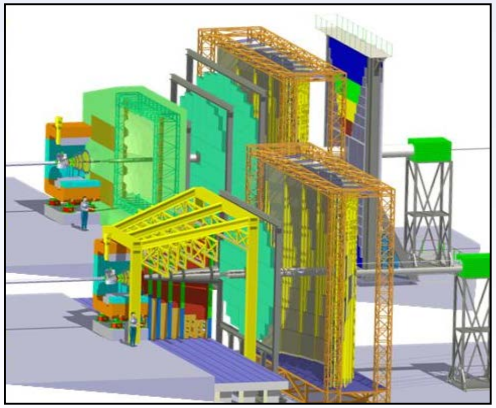
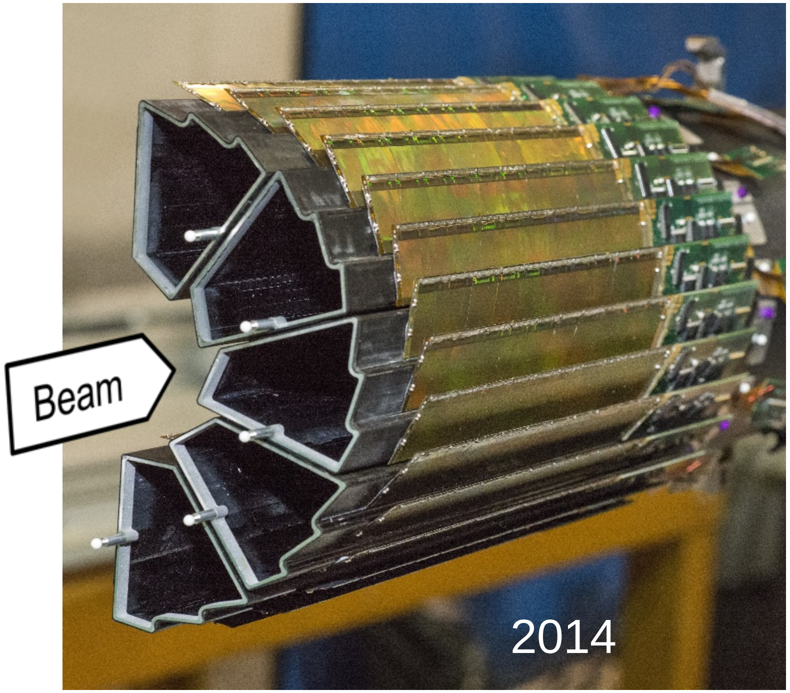
The beam halo requirements of CBM

… and what is being done to relax them.

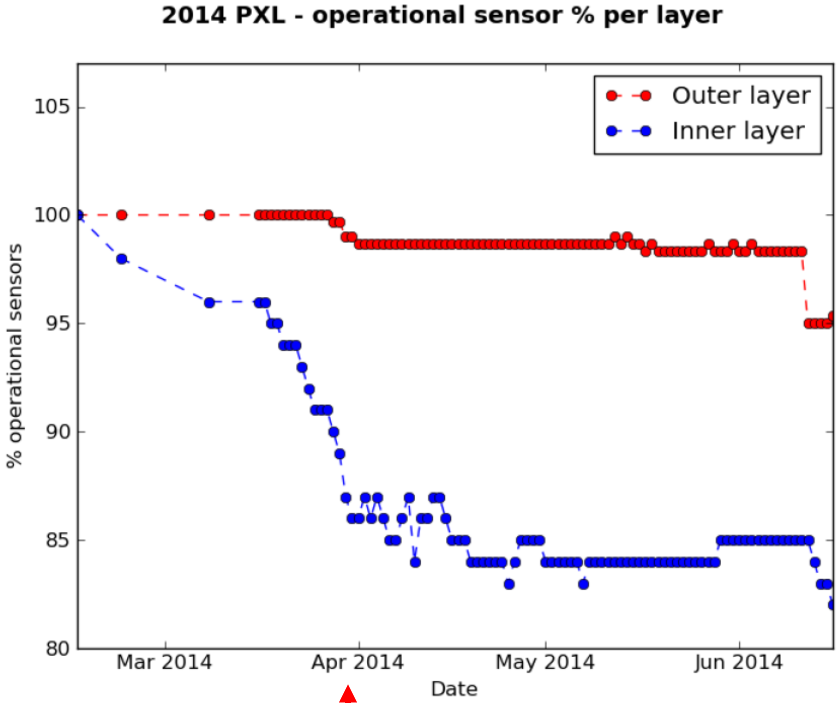
M. Deveaux, Goethe University Frankfurt
on behalf of the CBM collaboration.



Introduction: Beam damage in the STAR-PXL



One half of The STAR-PXL detector.



G. Contin, the STAR collaboration, 2016 JINST 11 C12068

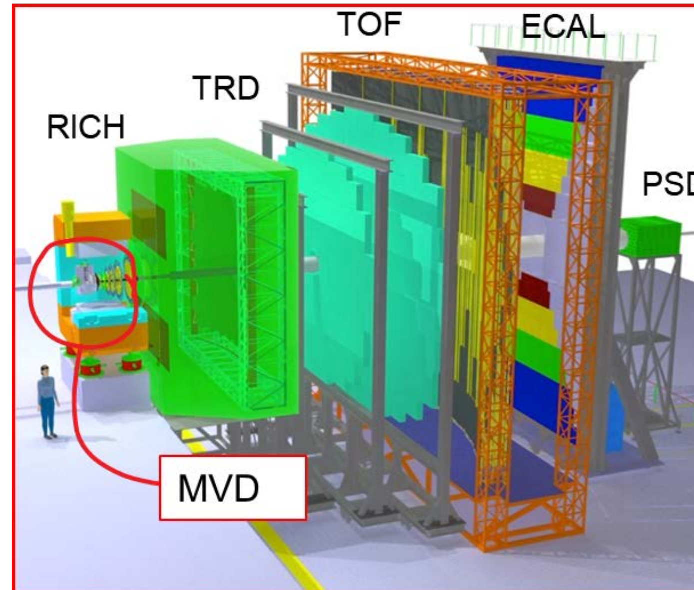
<u>Operation experience with the STAR-PXL (2014):</u>

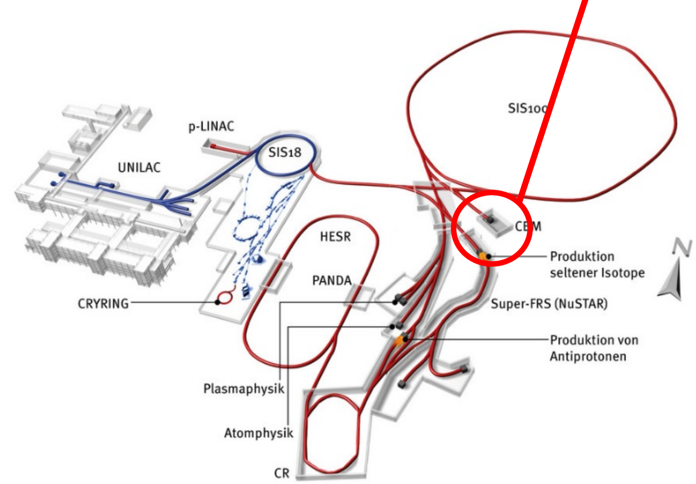
- Loss of 14% of sensors (inner layer) within 2 weeks.
- Anticipated origin: Impact of heavy beam ions (halo).
- Solved by modifying existing protection system.

Related system tests and existing latch-up protection strategy did not avoid incident.

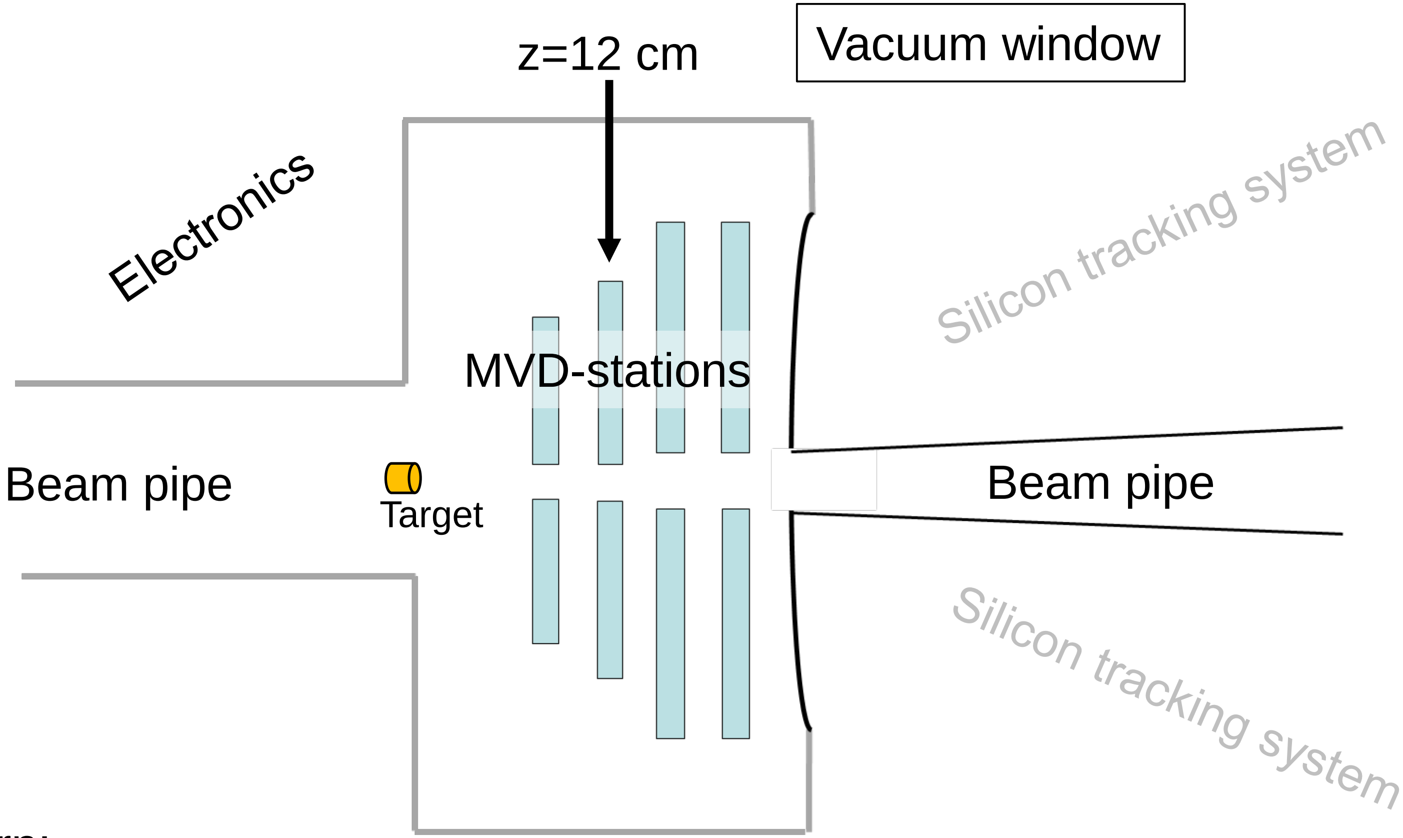
Outline

1. The CBM-MVD: Geometry and sensors.
2. Ion radiation damage in CMOS devices.
3. MVD sensor protection strategy.
4. Requirements on the beam.





The MVD region (not to scale)



Main concern:
- Radiation damage in sensors.

Worst case:
- Sudden death of sensors.

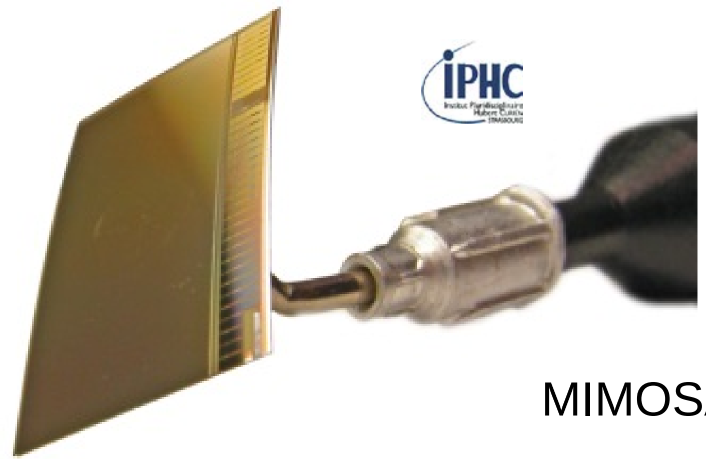
Our topic today

Main concern:
- Secondary reactions

Worst case:
- See secondaries instead of physics

CMOS Monolithic Active Pixel Sensor (MAPS)

	MIMOSIS design goal
Spatial resolution	~5 µm
Time resolution	5 µs
Pixel Pitch	30x27µm²
Thickness	50 µm
Rad. tolerance	~ 3Mrad
	3 x $10^{13} n_{eq}/cm^2$



MIMOSA-26

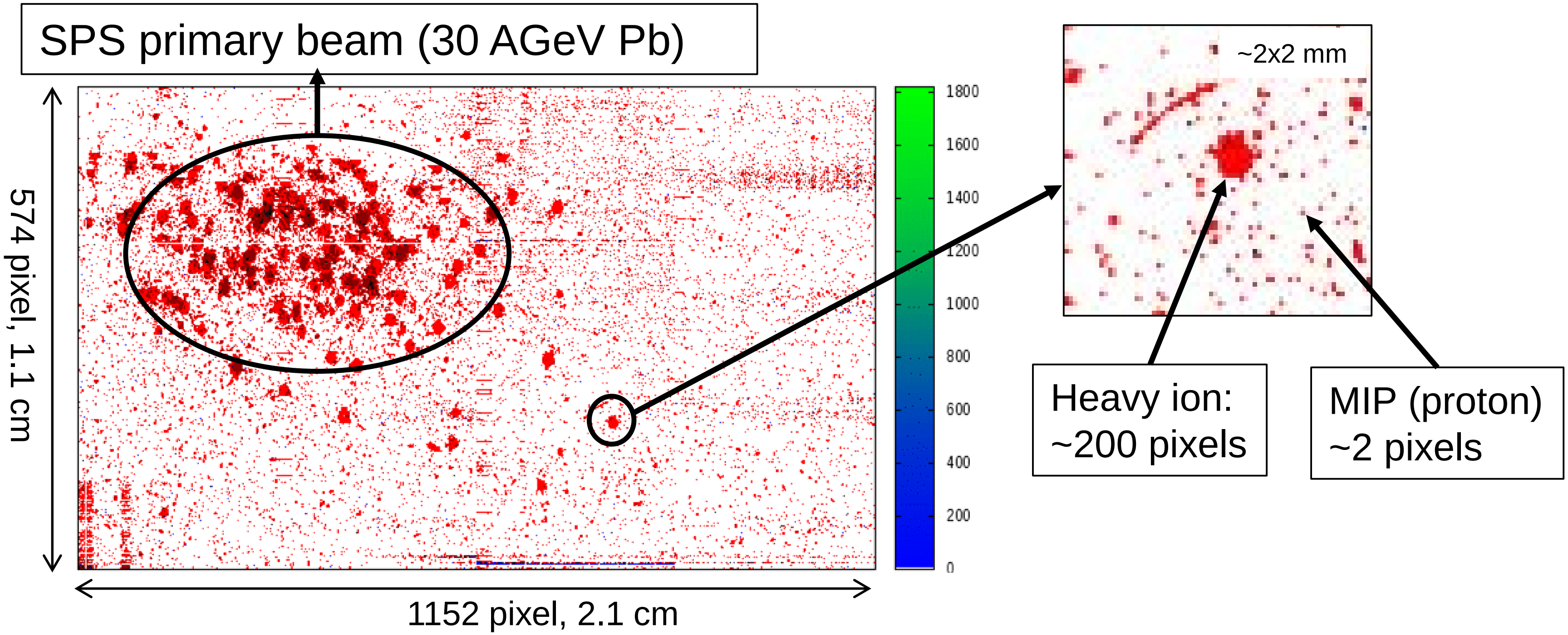
Pixel
- Sensitive to integrated radiation damage.

On-chip computer (etc.)
- Mostly sensitive to sudden (Single Event) Effects.

Radiation hardening techniques exist in both fields…
… but will not do miracles.

Using a MAPS as beam monitor…

Test carried out by the NA61/SHINE collaboration.



An Au-ion creates ~6200 x more ionization than a proton.
⇒ More radiation damage.
⇒ More charge at unwanted places (e.g. in memory cells)

On "sudden damage"

"Sudden damage" in digital electronics

Single event effect

Latch up

Single event upset (e.g. bit flip)

Impact of ions

Integrated damage

Ionizing (TID)

Non-Ionizing

"Slow damage" in sensors

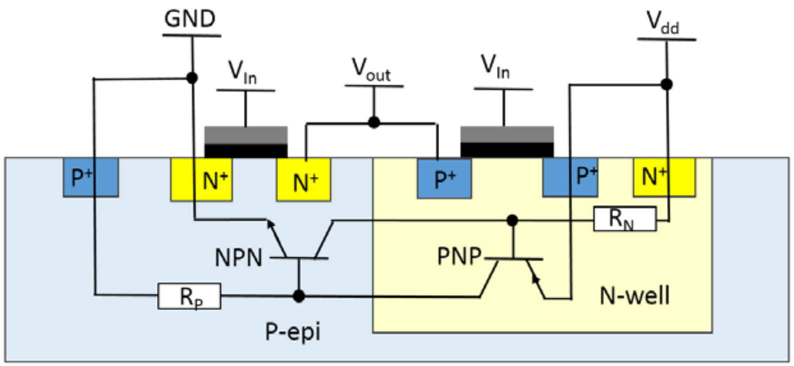
What do we know on latch up?

Latch up:

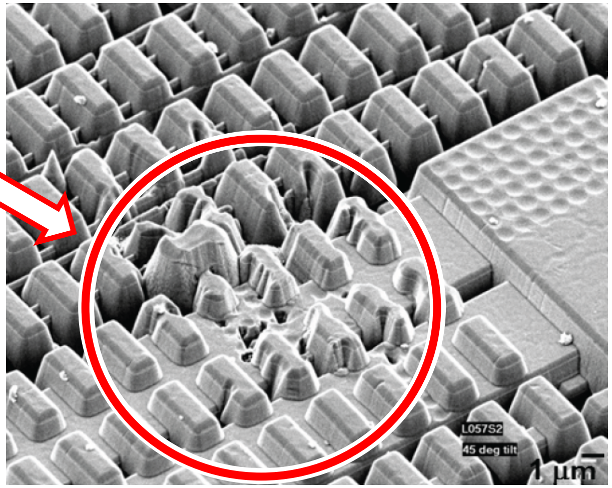
Ion creates short circuit in vulnerable CMOS-structures.

Reversible, may be cured by power cycling.

No power cycling => Thermal destruction of the device.



Vulnerable structure: e.g CMOS inverter.



Created the STAR-incident.

- Automatic power cycling installed but initially too high reaction threshold.
- Reason: Thin sensors more vulnerable than the thick ones used for test.

G. Contin, 2016 JINST 11 C12068

Situation at CBM:

MIMOSIS might be immune to this (operates at 1.8V instead of 3.3V).
MVD will be equipped with improved latch-up protection hardware.

Should avoid sensor losses. Still system up-time might be affected.

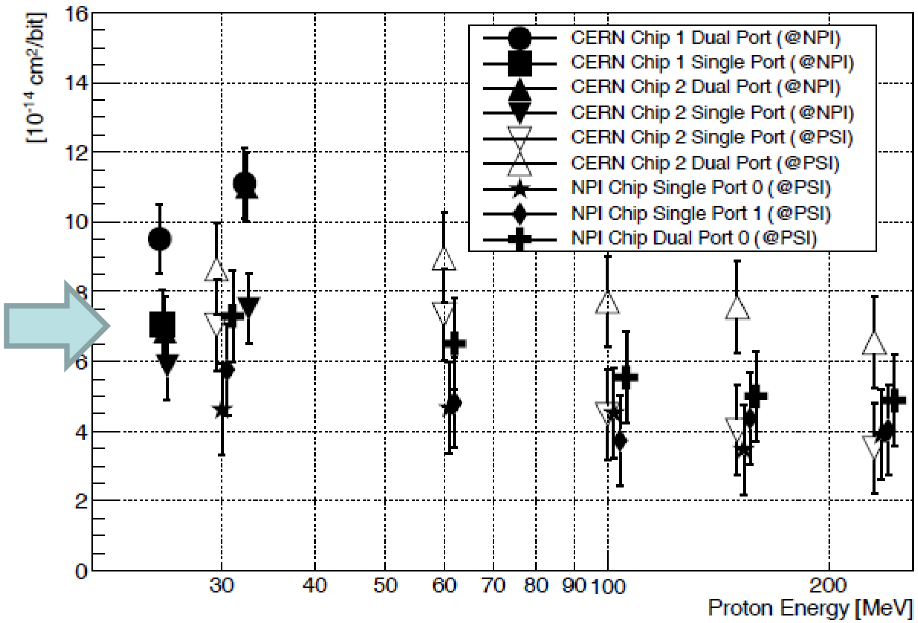
What do we know about bit-flips?

Bit flips in CMOS devices

Vulnerability depends on CMOS process and memory design.

Results for MIMOSIS-like devices exist for protons.

Tests for ions pending. Expect higher rates.



B Abelev et al and The ALICE Collaboration 2014, J. Phys. G: Nucl. Part. Phys. 41 087002

What is done about it at CBM:

All important steering units of MIMOSIS will be carried out in triple-vote-logic.
⇒ Sensor may detect and correct individual bit flips e.g. by reset.

Data memories are not protected
⇒ Data may be corrupted. Impact on over all data quality is marginal.

Should avoid system fail. Still system down-time for recovery may add up… .

“Slow” radiation damage

“Sudden damage” in digital electronics

Latch up

Single event effect

Single event upset (e.g. bit flip)

Impact of ions

Ionizing (TID)

Integrated damage

Non-Ionizing

“Slow damage” in sensors

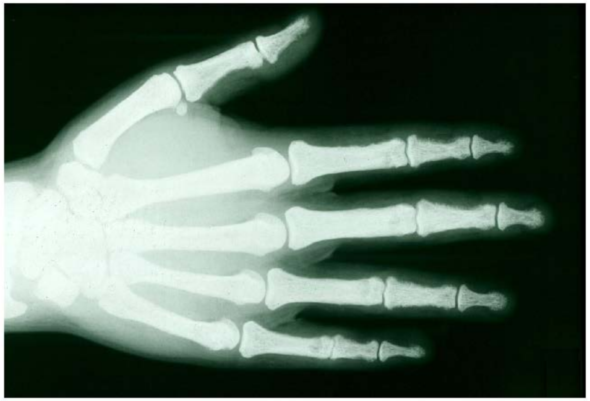
Integrated damage

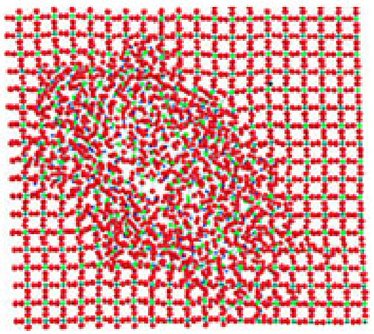
To be measured and improved: Radiation hardness against…

Ionising radiation:

- Energy deposited into the electron cloud.
- May ionise atoms and destroy molecules.

=> Damage in transistors and photo diodes.





Non-ionising radiation:

- Energy deposited into the crystal lattice.
- Atoms get displaced.

=> Damage in photo diodes.

Farnan I, HM Cho, WJ Weber, 2007. "Quantification of Actinide α-Radiation Damage in Minerals and Ceramics." *Nature* 445(7124):190-193.

Both damage mechanisms add up.
=> Must validate immunity to each individual damaging mechanism.

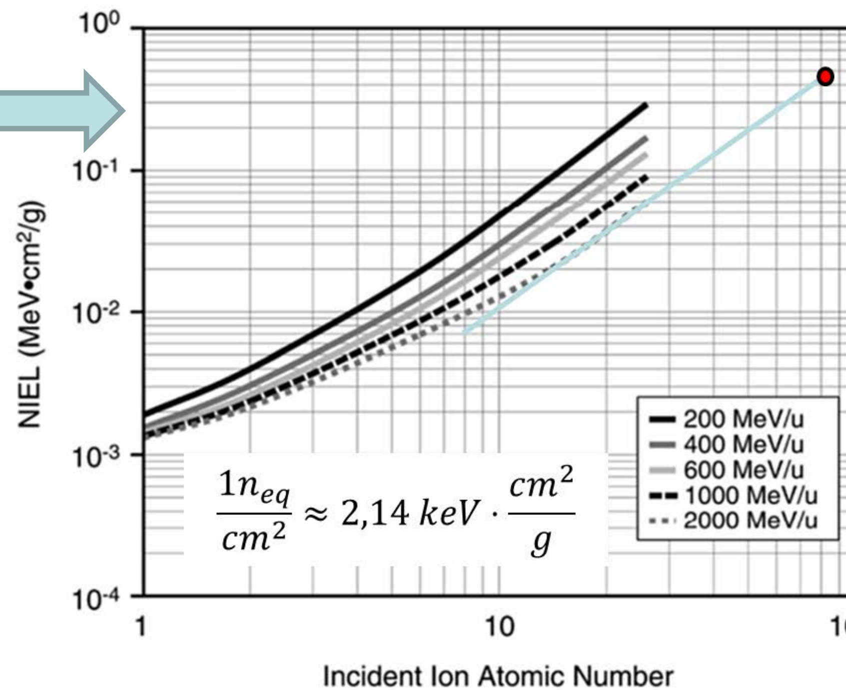
Integrated damage (non-ionizing)

Few knowledge, mostly theory calculations for space/satellite community.

CBM energy range not covered, guess work based on extrapolation done (initially for NA61/SHINE).

Results suggests:
Pb-hardness factor $\approx 300\ \mathrm{n_{eq}/cm^2}$.

No empiciral data available (to the best of my knowledge) => Tests needed.

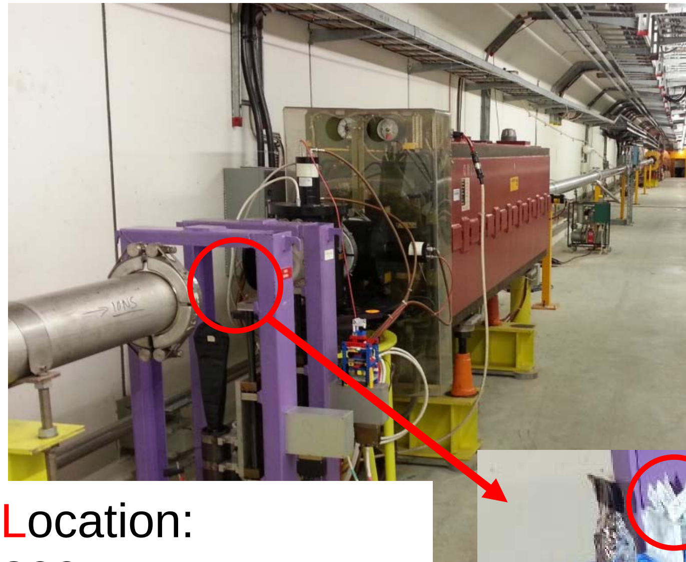


Pb A=81
Au A=79

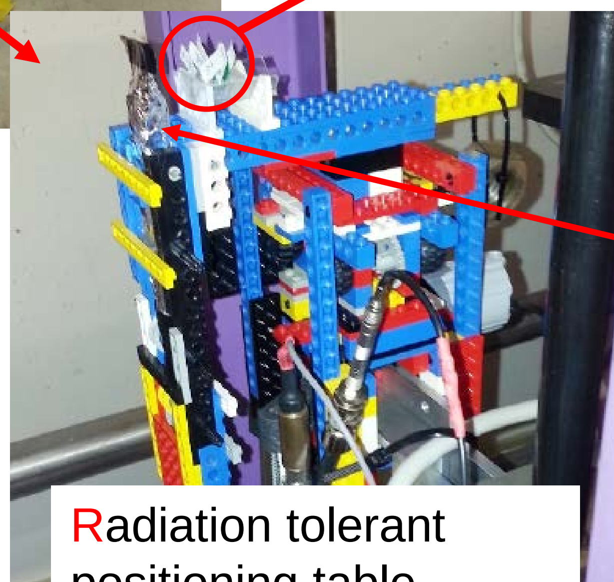
M. A. Xapsos, et al., IEEE TNS Vol. 51 (2004), P. 3250-3254

=> Test campaing started together with NA61/SHINE at the CERN/SPS

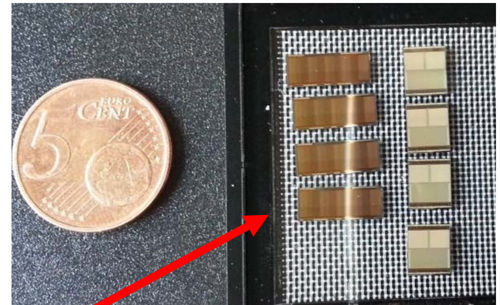
Integrated damage (non-ionizing)



Location:
200m upstream
NA61 target.



Radiation tolerant
positioning table



MIMOSA-34THR
Tower/Jazz 0.18µm CMOS

Dosimetry:
4x4mm² scintillator

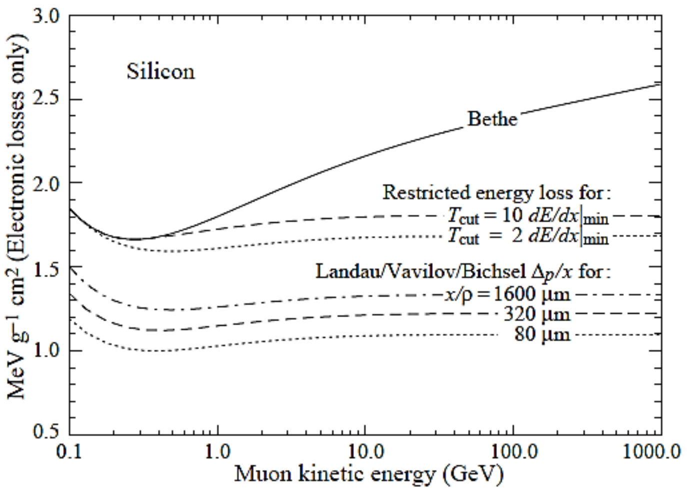
Dose reached:
1.2×10^{10} Pb/cm² (30*A* GeV/*c*)

Result: Conversion factor confirmed (1 Pb-Ion < 300 n_{eq}/cm²)

Integrated damage (ionizing)

Idea:

Rely on Bethe-Bloch-Equation.



Projectile charge

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

⇒ Dose: $D[\text{krad}] \approx \Phi \left[\frac{\text{ions}}{\text{cm}^2}\right] \cdot z^2[1] \cdot 2.86 \times 10^{-11} \text{krad} \cdot \text{cm}^2$

⇒ Holds for “minimum ionizing particles”, expect higher damage e.g. for target fragments (not covered today).

Maximum halo rates allowed (normal operation)

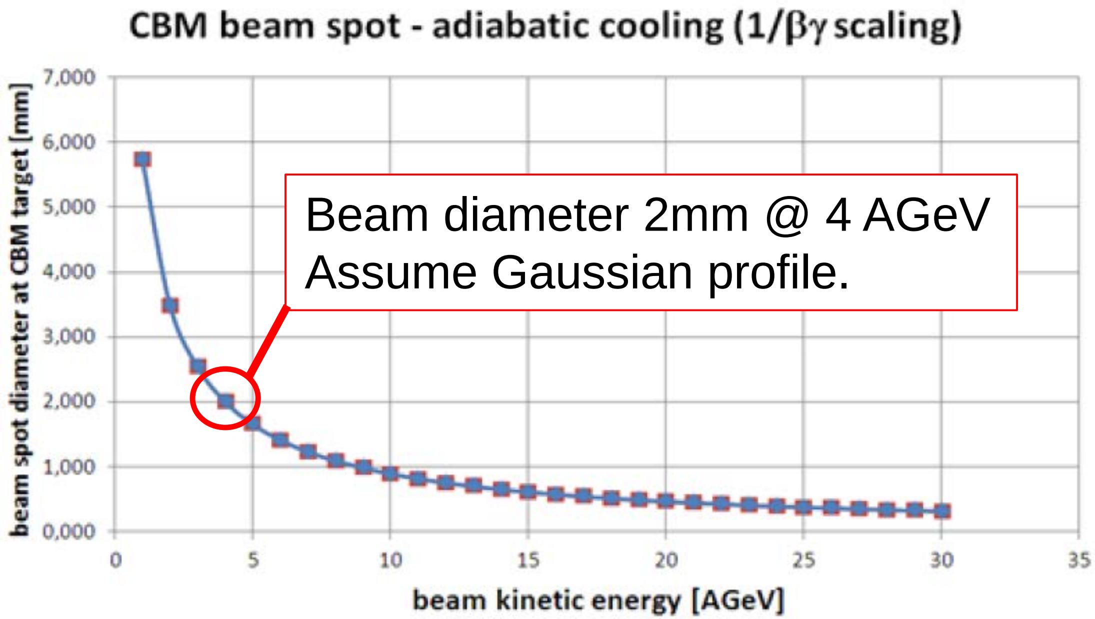
Most exposed detector – MVD:

- Max. 100 kHz Au-Au or 10 MHz p-Au (collision rate).
  => Beam intensity 10^7 Au/s, 10^9 p/s with 1% interaction target.
- Integrated damage must not exceed 30% of projected sensor radiation tolerance within 1 year of operation.

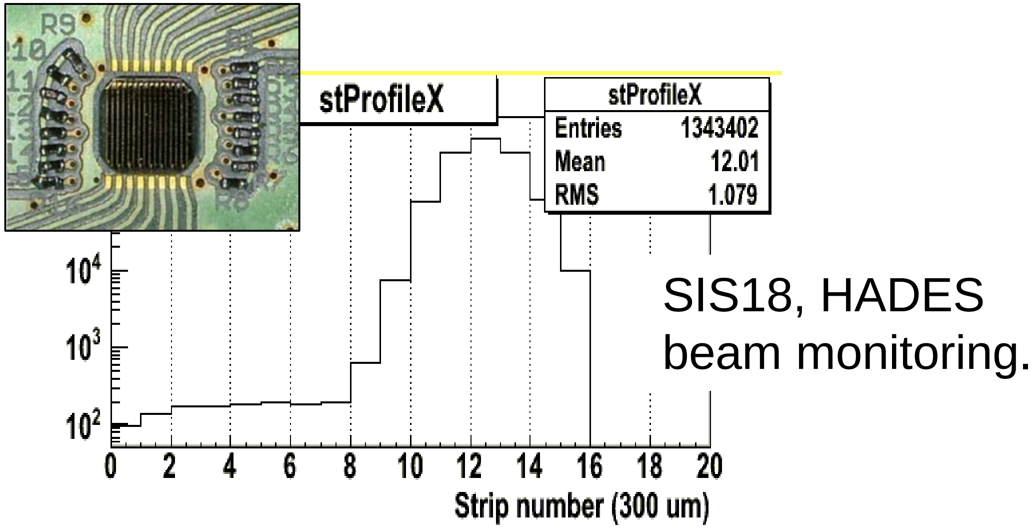
	Protons	**Au-ions**
Max. flux (to respect ioninzing dose limit).	60 kHz/mm²	10 Hz/mm²
Max. flux (to respect non-ioninzing dose limit).	1.8 kHz/mm²	60 Hz/mm²
Limit	1.8 kHz/mm²	10 Hz/mm²

Must be fulfilled for r=5mm from the ***nominal*** beam axis at z=5-12 cm behind the CBM target. Also in case the beam moves!

Requirement vs. information on beam



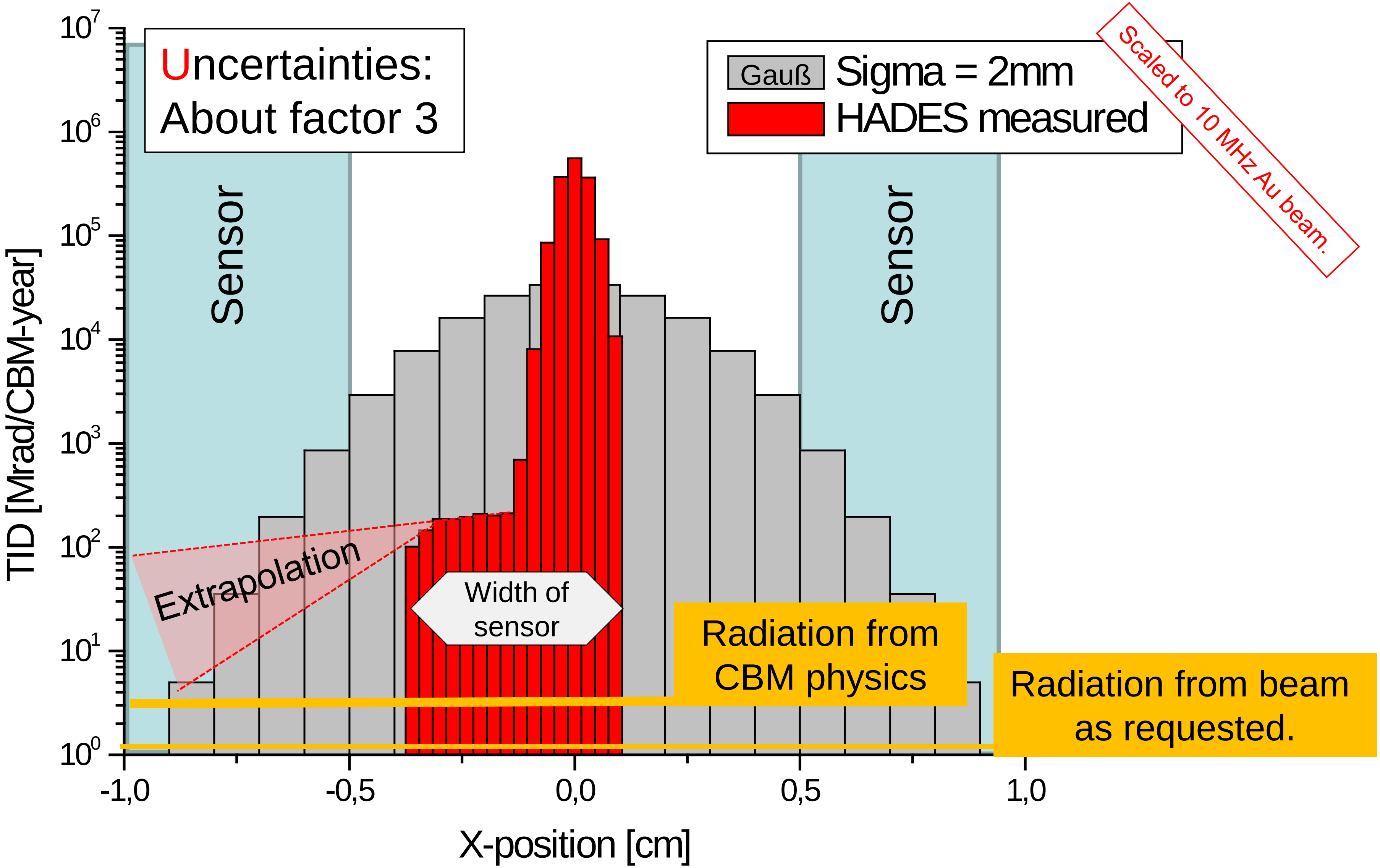
J. Pietraszko: "CBM+HADES in FAIR Beam Parameter Booklet", CBM Technical Board, 4. Sept. 2018.



J. Pietraszko, The Slow Extraction Workshop, Darmstadt, 1-3 June 2016

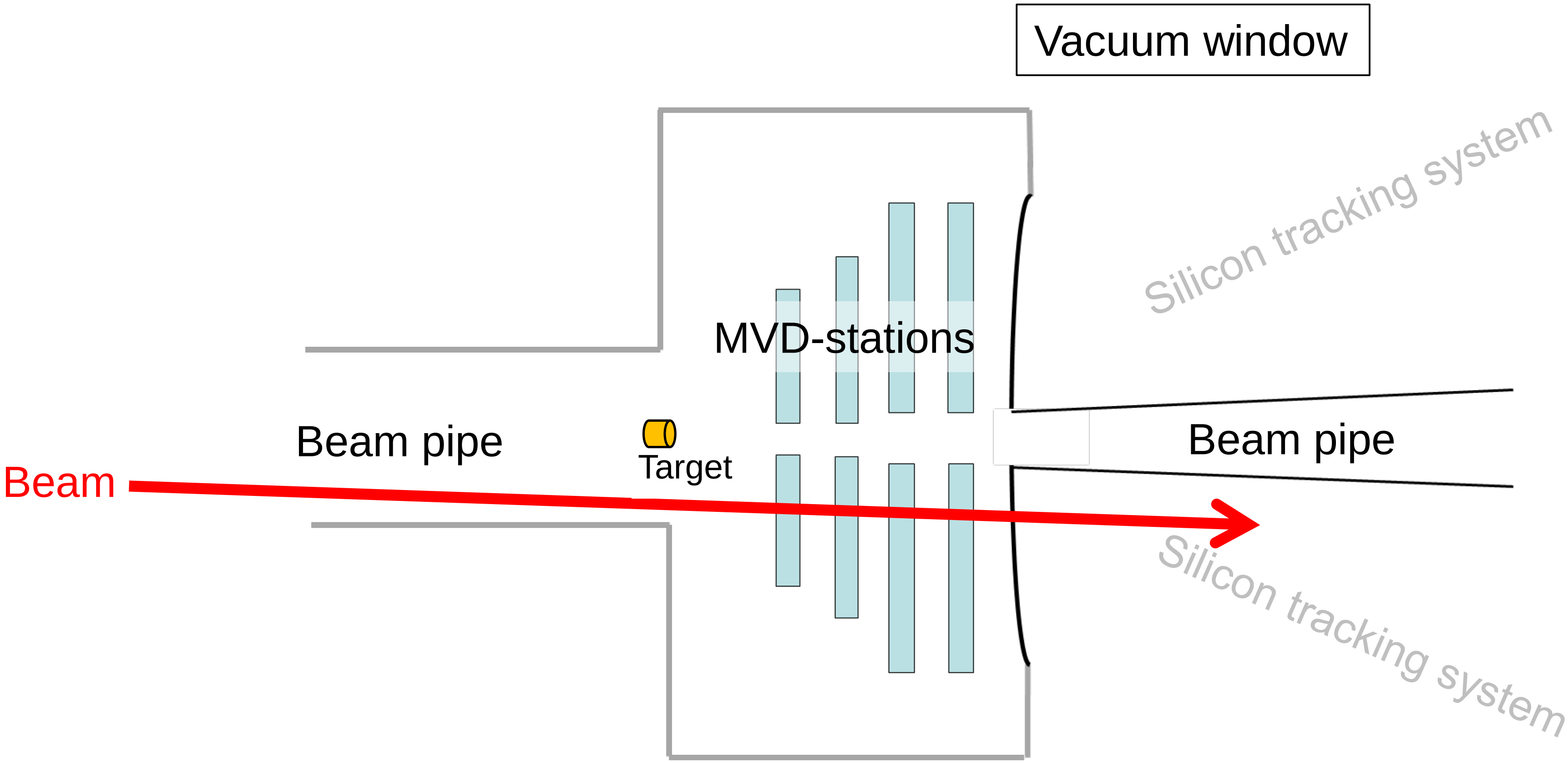
Note: Option of additional collimation (next talk) ignored.

Why I got worried…



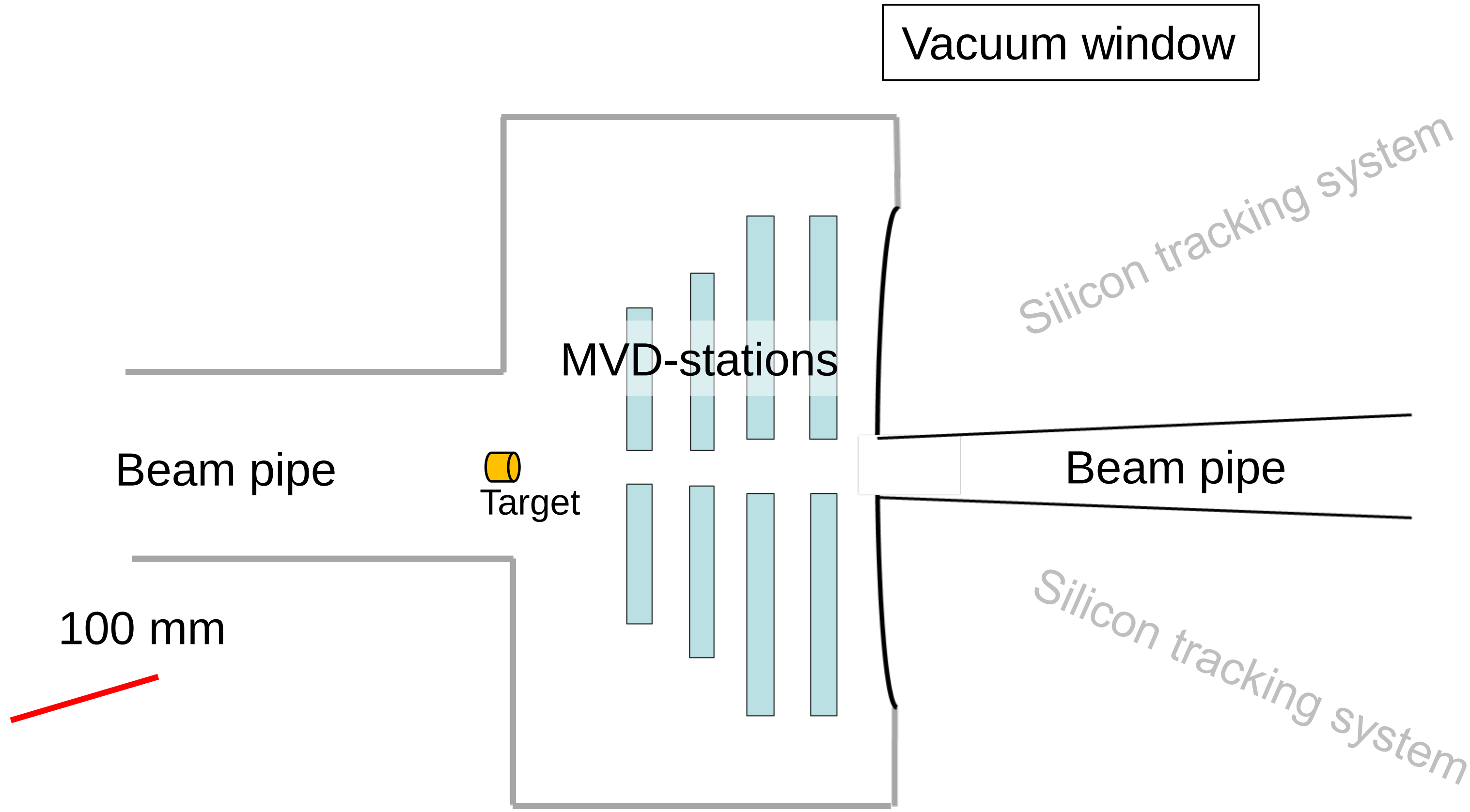
Radiation doses in both scenarios exceed the limit by orders of magnitude.
Beyond reach of sensor design => Help from accelerator community needed.

Beam loss to detector



The worry:
Beam steering fail => Detector is hit by full beam.
Consequences => Somewhat unknown (nothing to permanent fail).

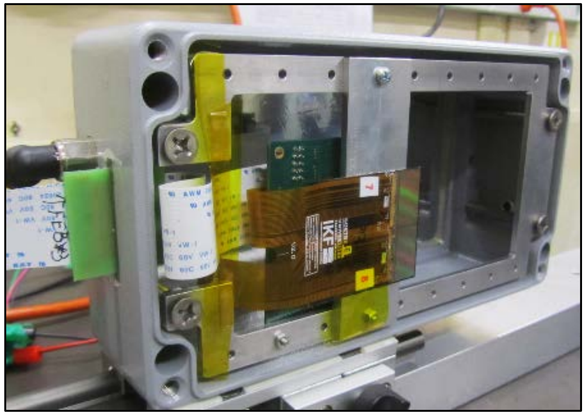
Measures for beam loss protection (beam tuning)

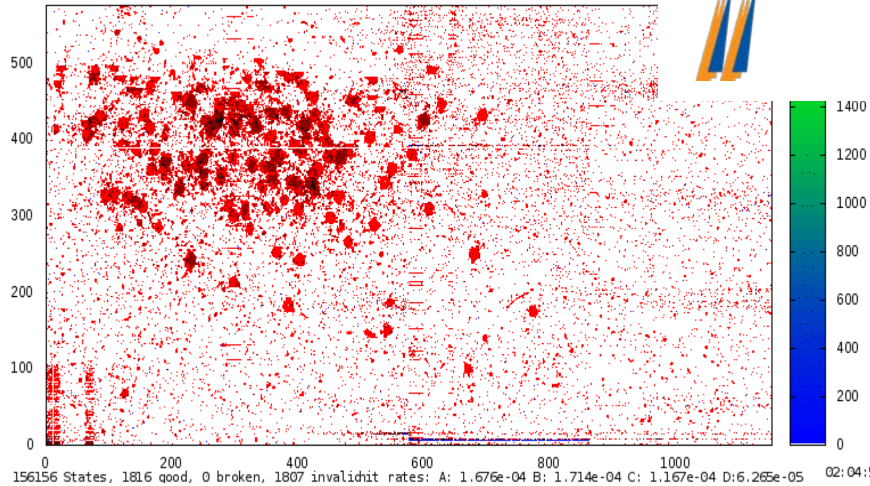


MVD will be equipped with moving engine:

- Power down and move out sensors during beam tuning.
- Movement will be slow (few minutes).
- Path to safe position should be minimized (major space concern).

Sensors – reaction to beam





MIMOSA-26 operated in direct SPS 30 AGeV Pb beam for ~24h
Observation @few kHz beam intensity:

- No obvious loss of functionality.
- Observed 3 latch-ups. One persisted several hours before discovery. Chip recovered after power cycling.

Sensor surprisingly robust. But test represents ~1 spill CBM.
=> Need to scale to CBM.

Beam impact studies (emergency stop)

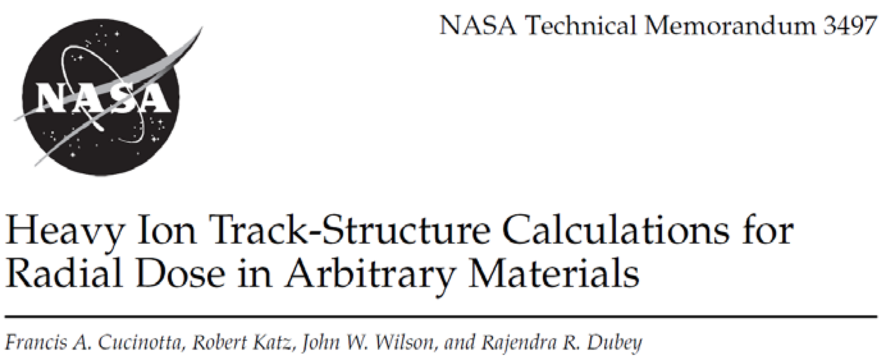
Idea:

Sensor tolerates charge of one ion at any point.
Assume no charge evacuation (time scale unknown).
⇒ Avoid overlaping hits by emergency beam stop.

Open issue:

To what surface is the charge of an ion distributed?

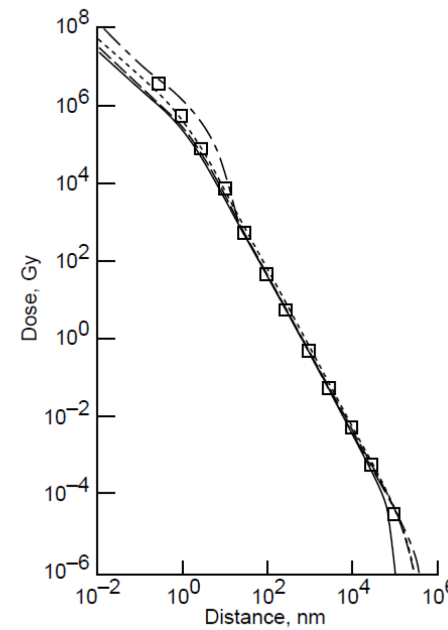
Input:



NASA Technical Memorandum 3497

Heavy Ion Track-Structure Calculations for Radial Dose in Arbitrary Materials

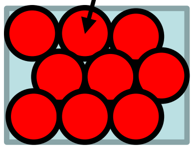
Francis A. Cucinotta, Robert Katz, John W. Wilson, and Rajendra R. Dubey



(g) For 90 MeV/amu ^{56}Fe ions.

Rough estimate: Most ion charge is concentrated in r=15μm.

Beam impact studies (emergency stop)



Assume beam with $f_{beam} = 10^7\ Hz$.
Maximum allowed number of Au - ions:

$$N_{max} = \frac{A_{Beam}}{A_{Ions}} \approx \frac{1\text{mm}^2}{\pi\ (15\ \mu\text{m})^2} = 1400$$

$$t_{max} = \frac{N_{max}}{f_{beam}} = 140\ \mu\text{s}$$

Shut within 140 µs needed.

Obvious: High uncertainties, includes corse assumptions on device physics and beam focusing...

Fast Beam Abort System @ FAIR FC2WG: M.S. Mandaković, CSCO 21.10.2015

Reaction Class	Reaction
0	no active reaction in due time possible: passive protection e.g. by collimators or redundancy of devices must be foreseen
1	a very fast beam abort within 40 µs and subsequent trigger within 600 µs of dumping magnet energy
2	a fast beam abort within about 1-5 ms and subsequent trigger within 600 µs of dumping magnet energy
3	a slow reaction within 100 ms is feasible and necessary
4	no reaction is necessary

Preliminary conclusion: Very fast beam abort system is required.
Note: Collimator, which defocuses/fragments the beam would already help (reduces z)

Summary and conclusion

Requirements on beam parameters (halo) were presented:

- Numbers driven by needs of CBM-MVD (avoid destruction).
- Numbers account for design safety features of MVD:
  - Advanced tolerance of sensors to integrated damage.
  - Latch-up protection system.
  - Triple vote logic for important sensor sub-systems.
  - Option to move sensors to safe position during beam tuning.

Beam halo limits for regular operation (r=5mm from beam axis):

	Protons	Au-ions
Limit	1.8 kHz/mm²	10 Hz/mm²

} Resonable precision

Reaction time for beam loss to detector: ~100 µs } Poor precision

Options of the detector community are mostly exhausted
=> Help from accelerator community is required.

Try to hit the target… and nothing else ☺

Radiation damage by ions in CMOS sensors

"Sudden damage" in digital electronics

Impact of ions

- Single event effect
  - Latch up
  - Single event upset (e.g. bit flip)
- Integrated damage
  - Ionizing (TID)
  - Non-Ionizing

"Slow damage" in sensors