European Nuclear Physics Conference 2025

CAEN, 21–26 Sept 2025

ITS3 in ALICE: pioneering bendable wafer-scale sensors for LHC Run 4

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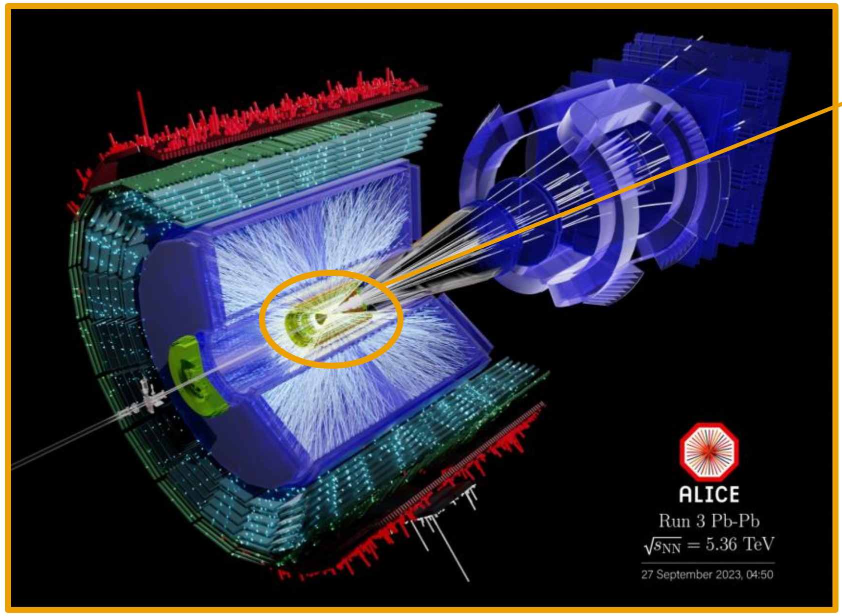
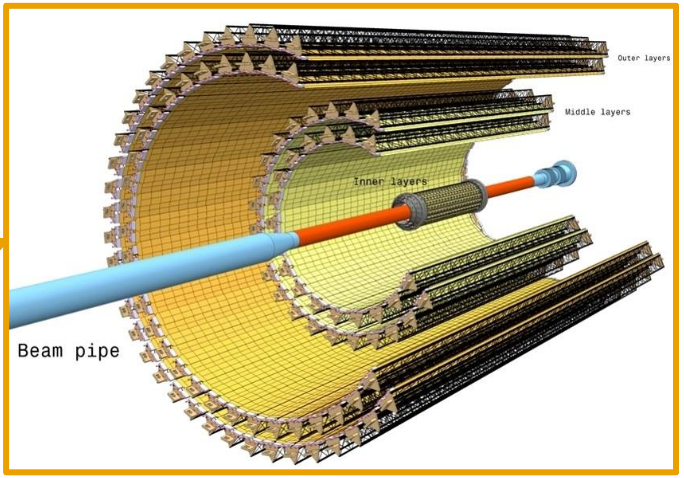
on behalf of the ALICE Collaboration

A Large Ion Collider Experiment

- Optimized for the study of the Quark Gluon Plasma (**QGP**) in heavy ion collisions at the CERN LHC
- Tracking and identification of particles in high multiplicity events
- Interest in low momentum (≲1 GeV/c) particle reconstruction

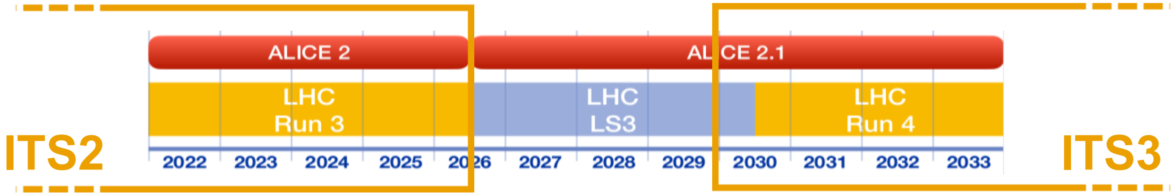


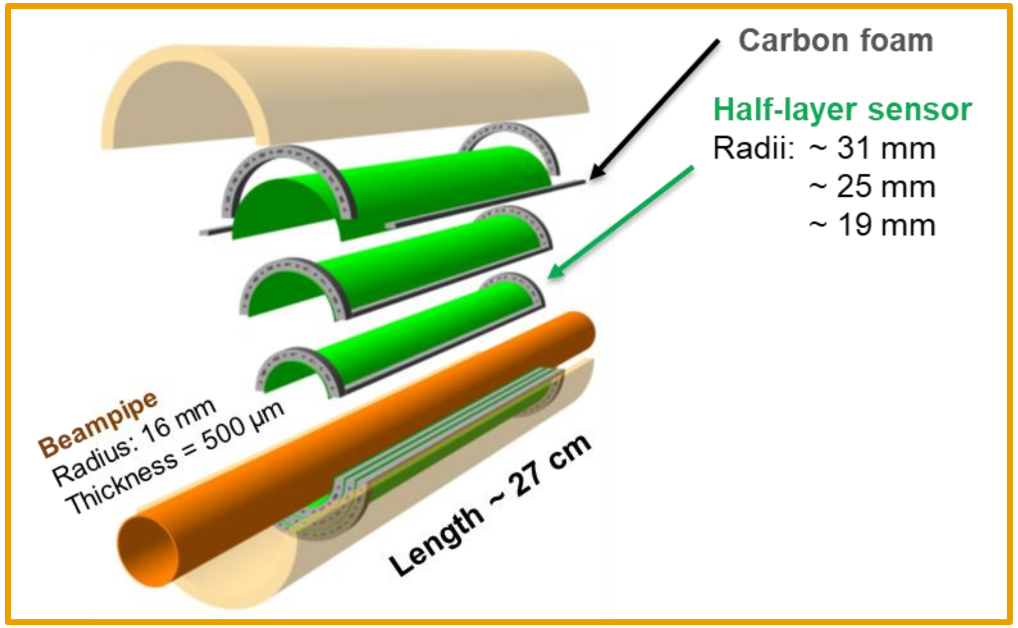


- Inner Tracking System 2 (**ITS2**): current vertex detector taking data since September 2021
- Largest Monolithic Active Pixel Sensor (**MAPS**) detector in high-energy physics
  - 7 layers: Inner Barrel (3 layers) + Outer Barrel (4 layers)
  - 1^{st} layer radius **24 mm**
  - Low material budget: **0.36% X_0** per layer

ITS3: upgrade of the ITS2

- Main physics motivations:
  - improve the precision in heavy-flavour measurements
  - enable detailed studies of (anti)(hyper)nuclei
  - observe rare short-lived states
- Basic idea: **minimize material budget and distance to interaction point**
- ITS3 replaces the Inner Barrel of ITS2 in LS3
- 3 layers of MAPS divided into half-layers:
  - Innermost layer **4mm closer to IP**
  - **Large area** sensors bent around beam pipe
  - **Self supporting**, no rigid mechanical structure
  - **Air cooling**
  - **No circuit boards**
  - Layer thickness reduced to **0.09% X_0**
- **Improvement of a factor 2 in the impact parameter resolution** with respect to ITS2



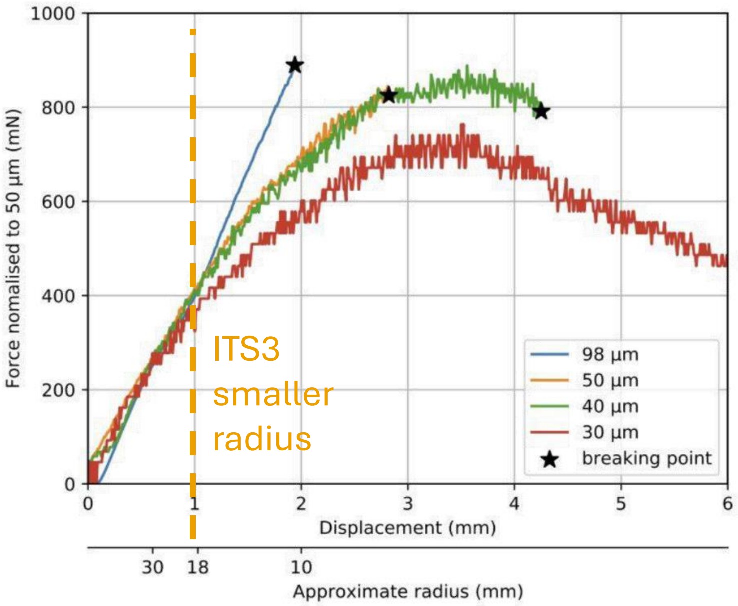


LOI: https://cds.cern.ch/record/2703140

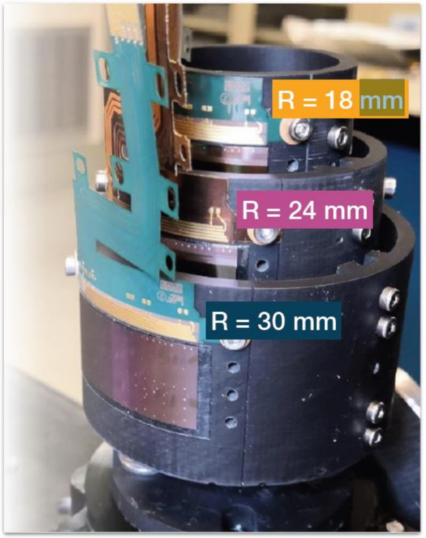
TDR: https://cds.cern.ch/record/2890181

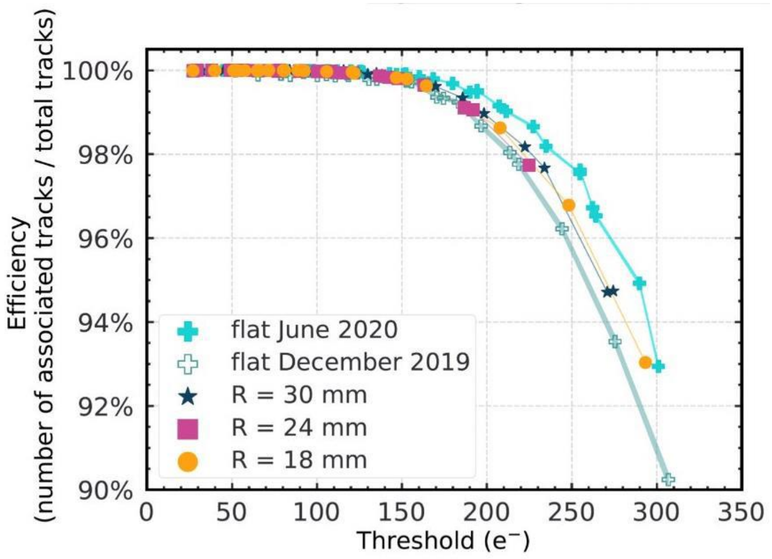
Bending of Silicon

- Project target for thicknesses and bending radii are in a “**not breaking**” regime



- Full mock-up “**µITS3**”: 6 ITS2 ALPIDE sensors bent to ITS3 target radii
- In-beam results show **no performance degradation - they work as flat chips!**
- Results validated on bent ITS3 small-scale prototypes



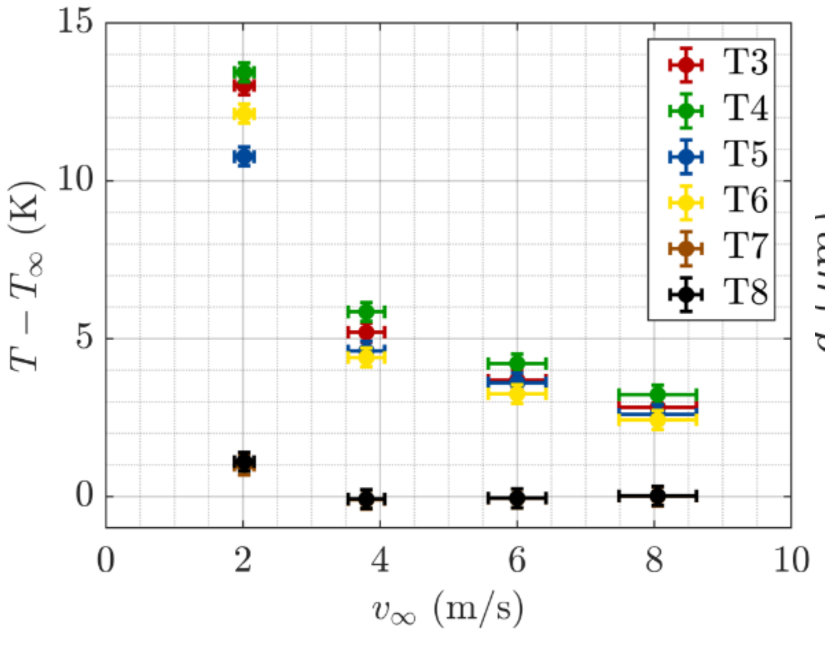


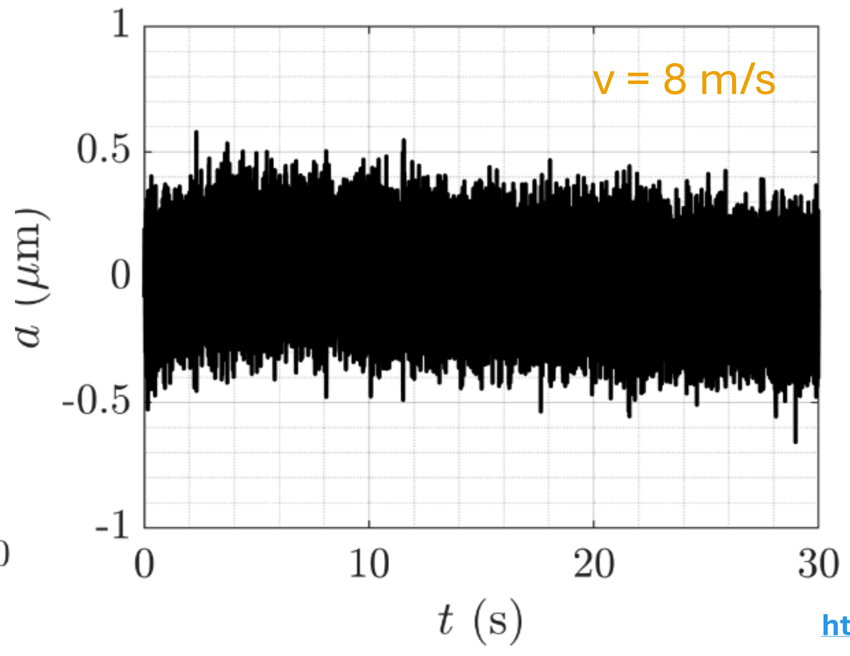
https://doi.org/10.1016/j.nima.2021.166280

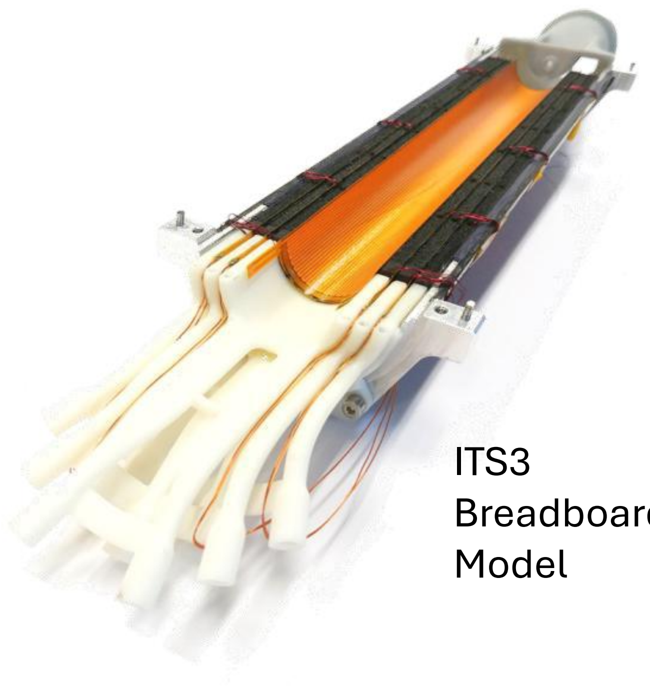
https://doi.org/10.48550/arXiv.2502.04941

Mechanics and cooling solutions

- **Carbon foam** used as support and radiator
- **Air cooling** to keep material budget low
- Tests in wind tunnel using thermal mock-up with heaters & temperature sensors
- Temperature rise well within limits, **ΔT < 5° C**
- Vibrations perpendicular to beam axis **± 0.4 µm** (RMS)







ITS3 Breadboard Model

https://doi.org/10.1016/j.applthermaleng.2023.121699
https://doi.org/10.1016/j.ast.2024.109313

Development of the sensor

Project requirements:

- 65 nm CMOS process
- Spatial resolution ~ 5 μm
- High efficiency > 99%
- Low Fake Hit Rate (FHR) < 10^{-6} /pixel/event
- Excellent radiation tolerance (up to 4 x10^{12} 1 MeV n_{eq} cm^{-2} and 400 krad)
- Wafer-scale chips
- Low power consumption 40 mW/cm^2 (air cooling)
- 50 μm thick (bending)

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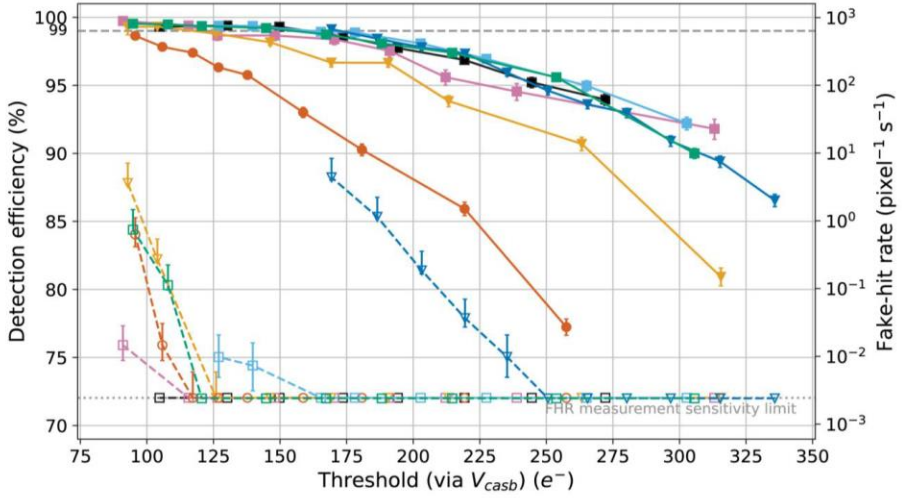
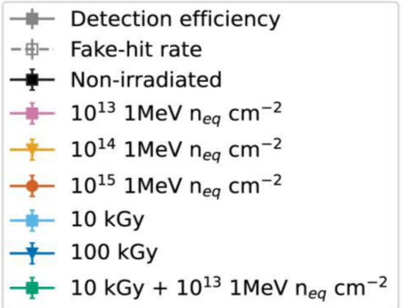
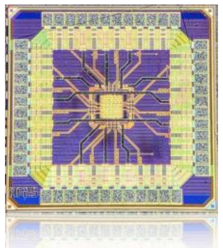


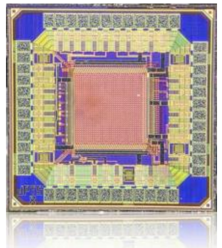


TECHNOLOGY VALIDATION

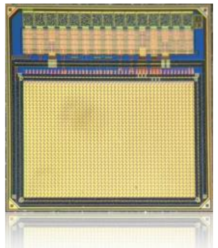
MLR1: Multi Layer Reticle 1
→ first submission in the 65 nm technology
Small area test structures:



APTS
4x4 px matrix with direct analog readout



DPTS
32x32 px matrix with digital asynchronous readout



CE65
64x32 px matrix with rolling shutter analog readout

DPTS https://doi.org/10.1016/j.nima.2023.168589
DPTS https://arxiv.org/abs/2505.05867
APTS https://doi.org/10.1016/j.nima.2024.169896
APTS https://doi.org/10.1016/j.nima.2024.170034

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- 65 nm CMOS process
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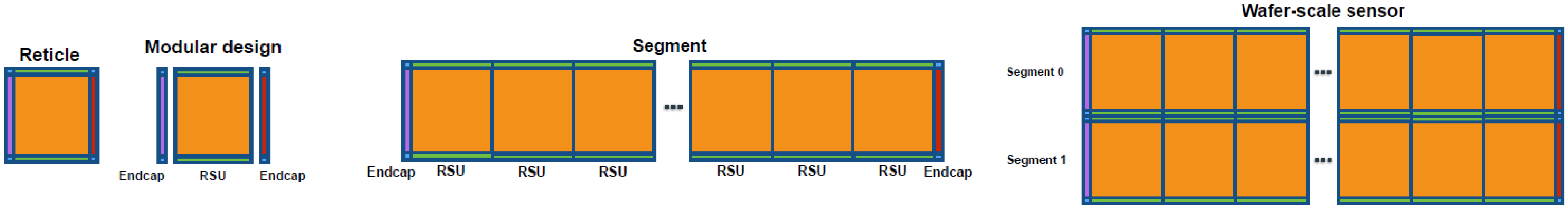
- Low Fake Hit Rate (FHR) < 10^{-6} /pixel/event
- Excellent radiation tolerance (up to 4 x10^{12} 1 MeV n_{eq} cm^{-2} and 400 krad)
- Wafer-scale chips
- Low power consumption 40 mW/cm^2 (air cooling)
- 50 μm thick (bending)

STITCHING

- Size of the chip usually limited to a few cm^2 by the reticle size in the production process
- Split the design on the reticle:
  Left End Cap (**LEC**)
  Repeated Sensor Unit (**RSU**)
  Right End Cap (**REC**)
- Endcaps and multiple RSUs can be interconnected to a **Segment**
- Multiple independent Segments can be diced out together forming a **wafer-scale sensor**

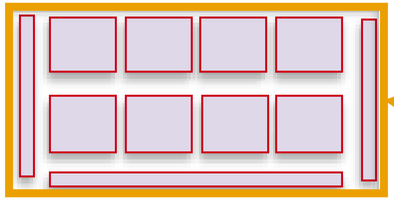


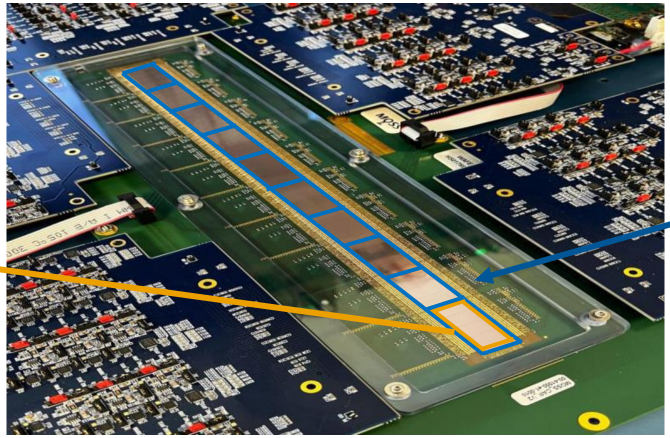
Wafer-scale stitched MAPS

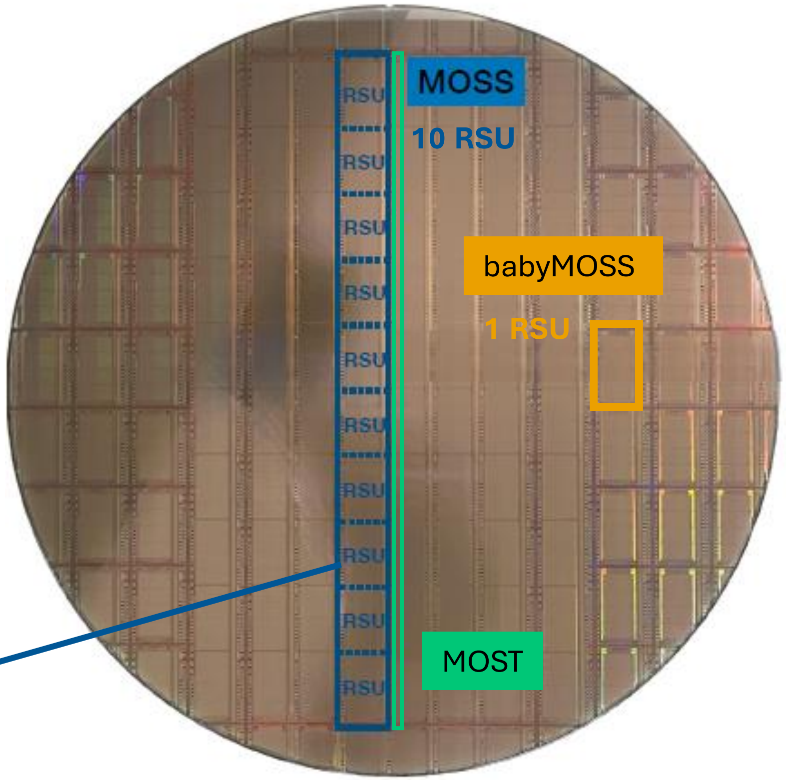
ENGINEERING RUN 1 (2022)

- First MAPS wafer-scale stitched sensors
- Wafer with various dies (“ MOSS ”, MOST ”, “babyMOSS”)
- **MOSS**: **MO**nolithic **S**titched **S**ensor
  - Size (14 x 259 mm^2):
  - 6.7 million pixels organised in 10 RSU
  - Each RSU subdivided in 8 individual regions

1 RSU







MOSS results

- Detailed characterisation in:
  - Laboratory
  - Several tests beam at CERN PS and SPS beam lines

MOSS results

- Detailed characterisation in:
  - Laboratory → functional yield higher than **98%**
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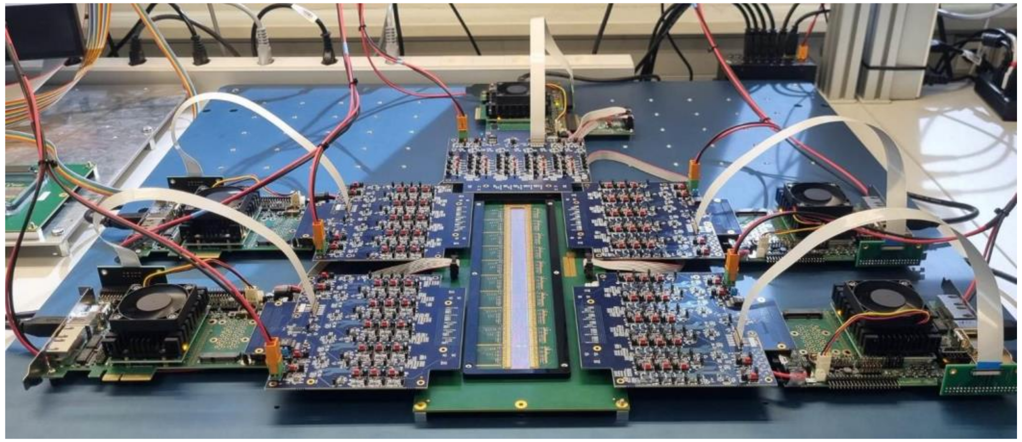
Before picking and bonding on carrier:

- Wafer-probing

In laboratory, 3 main steps:

- Impedance tests between power nets
- Power ramp
- Functional tests



Tests on all 82 sensors from 14 wafers
→ **Good performance, uniform behavior, high yield**

MOSS results

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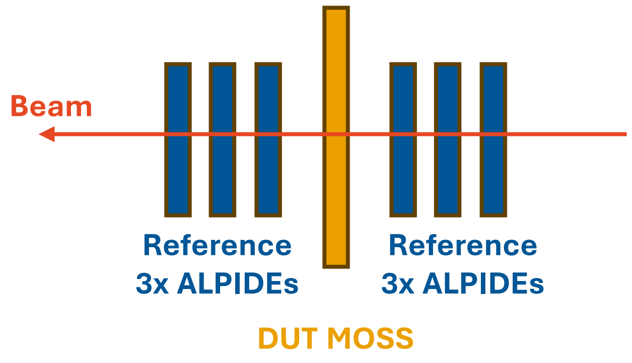

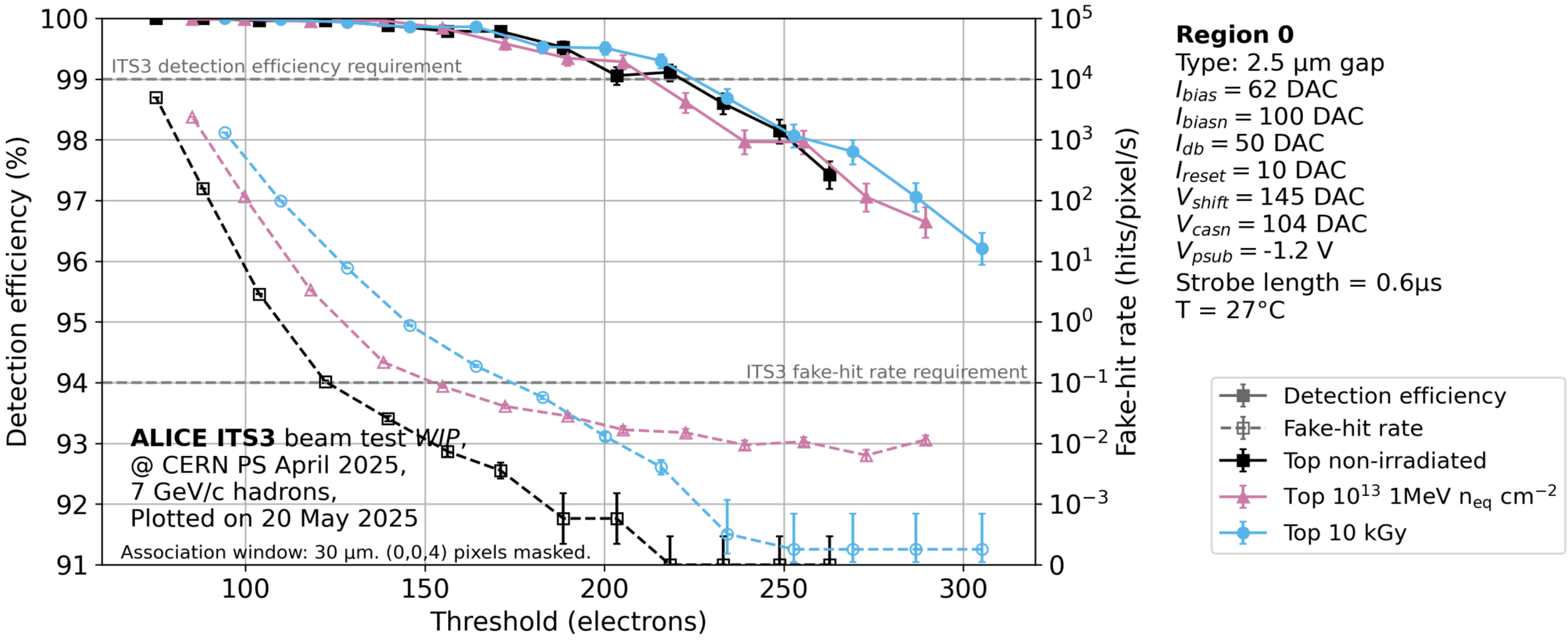

Region 0
Type: 2.5 µm gap
I_{bias} = 62 DAC
I_{biasn} = 100 DAC
I_{db} = 50 DAC
I_{reset} = 10 DAC
V_{shift} = 145 DAC
V_{casn} = 104 DAC
V_{psub} = -1.2 V
Strobe length = 0.6µs
T = 27°C

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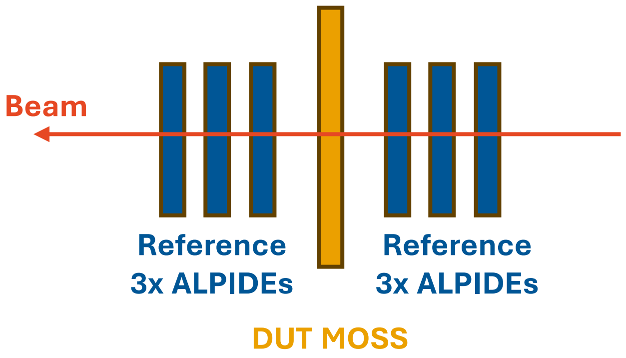

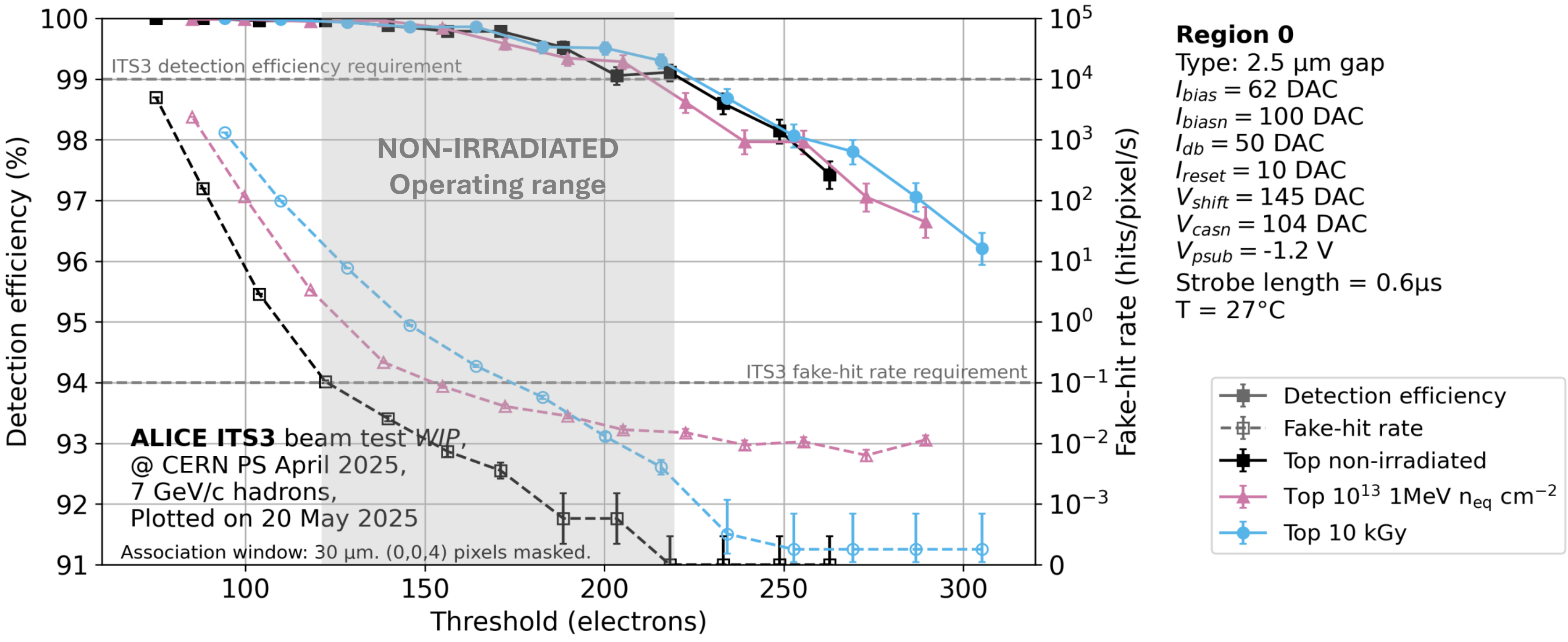

MOSS results

- Detailed characterisation in:
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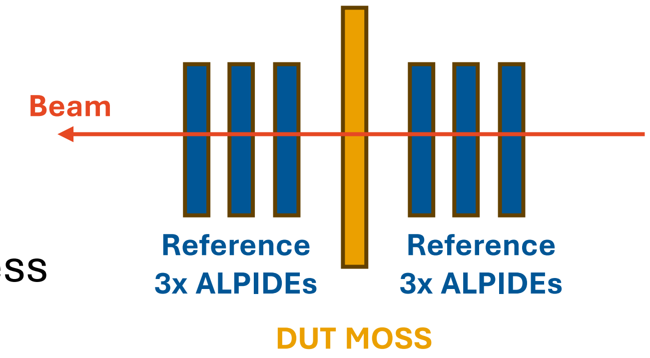
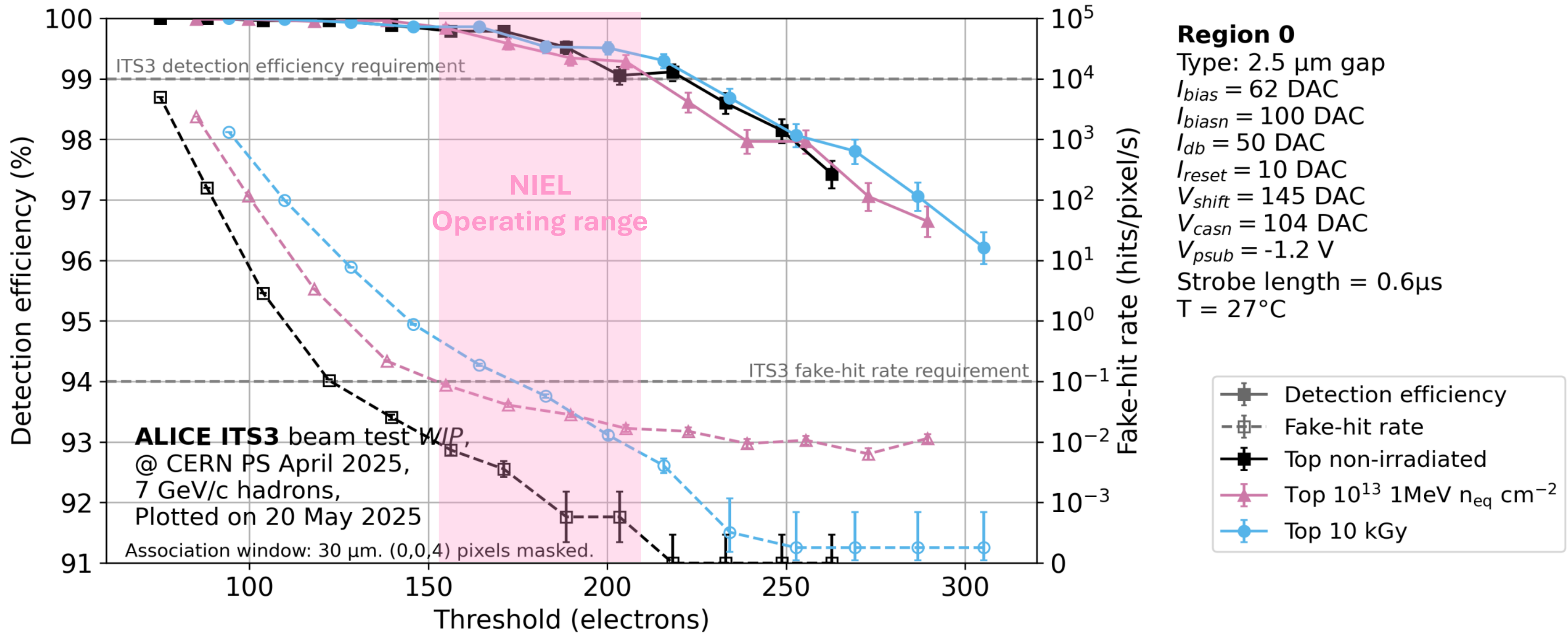
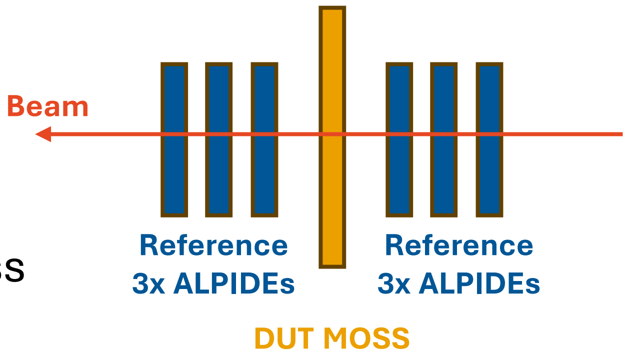
  - Non-Ionizing Energy Loss (**NIEL**) affects mainly the charge collection process

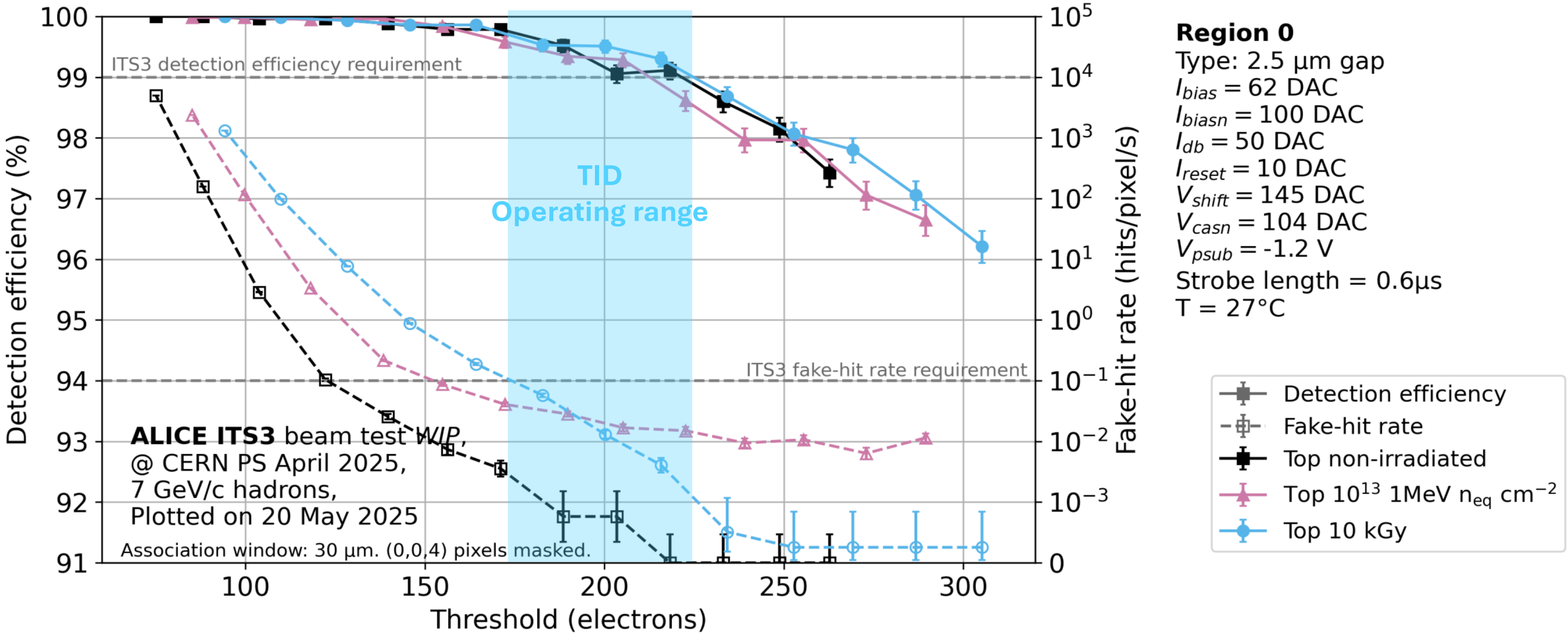




MOSS results

- Detailed characterisation in:
  - Laboratory → functional yield higher than **98%**
  - Several tests beam at CERN PS and SPS beam lines
  - Non-Ionizing Energy Loss (**NIEL**) affects mainly the charge collection process
  - Total Ionizing Dose (**TID**) radiation affects the in-pixel front-end

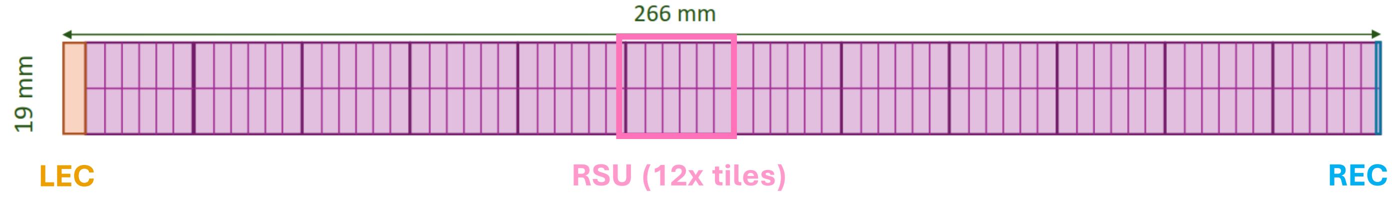


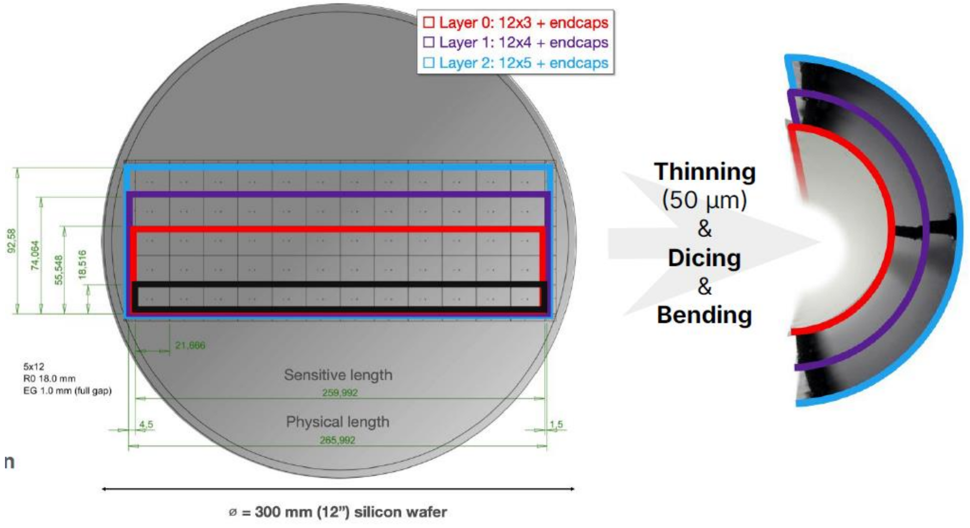


MOSAIX -full functionality prototype ITS3 sensor

ENGINEERING RUN 2 (submitted in July 2025)

- **MO**nolithic **S**titched **A**ctive p**IX**el: incorporate learnings from MLR1, MOSS and MOST testing
- **Modular design**: each sensor is divided into 3, 4, or 5 segments with 12 RSUs
- Pixel pitch: **20.8 x 22.8 μm^2** (9.97 M pixels in 1 segment)
- **Stitched metal lines** carry both power and data
- Sensitive area fraction: **93%**
- Several variants of analog front-end for optimization studies





Outlook…

- **CHARACTERIZATION OF ER2 MOSAIX CHIPS** – starting from Dec 2025
- **QUALIFICATION MODELS (QMs)**
  - Fully integrated, final-grade assemblies including MOSAIX sensors (+ mechanics, cooling, slow control, powering, readout…)
  - Goals: test half-detector performance and serve as reference system for Run 4
- **ENGINEERING RUN 3** – final sensor production (2026)
- **ITS3 INSTALLATION** in 2028 for Run 4

…and conclusions

ITS3 activities progressing on schedule:

- Bent MAPS: operability proven
- 65 nm CMOS process: validated
- Large-area sensors: qualification being finalized
- Mechanical & thermal: validated

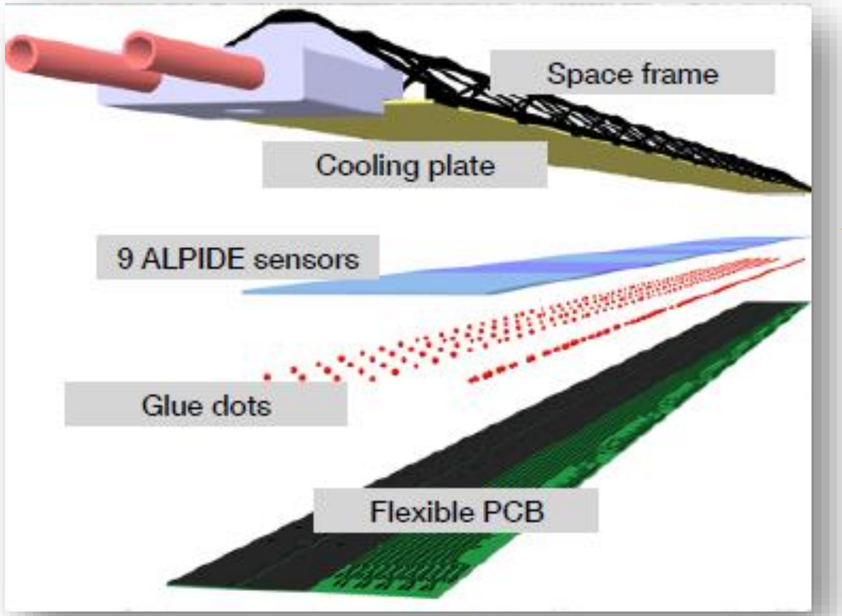
ITS3 technology will seed the new ALICE3 tracker, proposed for LHC Run 5

(see D. Colella talk "ALICE upgrades for LHC Run 4 and beyond ")

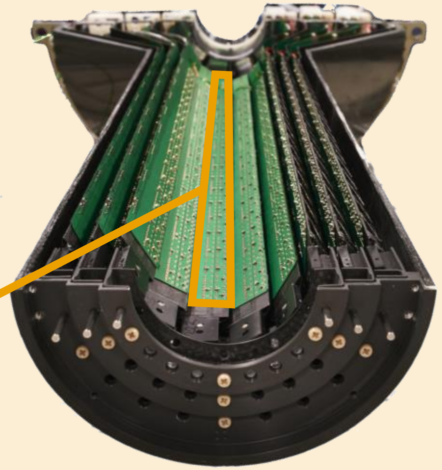
Thank you!

Backup slides

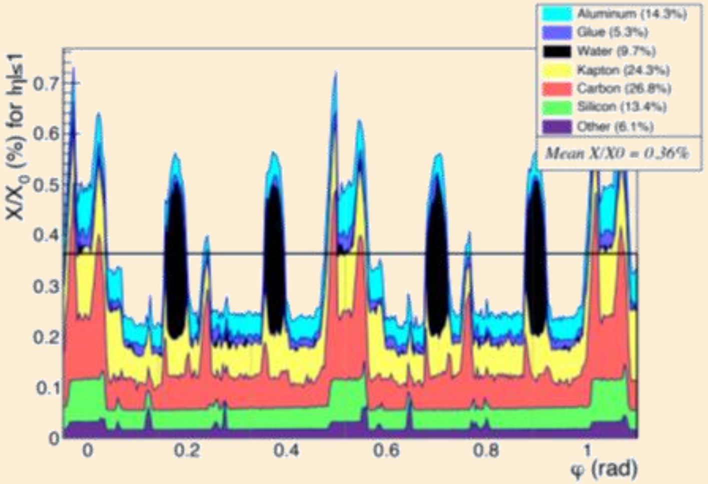
From ITS2 to ITS3



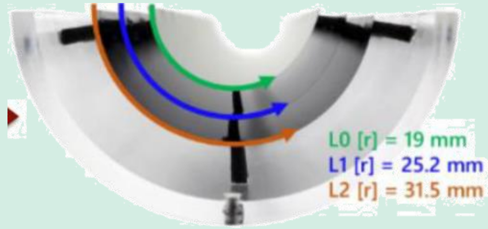
Innermost half-layer: 54 sensors replaced by 1!



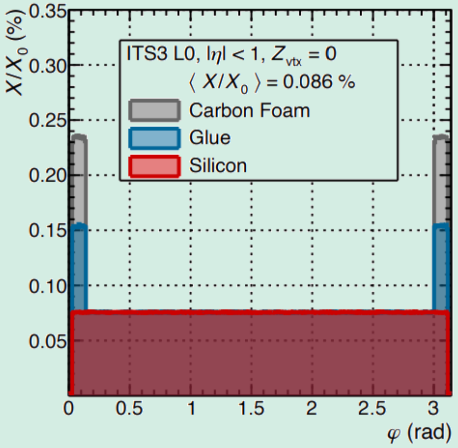
ITS2 Inner half-barrel



ITS2 Layer 0



ITS3



ITS3 Layer 0

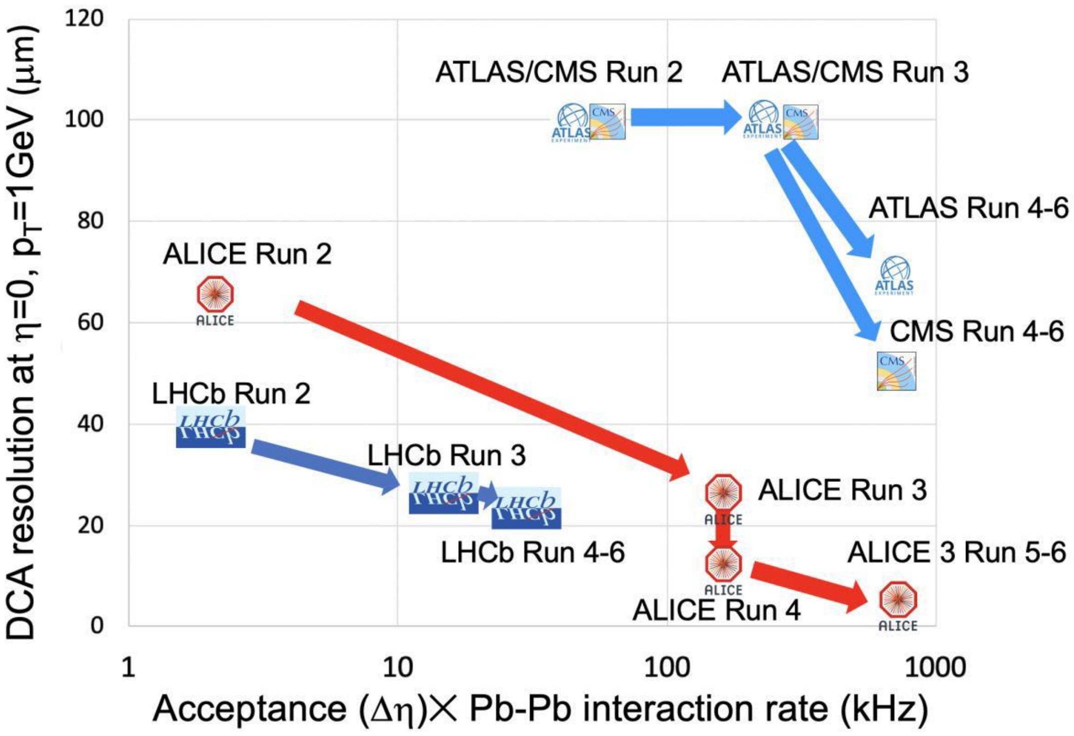
ITS3 Physics Motivations

ALICE 2 → ALICE 2.1

- Impact parameter resolution reduced by a factor of ~2 in low p_T region
- Tracking efficiency up to more than 30% higher, in low p_T region

Most striking improvements in the study of:

- Low momentum charm and beauty hadrons
- Low-mass dielectrons
- Beauty baryons
- Beauty-stange mesons
- Charm strange and multi-strange baryons
- Light charm hypernuclei



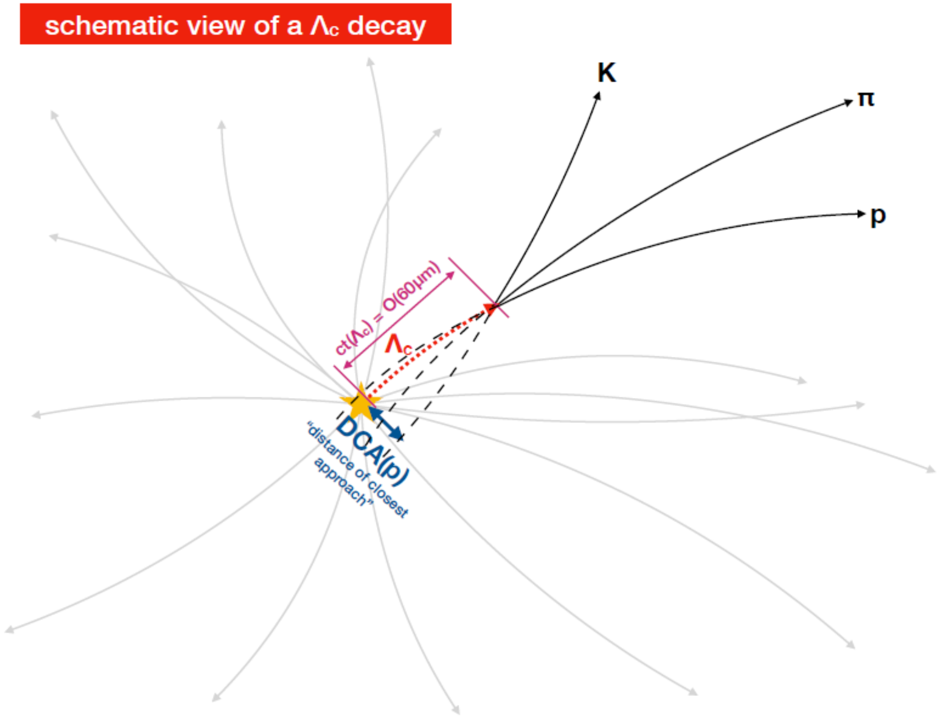
Measurement of Lamba-c (Λc)

In heavy-ion collisions the production of charm and beauty baryons is expected to be significantly enhanced:

- recombination with light-flavour quarks present inside QGP
- hadron-mass-dependent radial collective flow

However current results have limited statistical precision!

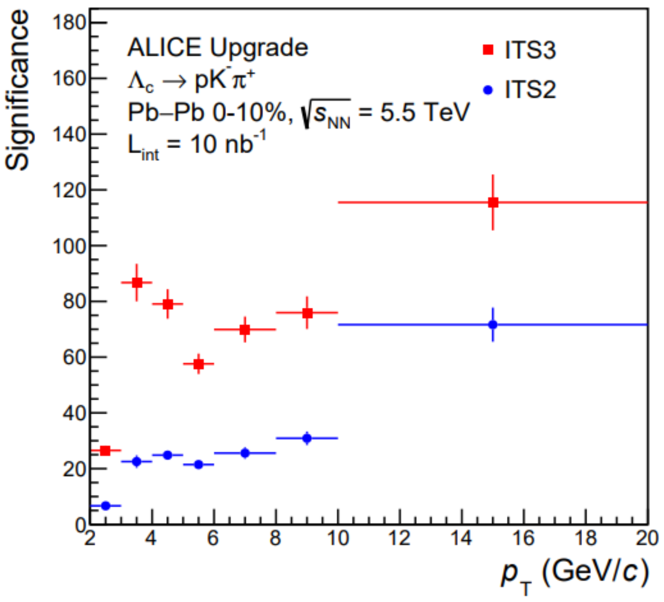
The measurement requires very precise tracking and impact parameter resolution

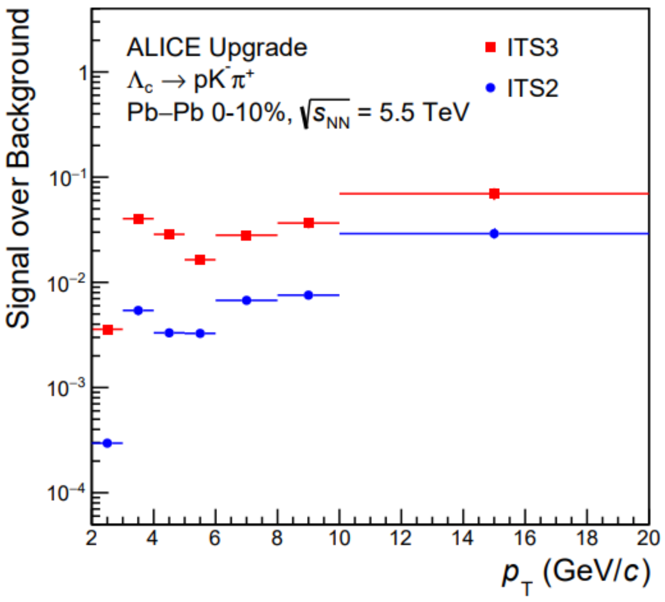


Measurement of Lamba-c (Λc)

Large improvement (wrt ITS2) of significance (factor 4) and S/B ratio (10), thanks to:

- better pointing resolutions → larger rejection of the combinatorial background
- larger efficiency for the signal selection





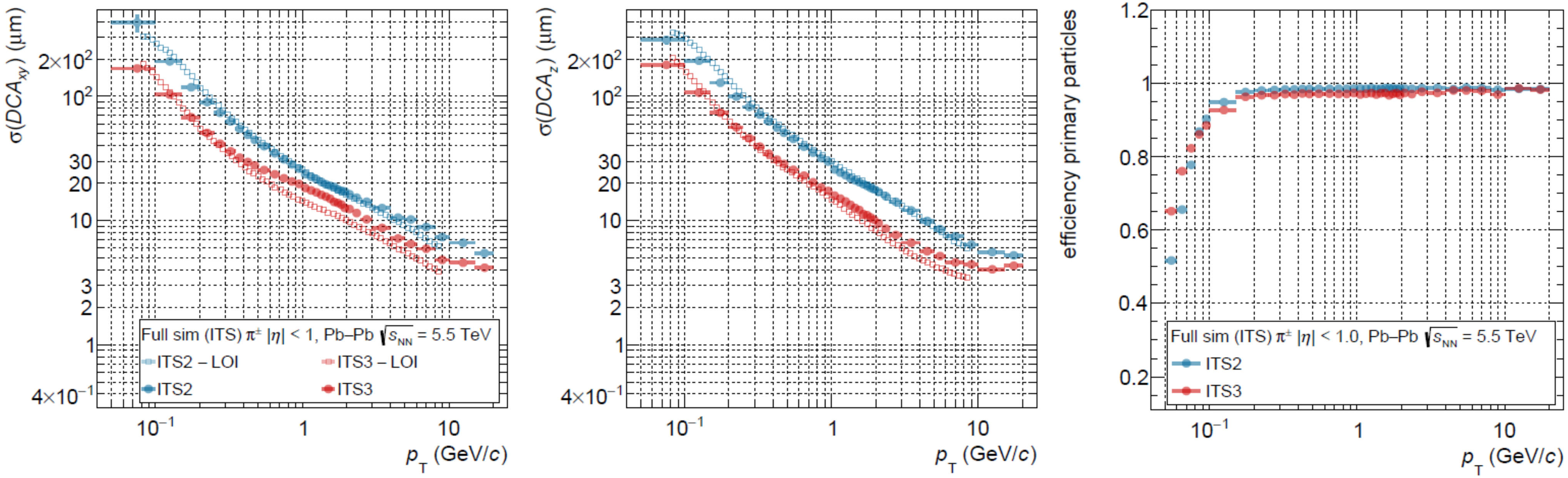
Precise measurement of Λc/D ratio at low p_T

- Λc production → total cc cross section

BENCHMARK FOR ITS3

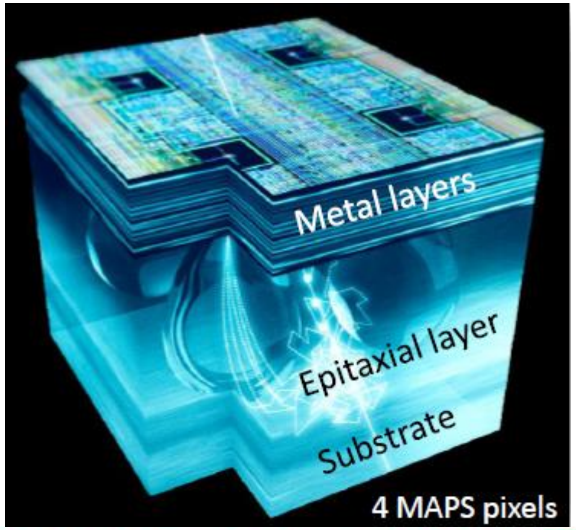
ITS3 Performance from simulations

Large improvement for low transverse momenta



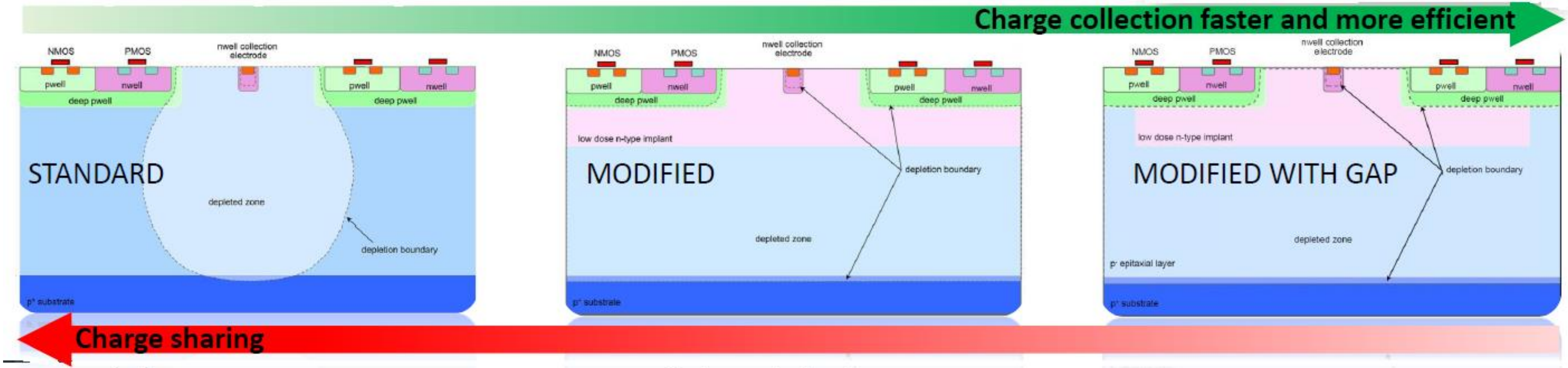
The 65 nm CMOS technology

- Tower Partners Semiconductor Co. (TPSCo) 65 nm CMOS imaging process for Monolithic Active Pixel Sensors (MAPS)
- Chosen for ALICE ITS3 detector and under study by the CERN EP R&D on monolithic pixel sensors



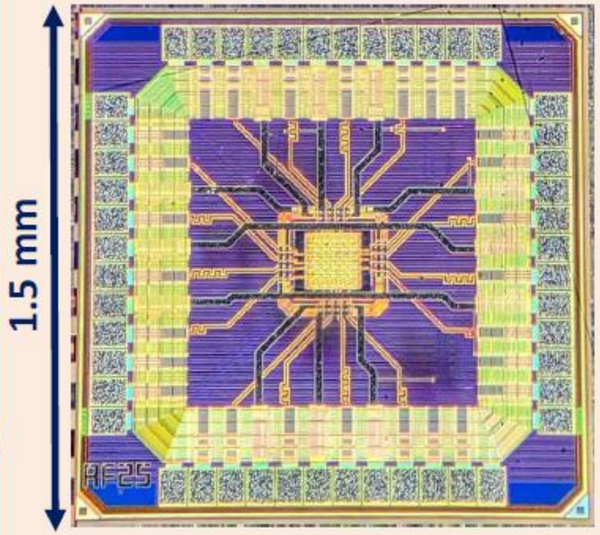
Key advantages:

- High radiation hardness
- Low power consumption
- 5 µm 2D spatial resolution
- Large wafers (Ø 300 mm)



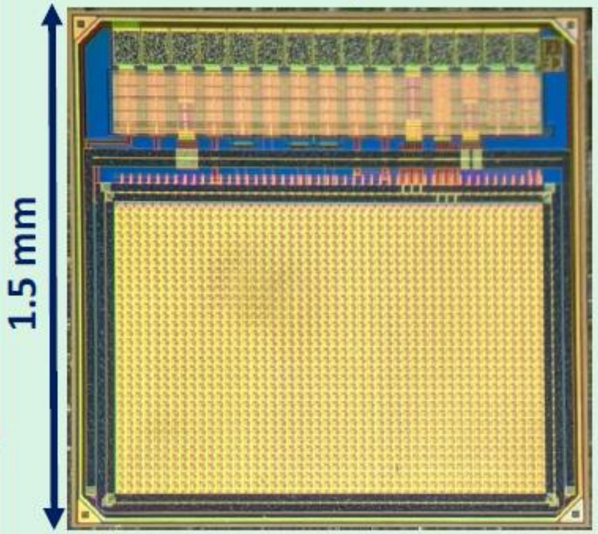
MLR1 sensor prototypes

APTS: Analog Pixel Test Structure



- 6×6 pixel matrix
- Pitch: 10, 15, 20, 25 µm
- Analogue readout of central 4×4 submatrix
- Output buffer in two versions: Source Follower (SF) and Op Amp (OA)
- **Goal**: explore pixel designs

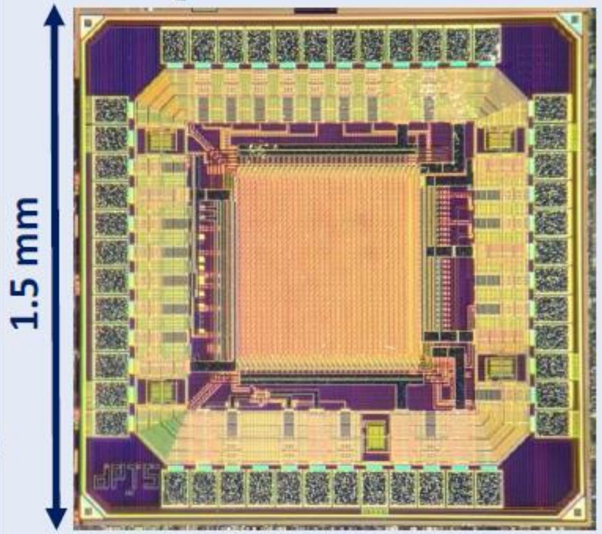
CE65: Circuit Exploratoire 65



- 64×32 pixel matrix, 15 µm pitch (3 subvariants: AC, DC and SF)
- 48×32 pixel matrix, 25 µm pitch
- Rolling shutter readout (50 µs integration time)

- **Goal**: explore pixel matrix uniformity and rolling shutter

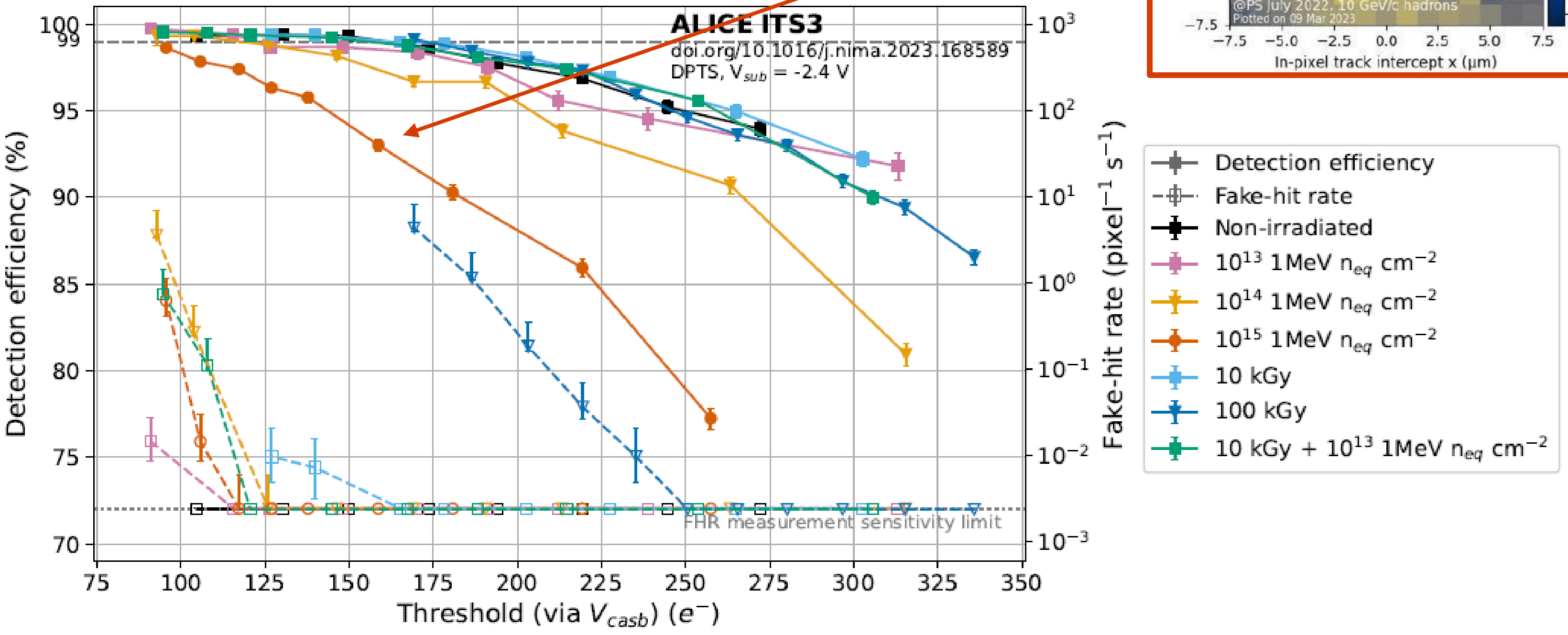
DPTS: Digital Pixel Test Structure

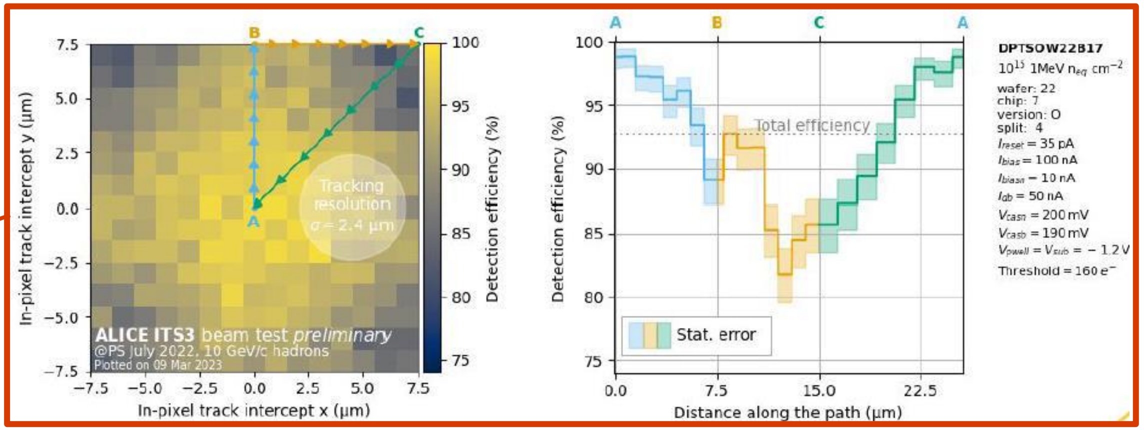


- 32×32 pixel matrix, 15 µm pitch
- Asynchronous digital readout
- Time-encoded pixel position
- Time-over-threshold measurements

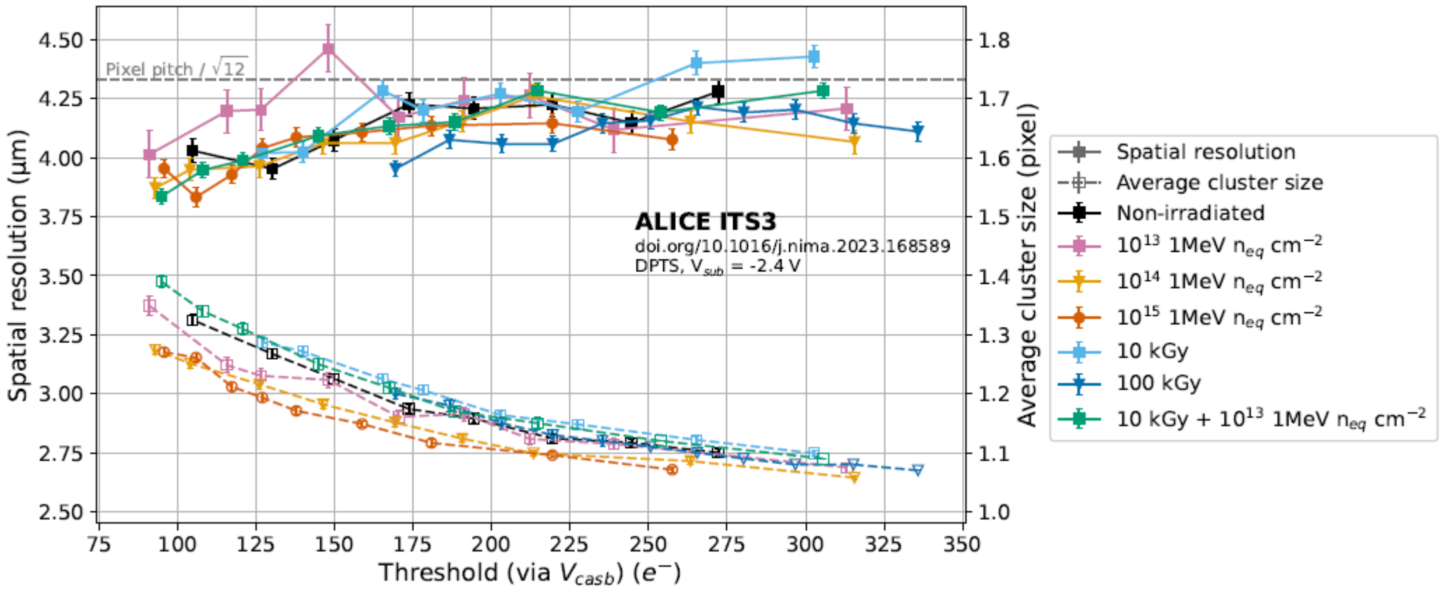
- **Goal**: study the in-pixel front-end

MLR1 – Radiation hardness





MLR1 – Spatial resolution

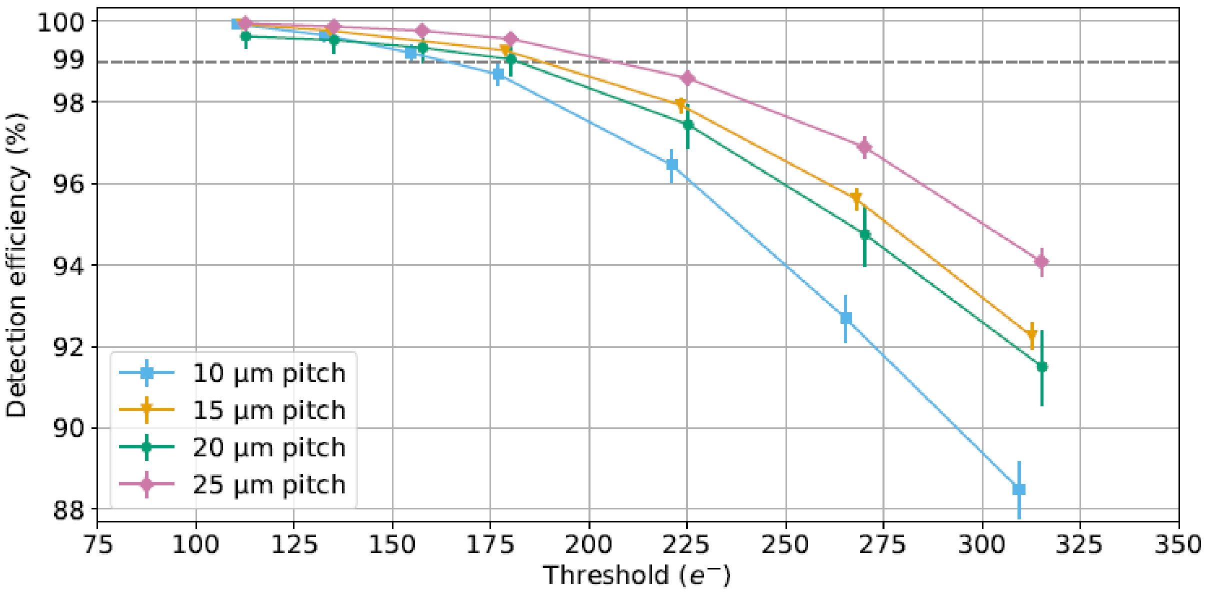


Spatial resolution and average cluster size Vs threshold and irradiation levels, as measured in testbeams on 15 μm pitch DPTS:

→ The spatial resolution measured slightly better than pixel pitch / √12 (no degradation with received dose)

→ Slight systematic decrease of average cluster size with the increasing non-ionising radiation dose

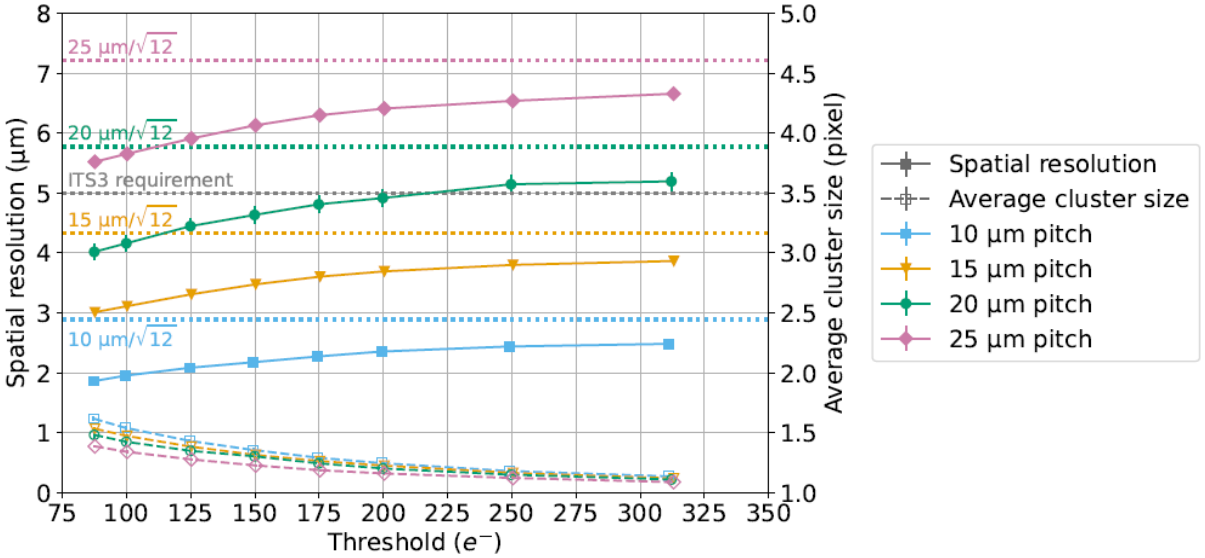
MLR1 – pixel pitch

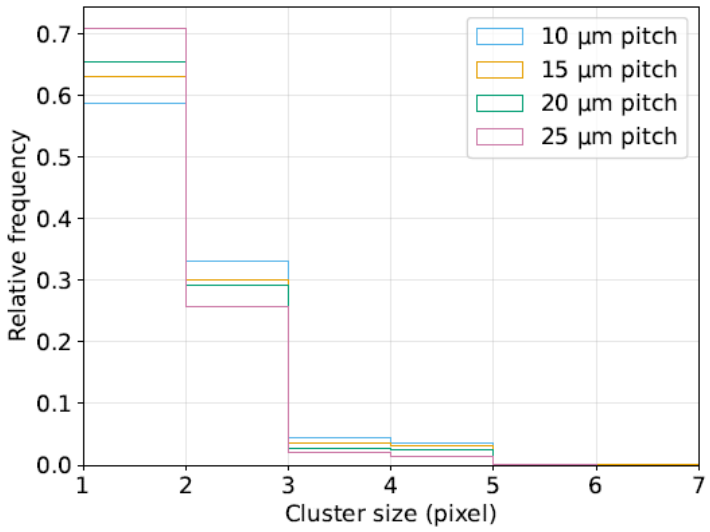


The detection efficiency increases with increasing pixel pitch

- Relative fraction of pixel border area decreasing with the increasing pixel pitch
- Pixel border only being less efficient due to geometrical sharing of the charge among neighboring pixels

MLR1 – pixel pitch

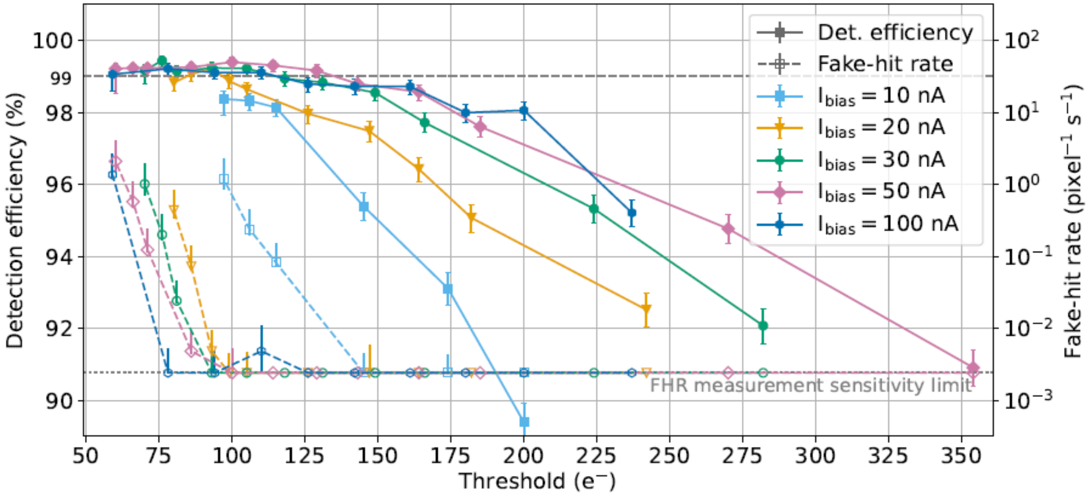




Spatial resolution and average cluster size VS threshold and pixel pitch, measured with APTS

- More charge sharing → improved resolution
- Considering the ITS3 target pitch size of 20.8 µm×22.8 µm, the expected spatial resolution is about **5 µm** for a threshold of 100 e^-
- For the ITS3 it is expected to have on average less than **1.5 pixels** above threshold for a minimum ionizing particle hit

MLR1 – Power consumption

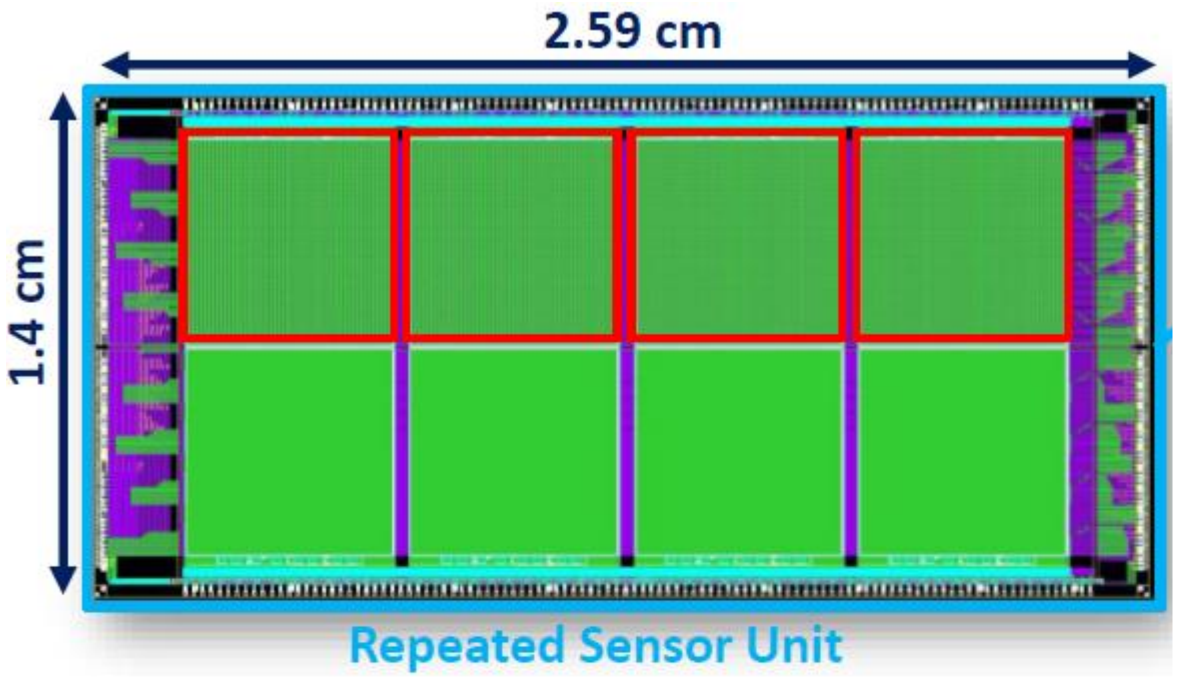


DPTS front end designed to investigate power consumption (ITS3 target < 40 mW/cm^2) :

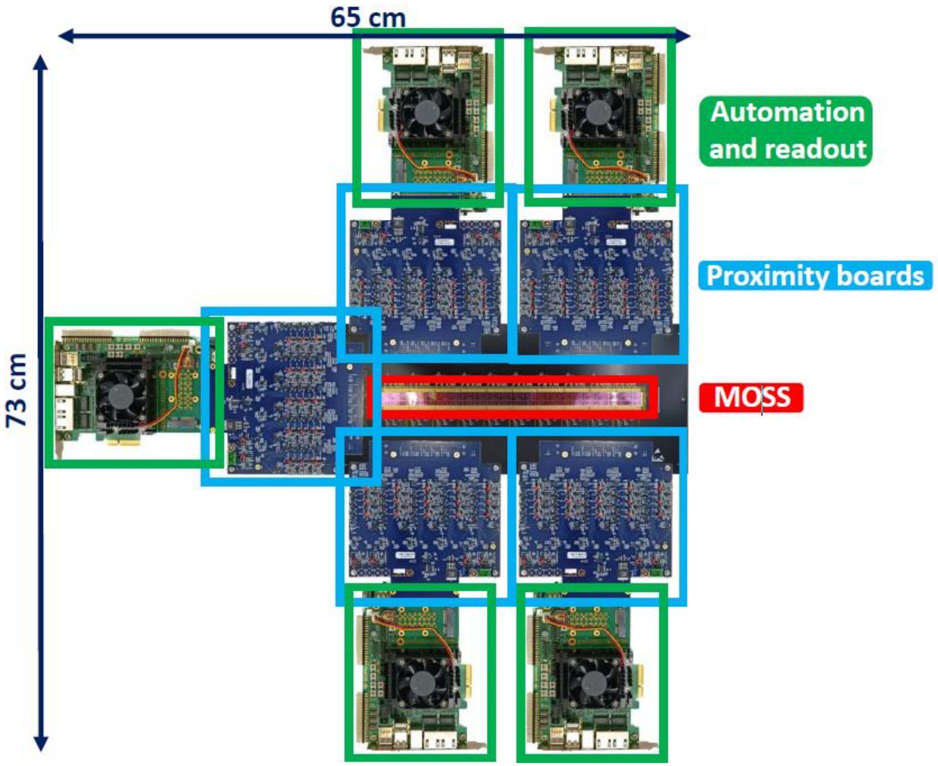
- At least a main current I_{bias} of 30 nA is needed
- 16 mW/cm^2 as measured on 15 μm pixel
- 7.6 mW/cm^2 if projected to the final ITS3 sensor pixel pitch

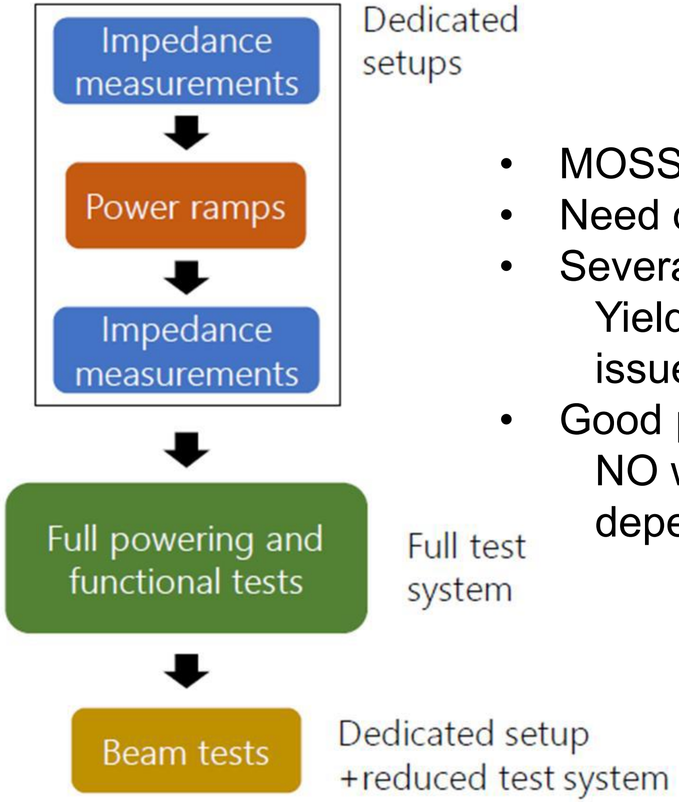
MOSS structure

- 10 Repeated Sensor Units (RSU)
  - 2 Half Units (HU) with 4 regions (each with different electronics)
  - TOP regions: 256 x 256 pixels, 22.5 μm pitch
  - BOTTOM regions: 320 x 320 pixels, 18 μm pitch



MOSS tests

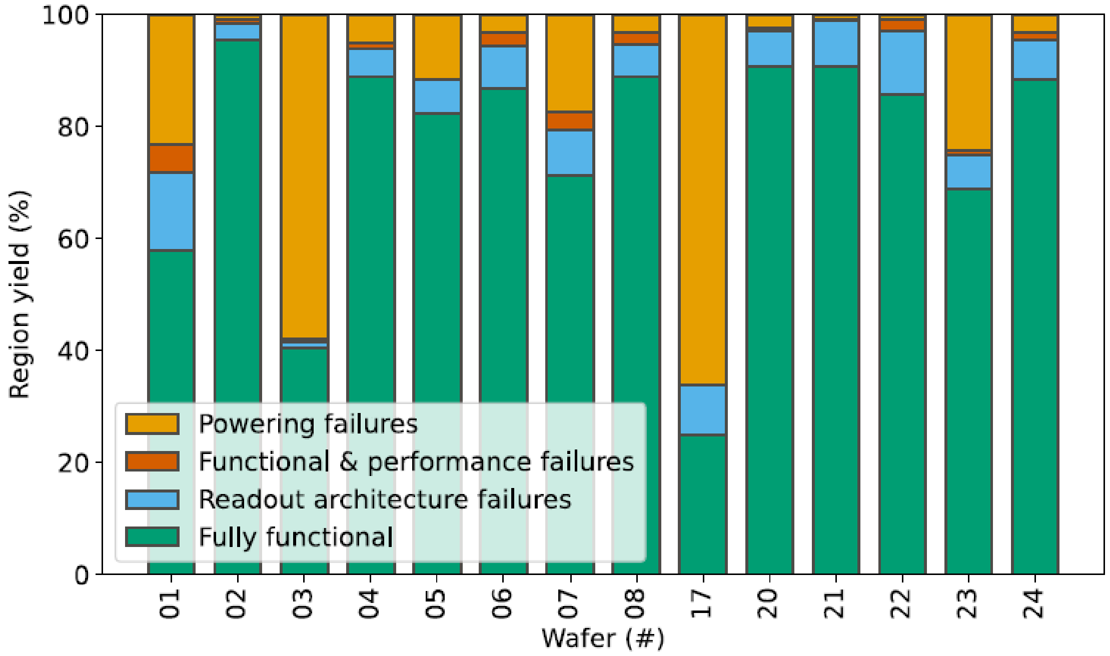


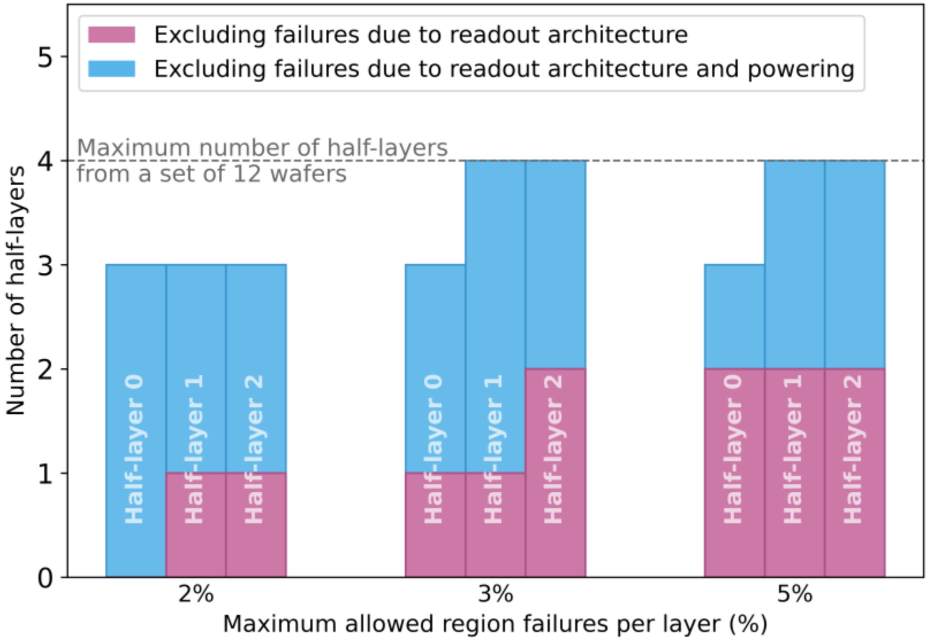


- MOSS: 2200 bonds!
- Need dedicated large-scale test setup
- Several functional tests on all 82 MOSS
  Yield ~89 % (~98% excluding readout issues)
- Good performance and uniform behavior
  NO wafer or sensor position dependence

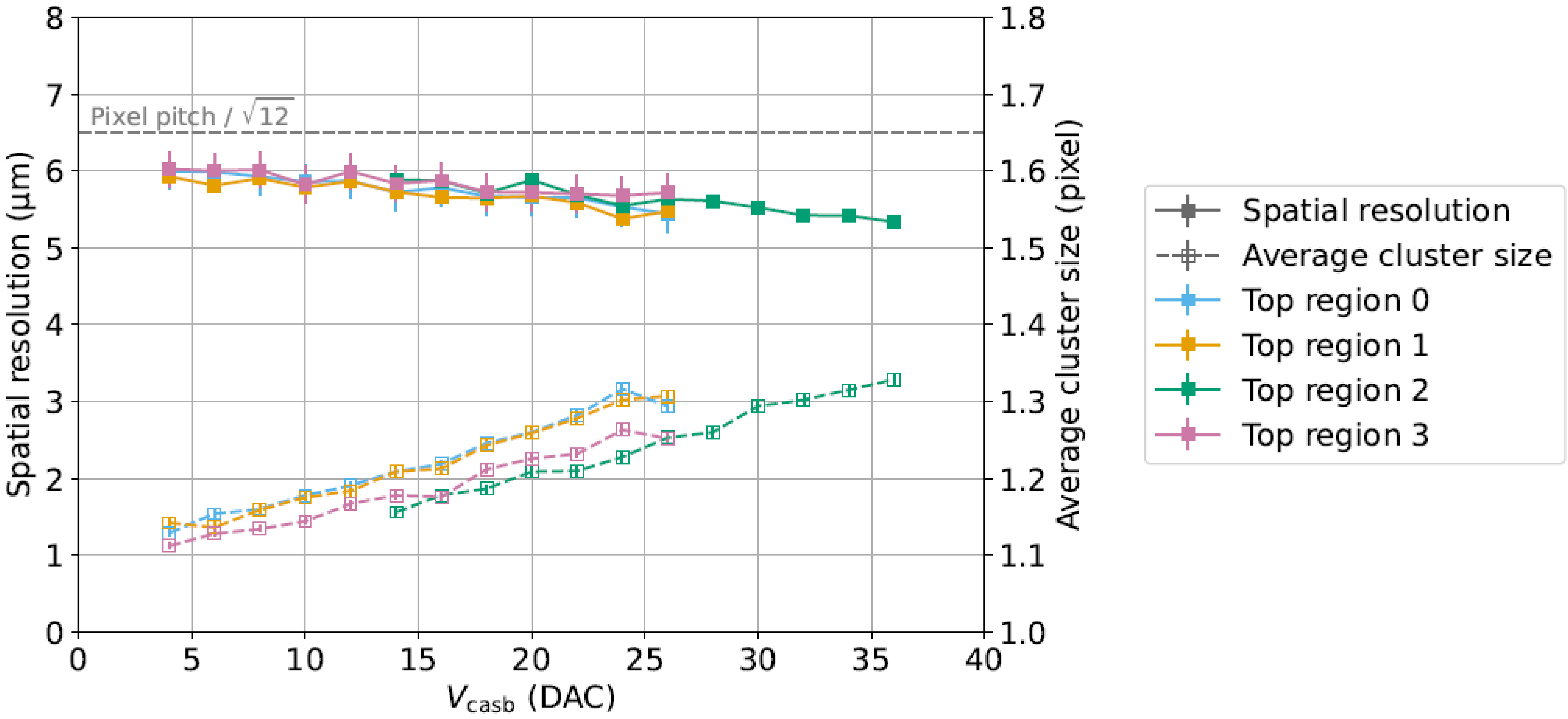
MOSS tests - Yield

Wafer-to-wafer variations





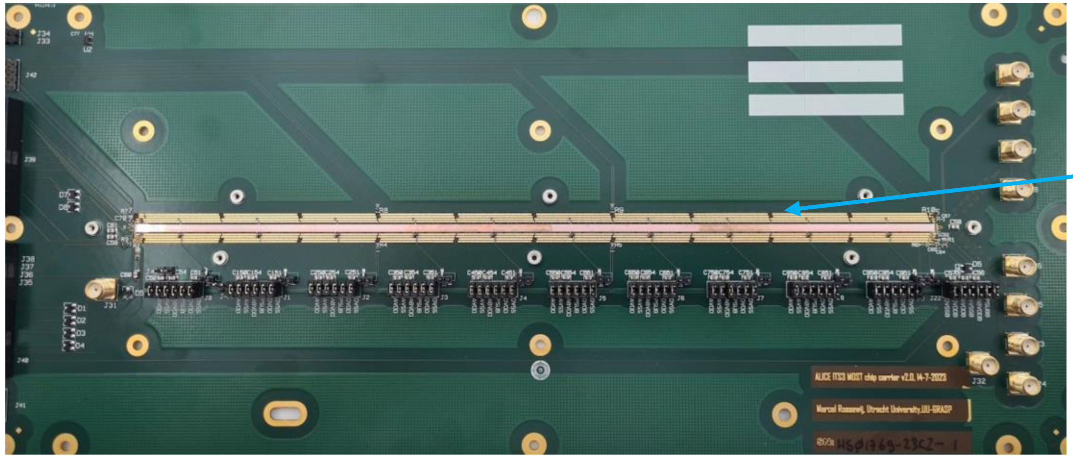
MOSS tests – spatial resolution

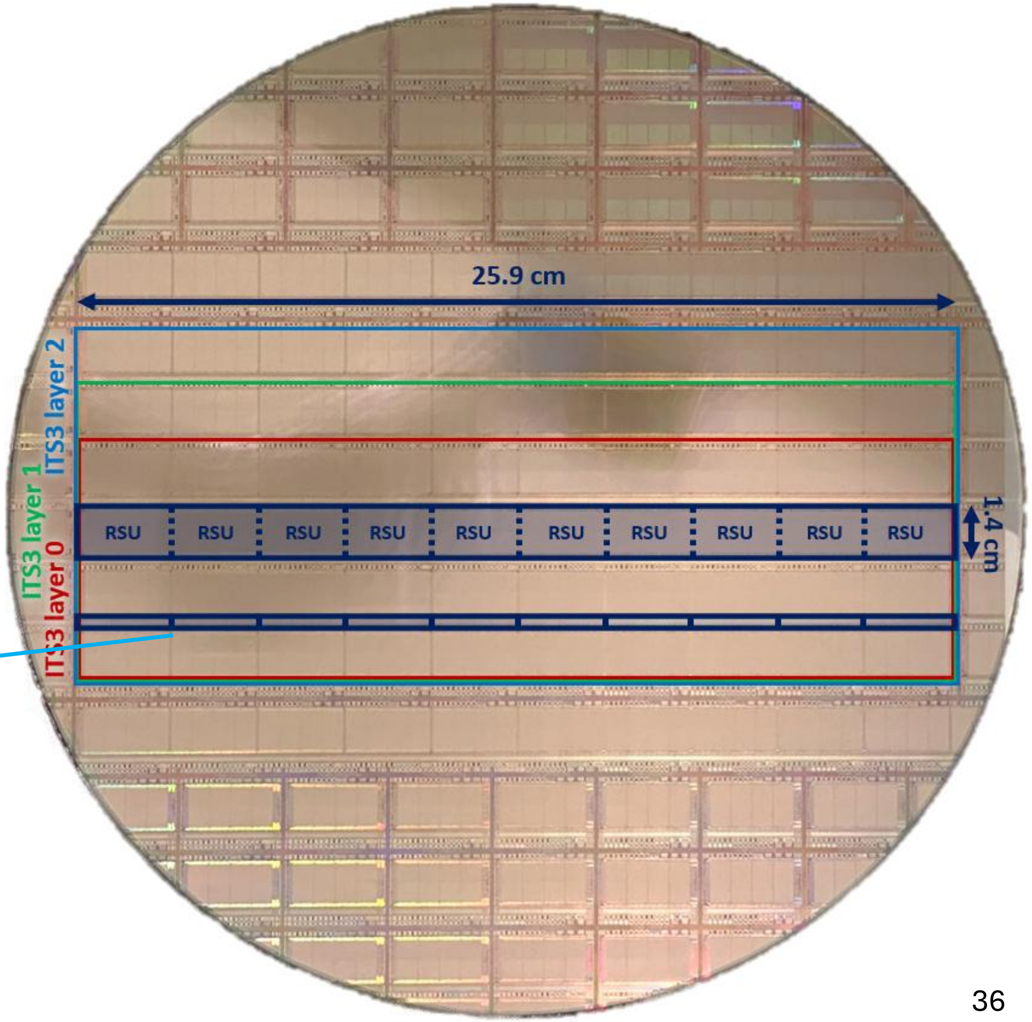


MOST tests

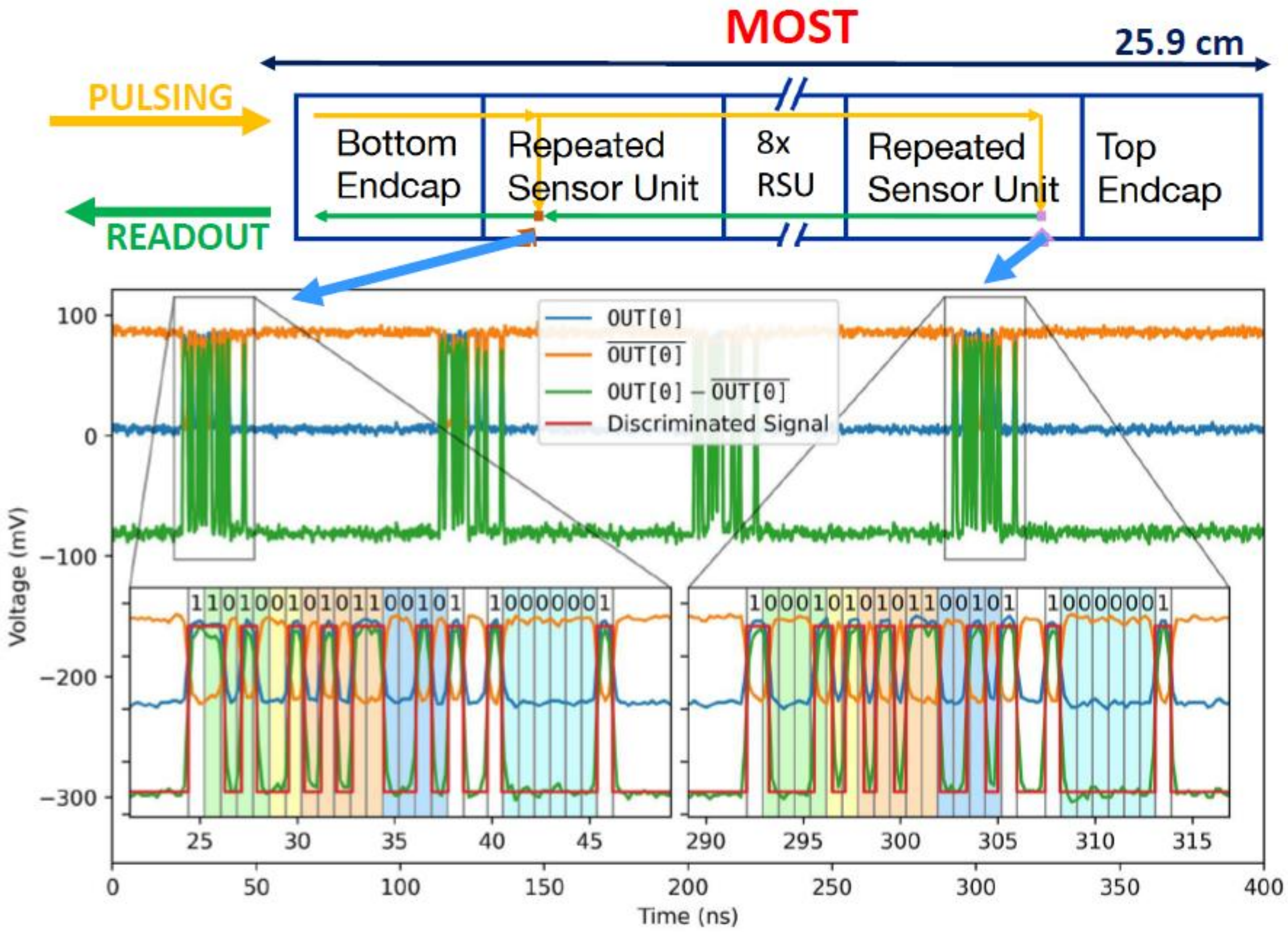
MOnolithic **S**titched sensor with **T**iming (**MOST**)

- Denser layout and power segmentation
- 25.9 × 0.25 cm^2
- 0.9 million pixels, 18 µm pitch
- Aimed at testing the transmission quality of high-speed data over the full length of the ITS3





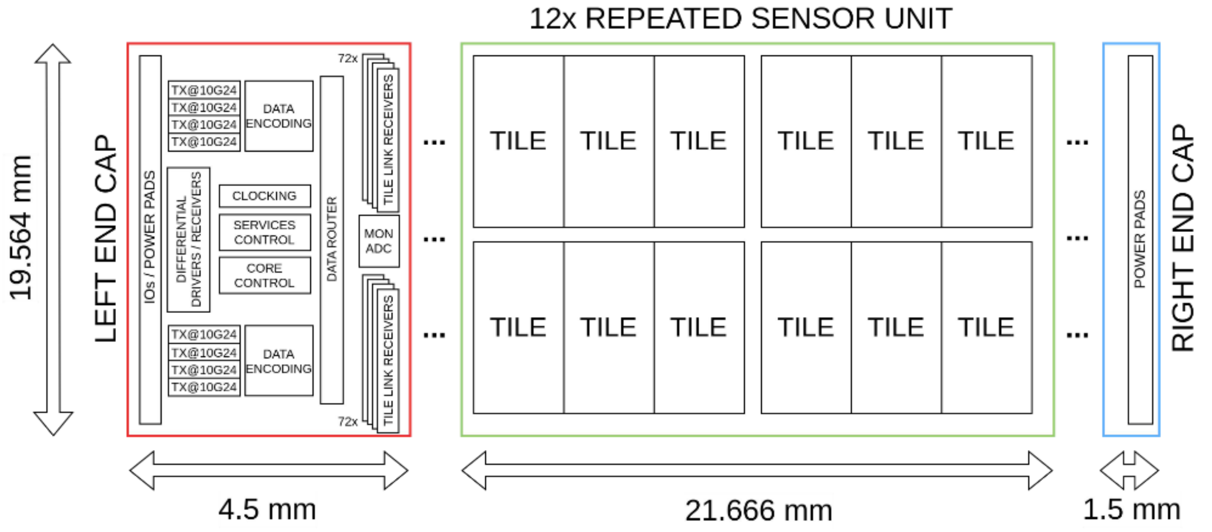
MOST tests



Test of the **data transmission across the full length**

- Pulsing and readout of different MOST RSUs
- Data transmission verified:
  1)1 Gbit/s
  2) over 25.9 cm
  3) across 10 stitched RSU

MOSAIX architecture details



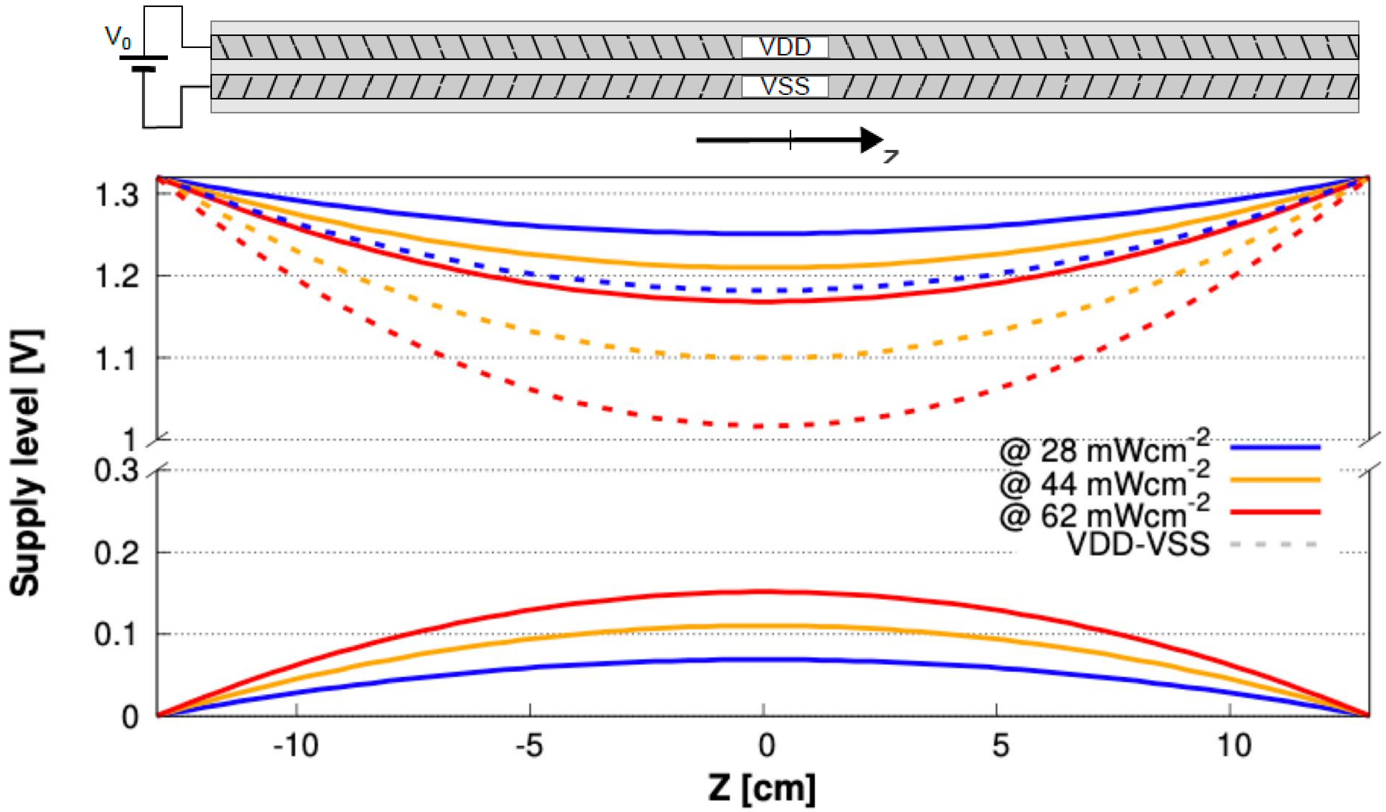
LEC:
- power pads
- data/control I/O
- 8 x 10.24 Gb/s serializers
- on -chip ADC for monitoring

12 RSUs:
- pixel matrix: 12 tiles , individually powered and read-out
- 12 variants of analog front front-end (1 per tile) for optimization studies
- Independent operation improves reliability and yields

REC:
- power pads (for supply redundancy)

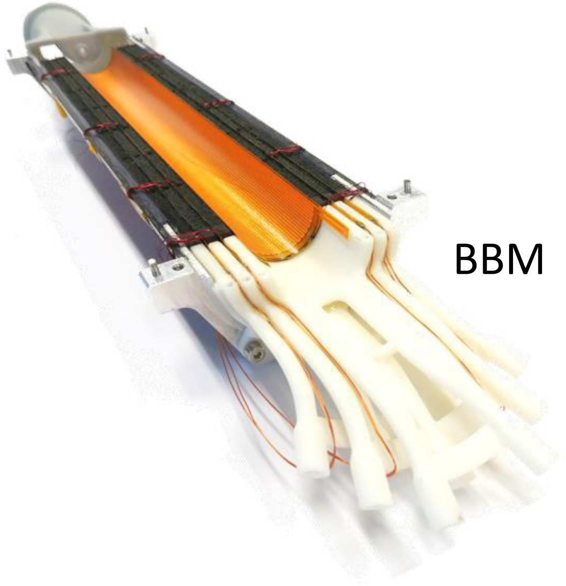
MOSAIX powering challenges

Challenges:
- ➢ Voltage drops on the on-chip metals of the CMOS stack significant
- ➢ Complex segmentation in many independent domains (tiles)

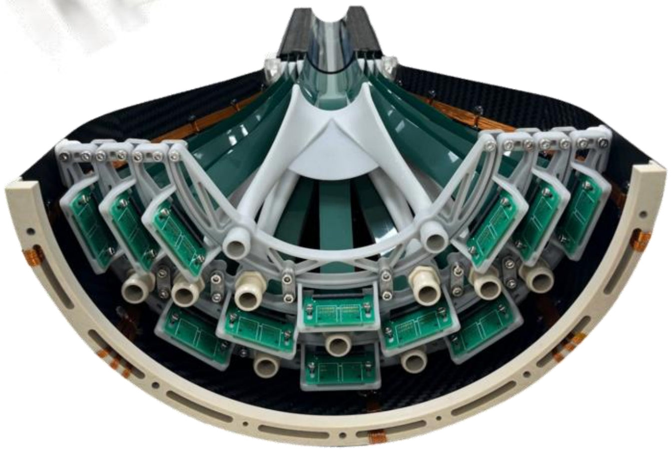


Development strategy

- **BreadBoard Models (BBMs)**
  - Initial prototypes representing selected features of the final design
- **Engineering Models (EMs)**
  - Used for design development; composed of a mix of final-grade and commercial components
- **Qualification Models (QMs)**
  - Fully integrated, final-grade assemblies including MOSAIX sensors (final full functional prototype), used for qualification tests
- **Final Models (FMs)**
  - Two final half-detectors for installation, plus two spare half-detectors



BBM

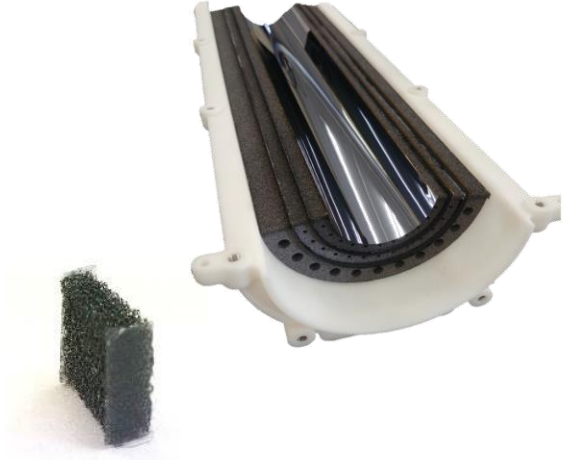


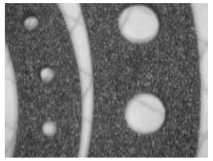
Full scale EM

Mechanics and cooling solutions

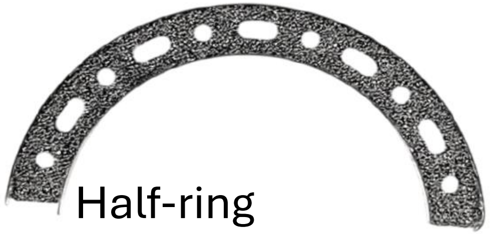
Ultra-light mechanics → material budget record
Carbon foam used as support and radiator:

- Carbon (RVC) Duocel® for mechanical support
- Allcomp K9 standard density as cooling radiator





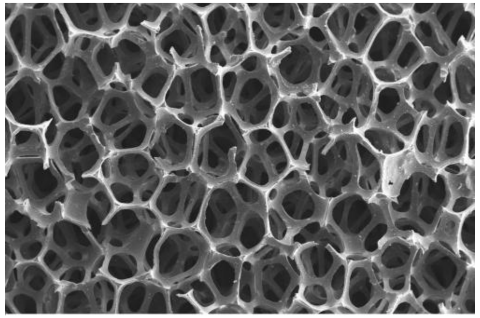
Longerons
(Allcomp K9 SD)



Half-ring
(ERG Duocel Carbon)

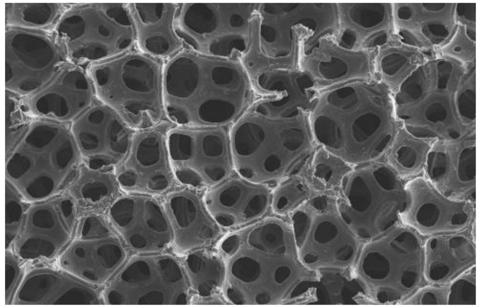
Half-ring
(Allcomp K9 SD)

ERG Carbon @Duocel
ρ = 0.045 kg/dm^3
k = 0.033 W/m·K



Support

K9 Standard Density
ρ = 0.2-0.26 kg/dm^3
k = >17 W/m·K

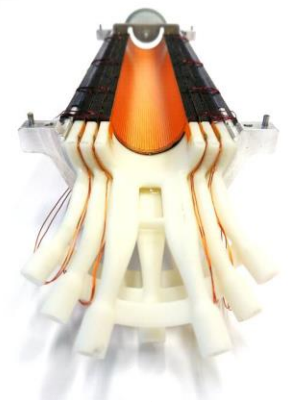


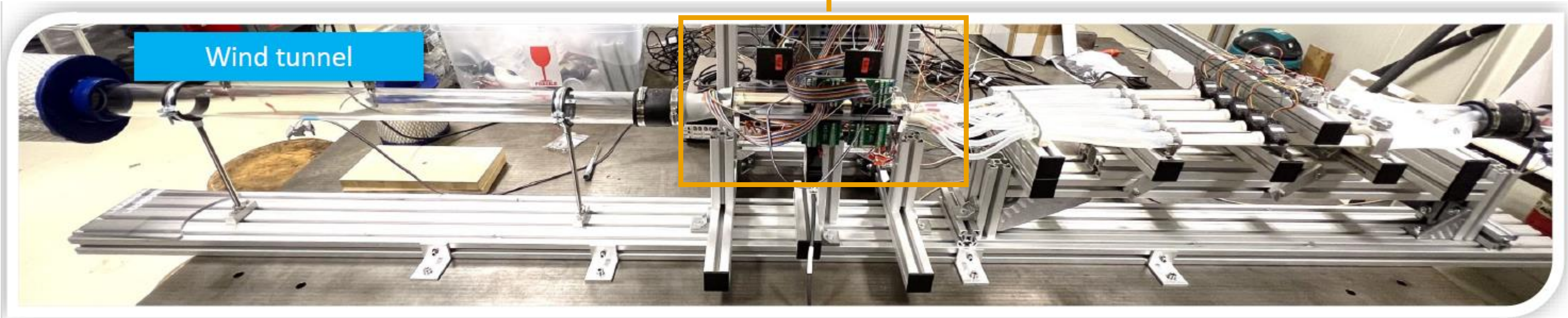
Support & Cooling

Wind tunnel: cooling test

ITS3 Breadboard Model 3 for thermal characterisation

- Copper heating traces on silicon in polyimide
- Temperature variation can be kept <5K

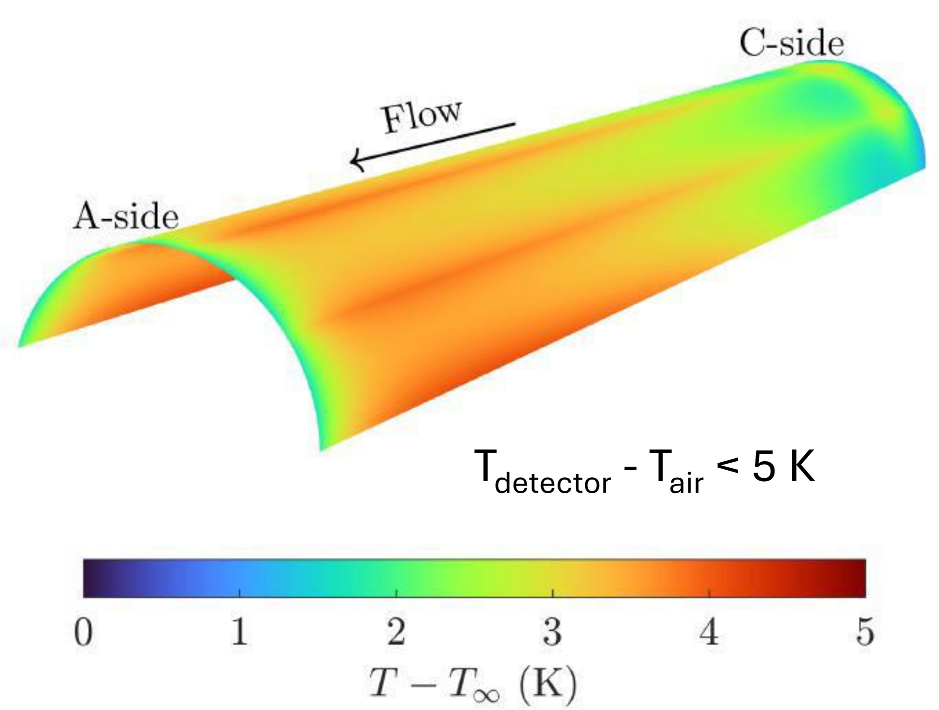


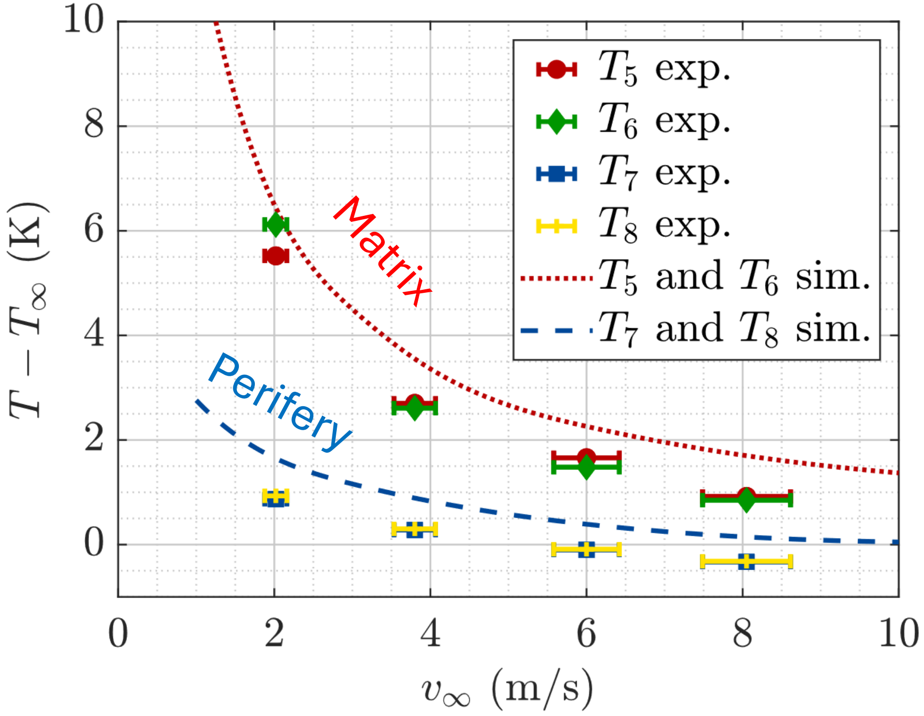


Wind tunnel: cooling test

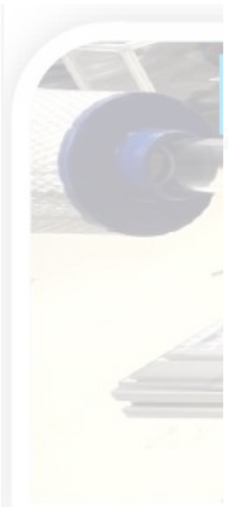
ITS3 Breadboard characterisation

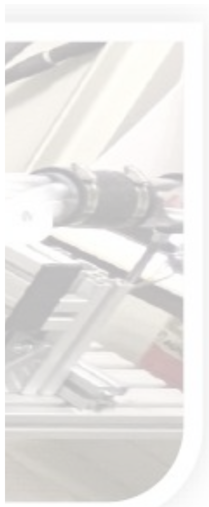
- Copper heatir... polyimide
- Temperature ...





Cooling 25 mW/cm^2

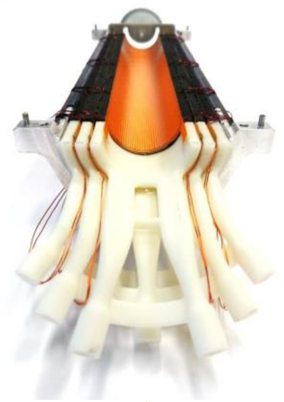




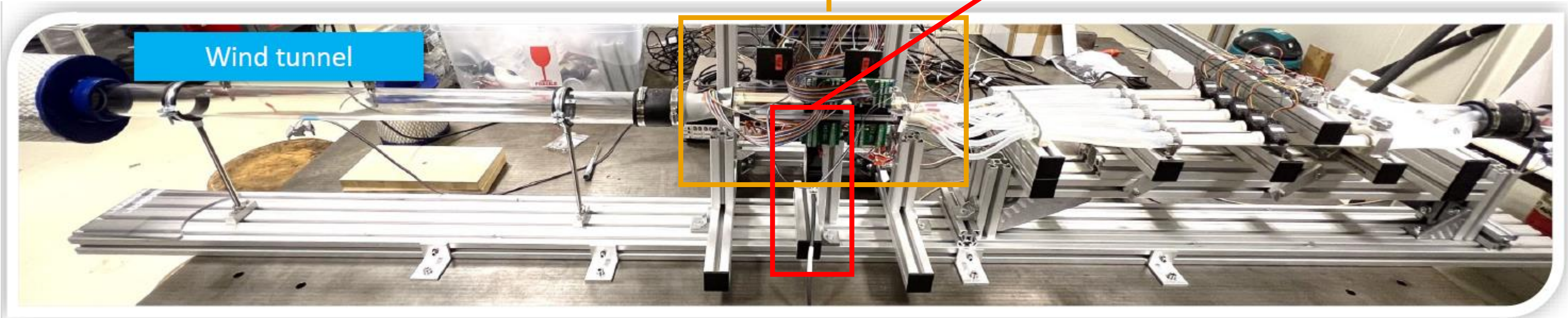
Wind tunnel: cooling test

ITS3 Breadboard Model 3 for thermal characterisation

- Copper heating traces on silicon in polyimide
- Temperature variation can be kept <5K

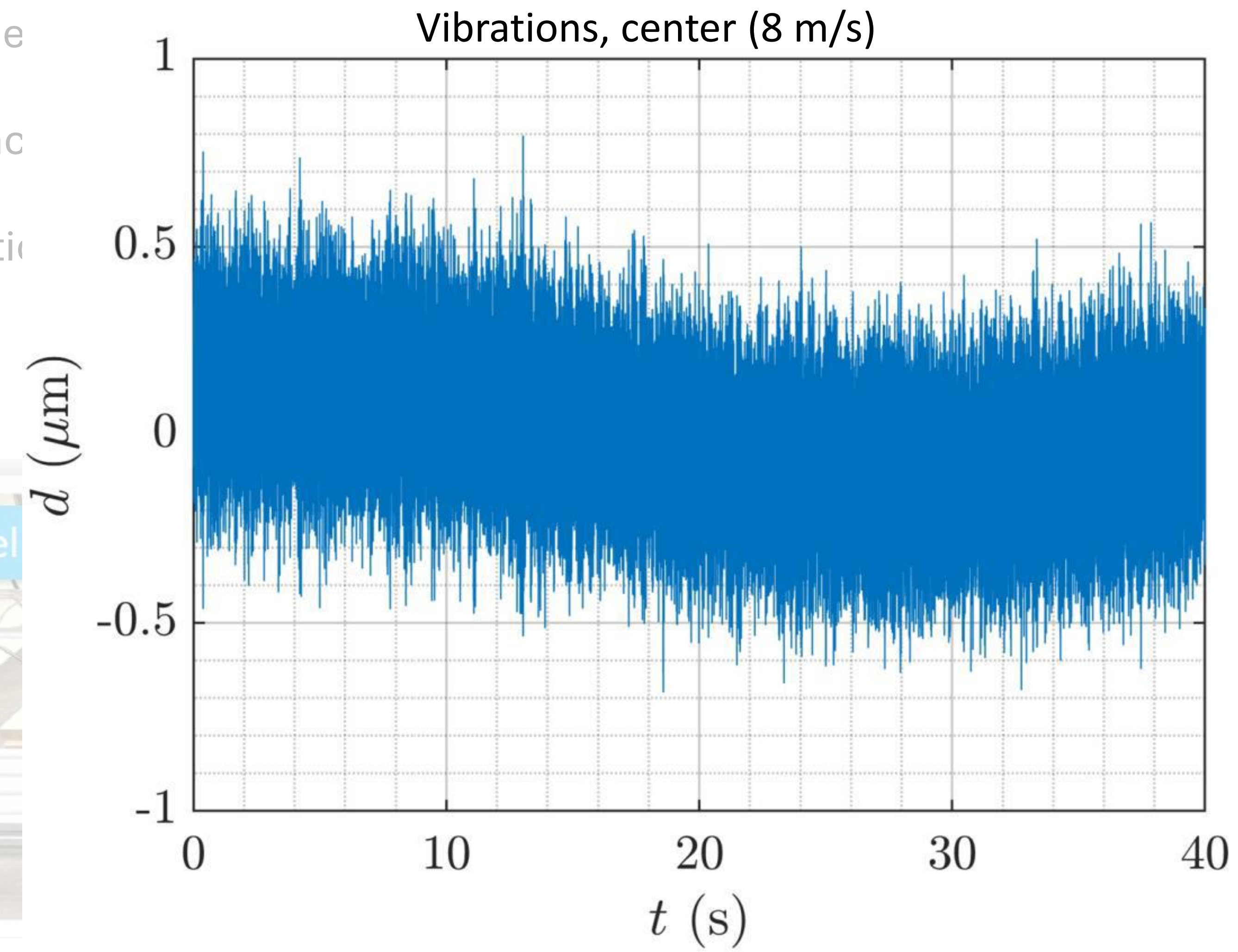


- Laser measurement machine for vibration analysis

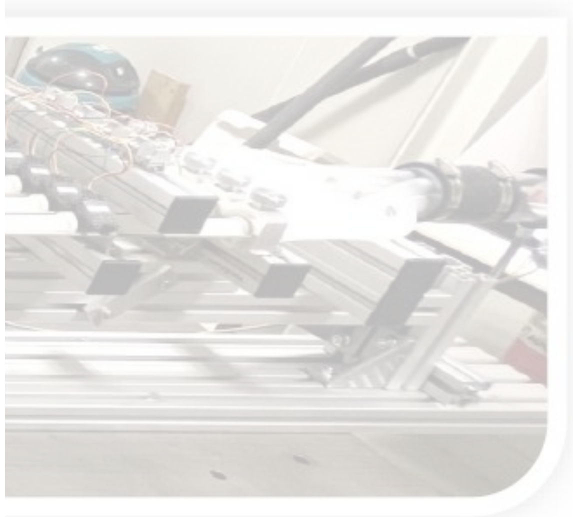


Wind tunnel: cooling test

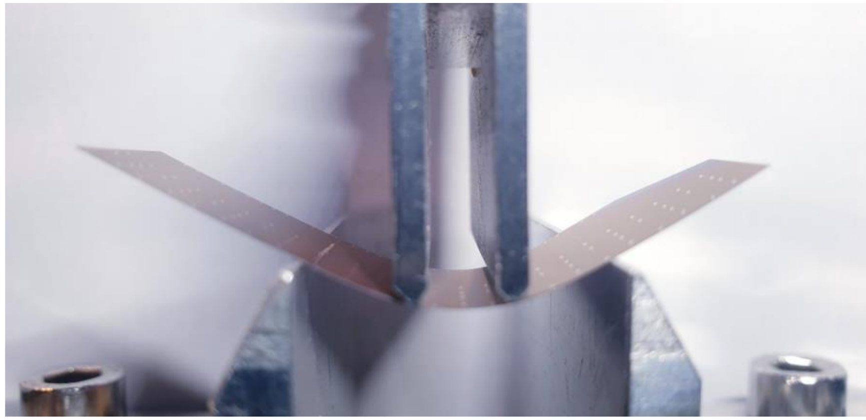
ITS3 Breadboard Mode
characterisation
- Copper heating trac
polyimide
- Temperature variati

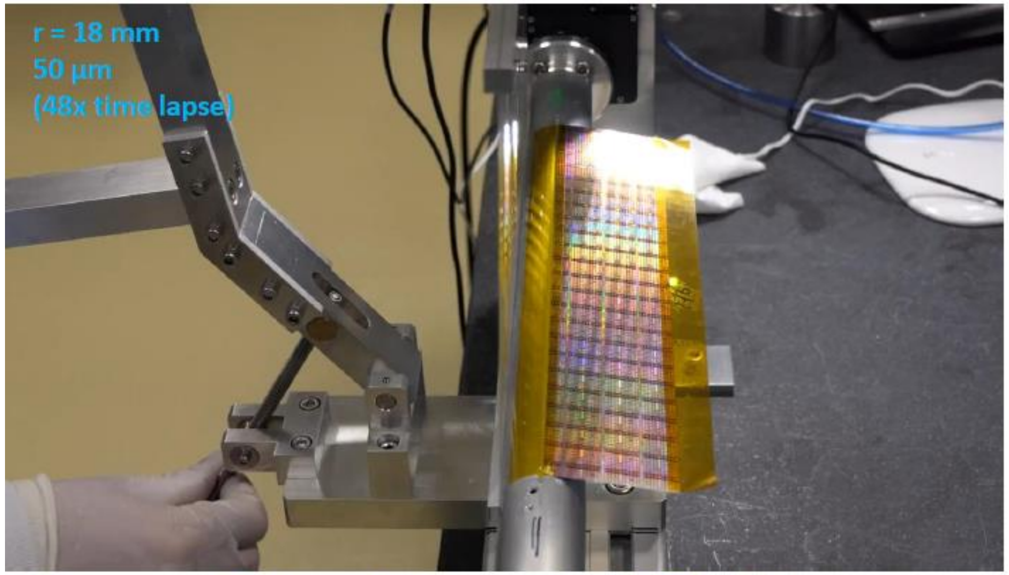


Laser measurement machine for vibration analysis

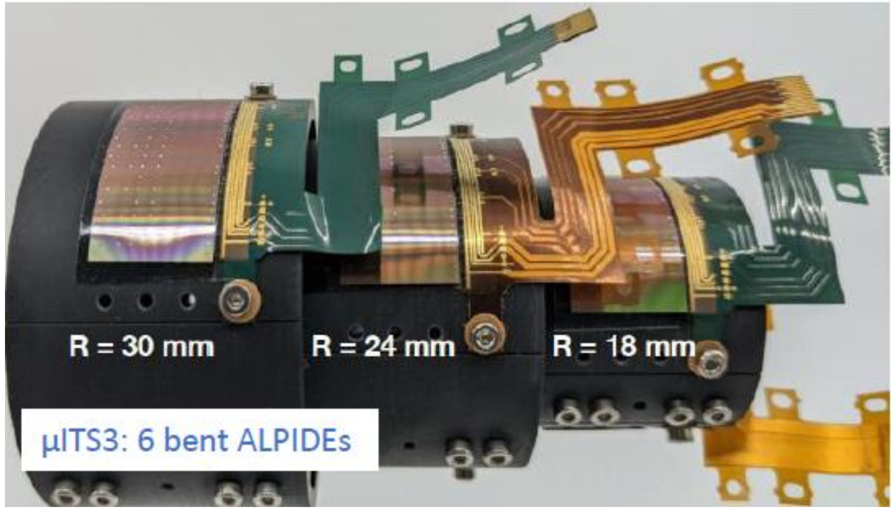


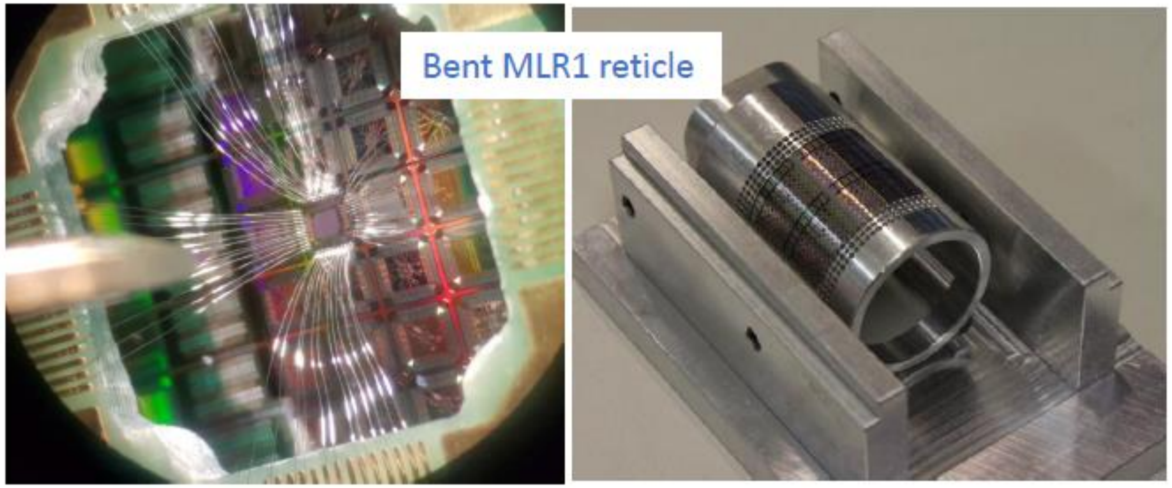
Bending



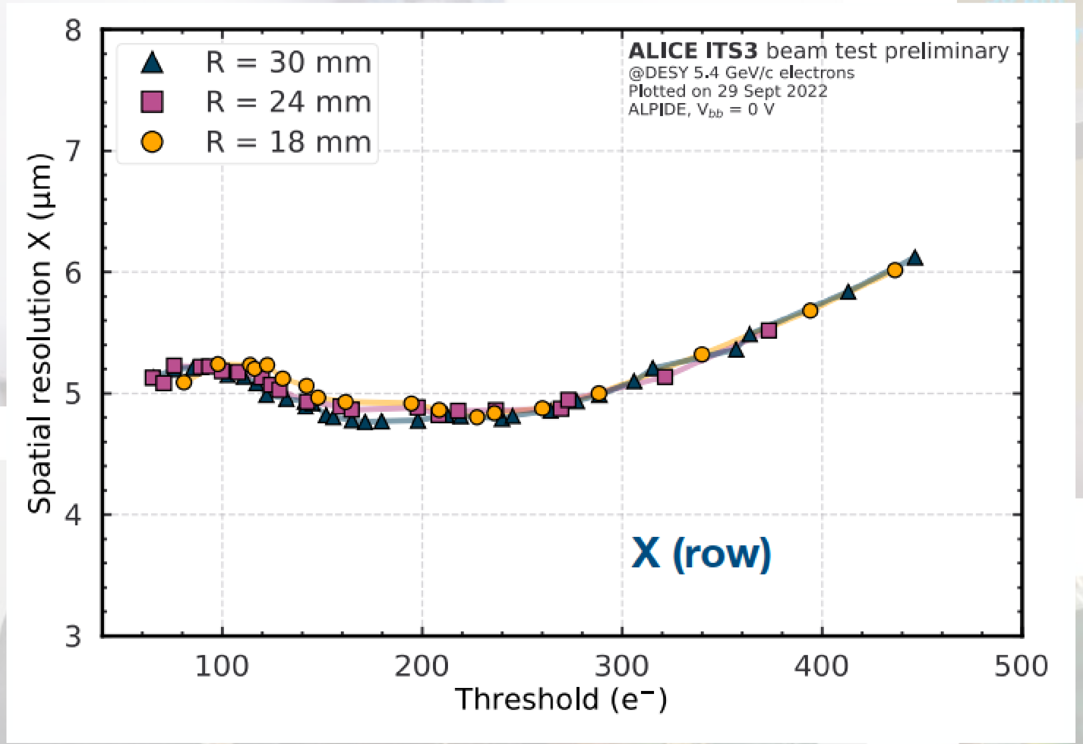


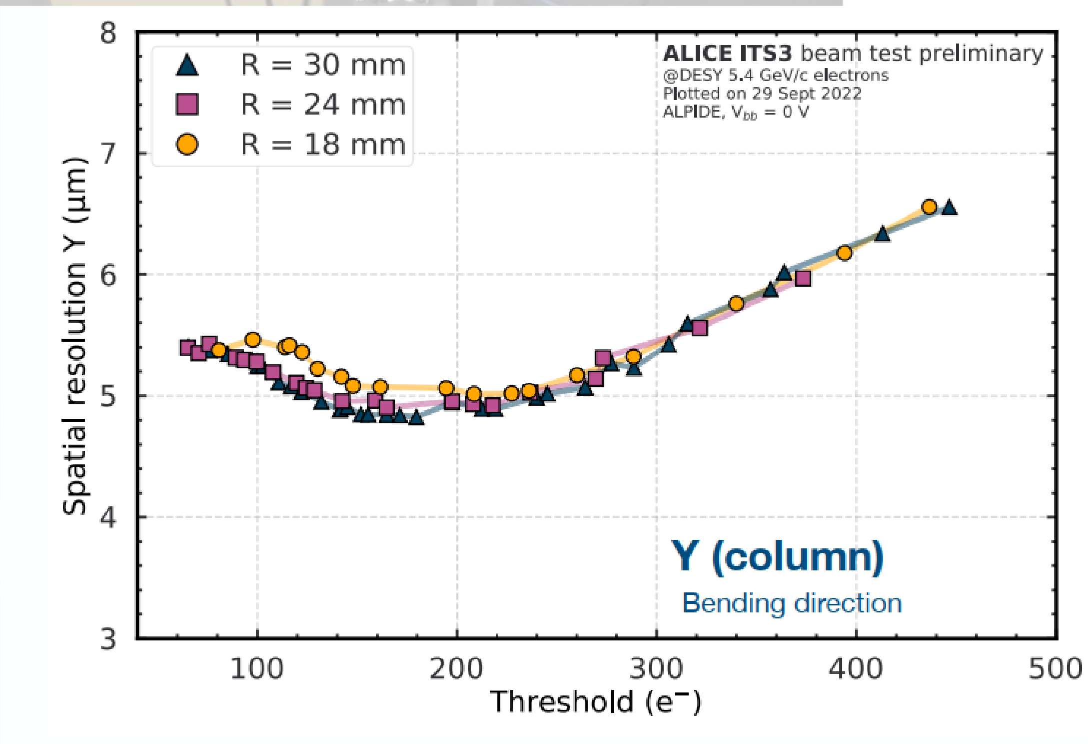
Bending wafer size sensor (using MLR1 wafer)



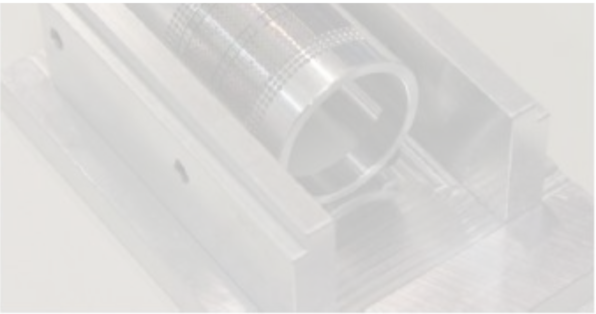


Bending

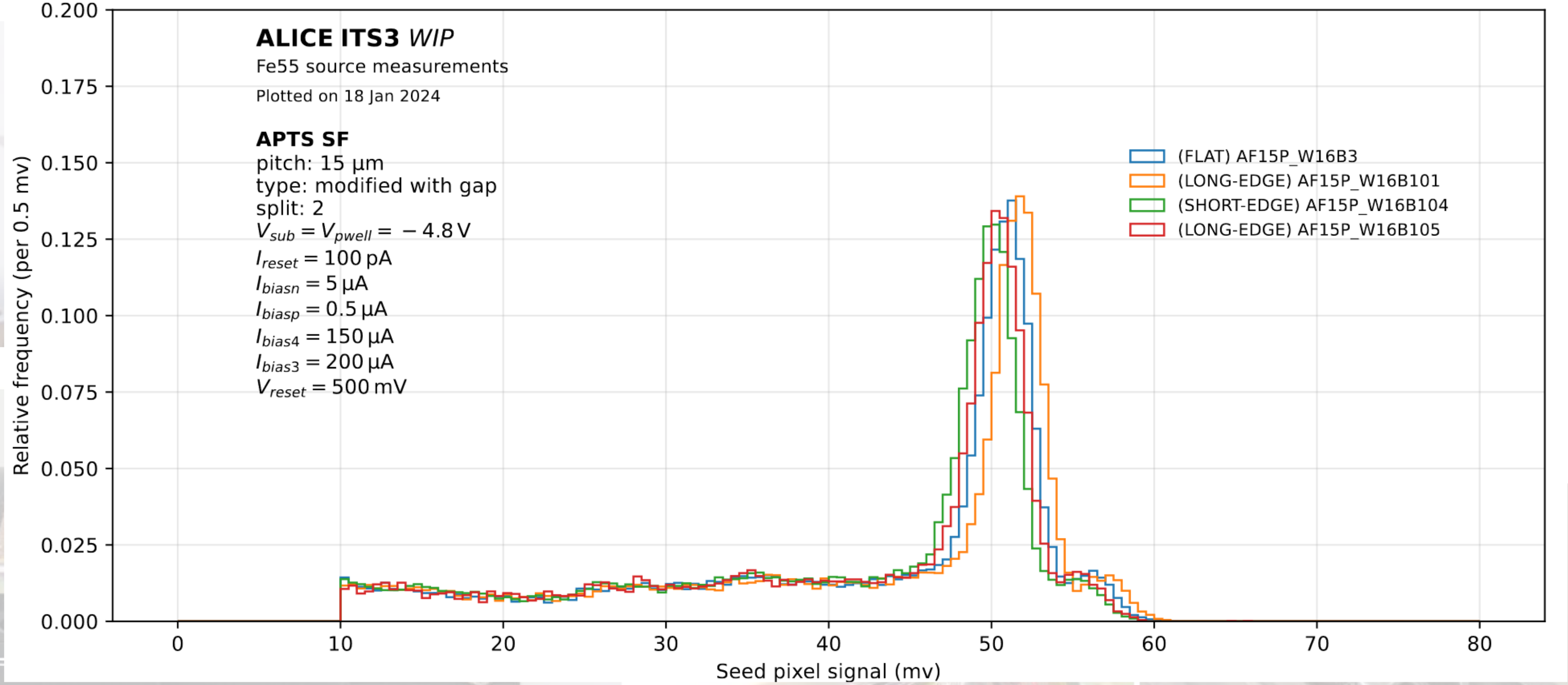




µITS3 Spatial Resolution

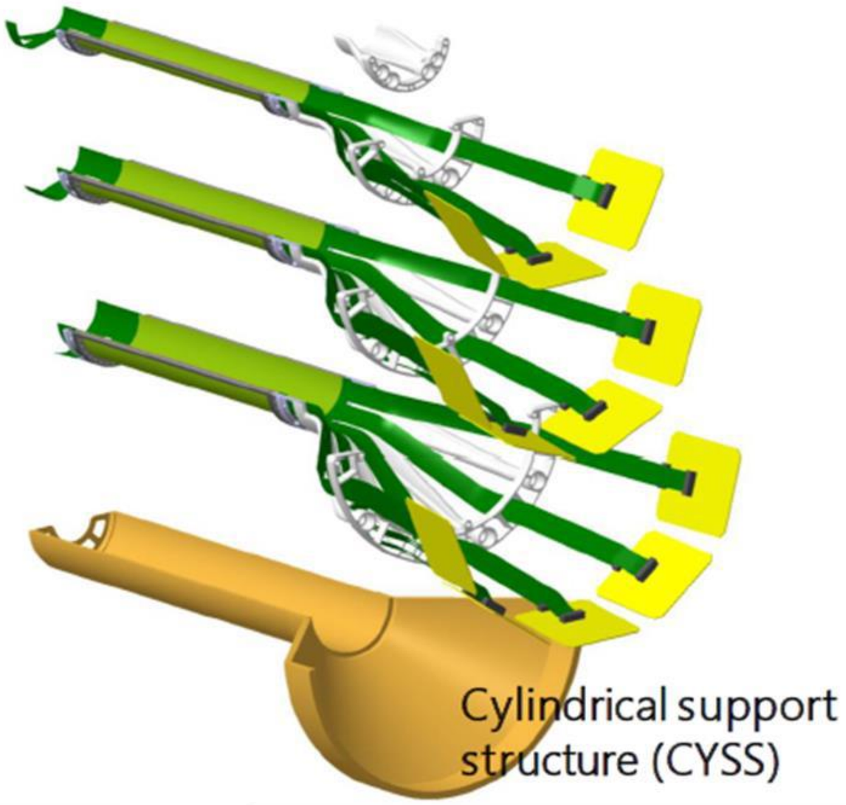


Bending



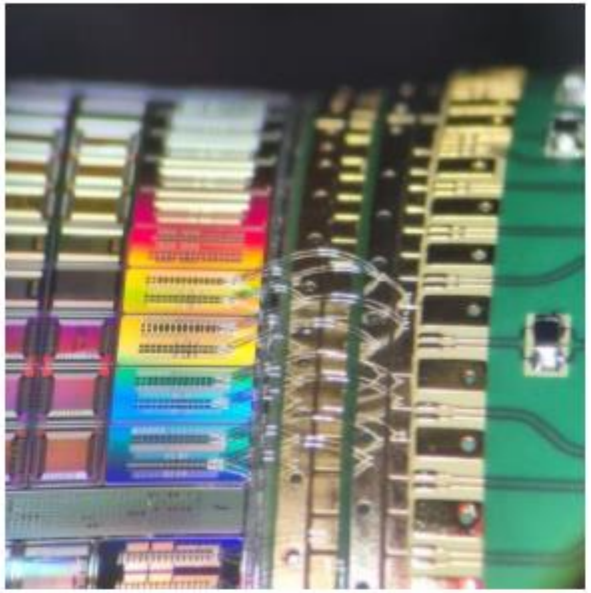
Bent analog pixel test structures

ITS3 Layout

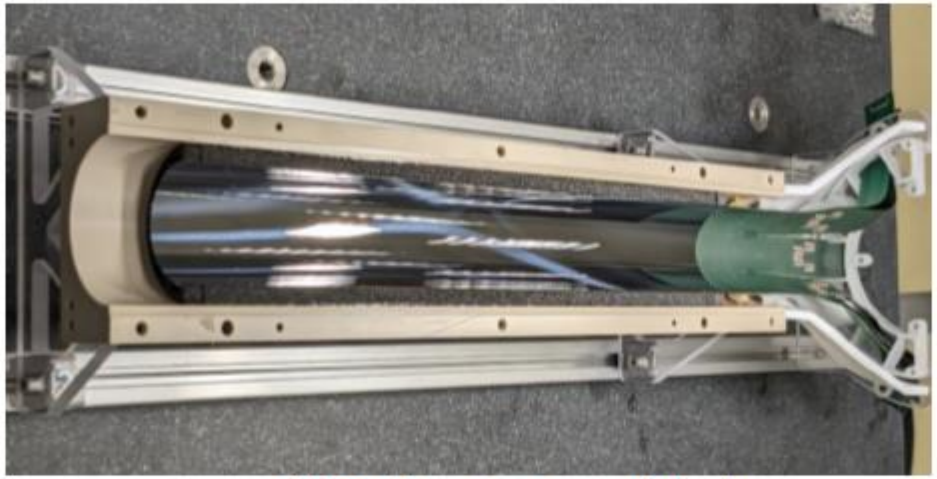


ITS3 assembly tests

FPC and Sensor on jig



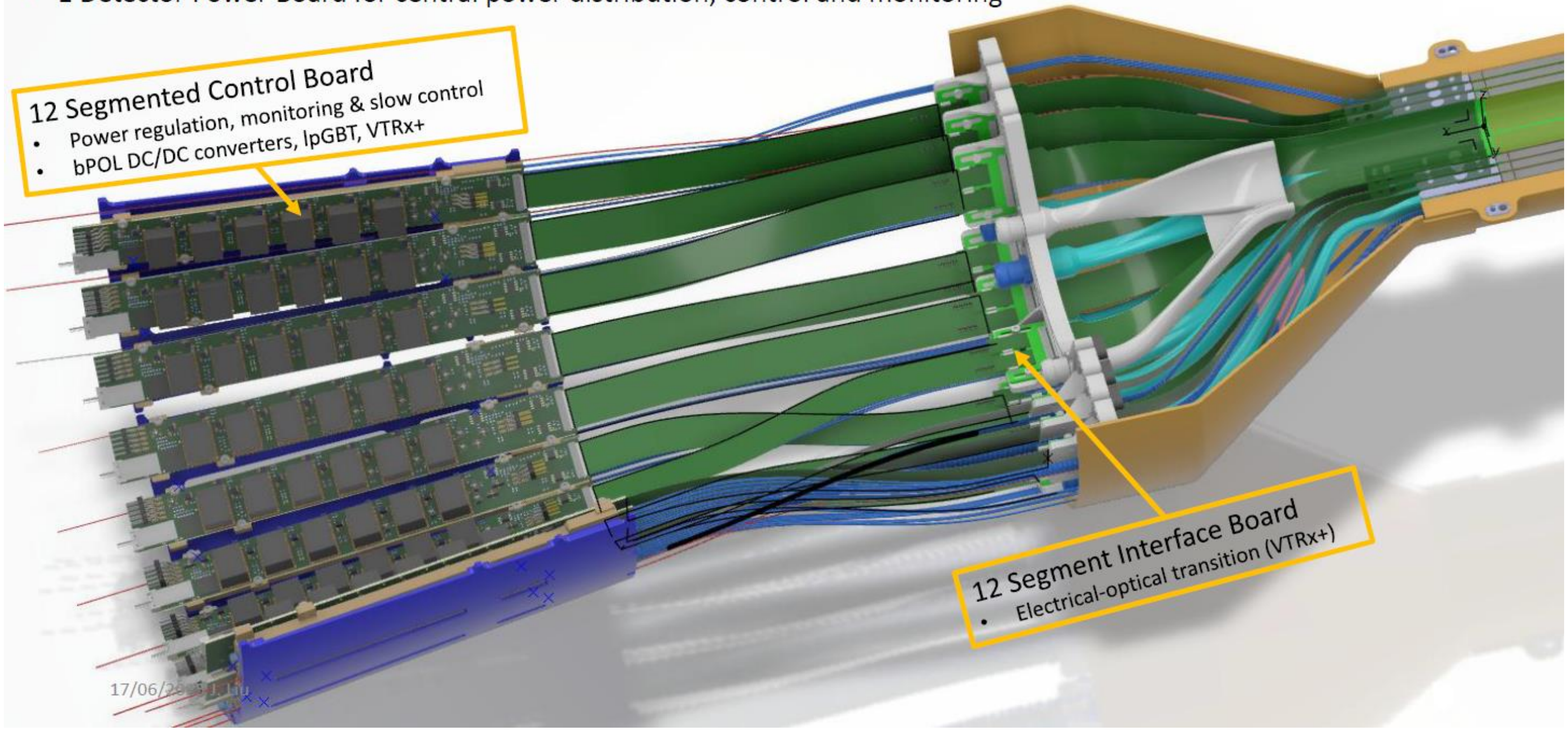
Wire bondings



First layer assembled

Detector Service Electronics

- 1 Detector Power Board for central power distribution, control and monitoring



ITS3 general parameters

Beampipe inner/outer radius (mm)	16.0/16.5		
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	19.0	25.2	31.5
Length (sensitive area) (mm)	260	260	260
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	407	507
Pixel sensors dimensions (mm^2)	266 × 58.7	266 × 78.3	266 × 97.8
Number of pixel sensors / layer		2	
Material budget ($\%X_0$ / layer)		0.07	
Silicon thickness (μm / layer)		≤50	
Pixel size (μm^2)		$O(20 \times 22.5)$	
Power density (mW/cm^2)		40	
NIEL (1 MeV n_{eq} cm^{-2})		10^{13}	
TID (kGray)		10	

[a] The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).