The ITS3 detector and physics reach of the LS3 ALICE Upgrade

Chunzheng Wang* (for the ALICE Collaboration)

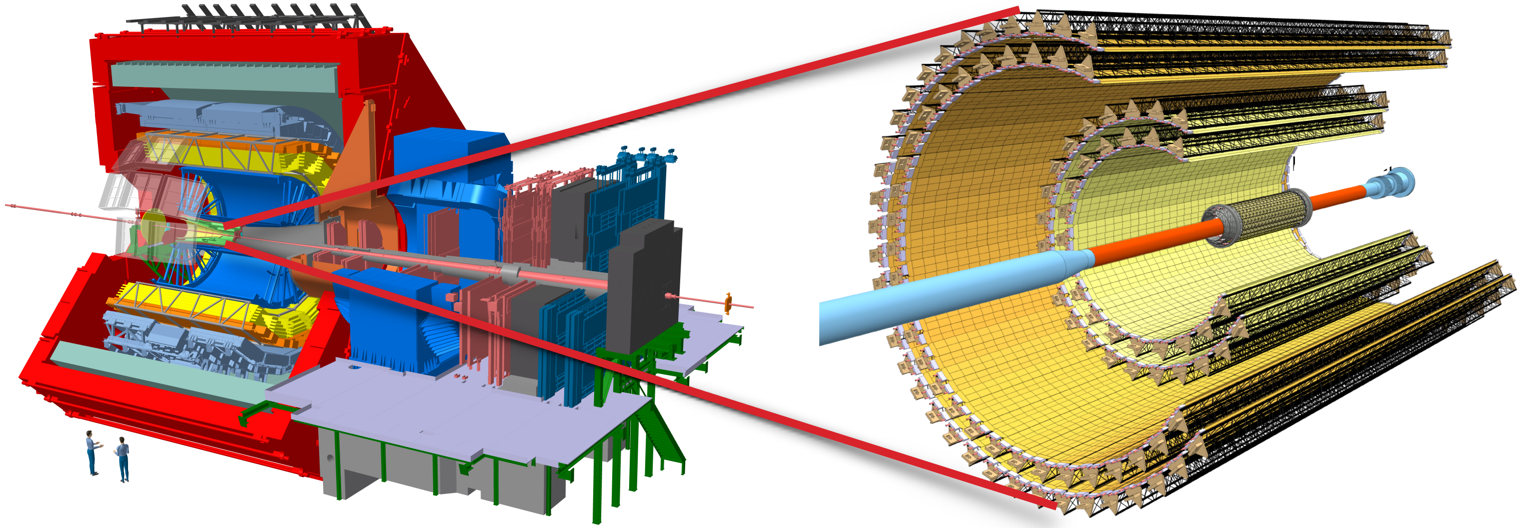
*Fudan University. June 4th, 2024.

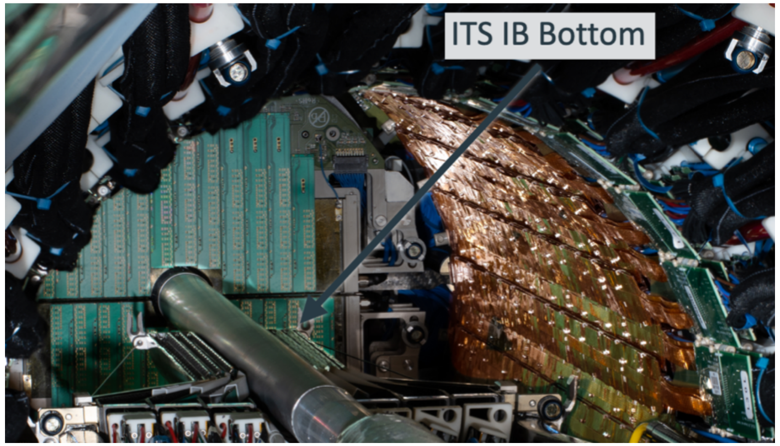
SQM Strasbourg 2024 Strangeness in Quark Matter

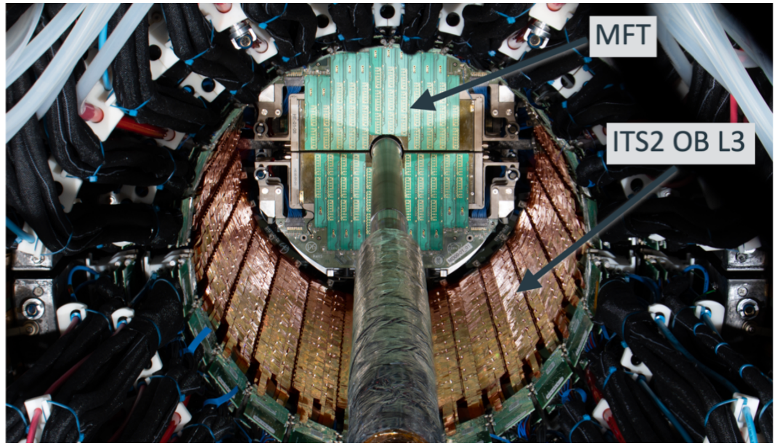
ALICE

FUDAN UNIVERSITY

ALICE Inner Tracking System in Run 3 (ITS2)







7 Layers:

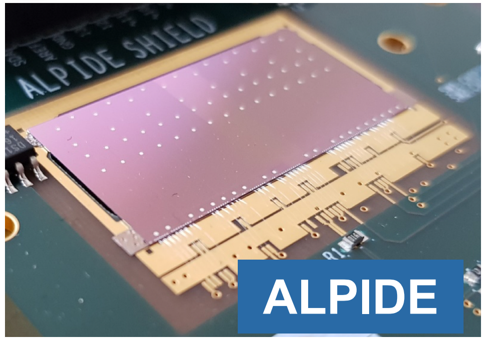
➡ 3 inner barrel (IB) and 4 outer barrel (OB)

Large active area and granularity

➡ $10 m^2$ active silicon area, 12.5×10^9 pixels

Built with ALPIDE chips

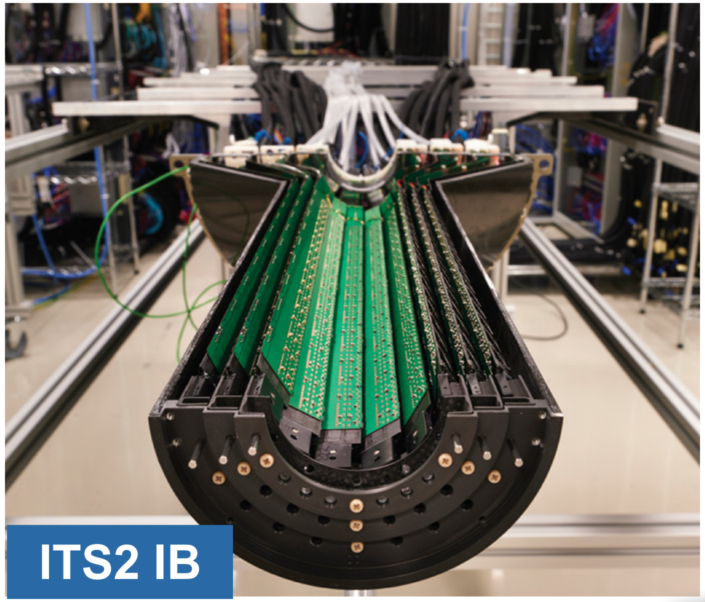
➡ 180nm CMOS MAPS, 15×30 mm^2, 512×1024 pixels

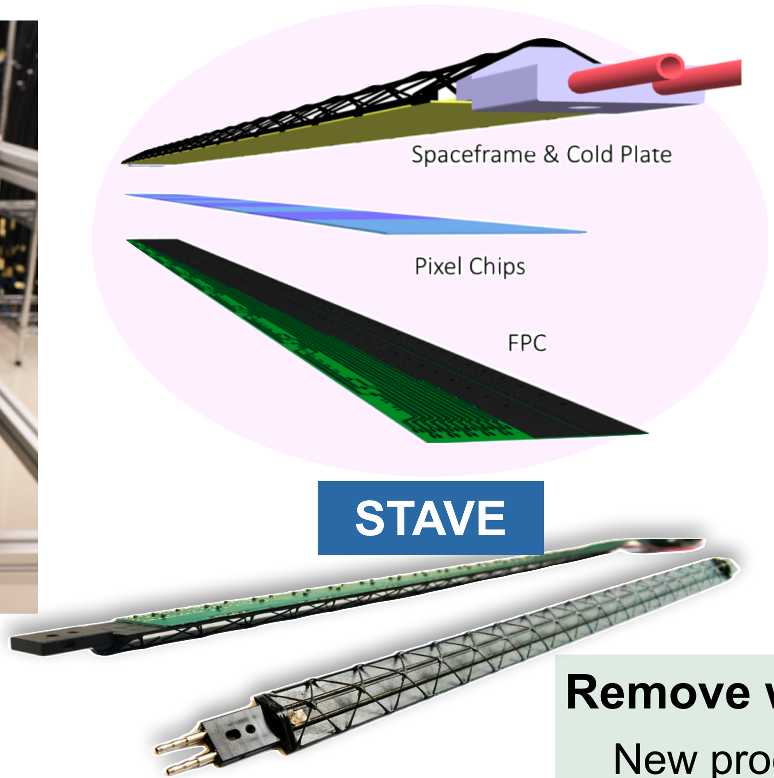


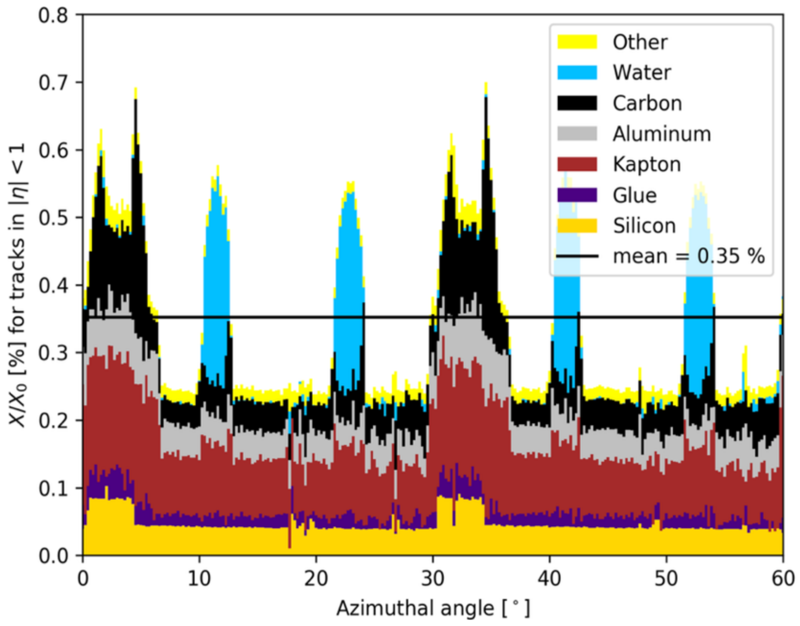
* M. Mager, for ALICE Collab, NIM-A 824, 434 (2016) * F. Reidt, for ALICE Collab, NIM-A 1005, 121793 (2021)

LHC LS2			LHC RUN3				LHC LS3			LHC RUN4			
2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032

How to improve ITS2?







Non-sensitive material

➡ Silicon has 1/7 of total material budget

Non-uniformly distributed material

➡ Stave overlapping, support and water cooling structure

Unable to be closer to the interaction point

➡ Mechanical constraints

Remove water cooling

New process chip (with lower power consumption) required to introduce air cooling

Remove the circuit board

New technology required to integrate data, control and power distribution on a single chip

Remove of mechanical support

New mechanical structure design required

ITS3: replacement of ITS2 inner barrel

Bent wafer-scale sensor ASIC
- ➡ 65 nm CMOS MAPS
- ➡ Fabricated with stitching
- ➡ Power density < 40 mW/cm^2

3 layers with 6 sensors

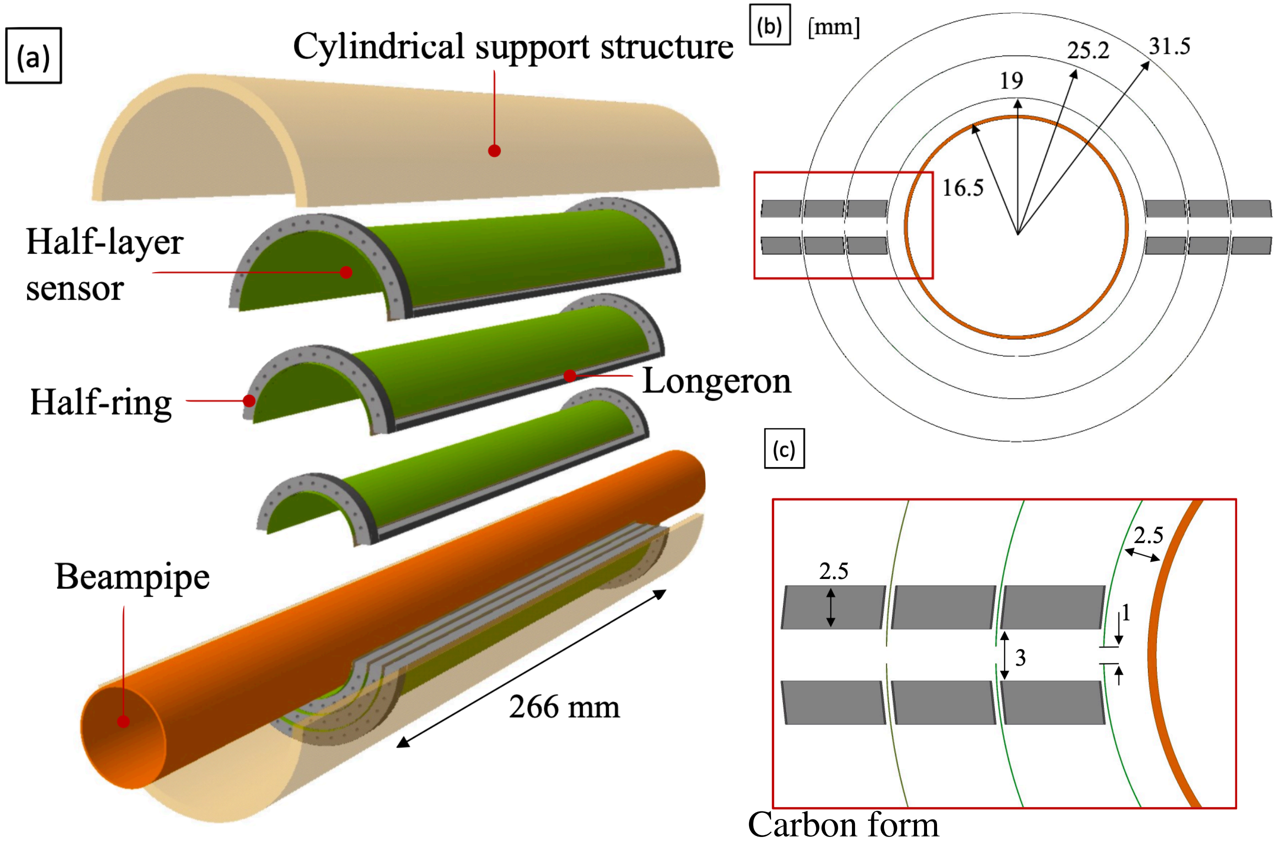
Air cooling between layers

Key benefit

Lower material budget
- ➡ 0.35% X_0 → 0.07% X_0 per layer

Uniformly distributed material

Closer to interaction point
- ➡ Beampipe: 18.2 mm → 16.0 mm
- ➡ Layer 0 position: ~24 mm → 19.0 mm



ITS3 TDR: CERN-LHCC-2024-003

LHC LS2			LHC RUN3				LHC LS3			LHC RUN4			
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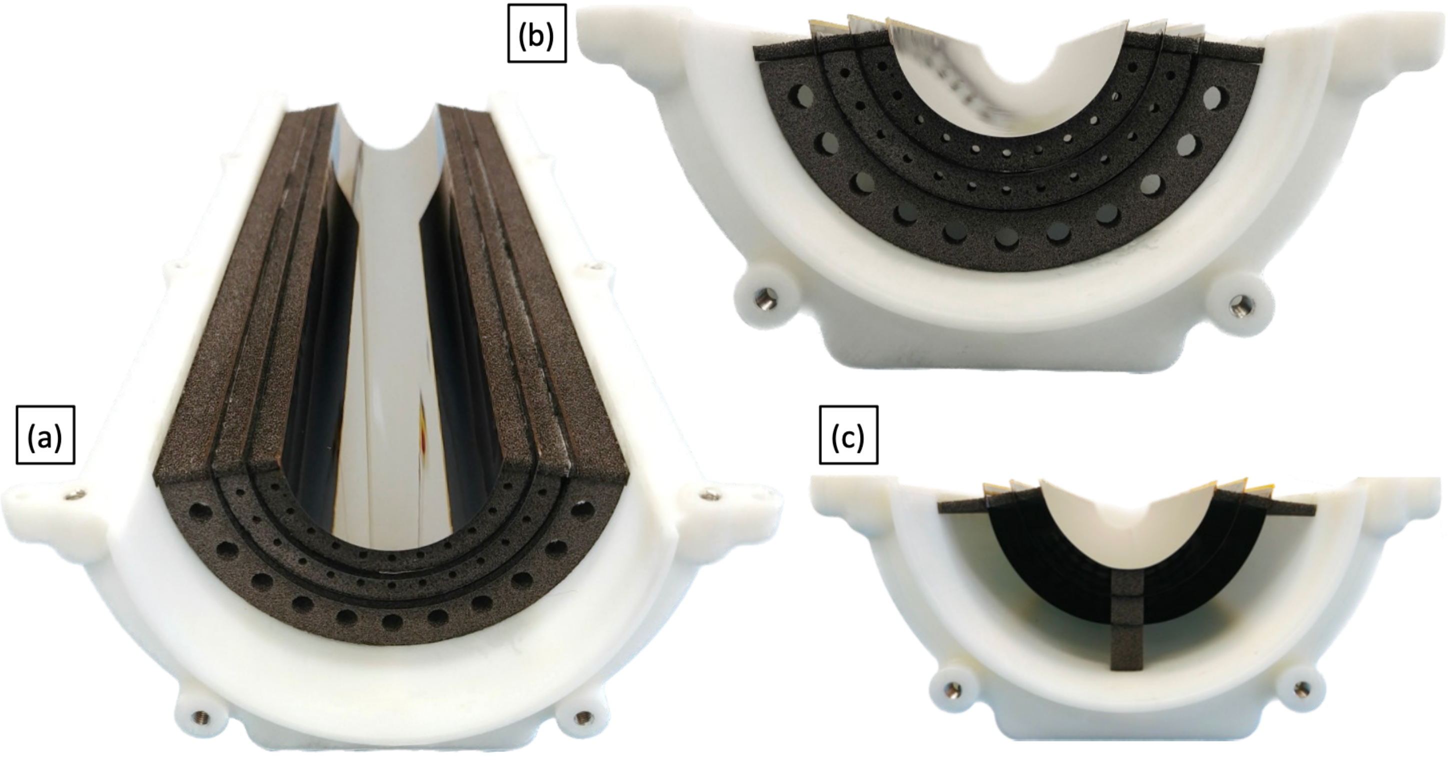

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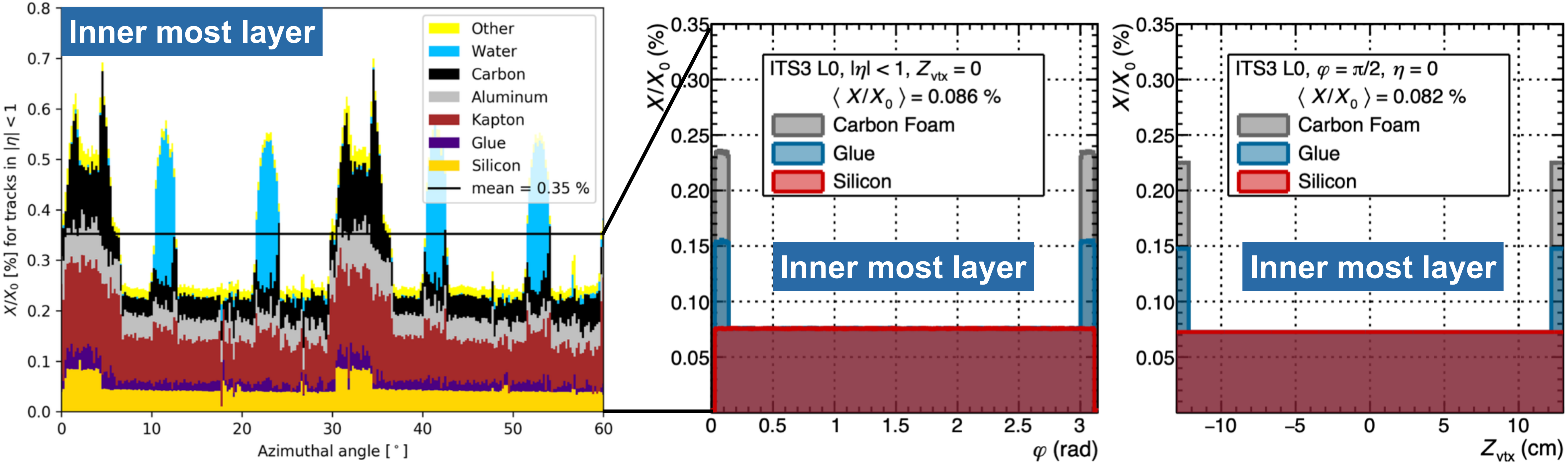
Material budget comparison between ITS2 IB and ITS3



ITS2 IB

Various non-sensitive material

Silicon has 1/7 of total material budget.

Non-uniformly distributed material

Stave overlapping, support and water cooling structure.

ITS3

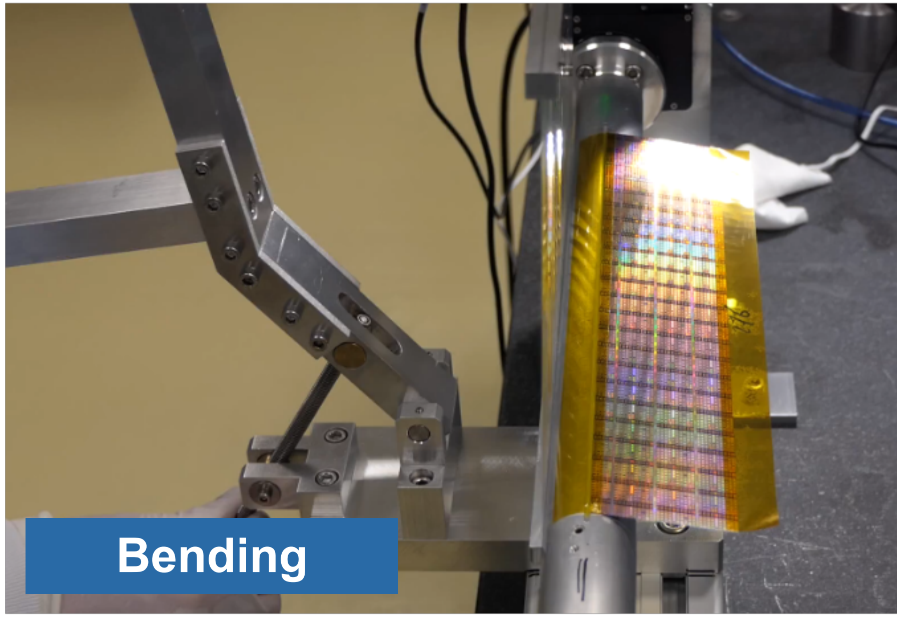
Few of non-sensitive material

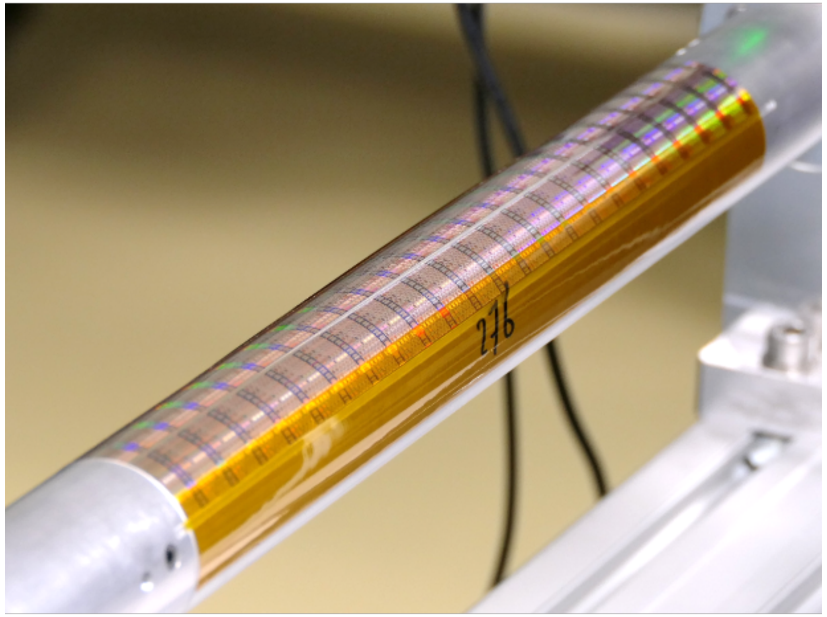
Sillicon dominates.

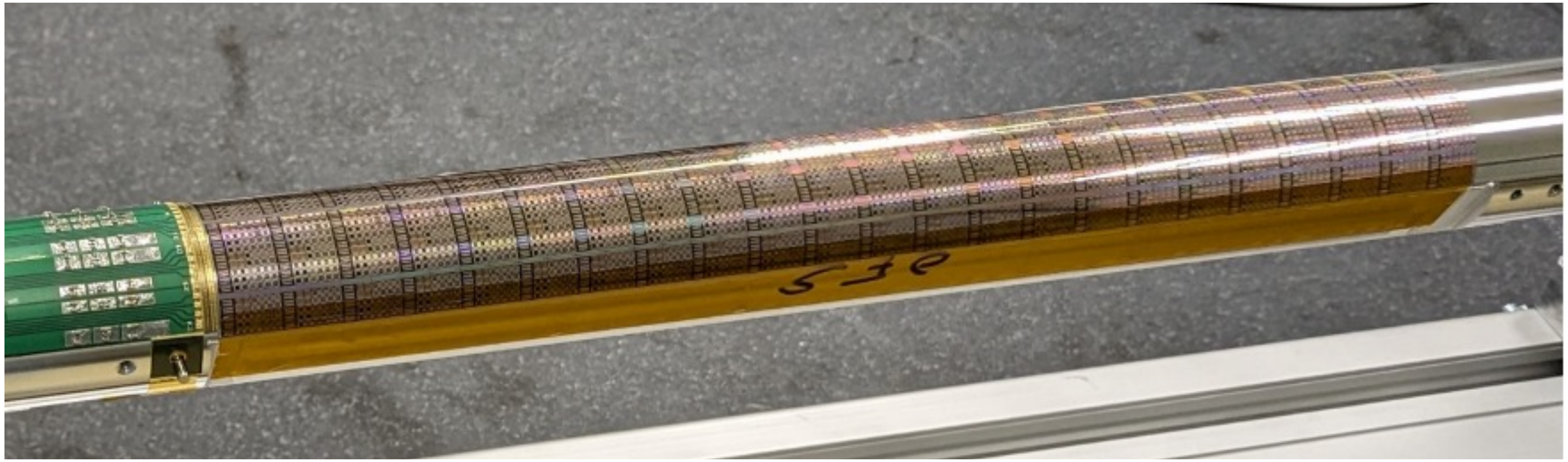
Uniformly distributed material

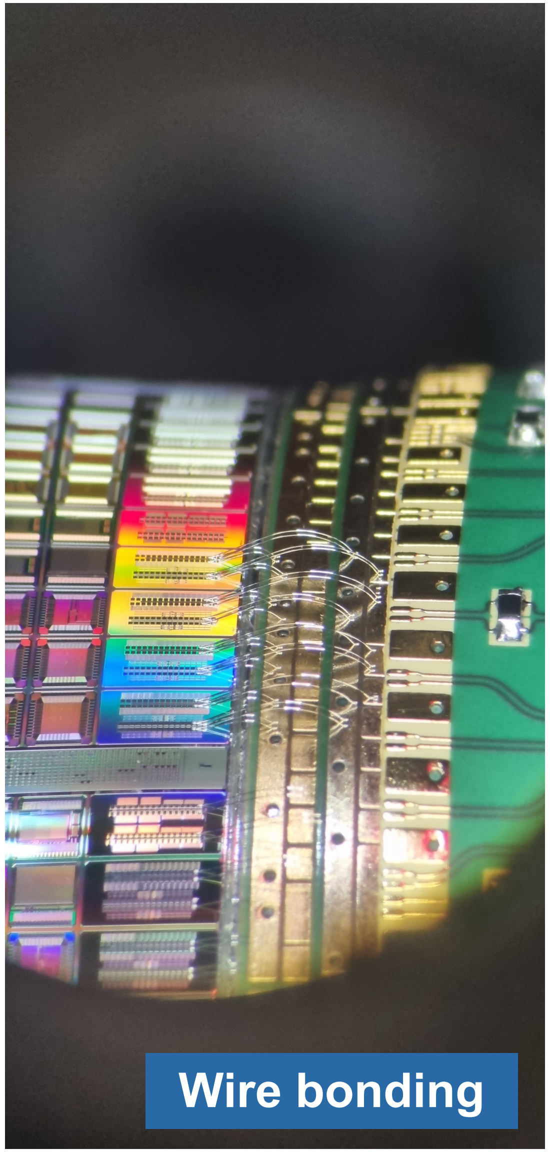
Only some lightweight carbon foam and glue distributed on the edge of the sensitive area.

Half-layer bending and electrical integration



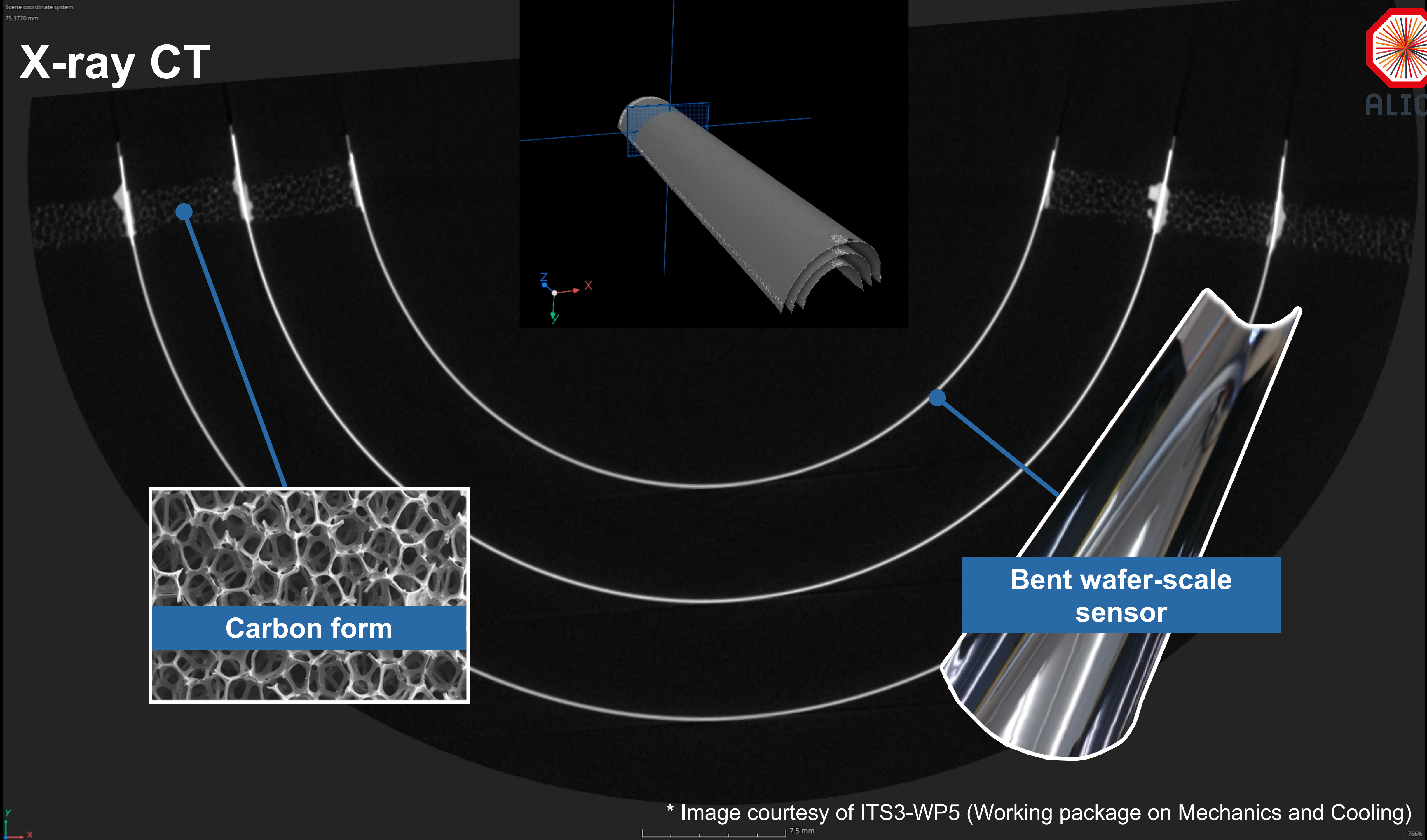






* Image courtesy of ITS3-WP5 (Working package on Mechanics and Cooling)

X-ray CT



* Image courtesy of ITS3-WP5 (Working package on Mechanics and Cooling)

Chip development roadmap

ALICE

MLR1 (Multi-reticle Layer Run 1)

- **First 65nm process MAPS**
- APTS, DPTS, CE65
- Successfully qualified the 65nm process for ITS3

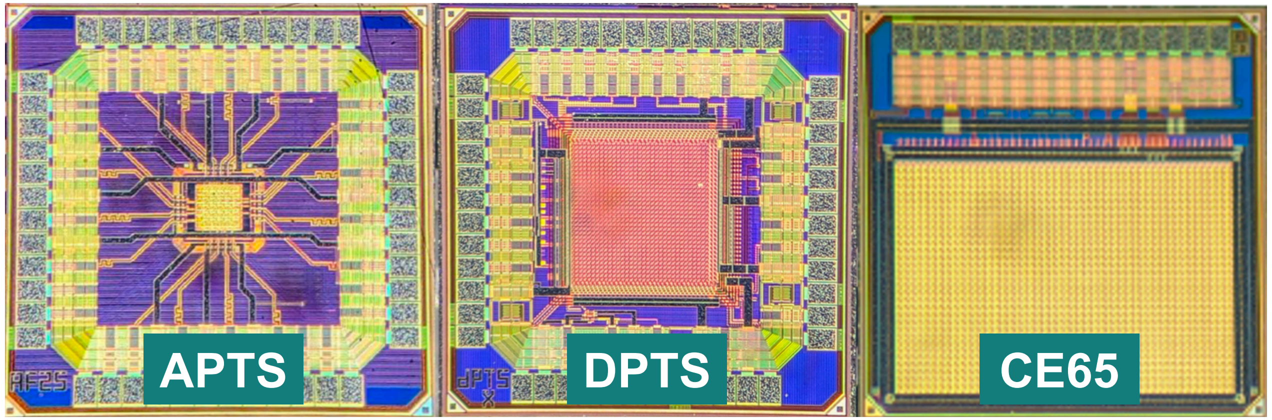
ER1 (Engineering Run 1)

- **First stitched MAPS**
- MOSS, MOST
- Successfully qualified the large scale sensor design

ER2 (Engineering Run 2)

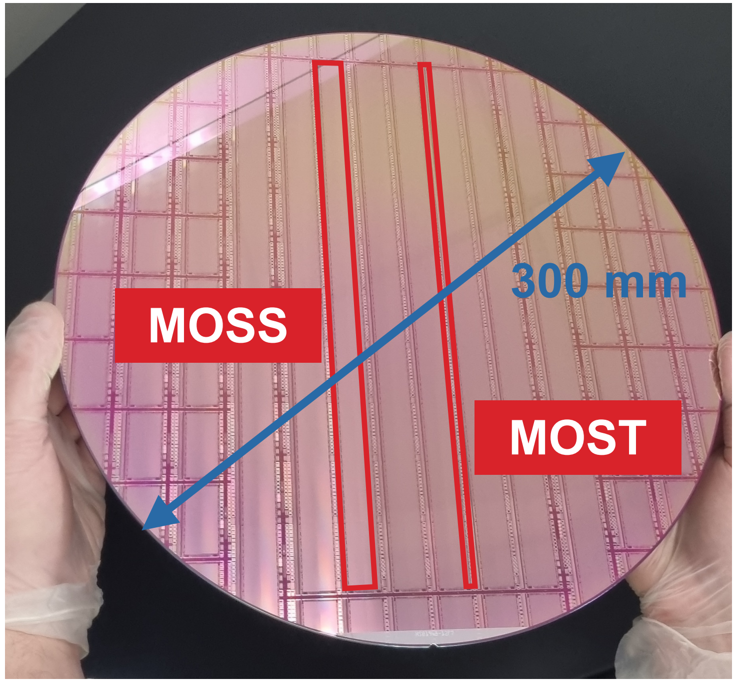
- **ITS3 sensor prototype**
- Specifications frozen
- Design ongoing

ER3 ITS3 sensor production

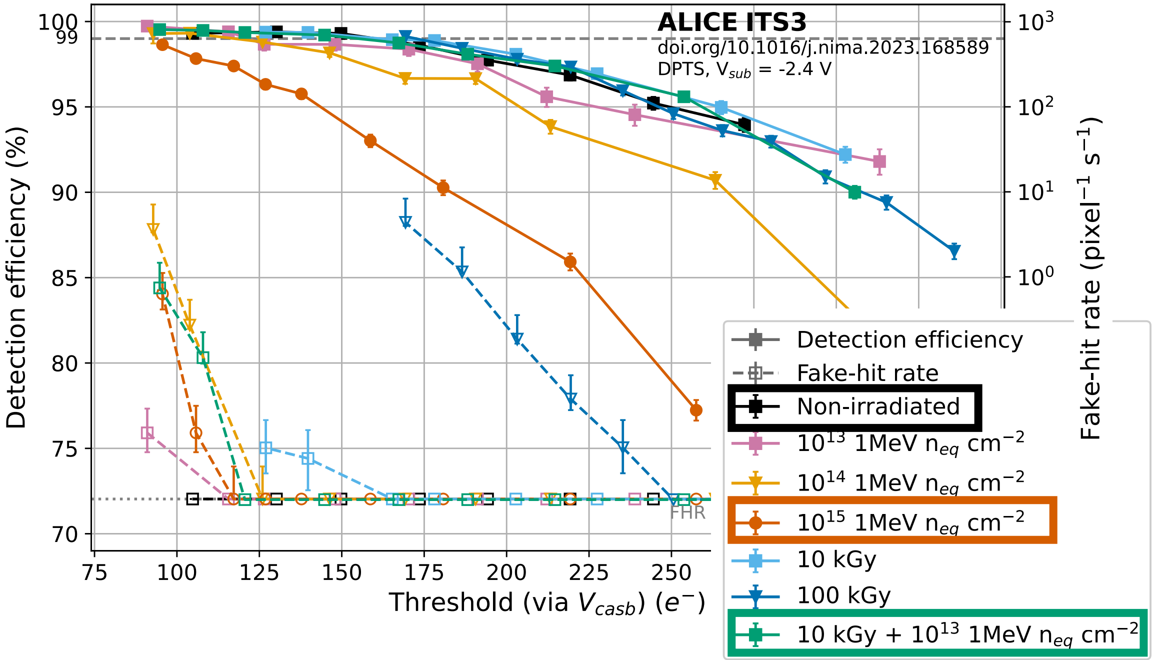


APTS
Analogue Pixel Test Structure
DPS
Digital Pixel Test Structure
CE65
Circuit Exploratoire 65 nm

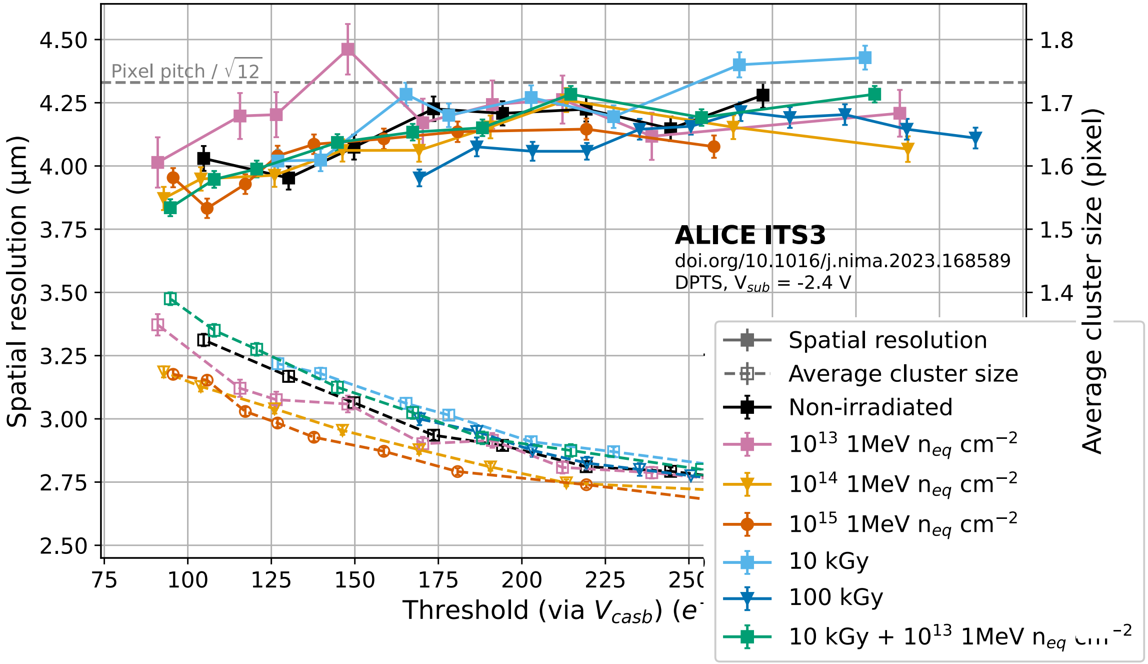
MOSS
Monolithic Stitched Sensor
MOST
Monolithic Stitched Sensor Timing



MLR1 testing results (selected)



ITS3 requirement

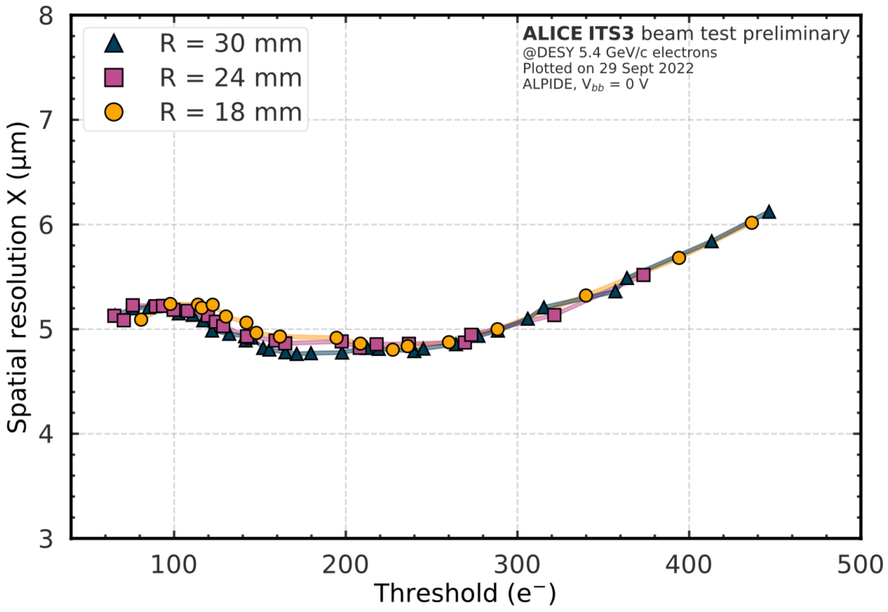


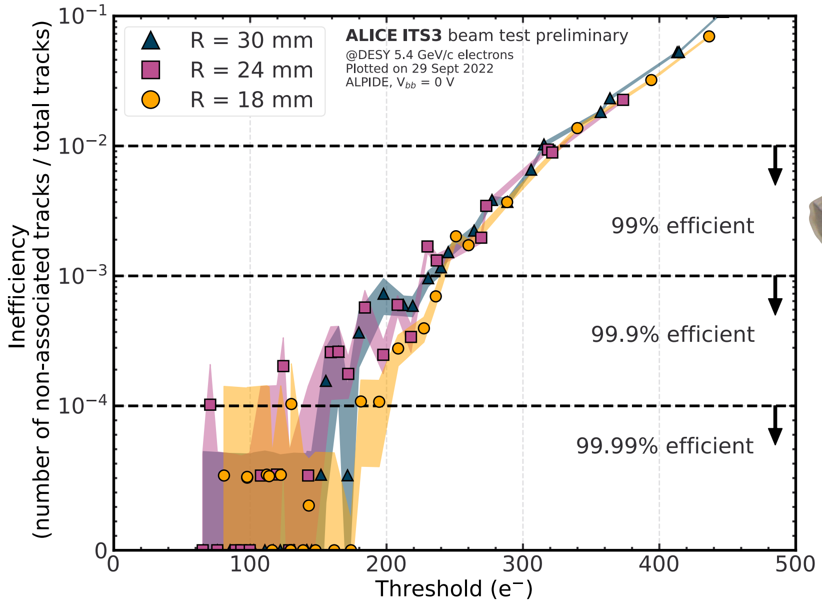
- Radiation hardness assessed
  - Under the irradiation requirements of ITS3, and even under higher levels, the chip operates normally
- Spatial resolution and cluster size
  - evaluated for different levels of irradiation: spatial resolution not affected by irradiation, average cluster size slightly increase with irradiation

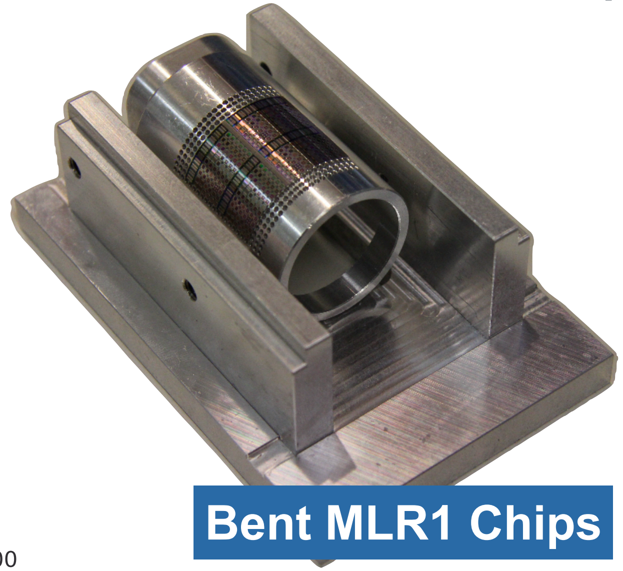
* G. A. Rinella et al., NIM-A 1056, 168589 (2023)
* G. A. Rinella et al., arXiv:2403.08952

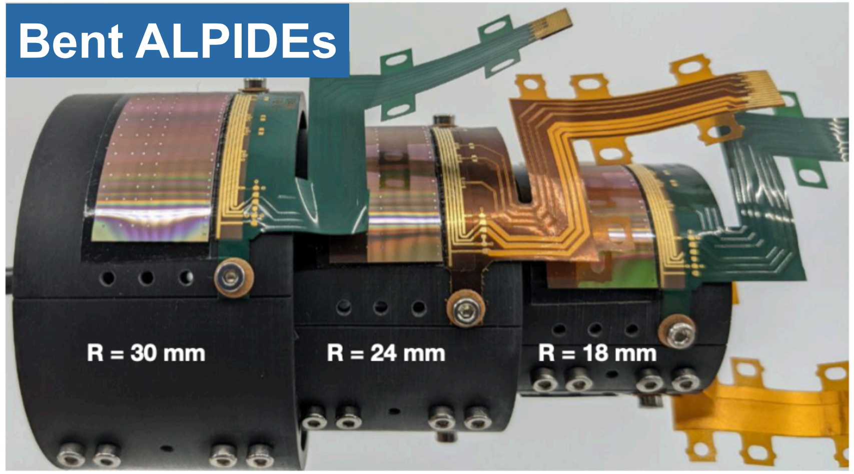
Excellent performances of the 65 nm technology have been established experimentally!

Bent MAPS characterization







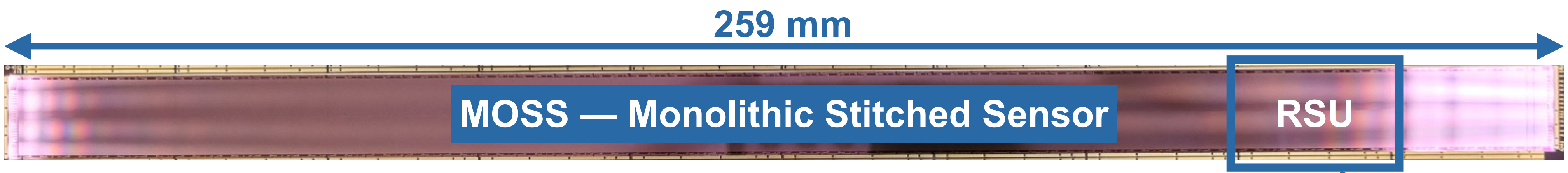


- No performance degradation observed when bending
  - Spatial resolution of 5µm consistent with flat ALPIDEs
  - Efficiency > 99.99% for nominal operating conditions
  - Inefficiency compatible with flat ALPIDEs
- MLR1 chips (65nm process) were also tested and the results were consistent

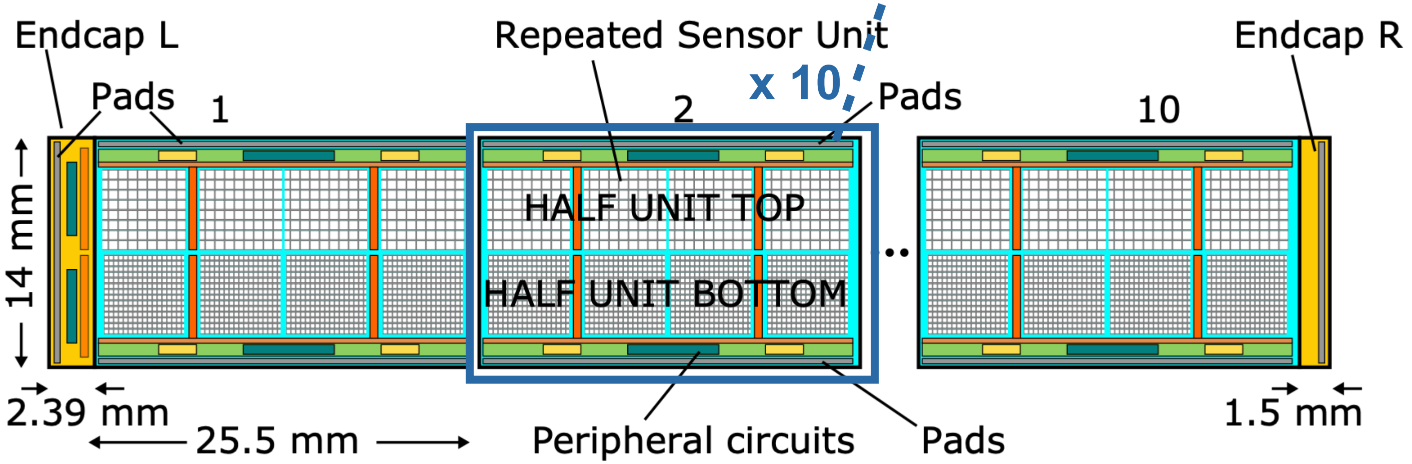
* ALICE ITS project, NIM-A 1028, 166280 (2022)

Bent chip work!

MOSS (ER1)

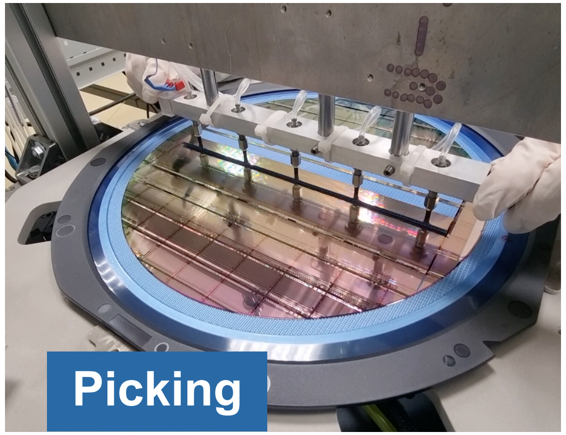


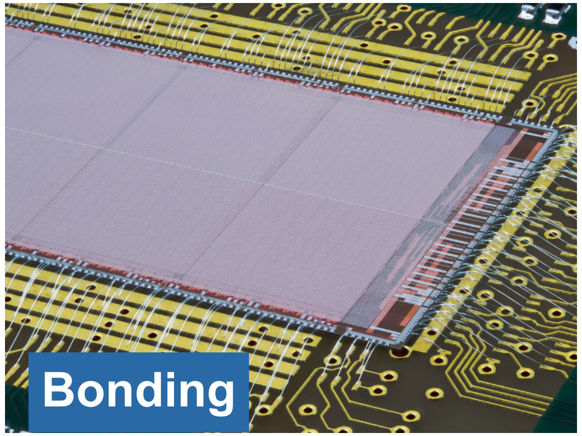
- **First stitched chips!**
  - **Full module on a single chip**
  - **Wafer-scale** (14 x 259 mm), **6.72 million pixels**
- MOSS is segmented into 10 repeated sensor units (RSU)
  - RSUs are divided into top and bottom half units with different pitches

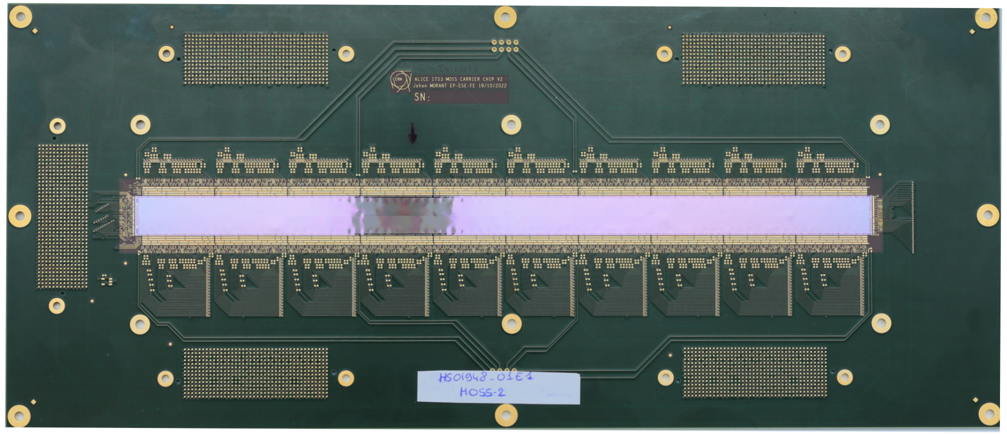


	Pixel matrix	Pixel size
Matrices on the top	256 × 256	22.5 μm
Matrices on the bottom	320 × 320	18 μm

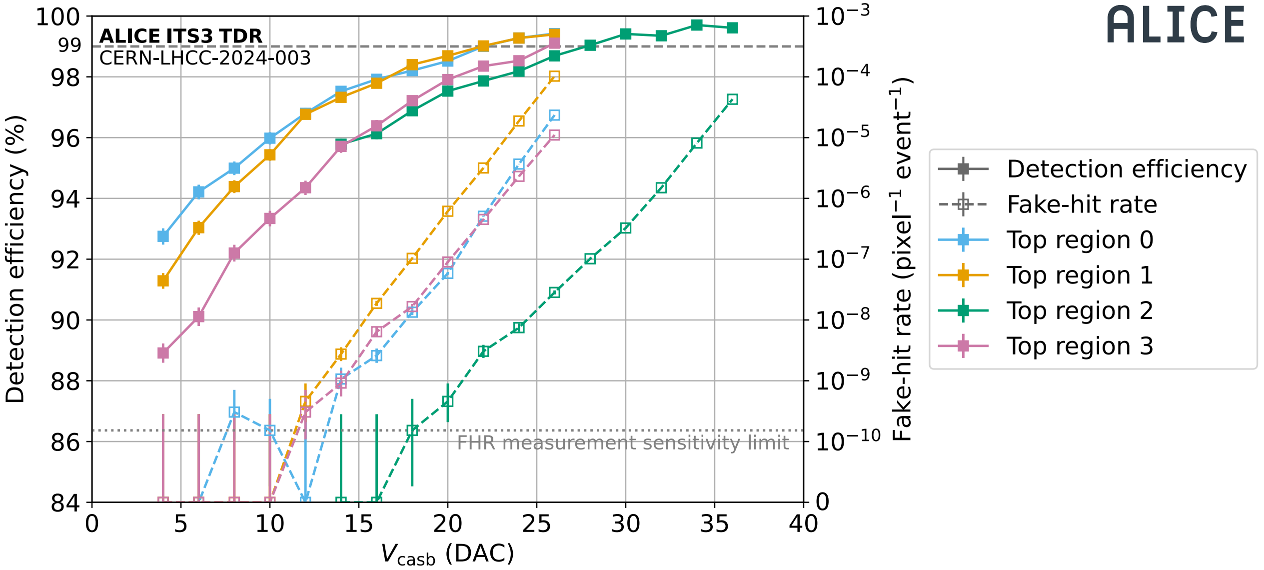
MOSS (ER1) testing results (selected)

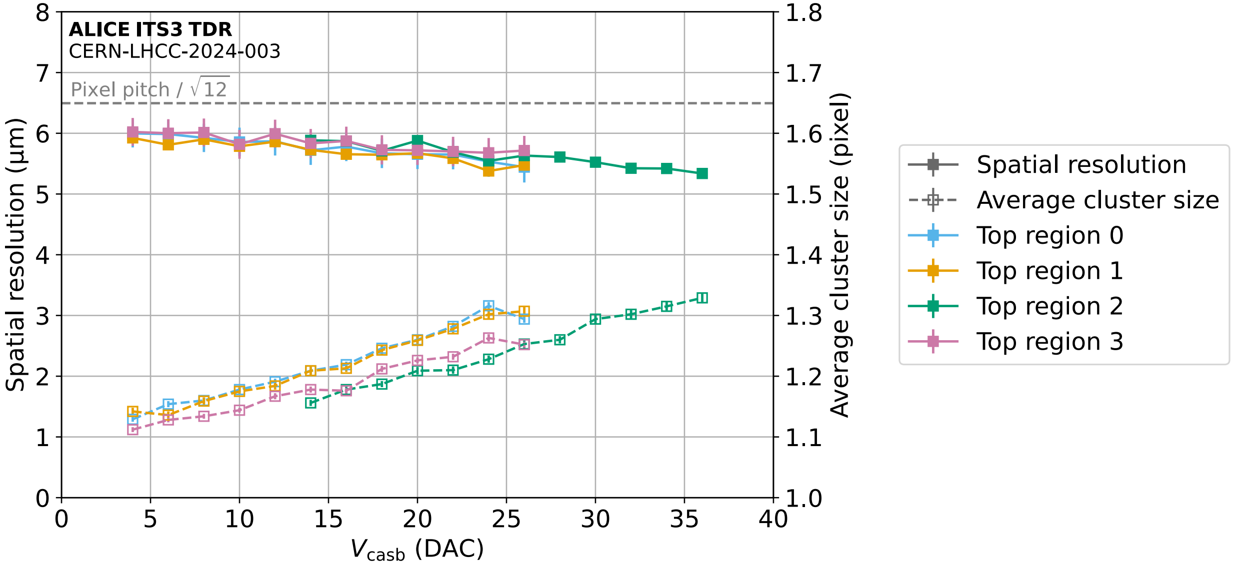






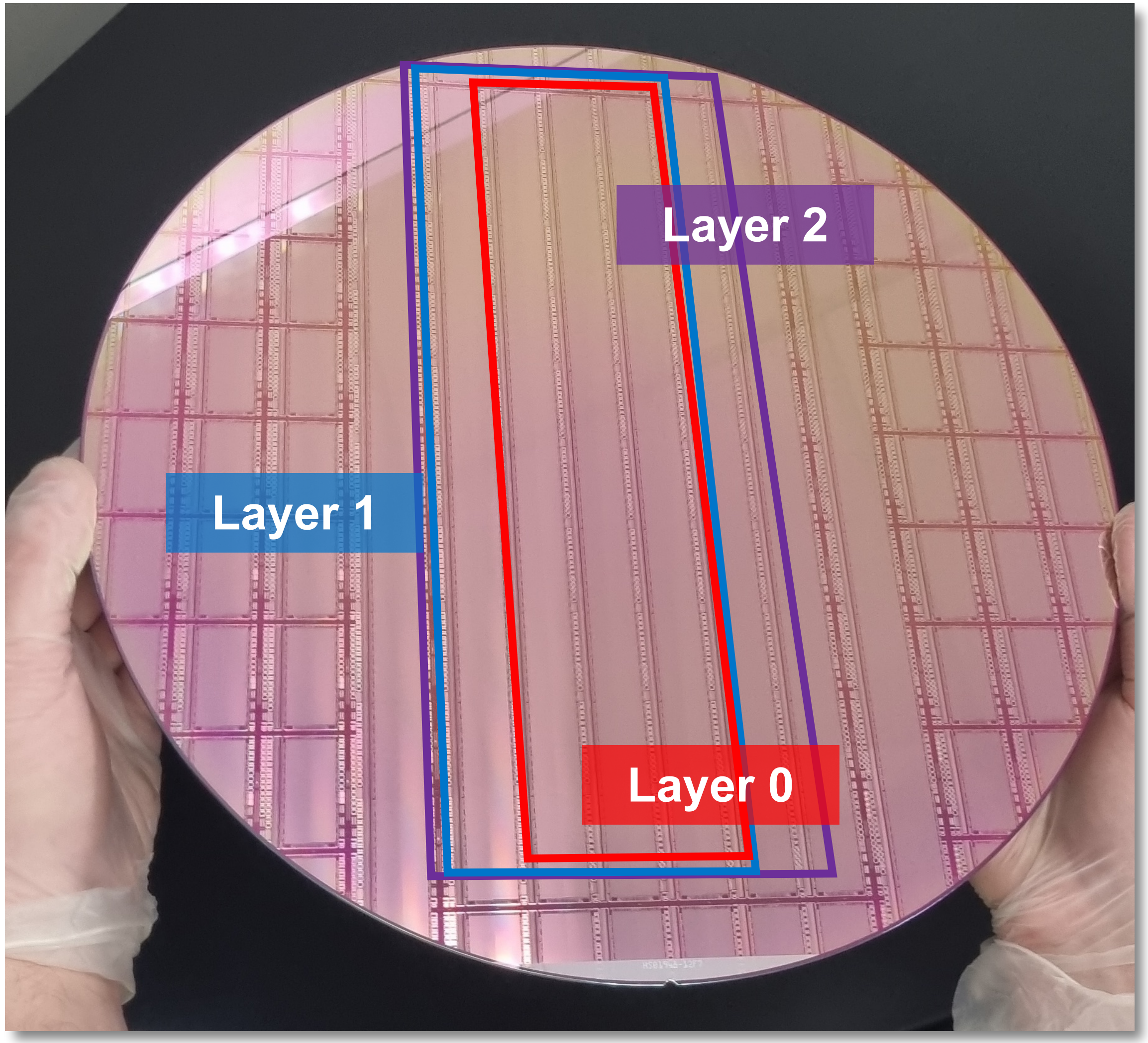
MOSS wire-bonded on the carrier card

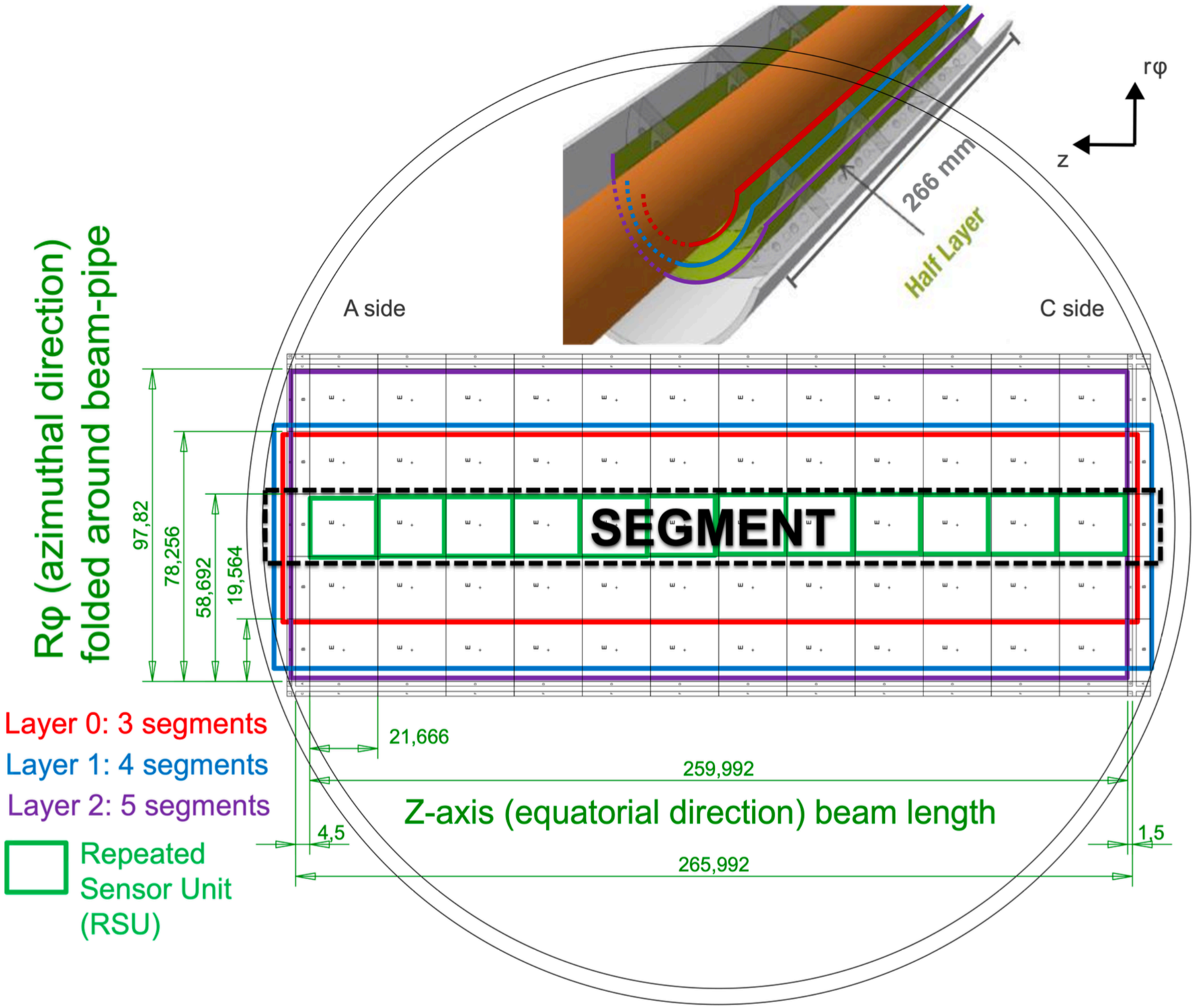




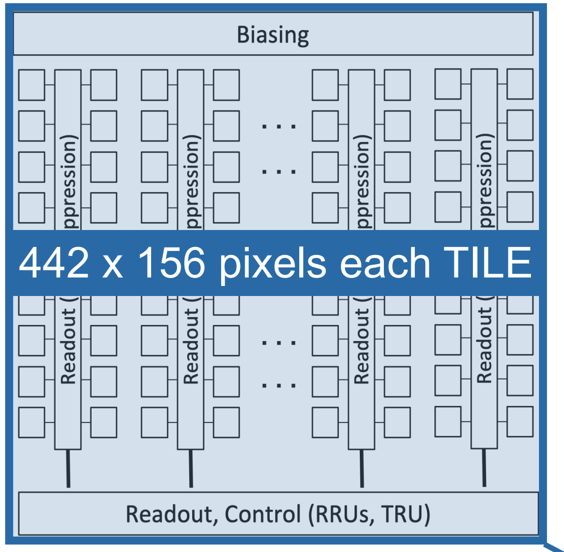
Efficiency and spatial resolutions that are expected from MLR1 chips are confirmed

Final Chip Design





Final Chip Design



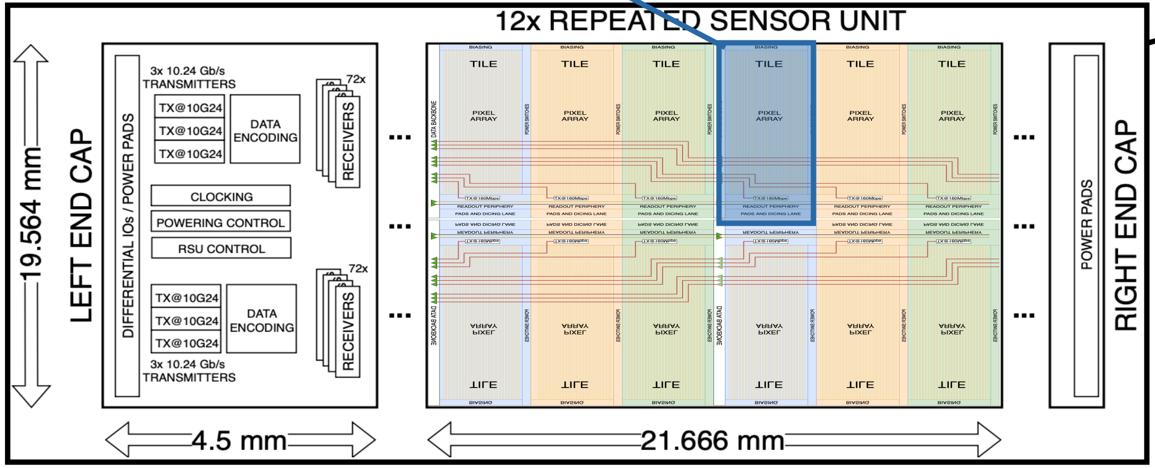
Power consumption:

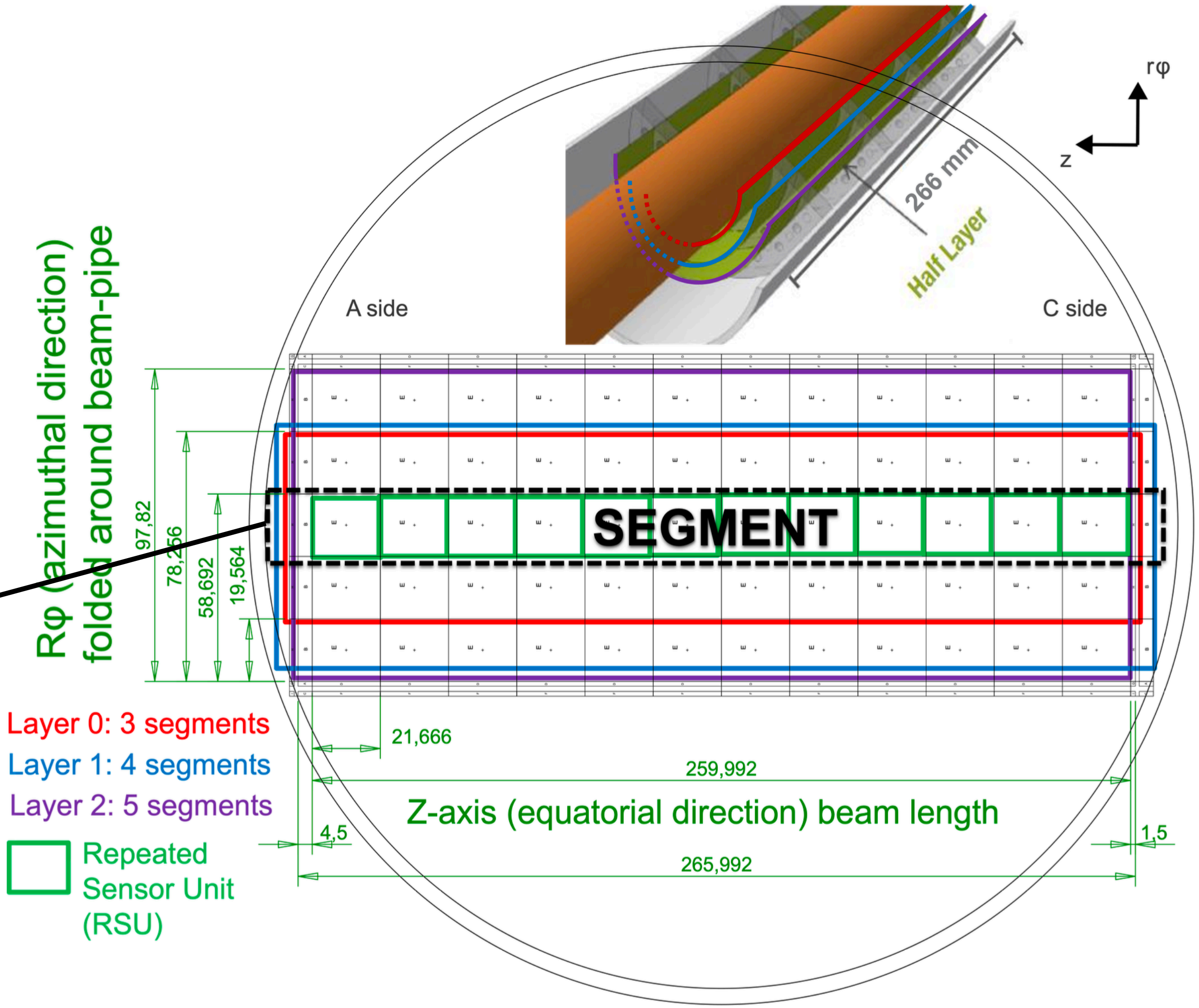
40 mW/cm^2

Total ITS3 Fill factor:

~93%

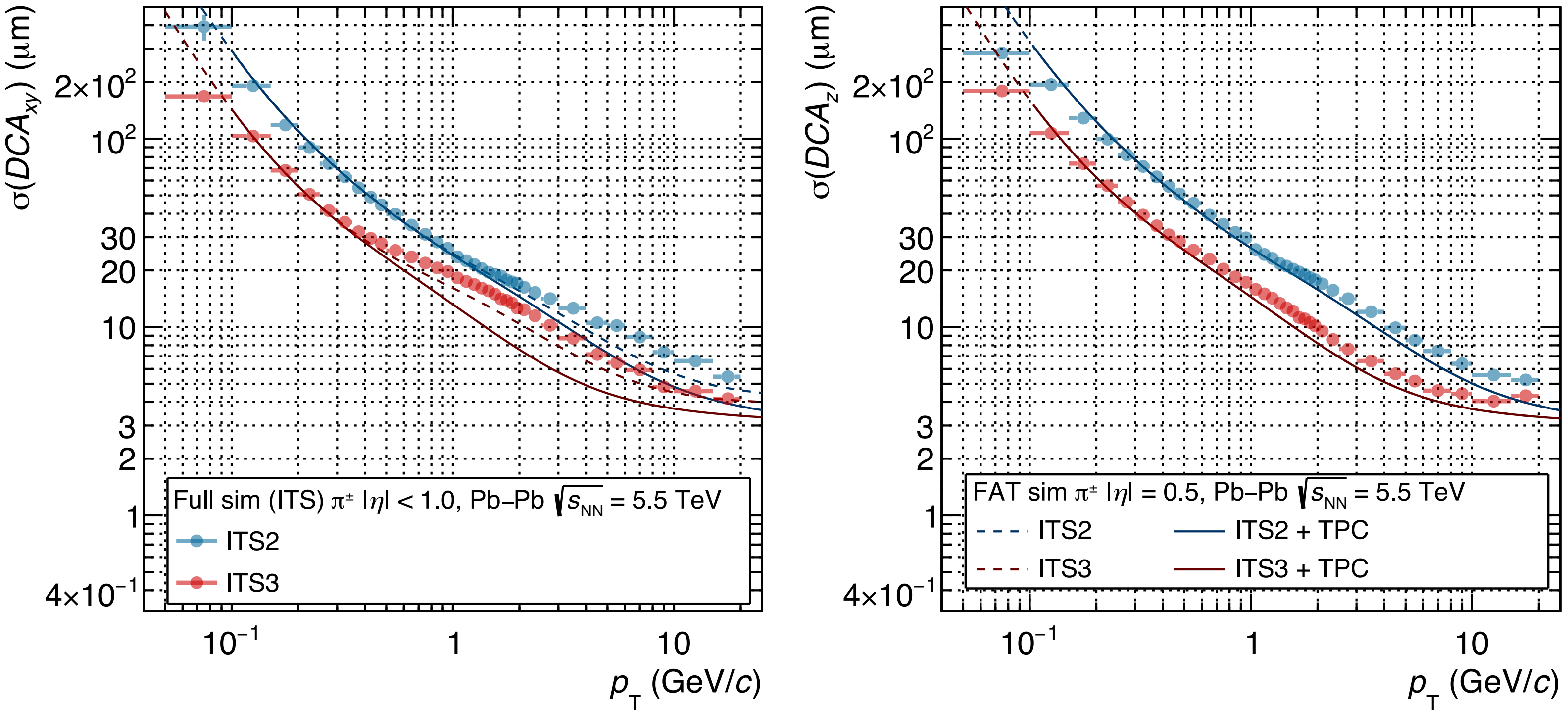
- possibly ~95.5% depending on ER2 test results.
- i.e. deadzone area: ~7%





Design is progressing well, with silicon back by early 2025

Physics performance — Single track in Pb-Pb collisions

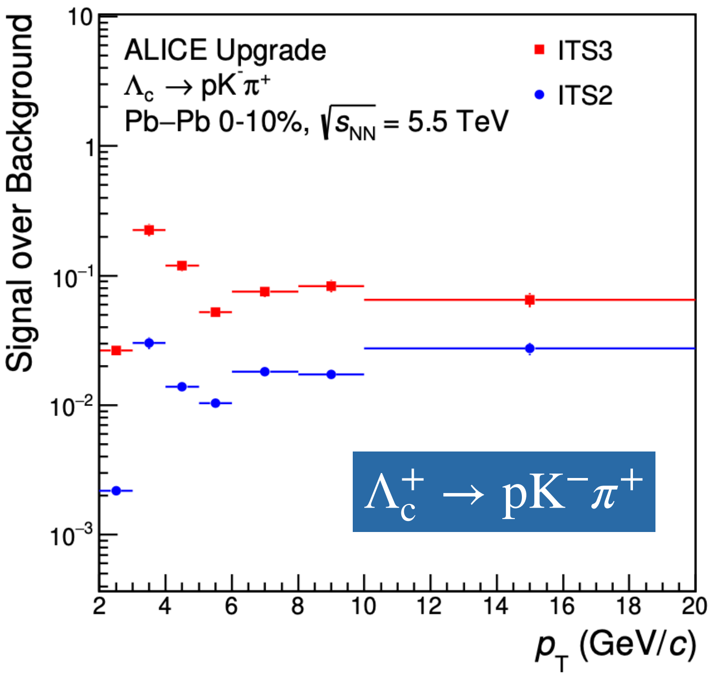


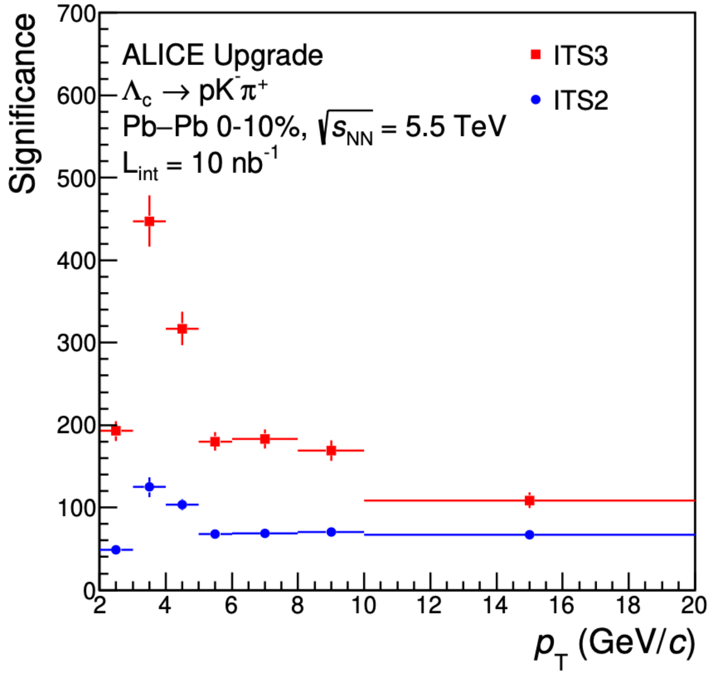
- Detailed description of geometry and material applied.
- Two simulation methods used
  - Full simulation
  - Fast simulation (FAT)

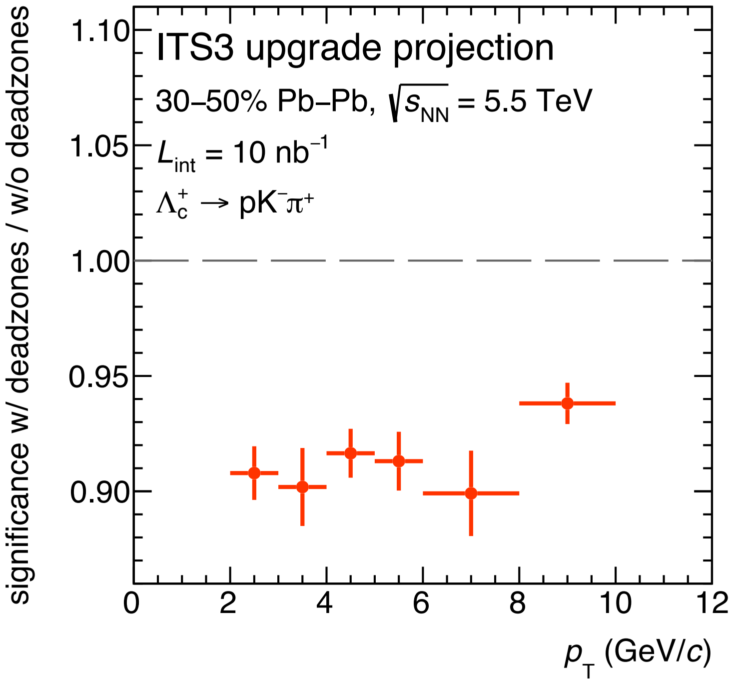
- ITS-only: Full sim and FAT results in good agreement for DCAxy and DCAz
  - Residual difference related to the material description (more accurate in full sim) or to tracking model
- Bump trend on DCAxy in $0.5 < p_T < 4$ GeV/c
  - Due to p_T resolution, significantly calibrated by the introduction of TPC

A twofold improvement in spatial resolution compared to ITS2

Physics performance — Heavy flavor hadron reconstruction





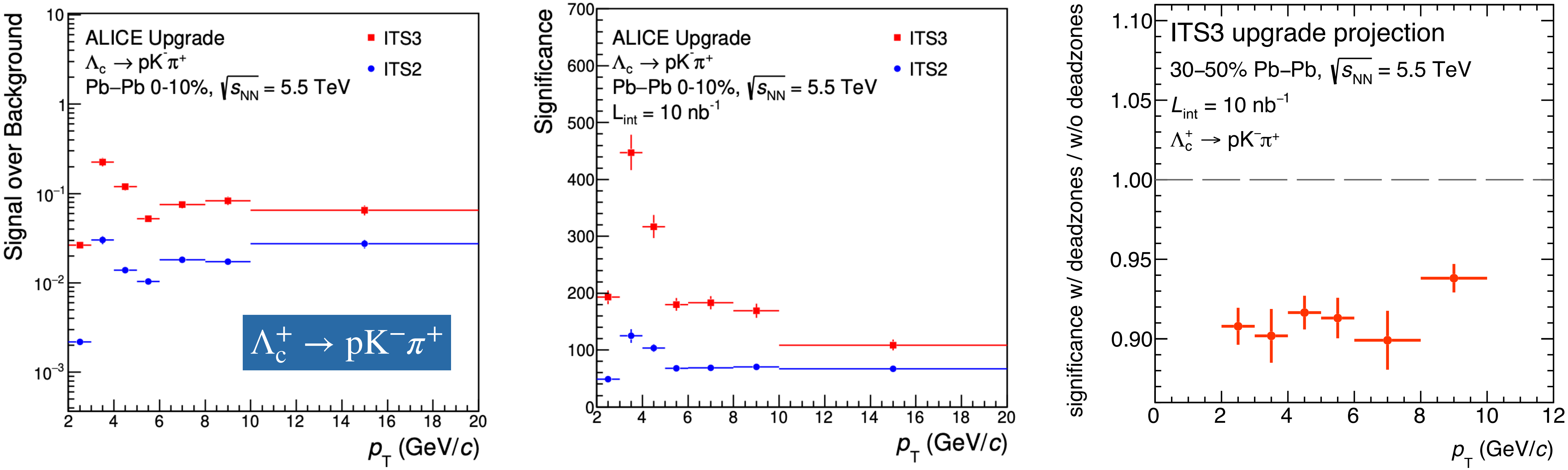


Public Note on ITS3 Physics Performance ALICE-PUBLIC-2023-002

- Λ_c^+ reconstruction as an example
- Nice benchmark to evaluate the improvement
  - ➡ Large 3-prong combinatorial background
  - ➡ Measurement of primary and decay vertices can benefit from ITS upgrades.

*Signal and background yields estimated in an invariant-mass interval of ±3σ around the Λ_c^+ mass

Physics performance — Heavy flavor hadron reconstruction



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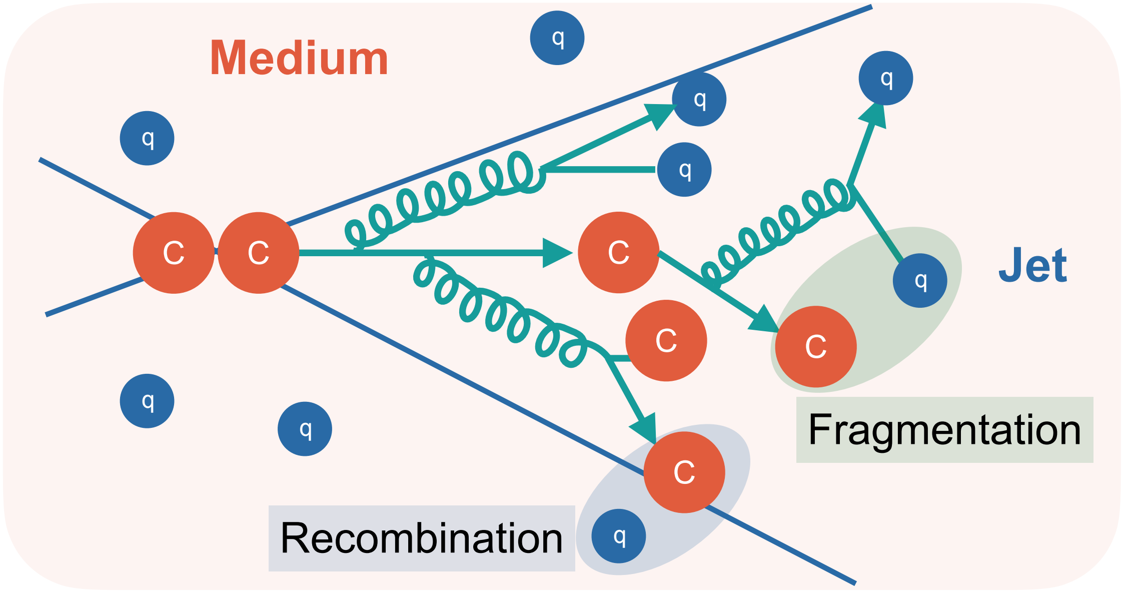
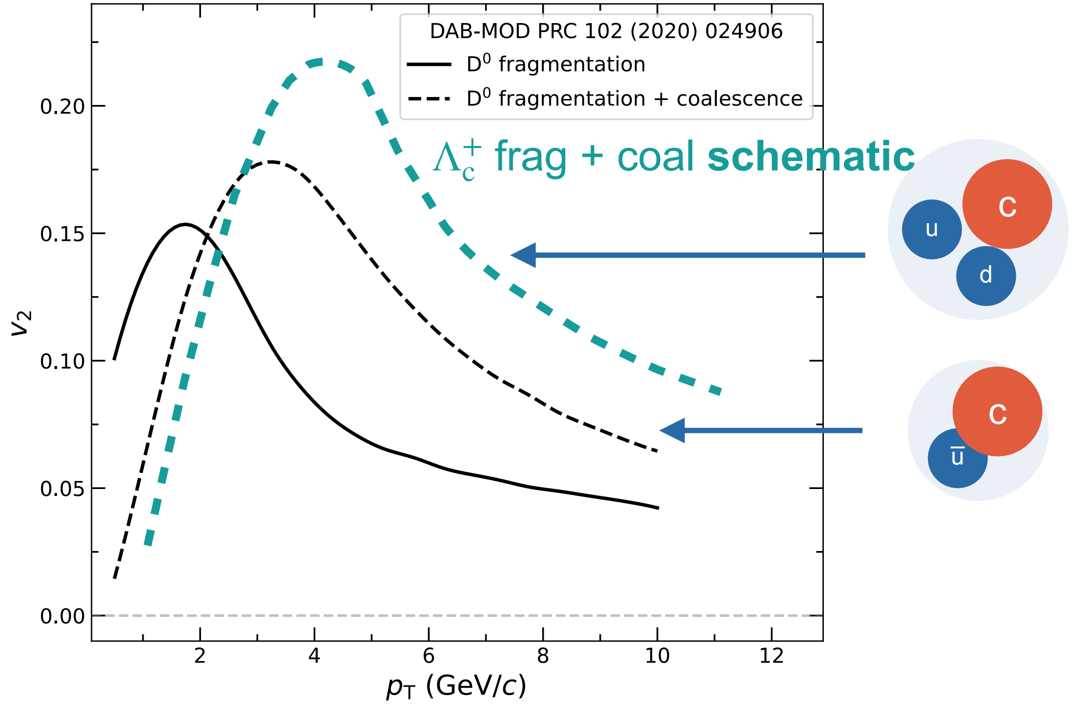
- Λ_c^+ reconstruction as an example
- Nice benchmark to evaluate the improvement
  - ➡ Large 3-prong combinatorial background
  - ➡ Measurement of primary and decay vertices can benefit from ITS upgrades.

- A factor of ~10 for the improvement on the S/B
- A factor of ~4 for the improvement on the significance
- Impact of deadzones negligible compared to the improvement between ITS2 and ITS3

*Signal and background yields estimated in an invariant-mass interval of ±3σ around the Λ_c^+ mass

Physics reach — Heavy flavor collectivity





Heavy-quark hadronization from the medium

Fragmentation $D_{q \to h}(z_q, Q^2)$

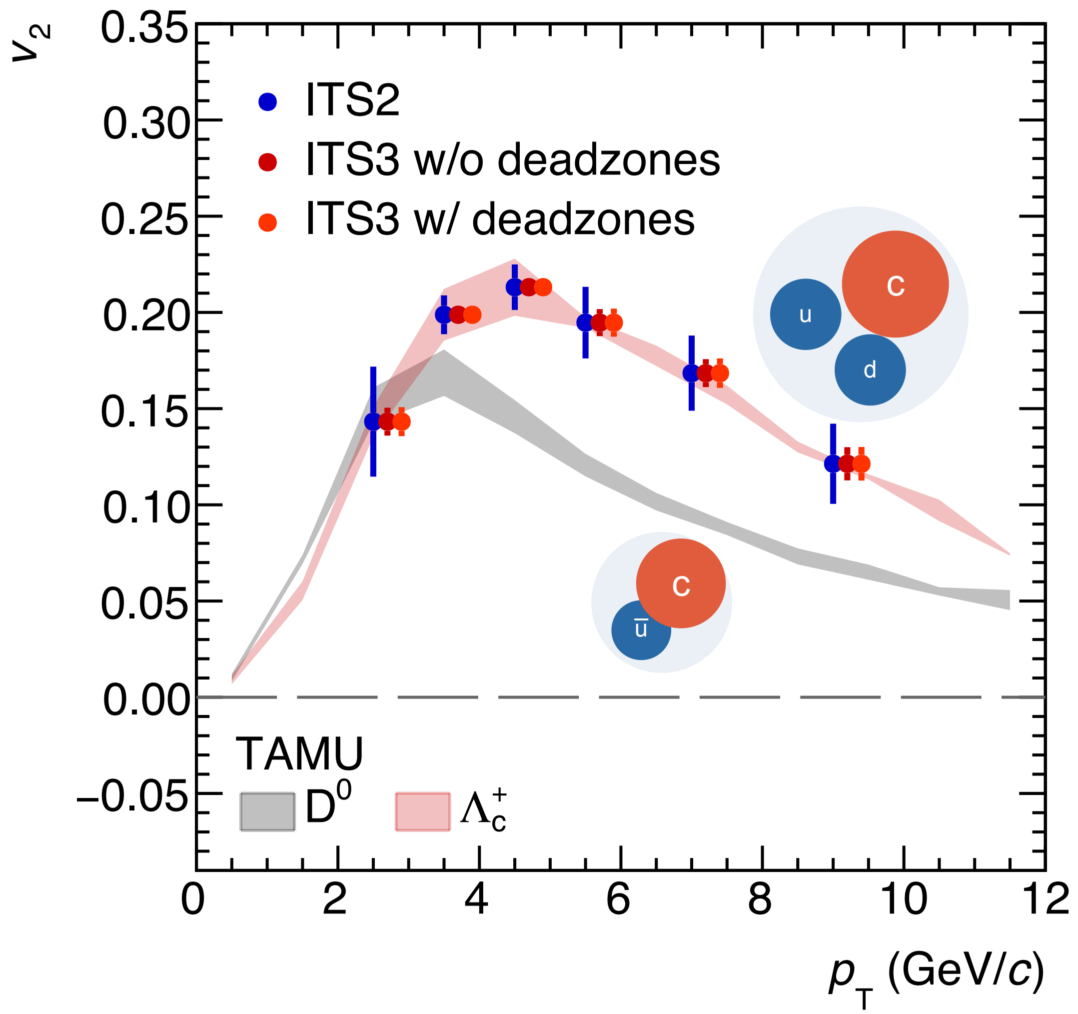
A fraction of the parton momentum z_q is taken by the hadron

Recombination/coalescence

Partons close in phase space can recombine

- Recombination of c-quarks with the medium light quarks could cause charm hadrons to partly inherit the flow of light quarks.
- Λ_c^+ (udc) has one more light quark than D^0, may inherit more "collective" characteristics of light quarks.

Physics reach — Heavy flavor collectivity



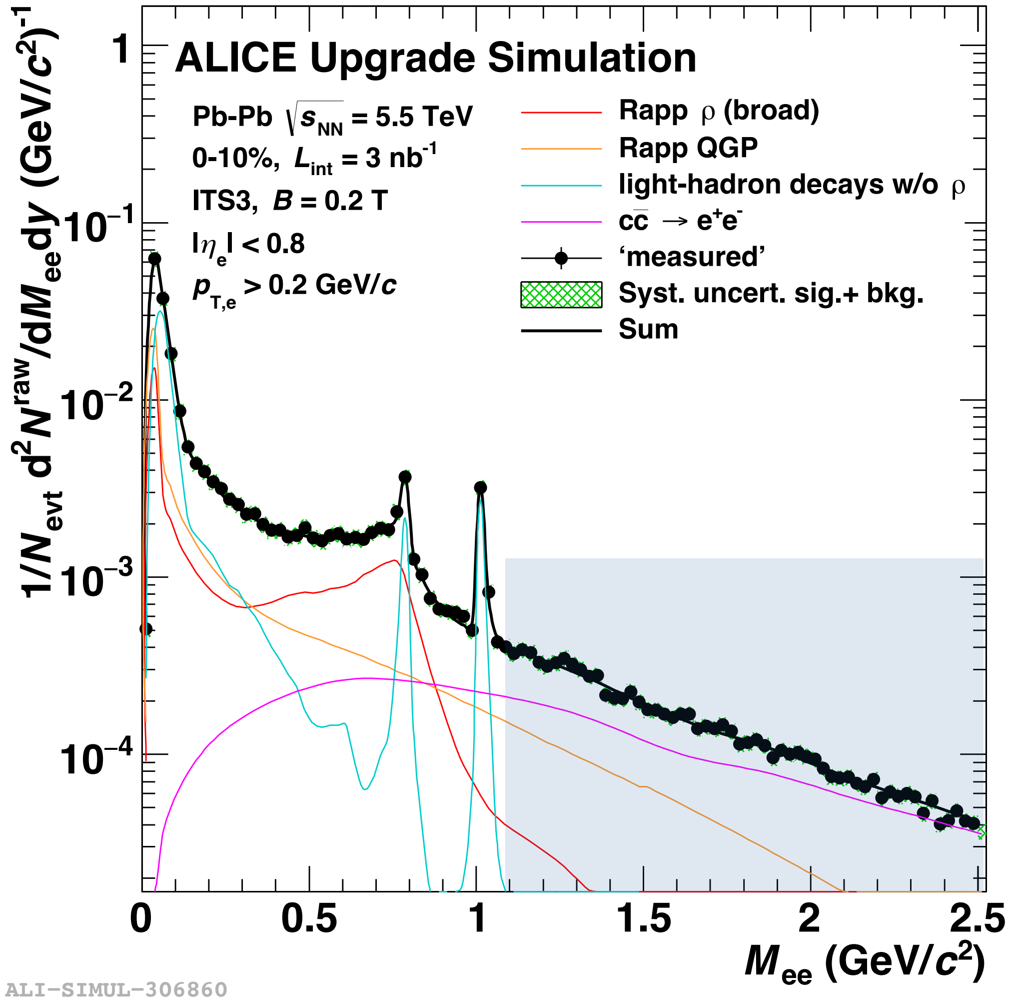
Expected to get a difference $\Delta v_2 \approx 0.03$ between D^0 and Λ_c^+ by TAMU Model*

* M. He and R. Rapp, PRL 124, 042301 (2020)

- Up to a factor of 4 reduction of the statistical uncertainty
- Impact of deadzones in ITS3 is negligible

Able to constrain the modeling of charm diffusion and hadronization in the QGP

Physics reach — Thermal dielectron measurement



ALI-SIMUL-306860

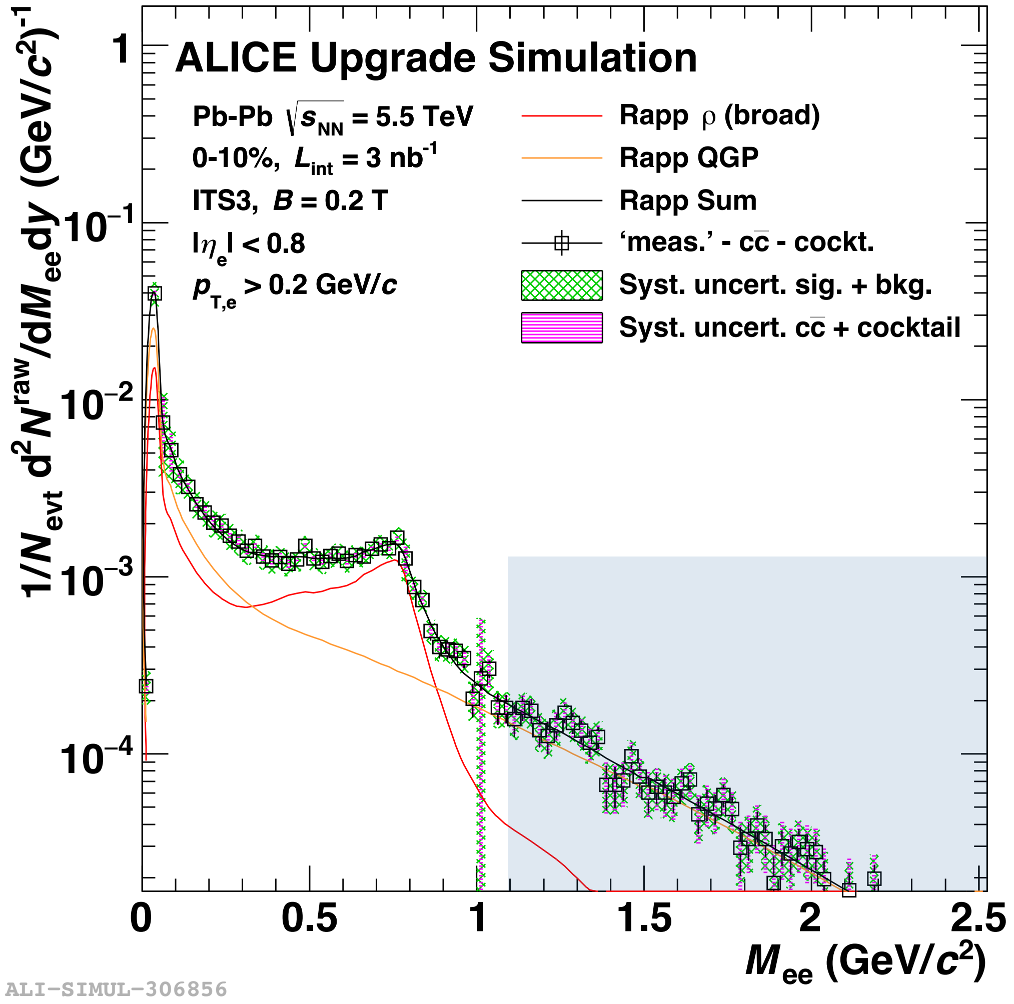
Complex invariant mass spectrum of e^+e^- pairs

- ➡ Light-flavor hadron decays
- ➡ Heavy-flavor hadron decays (suppressed using DCA to primary vertex)
- ➡ Thermal radiations:
  - ➡ from hadron gas
  - ➡ from QGP

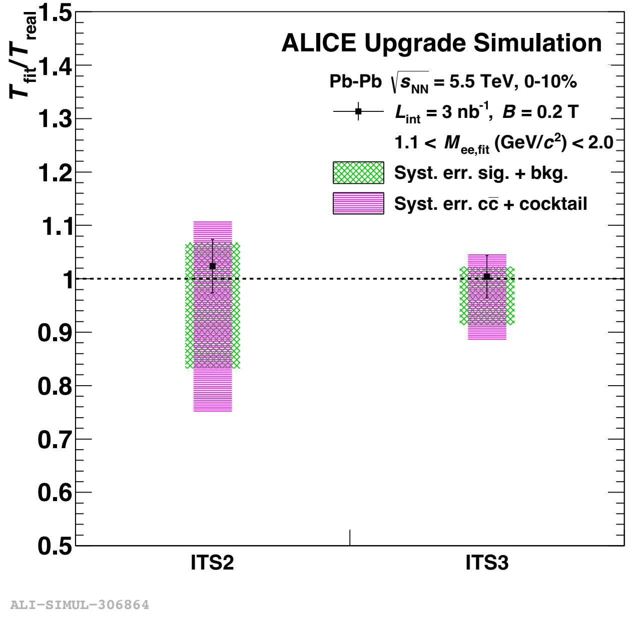
In the region where M_{ee} > 1.1GeV/c^2

- The $c\bar{c} \rightarrow e^+e^-$ process and the thermal radiations from QGP dominate
- Suitable for extracting the QGP temperature

Physics reach — Thermal dielectron measurement



- Less material results in fewer electrons from photon conversions.
- Enhanced low-p_T electron tracking improves photon conversion reconstruction efficiency, reducing the combinatorial background.
- Improved DCA resolution suppresses contributions from heavy-flavor hadron decays.

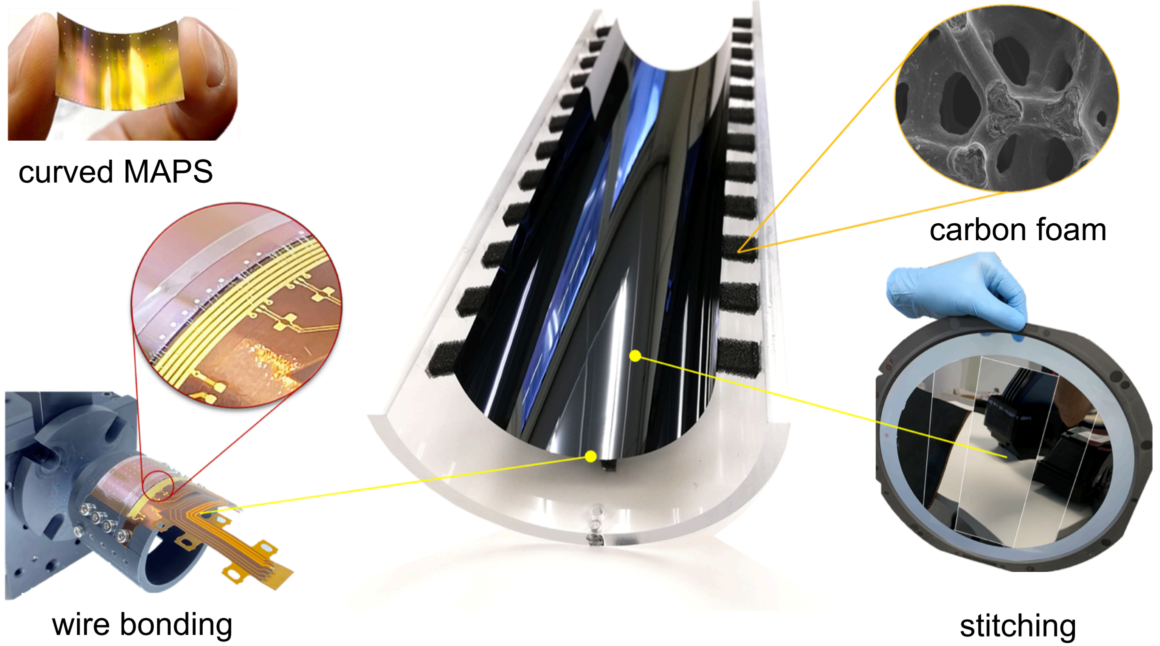


The systematic uncertainty with ITS3 reduced by a factor of 2 compared to ITS2

Outlook: $p_{T,ee}$ differential measurement with ALICE 3, see the talk by Giacomo Volpe

Summary and outlook

- **ITS3 — a bent wafer-scale monolithic pixel detector**
- **ITS3 project is on track for installation in LS3**
- **A twofold improvement in spatial resolution wrt. ITS2**
  - ➡ a significant improvement in the reconstruction of heavy flavor hadrons
- **The following analysis significantly benefit from ITS3**
  - ➡ heavy flavor collectivity
  - ➡ thermal dielectron measurement
  - ➡ and many more analyses…

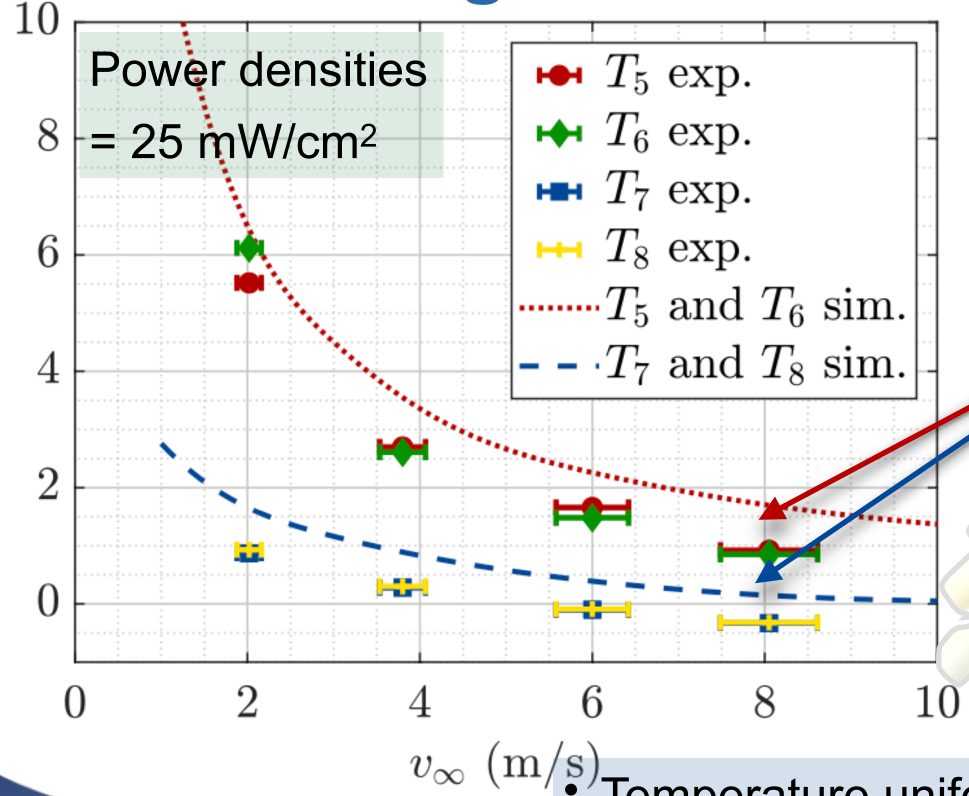


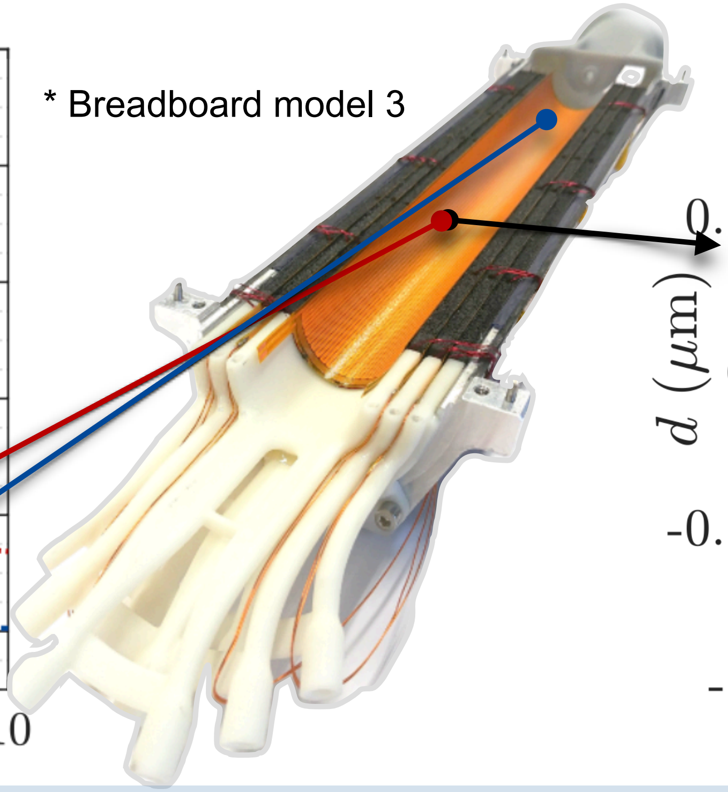
ITS3 TDR: CERN-LHCC-2024-003

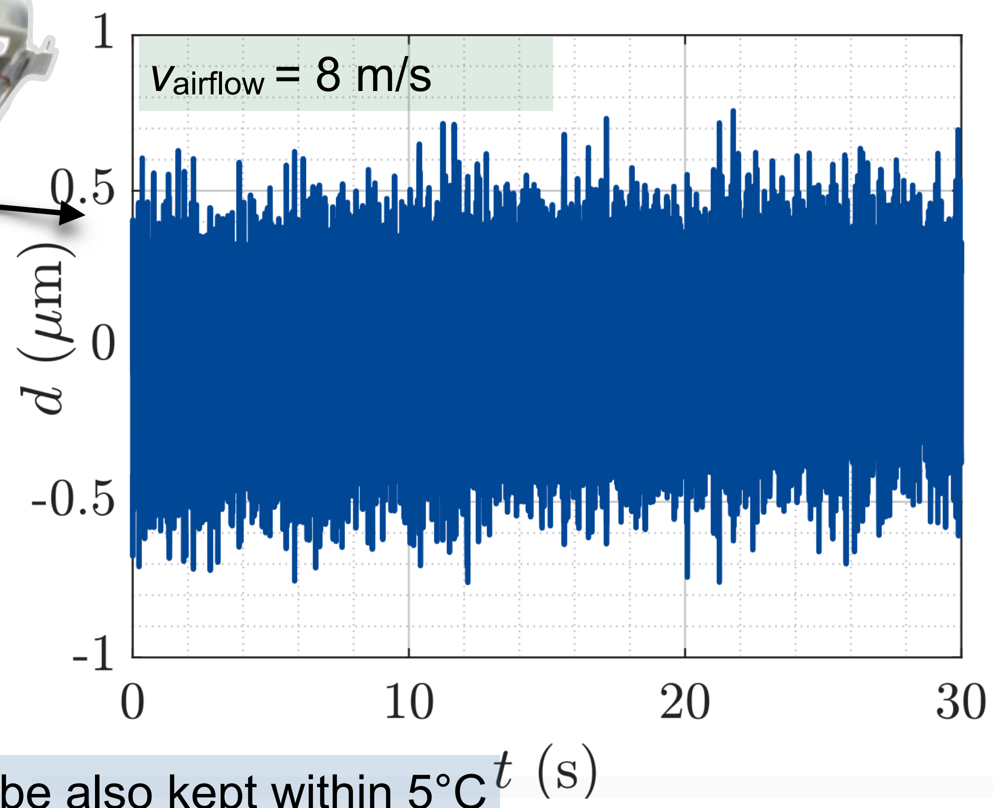
Thanks!

Backup

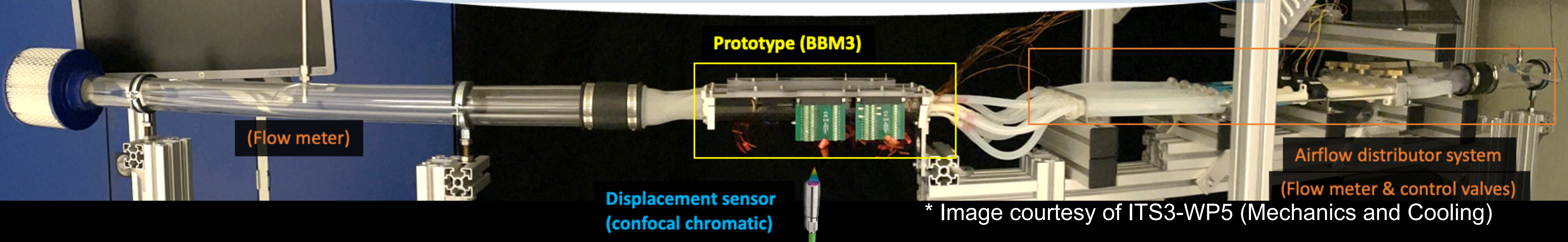
Air cooling







- Temperature uniformity along the sensor can be also kept within 5°C
- Integrated displacement RMS < 0.4μm

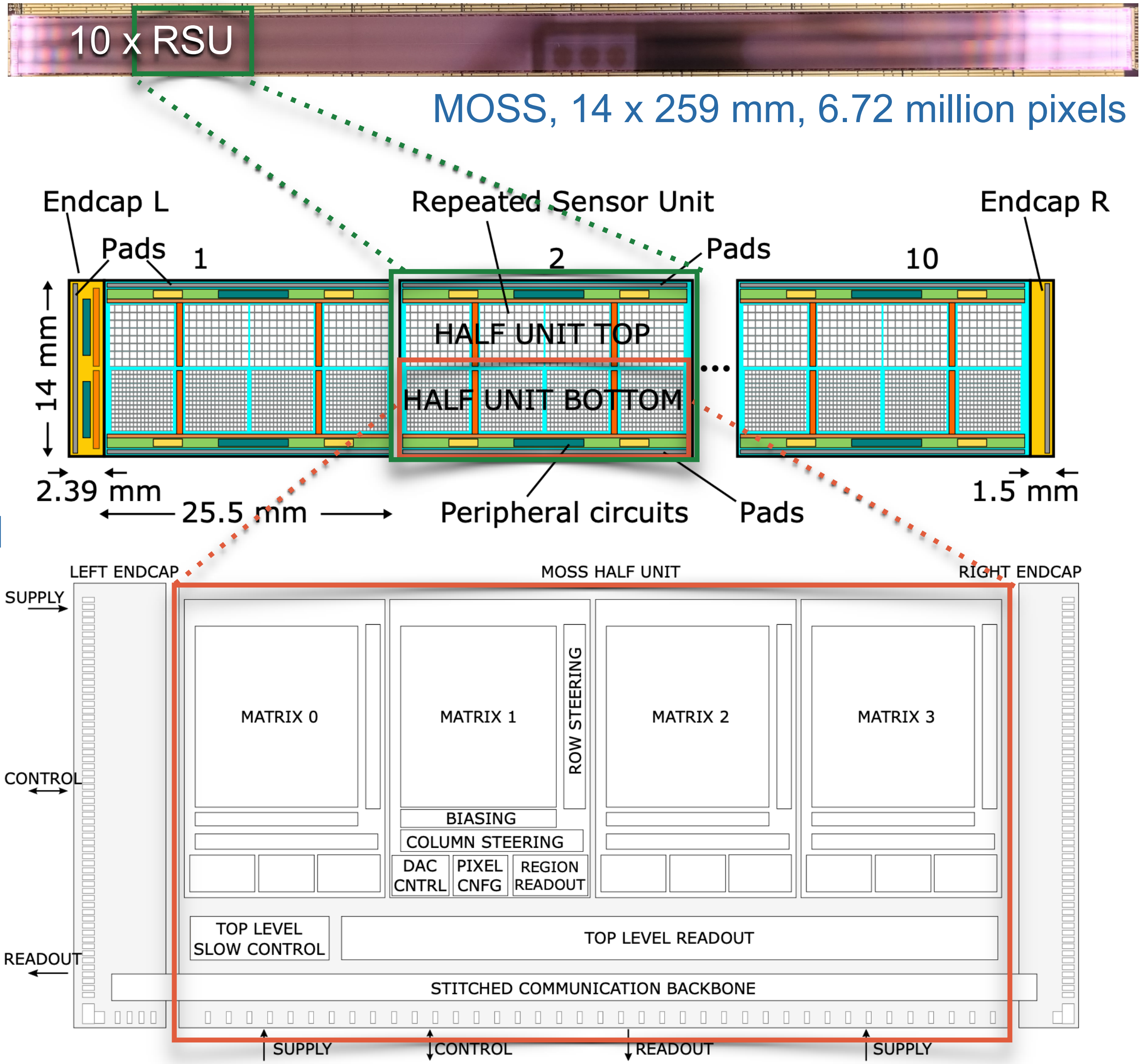


* Image courtesy of ITS3-WP5 (Mechanics and Cooling)

MOSS details

- MOSS is segmented into 10 repeated sensor units (RSUs) and the left / right end-caps (LEC / REC)
  - Each RSU split into top and bottom half units with different pitches
    - Each half unit contains 4 matrices with different distinct analog components and a top level peripheral control and readout
- Each half unit can be controlled, readout, and powered
  - by LEC (via stitched communication backbone)
  - independently, enabling separate testing to identify yield discrepancies and potential defects.

	Pixel matrix	Pixel size
Matrices on the top	256 × 256	22.5 µm
Matrices on the bottom	320 × 320	18 µm



ITS3 and sensor ASIC design parameters

Table 2.1: ITS3 general parameters.

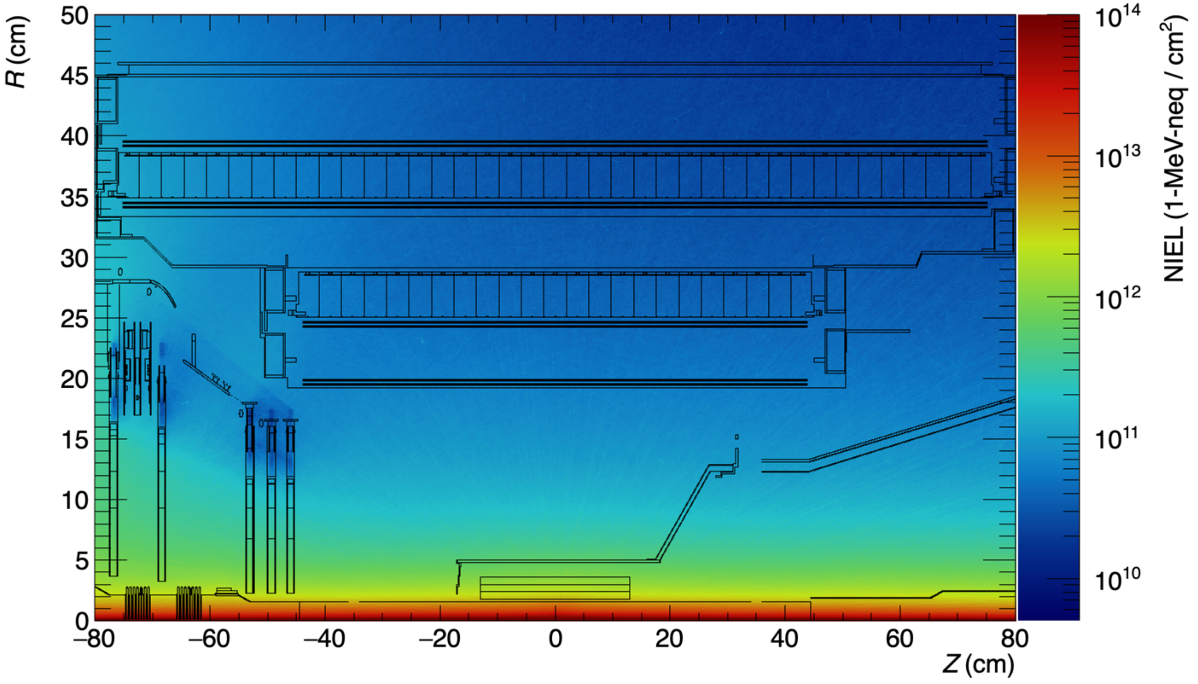
Beampipe inner/outer radius (mm)		16.0/16.5	
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	19.0	25.2	31.5
Length (sensitive area) (mm)	260	260	260
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	407	507
Pixel sensors dimensions (mm^2)	266×58.7	266×78.3	266×97.8
Number 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	

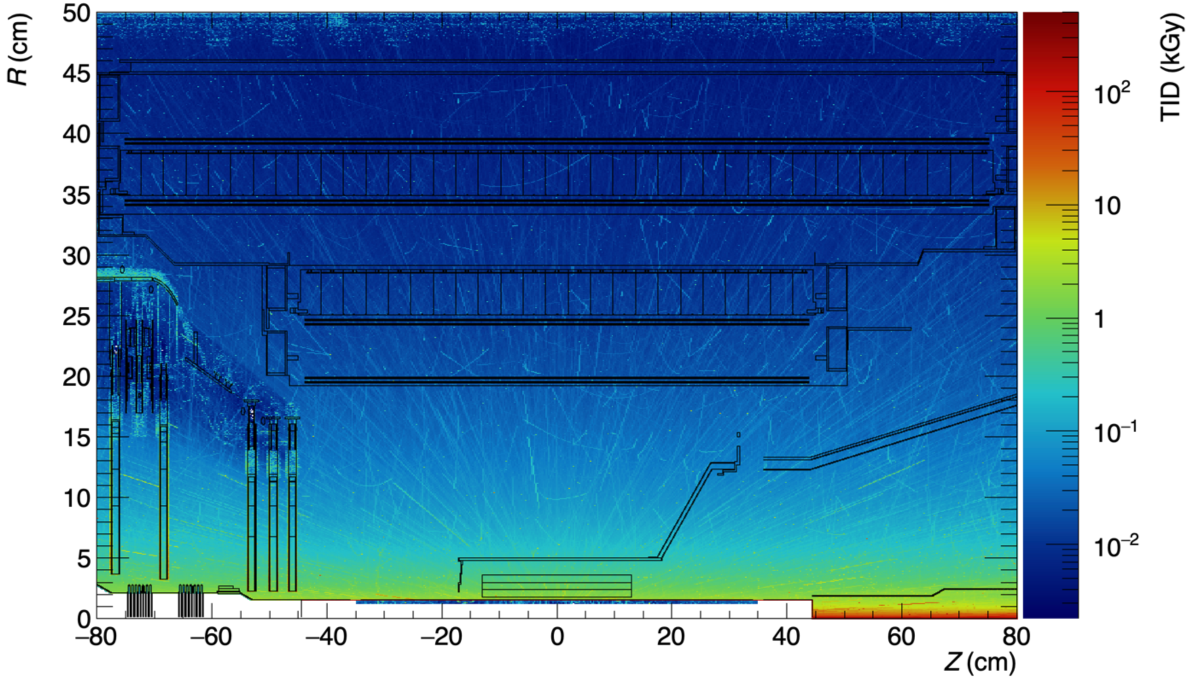
[a] The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).

Table 3.2: General requirements for the sensor ASIC design.

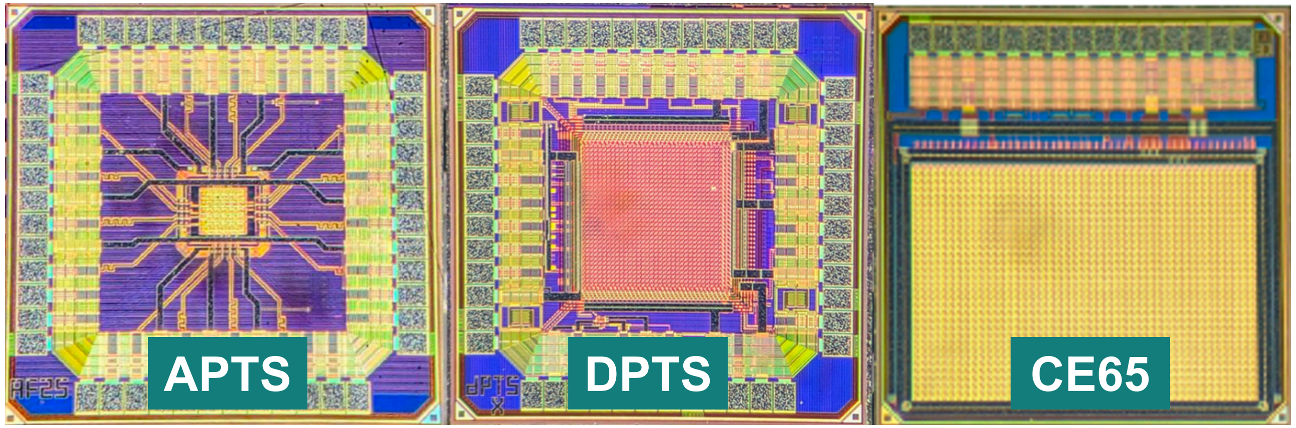
Particle Rate	
Pb-Pb Interaction Rate (average)	50 kHz
Pb-Pb Interaction Rate (expected peak rate including safety factor of 2)	164 kHz
Total particle flux (@164 kHz, Layer 0, z=0 cm)	5.75 MHz cm^{-2}
Hadronic flux (all centralities, @164 kHz, Layer 0, z=0 cm)	2.55 MHz cm^{-2}
QED electrons flux (@164 kHz, Layer 0, z=0 cm)	3.20 MHz cm^{-2}
Detection Performance	
Single point resolution	$\lesssim$ 5 µm
Pixel pitch	< 25 µm
Fill factor (fractional sensitive area)	> 92%
Detection efficiency	> 99%
Fake-hit rate	< 0.1 $pixel^{-1}$ s^{-1}
Fake-hit occupancy (10 µs Frame Duration)	< 10^{-6} $pixel^{-1}$ $frame^{-1}$
Frame duration programmable	2 – 10 µs
Readout Efficiency	
Fraction of Pb-Pb interactions fully recorded, Layer 0	> 99.9%
Fraction of incomplete Pb-Pb interactions, Layer 0	< 1×10^{-3}
Power Budget	
Power Dissipation Density, Active Region	< 40 mW cm^{-2}
Power Dissipation Density, Peripheral Region	< 1000 mW cm^{-2}
Radiation Load	
NIEL	10^{13} 1 MeV n_{eq} cm^{-2}
TID	10 kGy
Environmental Conditions	
Target Operating Temperature	15 °C to 30 °C

Radiation load simulation



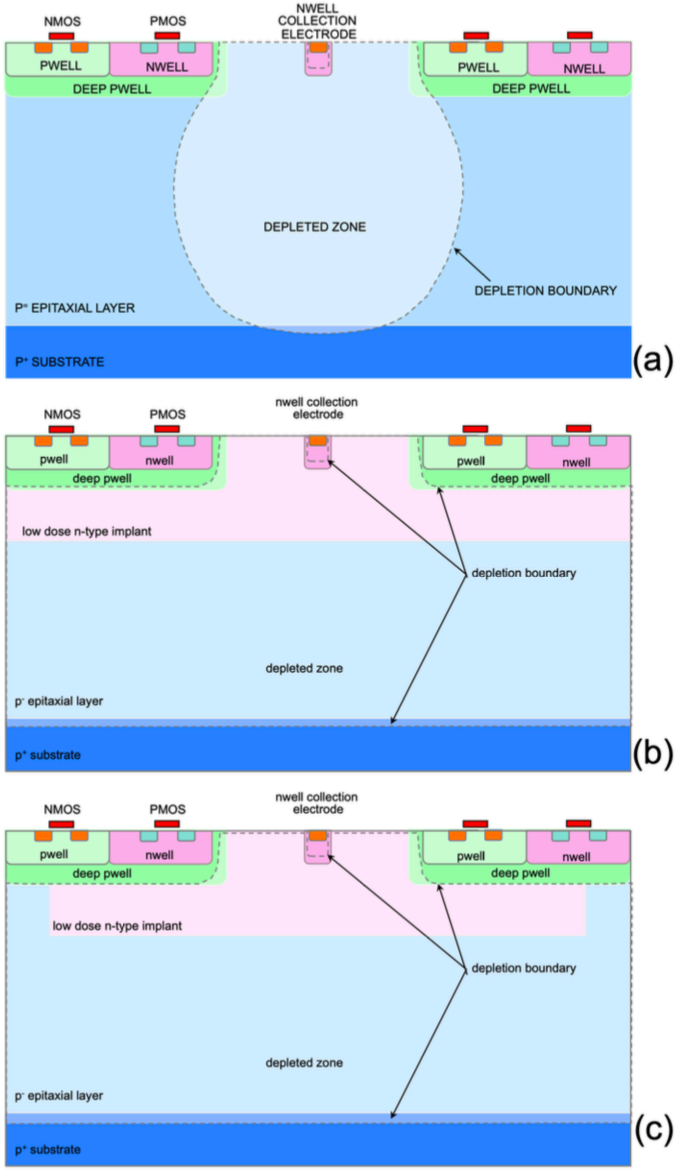


MLR1 chips



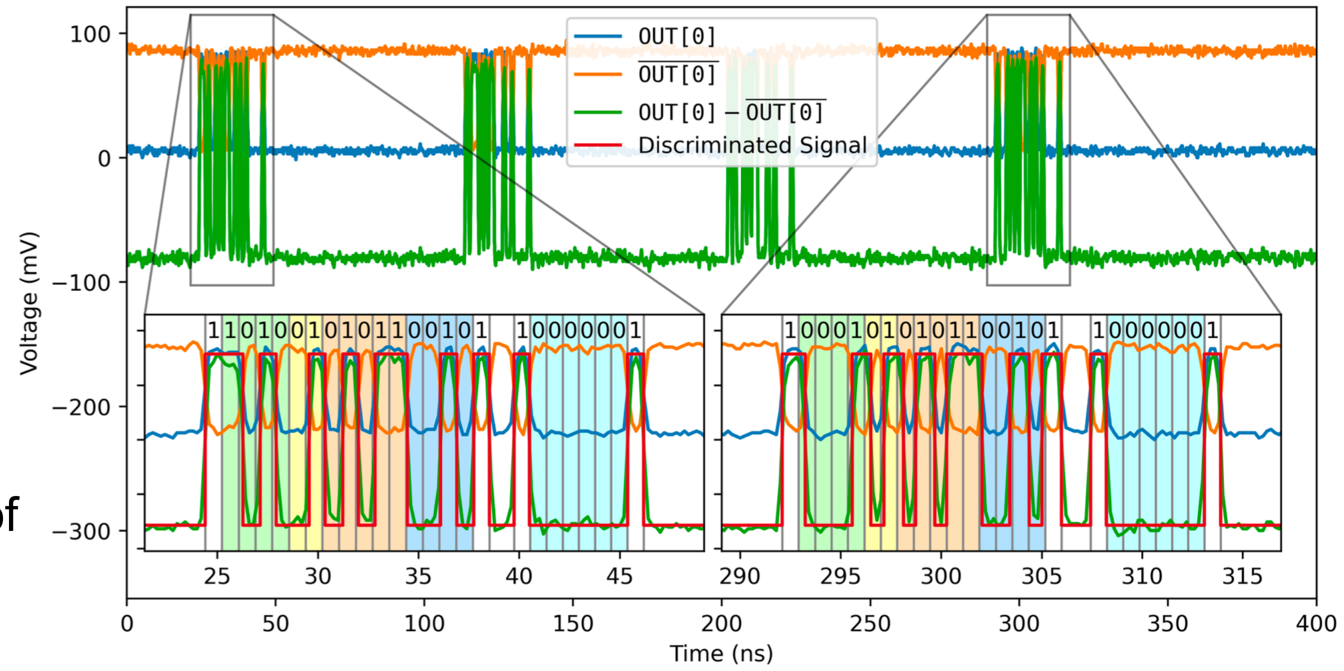
After an incredible work and effort from all the institutes involved, the **65 nm technology is validated for ITS3:**

- **APTS-SF** allowed us to establish the **most suited chip** variant in terms of performance: modified with gap, split 4, reference collection diode geometry
- **APTS-OA** enabled all the time response studies, useful beyond ITS3
- **CE65** explored different processes and pitches, confirming what observed also in other test structures
- **DPTS** was crucial for detection efficiency, spatial resolution, cluster size and radiation hardness evaluation, satisfying all the ITS3 requirements



MOST (ER1) test results

- Very densely integrated pixel matrix
  - 259 mm × 2.5 mm, 0.9 million pixels
- Power is distributed globally
  - yield is addressed by a highly granular set of switches that allow to turn off faulty parts locally
- Readout is purely asynchronous and hit-driven
  - low power consumption + timing information



Example address pulse trains from the digital pulsing of four different pixels of MOST, demonstrating a correct communication across stitching boundaries and along the chip length of 26 cm.

Detector interface with the beampipe during installation