ALICE ITS3

the ultimate paper wrap pixel detector

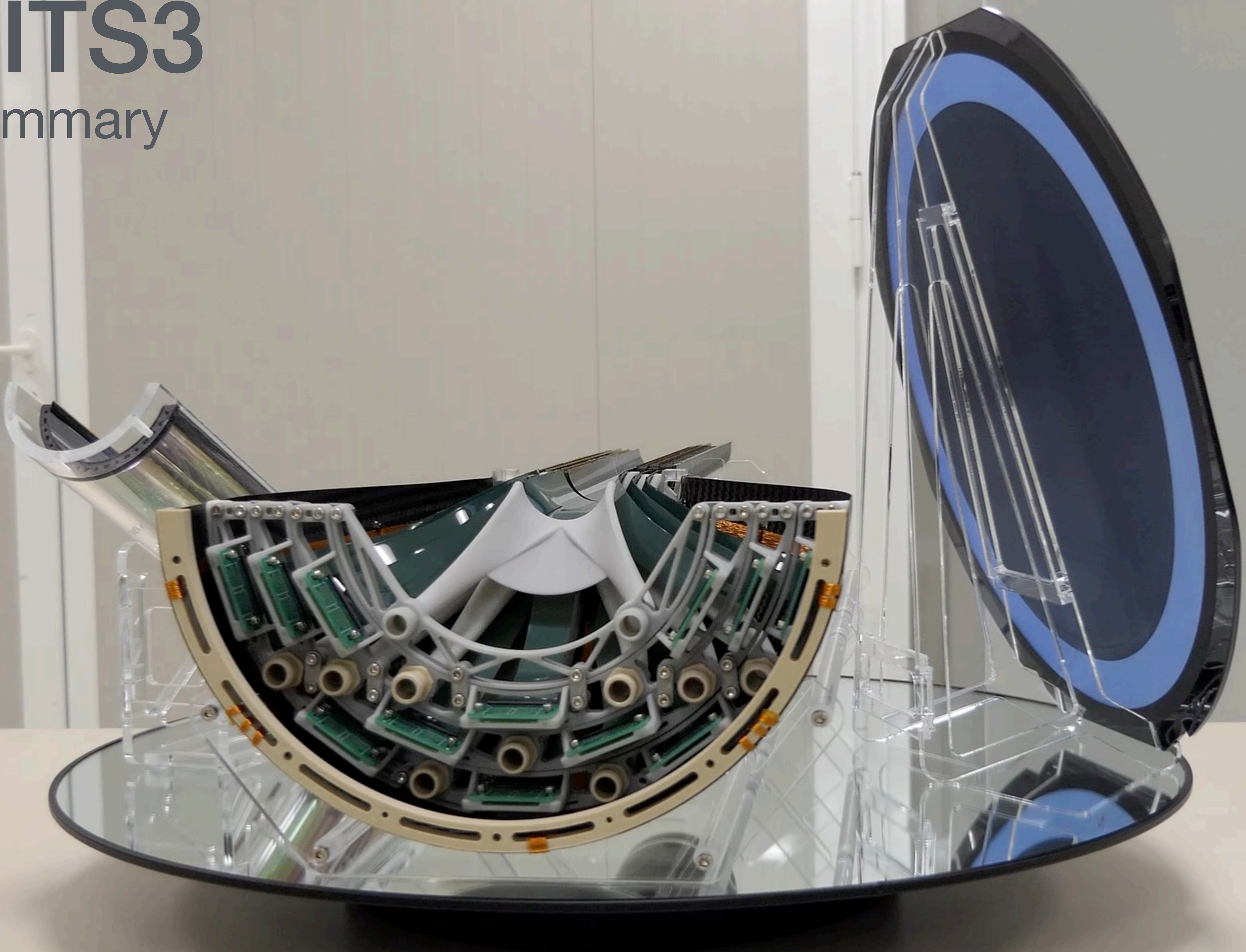
Magnus Mager (CERN) on behalf of ALICE

11.09.2025 Göttingen

Quantum2025

ALICE ITS3

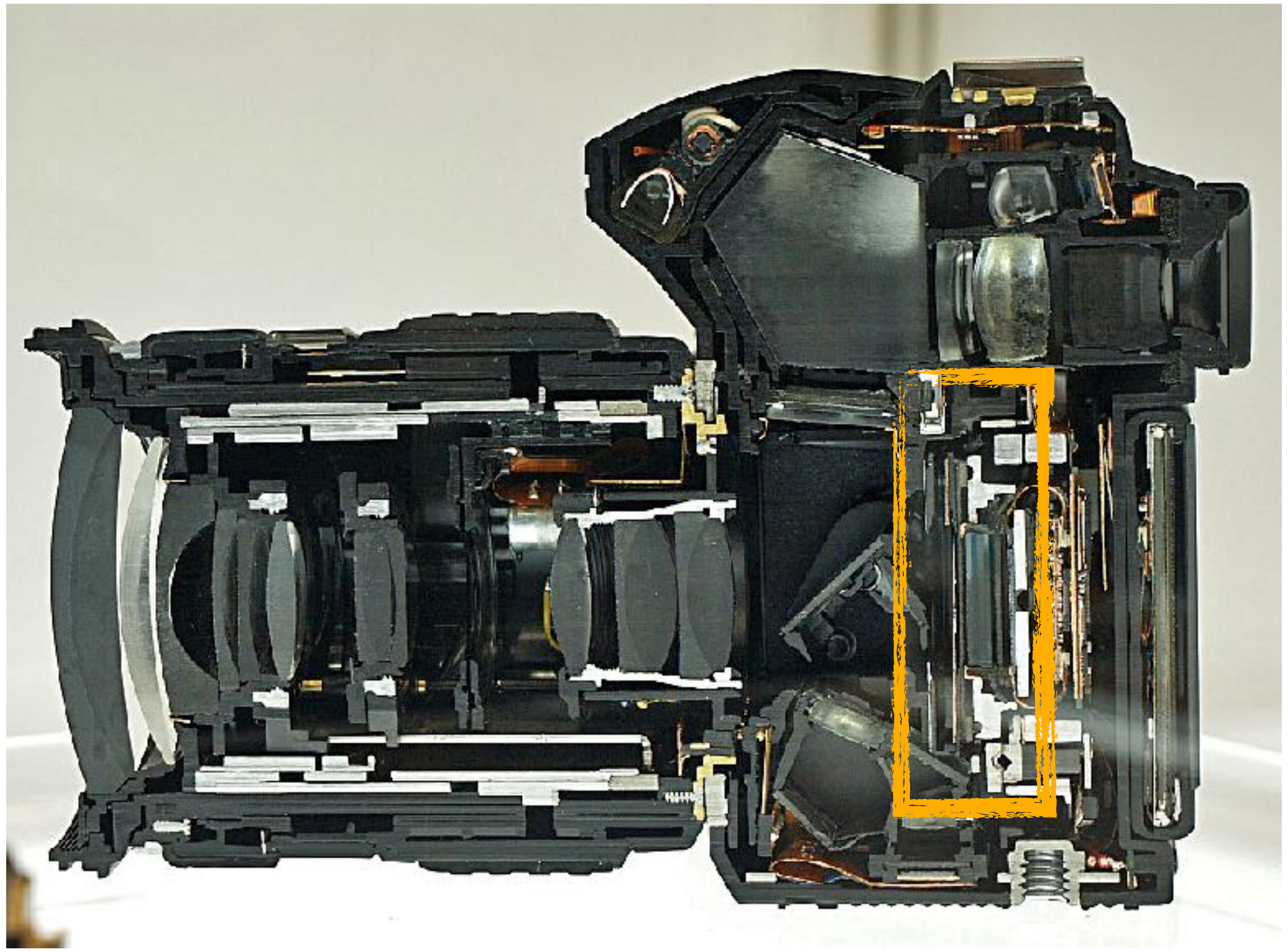
executive summary



Pixel sensors

… are nowadays everywhere — mostly to capture (visible) light

Nobel Prize in Physics 2009
Willard S. Boyle and George E. Smith
"for the invention of an imaging semiconductor circuit – the CCD sensor."



[https://commons.wikimedia.org/wiki/File:E-30-Cutmodel.jpg]

Cut through a modern DSLR
Pixel detectors are abundant (smartphones, surveillance, etc.)
though mostly for (visible) light

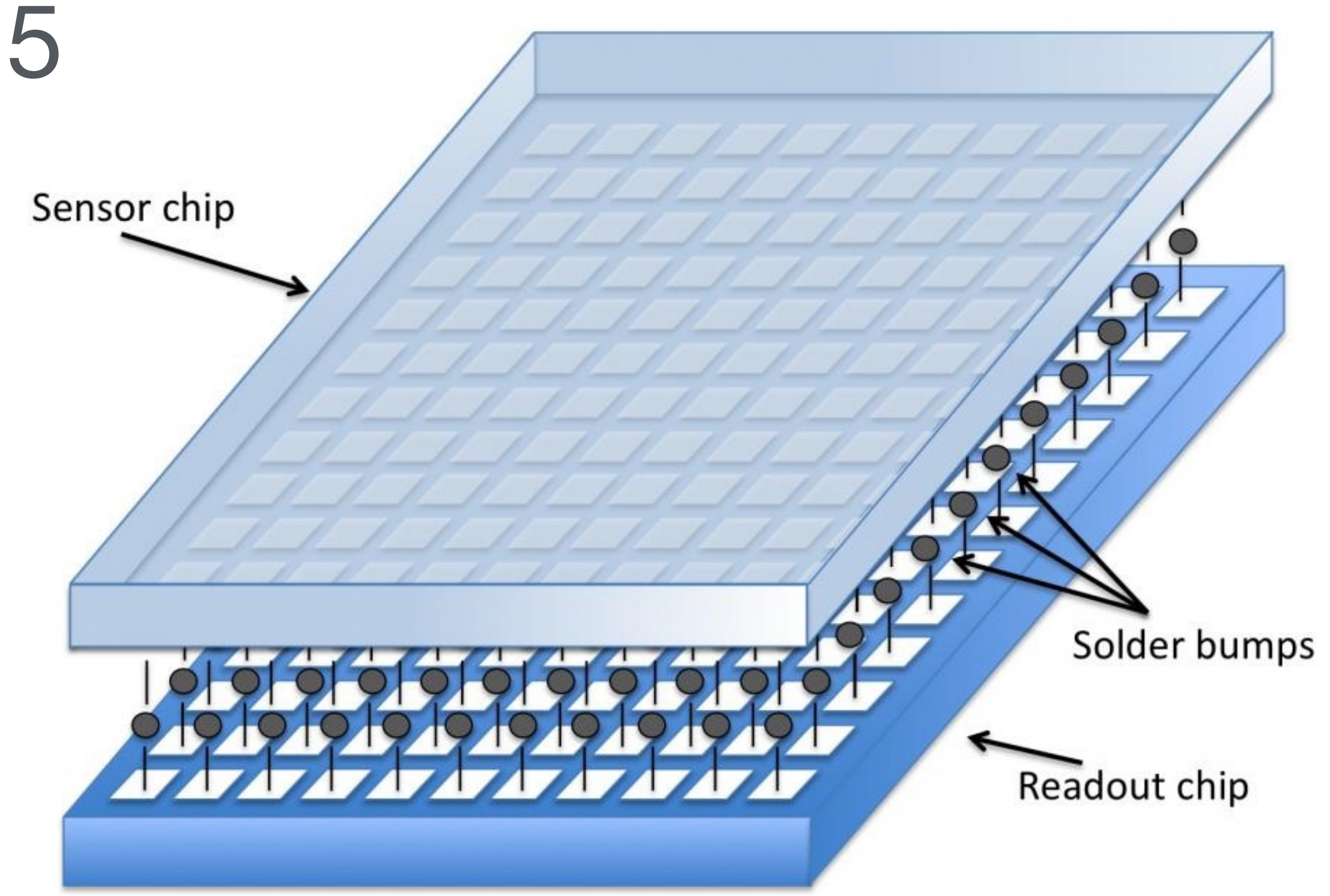
Pixels sensors as particle detectors

first steps in HEP

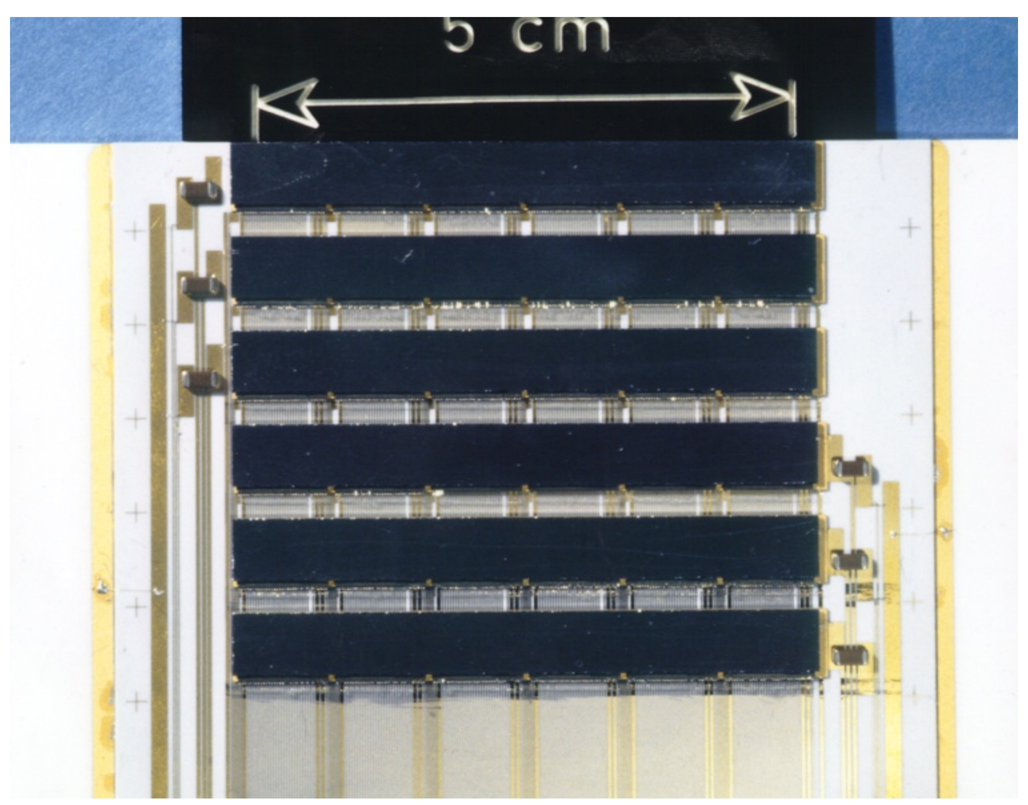
- *“The silicon micropattern detector: a dream?”*
  E.H.M Heijine, P. Jarron, A. Olsen and N. Redaelli, NIM **A 273** (1988) 615

- *“Development of silicon micropattern detectors”*
  CERN RD19 collaboration, NIM **A 348** (1994) 399

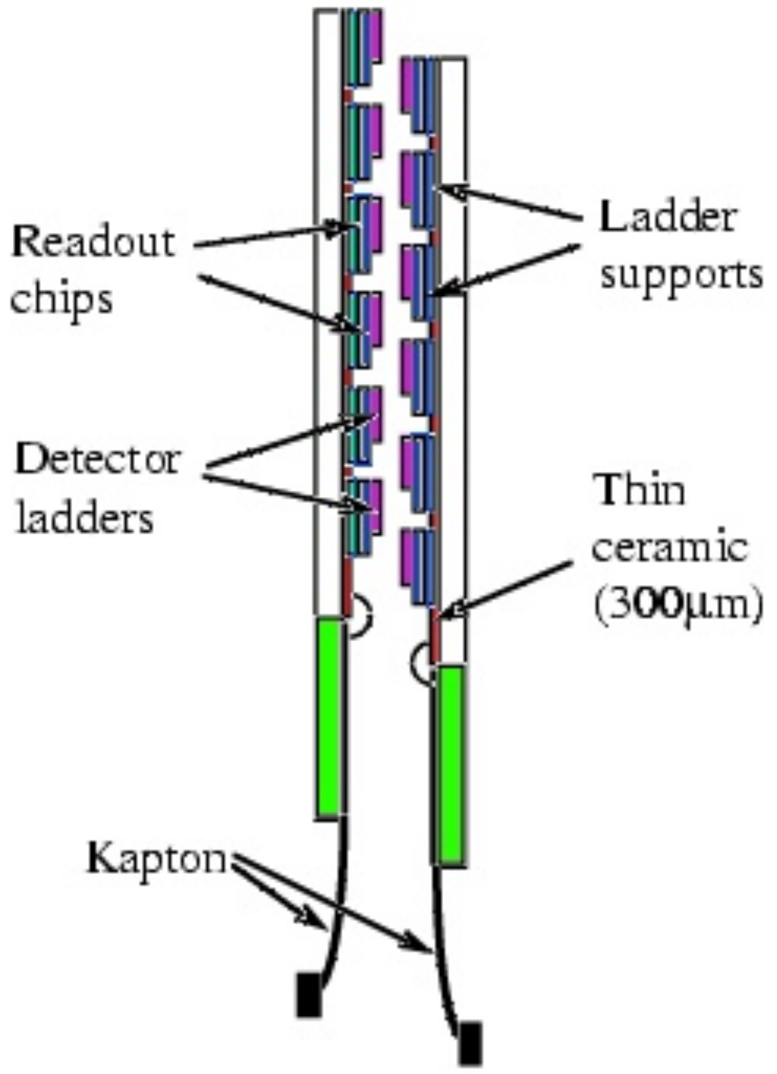
- **1995** First <u>Hybrid Pixel</u> detector
  installed in WA97 (CERN, Omega facility

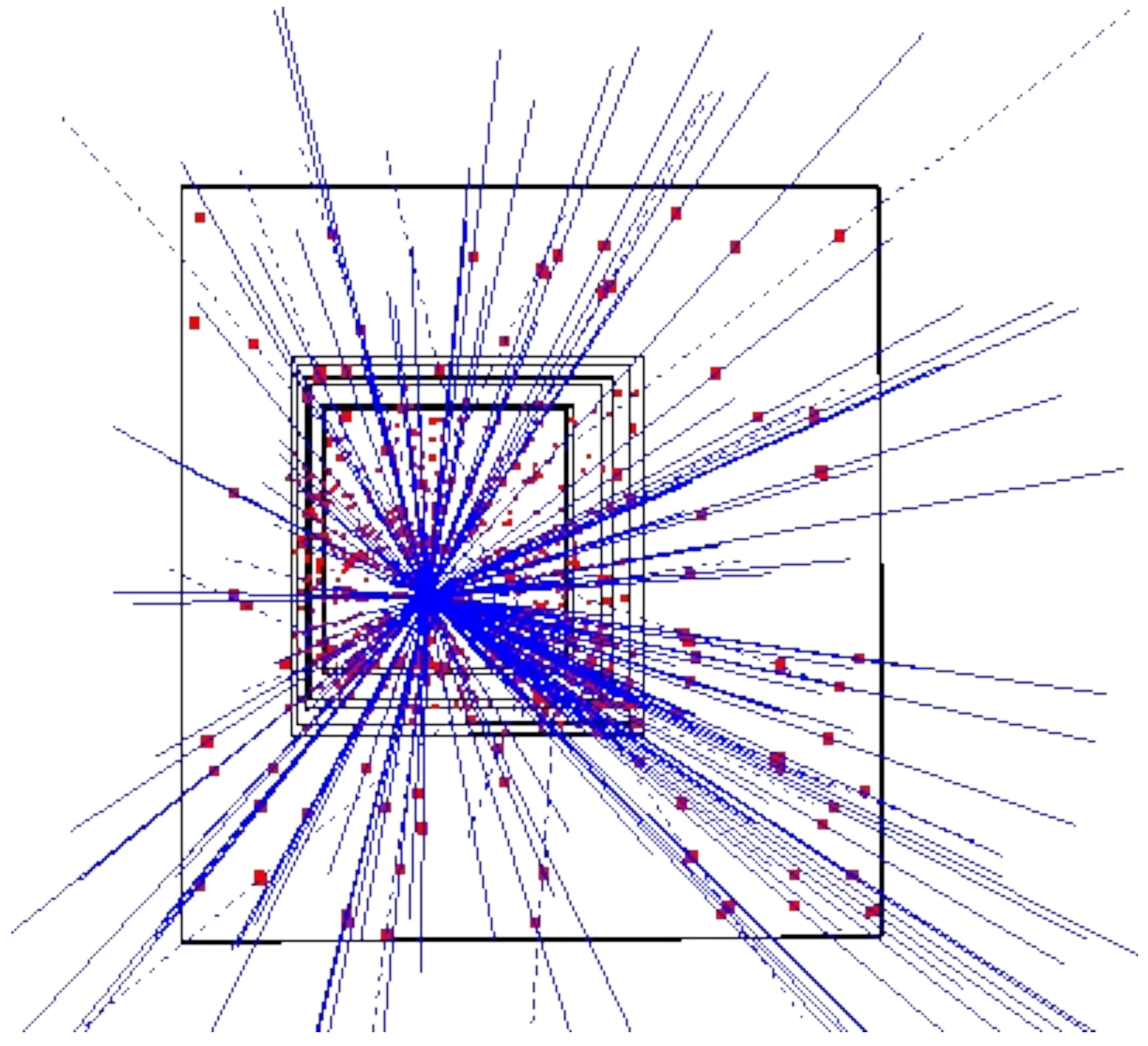


WA97 Experiment (1995)
- 5×5 cm^2 area
- 7 detector planes
- ~0.5 M pixels
- Pixel size: 75 x 500 μm^2
- 1 kHz trigger rate
- Omega2 chip



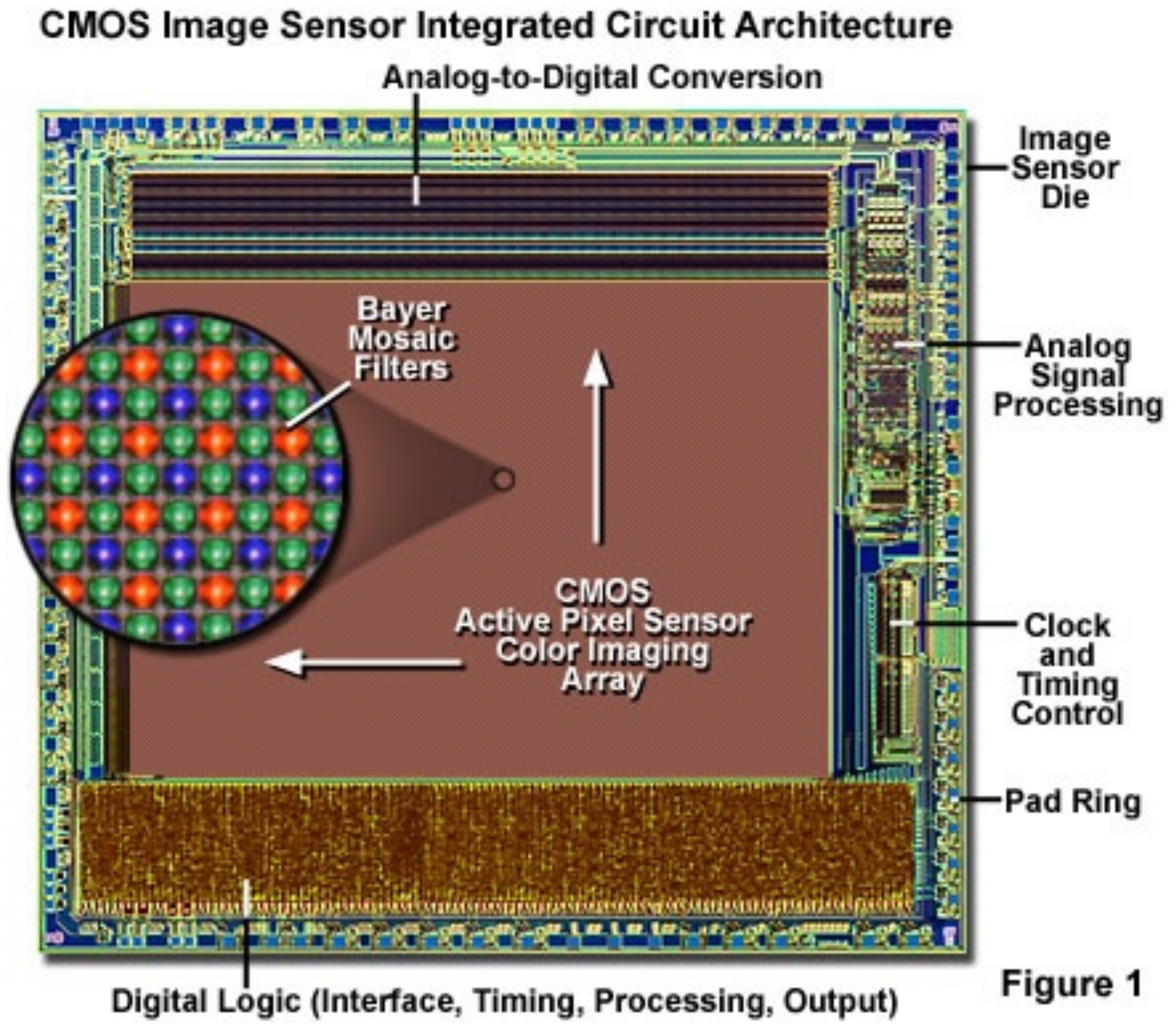
E. Heijne, E. Chesi

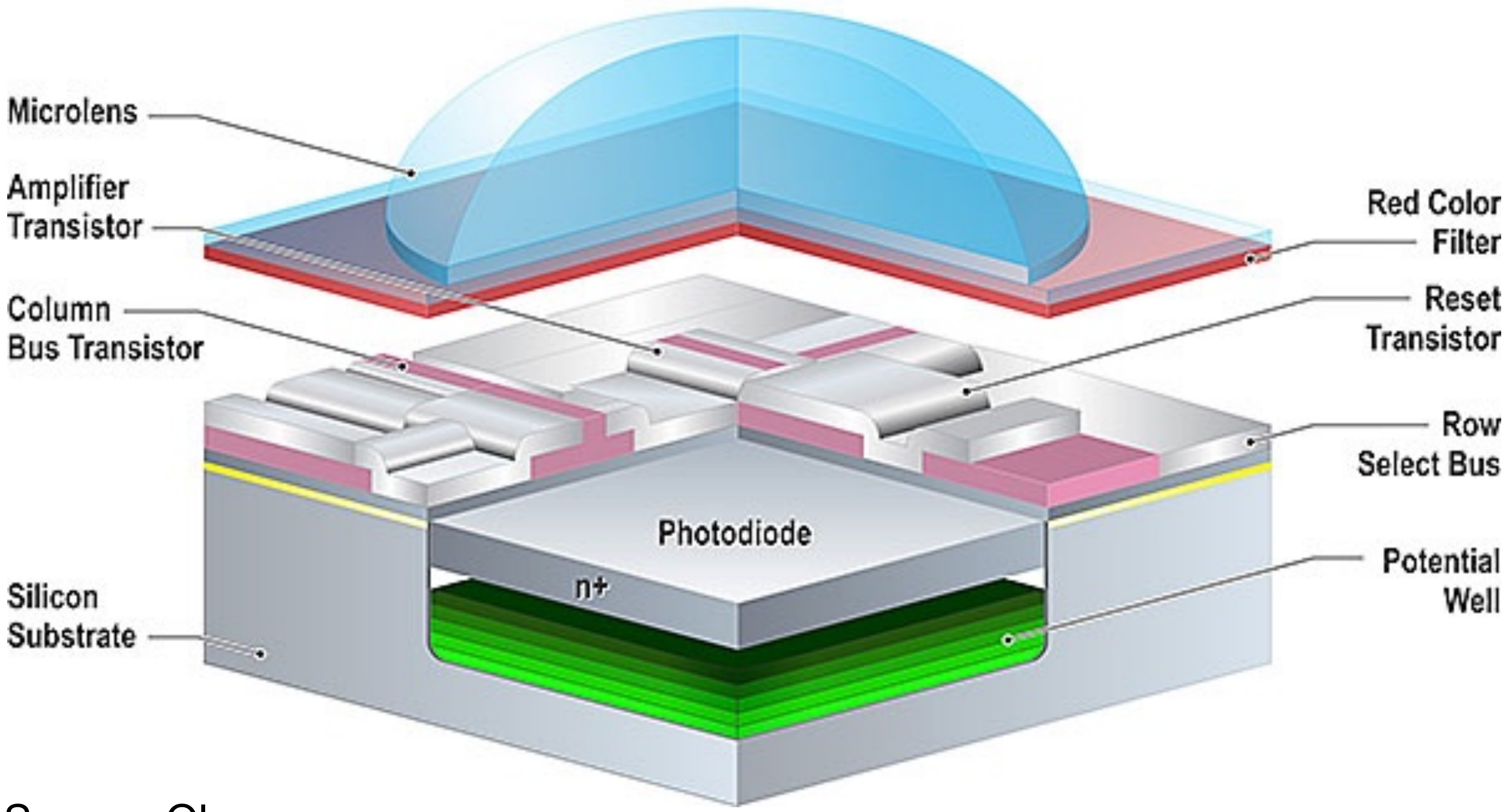




Monolithic CMOS pixel sensors

sensor and readout on same chip



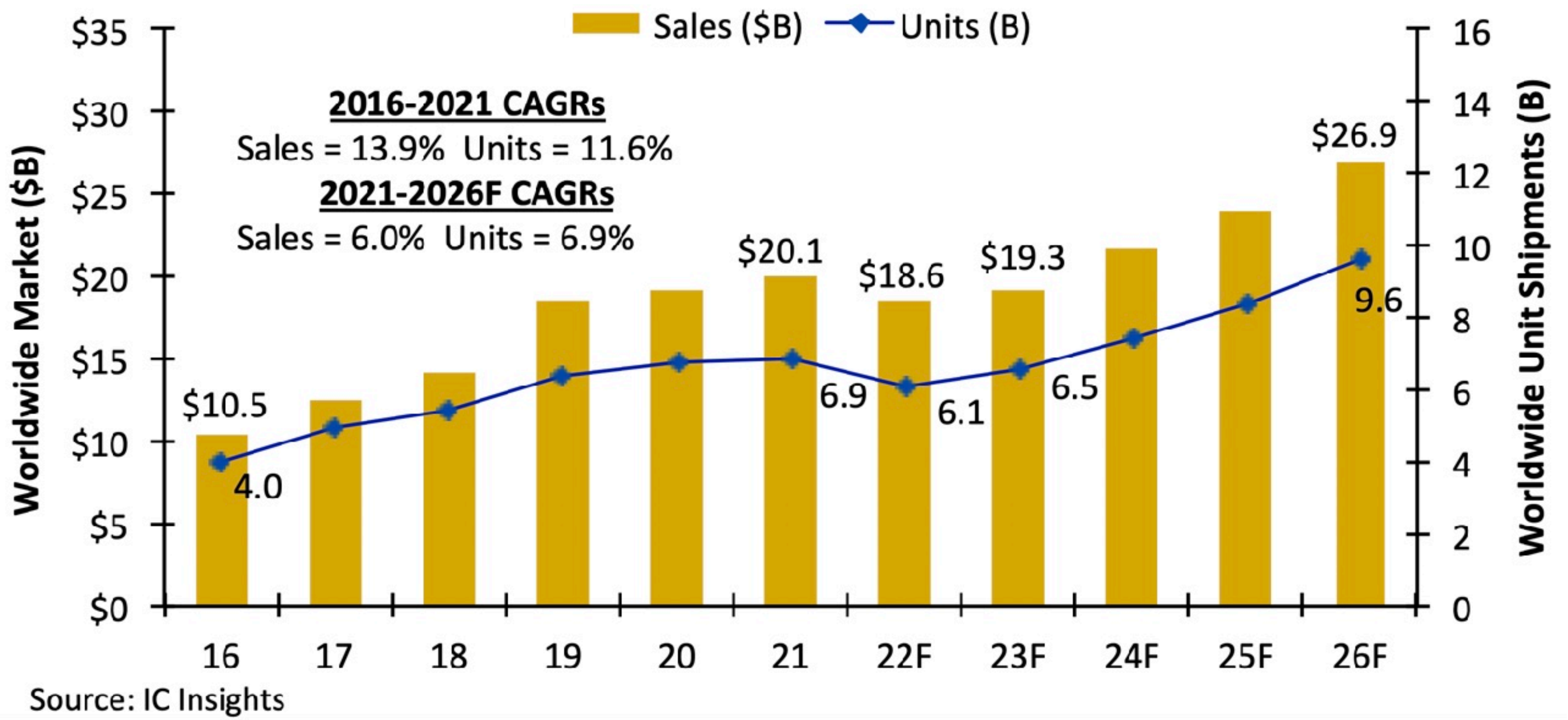


Source: Olympus

- Nowadays the most widespread implementation of image sensors
  - main advantage: price

- Light vs charged particles:
  - both generate electron/hole pairs
  - need to increase sensitive area to 100% (no focussing lenses for charged particles)

CMOS image sensor market



- Rapid increase of sales
- HEP *can* profit from a huge commercial interest
- Our job: make these light sensors particle sensors

ALPIDE

the state of the art Monolithic Active Pixel Sensor

hips produced and tested

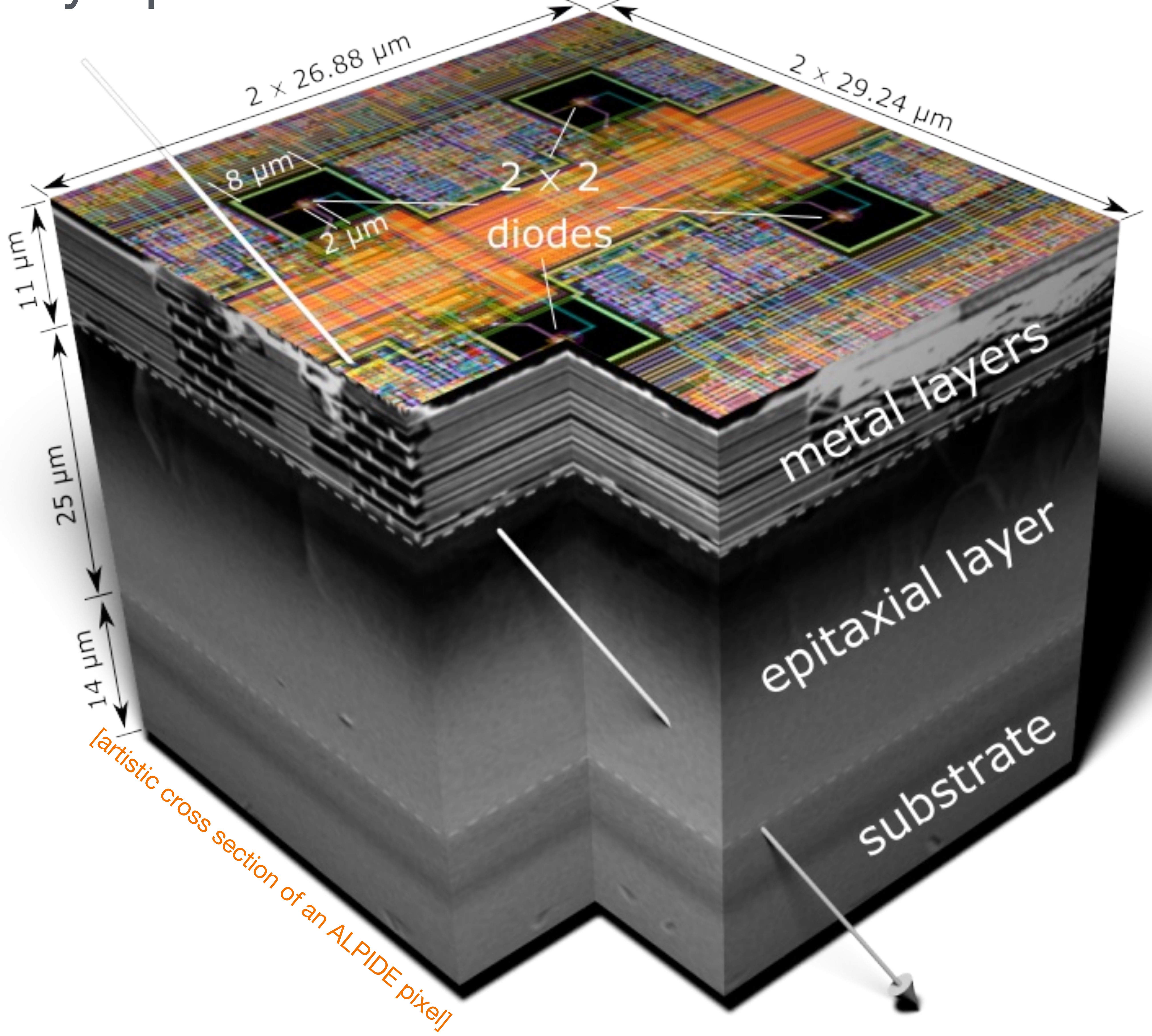
continuous operation in ALICE

+ several other applications

rameter	Req.	ALPIDE
atial resolution (µm)	≈ 5	≈ 5
Integration time (µs)	< 30	< 10
Fake-hit rate (/pixel/event)	< 10^{-6}	<< 10^{-6}
Detection efficiency	> 99%	>>99%
Power density (mW/cm²)	< 100	< 47
TID (krad)	> 270 (IB)	OK
NIEL (1 MeV n_{eq} / cm²)	> $1.7x10^{12}$	OK

Monolithic Active Pixel Sensors (MAPS)

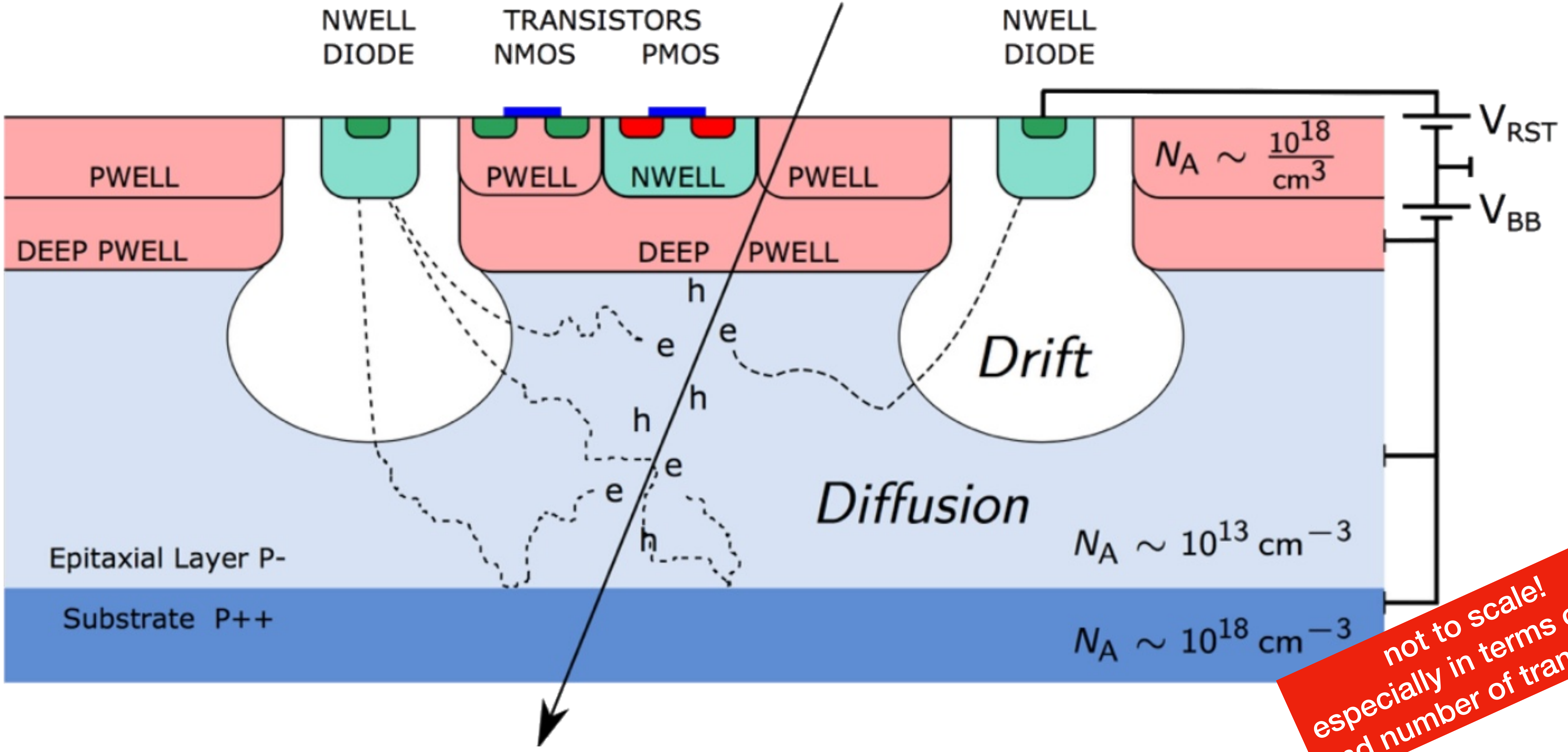
key specifications of state of the art sensors



- **Thin:** O(50 µm)
- **Very granular:** O(10-30 µm)
- **Small diodes:** capacitances of O(1-5 fF)
- **Highly integrated:** O(100) transistors/pixel

Monolithic Active Pixel Sensors (MAPS)

working principle

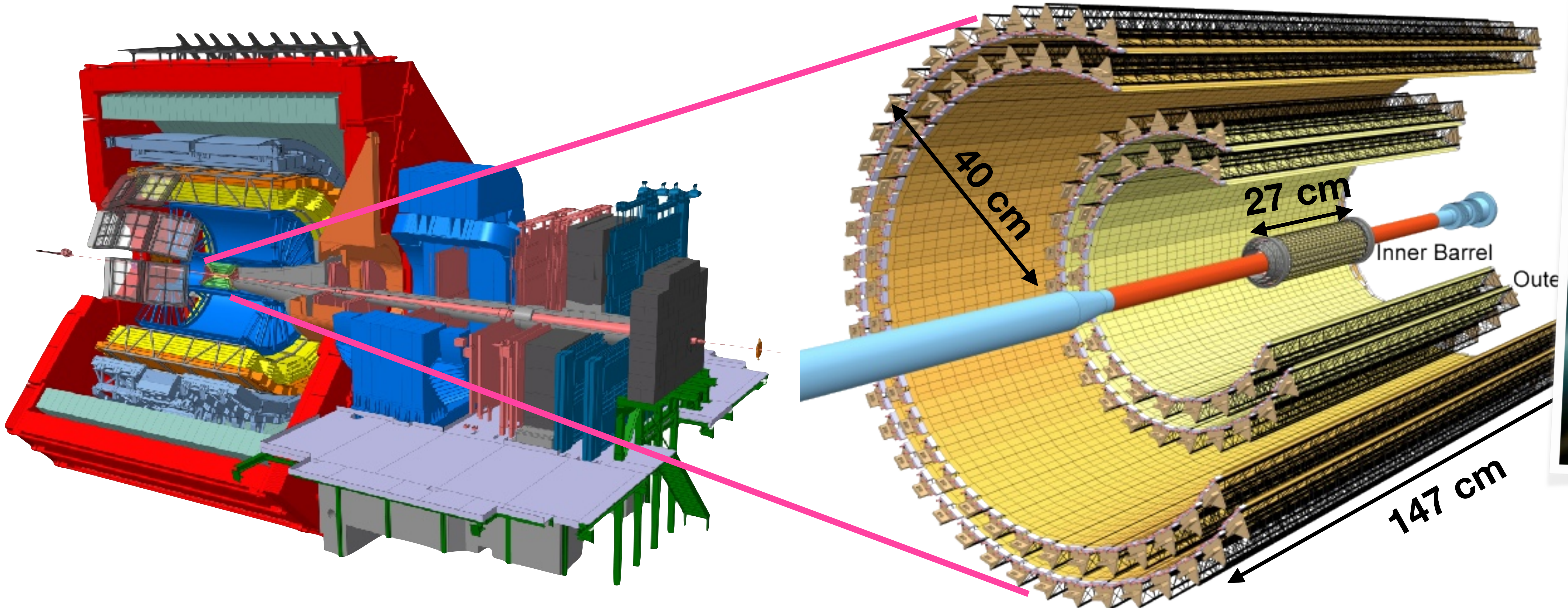


not to scale!
especially in terms of size
and number of transistors.

ALICE ITS2

the large-scale application of MAPS

- **Largest application of MAPS in HEP**
  - 24k **ALPIDE** chips are currently working to produce physics
- **10 years of R&D** & C&I
  - development of the ALPIDE ASIC
  - light, carbon truss based support structures
- Technology used also forward (ALICE MFT) + replica of Inner Barrel for sPHENIX + ALICE FoCal + medical applications

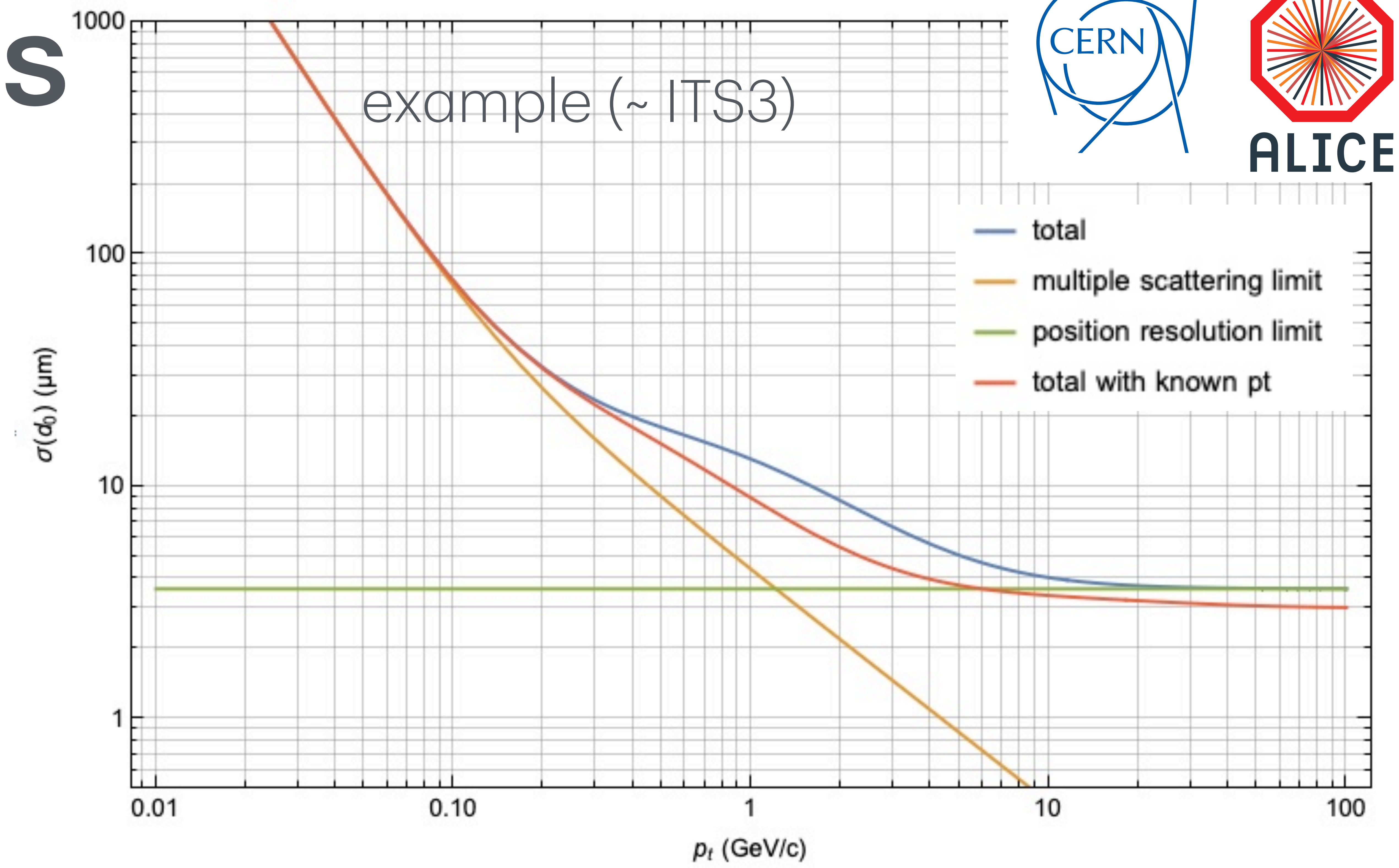


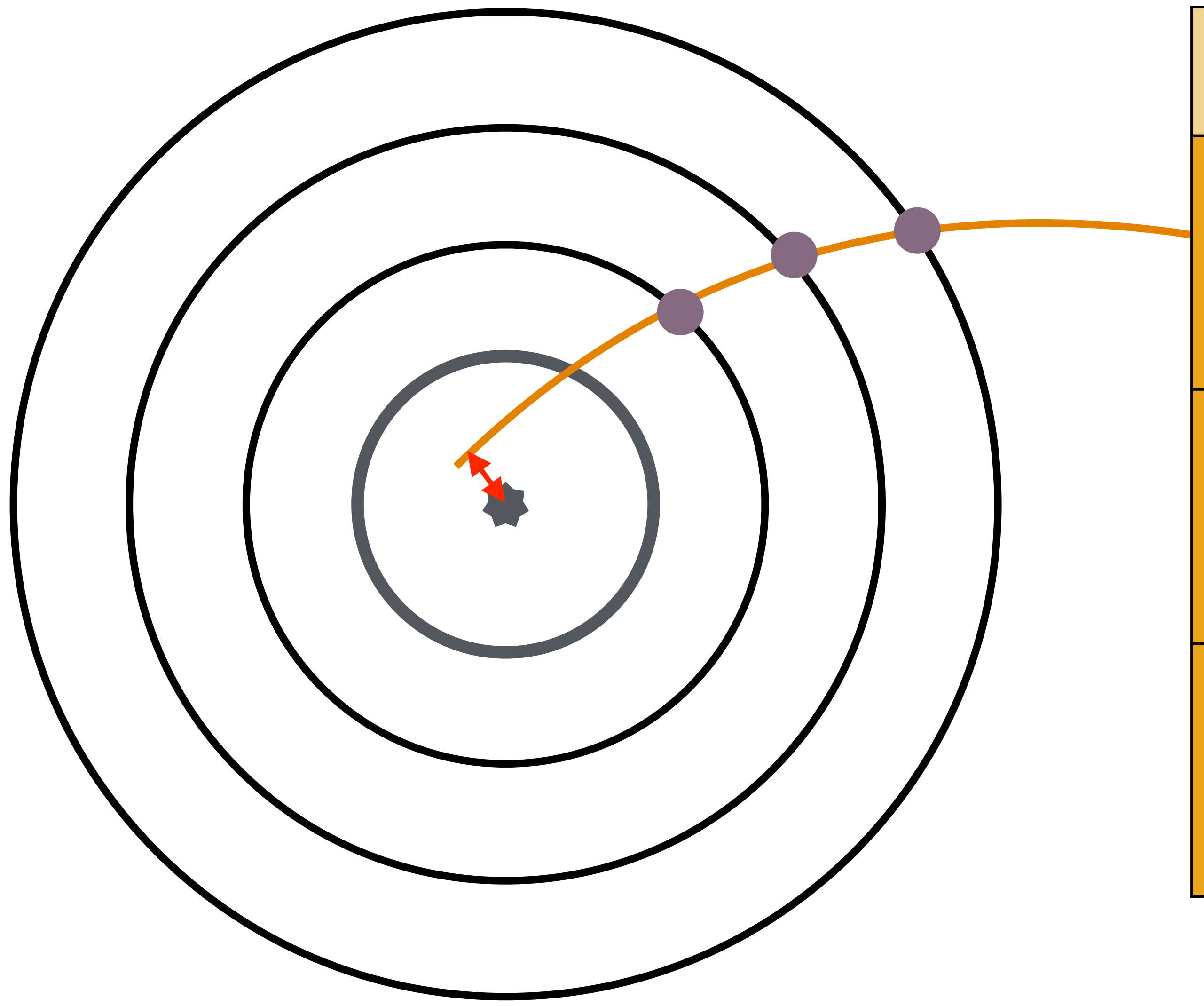

ALICE
ALICE
Pb-Pb 5.36 TeV
LHC22s period
18th November 2022
16:52:47.893
see also:
A. Andronic
Fri 9:30

Key performance figures

resolution, material budget

- Tracking and vertexing is based on finding *and* extrapolation of tracks
- **Performance figures**
  - impact parameter resolution
  - momentum resolution
  - readout rate (“time resolution”)
  - tracking efficiency
- **Three key contributions**
  - material budget
  - distance to interaction point
  - intrinsic sensor position resolution
  - (intrinsic detector efficiency)

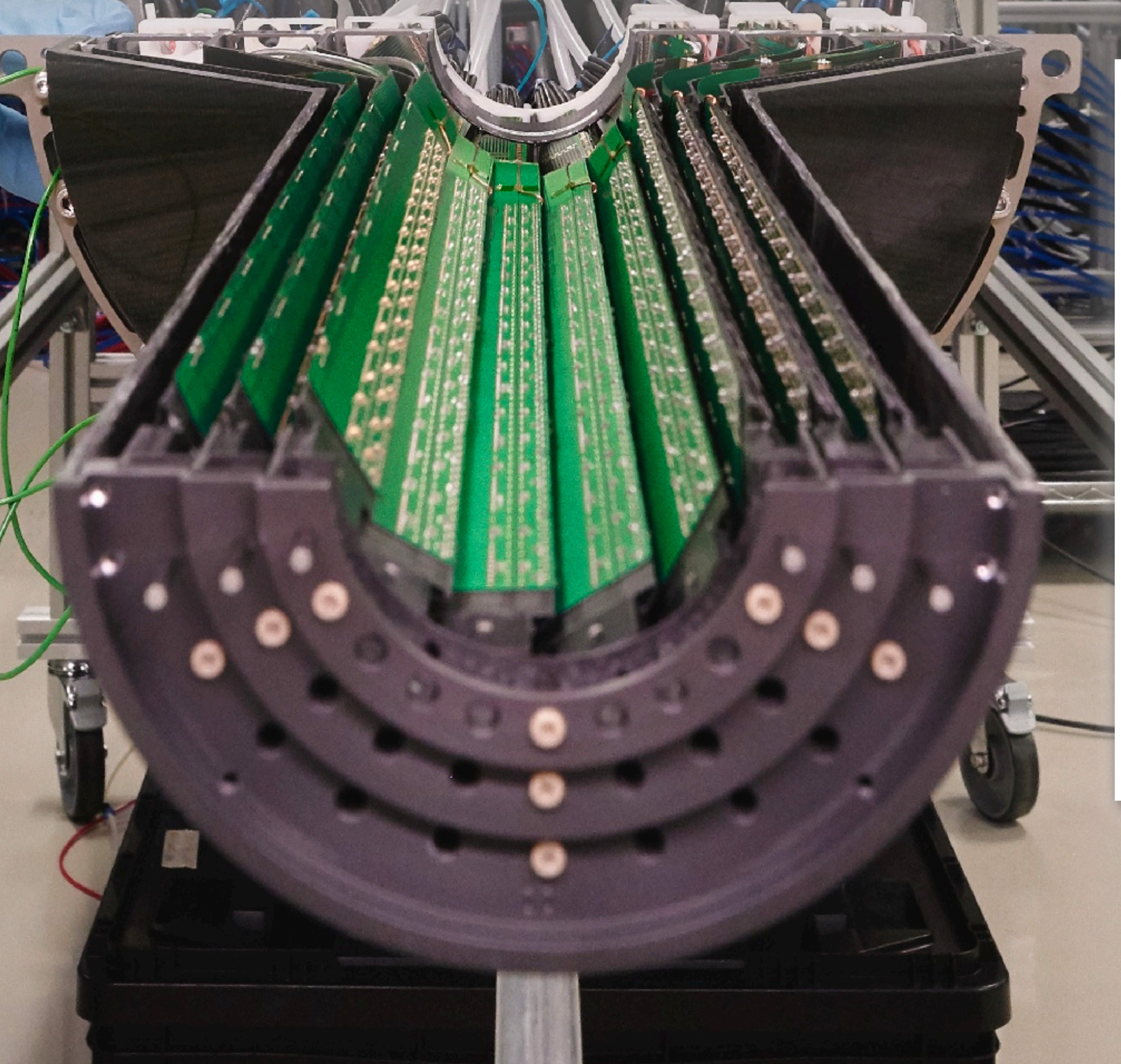


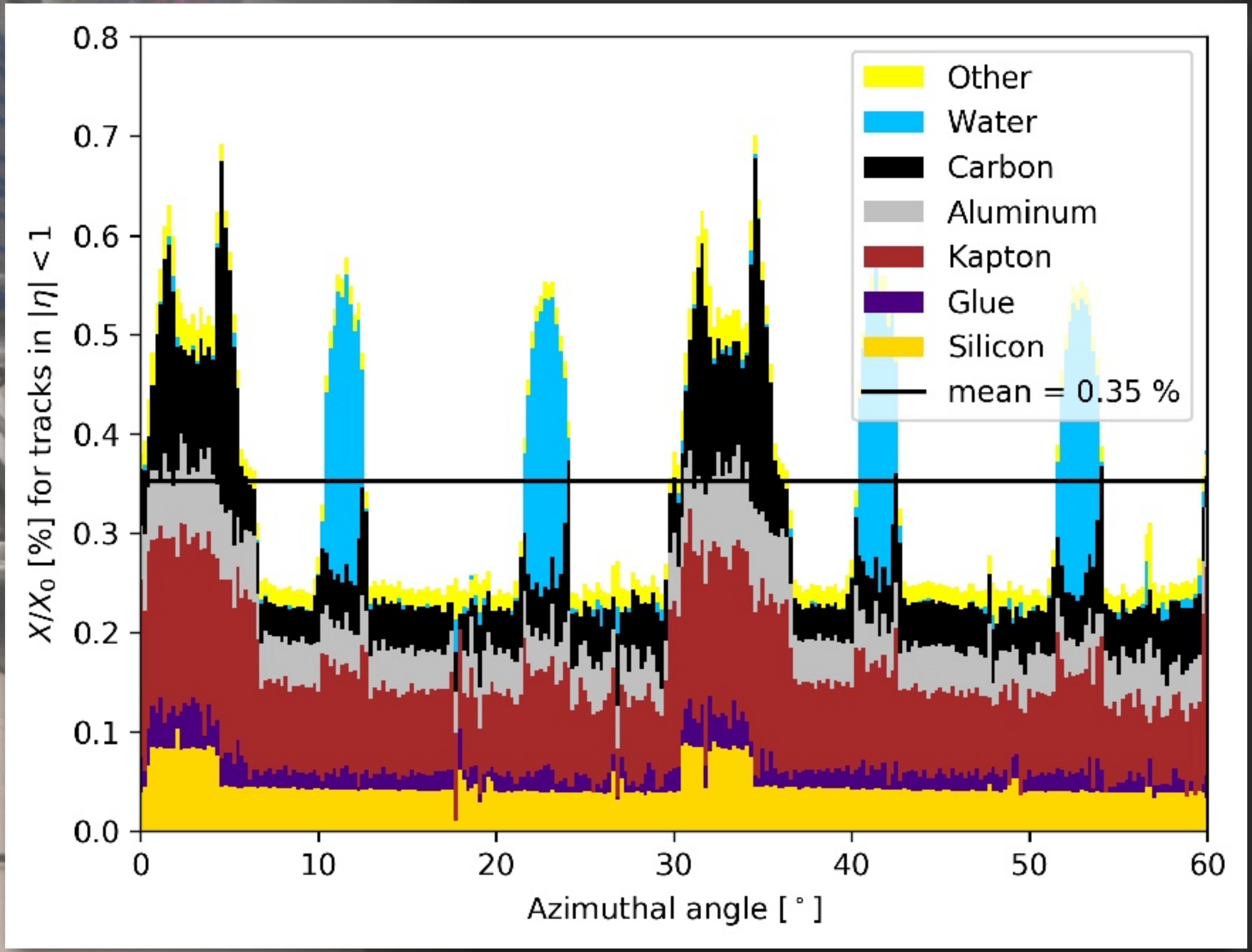


Limit	Momentum	Pointing
	$\frac{\Delta p_t}{p_t}$	$\Delta d_{0,xy}$
sensor resolution	$\propto \frac{\sigma p_t}{BL^2}$	$\propto r_0 \sigma$
material budget	$\propto \frac{1}{\beta BL}\sqrt{x/X_0}$	$\propto \frac{r_0}{\beta p_t}\sqrt{x/X_0}$

more info: [doi:10.1016/j.nima.2018.08.078]

ITS2 Inner Barrel





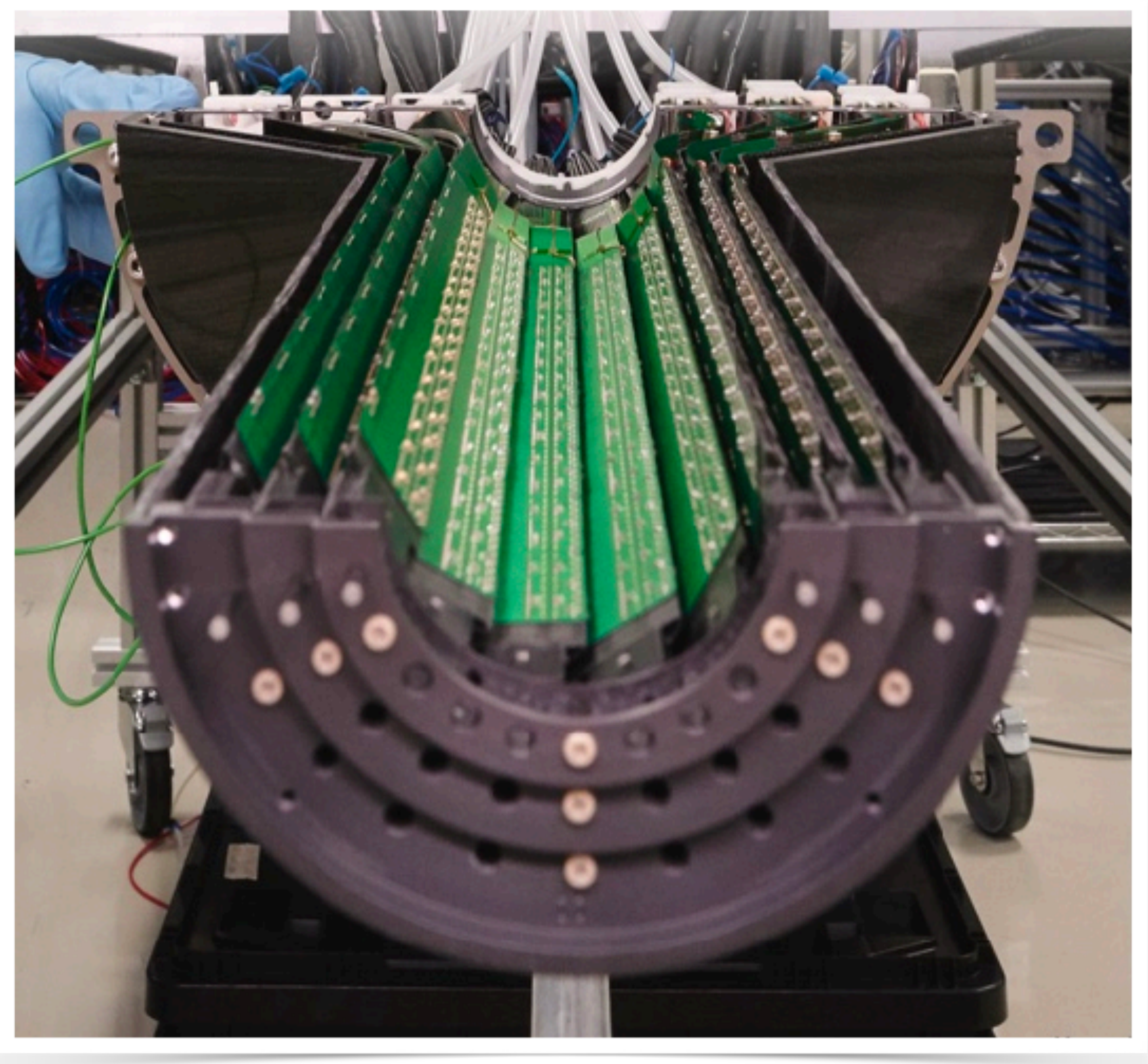
Very light detector (0.35% X0)

Yet, dominated by support structures

ALICE ITS3

TDR [CERN-LHCC-2024-003 ; ALICE-TDR-021]

conceptional idea

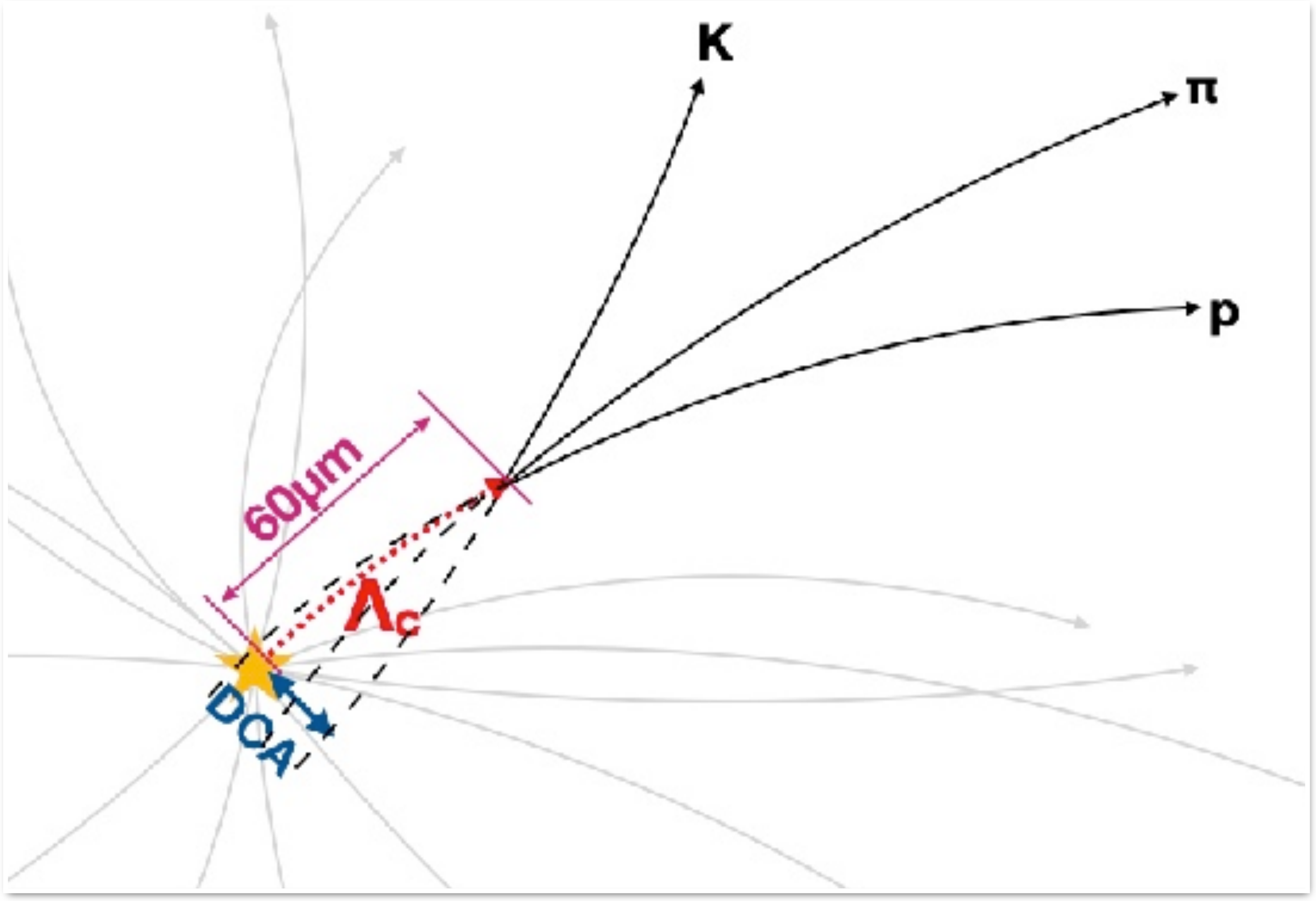


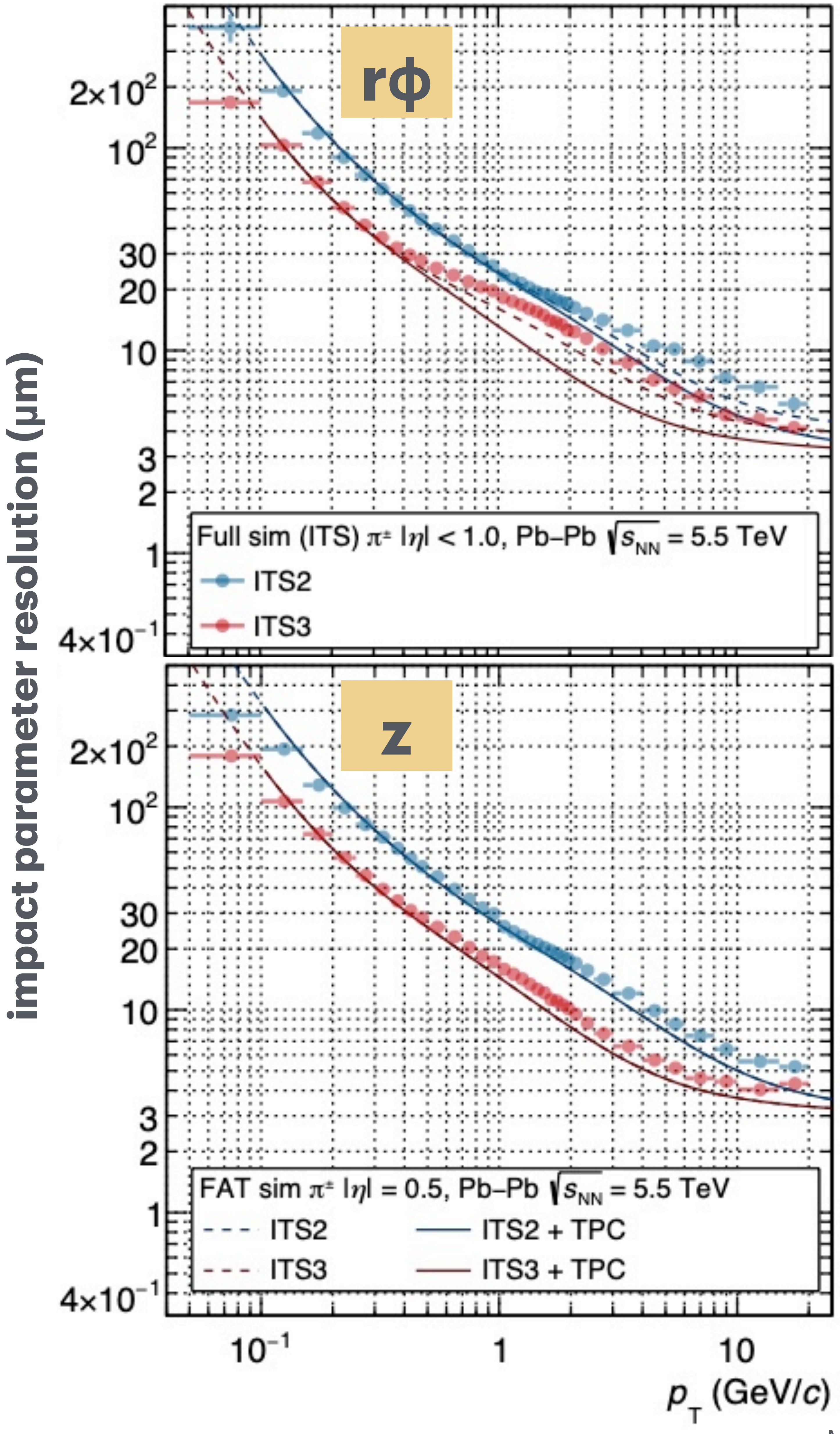
Only 1/7th of the material budget!

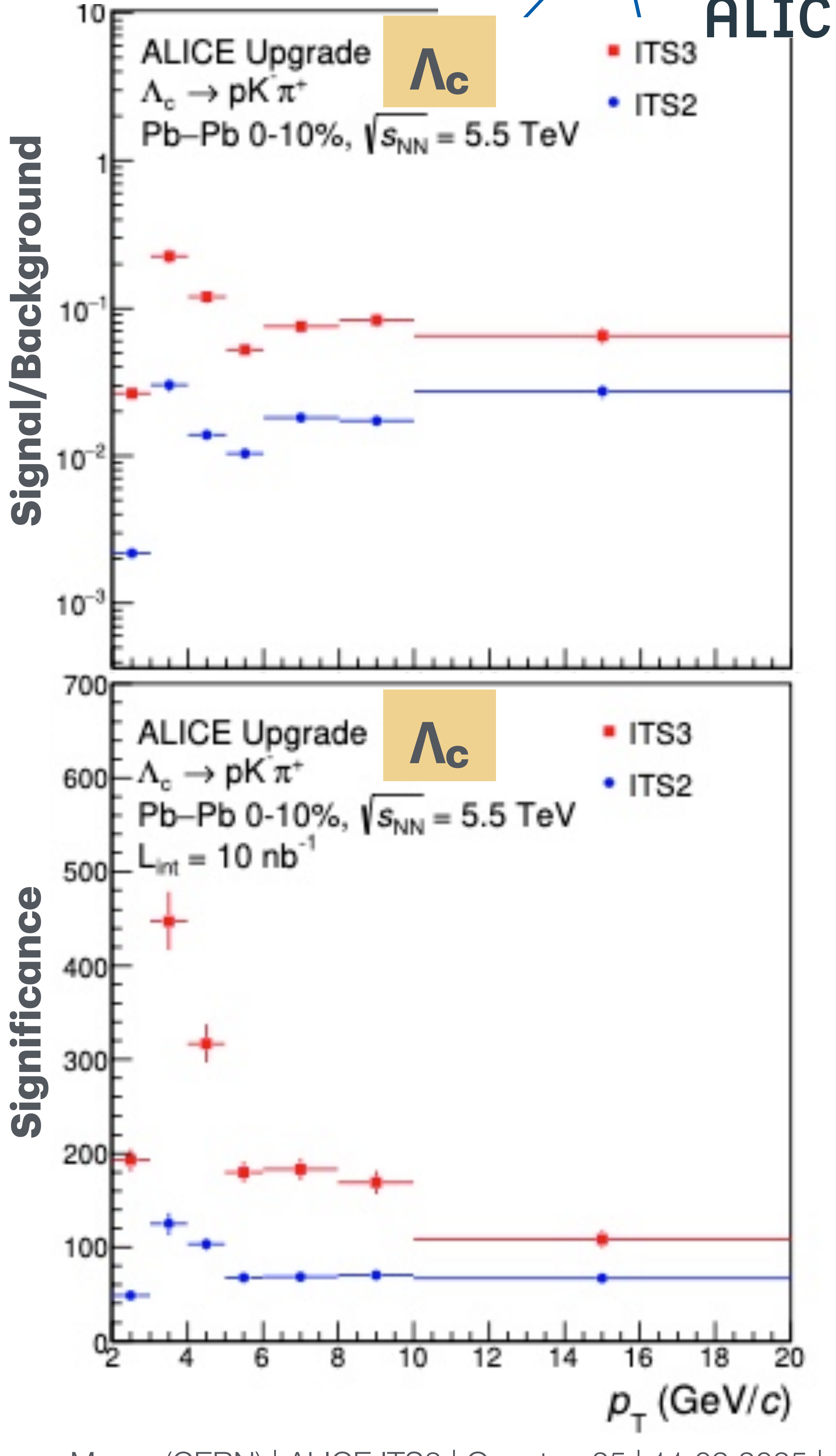
- Replacing the barrels by real half-cylinders (of **bent, thin** silicon)
- Rely on **wafer-scale sensors** (1 sensor per half-layer) in **65 nm** technology
- **Minimized material budget** → large improvement of vertexing precision and physics yield (“**ideal detector**”)

Projected performance boost

- Improvement of pointing resolution by:
  - drastic reduction of **material budget** (0.3 → 0.07% X0/layer)
  - being **closer** to the interaction point (24 → 19 mm)
  - thinner and smaller **beam pipe** (700 → 500 µm; 18 → 16 mm)
- Directly boosts the ALICE core physics program:
  - low momenta
  - secondary vertex reconstruction
- E.g. Λ_c S/B improves by factor 10, significance by factor 4

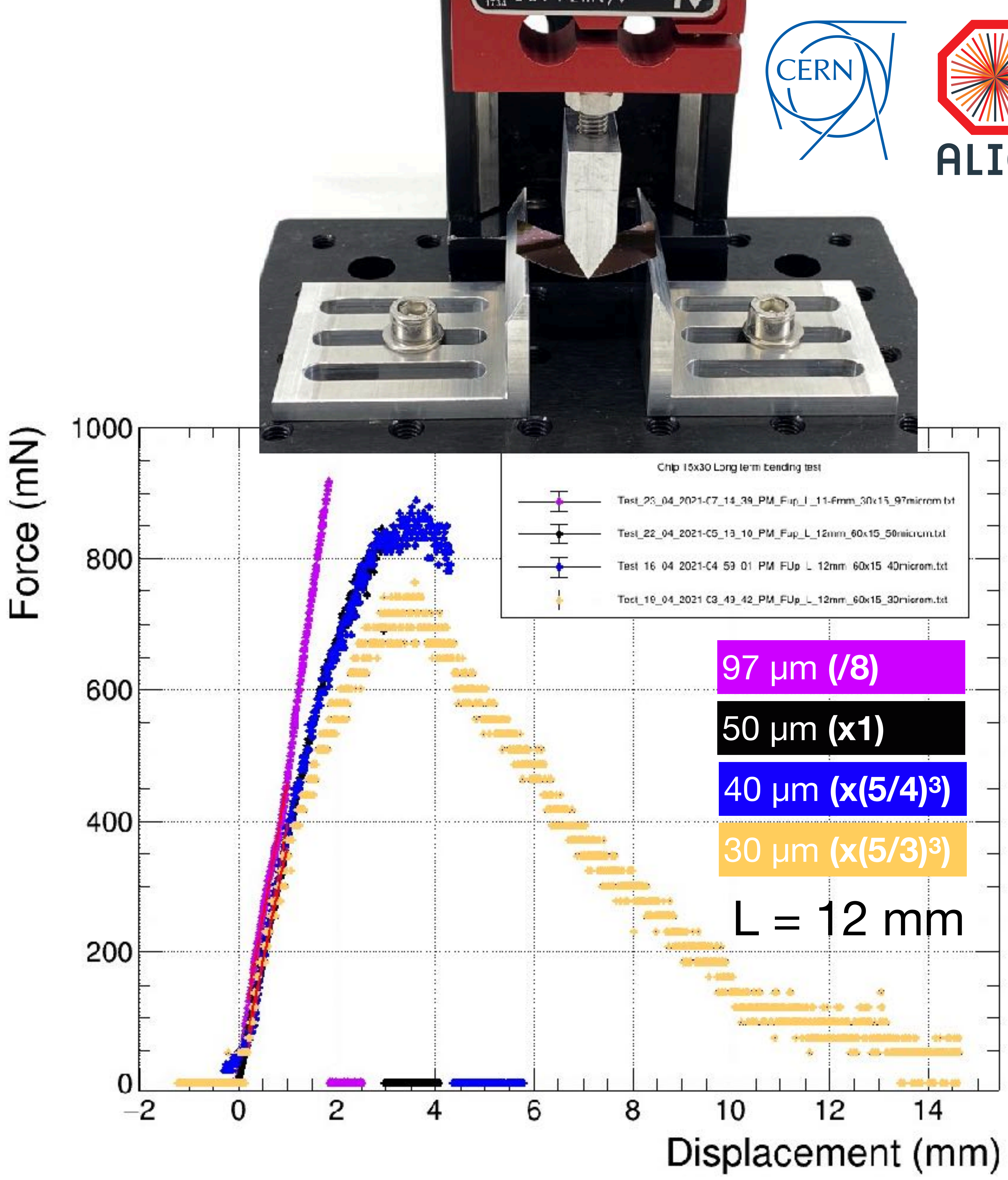






Flexibility of silicon

- **Monolithic** Active Pixel Sensors are quite flexible
- Bending force scales as (thickness)$^{-3}$
  - large benefit from thinner sensors



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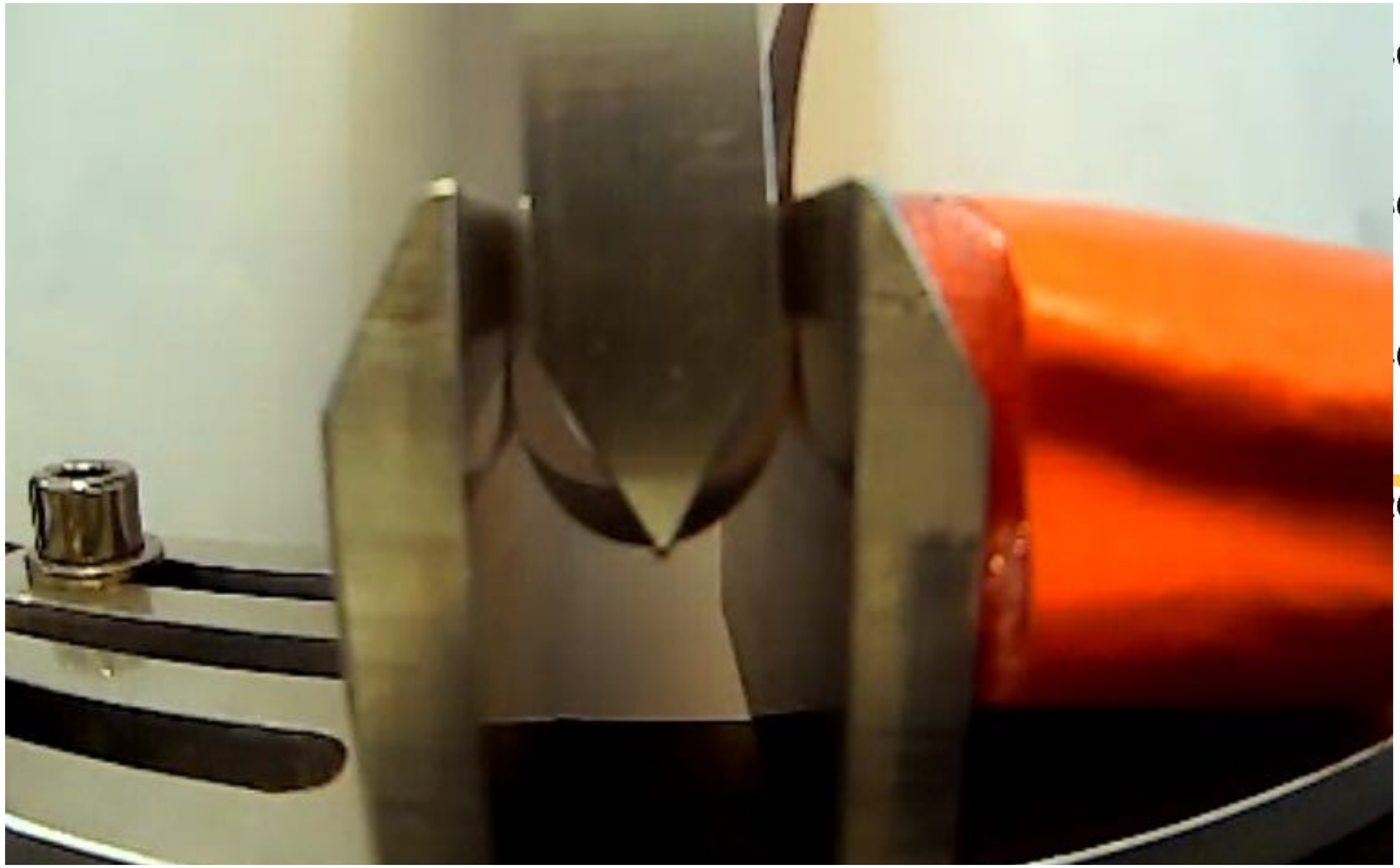
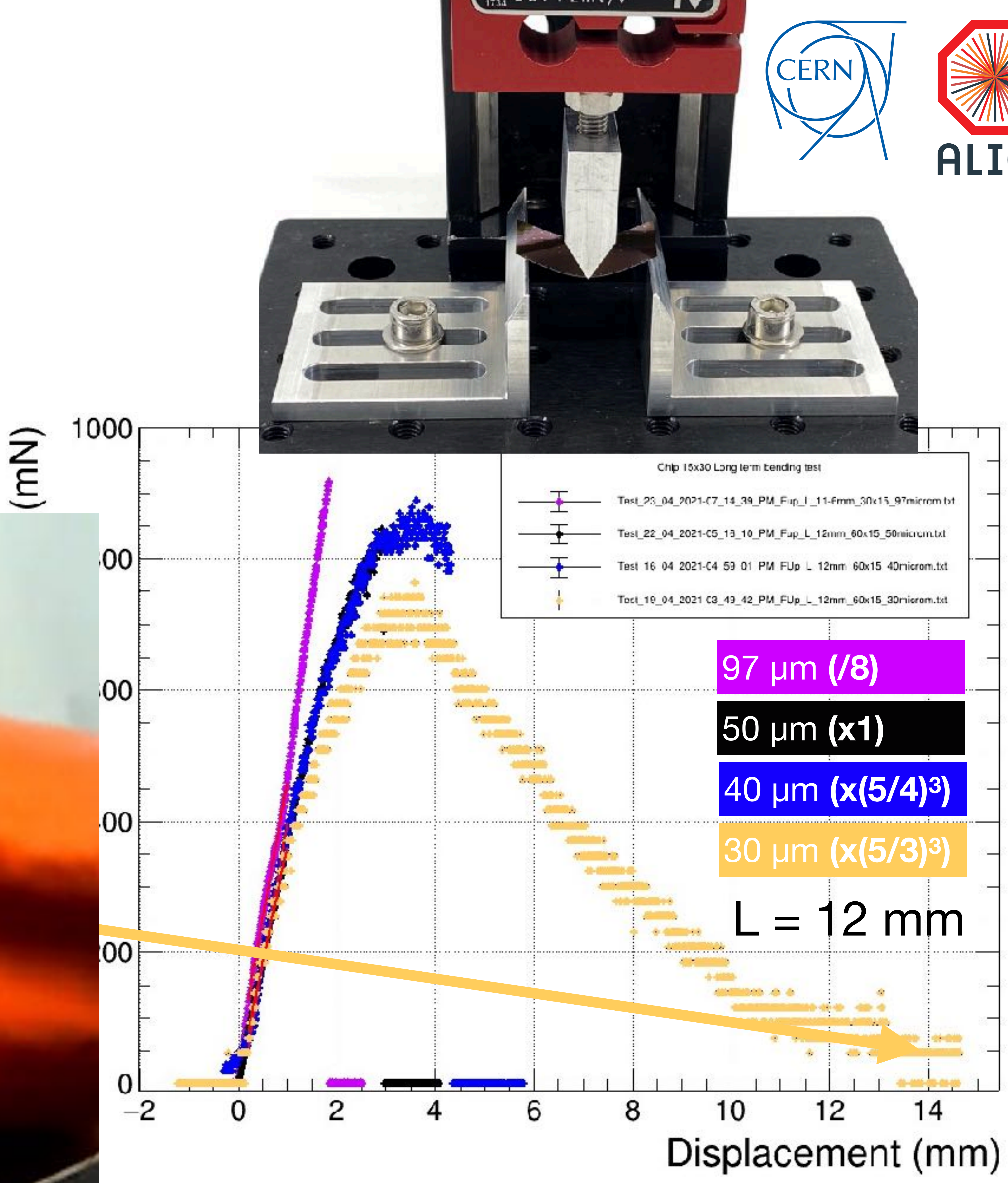
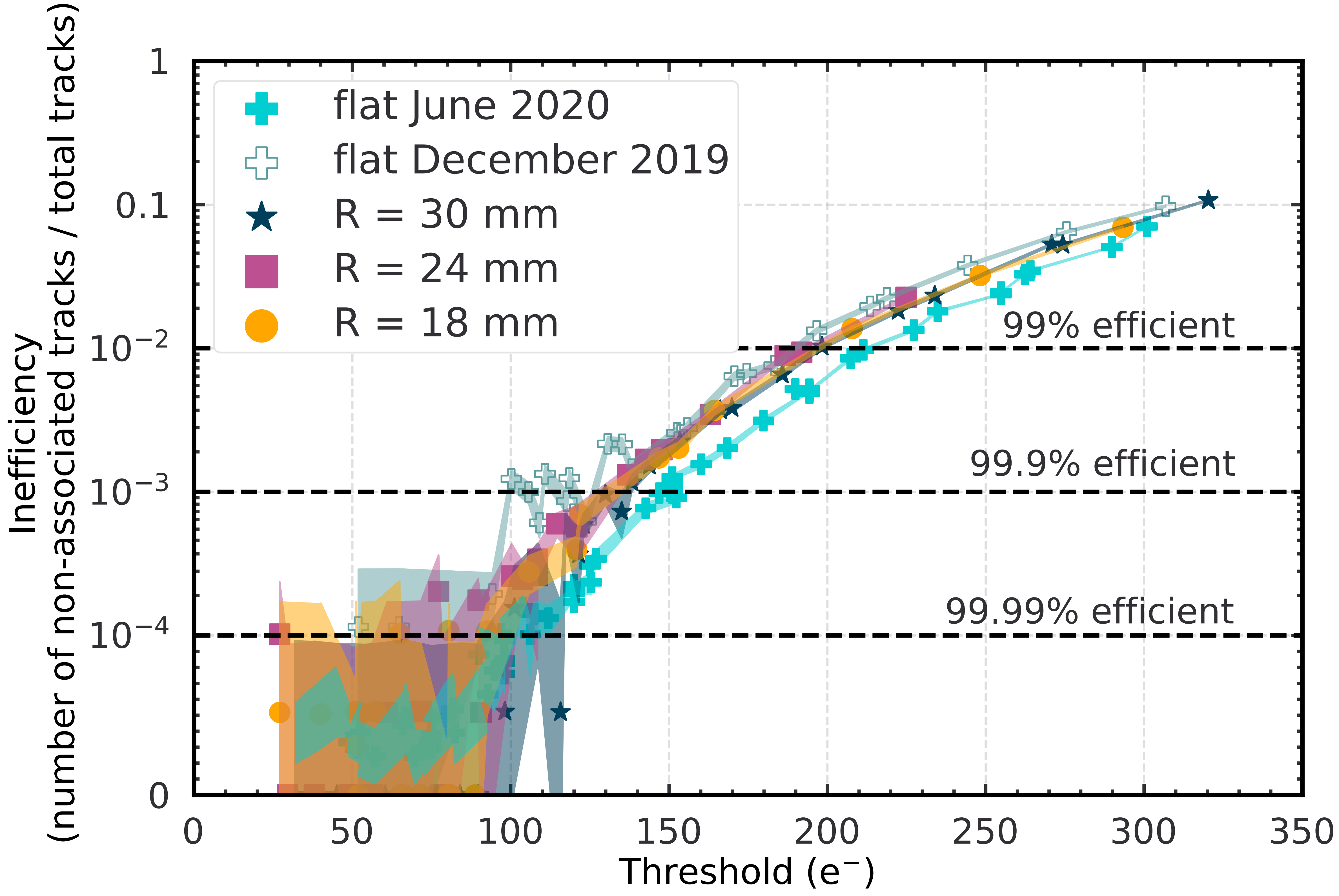




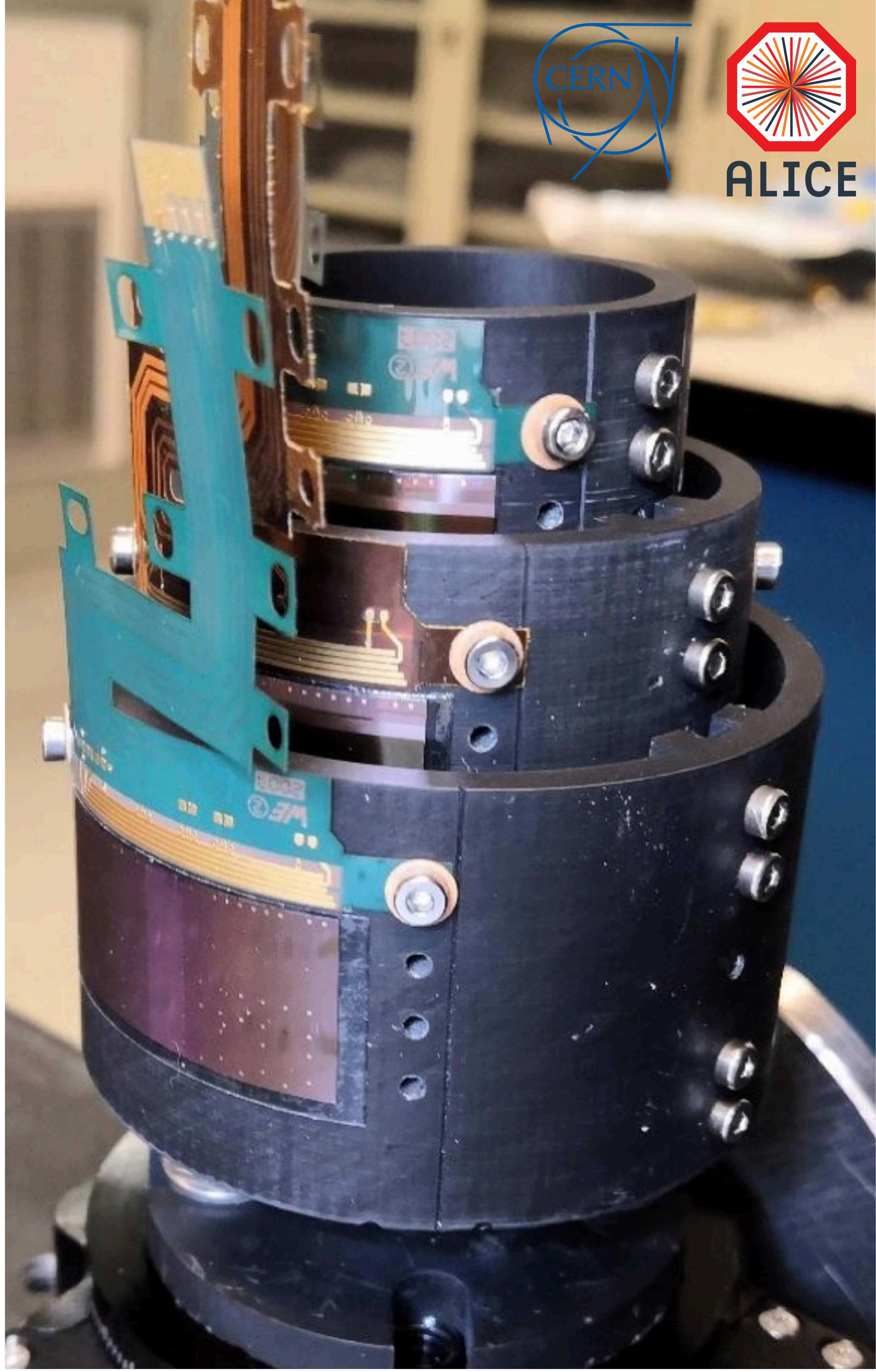
Bending ALPIDE

Bent MAPS

- Functional chips (ALPIDEs) are bent routinely
  - chips continue to work
  - tested at several beam campaigns

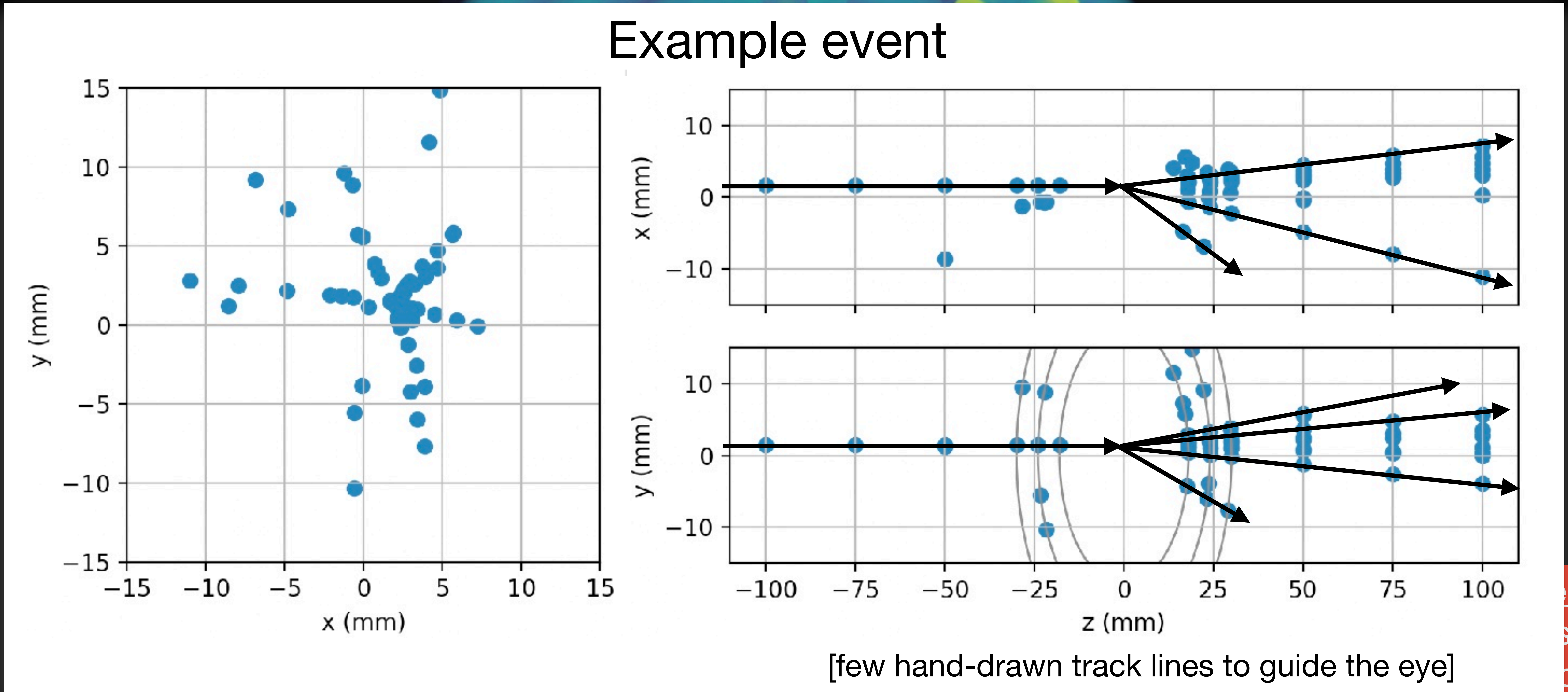


[doi:10.48550/arXiv.2502.04941]



“µITS3”

"µITS3"



…esults:
…solution
…ction efficiency
no effect of bending

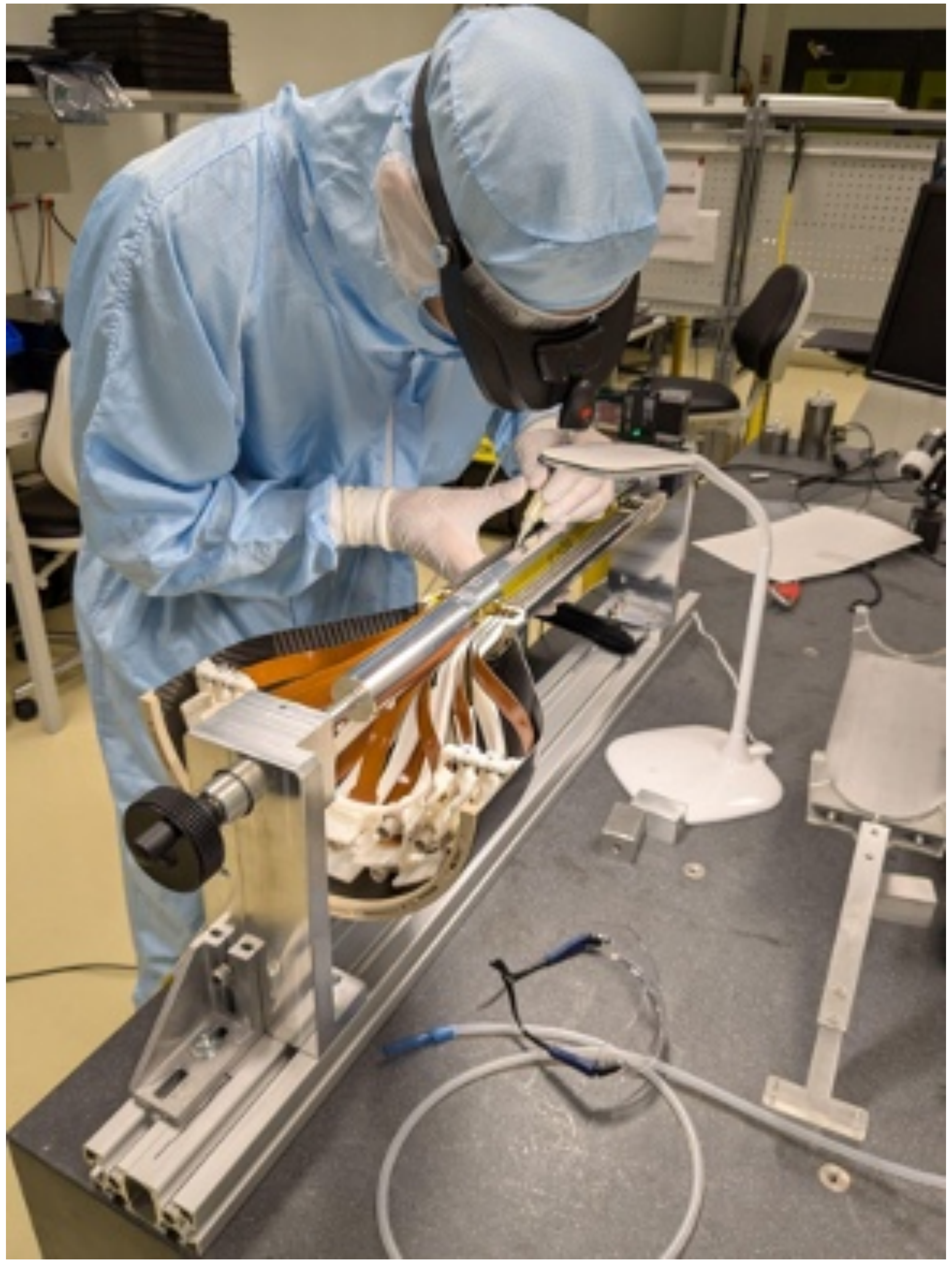
Bending of fully processed wafers

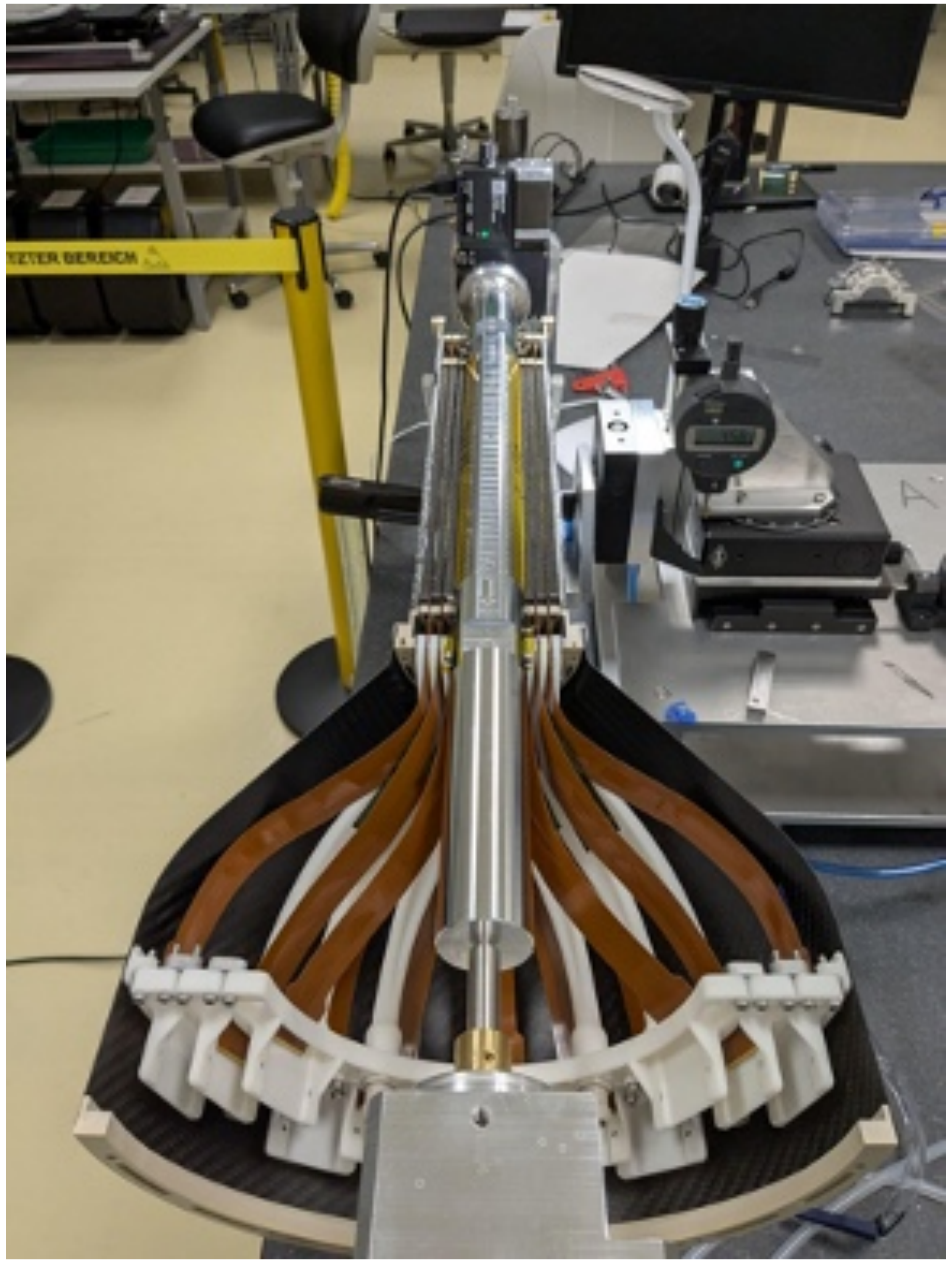
R = 18 mm

50 µm fully processed silicon

Engineering Models

including services

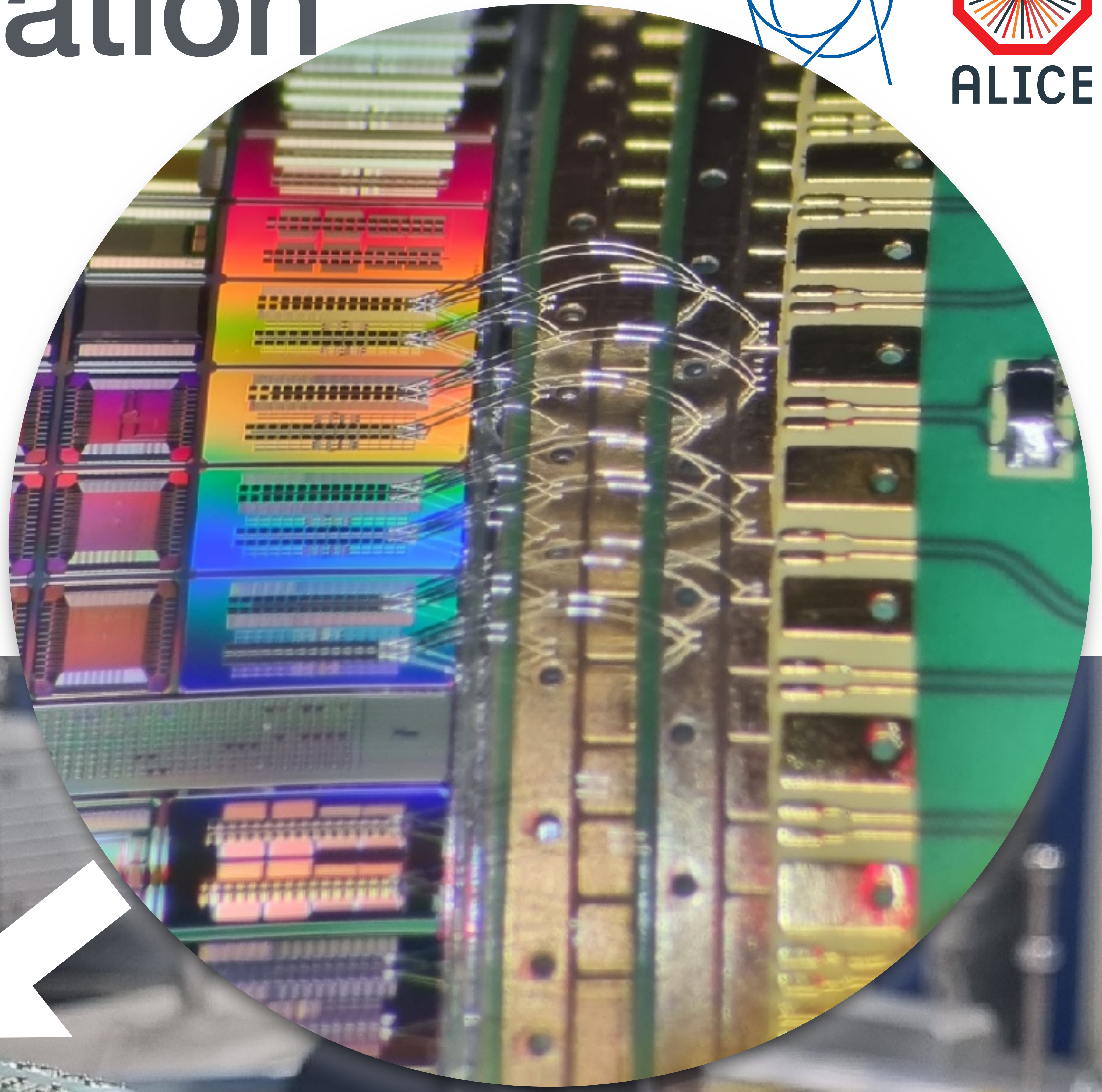




X-ray tomography

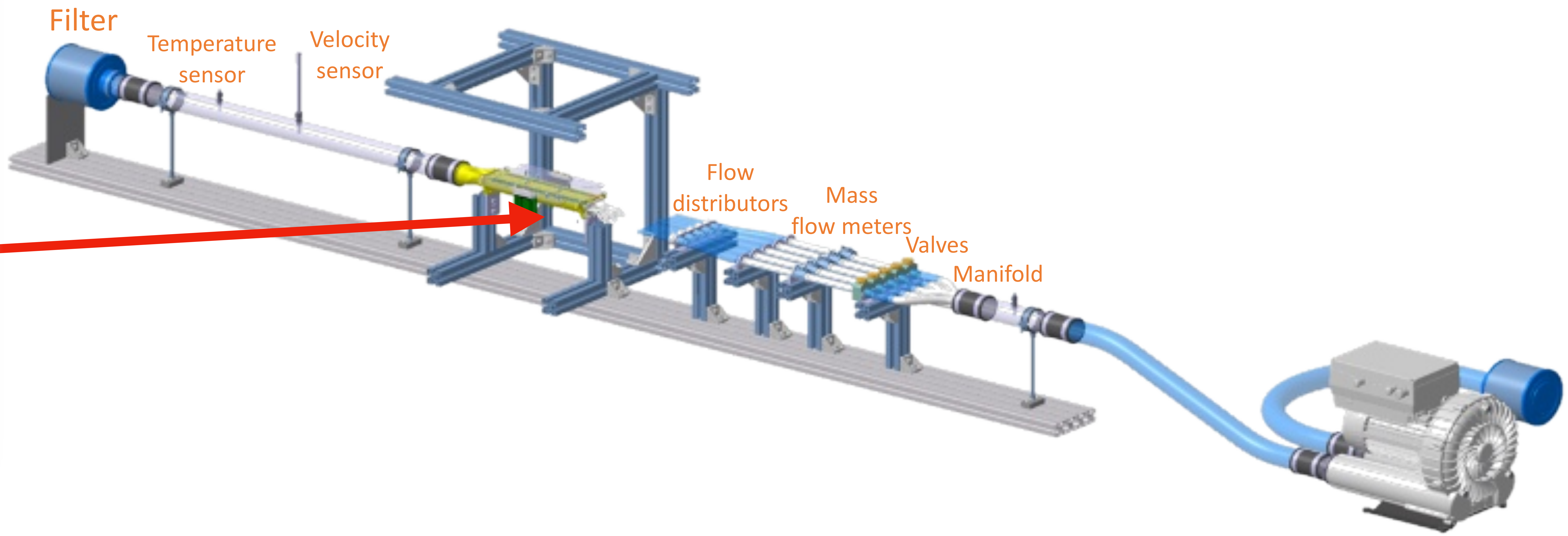
Electromechanical integration

- Wire-bonded to an FPC after bending



Wind tunnel

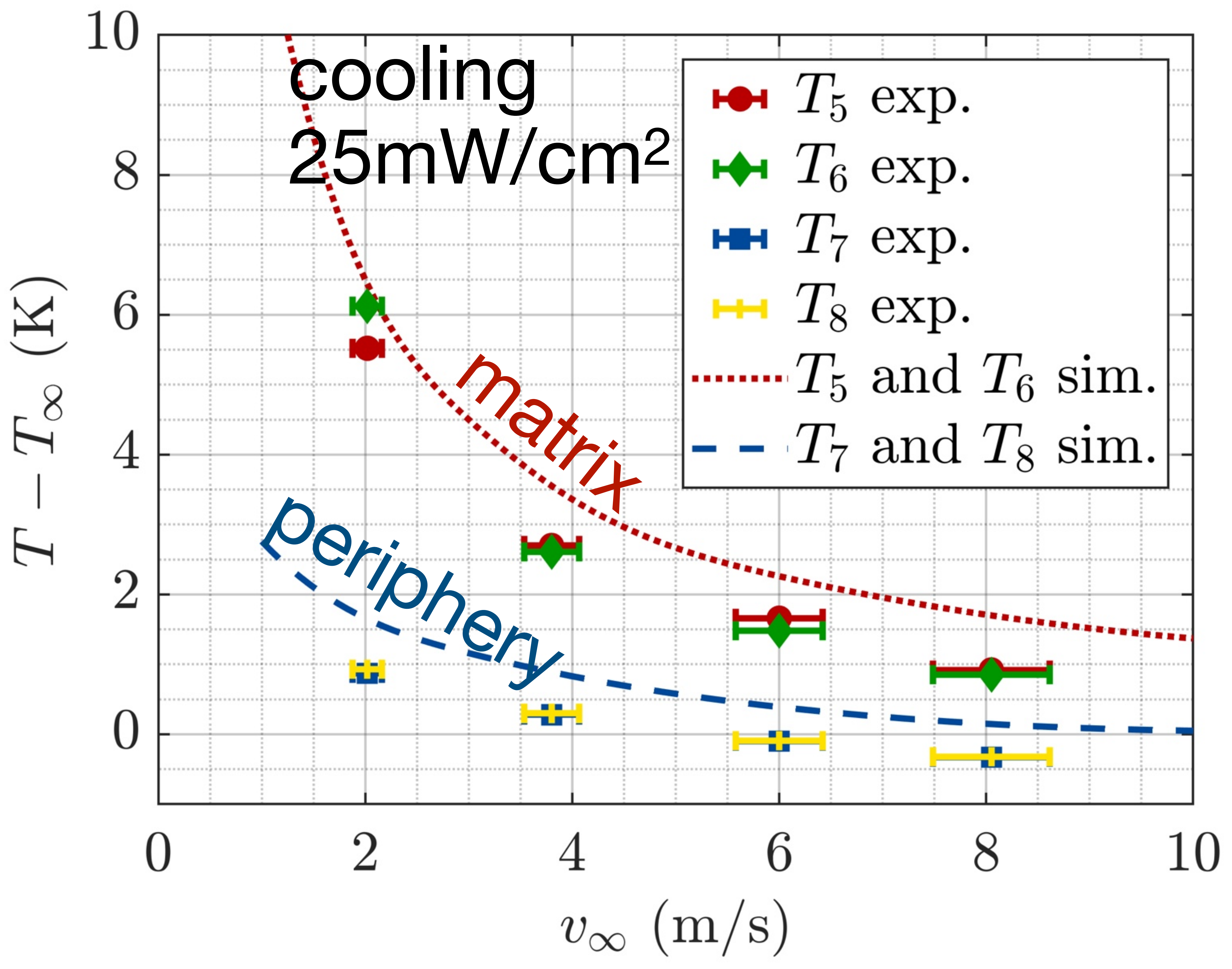
laser measurement system

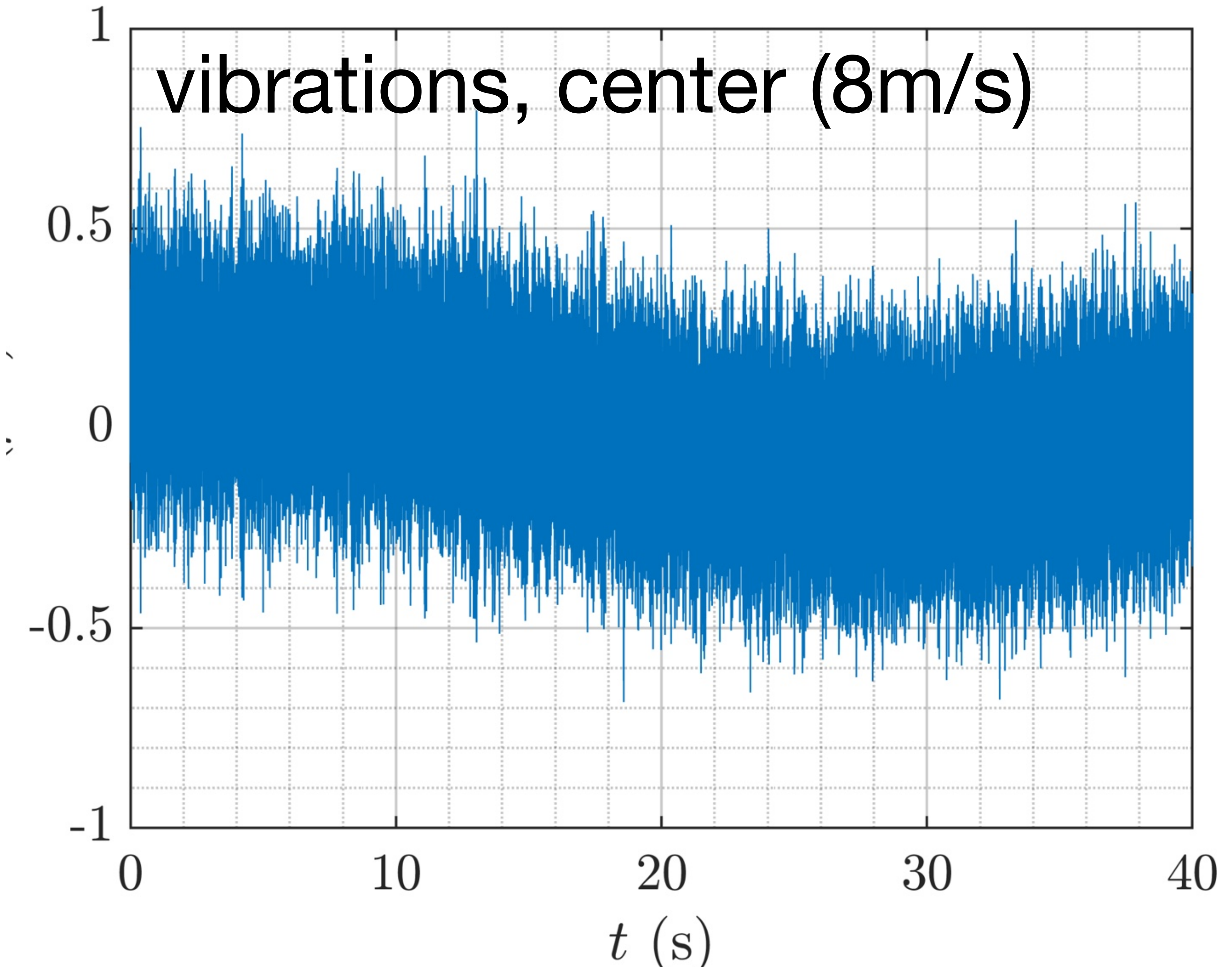


Filter
Temperature sensor
Velocity sensor
Flow distributors
Mass flow meters
Valves
Manifold

Wind tunnel

las
measur
syst



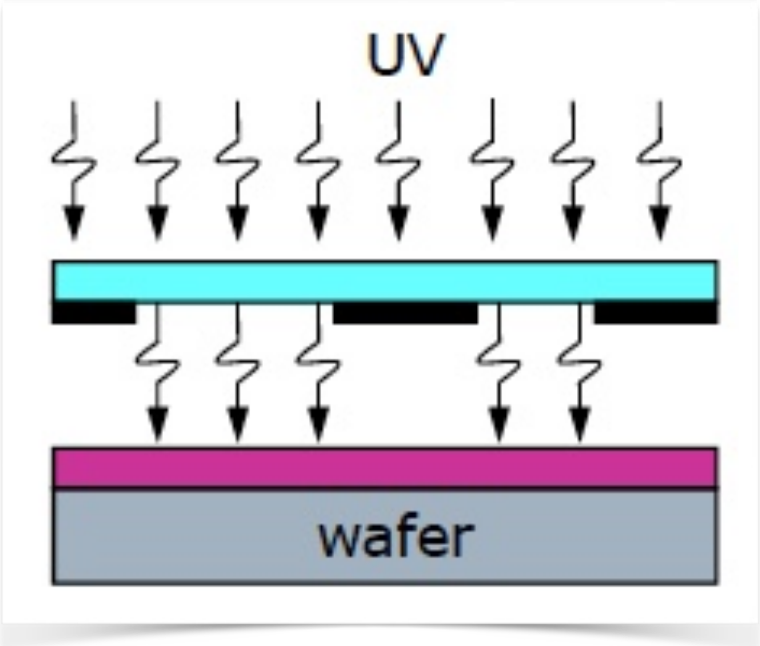


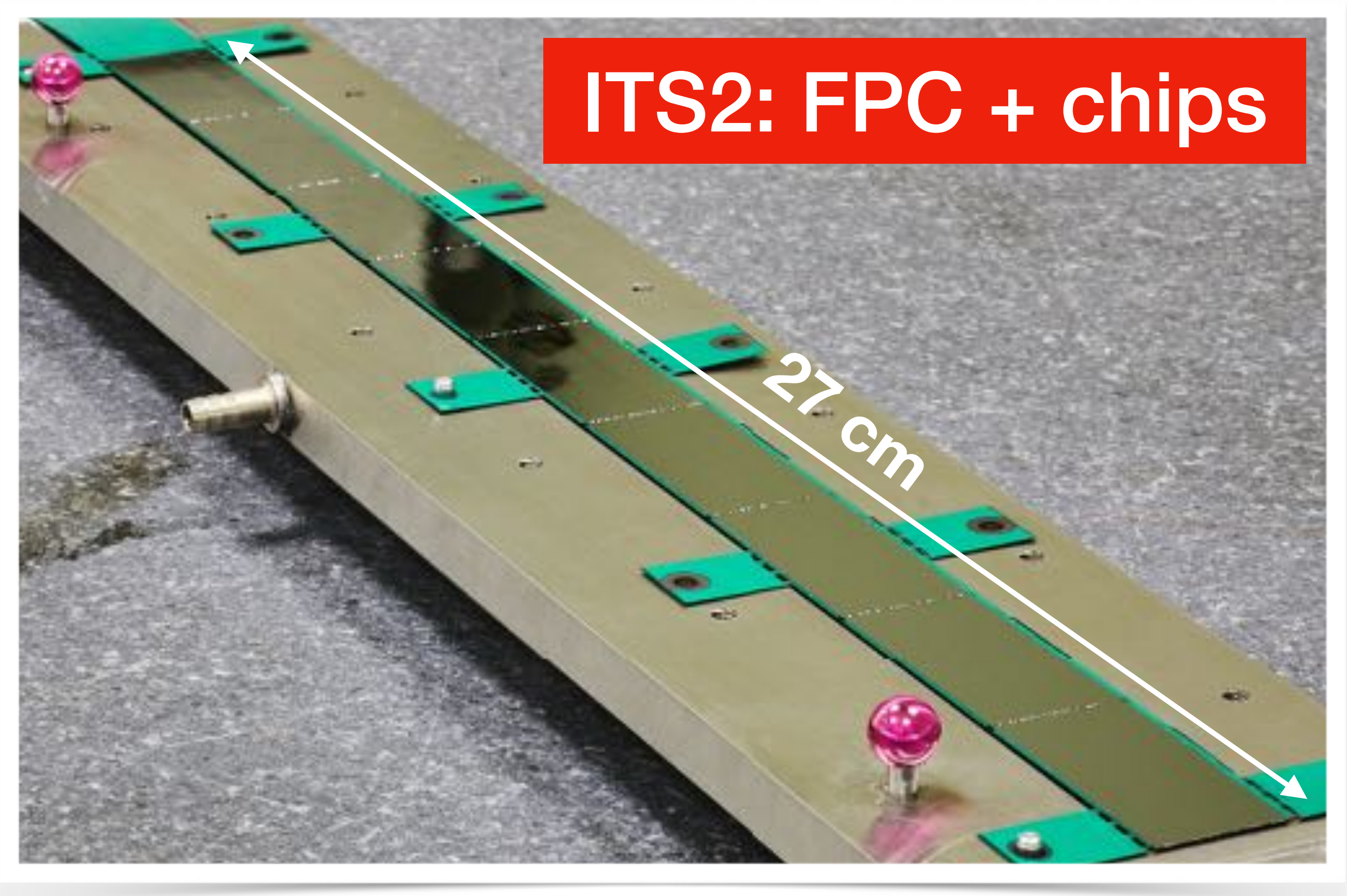
very good results with quite some margin: current target 40 mW/cm²

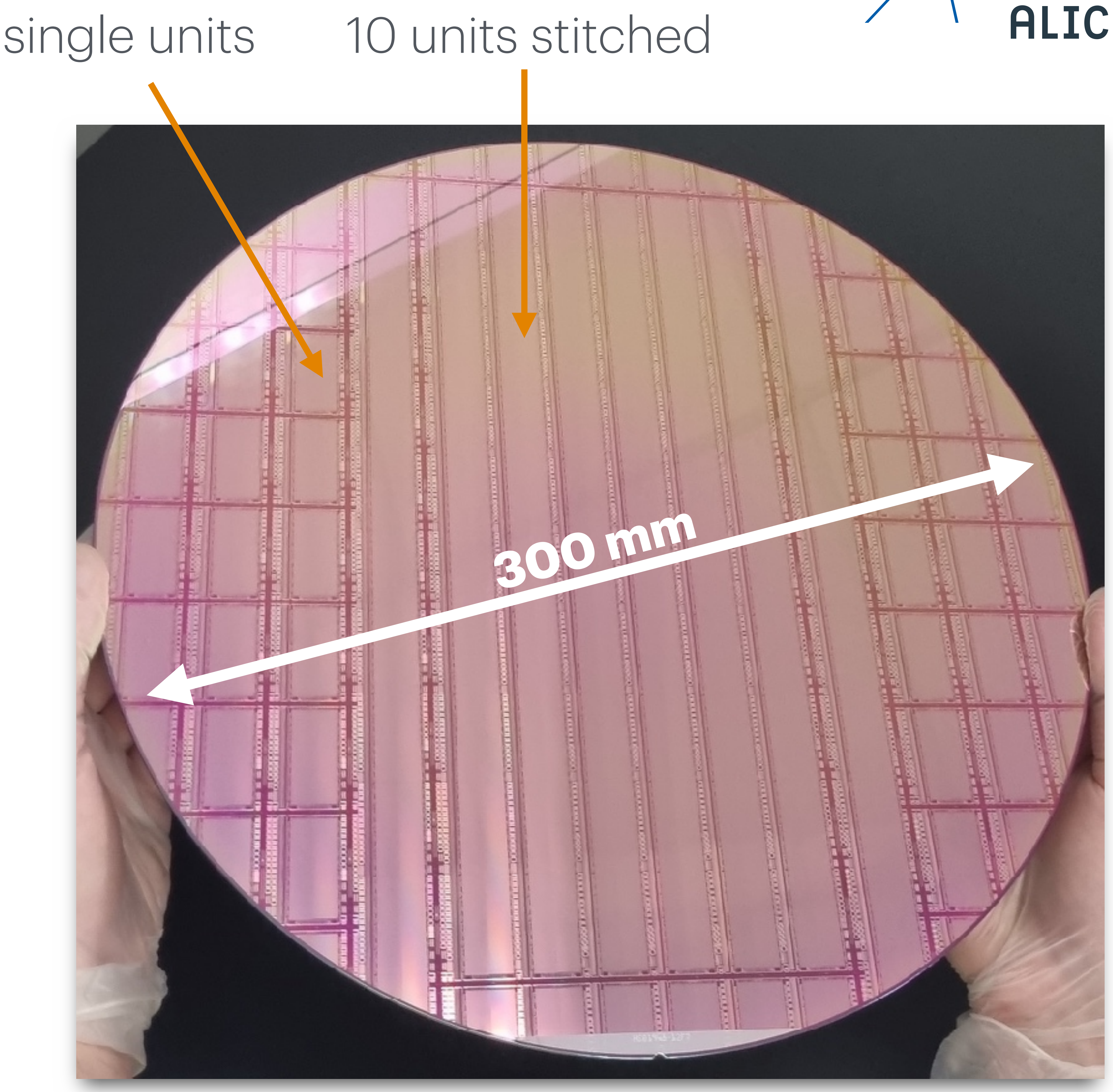
Wafer-scale sensors

concept

- **Previous** chip sizes are O(1-3 by 1-3 cm^2)
  - dictated by mask size
  - masks are exposed once for each chip
  - chips diced out and qualified/selected
  - interconnection on circuit boards ("modules")
- **Wafer-scale** "chips"/sensors: stitching of exposures
  - same mask exposed in a precisely aligned fashion
  - design is made periodic (metal lines stitch together)
  - *chip is a module*
  - **but:** more sensitive to manufacturing defects (yield)

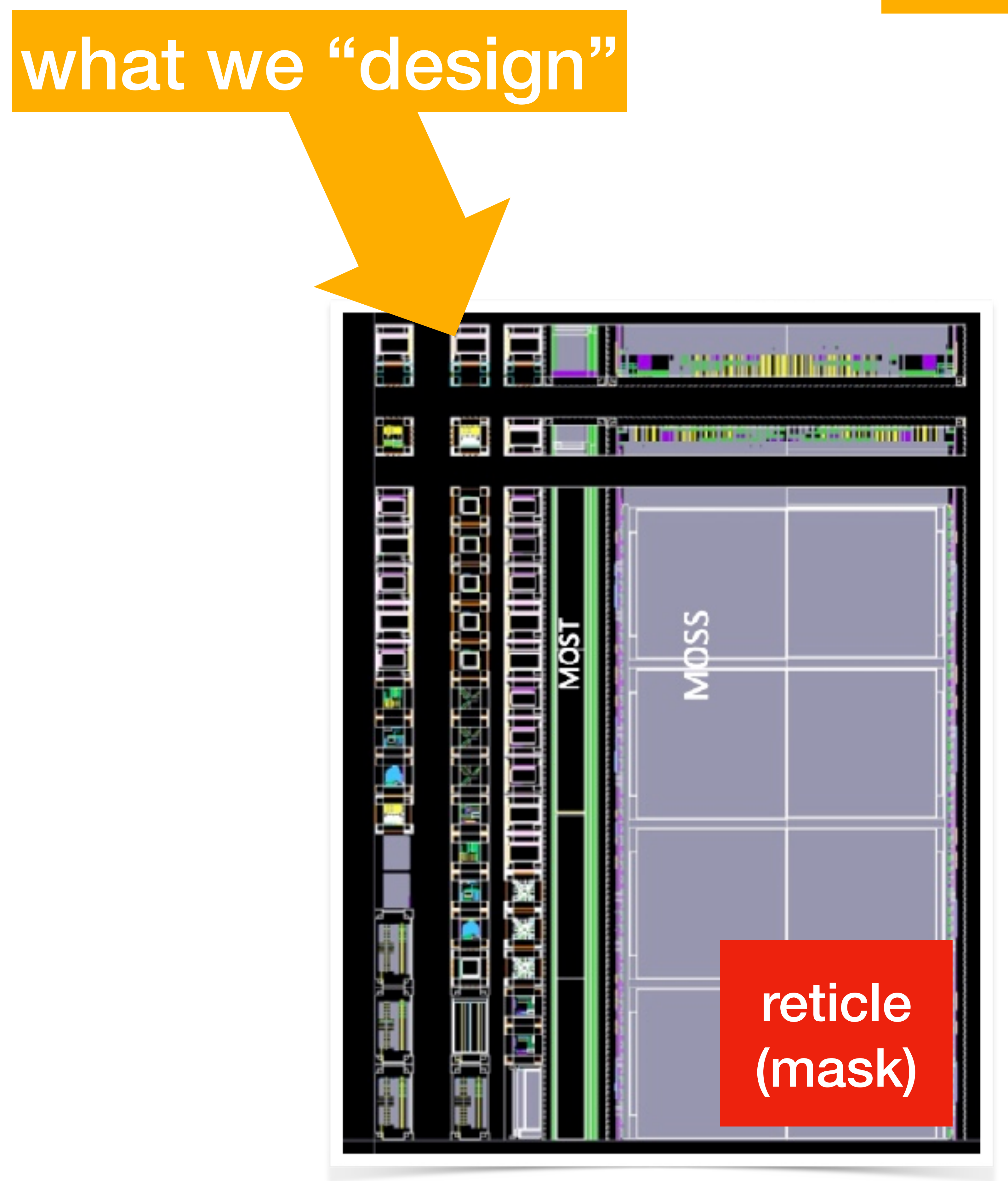


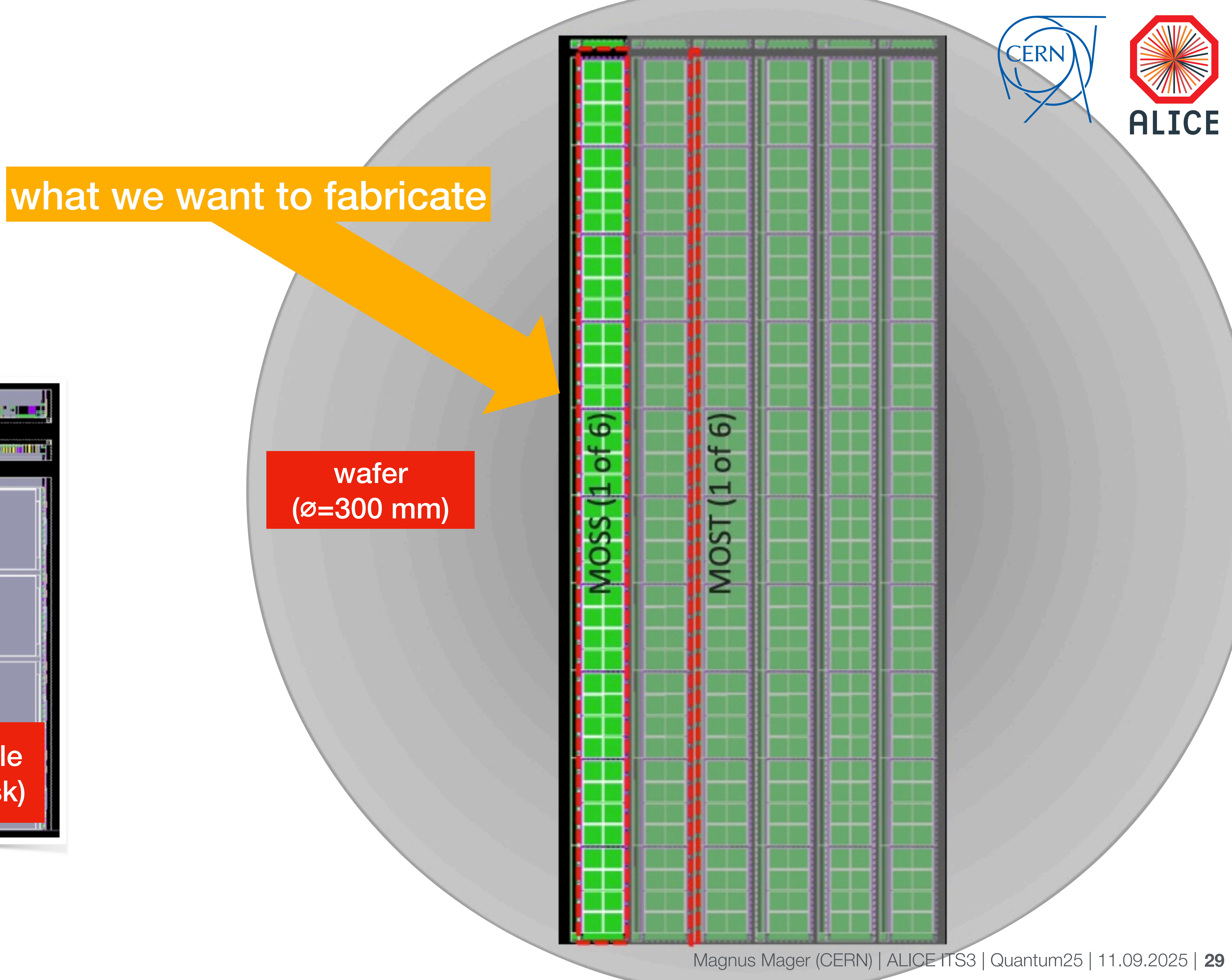




Stitching

rough principle

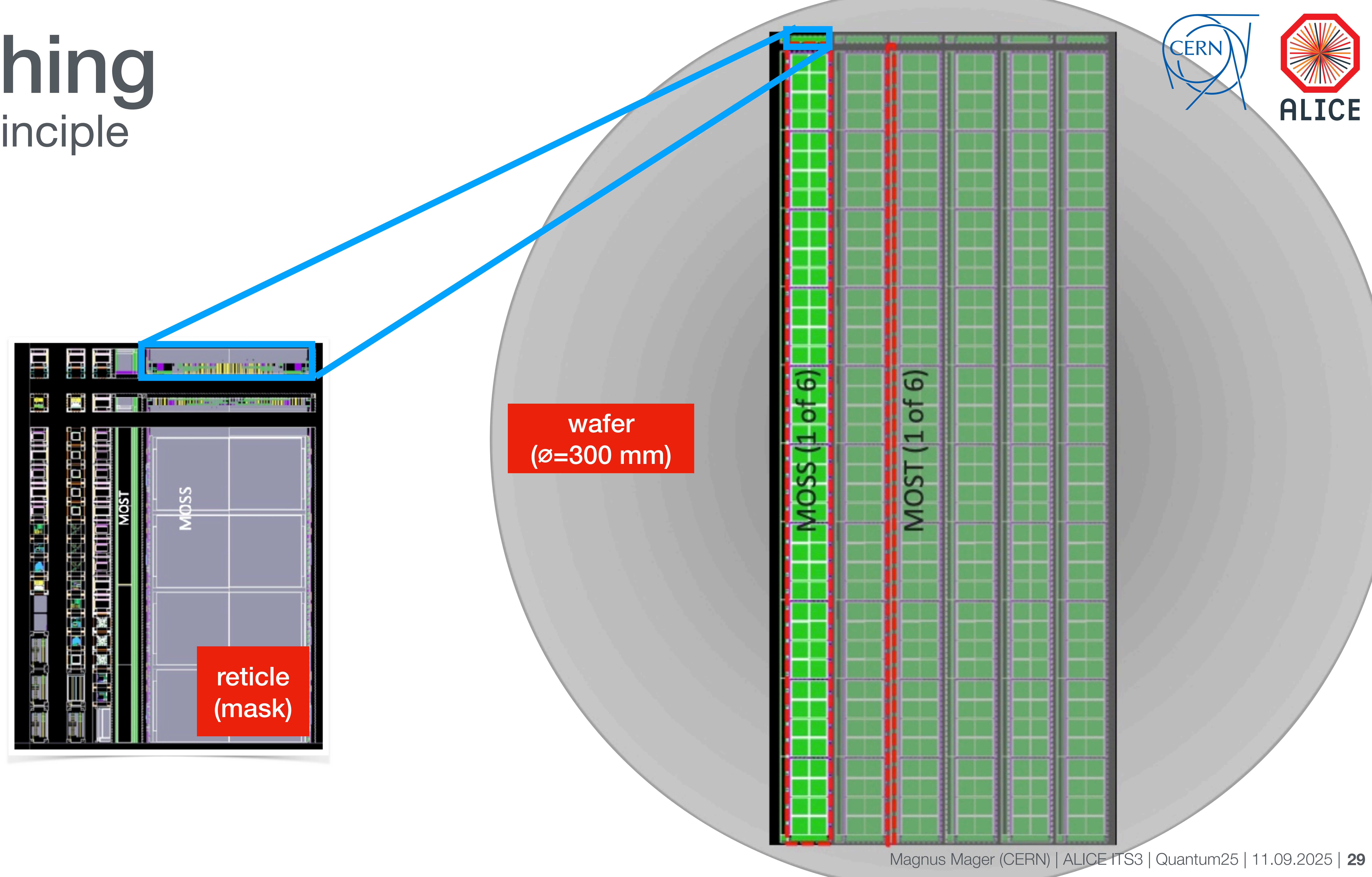




Stitching

rough principle

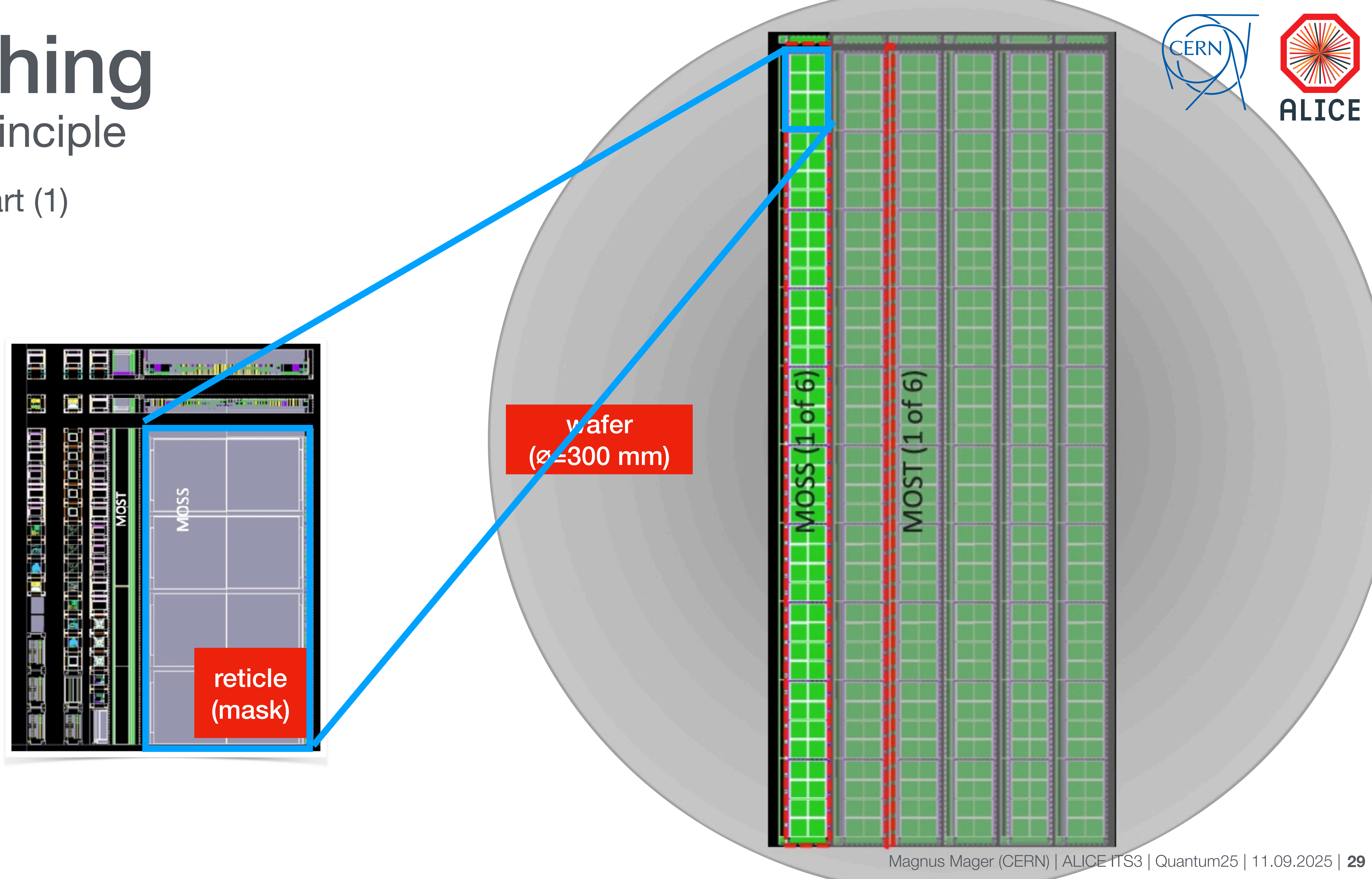
- top part



Stitching

rough principle

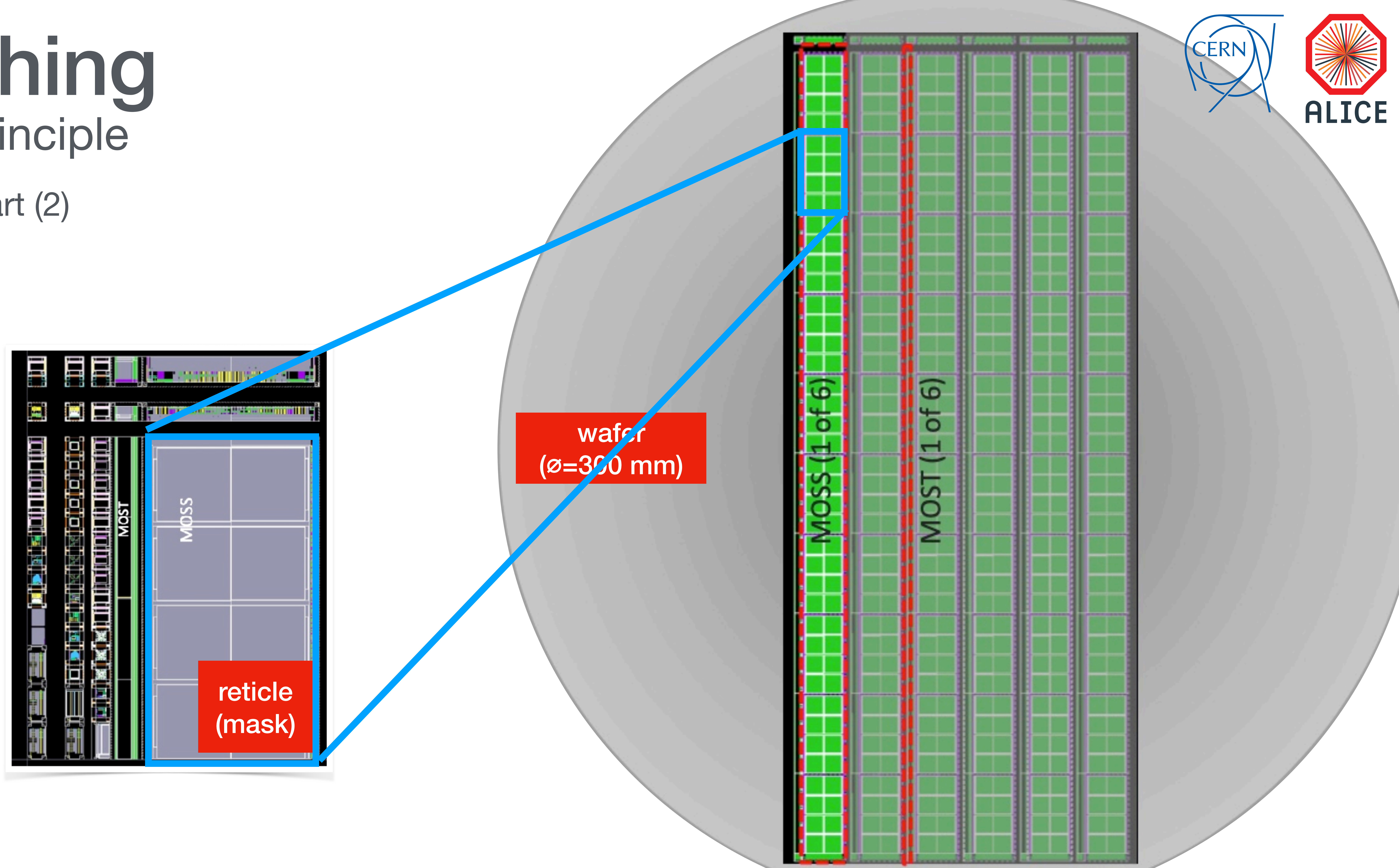
- central part (1)



Stitching

rough principle

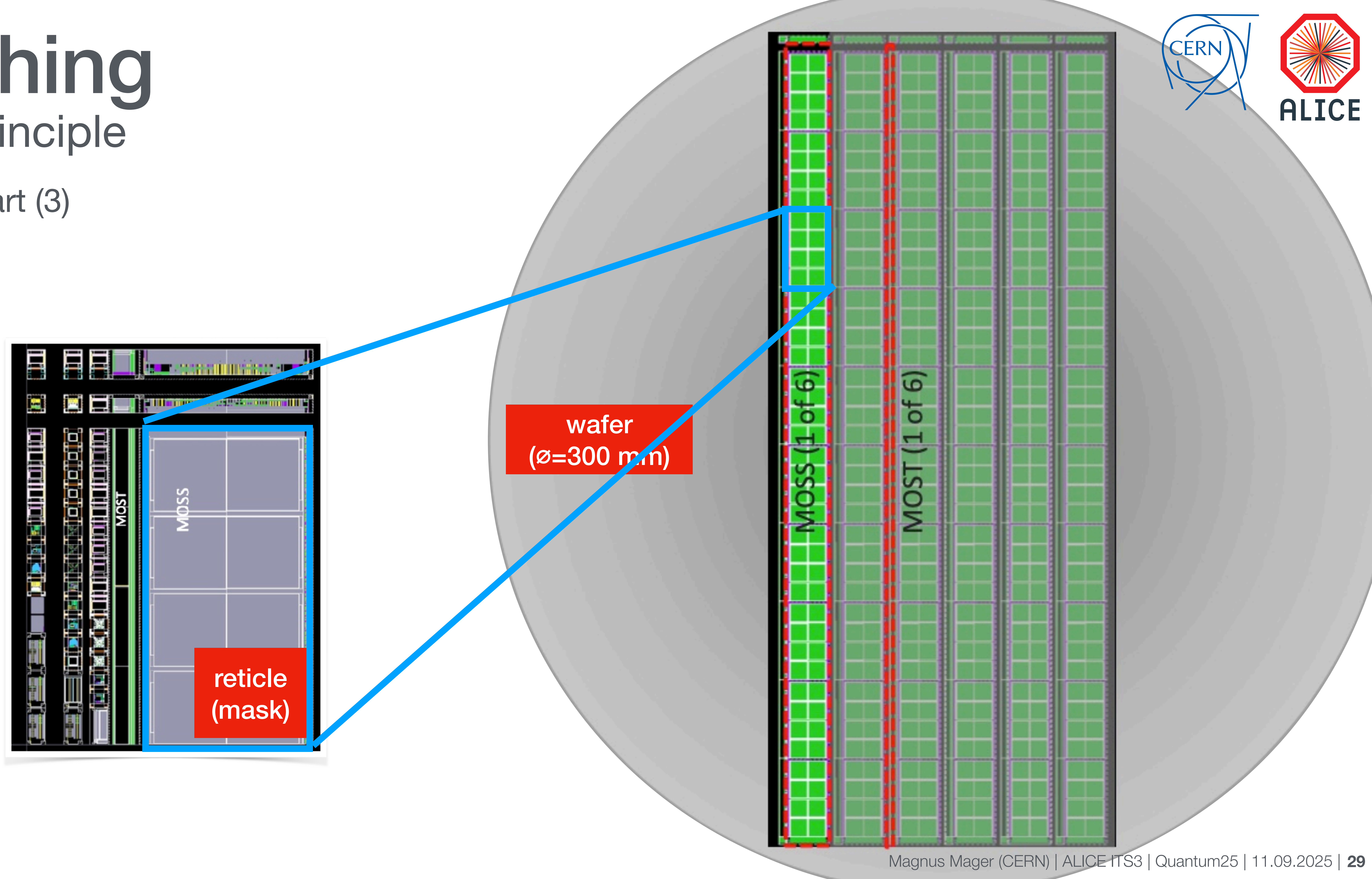
- central part (2)



Stitching

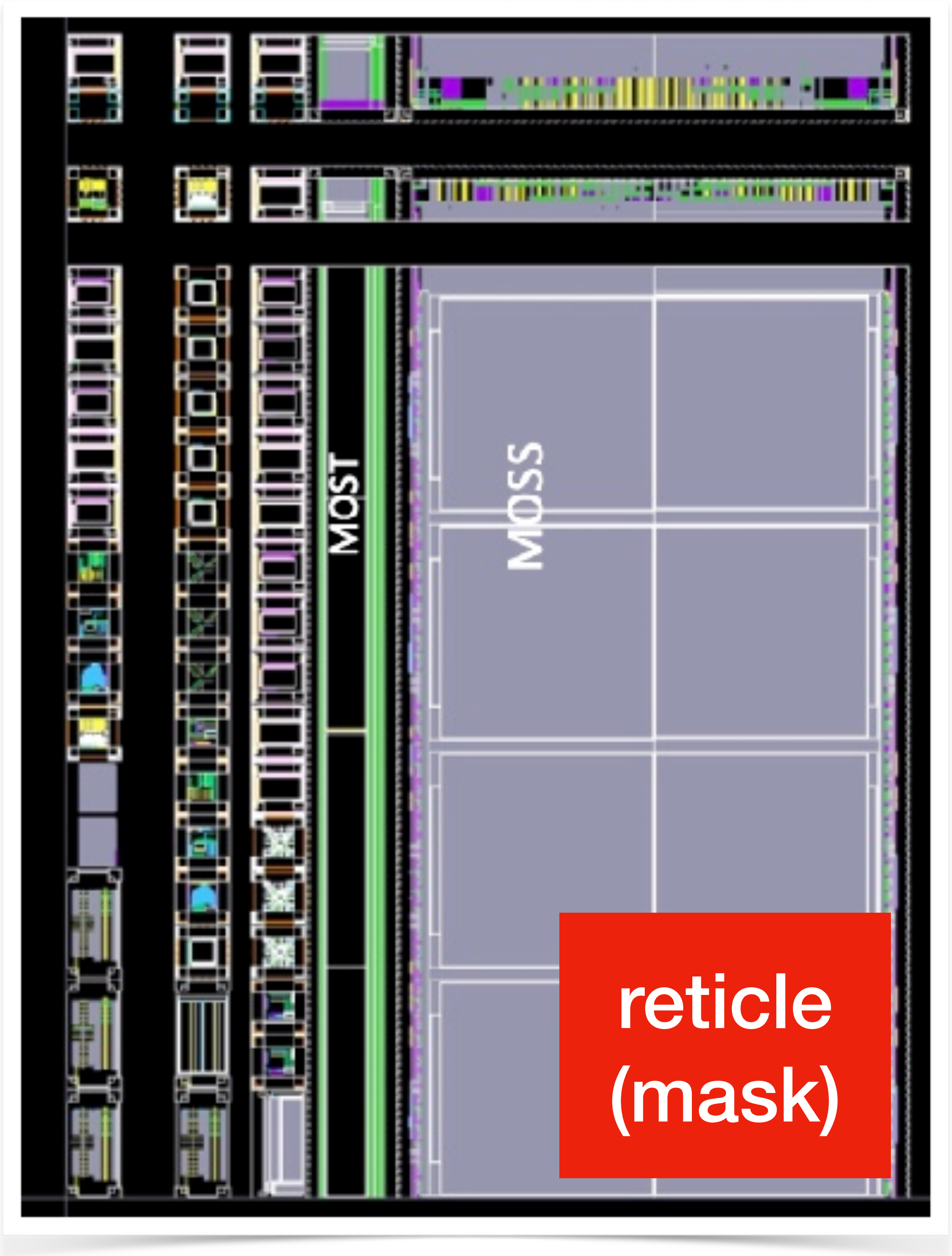
rough principle

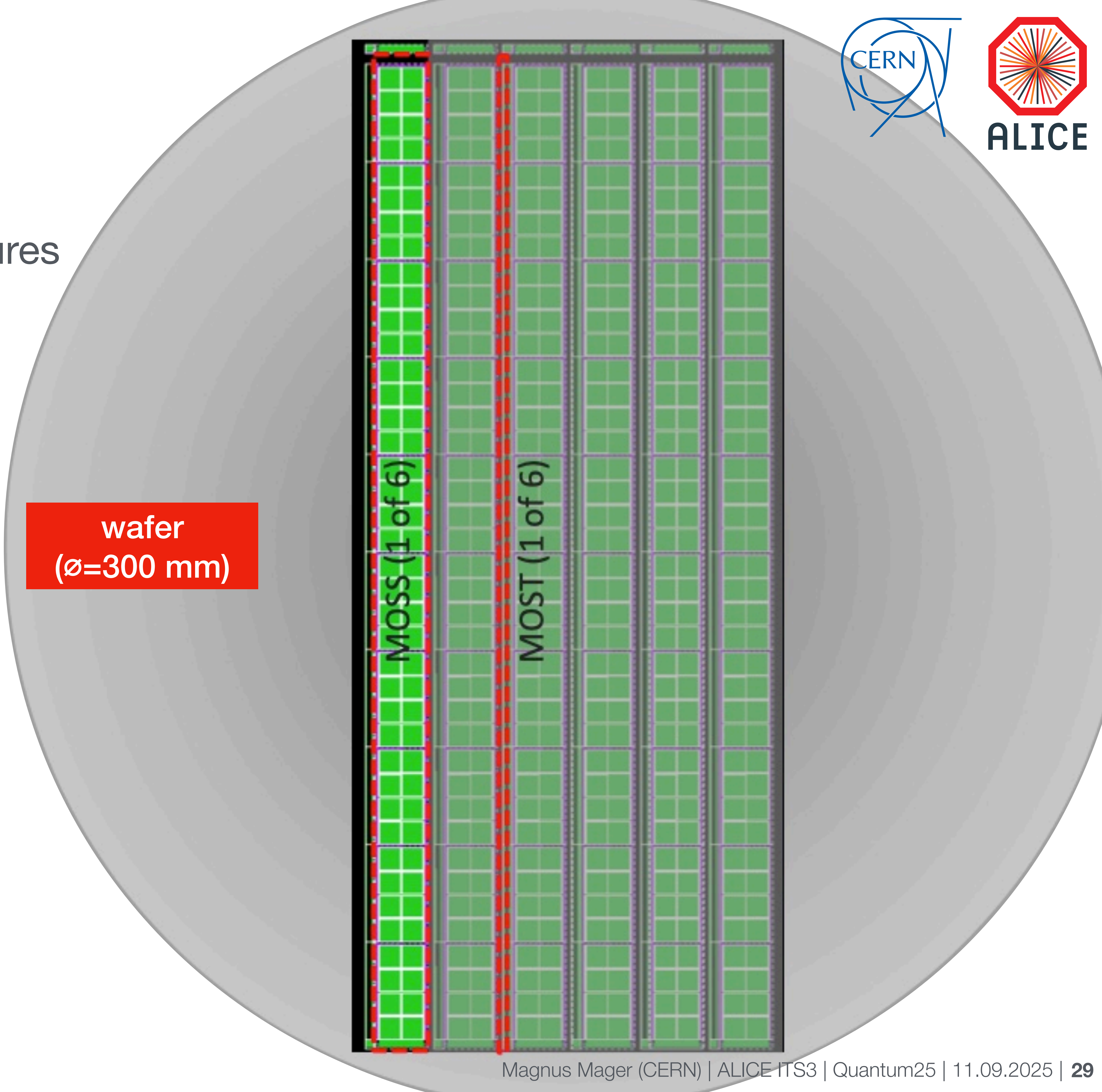
- central part (3)



Stitching
rough principle

- final chip is the concatenation of all exposures





Chip development roadmap

past

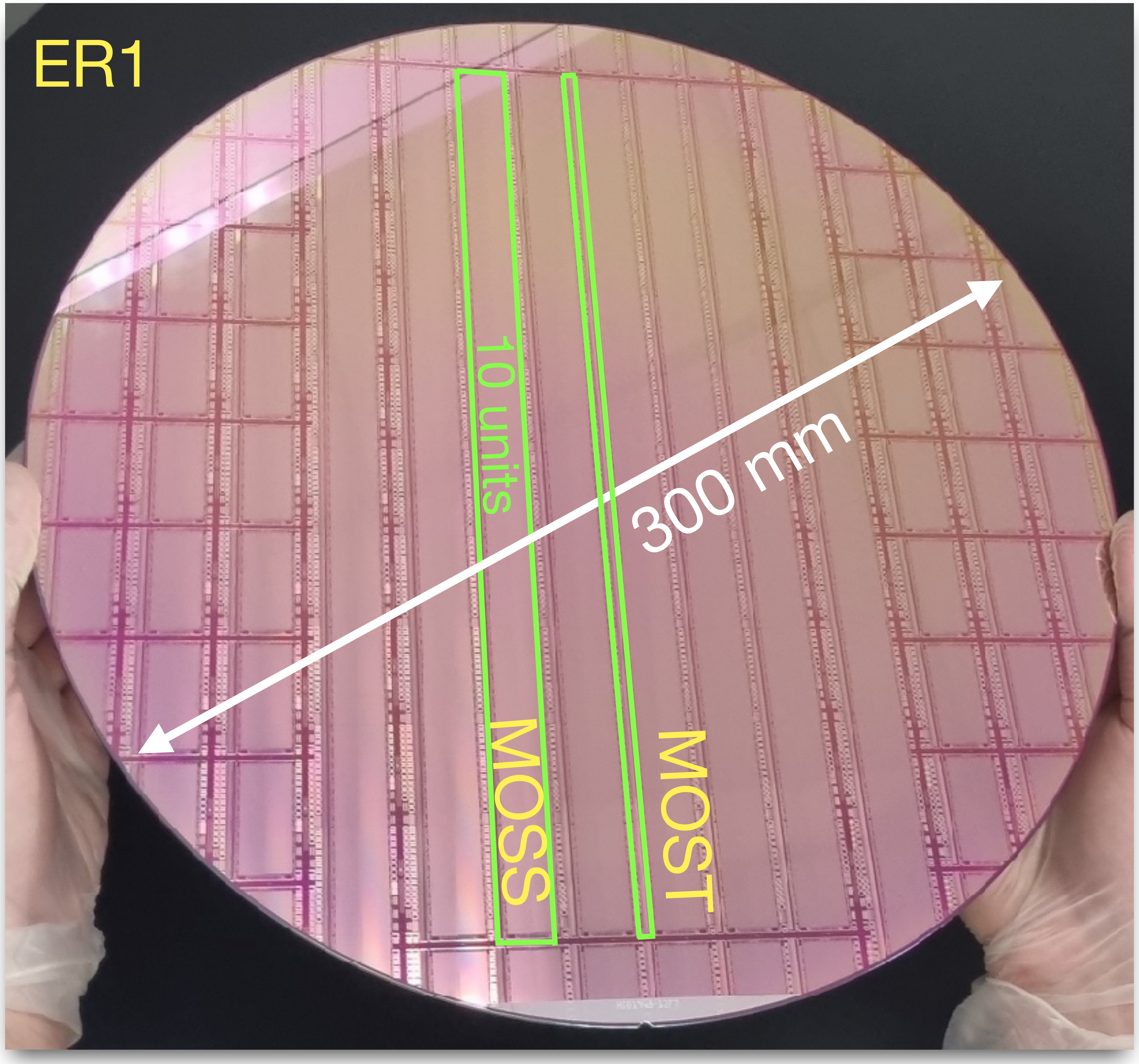
- **MLR1: first MAPS in TPSCo 65nm** (2021)
  - successfully qualified the 65nm process for particle detectors

present

- **ER1: first stitched MAPS** (2023)
  - large design "exercise"
  - "**MOSS**": 14 x 259 mm, 6.72 MPixel (22.5 x 22.5 and 18 x 18 μm²): conservative design, different pitches
  - "**MOST**": 2.5 x 259 mm, 0.9 MPixel (18 x 18 μm²): more dense design
- **ER2: "MOSAIX"** (2025)
  - full-scale, fully functional prototype
  - currently in production

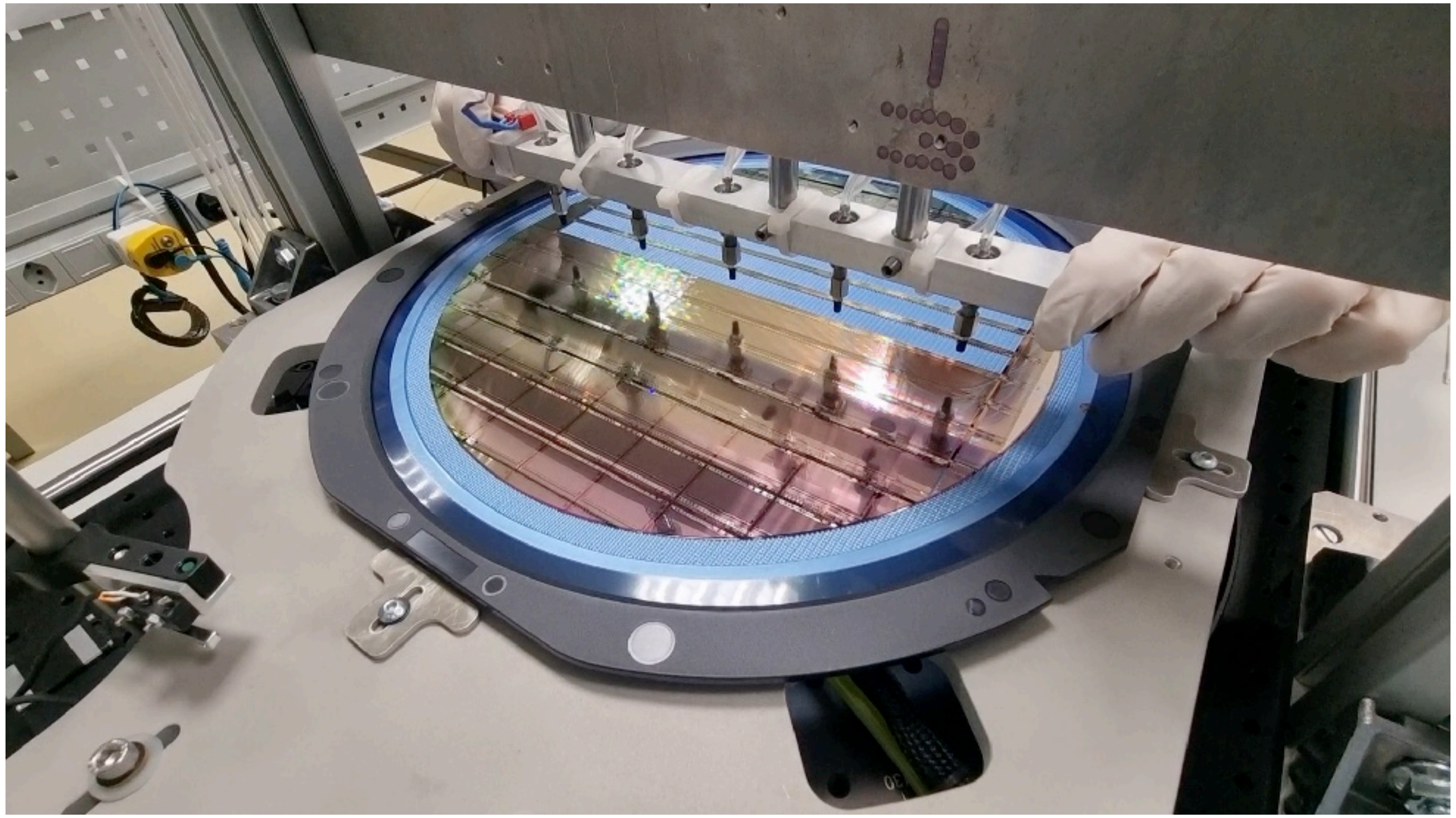
future

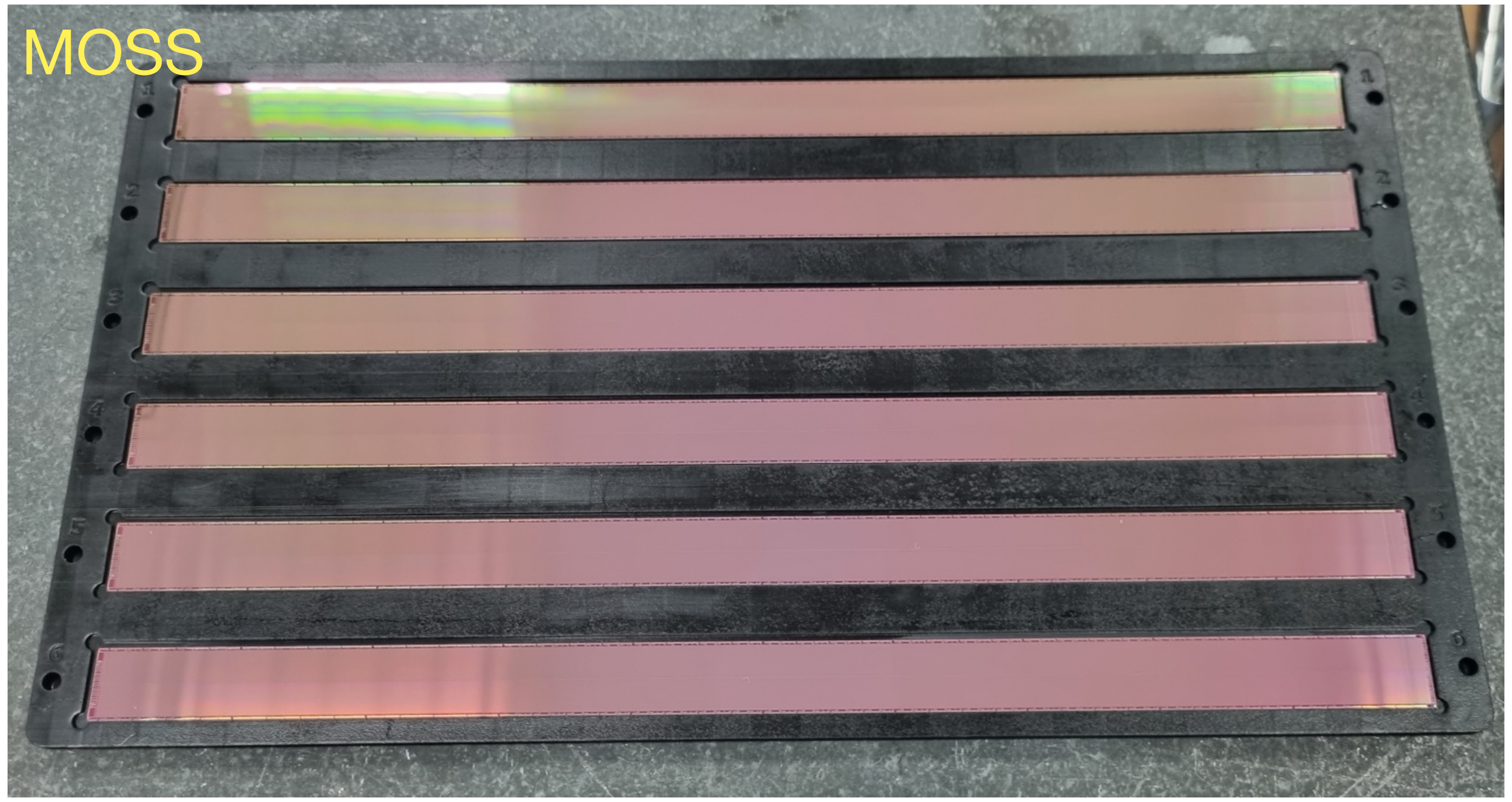
- **ER3: ITS3 sensor production** (2026)

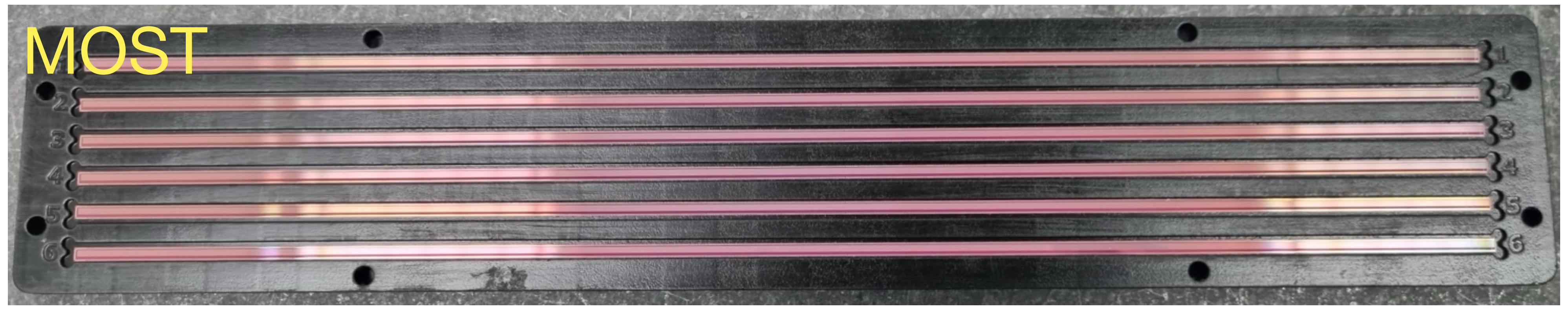


Sensor handling

- First time to handle large (26 cm-long) <u>and</u> thin (50 μm) chips
- Dedicated tooling needed to be developed
- Now done routinely



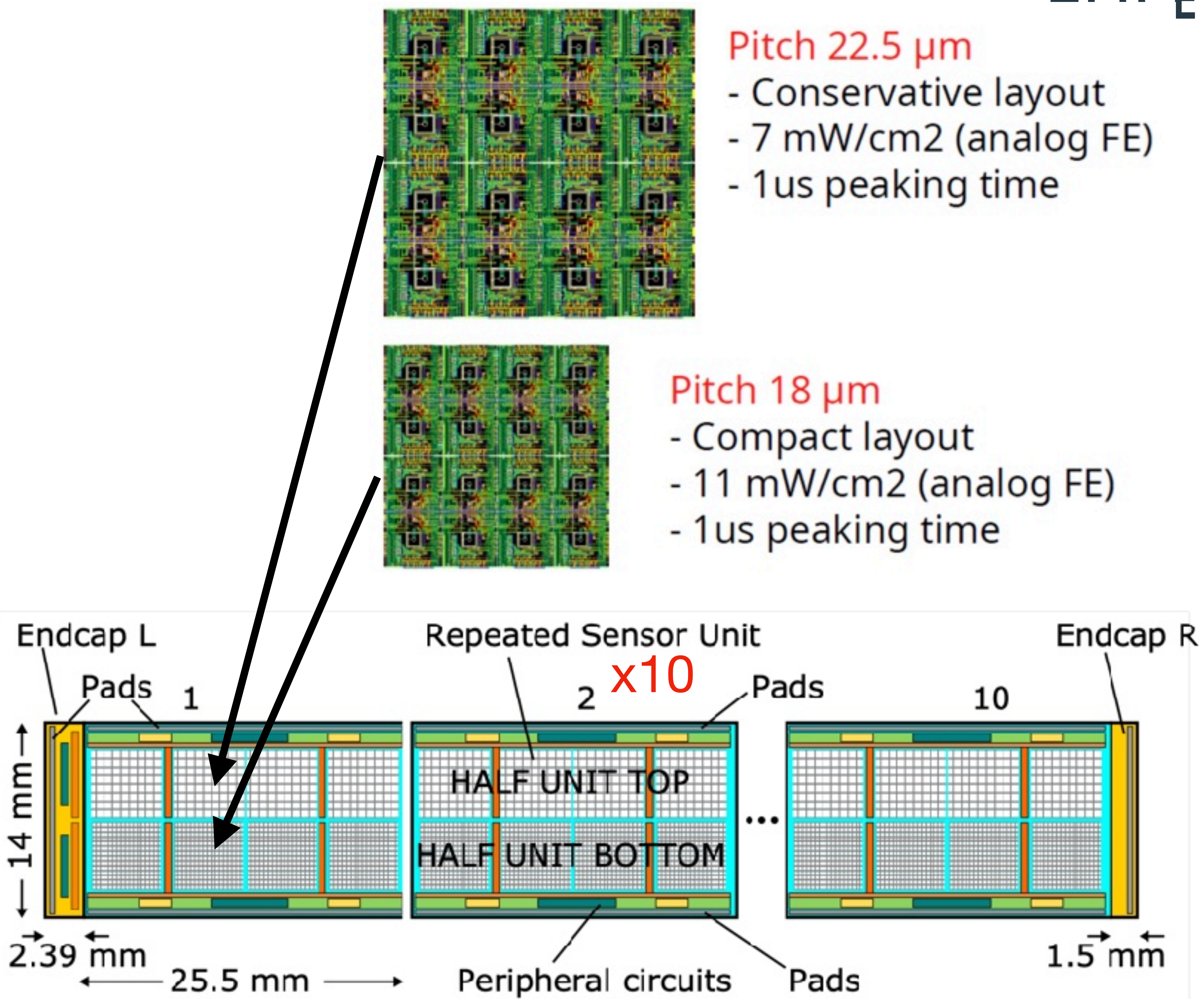




ER1: MOSS

stitching prototype

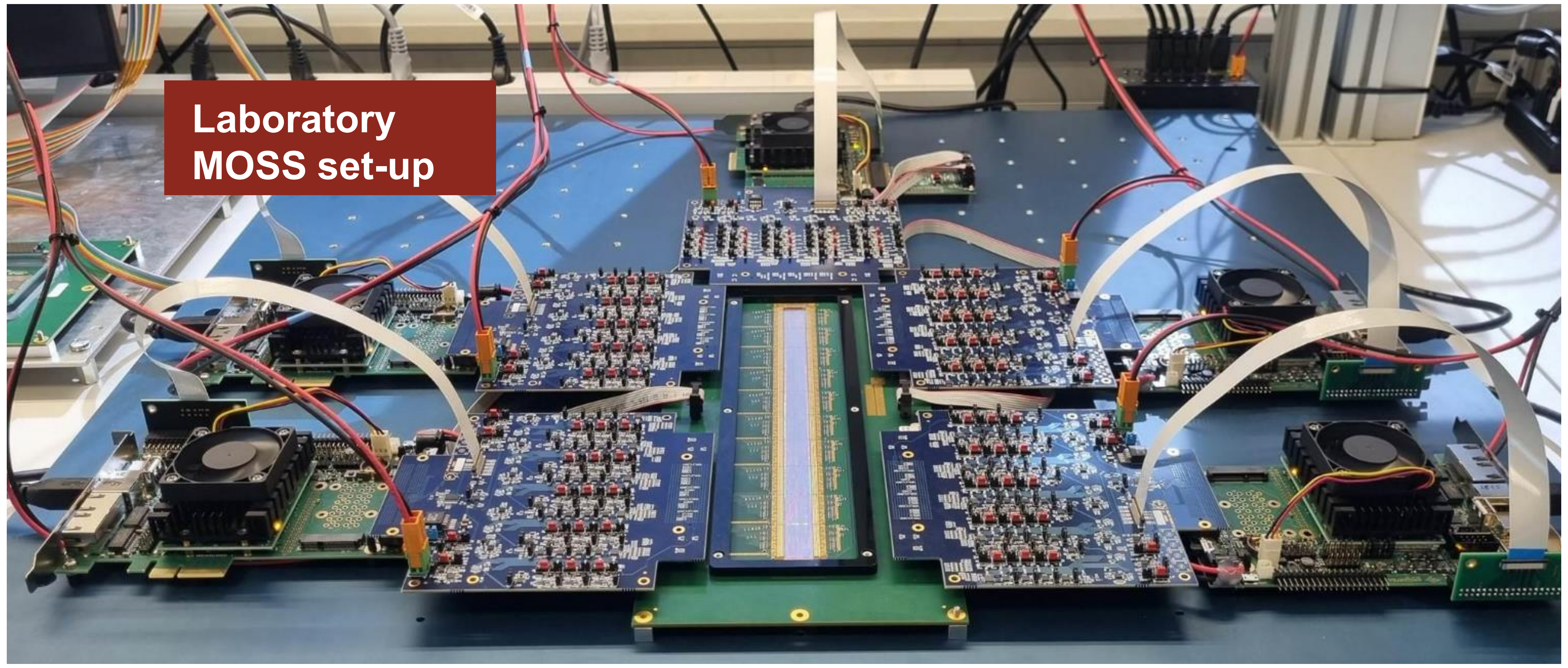
- 14 x 259 mm, 6.72 Million Pixels
- Segmented into:
  - 10 repeated sensor units (RSU)
  - top and bottom halves with different pitches (22.5 and 18µm)
  - four different sub-matrices each with different analog designs
- Each half RSU is powered and can be tested independently
  - goal: understanding of yields and possible defects
  - difficulty: large number of power domains
- Stitched “back-bone” allows to control and readout the sensor from the left short side



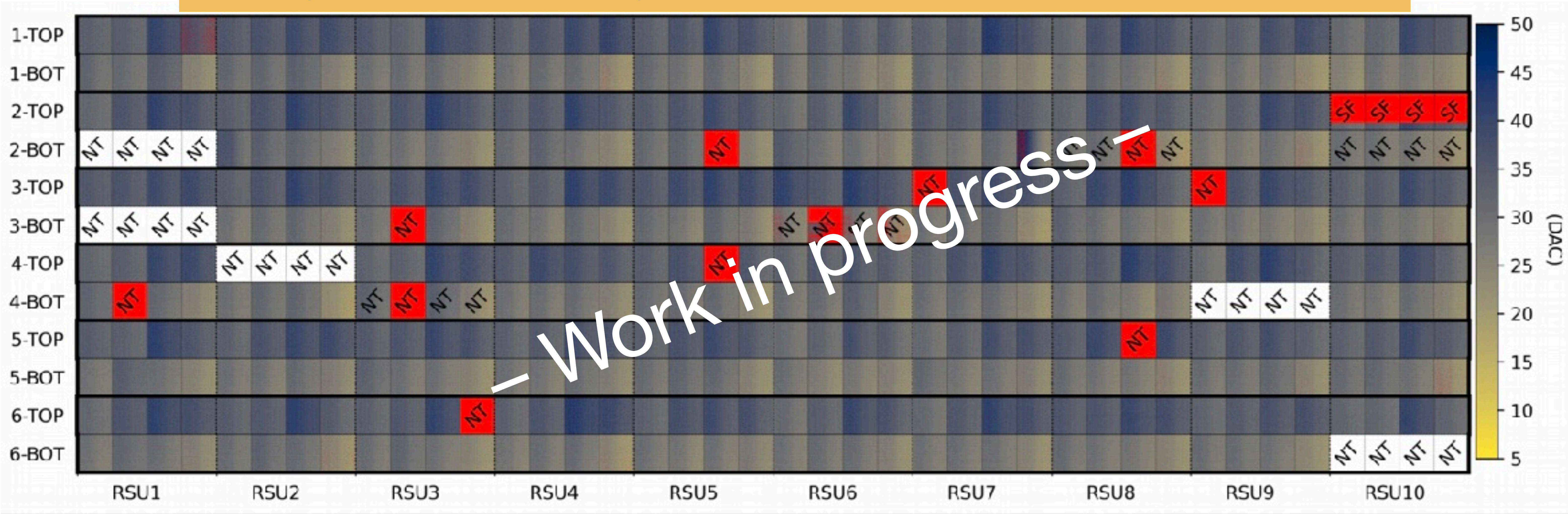
ER1: MOSS

understanding of yield

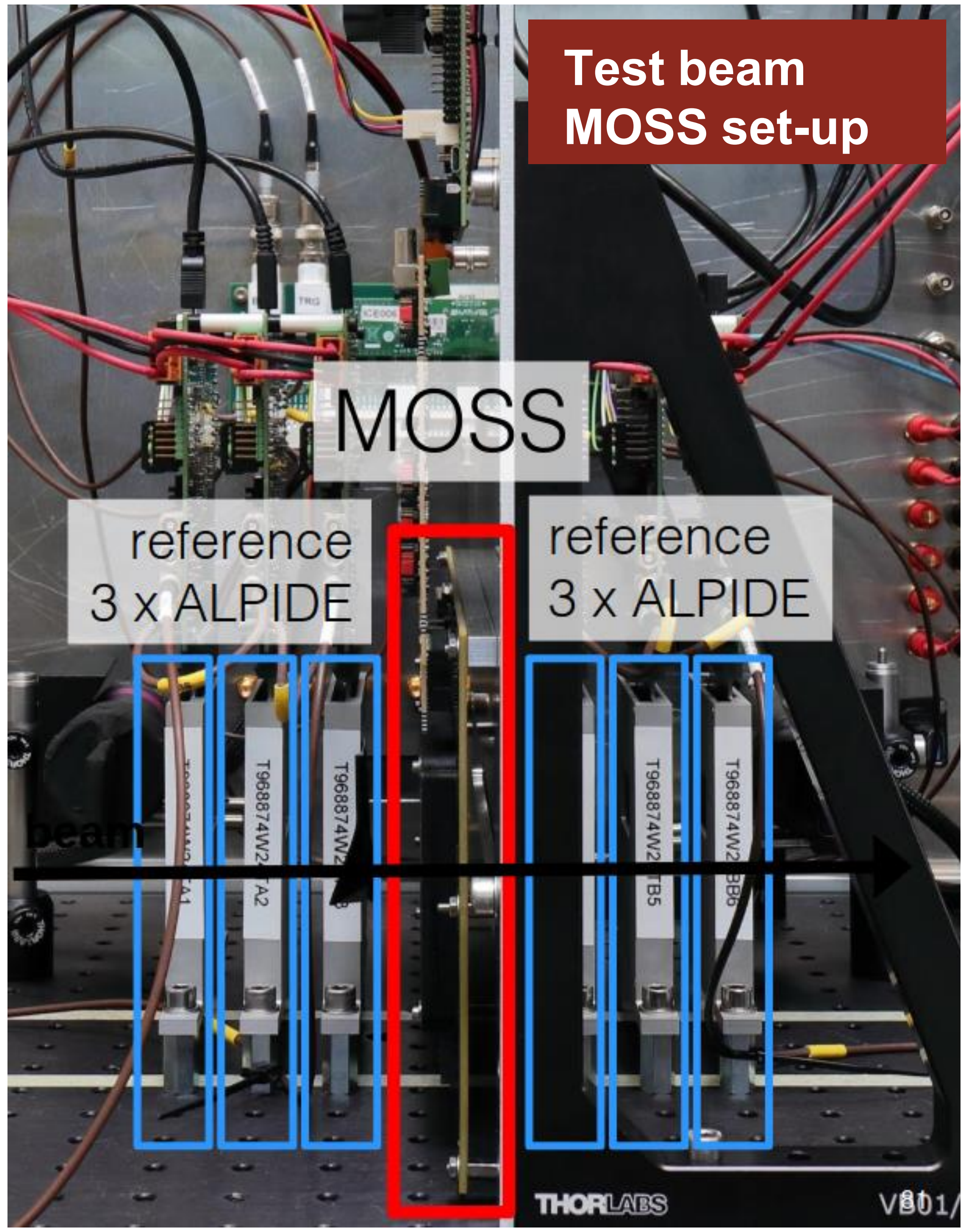
- **Detailed understanding** of yield is gained with first prototypes
- **Mitigation** strategy based on:
  - hardening critical circuitry
  - fine-grained isolation of eventually malfunctioning blocks
- **Very encouraging** results
  - extrapolated functional yield >98%

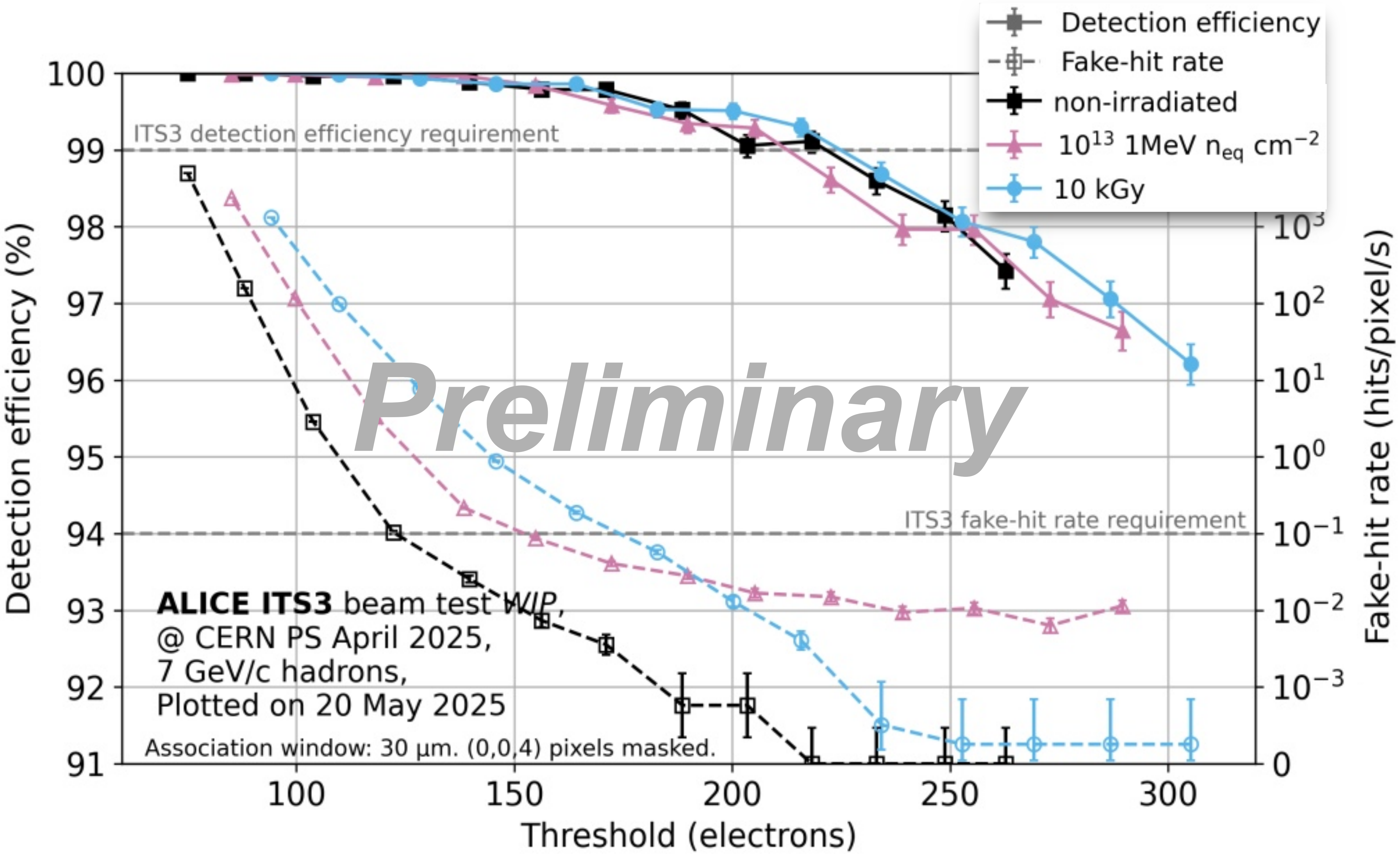


Example threshold map of 40 MPixel over 10x26 cm of silicon



ER1: MOSS
operation in beam tests

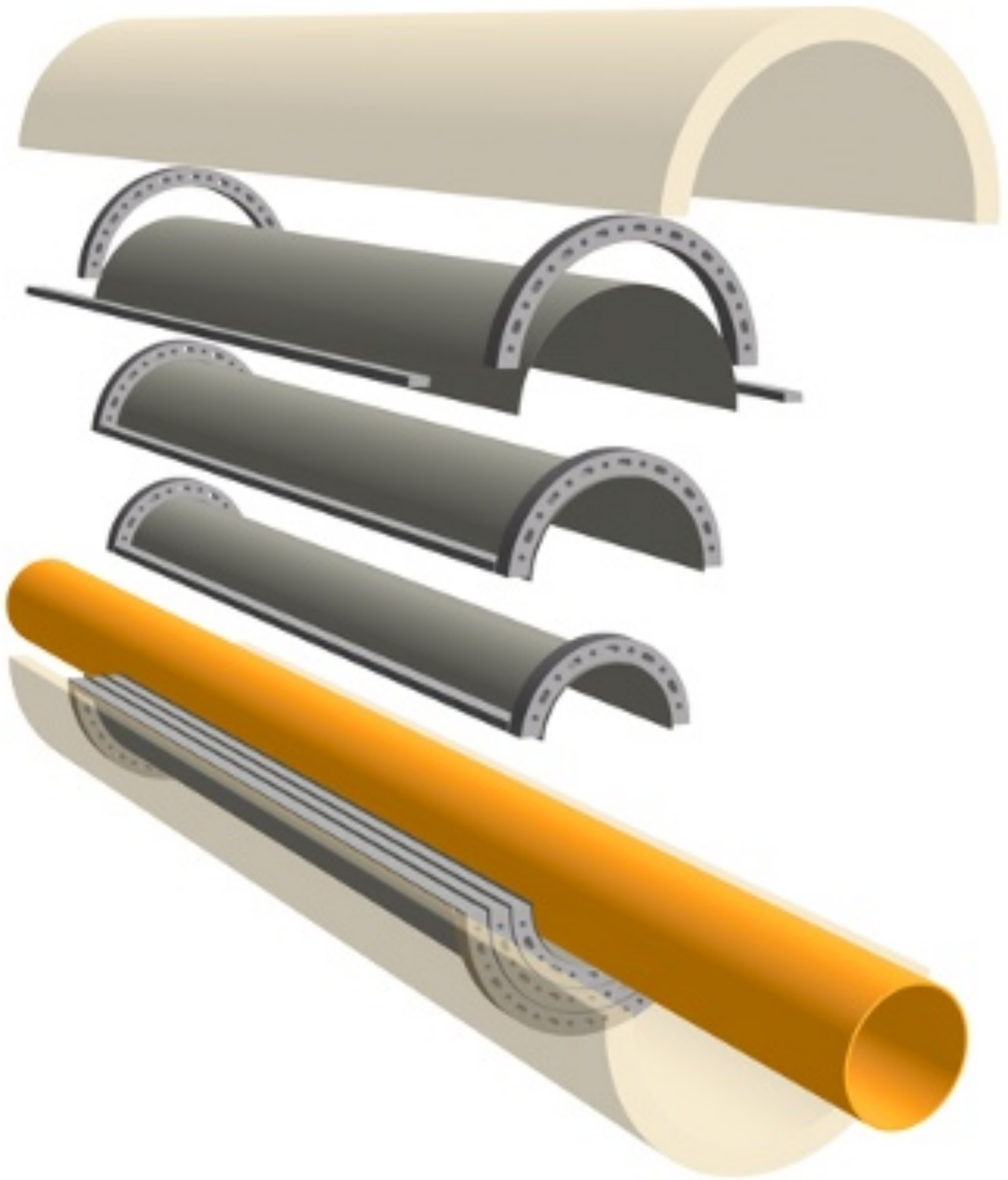




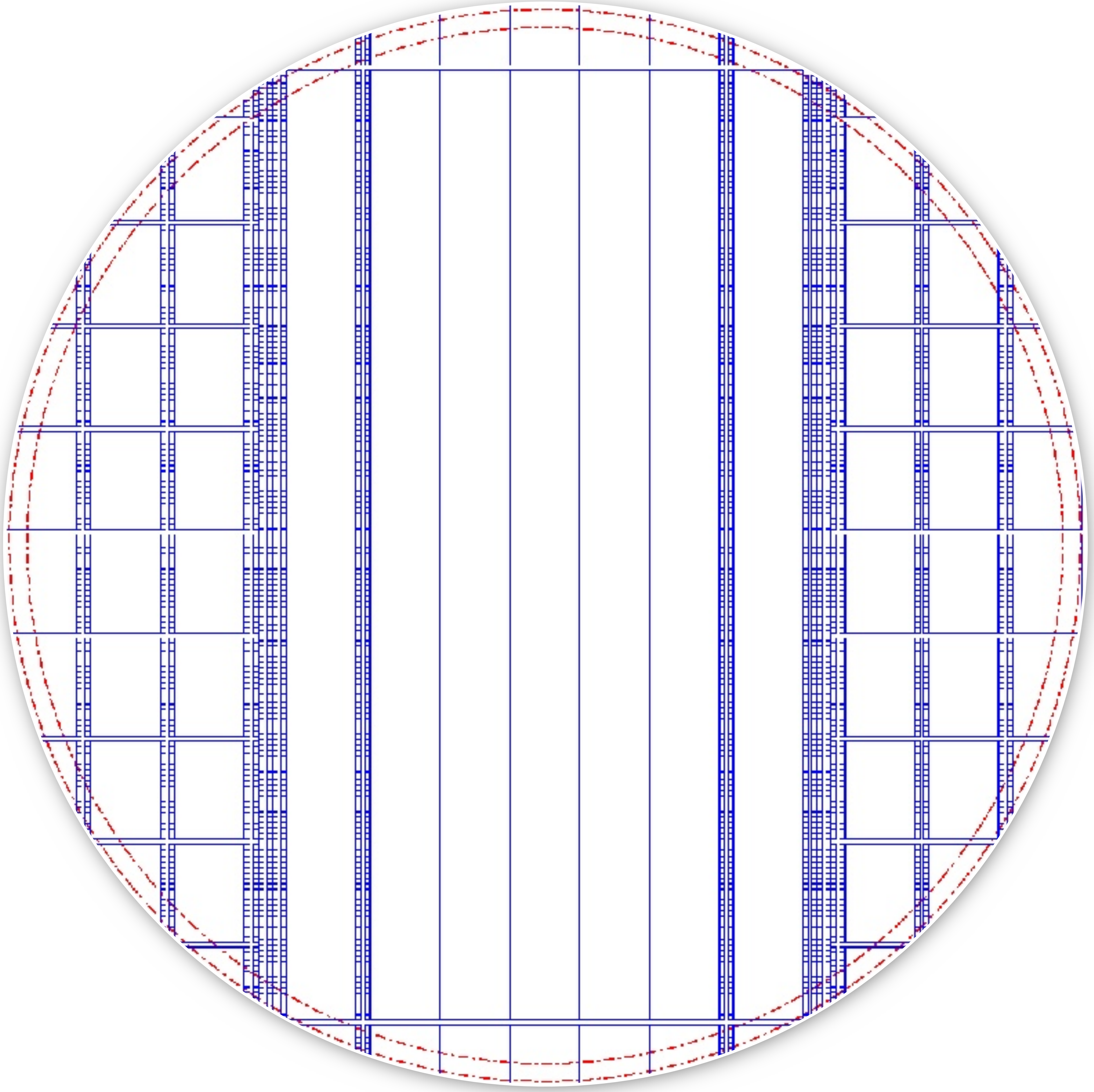
- Prototypes **work well** in beam tests
- **Operational margin** (efficiency >99% and fake-hit rate <10^{-6}) is maintained at ALICE radiation levels

ER2: MOSAIX

the full-scale prototype



ER2 wafer layout

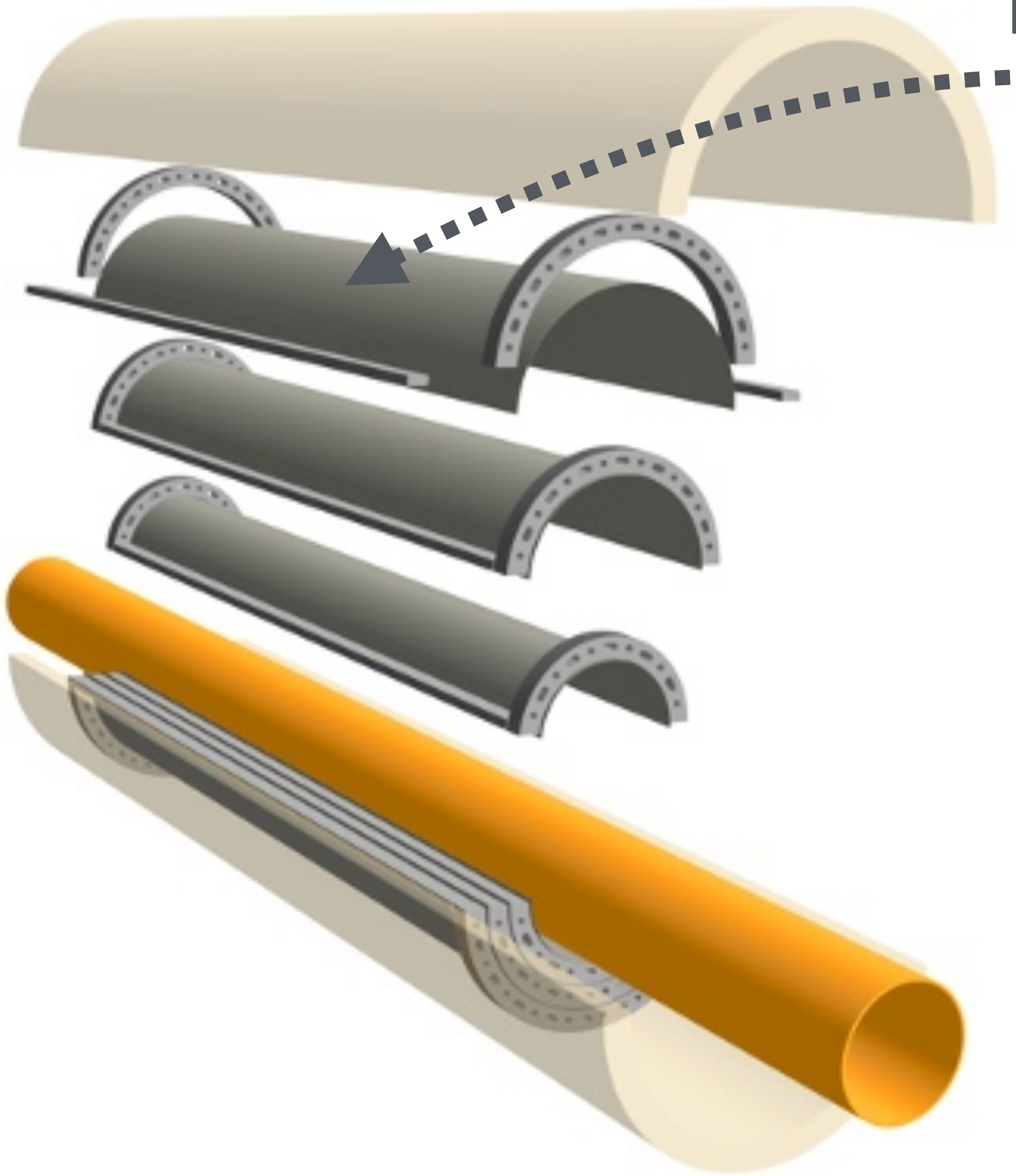


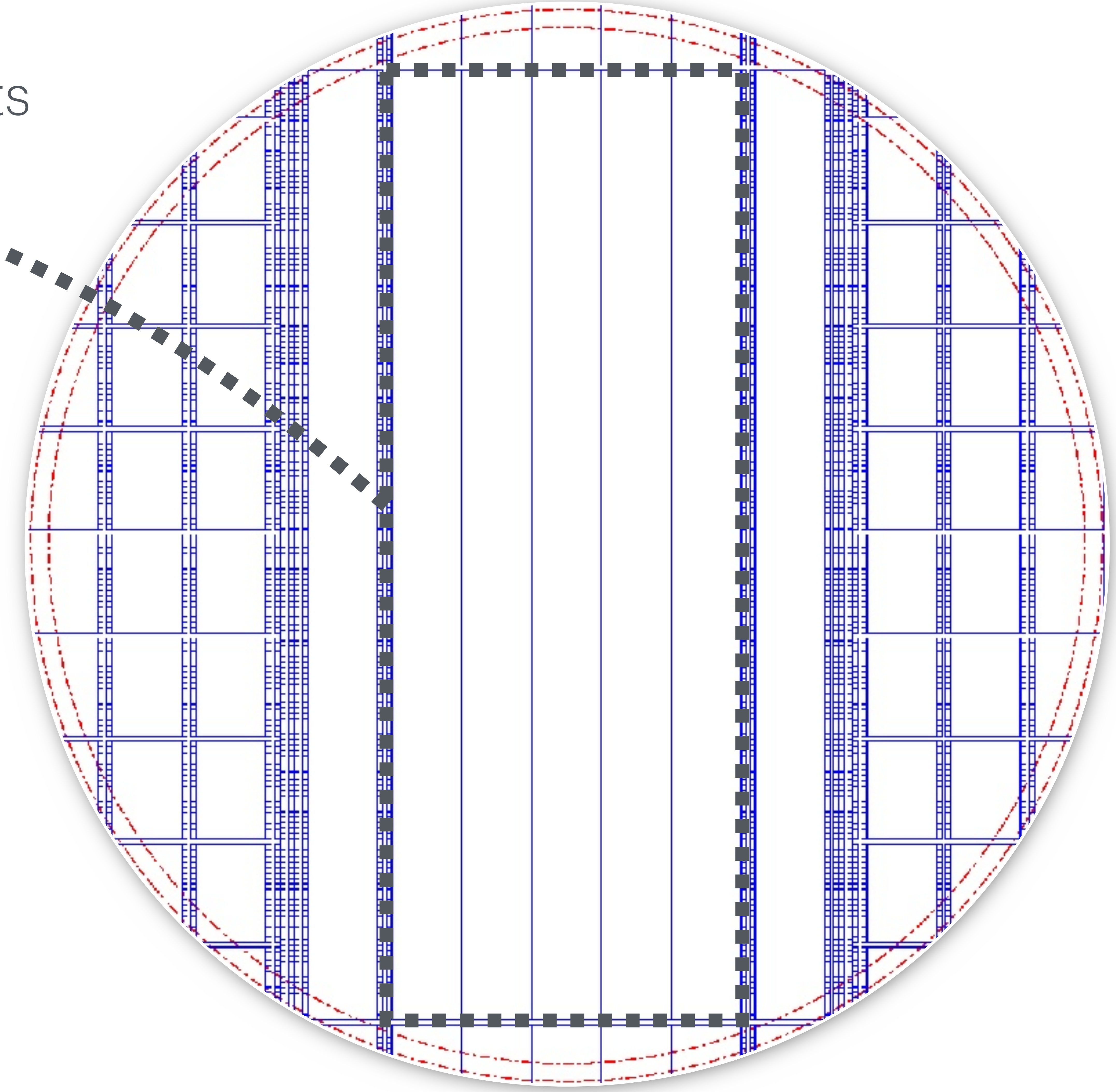
ER2: MOSAIX

the full-scale prototype

ER2 wafer layout

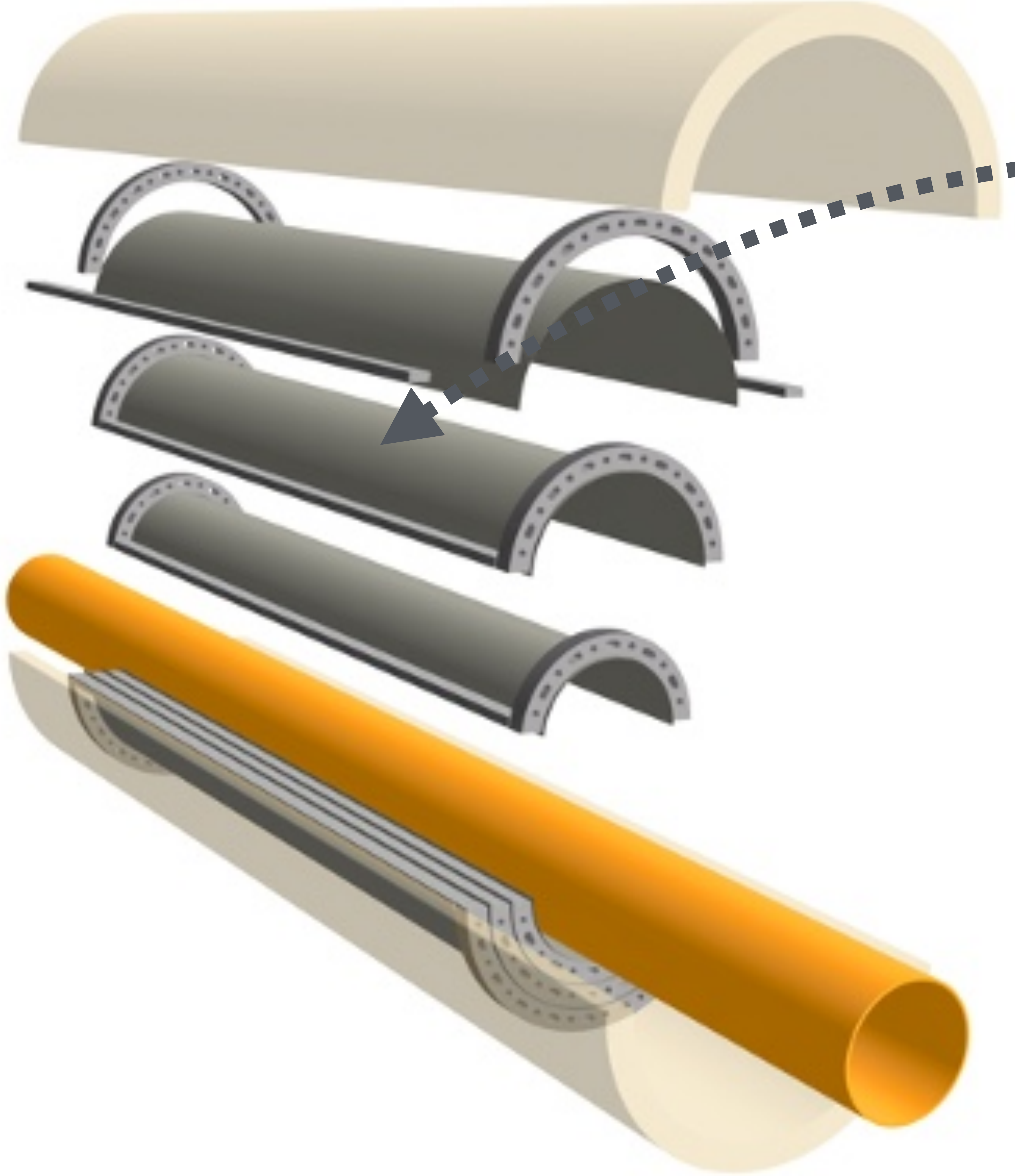
Layer 2: 5 segments





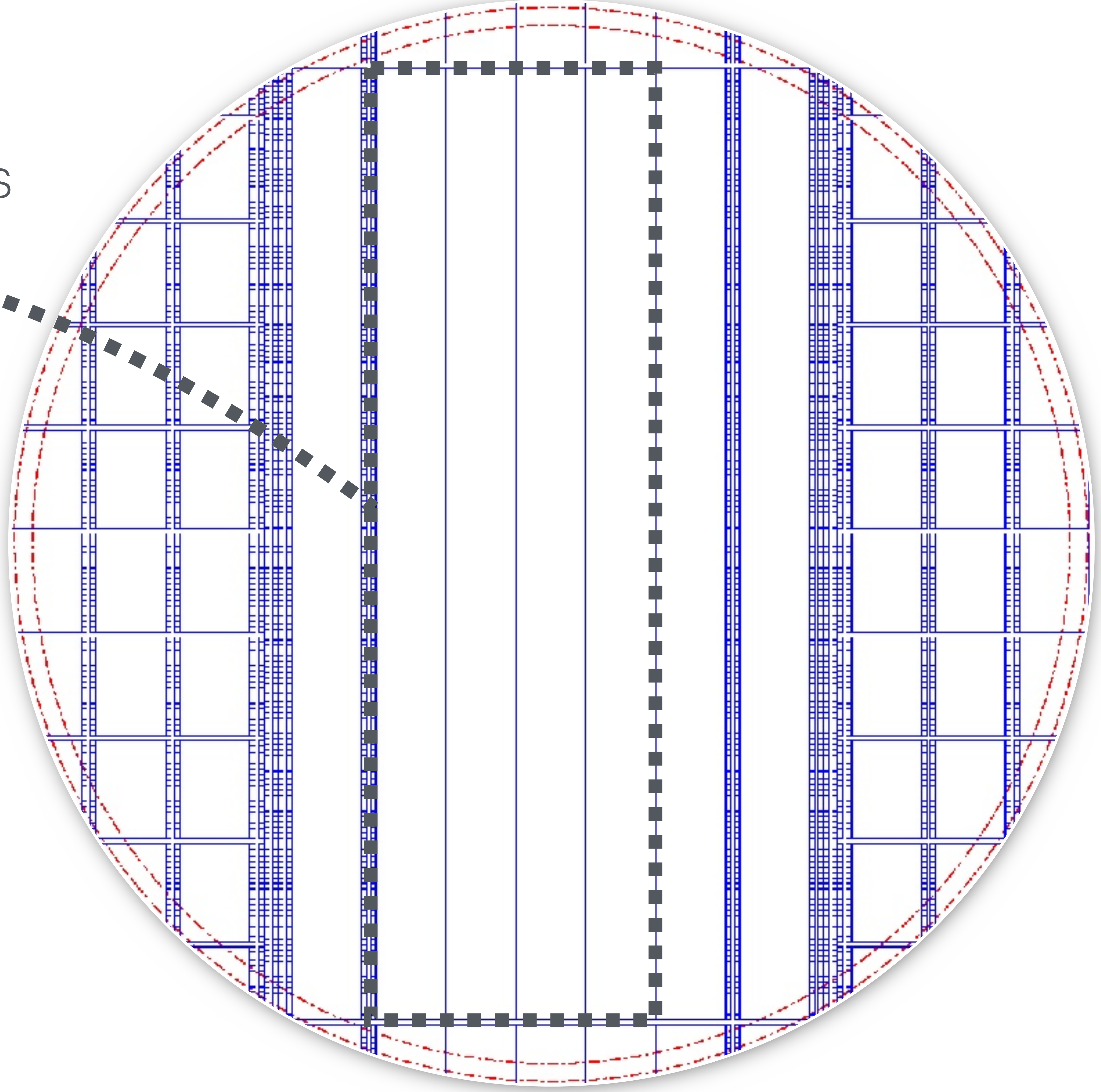
ER2: MOSAIX

the full-scale prototype



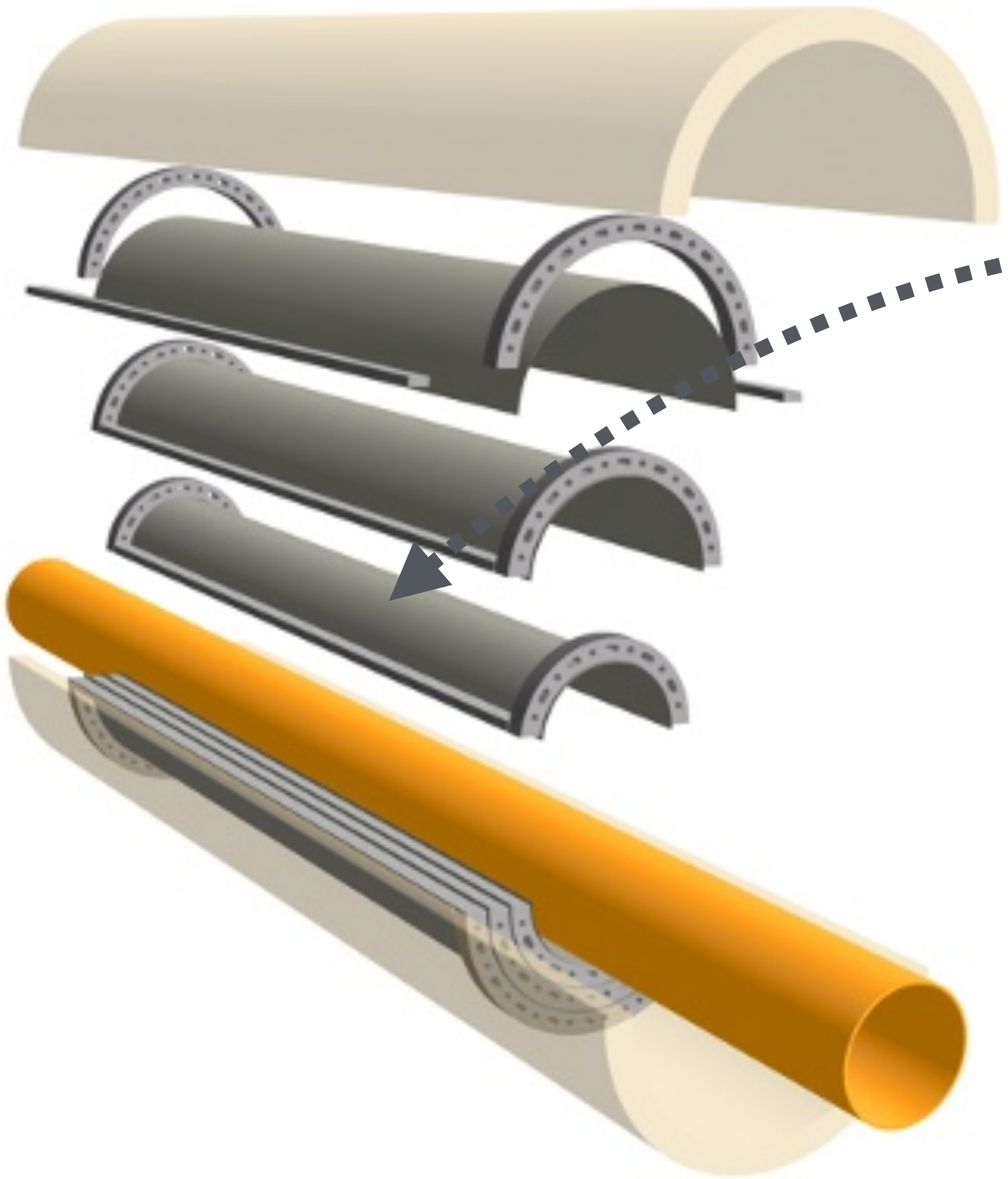
Layer 1: 4 segments

ER2 wafer layout



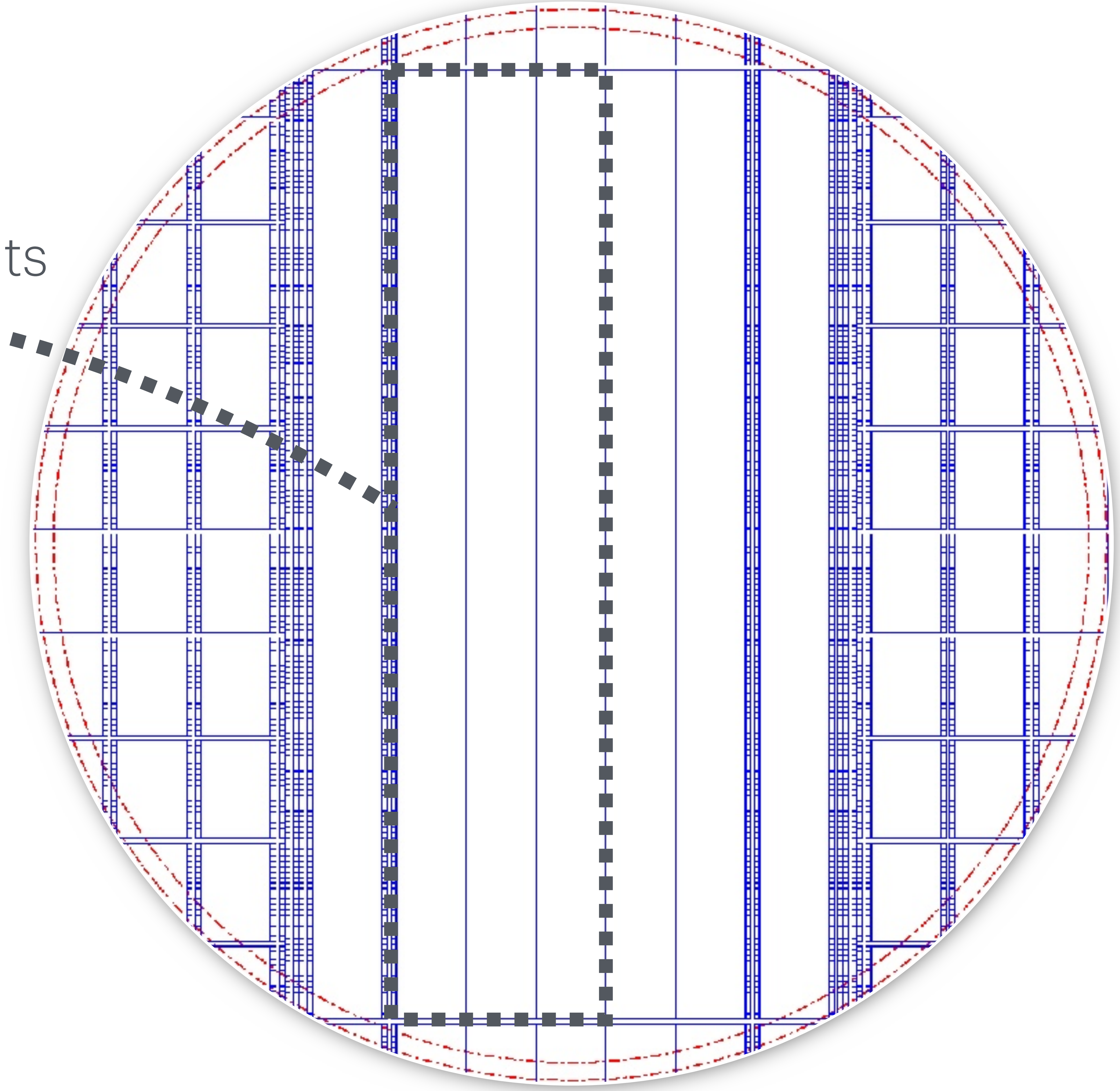
ER2: MOSAIX

the full-scale prototype



Layer 0: 3 segments

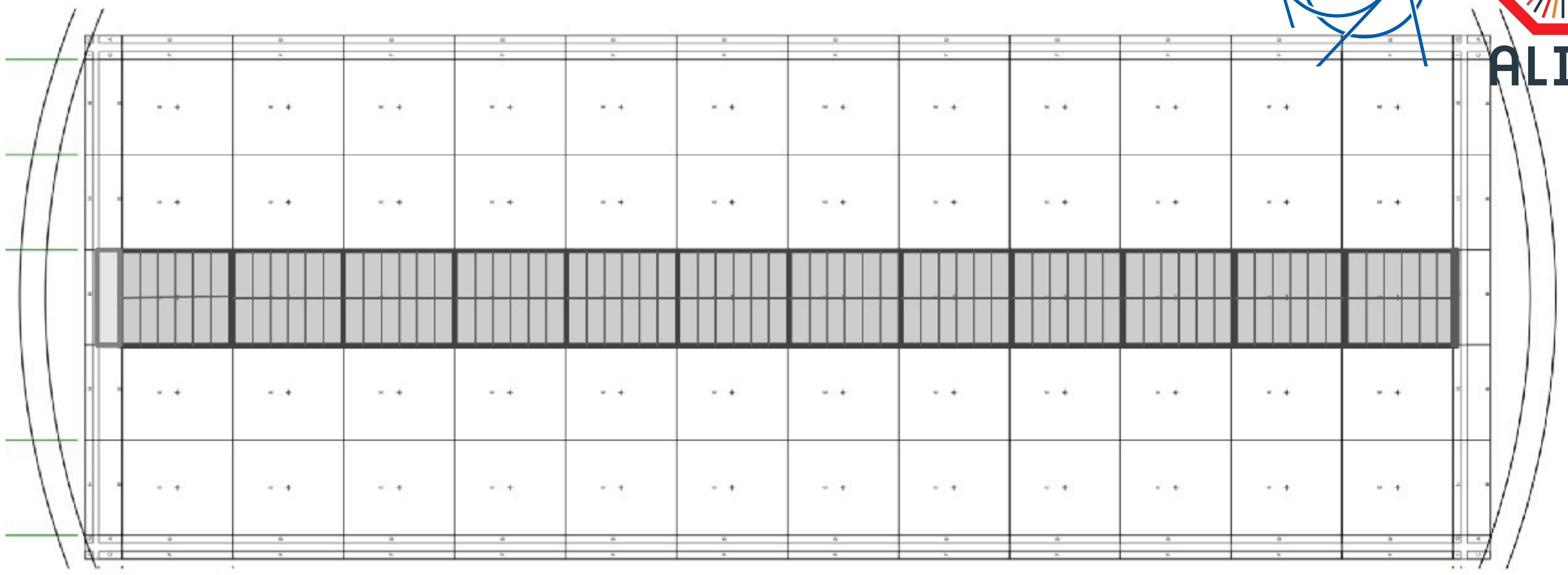
ER2 wafer layout

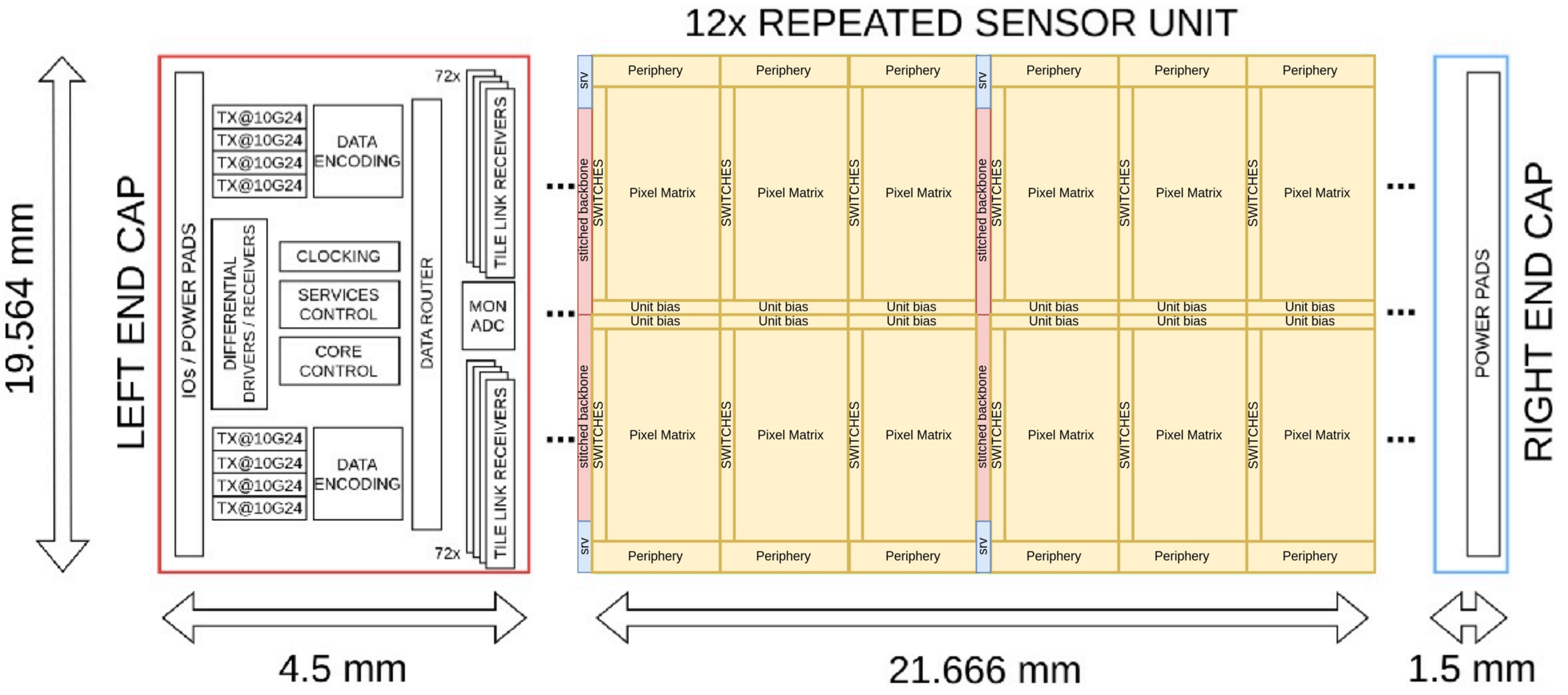


ER2: MOSAIX

architecture

- Same size and full functionality of final chip
  - “module on a chip”
  - including data/event management and high-speed links
- High-granularity power network
  - 144 units can individually be switched off in case of malfunctioning
- 12 different pixel/matrix variants to fine tune operational margins
  - pitch: $20.8 \times 22.8\ \mu m^2$
- In production
  - submission last month
  - test systems being finalised and tested





Summary and outlook

- CMOS Monolithic Active Pixel Sensors (**MAPS**) are an **established technology**
  - provide excellent spacial resolution at lowest material budgets
  - ALICE is currently operating 24k sensors on its inner tracking system (ITS2)
  - rapid development over last 2 decades
- **ITS3** project **introduced *and* proved feasibility** of a new class of ultra-light vertex detectors
  - **bent MAPS** work very well
  - **65 nm** process is established for HEP applications
  - **Stitched** (wafer-scale) design and associated yield is understood
  - **Bent, large, thin** sensors can be handled and mechanically integrated
  - **Air cooling** is proved to be sufficient
- ITS3 detector to be installed in the ALICE experiment in LHC Long Shutdown 3 (2027-29)
  - detailed Technical Design Report approved
  - full-scale prototype sensor “MOSAIX” is in production
- *The ITS3 project-driven R&D, together with a tight link to the CERN EP strategic R&D program, paves the way for many future applications within and outside HEP*


Thank you!