Overview of ALICE Inner Tracking System: Current Performance and Future Upgrade

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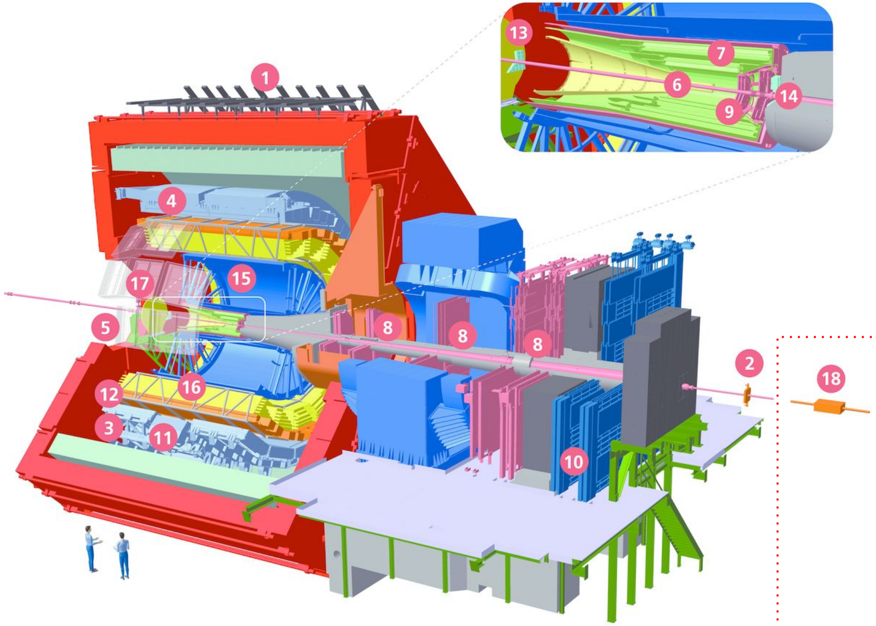
The 29th International Nuclear Physics Conference

30, May 2025

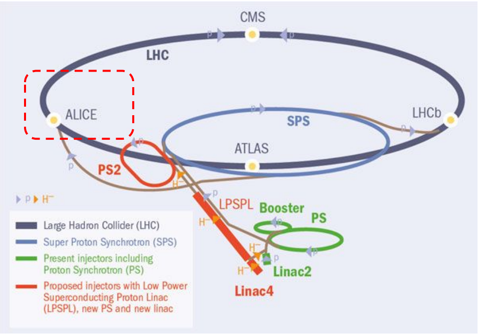
DCC, Daejeon, Korea

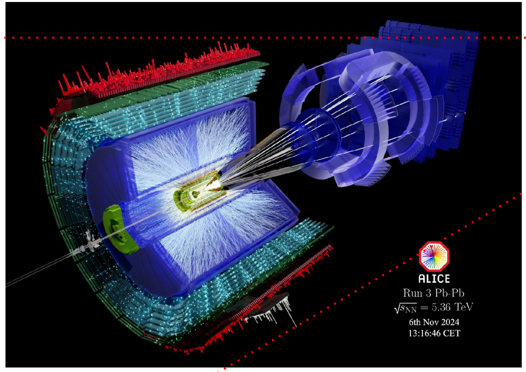
A Large Ion Collider Experiment (ALICE)

Detector and main goals



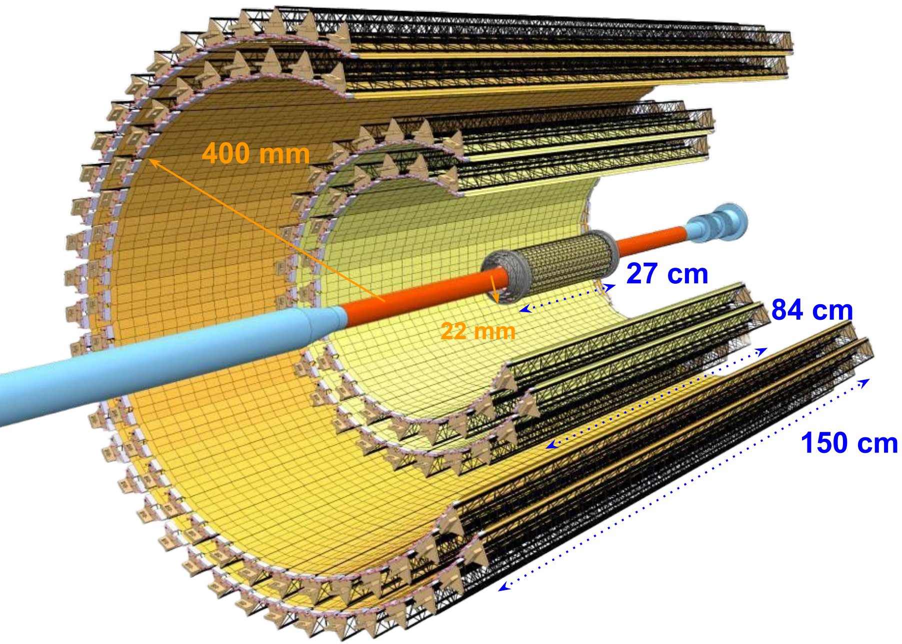
1. ACORDE, 2. AD, 3. DCal, 4. EMCal, 5. HMPID, **6. ITS-IB, 7. ITS-OB,** 8. MCH, 9. MFT, 10. MID, 11. PHOS / CPV, 12. TOF, 13. T0+A, 14. T0+C, 15. TPC, 16. TRD, 17. V0+, 18. ZDC





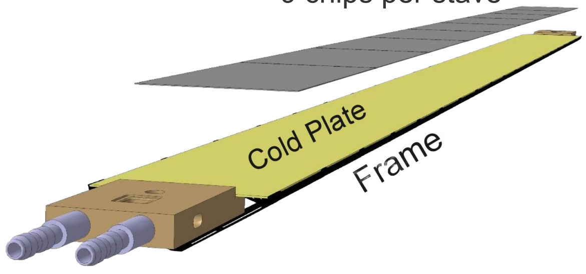
- Study of Quark-Gluon Plasma (QGP) created in heavy ion collisions at the LHC
- Reconstruction of charm and beauty hadrons
  ⇒ High resolution and low mass inner tracker close to the beam point
- Inner Tracking System (ITS) has been updated from ITS1 to ITS2 and operating since 2022
- R&D of the next upgrade (ITS3) is ongoing. It will be installed during LHC Long Shutdown 3

ITS2 detector layout

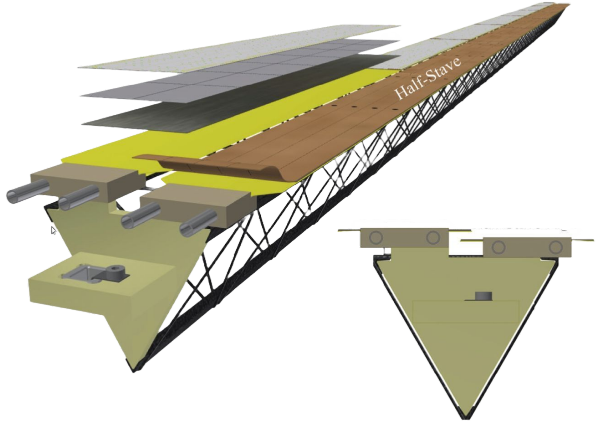


- **Vertexing and track reconstruction**
- 7 layers
- **Radius from interaction point: 22 mm - 400 mm**
- Water cooling system

- Inner Barrel (IB): 3 layers

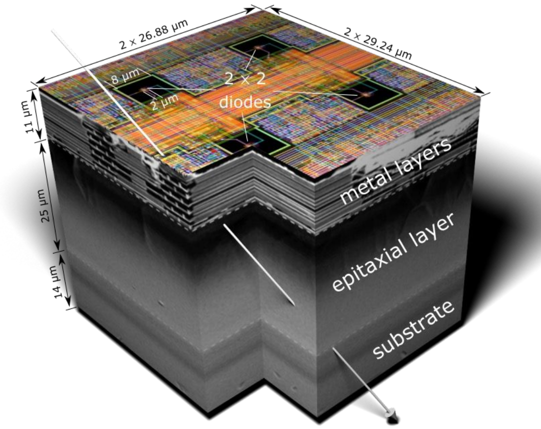


- Outer Barrel (IB): 4 layers

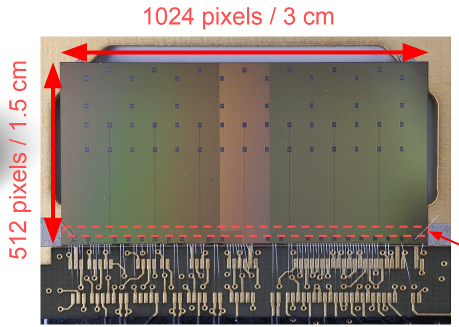


ALICE Pixel Detector “ALPIDE” - the pixel chip for the ITS2

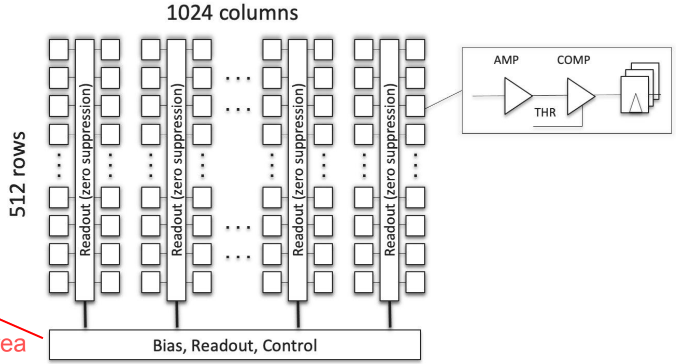
- TowerJazz 180 nm CMOS Imaging Sensor Process
- **Pixel pitch: 29 μm x 27 μm**
- Highly integrated circuit: *O*(100) transistors in-pixel:
  - Analog and digital signal processing, control and readout functionalities
- Maintain **detection efficiency (> 99%)** and **fake-hit rate (< 10^{-6} /pixel/event)** beyond a Total Ionizing Dose (TID) of **270 kRad** and Non-Ionizing Energy Loss (NIEL) of **2.7×10^{12} 1 MeV n_{eq}/cm^2**



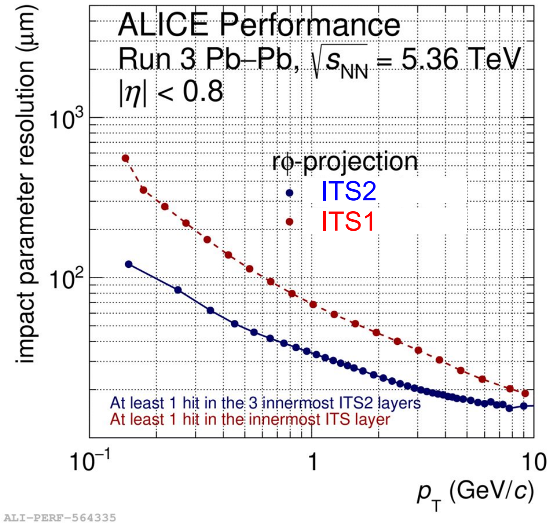
ALICE, JINST 19 (2024) P05062



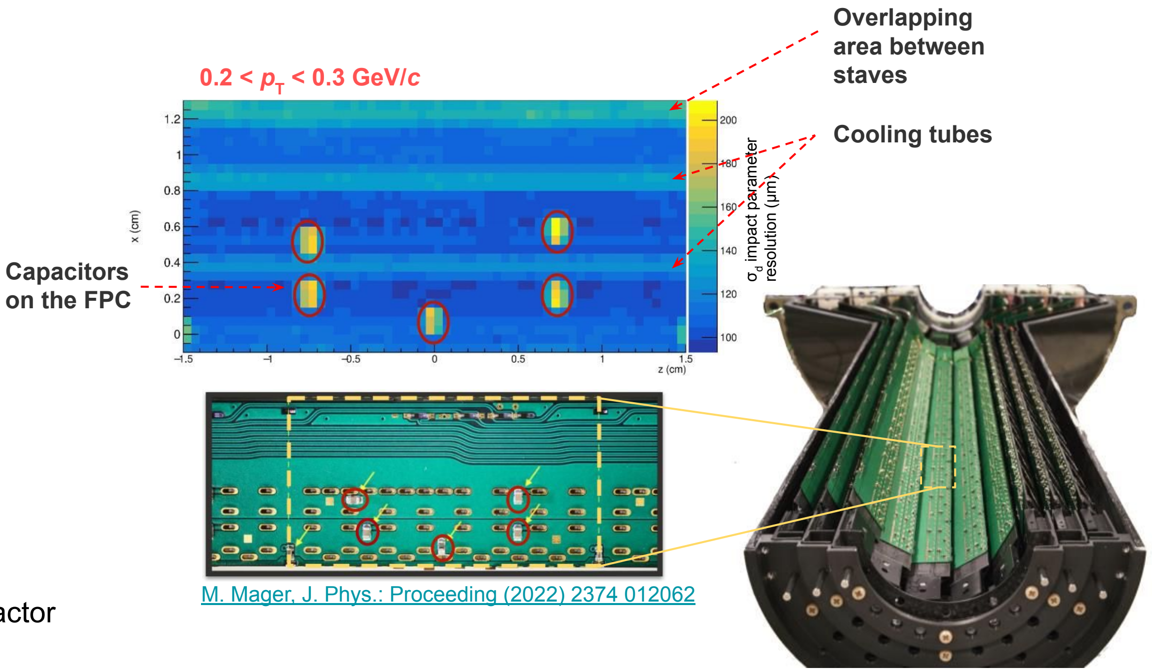
Chip periphery area
(1.2 mm x 3 cm)



Impact parameter resolution



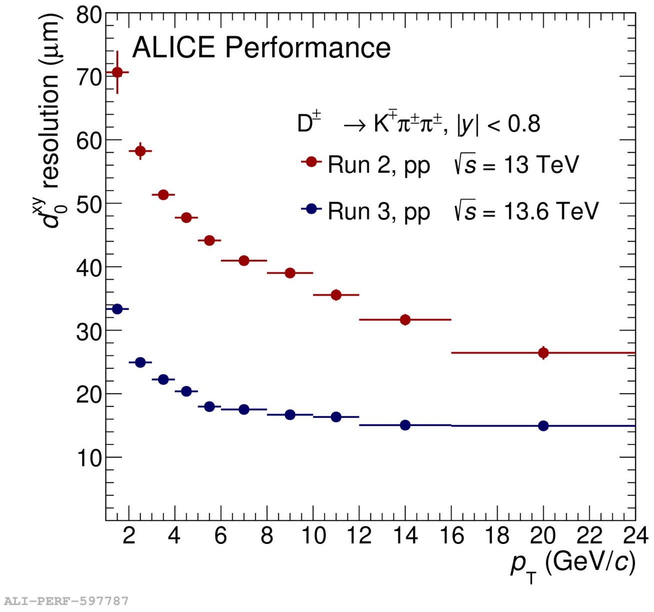
- Compared to the previous ITS1, ITS2 shows enhanced impact parameter resolution by a factor of more than 2 for particles with p_T < 1 GeV/c

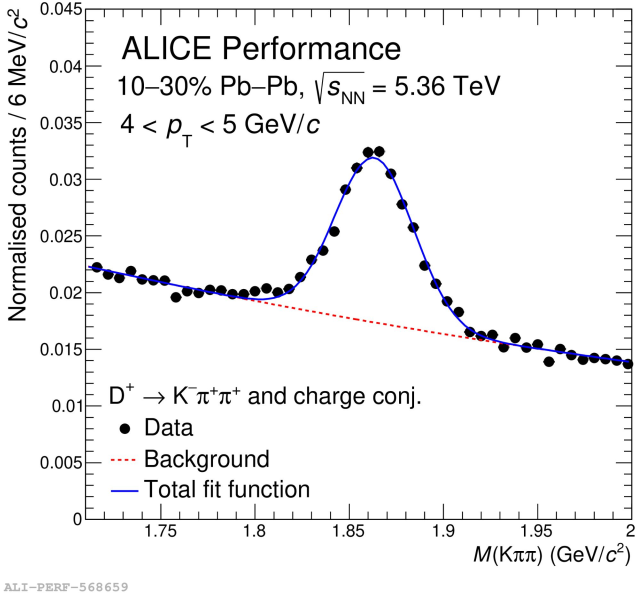


M. Mager, J. Phys.: Proceeding (2022) 2374 012062

- Details being studied:
  - Detailed material composition of the first layer clearly visible
  - Improving detector description in simulations

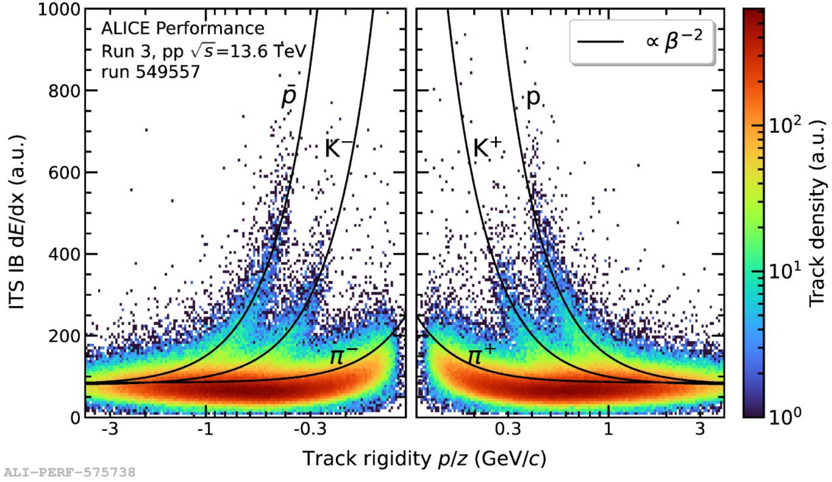
Physics performance



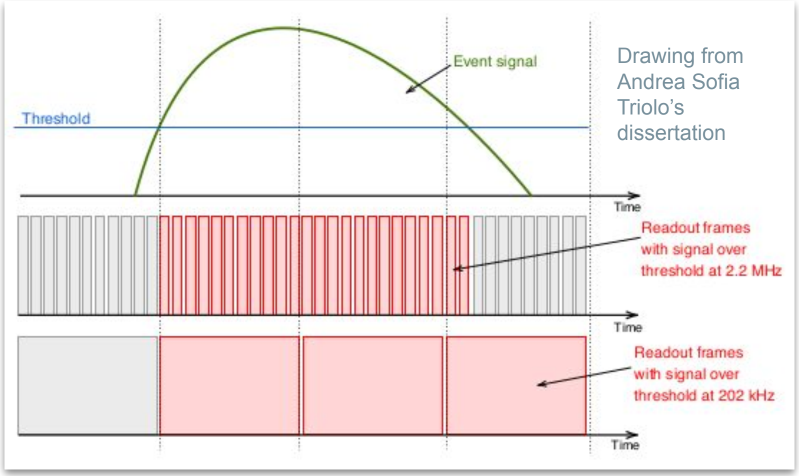


- Measurement of impact parameter with charmed $D^{\pm}$ mesons ($c\tau$ ~ 300 μm)
  - Factor 2-5 improvement in impact parameter resolution compared to Run 2 (ITS1) with Run 3 (ITS2)
- Improvement of the reconstruction of weak-decaying particles in Pb–Pb

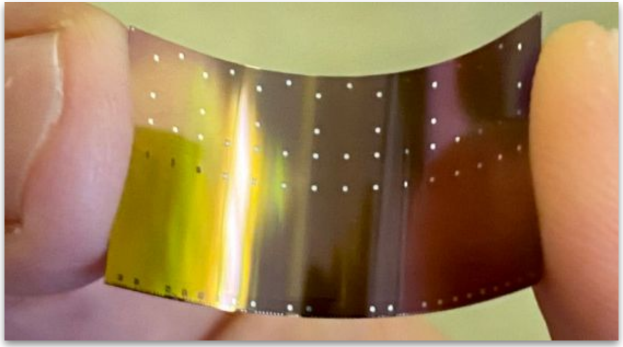
Particle identification with ALPIDE - **ITS Color run**



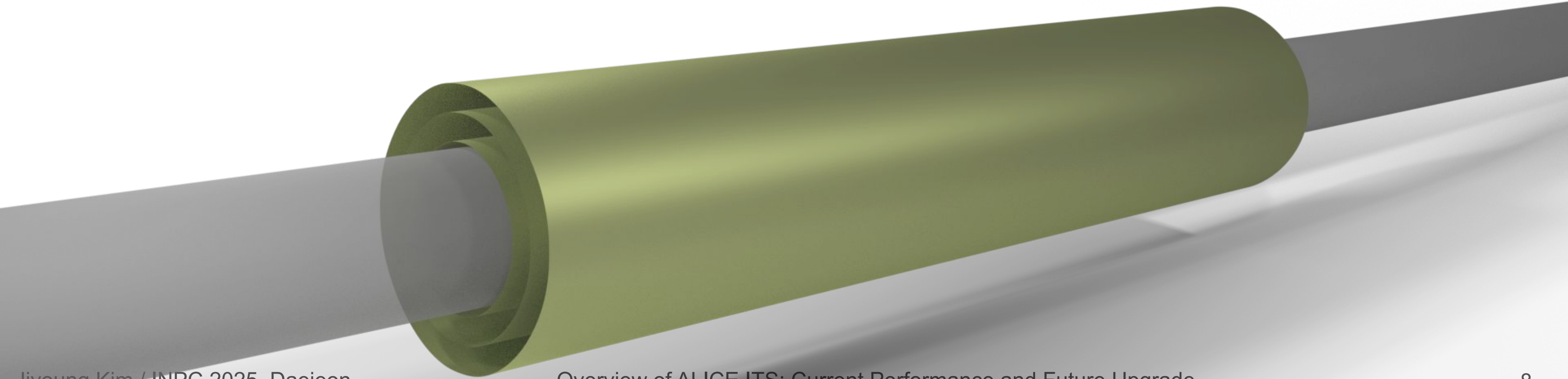
- Usage of Time over Threshold (ToT) information to access the particle energy loss in the ALPIDE sensitive layer
- Proof of concept of d*E*/dx measurement with binary readout MAPS
- Oversampling with increased the framing rate to obtain the ToT information proportional to the deposited charge



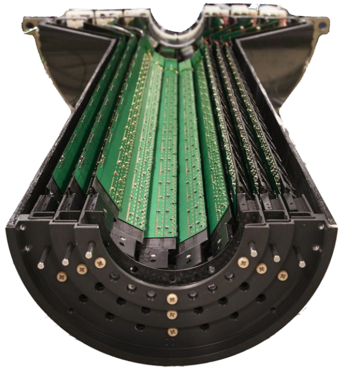
- Detector parameters during color run
  - Only feasible at low Interaction rate in p–p
  - High readout rate (2.2 MHz)
  - Deactivation of signal clipping
    - In the nominal operation, the signal is clipped to avoid double counting of hits from the same particle

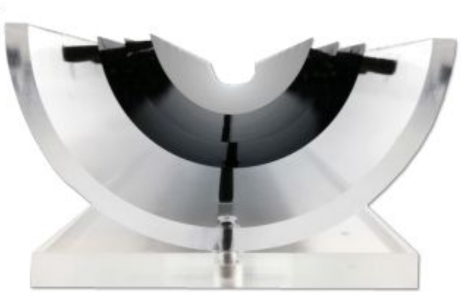


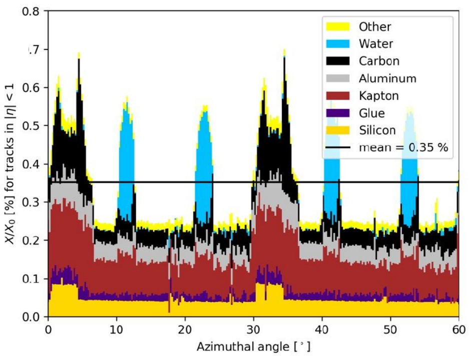
Future upgrade: ITS3



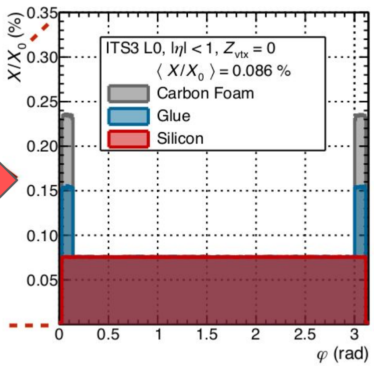
ITS3 upgrade - key concept





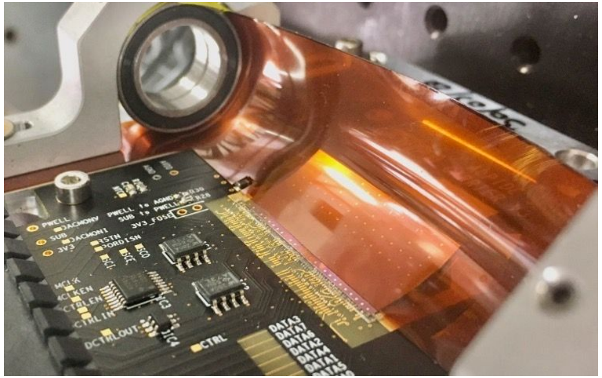


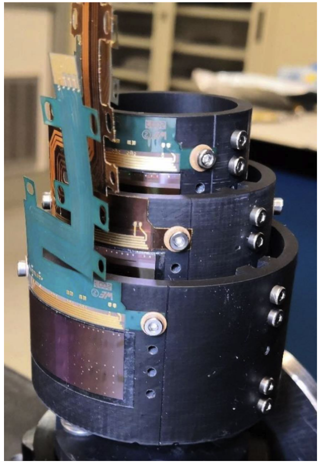
ITS3 TDR — CERN-LHCC-2024-003



- Replacement of ITS2 Inner Barrel with 3 layers of **curved, 50 um thick, wafer-scale MAPS**
- **Air cooling & ultra-light mechanical supports**
- Reduced material budget of on average:
  0.36 % X_0 per layer ➞ **0.09 % X_0 per layer**
- Smaller radius of the innermost layer:
  23 mm ➞ **19 mm**
- Key items in R&D
  - Bending of silicon wafer
  - Stitching
  - Air cooling

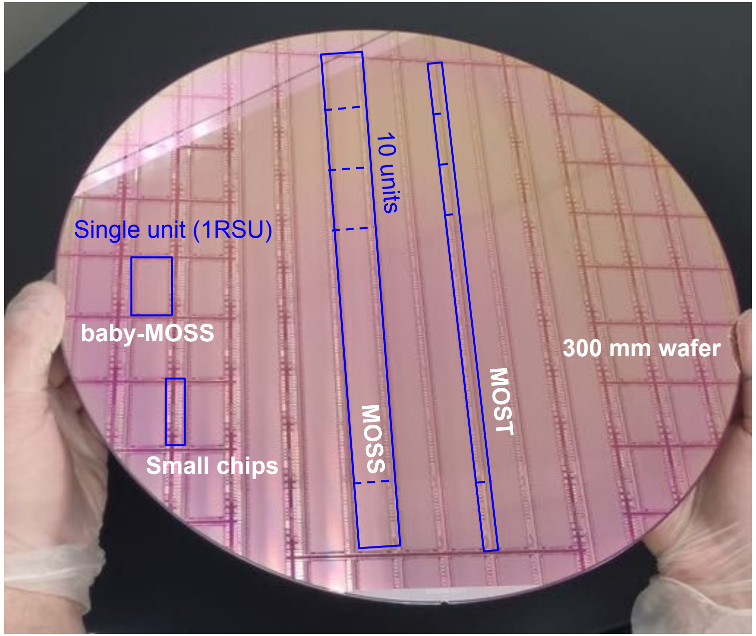
ITS3 TDR — CERN-LHCC-2024-003
j.nima.2021.166280
arXiv:2502.04941





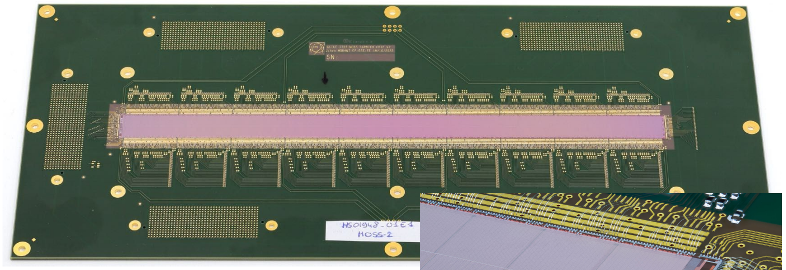
Stitched wafer-scale MAPS

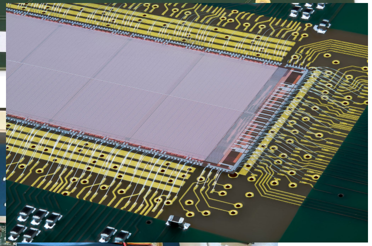
- **E**ngineering **R**un **1**
  - First MAPS for HEP using stitching
- **Monolithic Stitched Sensor (MOSS)**:
  14 x 259 mm, 6.72 MPixels (22.5 x 22.5, 18 x 18 μm^2)
  - Conservative design
  - Different pitches
- **Monolithic stitched Sensor - Timing (MOST)**:
  2.5 x 259 mm, 0.9 MPixels (18 x 18 μm^2)
  - More dense design
  - Power segmentation
- **Baby-MOSS** (single stitch ~ reticle-sized)
- Plenty of small chips (like MLR1)

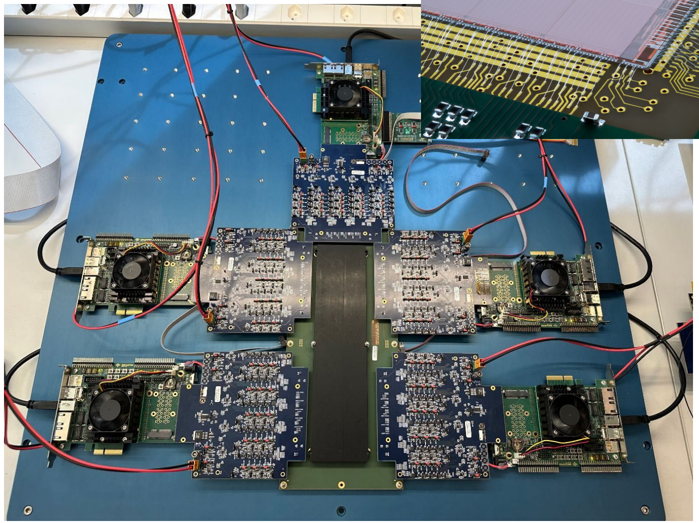


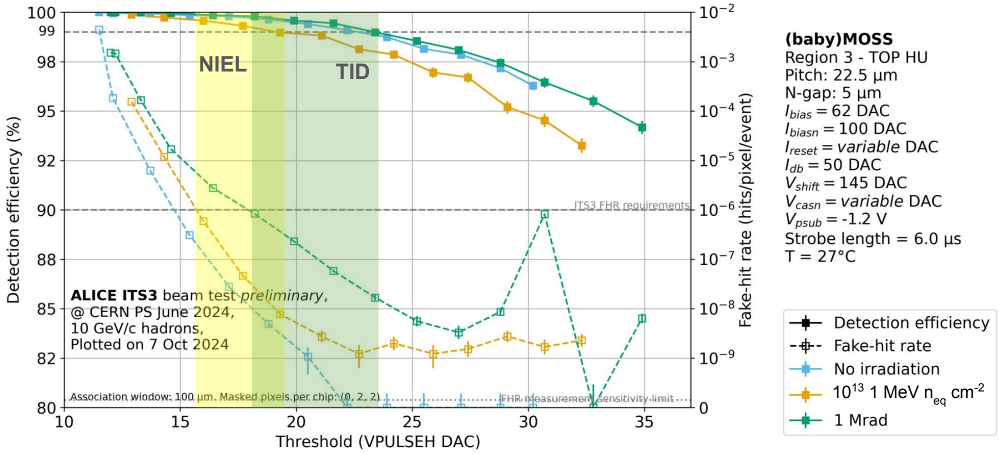
Multi-Layer reticle 1	Engineering Run 1	Engineering Run 2	Engineering Run 3
Validated 65 nm CIS TPSCo process	First submission of large-scale stitched MAPS	Specifications close to final ITS3 sensor	Final sensor to be used in ITS3

Stitched wafer-scale MAPS – MOSS – latest results



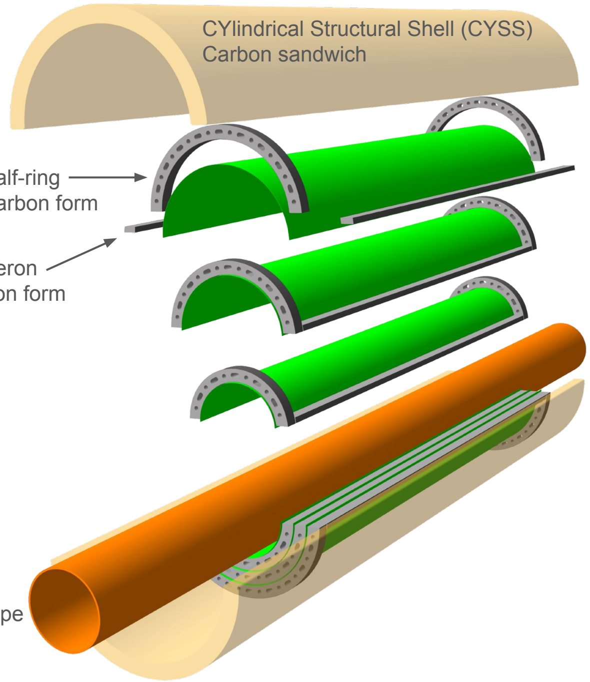


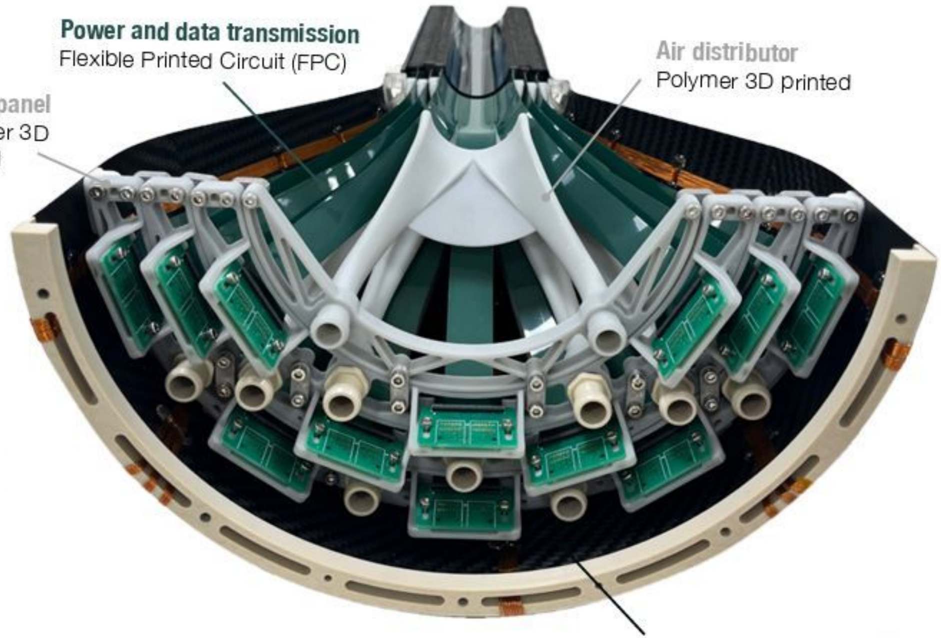




- Detailed characterisation at the laboratory and at test beam
- Operational margin (efficiency > 99% and fake-hit rate < 10^{-6} /pixel/event) is maintained at the ALICE radiation levels, 400 krad and 4 × 10^{12} 1 MeV n_{eq} cm^{-2}

Mechanical support and integration test





- The R&D of mechanical supports and air cooling is ongoing in parallel with sensor development
- Engineering model has been produced and performed the integration test

Summary and outlook

- **ITS2 has demonstrated excellent performance**
  - Impact parameter resolution and reconstruction of weakly-decaying secondary particles
  - **Successful color run demonstration for particle identification capability**

- R&D of ITS3 upgrade under preparation
  - **Replacement of 3 innermost layers with curved, ultra-light, wafer-scale MAPS**
  - **Characterized the first stitched wafer-scale sensor**
  - Mechanical support and cooling study ongoing in parallel

- **Next steps:** Full functionality prototype chip (ER2) is expected to come in the end of 2025. Stay tuned!

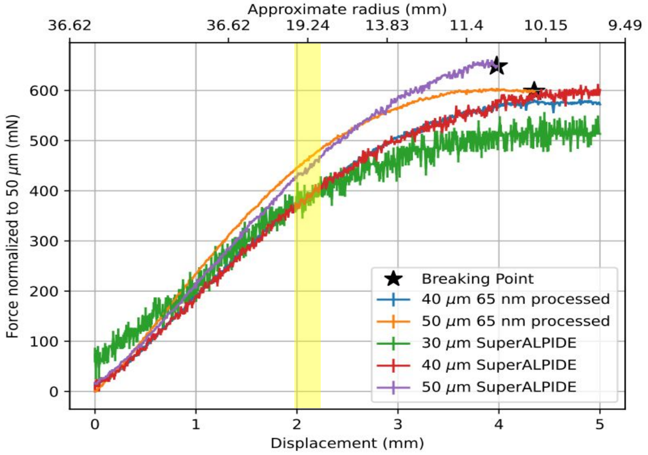
Multi-Layer reticle 1	**Engineering Run 1**	**Engineering Run 2**	**Engineering Run 3**
Validated 65 nm CIS TPSCo process	First large-scale stitched MAPS	Specifications close to final ITS3 sensor	Final sensor to be used in ITS3

Thank you for listening

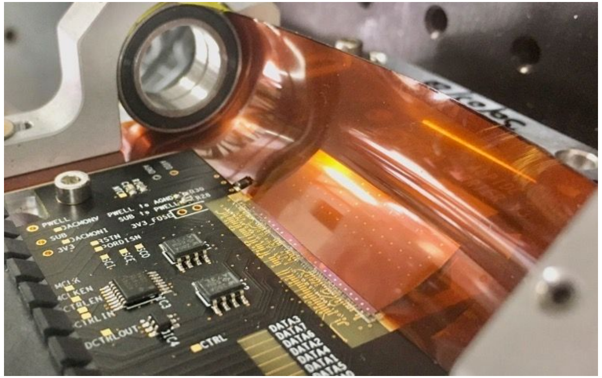
Backup

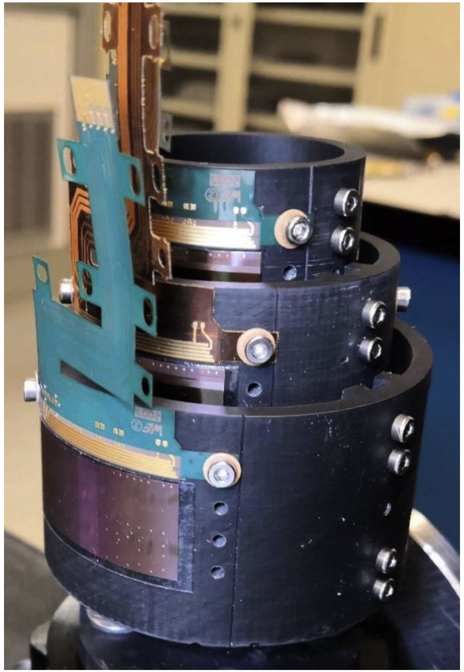
ALPIDE chip bending test

- Bending test with diverse thicknesses → Very Flexible. Fully bent to 19 mm
- Beam tests of bent chip at DESY
  - Bent MAPS feasibility demonstrated for the first time
  - Important milestone in the R&D for ALICE ITS3
- Demonstration of fully bent sensor on FPCB is done as well

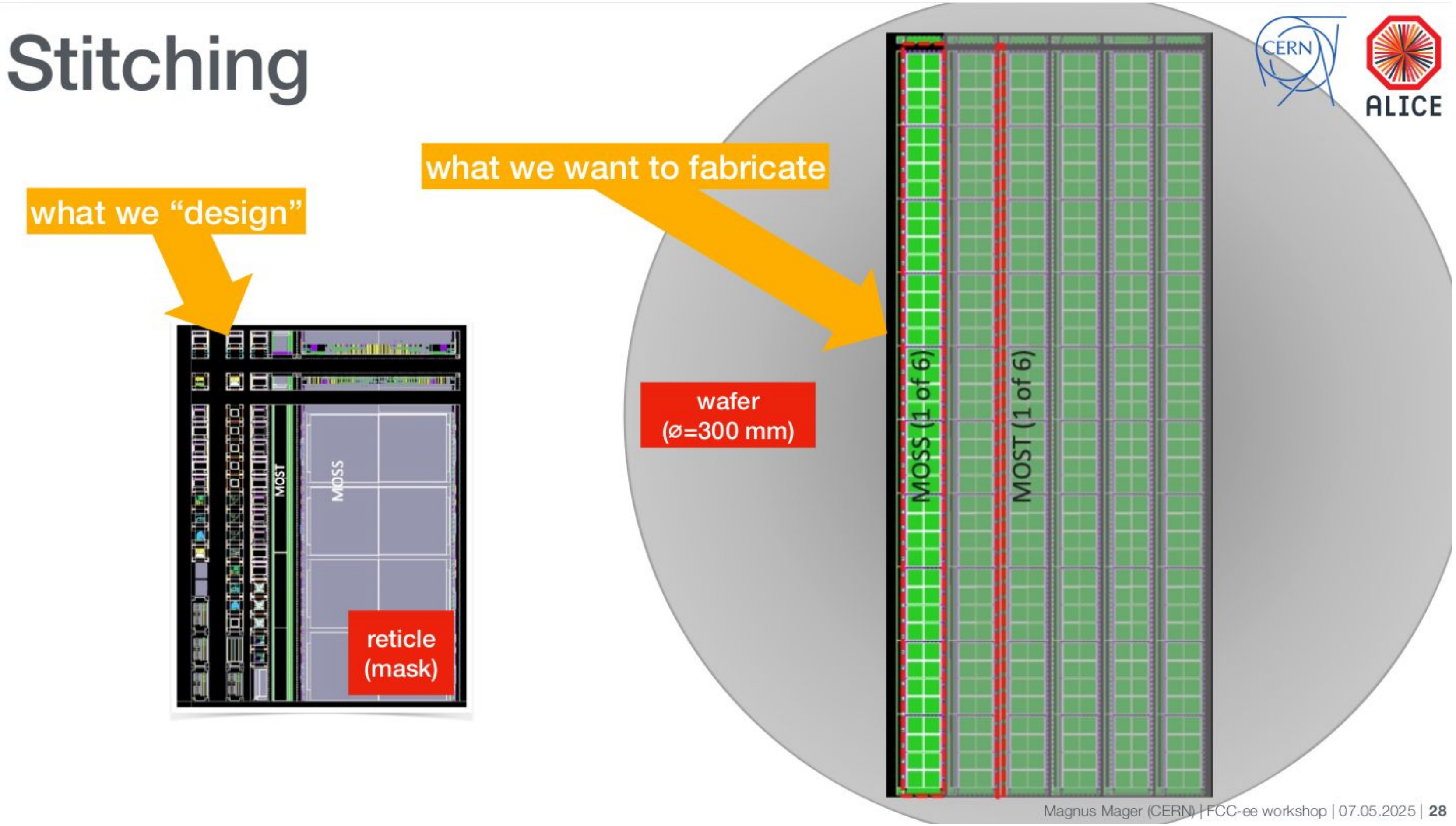


ITS3 TDR — CERN-LHCC-2024-003
j.nima.2021.166280
arXiv:2502.04941





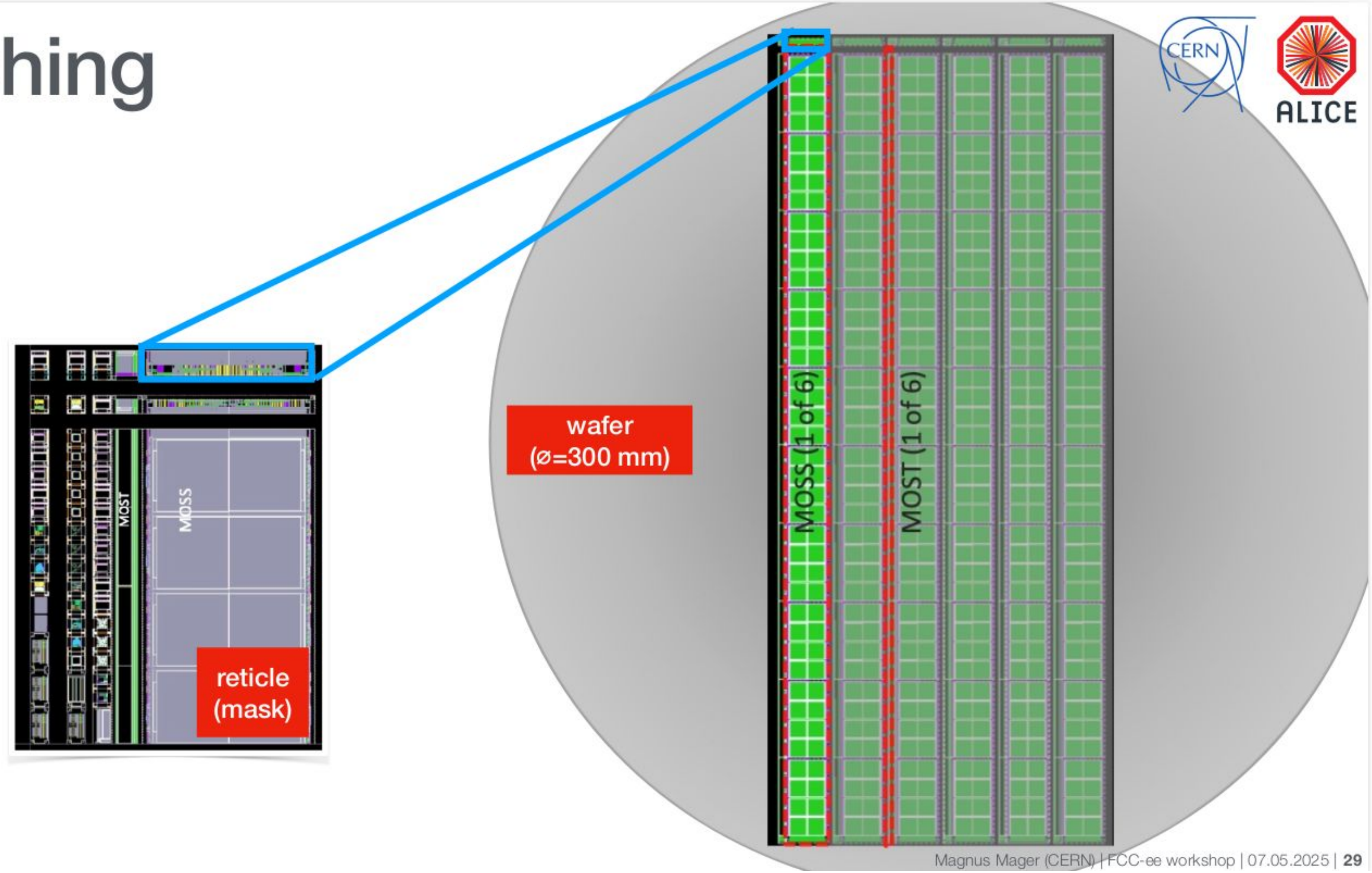
Stitching



what we "design"
what we want to fabricate
MOST
MOSS
reticle
(mask)
wafer
(ø=300 mm)
MOSS (1 of 6)
MOST (1 of 6)
CERN
ALICE
Magnus Mager (CERN) | FCC-ee workshop | 07.05.2025 | 28

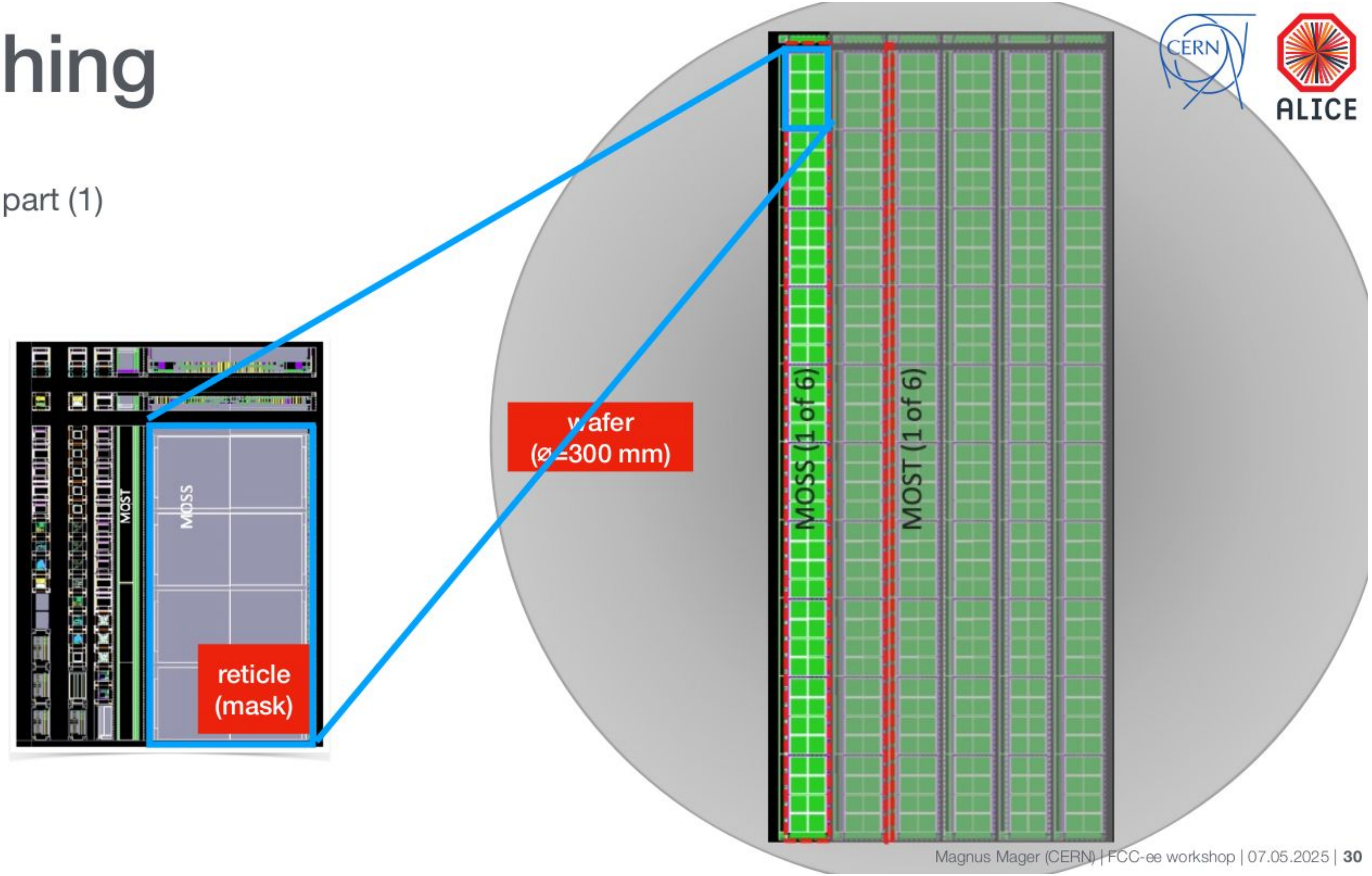
Stitching

- top part



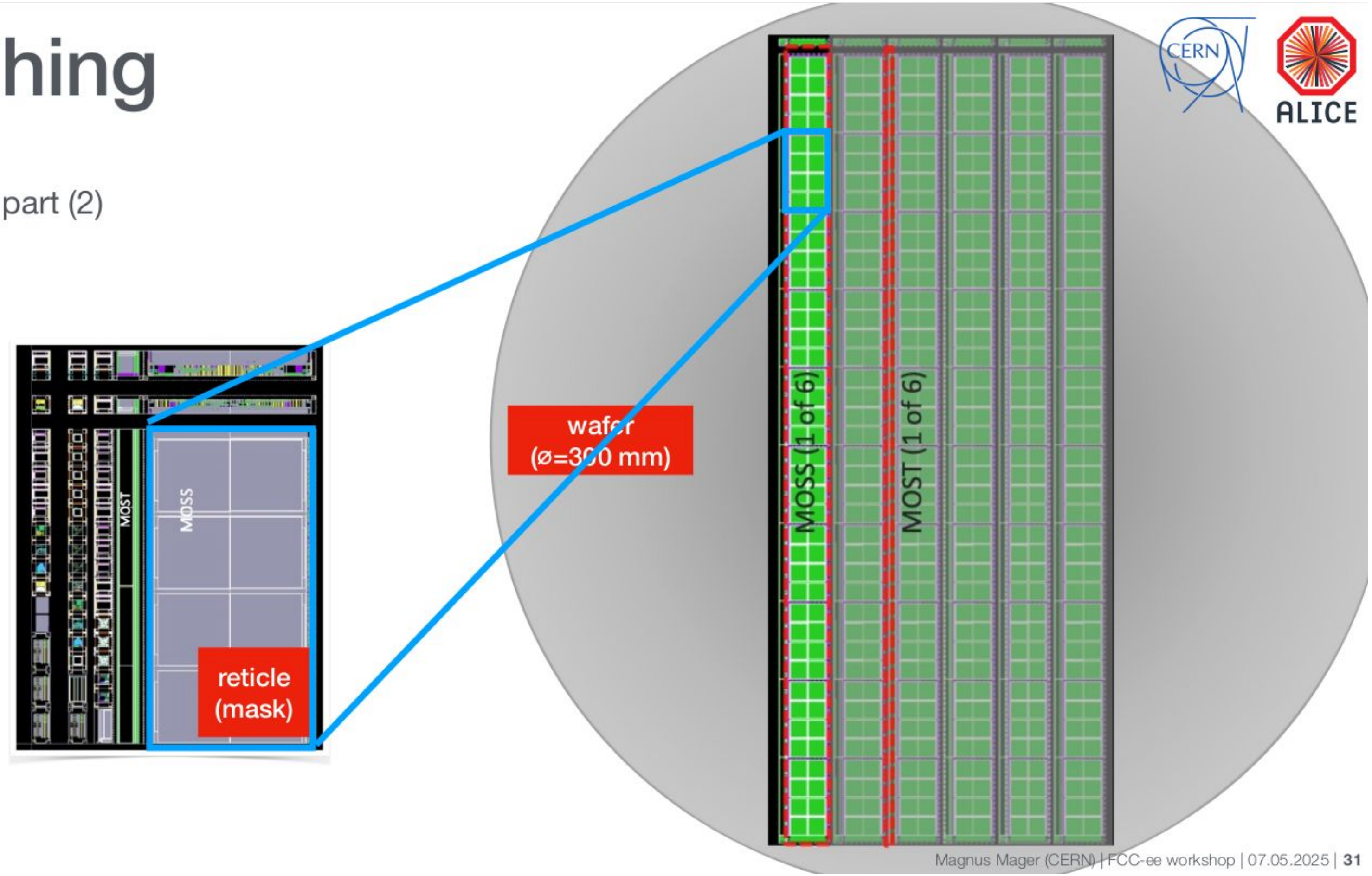
Stitching

- repeated part (1)



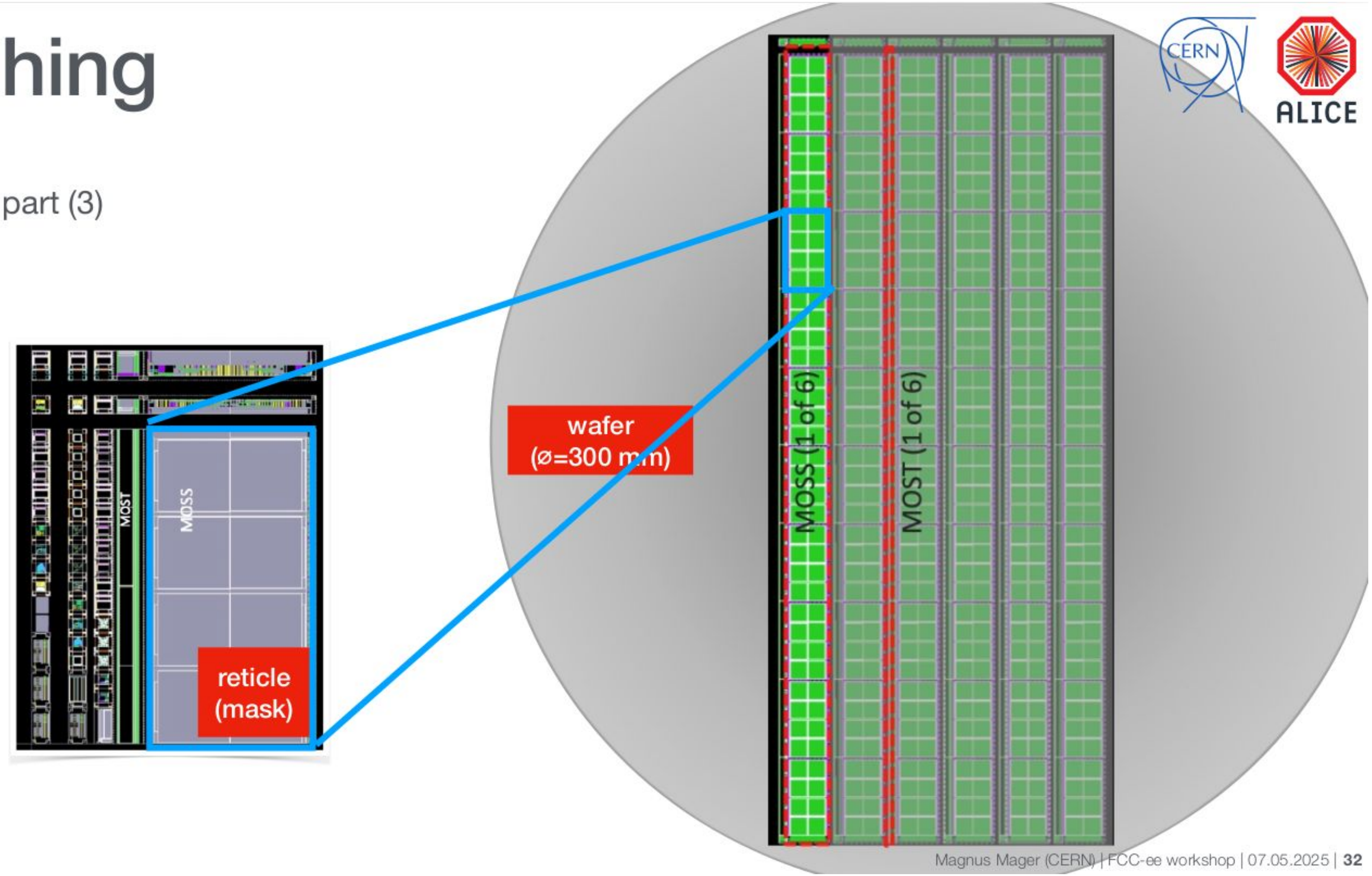
Stitching

- repeated part (2)



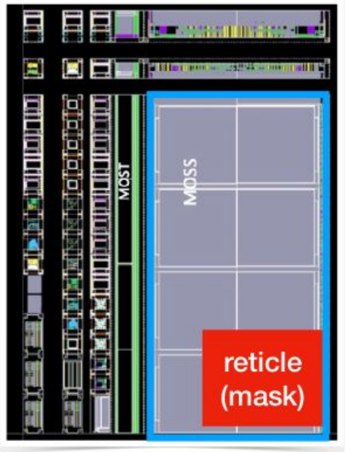
Stitching

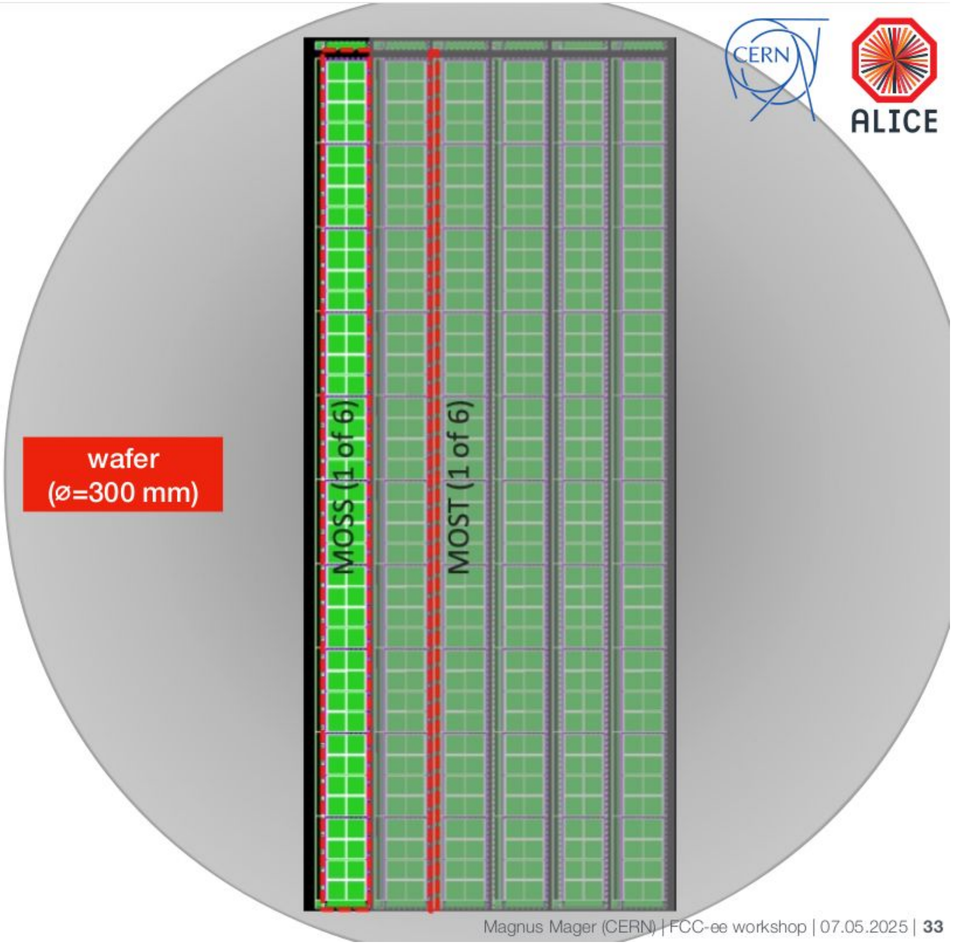
- repeated part (3)



Stitching

- final circuit is a concatenation of different parts of the masks





Detection efficiency and fake-hit rate of non-irradiated and irradiated ALPIDEs

Beam: 6 GeV/c pions

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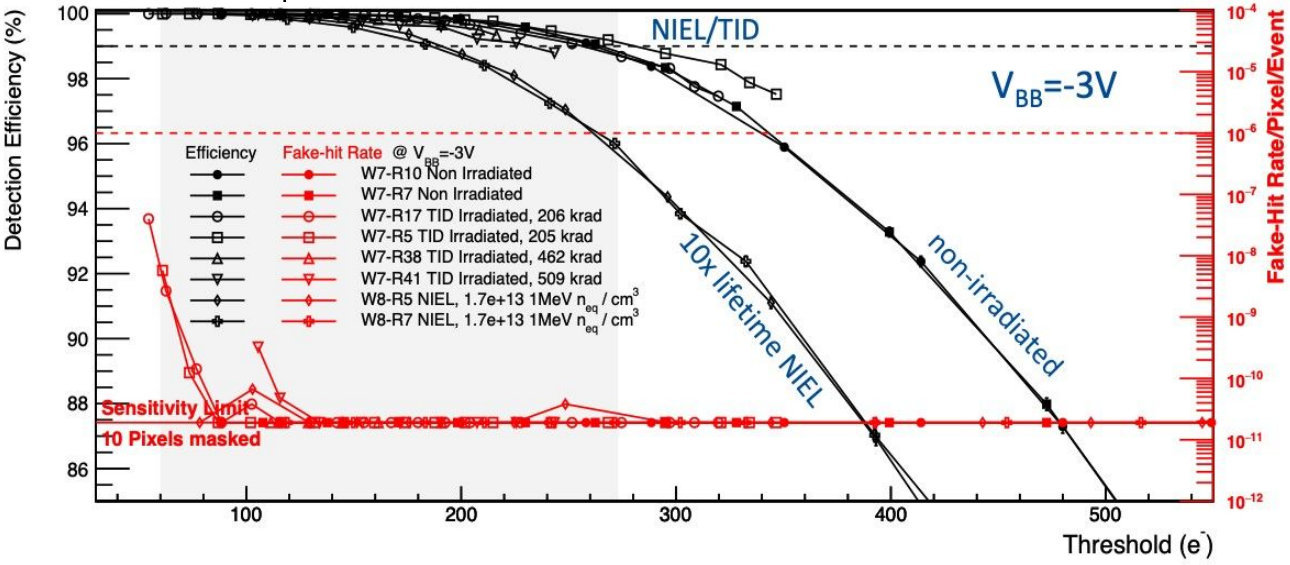
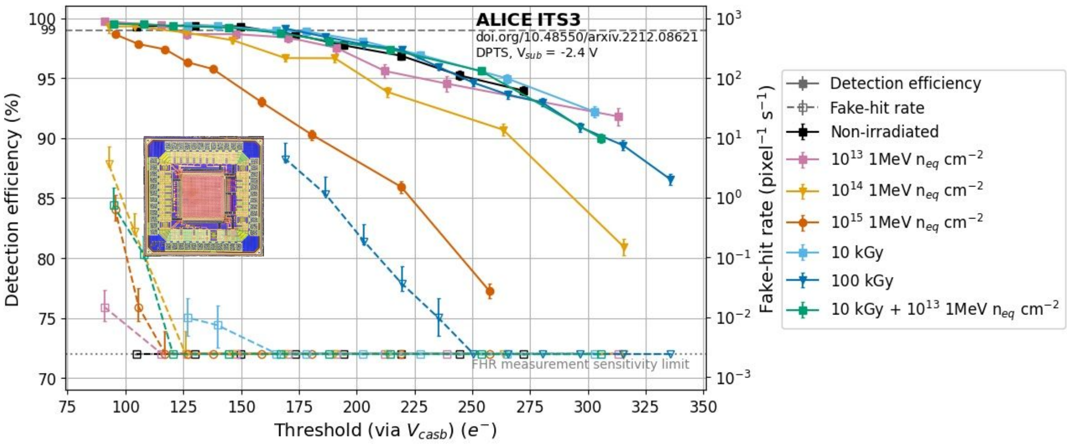


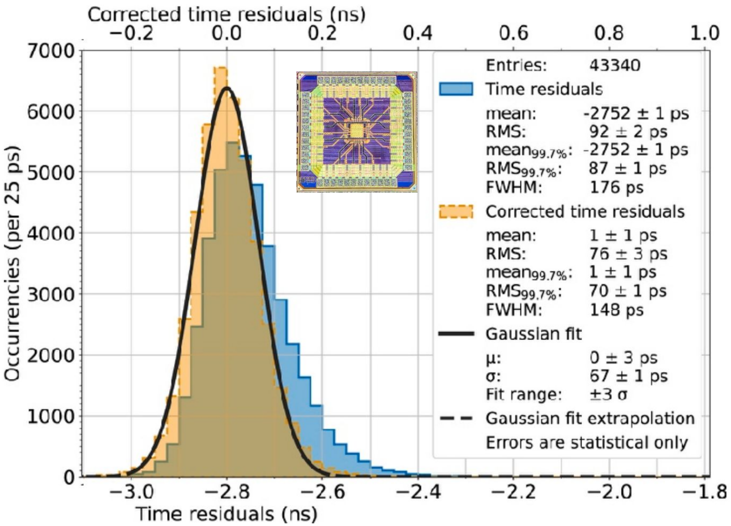
- Detection efficiency ~ Charge collection performance
- Fake hit rate/pixel/event ~ Noise level
- Efficiency drops according to higher threshold values as expected
- Operational margin
  - > 99 % efficiency
  - < 10-6 fhr/pixel/event
- After high-does irradiation, ALPIDE keeps high efficiency and low noise level based on ample operating margin
- Nominal operating point is at 100 e-

Process modification: 10.1016/j.nima.2017.07.046
APTS paper: arXiv:2403.08952
DPTS paper: NIM A.2023.168589
Time resolution: arXiv:2407.18528

TPSCo 65 nm technology qualification

- pixel prototype chips (selection)





- Multi-Layer Reticle 1 (MLR-1): common effort by ALICE ITS3 and CERN EP R&D
  - Various small scale prototypes with pixel matrices and ancillary circuitry
  - Technology explored far beyond the requirements of ITS3 in terms of radiation hardness and time resolution
    ⇒ Promising also for future applications like ALICE 3 Vertex Detector and FCC-ee

Multi-Layer reticle 1 → **Engineering Run 1** → **Engineering Run 2** → **Engineering Run 3**

The next chip
baseline specifications

Parameter	ALPIDE (existing)	Wafer-scale sensor (this proposal)
Technology node	180 nm	65 nm
Silicon thickness	50 μm	20-40 μm
Pixel size	27 x 29 μm	O(10 x 10 μm)
Chip dimensions	1.5 x 3.0 cm	scalable up to 28 x 10 cm
Front-end pulse duration	~ 5 μs	~ 200 ns
Time resolution	~ 1 μs	< 100 ns (option: <10ns)
Max particle fluence	100 MHz/cm^2	100 MHz/cm^2
Max particle readout rate	10 MHz/cm^2	100 MHz/cm^2
Power consumption	40 mW/cm^2	< 20 mW/cm^2 (pixel matrix)
Detection efficiency	> 99%	> 99%
Fake-hit rate	< 10^{-7} event/pixel	< 10^{-7} event/pixel
NIEL radiation tolerance	~3 x 10^{13} 1 MeV n_{eq}/cm^2	10^{14} 1 MeV n_{eq}/cm^2
TID radiation tolerance	3 MRad	10 MRad

ALPIDE is a great starting point, samller technology node will open further possibilities!

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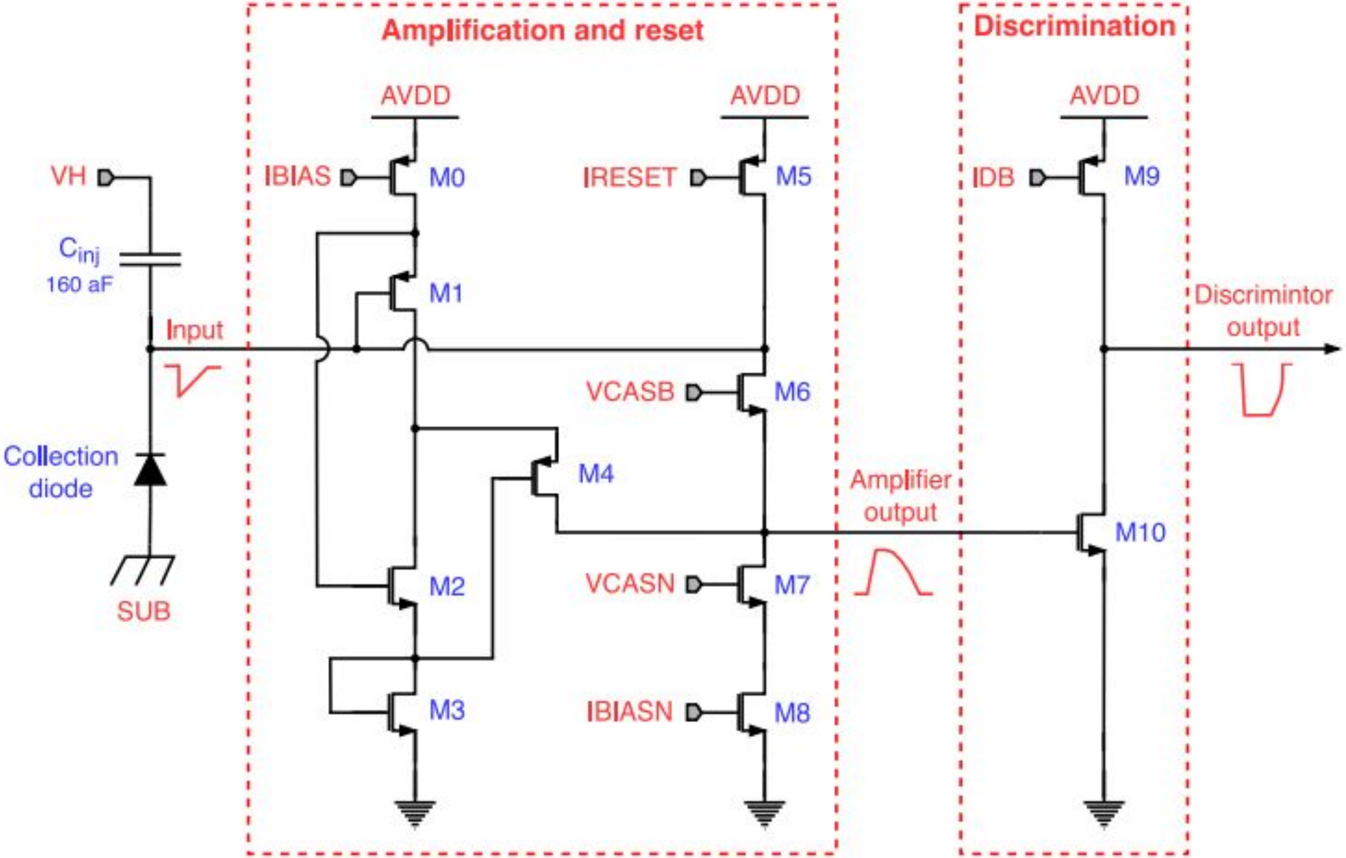

Fig. 3. In-pixel amplifying, discriminating and reset circuit. All front-end biases are provided externally, in common to all pixels.

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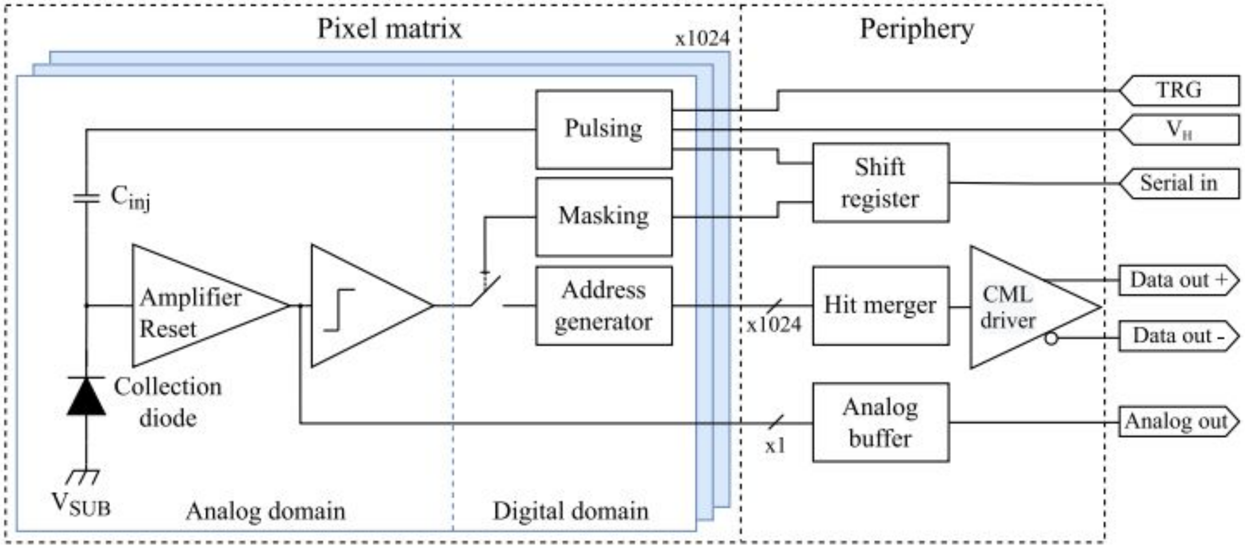
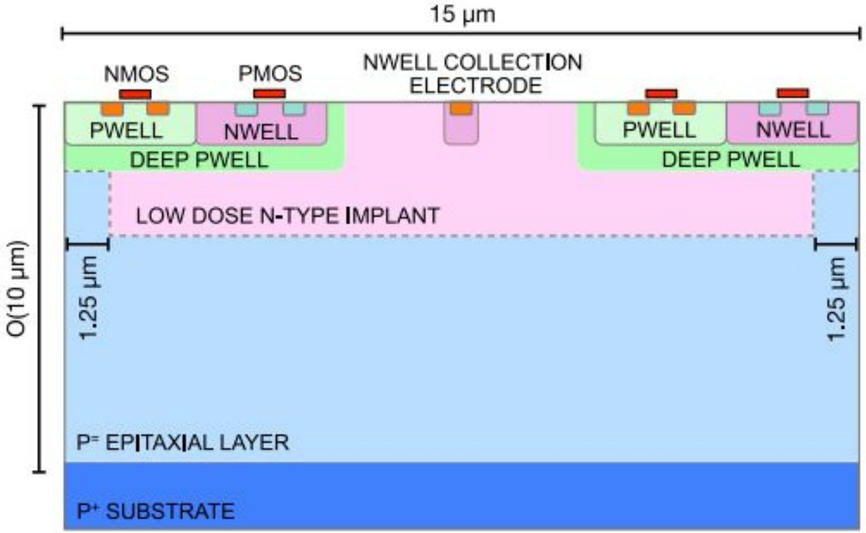
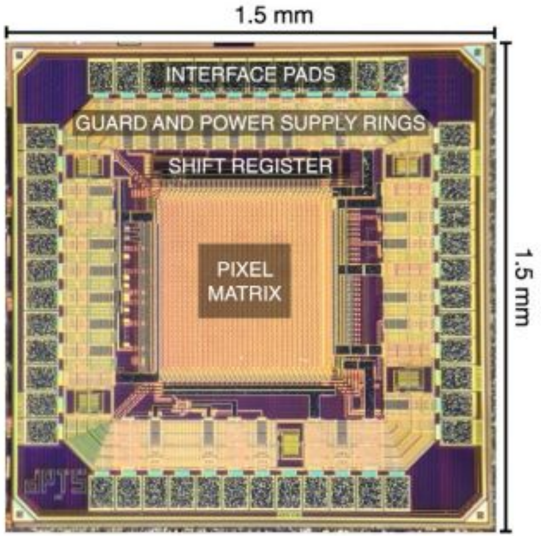


Fig. 2. DPTS functional diagram. 1024 pixels can be masked from readout and selected for pulsing via a shift register. The addresses of hit pixels are read out via a differential digital output line. The in-pixel amplifier output of a single pixel is connected to an interface pad.



(a) Pixel cross section. Not to scale.



(b) Chip under microscope.

Fig. 1. A cross section of a DPTS pixel and a photo of the chip under a microscope.

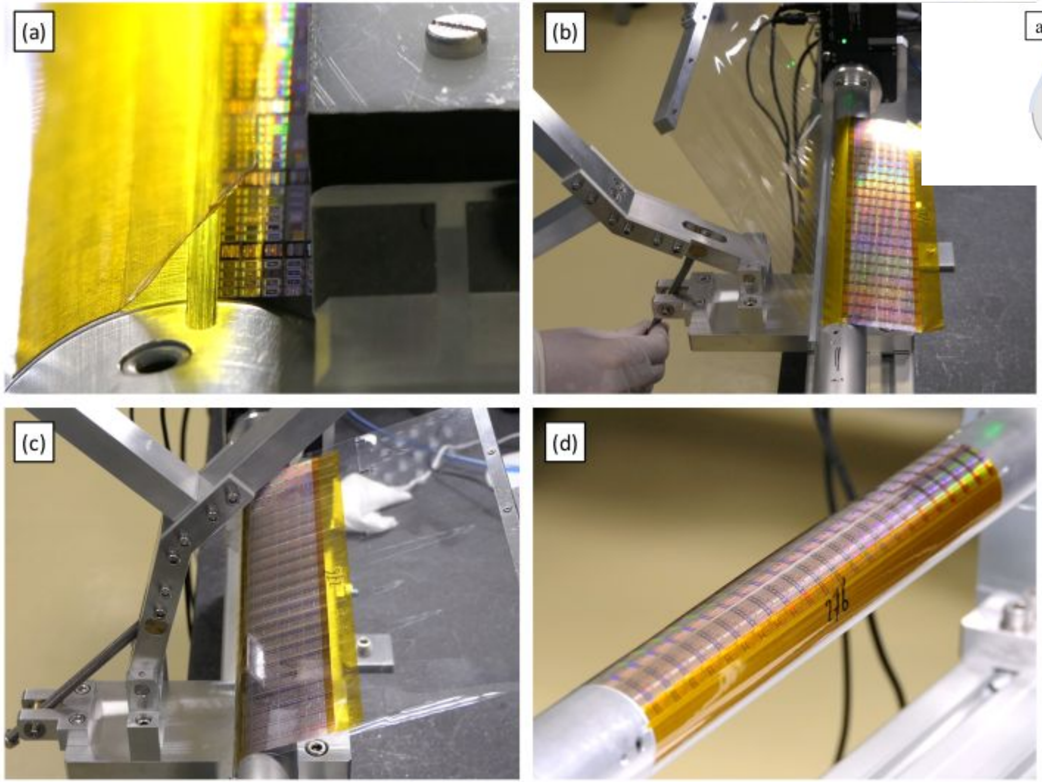
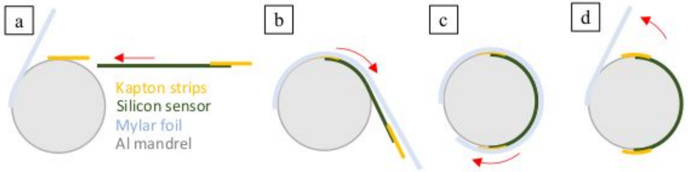
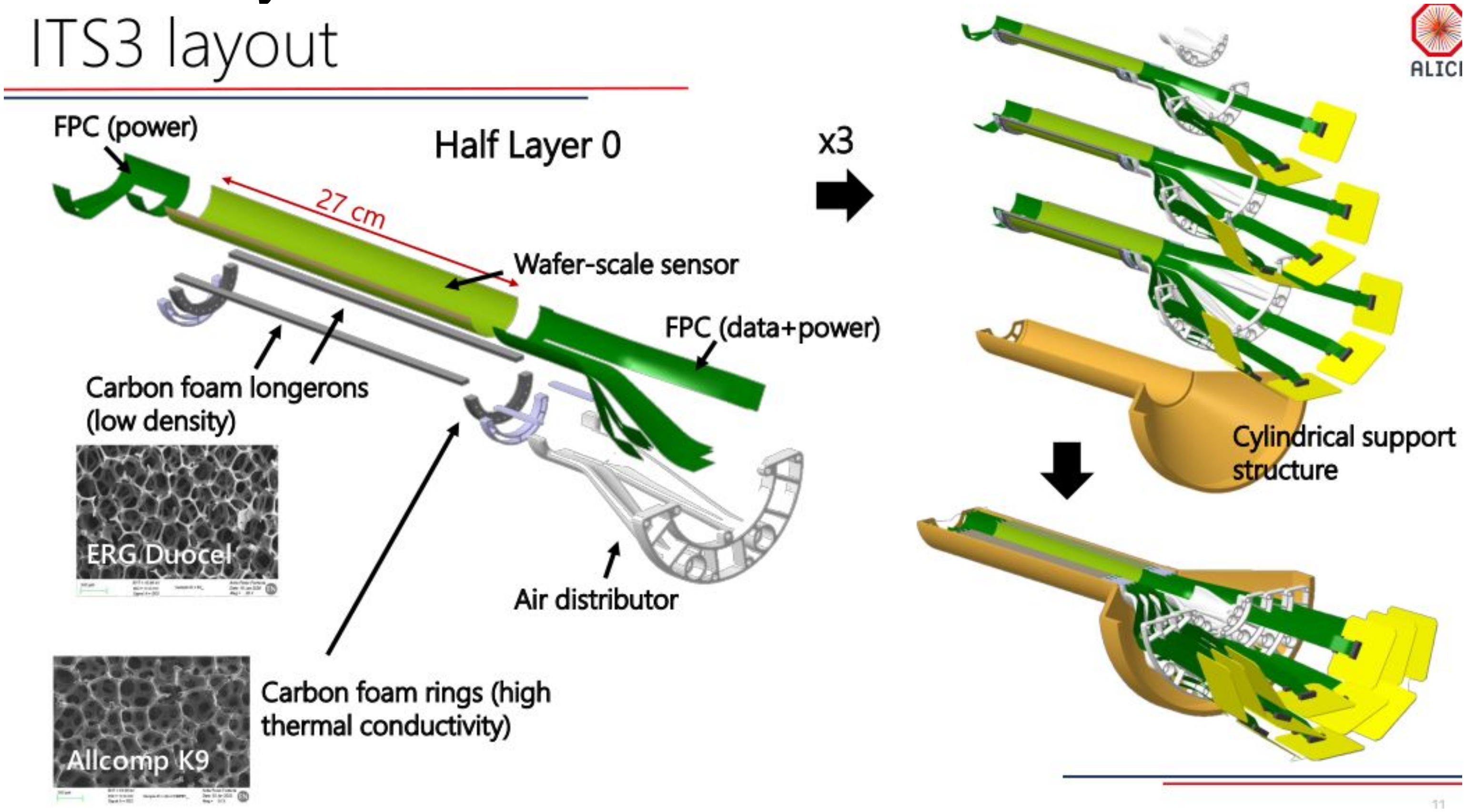
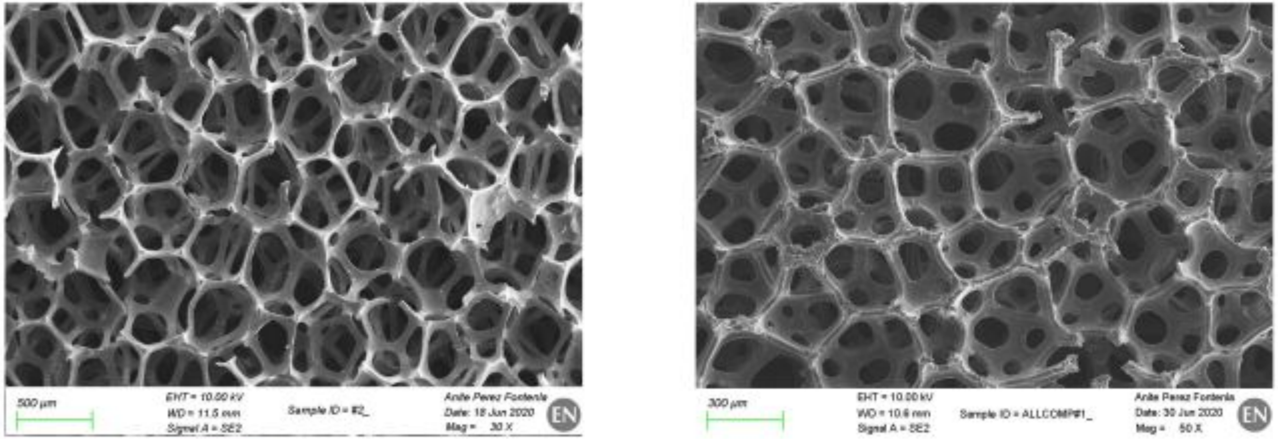


Figure 4.35: Bending of an MLR1 central piece with H-L0 dimension. (a) Alignment of the half-layer, (b) start of the bending procedure, (c) half-layer during bending and (d) bent.



ITS3 layout


ITS3 layout
FPC (power)
Half Layer 0
27 cm
x3
Wafer-scale sensor
FPC (data+power)
Carbon foam longerons
(low density)
ERG Duocel
Air distributor
Carbon foam rings (high
thermal conductivity)
Allcomp K9
Cylindrical support
structure
ALICE



(a) Carbon (RVC) Duocel®

(b) Allcomp K9 standard density

Figure 4.6: Microscopy images of the carbon foams used in ITS3 cooling system. The two images have different scales.