DPG Spring Meeting Köln, 10.03 - 14.03.2025

Precision redefined: Unlocking new frontiers with Monolithic Active Pixel Sensors (MAPS)

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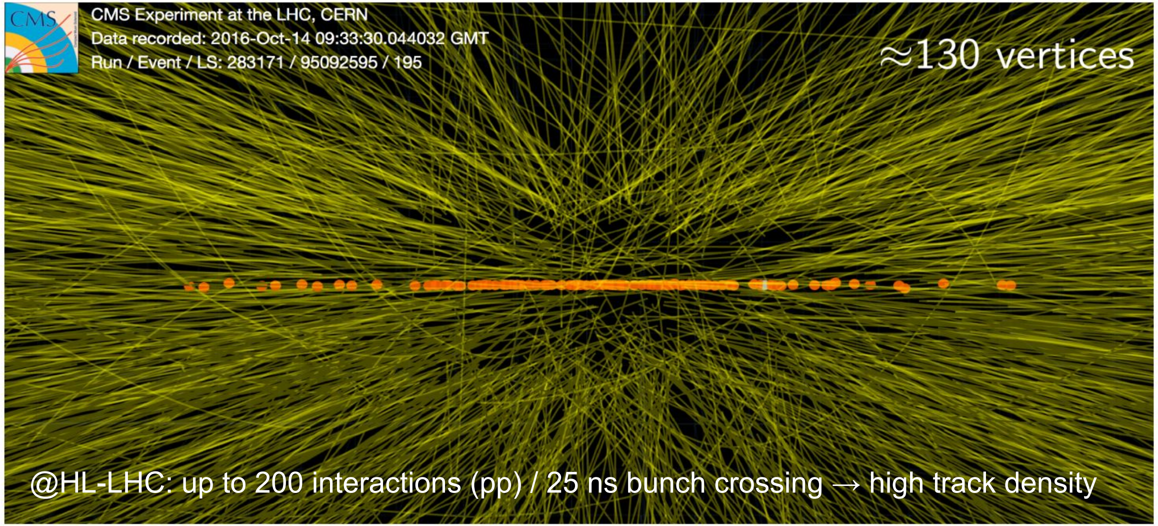
12.03.2025

CERN Courier

Tracking & vertexing at accelerators

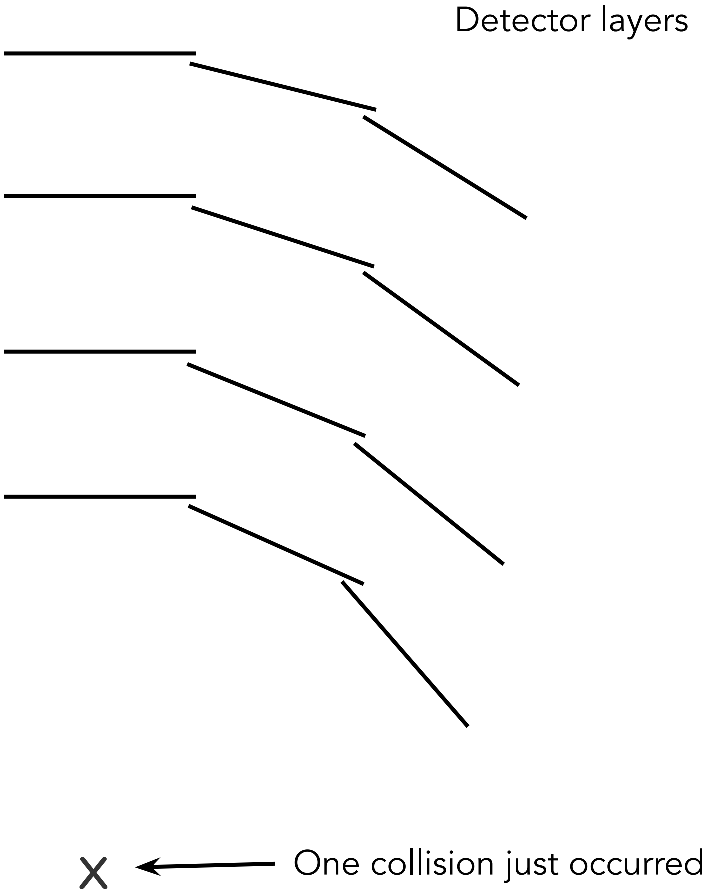
- A common challenge in experiments:
  confusion scales with the number of collisions and/or the **track multiplicity**
- How to tackle this problem in our trackers?



- The rise of **pixel sensors**
  - detectors at accelerators
- (some) current **MAPS**
  (monolithic active pixel sensor)
  technologies and advances

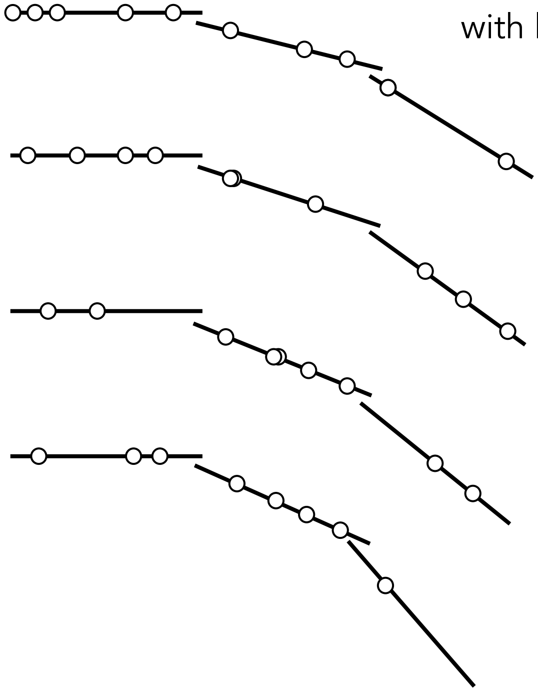
Information collated from various sources (list not exhaustive): ECFA, L. Linssen, E. Sicking, R. Santoro, A. Kluge, M. Mager, J. Pater, S. Spannagel, F. Hugging, M. Winter, L. Huth, P. Leitao, F. Reidt, W. Snoeys

From hits to tracks



From hits to tracks

Detector layers with hits



X ← One collision just occurred

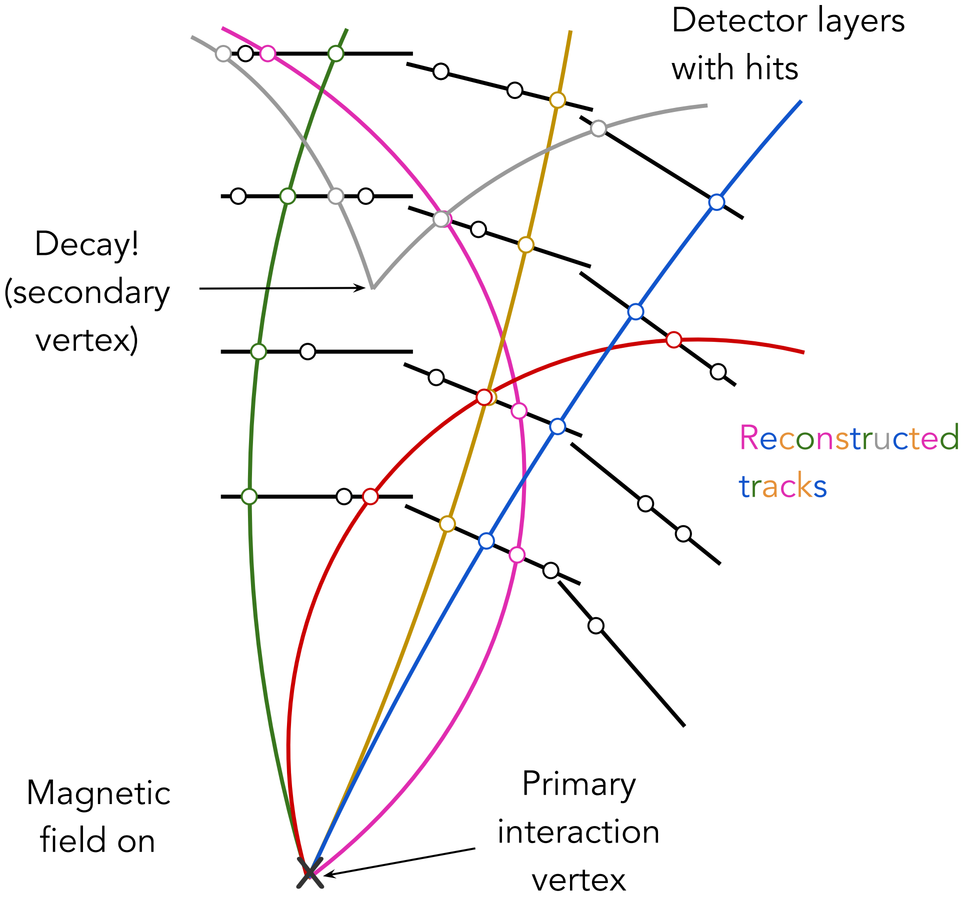
➠ **Snapshots** of collision

Canon EOS RP Mirrorless Camera

➠ Particles need to be tracked with detectors
  - **Surround** the collision point

➠ Name of the game: associate points to tracks (of particles)

From hits to tracks



➠ **Snapshots** of collision

Canon EOS RP Mirrorless Camera

We need just the sensor

➠ Particles need to be tracked with detectors
- **Surround** the collision point

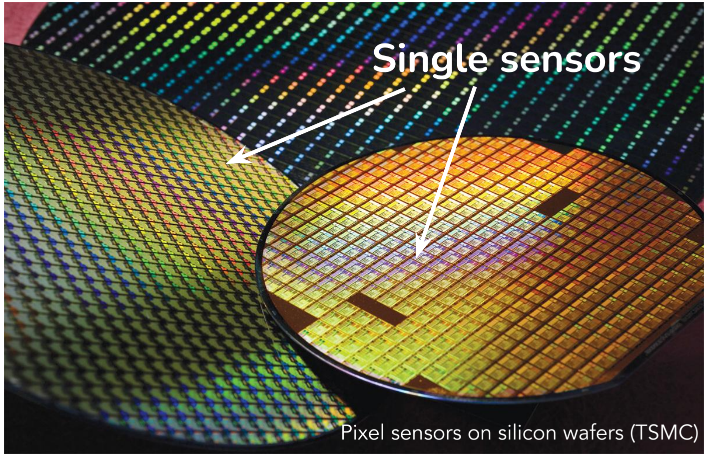
➠ Name of the game: associate points to tracks (of particles)
- **Pixel sensors**

Pixel sensors at accelerators

- ➠ Tracking & vertexing

- ➠ **High granularity**
- ➠ **Close to the interaction point**
  - ▸ harsh environment

- ➠ **Ubiquitous**
- ➠ Various designs for various experimental needs



Pixel sensors on silicon wafers (TSMC)

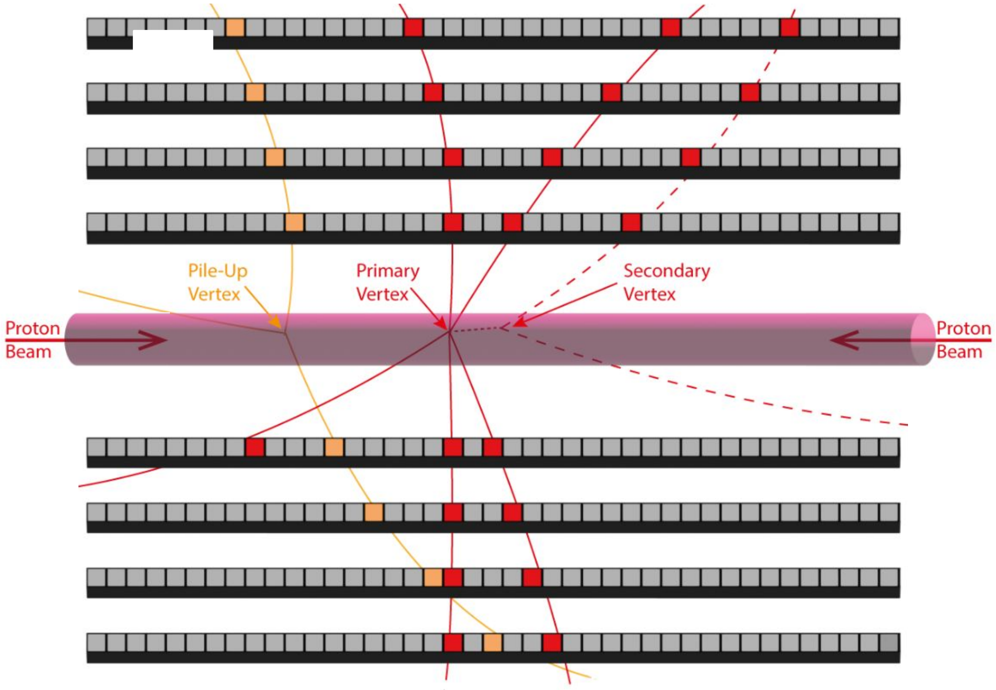
Requirements of a vertex detector

➠ **Position resolution** (~μm)
‣ where the particle was
→ distinguish secondary vertices

➠ **Timing resolution** (~ns)
‣ when the particle passed
→ Overlapping signals

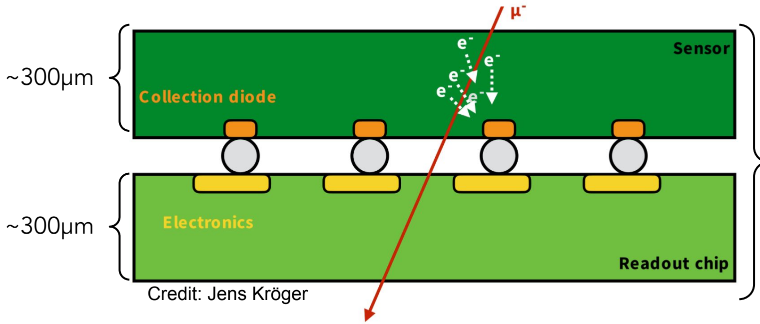
➠ **Efficiency** (>99%)

➠ **Radiation tolerance** (hardness)
‣ keep working under particle-induced radiation exposure



https://arxiv.org/pdf/2501.06896

Hybrid vs monolithic designs

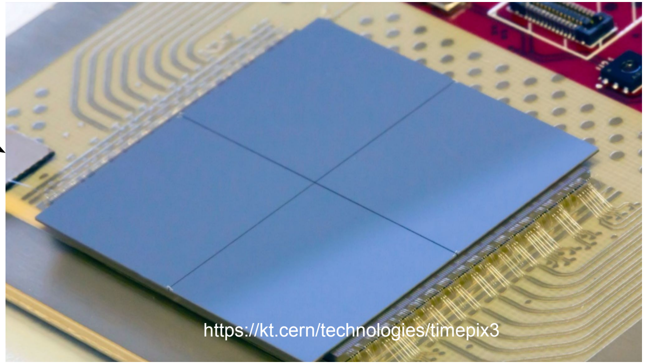


Hybrid pixel sensor

- high radiation hardness
- fast (charge collection via drift)
- complex fabrication
- large material budget (thick)

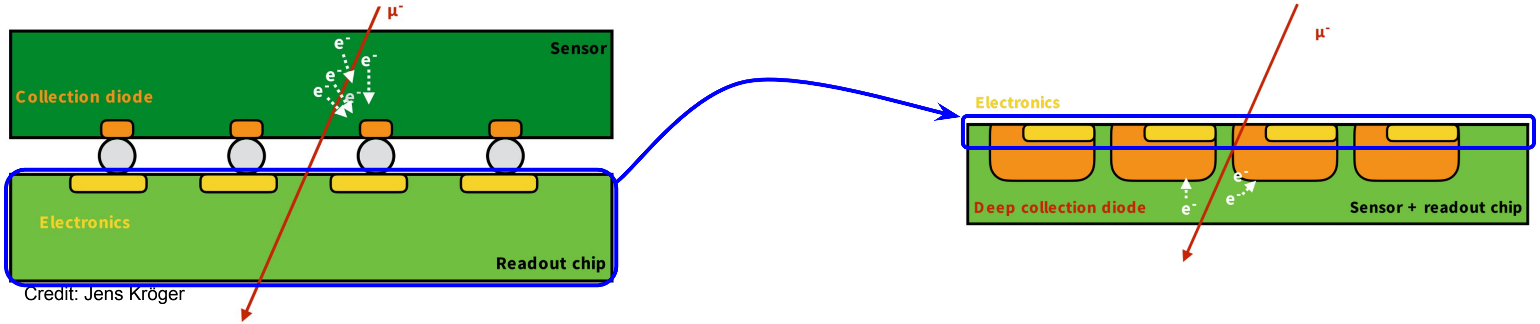
Example of readout chip: Timepix4 chip

- 4 edgeless Si sensors on top



Other examples: VeloPix, FE-I4, RD53A, ITkPixV2, …

Hybrid vs monolithic designs



Credit: Jens Kröger

Hybrid pixel sensor

- high radiation hardness
- fast (charge collection via drift)
- complex fabrication
- large material budget (thick)

Monolithic pixel sensor

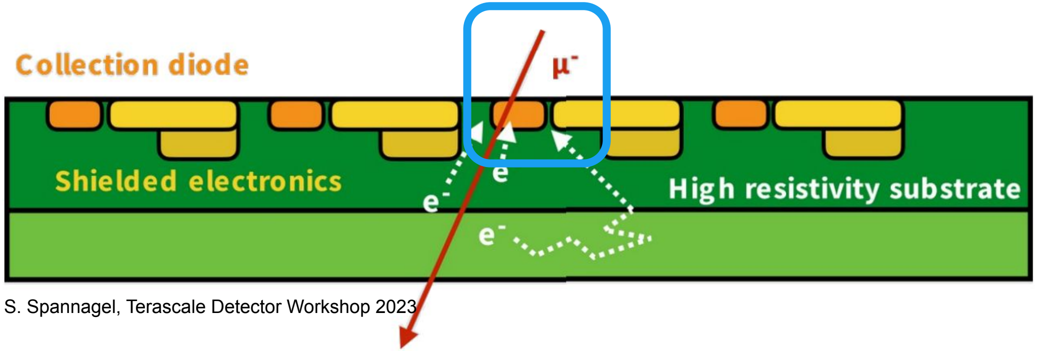
- moderate radiation hardness
- commercial process (cheap)
- complex design
- low material budget (thin)
- slow and fast → 2 variants

The technology choice is application driven

Working principle of MAPS

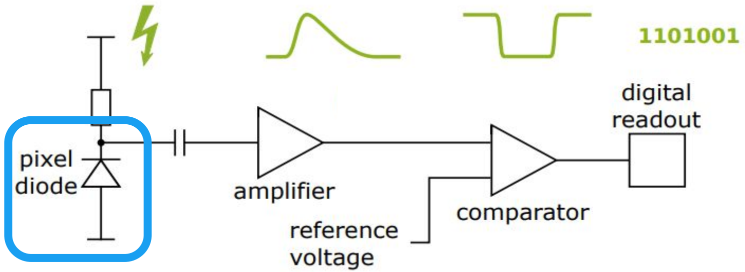
Operation principle of a CMOS MAPS:

- ➠ energy loss via **ionization** → electron-hole pairs
- ➠ movement (drift and/or diffusion) **induces a current**
- ➠ signal is **amplified & discriminated**



S. Spannagel, Terascale Detector Workshop 2023

Simplified schematic

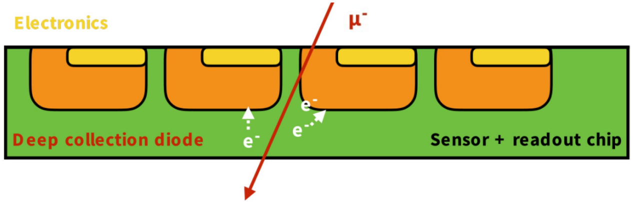


50 μm thin sensor → drift: ~1ns
→ diffusion: up to 100ns

Front-end can be made slow → less power consumption

HV-MAPS (High voltage MAPS)

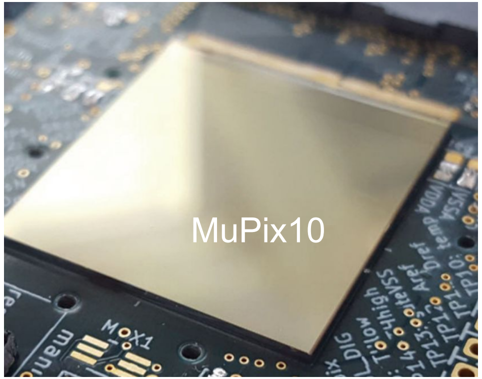
Large diode design



- ➠ **Large bias voltage** (~100 V)
- ➠ Radiation tolerance

- ➠ However, large diode
  - ▸ **large input capacitance** (>100fF ; noisy)
  - ▸ increased power consumption

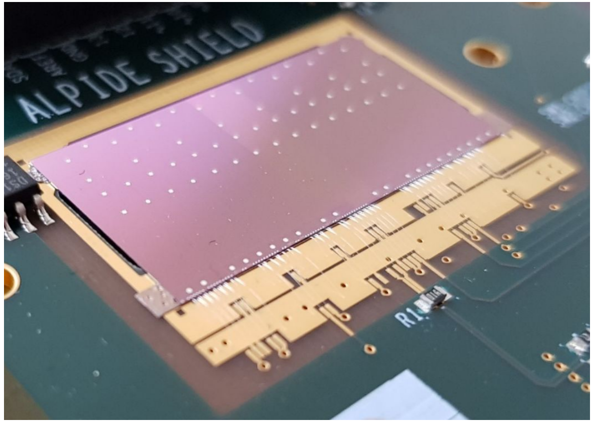
Example: MuPix family
- ▸ mu3e experiment



https://indico.psi.ch/event/11934/contributions/31741/attachments/20076/32580/Prep_Review_Mupix11.pdf

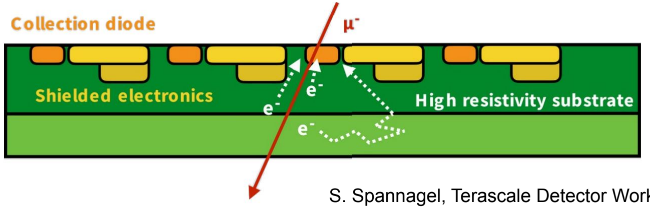
HR-MAPS (High resistivity MAPS)

Example: ALPIDE sensor
- ALICE experiment @ CERN → ITS



https://ep-ese.web.cern.ch/project/alice-its

Small diode design



S. Spannagel, Terascale Detector Workshop 2023

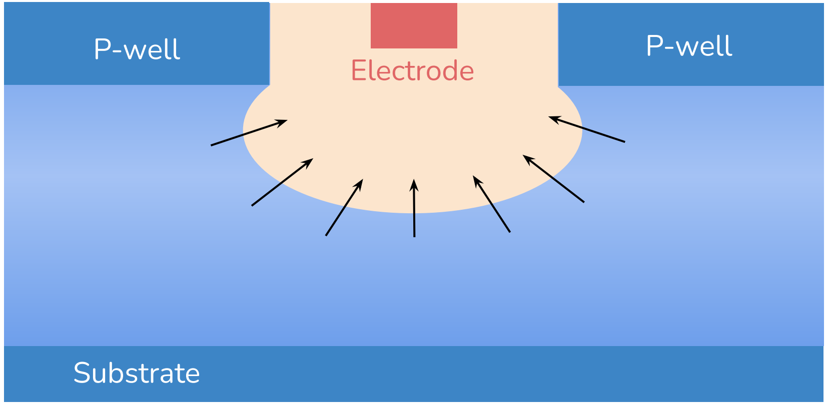
➠ **High-resistivity** material (less dopants)
➠ Small capacitance (little noise)

➠ Slow (front-end)
- **low power** → air cooling (low material)

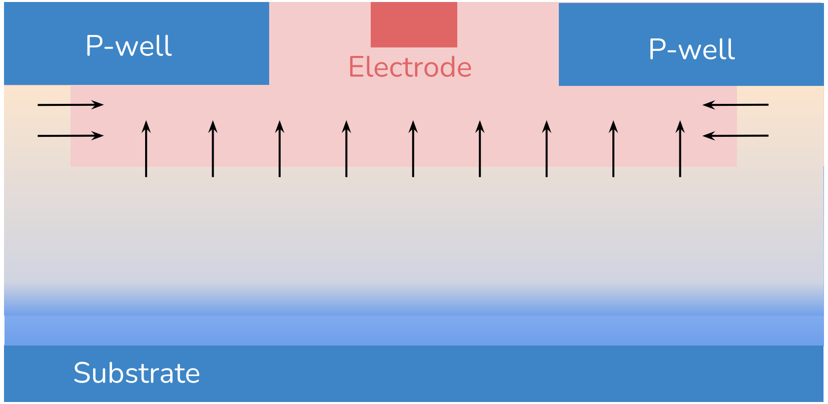
➠ Diffusion dominated
- **moderate** radiation hardness

Blurry line for HR-MAPS

Standard process



Modified process



Diffusion dominated

- sensor not fully depleted

improvement →

Drift dominated

- sensor can be fully depleted
- **improved radiation hardness** !!
- E_{field} in corners

➠ Distinction HV & HR-MAPS (fast vs slow ↔ radiation tolerance) not so obvious anymore

➠ **Still, the front-end is slow (intentionally!)**

- **low power dissipation → air cooling → low material budget**

Radiation hardness

- How well a sensor **withstands radiation** damage over time
- Pixel detectors built and installed → **no** way to **access** them for years!
- Two main types of damage:

Ionizing radiation → charge buildup

https://santafeglass.com/wp-content/uploads/2024/02/lfoggy-window-1.jpeg

Surface damage → electronics

High energy particles (eg: n, p) displacing Si atoms

https://www.reddit.com/media?url=https%3A%2F%2Fi.redd.it%2Ffx2rvnybbjwa1.jpg

Bulk damage → defects

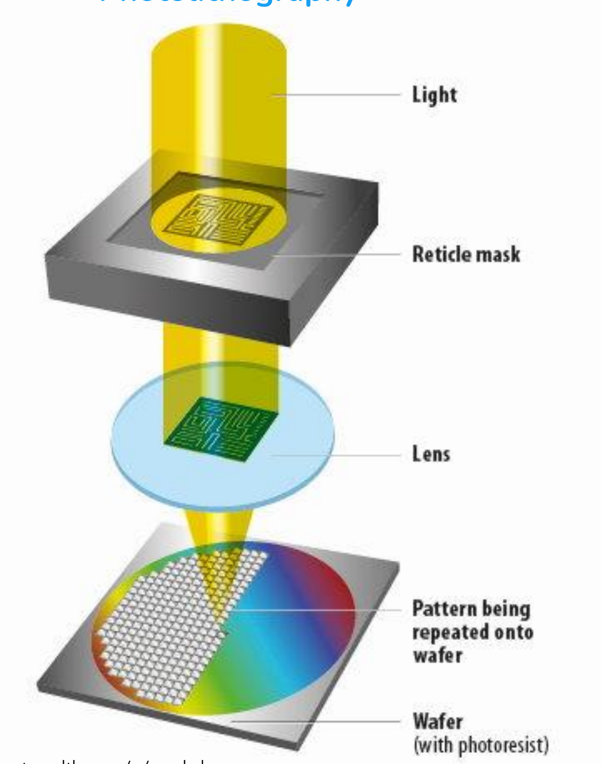
What to pick?

- Hybrid and HV-MAPS
  - **need:** radiation hard → fast → large power consumption → cooling required → large material budget
- HR-MAPS
  - **need:** small material budget → small power dissipation → sensor (circuitry) **made** slow **intentionally**

CMOS & photolithography

- ➠ CMOS : technology used in commercial electronic components
  - the **dominant** image sensing device
  - made of transistors
  - CMOS node ~ how small a transistor is (180 nm, 65 nm)
- ➠ Pixel sensor:
  - array of tiny pixels (each contains circuitry for signal processing)
  - e.g. camera in your smartphone
- ➠ Photolithography
  - transfer pattern, move and repeat

Photolithography

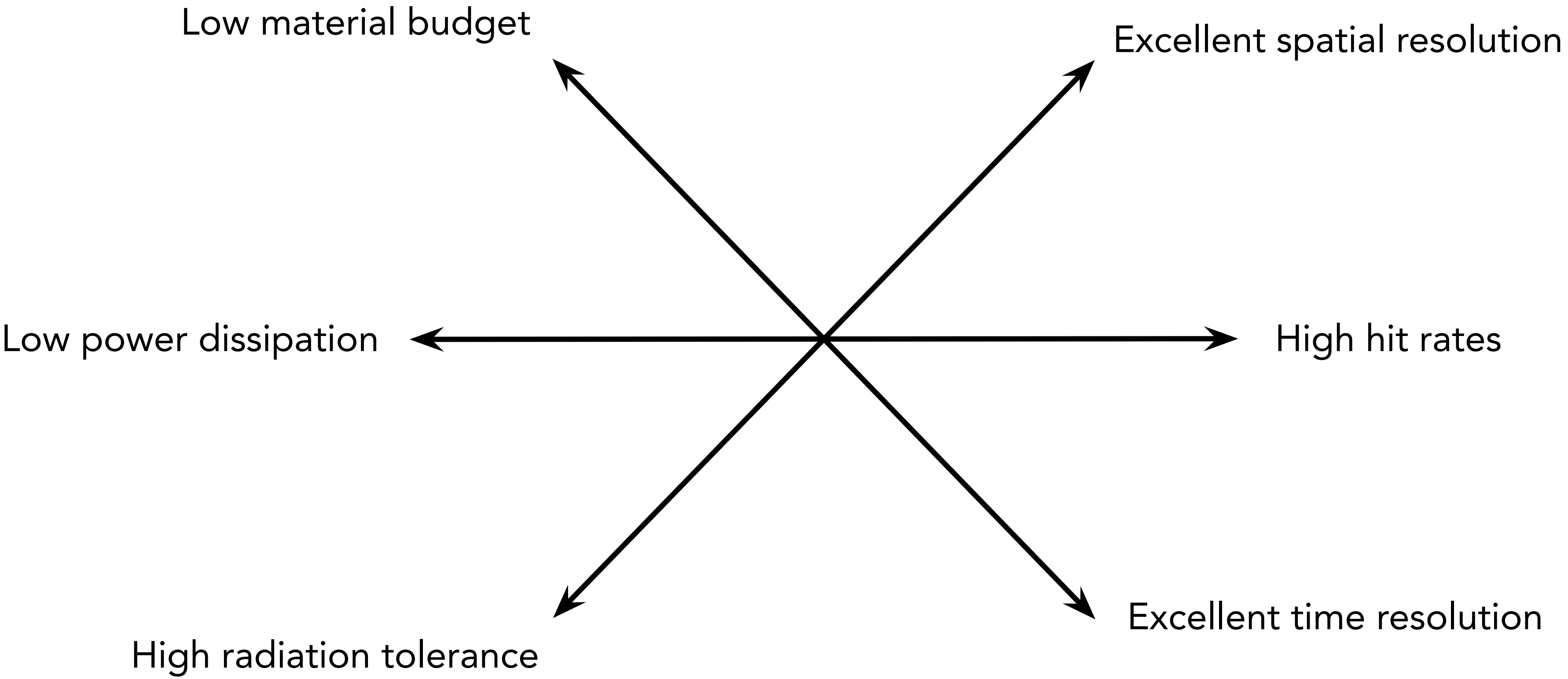


https://www.mmmtwealth.com/p/asml-deep-dive-is-the-moat-as-strong

CMOS imaging sensors for physics

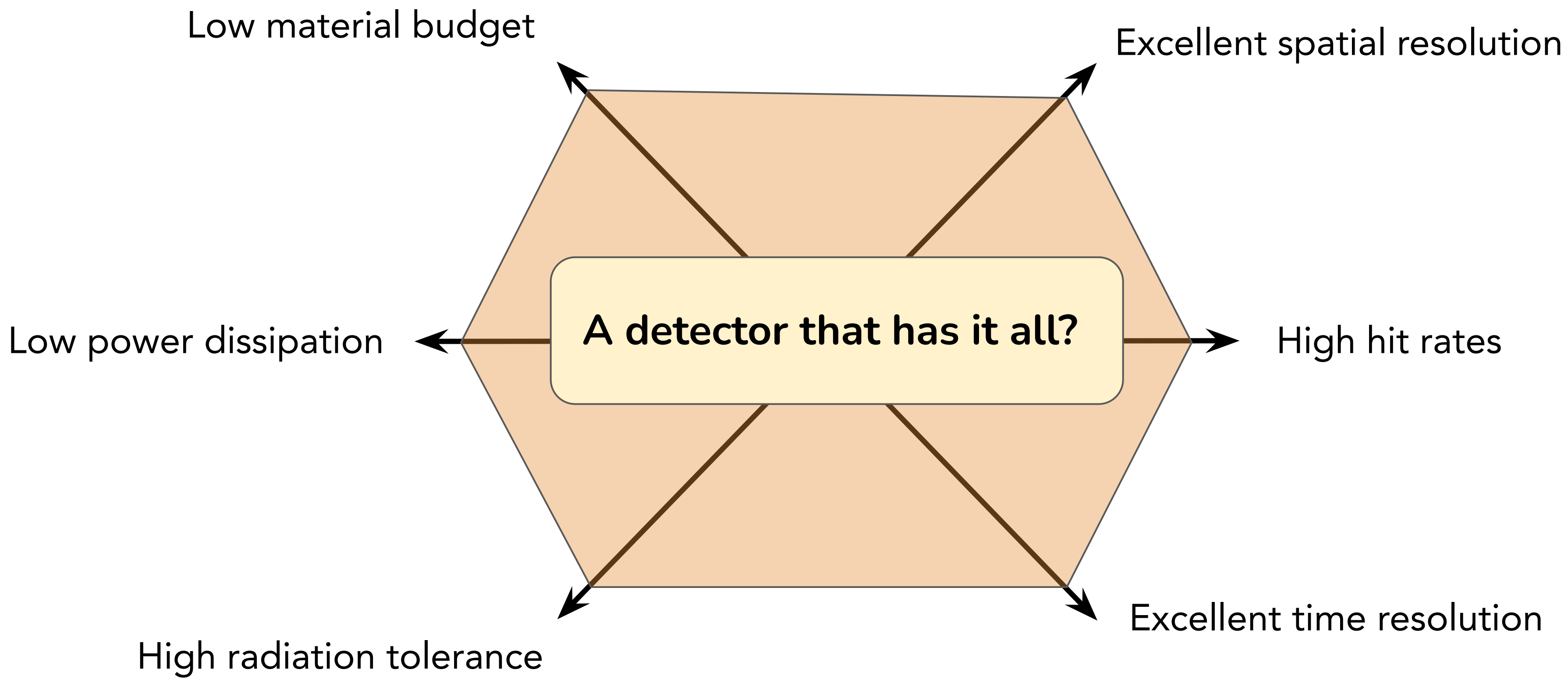
Consumer market	Physics
Slow (rolling shutter, readout = row by row) (few hundred fps)	Excellent time resolution (down to 25 ns) (few hundred **million** fps)
No time info stored	Timestamp required
Small fill factor (<80%) (= sensitive/total area)	100% (don't miss particles)
70-80% efficiency (enhanced images)	>99%
—	Radiation tolerant
Small pixels (~1 μm) (1-4 transistors)	Large pixels (10–100 μm) (~few hundred transistors)

Pixel detectors – orders of magnitude



Adapted from: C. Marinas (https://indico.ific.uv.es/event/6991/)

Pixel detectors – orders of magnitude



Adapted from: C. Marinas (https://indico.ific.uv.es/event/6991/)

Pixel detectors – orders of magnitude

Low material budget

Excellent spatial resolution

Low power dissipation

High hit rates

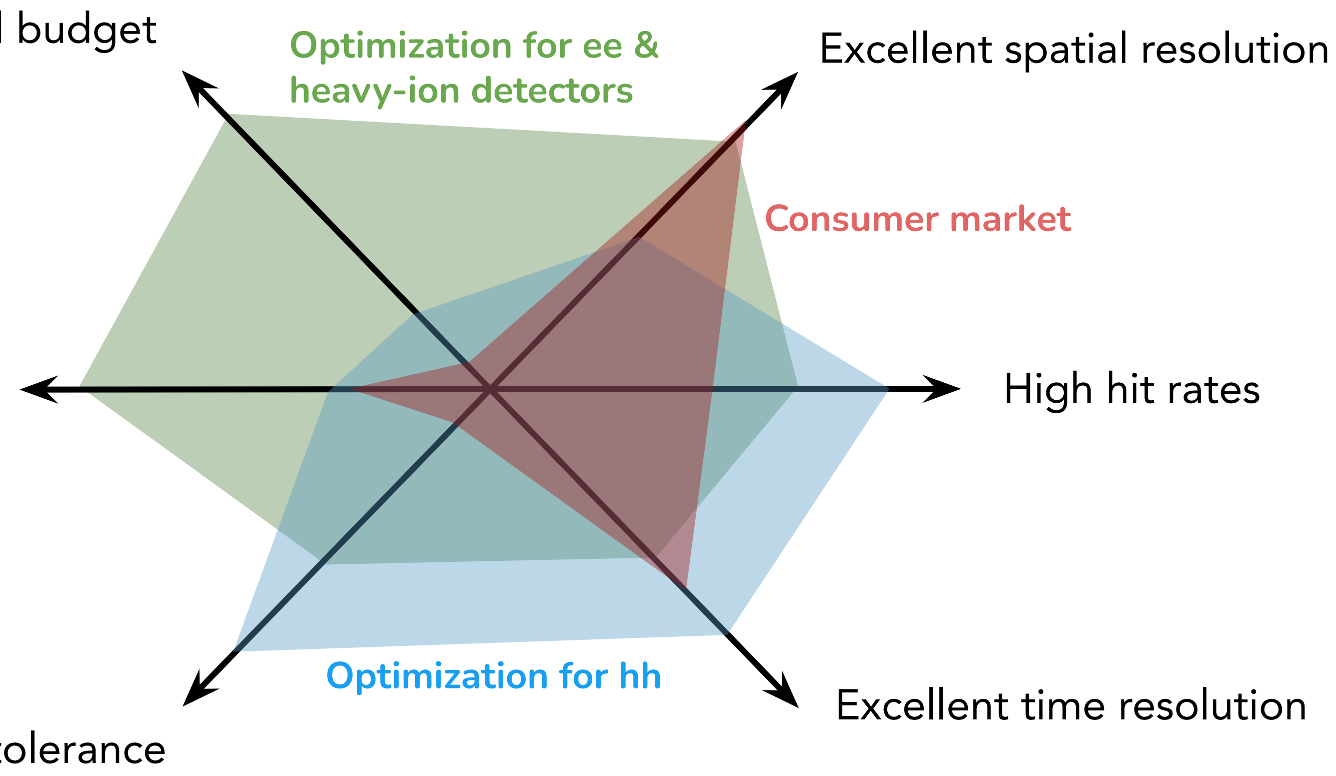
High radiation tolerance

Excellent time resolution

So far, no single chip satisfies all requirements. For now compromises have to be made depending on the needs of the specific application

Adapted from: C. Marinas (https://indico.ific.uv.es/event/6991/)

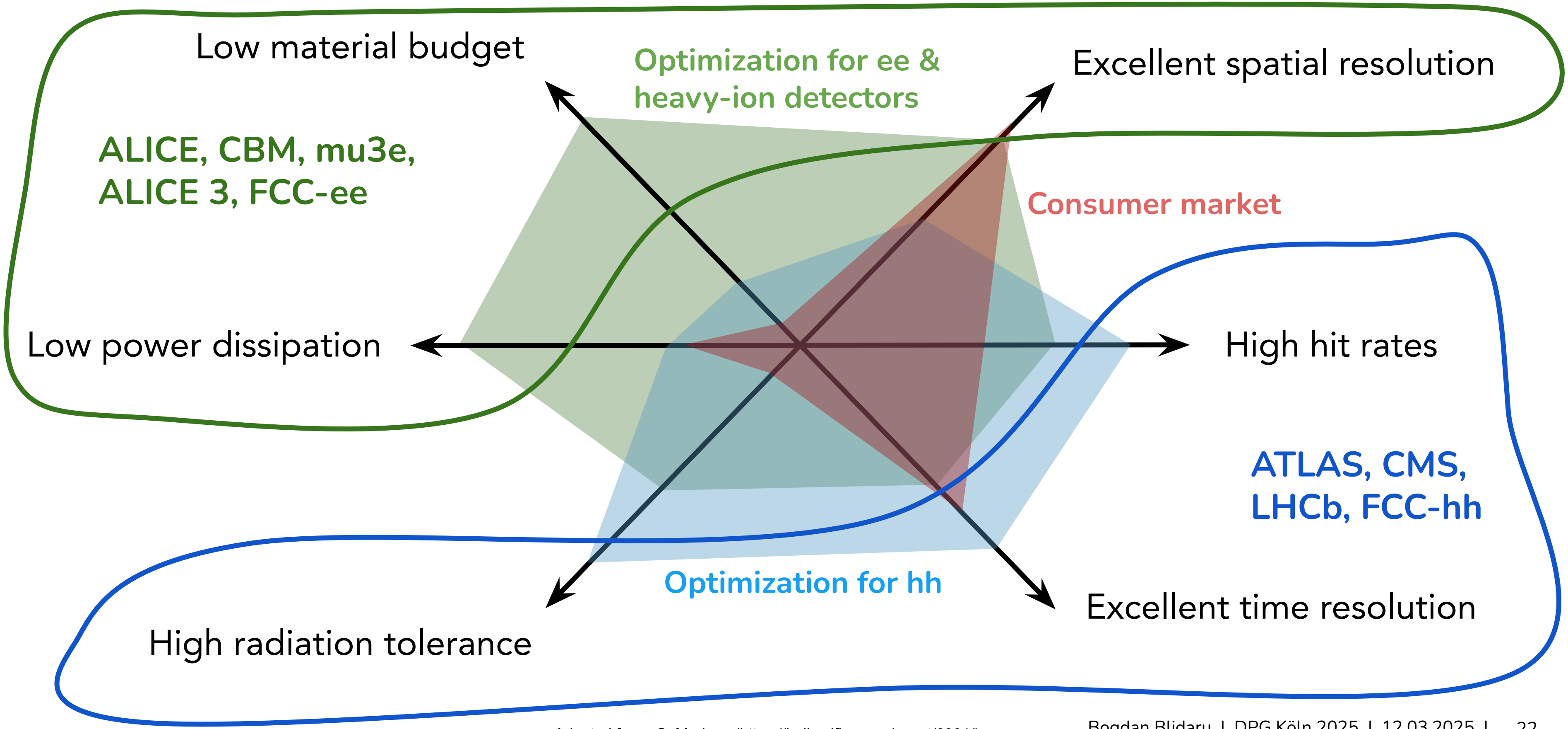
Pixel detectors – orders of magnitude



Some performance are anticorrelated!

Adapted from: C. Marinas (https://indico.ific.uv.es/event/6991/)

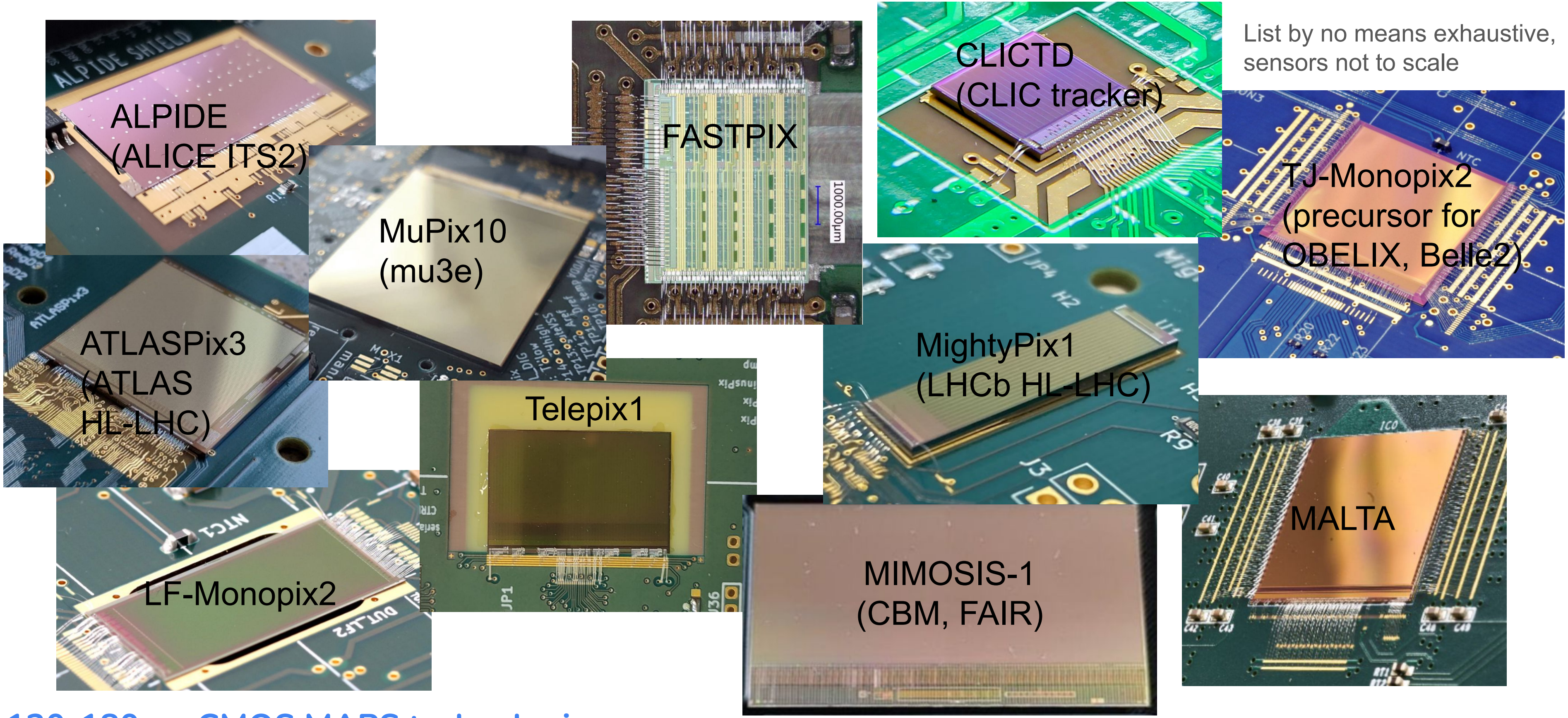
Pixel detectors – orders of magnitude



Adapted from: C. Marinas (https://indico.ific.uv.es/event/6991/)

A myriad of MAPS

List by no means exhaustive, sensors not to scale



130-180nm CMOS MAPS technologies

What can we do with MAPS?

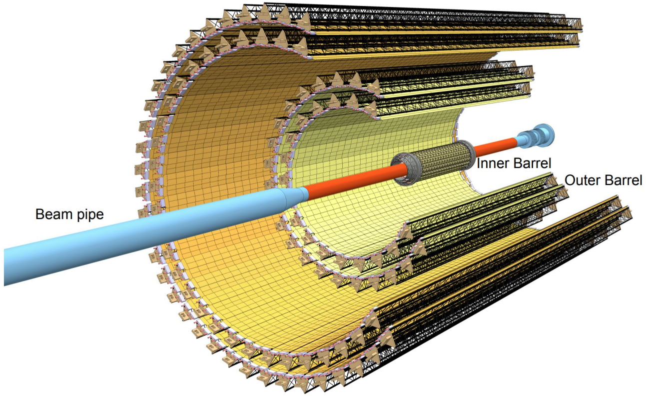
Disclaimer

- ➠ Next: unique application of MAPS for heavy-ion physics
- ➠ From the perspective of ALICE → ITS3
  - ▸ reflects personal work & exciting directions

MAPS in experiments

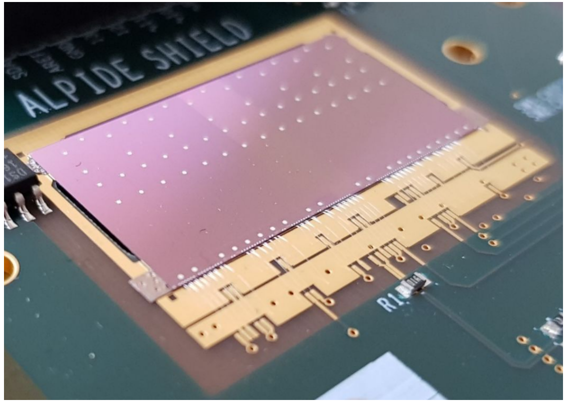
ALICE ITS2 at CERN

- largest MAPS in operation ($10m^2$)
- 12.5 Gpx particle camera



TDR ITS Upgrade
CERN-LHCC-2013-024

ALPIDE sensors

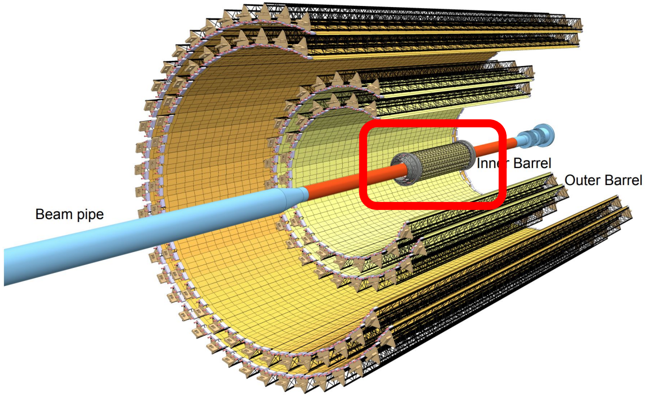


- Tailored for ALICE needs
- Not suited for high rates and high radiation damage!
- Slow sensor (intentionally → front end)
- Moderate radiation damage

MAPS in experiments

ITS2 Inner Barrel

- **3 layers** ALPIDE staves



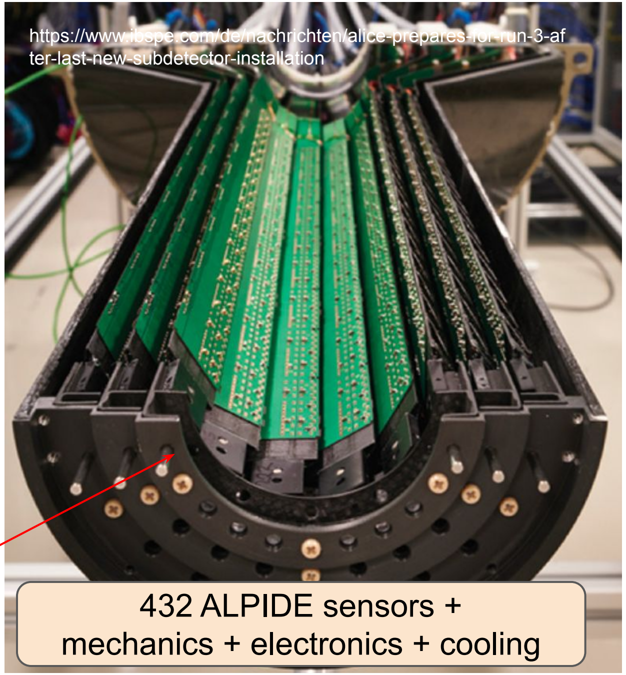
TDR ITS Upgrade
CERN-LHCC-2013-024

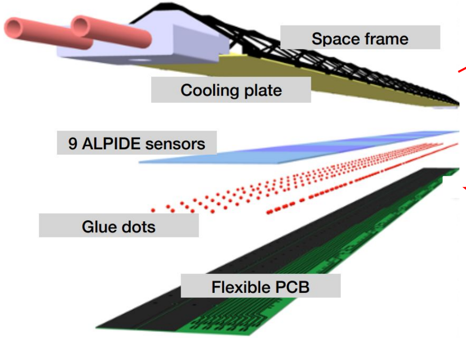
From ITS2...

ITS2 bottom Inner Barrel (half)

ITS2

- position resolution limited at low momentum by **material budget**



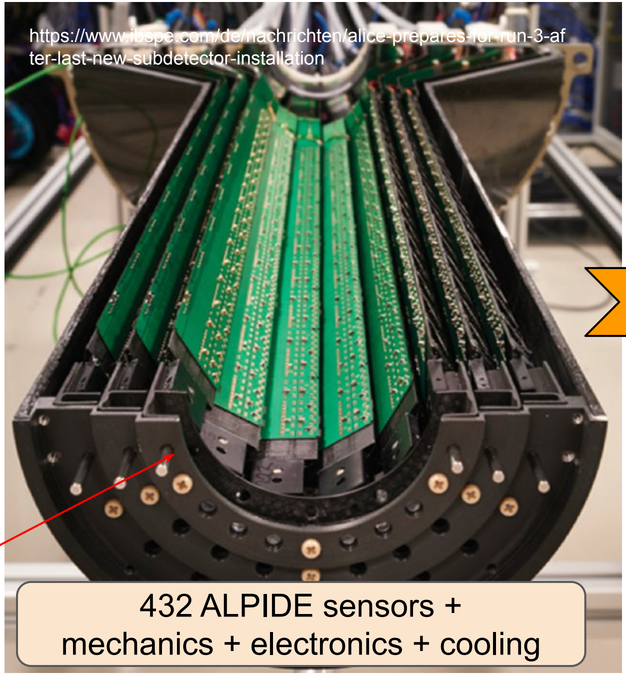


From ITS2... to ITS3

ITS3 upgrade

- replace the 3 inner layers of the ITS2
- **ultra light**, **wafer-scale**, **curved sensors** in 65nm

ITS2 bottom Inner Barrel (half)

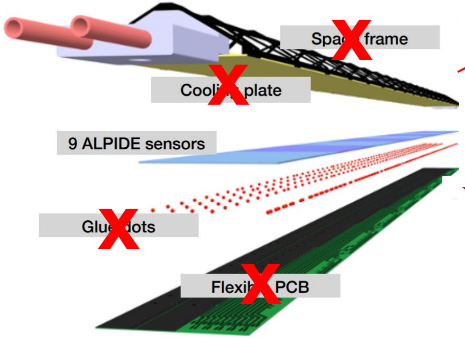


432 ALPIDE sensors + mechanics + electronics + cooling

2028

ITS3 bent sensors (half)

ONLY 6 sensors ! (carbon foam, air cooling)



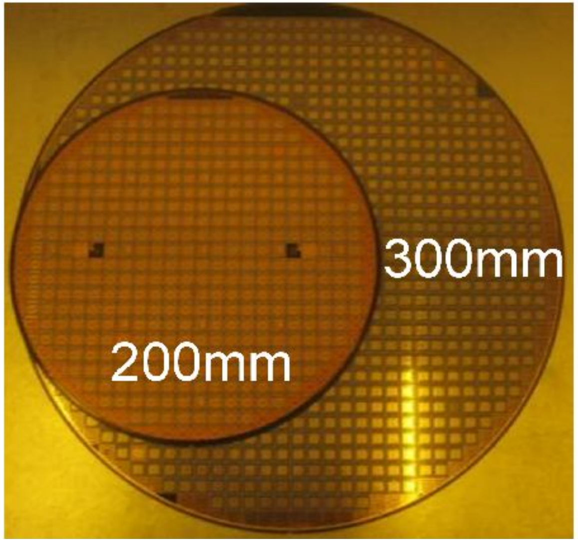
Advancing the technology node

- Change to **65 nm**

- **More compact logic**
  - smaller pixels (more radiation hard)
- **Larger wafers**
- Companies phasing out **old technology**

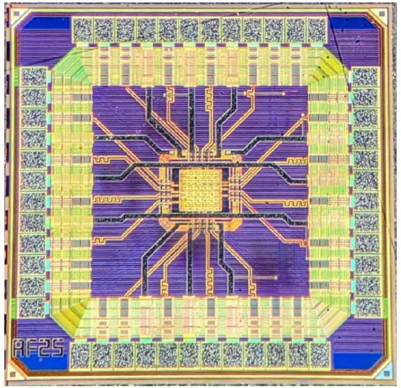
- Why not lower?
  - **cost**
  - **design complexity**
  - fit transistors

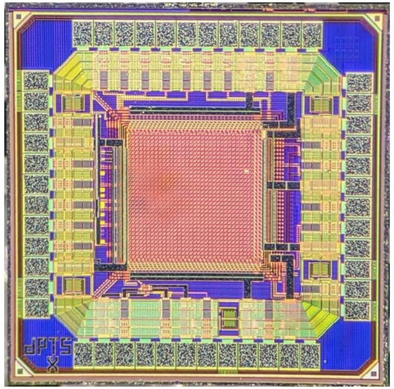
- Large interest (ECFA DRD3)
  - the technology for future accelerator experiments

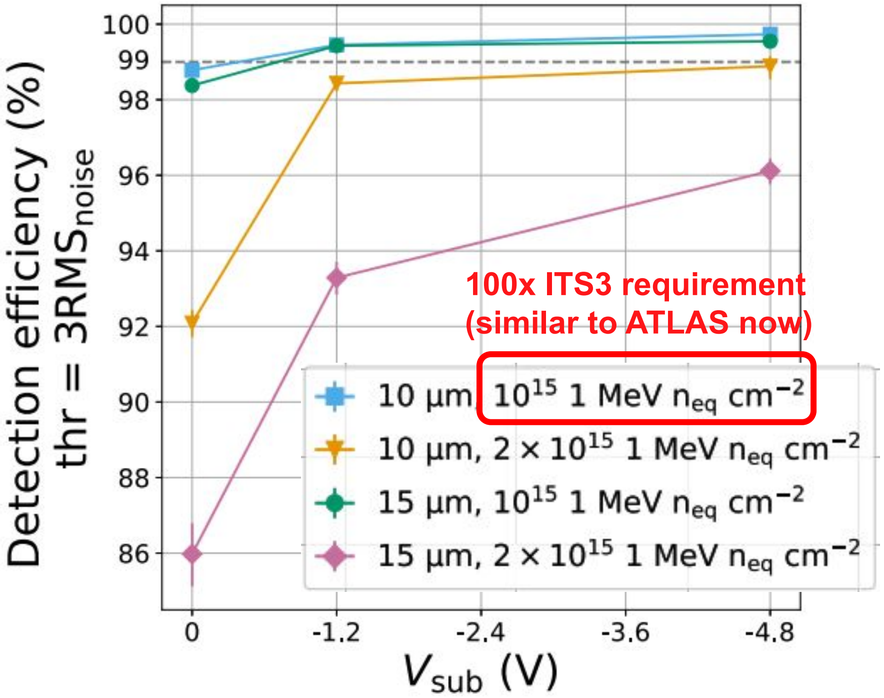


https://ieeexplore.ieee.org/document/6142403

65nm qualification studies





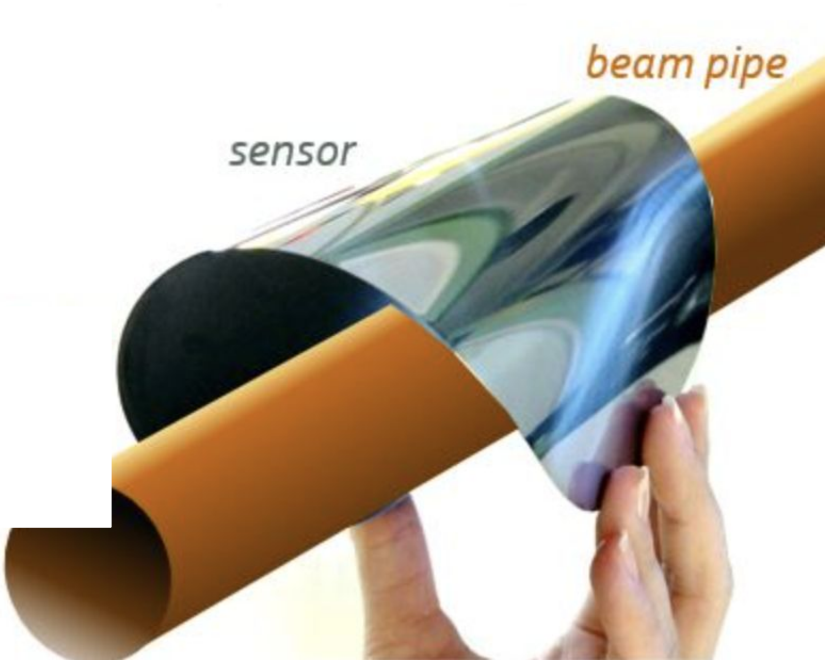


Qualifying 65nm for usage in HEP

- Prototypes work very well!
- >99% detection efficiency after large radiation load
- Suited for ALICE ITS3 and even ALICE 3

More info: NIM A 1069 (2024) 169896

Bending sensors



https://ep-news.web.cern.ch/content/meeting-challenges-tracking-detector-mechanics

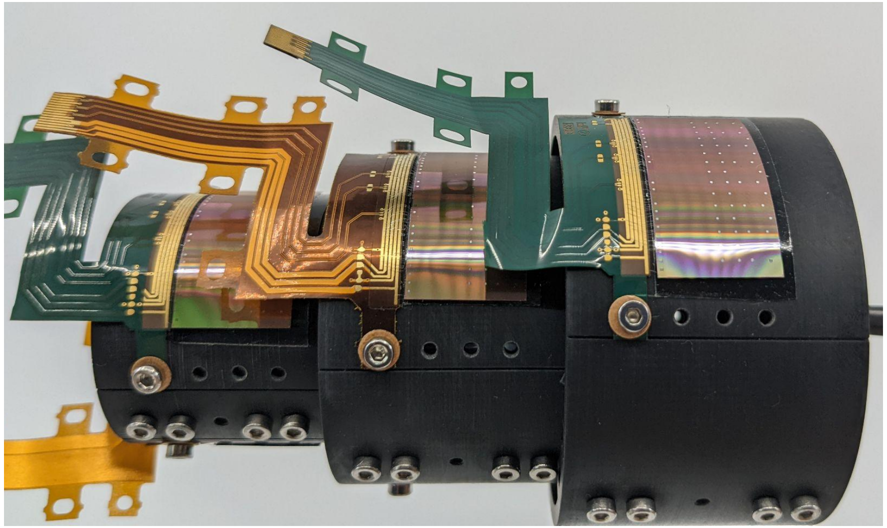
Not trivial!

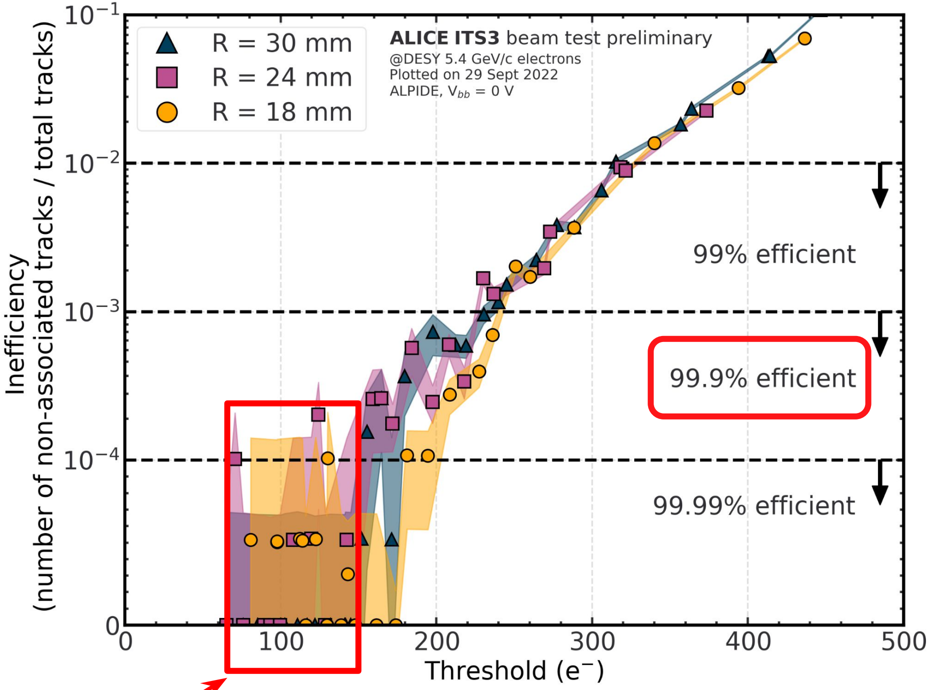
- must not break
- retain functionality

Bending sensors

Bent MAPS working well! Performance unchanged!

➠ attractive design choice for other experiments





Nominal operating point

More details:
10.1016/j.nima.2021.166280

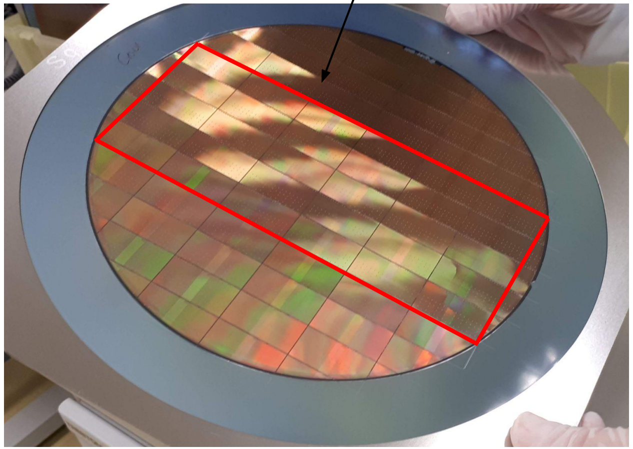
Going wafer scale: stitching

Going wafer-scale

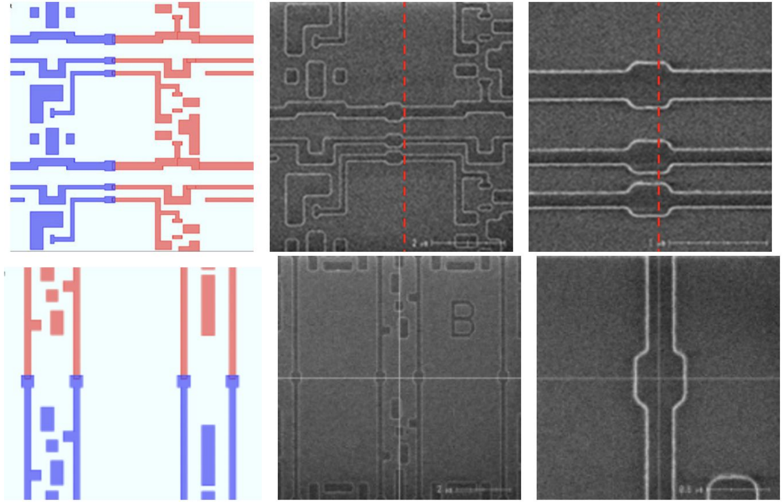
- Size of sensors is limited to ~3×2.5cm^2
- Solution: **stitching**
  - concatenation of different parts of the mask (alignment ~nm)
  - **repetitive element** (pixel matrix) and a periphery

(power and data to outside)

What we want: make this **one single sensor**!



https://cds.cern.ch/record/2748315

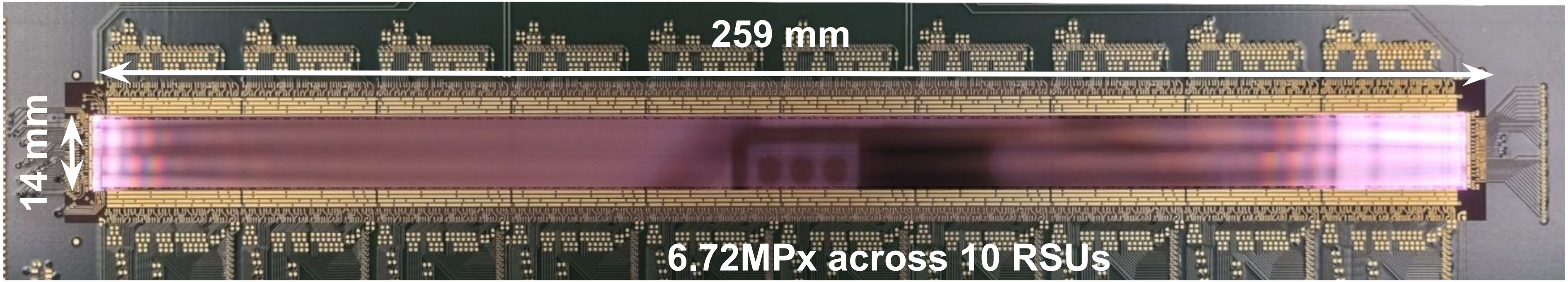


https://www.jstage.jst.go.jp/article/elex/13/15/13_13.20160441/_pdf/-char/en

Wafer-scale stitched sensors

MOSS (MOnolithic Stitched Sensor)

- **fully functional** ITS3 **stitching demonstrator**
- confirmation of expected performance from small-scale prototypes



https://indico.cern.ch/event/1255624/contributions/5443786/

MOSAIX

- upcoming second iteration stitched sensor (design being finalized, submission 2025)
- **full size**, fully functional, **stitched sensor prototype** for the ITS3

Future MAPS detectors

Andrea Dainese (HK 39.1)

Future detectors

- predominantly made with silicon technologies

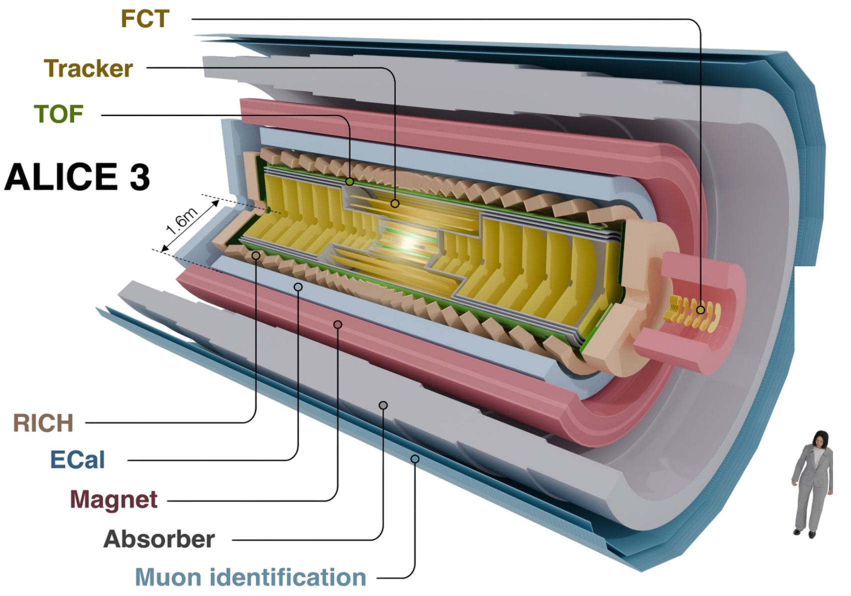
ALICE 3 (2036+)

- tracking by Si **MAPS** → evolution from ITS3
- timing by fast Si

Big challenges

- Large area to instrument (70m^2)
- Sensors in vacuum
- 2.6m long staves

ATLAS pixel detector (2030+): 13m^2
CMS pixel detector (2030+): 5m^2
Belle II pixel detector (2030+): 1m^2
CBM MVD pixel detector (2028+): 0.1m^2



https://alice-collaboration.web.cern.ch/menu_proj_items/ALICE-3

Why are MAPS a must-have?

- MAPS matured in the past years
  - a **plethora of prototypes** and full detectors
    → fast detectors, radiation hard
    → slower, low mass
- CMOS MAPS are and will continue to be a **key technology** for future trackers
- Developments in the direction of
  - timing, radiation hardness
  - all-in-one sensor (?)
- Many institutes involved and collaborating

Acknowledgements

GSI: Detector Laboratory, C. Schmidt, M. Deveaux, C. Simmons, R. Visinka, O. Kiselev, P. Gasik, …
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DESY: S. Spannagel, L. Huth, R. Diener, N. Meyners, M. Stanitzki, P. Schutze, H. Wennlöf, F. Feindt, S. Lachnit, A. Simancas, S.R. Daza, G. Vignola, …
KIT: M. Caselle, F. Simon, …

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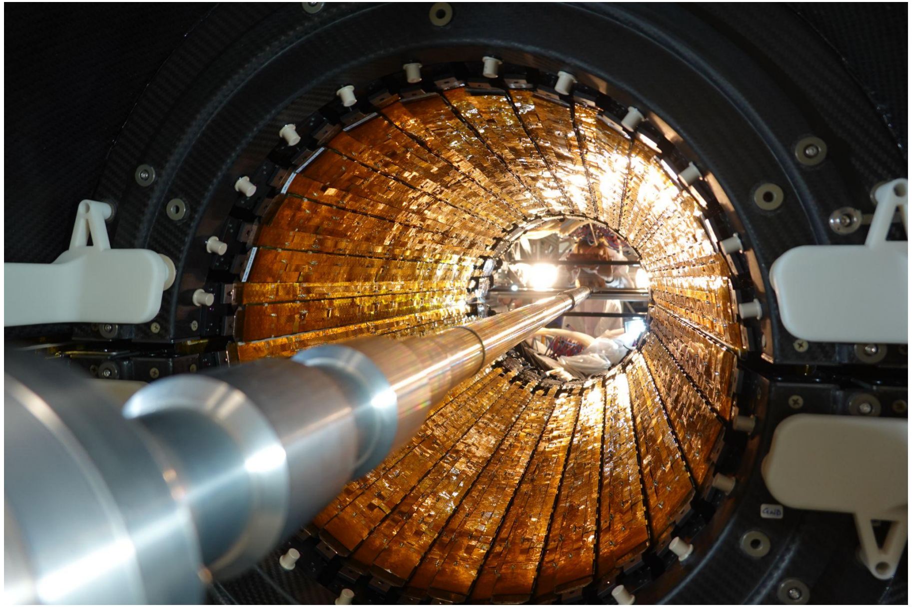
ALICE Germany colleagues involved in MAPS

Thank you!

"From their beginnings at CERN half a century ago, silicon pixel detectors for particle tracking have blossomed into a vast array of beautiful creations that have driven numerous discoveries, with no signs of the advances slowing down"

– Chris Damerell (Rutherford Appleton Laboratory)
(https://cerncourier.com/a/tracking-the-rise-of-pixel-detectors/)



https://cerncourier.com/a/alice-tracks-new-territory/