => Au = 6200 M.I.P
- Bethe Bloch: "Slow" ions create higher LET than relativistic ions.

Latch-up: Vulnerable structure



Minority charge carriers excited by ions may:

- Break transistor gates => Gate rupture — Irreversible destruction
- 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



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

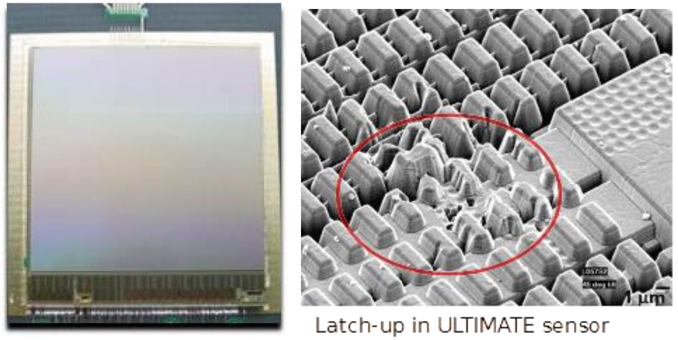
Macroscopic damage by individual ion: **Single Event Effect.**

SEE cross section: $\sigma = \frac{N_{events}}{N_{ions}} \cdot A_{device}$ (JESD57A standard)

SEE probability: $p = \frac{N_{events}}{N_{ions}} = \frac{\sigma}{A_{device}}$ size independent.

What do we know?

ULTIMATE for STAR PXL detector

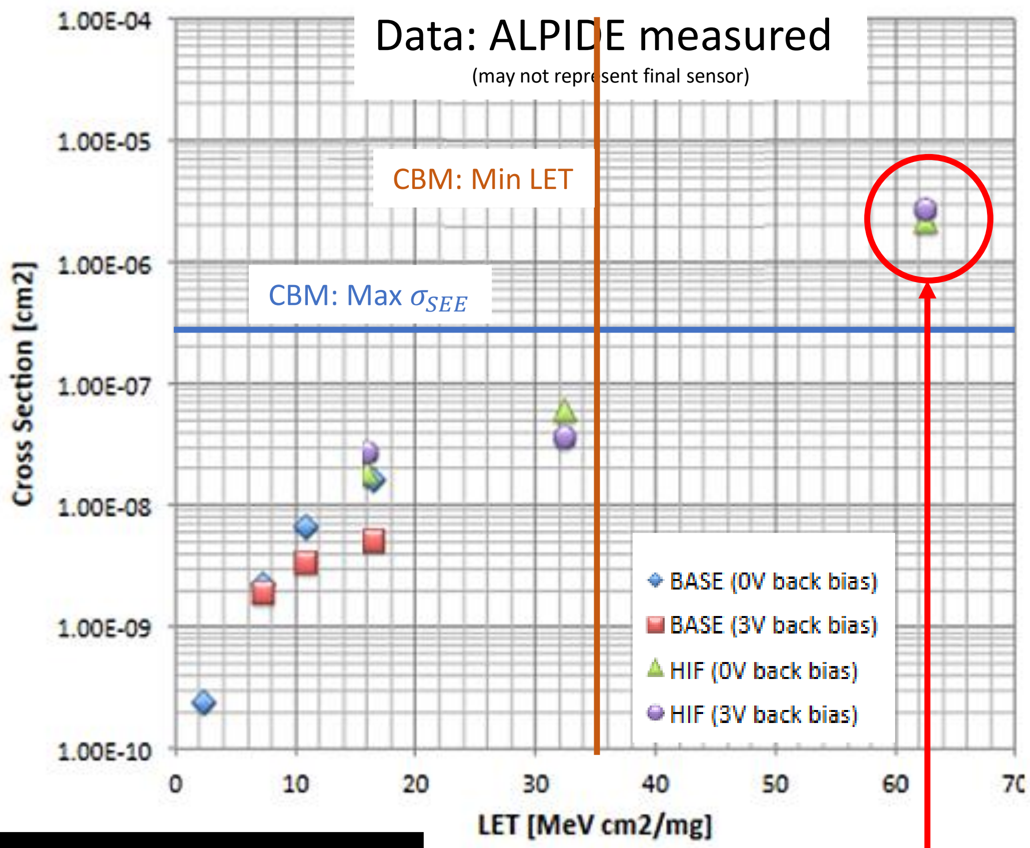


Latch-up in ULTIMATE sensor
G. Contin, JINST 11 C12068 (2016)

- Latch-ups for particles with LET > 3 MeV cm²/mg.
- Sensor destruction during experiment observed.
- Old AMS 0.35 µm process

ALPIDE for ALICE-ITS2

- Latch-ups in digital part only
- $\sigma_{BitFlip} \ll \sigma_{LatchUp}$
- Tower Jazz 180 nm

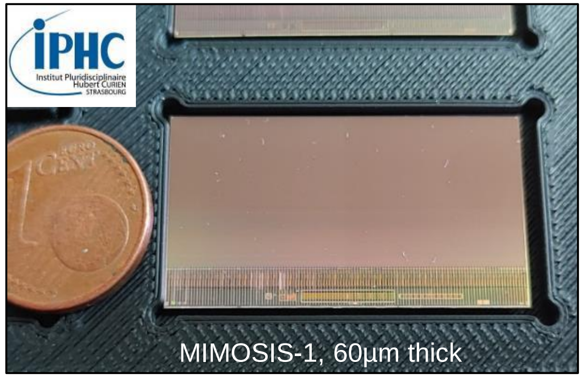


H. Hillemanns, https://tinyurl.com/23dn8pdy, retrieved 10.06.2022

CBM - MVD	Requirement	Remark
LET tolerance (gate rupture)	> 35 MeV cm²/mg	Fulfilled by ALPIDE (same process)
Flux tolerance @ 12 MeV cm²/mg	~ 300 MHz/cm²	no damage for > 150 µs (until beam stop)
σ_{SEE} per sensor @ 12 MeV cm²/mg	< 3 x 10^{-7}cm²	< 1 SEE/h (in 1 kHz Au beam halo)

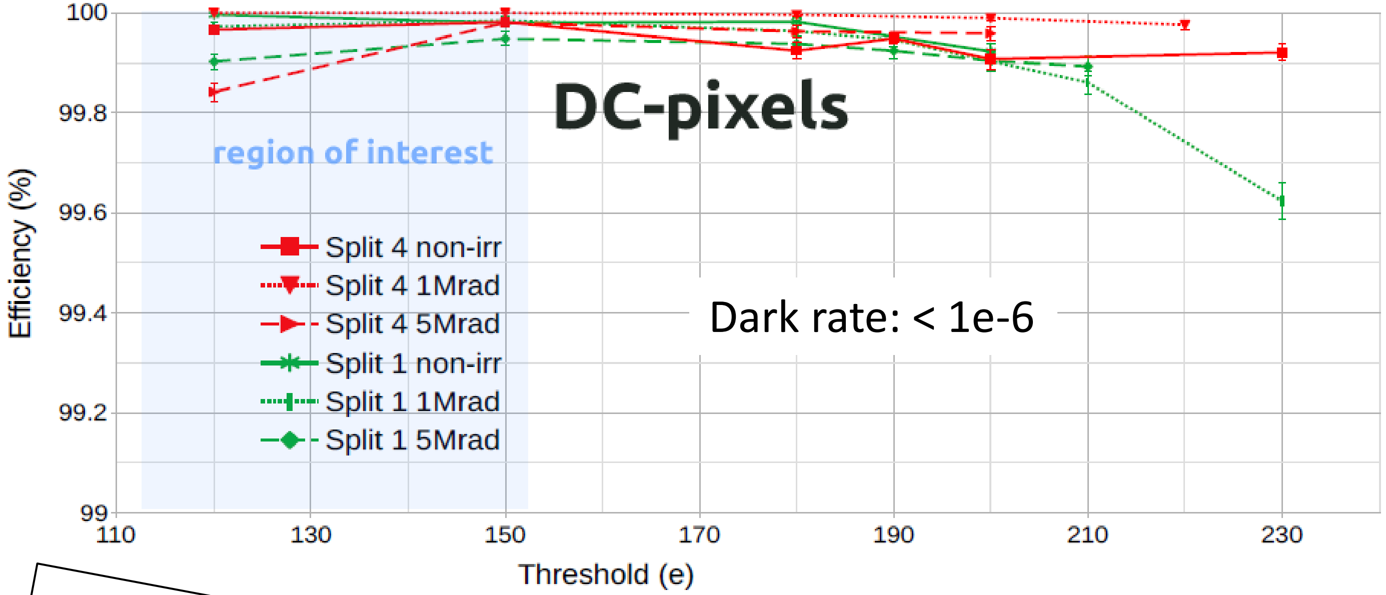
ALPIDE: Valuable guideline (same Tower Jazz 180 nm process as MIMOSIS).
But: MIMOSIS has different digital electronics => Must remeasure.

The sensor under test: MIMOSIS-1



produced in TowerJazz CIS 180nm process

	MIMOSIS - 1
Spatial/time resolution	~5 µm/5 µs
Thickness	60 µm
Rate (average/peak)	20 / 80 MHz/cm²
Pixel	> 20V top bias fully depleted

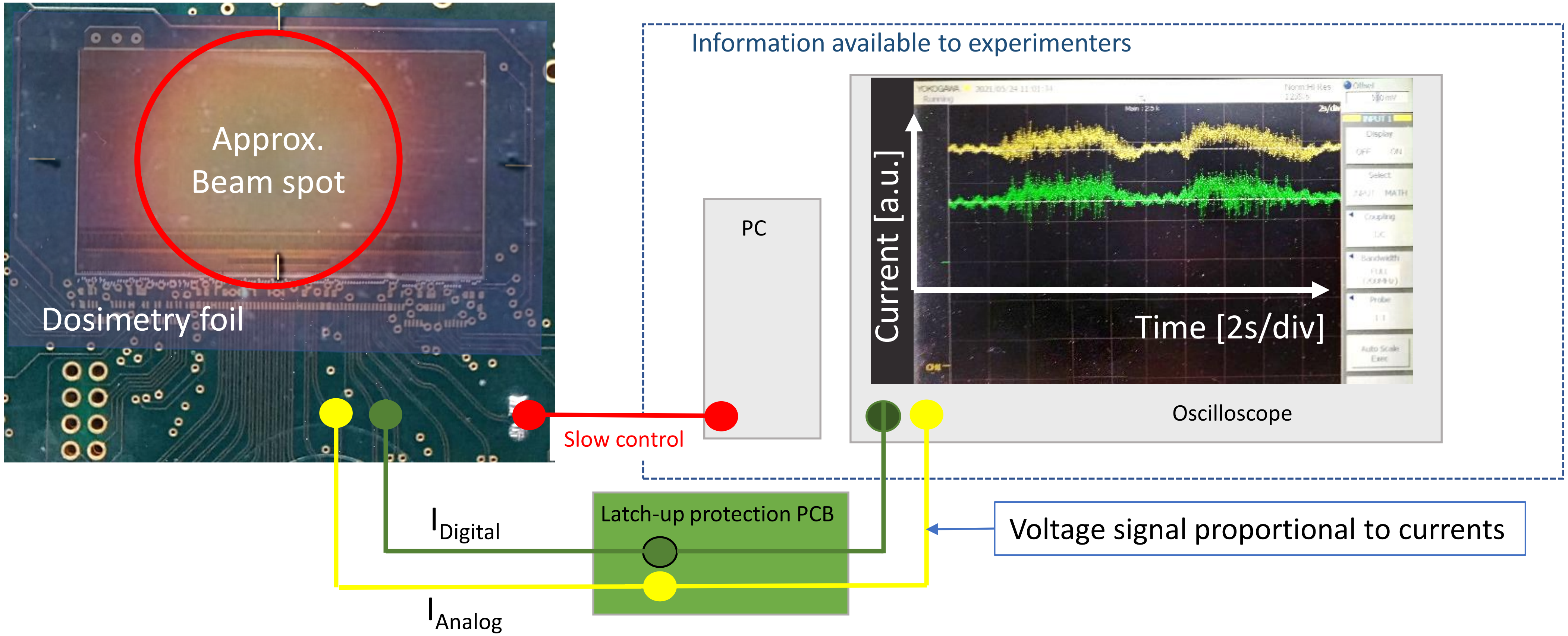


More Details: H. Darwish, poster 137, this conference.

Hardening strategy for MIMOSIS:

- "Latch up" protective design rules.
- Bit error correction for important status registers (Hamming encoding).
- Triple retundancy of important state machines (future MIMOSIS-2).
- Data registers remain unprotected.

Initial experimental strategy



Latch-up detection/protection:

- Over-current detection.
- Automatic shut down, manual counting.

Bit flip detection:

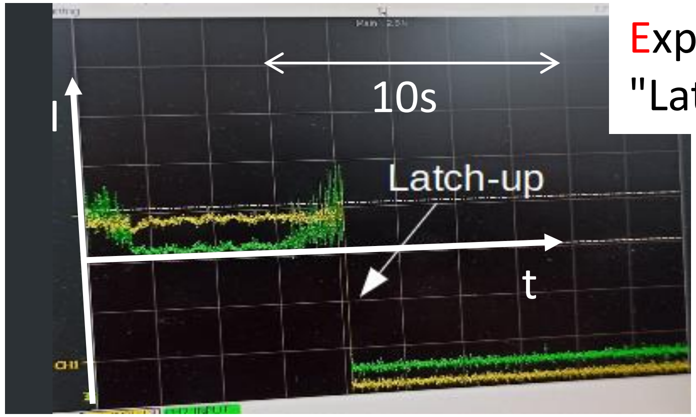
- No/few bit flips expected.
- Manual read-back of slow control data.

Beam line	Beam	LET
GSI (mCBM)	Pb, 1.05 *A* GeV	12 MeV cm² / mg
GSI (mCBM)	Xe, 1.3 *A* GeV	5 MeV cm² / mg

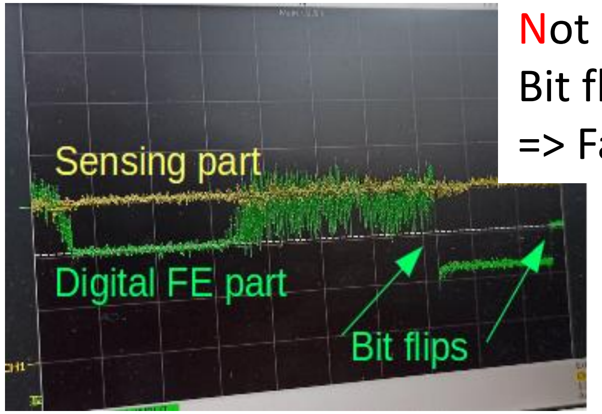
Few hours in Parasitic mode

- Beam intensity up to 20 MHz/cm²
- Dosimetry: Beam instrumentation, foil (both not really accurate)

Observations (~ 1 *A* GeV ions)



Expected:
"Latch-ups"



Not expected:
Bit flips exist and modify currents.
=> False LU – signatures?

	Pb, 12 MeV cm² / mg	Xe, 5 MeV cm² / mg
LU	71 (LU + Bit flip)	17
Bit flip		149
Ions on sensor	~ 3 x 10^9	~ 10^{11}
σ per 5.3cm² sensor	1.2 x 10^{-7} cm²	LU: 9 x 10^{-10} cm² BF: 8 x 10^{-9} cm²

preliminary

→ LU if not recoverable with soft reset.

→ BF if recoverable with soft reset.

} Uncertainty rough factor 3 (dosimetry)

- LU cross section seems in acceptable range.
- High bit flip cross-section.

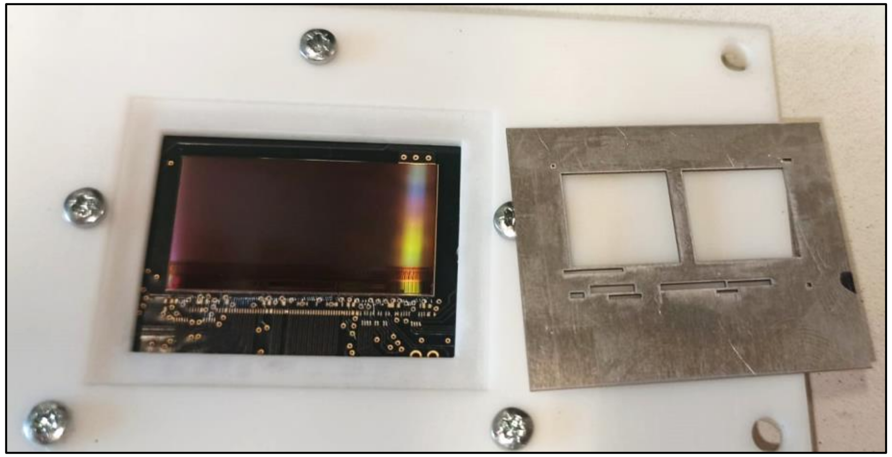
Bug in Hamming Code implementation. Fixed in MIMOSIS-2.
Recovery may require hard reset…

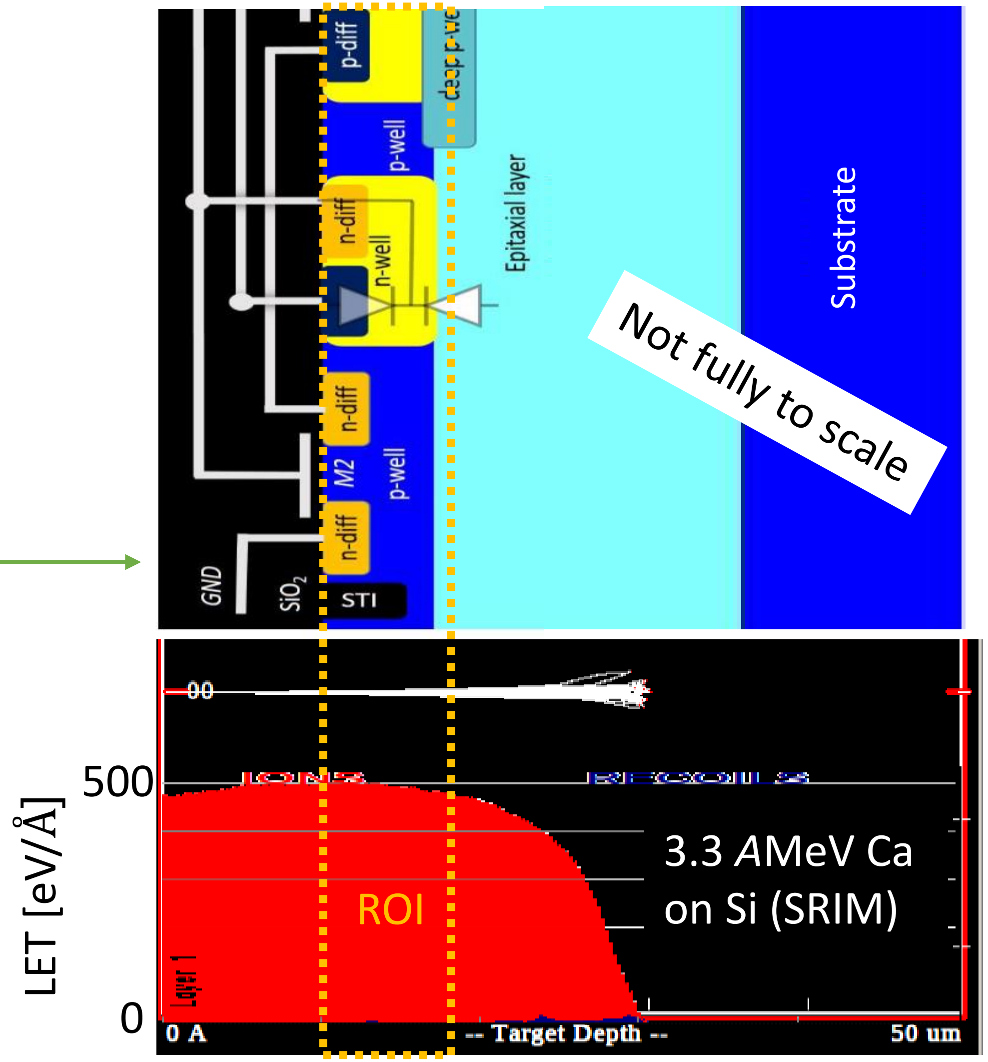
1. Results match requirements. Sensor bug spotted and fixed.
2. Hard to distinguish BF and LU, major bias possible.

Test at GSI - M3 beam line

	M3 @ GSI UNILAC
Energy / ion type	3.2 *A* MeV Ca
Beam spot	1.5 x 1.5 cm² mostly uniform
Beam time structure	5 Hz pulses of 6 ms
Beam intensity (mean)	~ 10^7 Hz/cm²
Beam intensity (pulse)	400 MHz/cm²
Dosimetry	Dedicated installation

Low beam energy: Sufficient to reach vulnerable structures? OK





New strategy:

- Use masks to isolate building blocks (most sensitive and representative as chosen by the designers)

Results

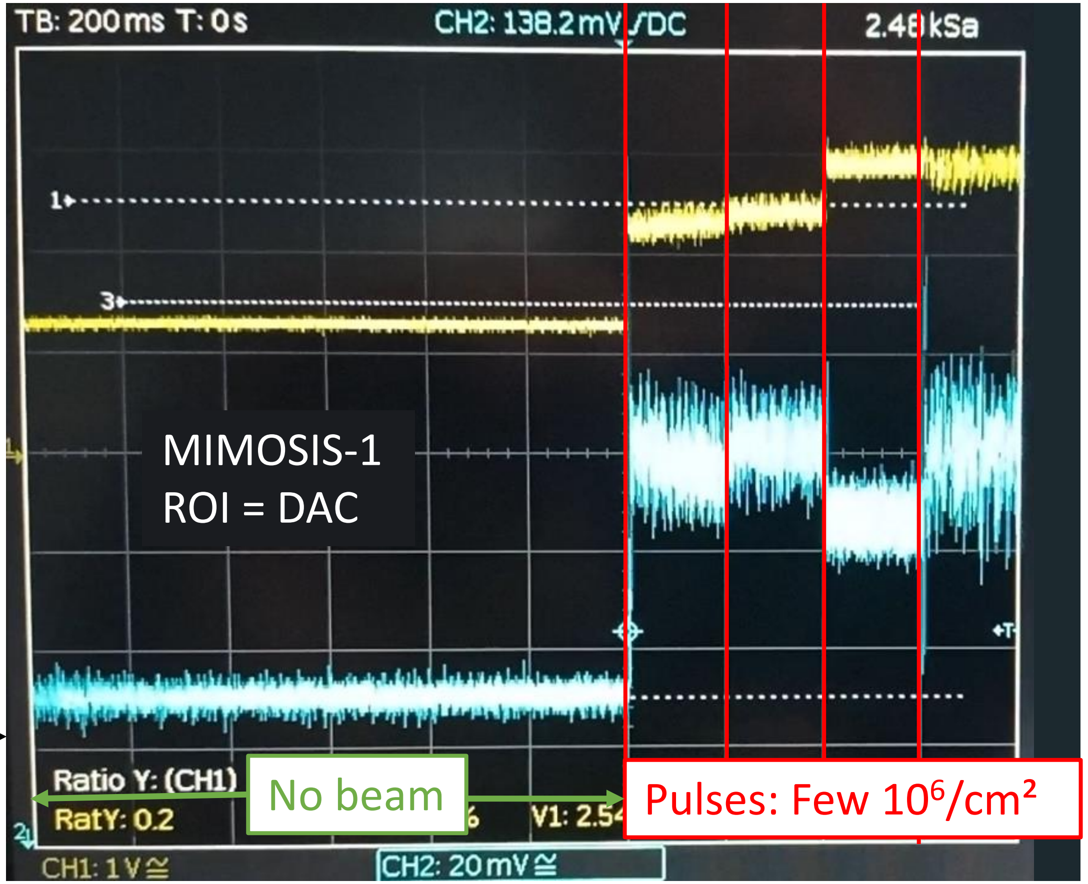
Latch-up:

	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 (but sensor senses ions).
=> Why discrepancy with previous results?

Observation on DAC:
- Bit flips in DAC generate current fluctuation.
  ⇒ will shrink after Hamming code bug fix.
- Cross-section not acceptable
  ⇒ will shrink after Hamming code bug fix.
- System instable, no detailed study possible.

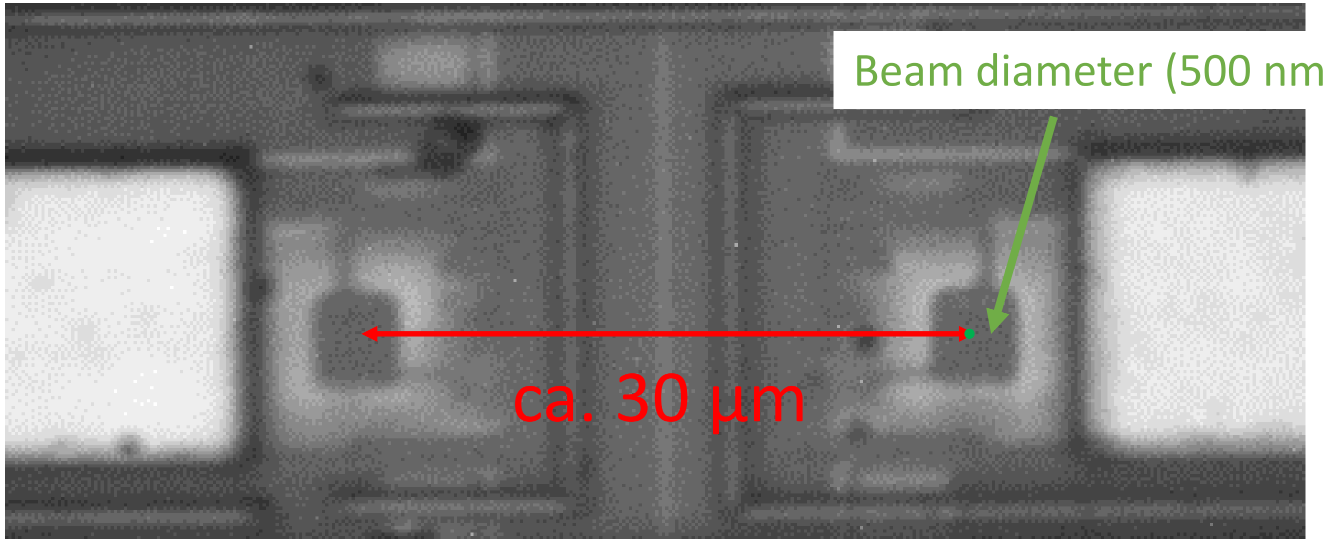


Previous observed latch-ups likely falsely interpreted bit flips in DAC.
⇒ Latch-up cross-section orders of magnitude better than required (all structurs except DAC) .

Outlook: Bit flip cross-sections

Beamline: GSI UNILAC X0
Beam: 4.8 *A* MeV Ca
Beam intensity: ~120 Hz
Beam diameter: 500 nm, raster scan possible.

Mode: Write and read back RAM.



Micro-Beam: Microscope view of the pixel area

Block	Window size	Ions	Bit flips to (1/0)	p [1]
DAC digital part	320 x 40 µm²	148/µm²	1140/902	1×10^{-4}
RAM	50 x 80 µm²	528/µm²	3030/4278	6×10^{-3}

Reminder:
Should be 5×10^{-8} over full sensor.

↑ Work in progress

Result depends on good choice of window. => Numbers subject to update.

Further data analysis needed (e.g. consider surface of RAM cells, beam to device alignment etc.)
Preliminary conclusion:

- Protection of status registers indeed required.
- Expect <200 data errors /s and sensor in the MVD.

Summary

MIMOSIS will be the sensor of the CBM-MVD.

- 5 µs, 5µm resolution, 80 MHz/cm² peak rate, continuous readout.
- 1024 x 504 pixels of 27x30 µm² pixels (fully depleted).

MIMOSIS-1 was tested for its tolerance to heavy ion impacts at GSI.

- Latch-up cross section <1.5 x 10^{-10} cm² at LET 20 MeV cm²/mg
- Beam intensity similar to beam loss scenario => successfully tested
- Unexpectedly many bit flips:
  - Bug in the Hamming code protection of status registers found and fixed.
  - Expect problem solved for MIMOSIS-2

Data for measuring bit flip cross-sections was taken, analysis under progress.

So far: MIMOSIS-1 matches the requirements of the CBM-MVD.

CBM-MVD collaboration members

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