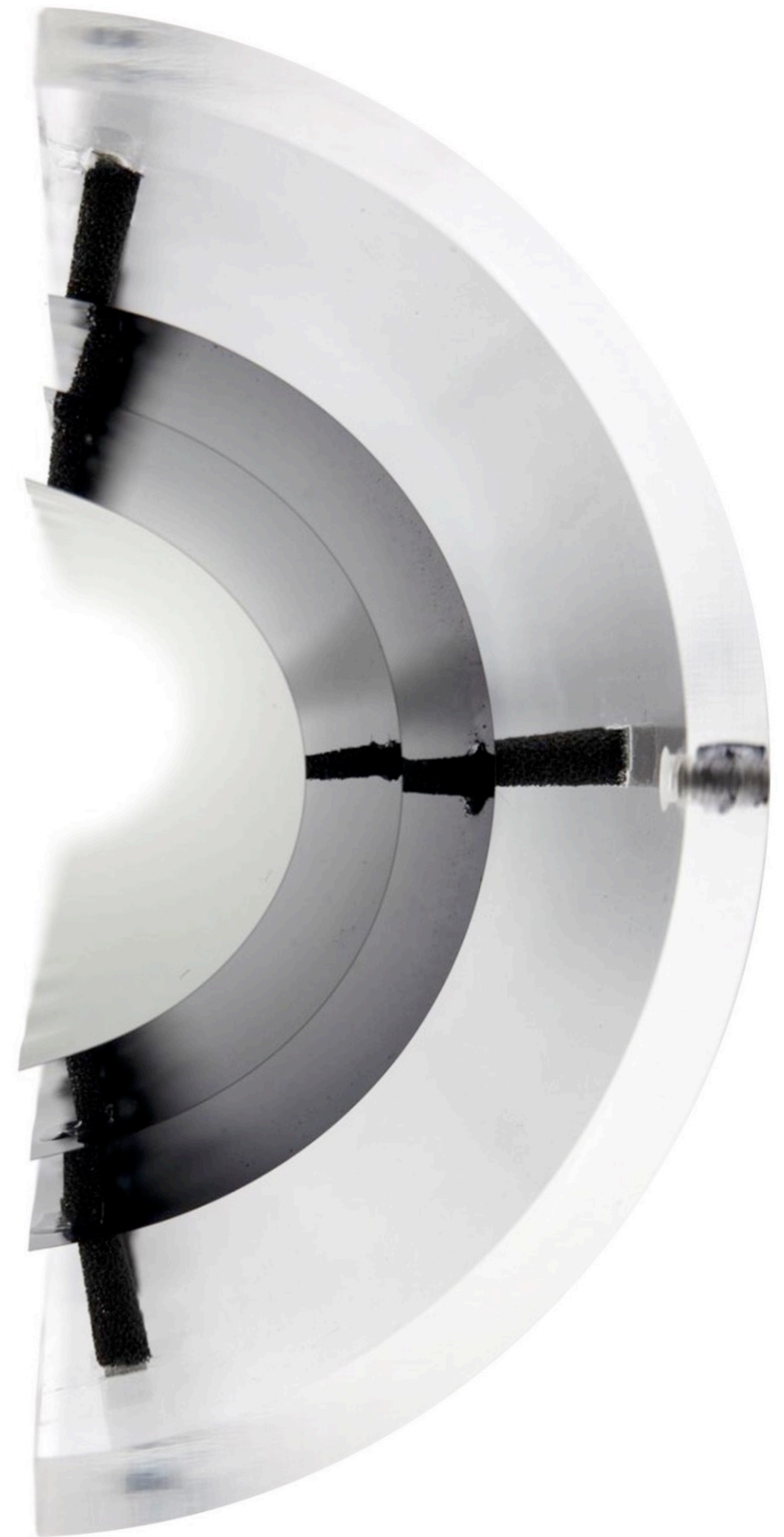
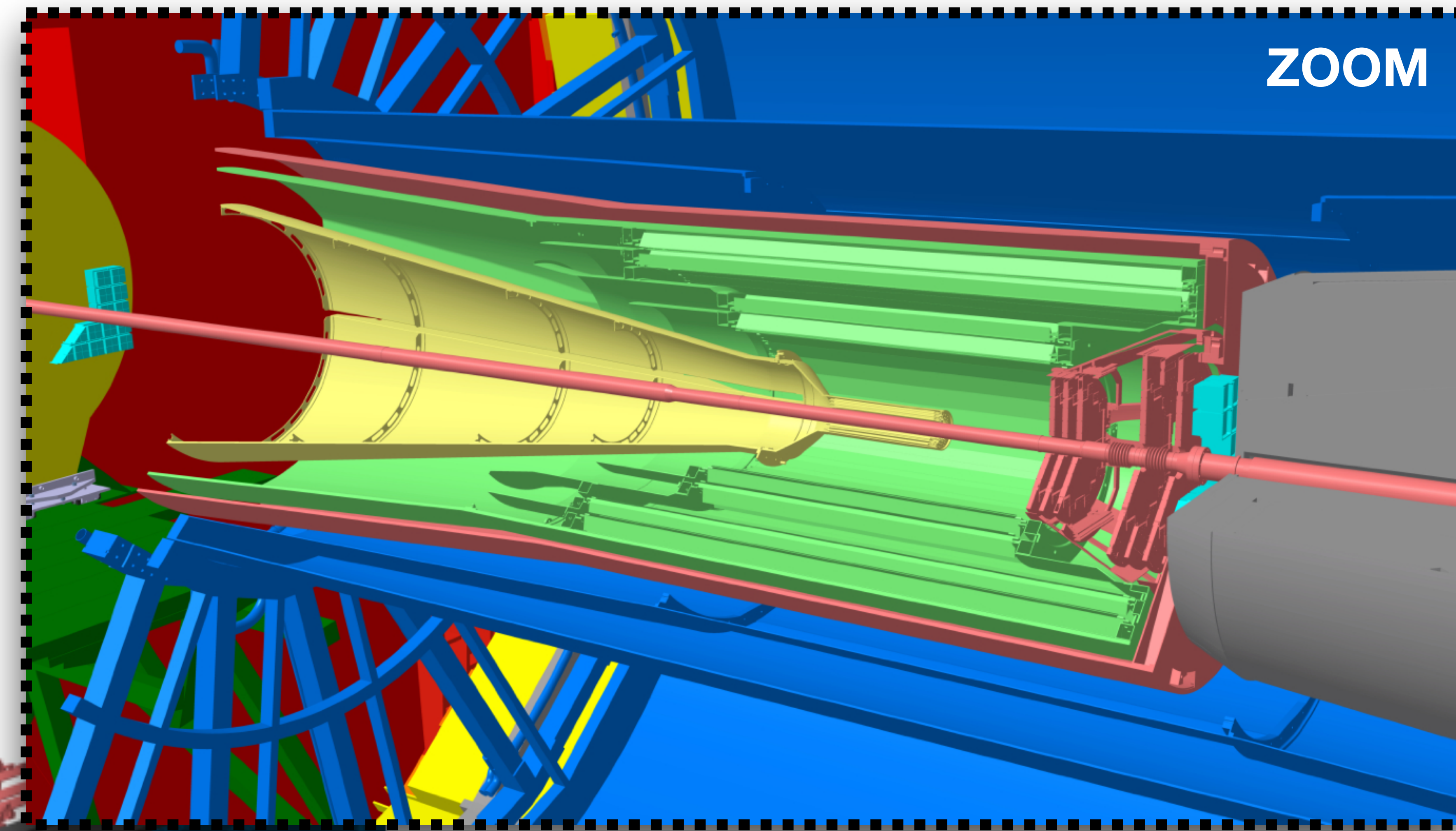
Design and expected performance of the ALICE ITS3 tracker upgrade

Bong-Hwi Lim (INFN Torino)
on behalf of ALICE collaboration

24/09/2024



The ALICE experiment



- Study of **strongly interacting matter at extreme densities (QGP)** in heavy-ion collisions at the LHC (CERN)
- **Very high multiplicities:** tracking of up to O(10k) particles in single event
- Charm and beauty hadron reconstruction
- Low momentum (≲1GeV/c) particle reconstruction

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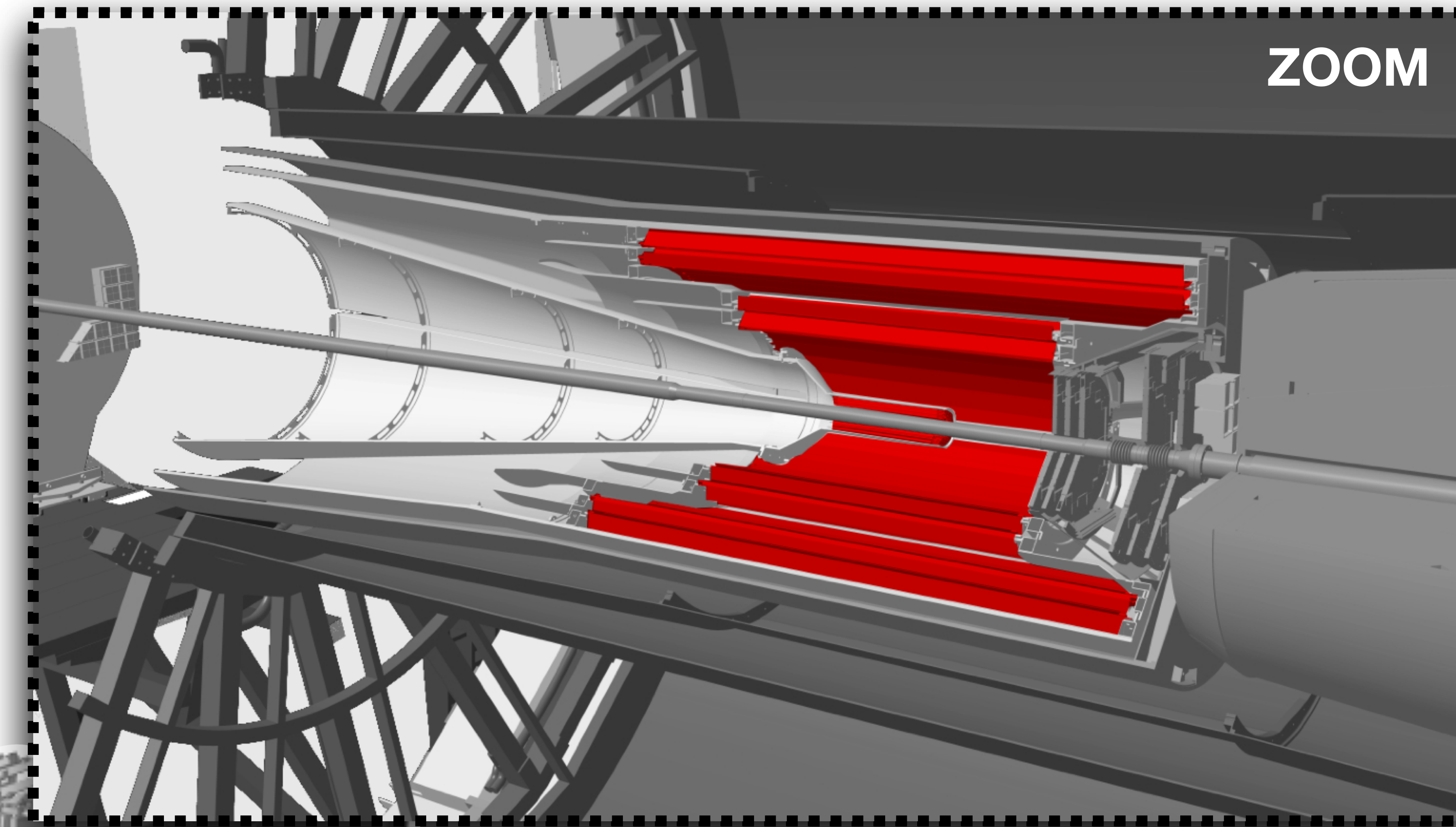

ZOOM

Inner Tracking System (ITS)

- Study of **strongly interacting matter at extreme densities (QGP)** in heavy-ion collisions at the LHC (CERN)
- **Very high multiplicities:** tracking of up to O(10k) particles in single event
- Charm and beauty hadron reconstruction
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What will be changed?

Conceptual understanding of ITS3

ALICE, CERN-LHCC-2019-018, 2019

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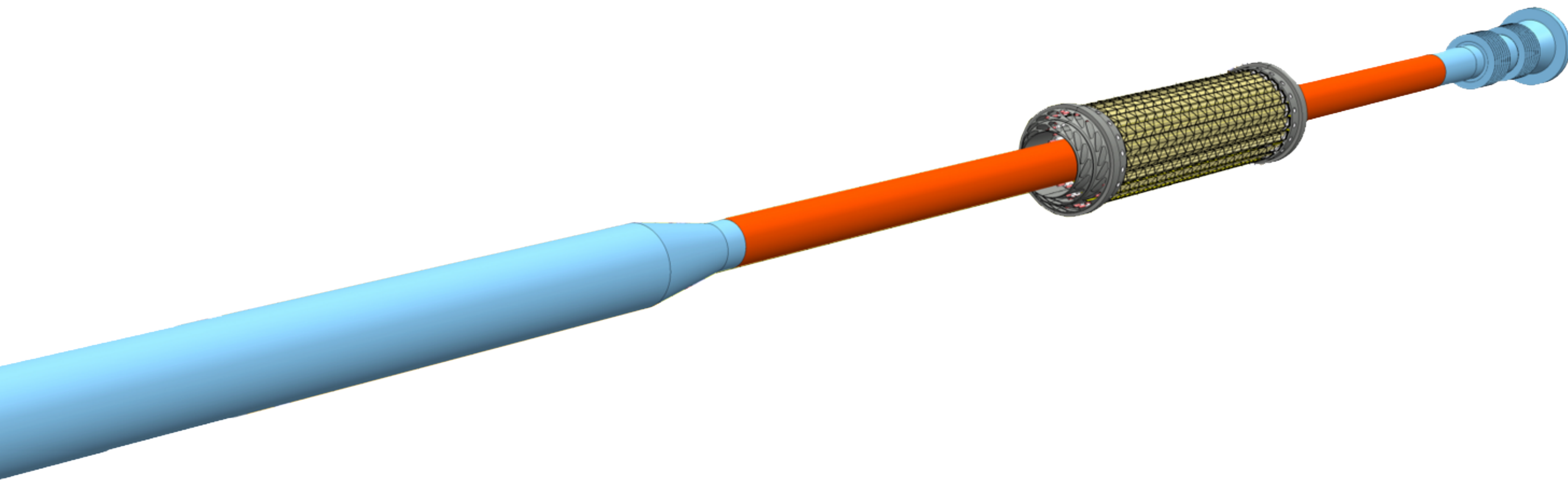

ALICE, CERN-LHCC-2019-018, 2019

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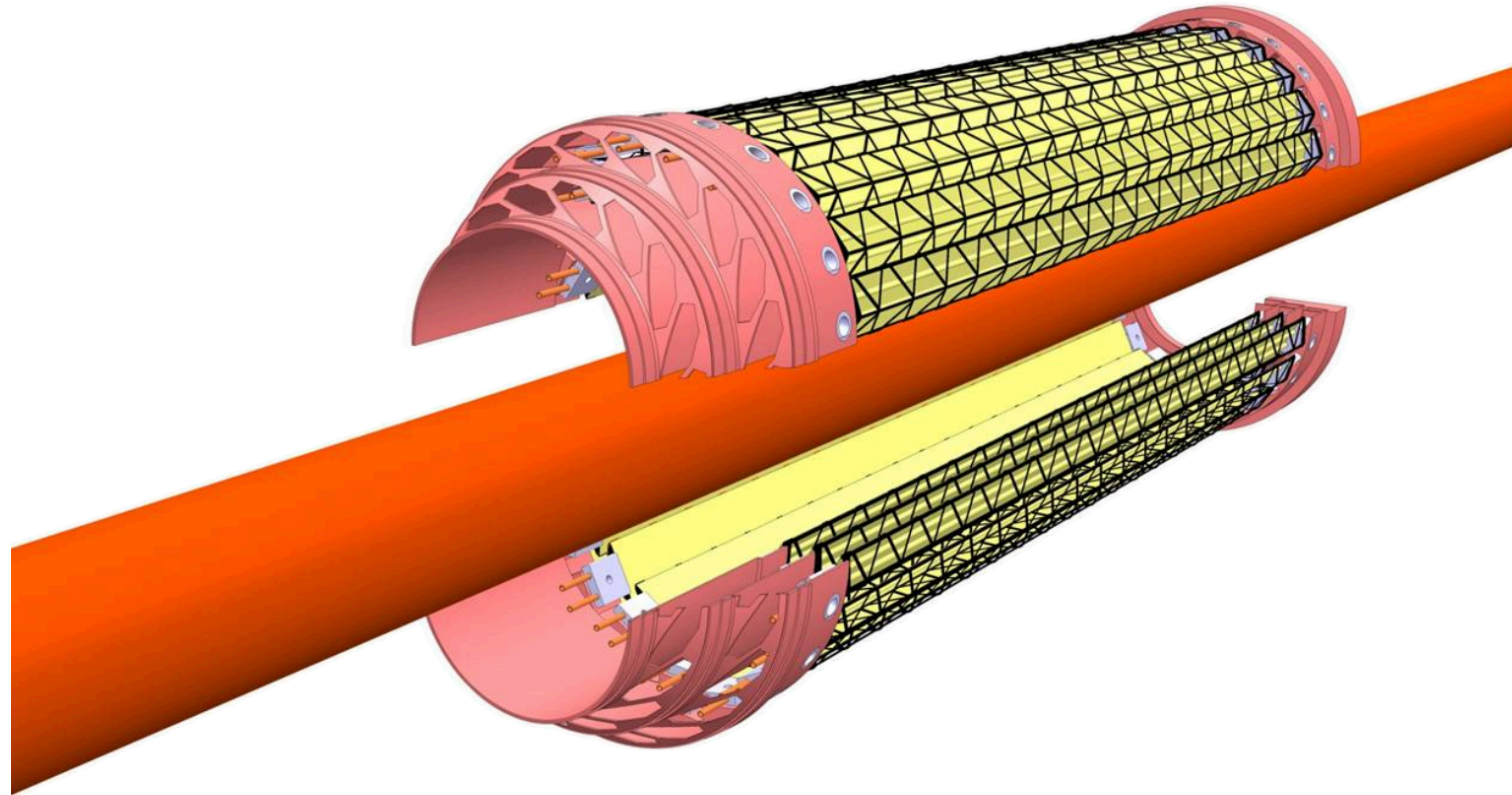

ITS Inner barrel

ALICE, CERN-LHCC-2019-018, 2019

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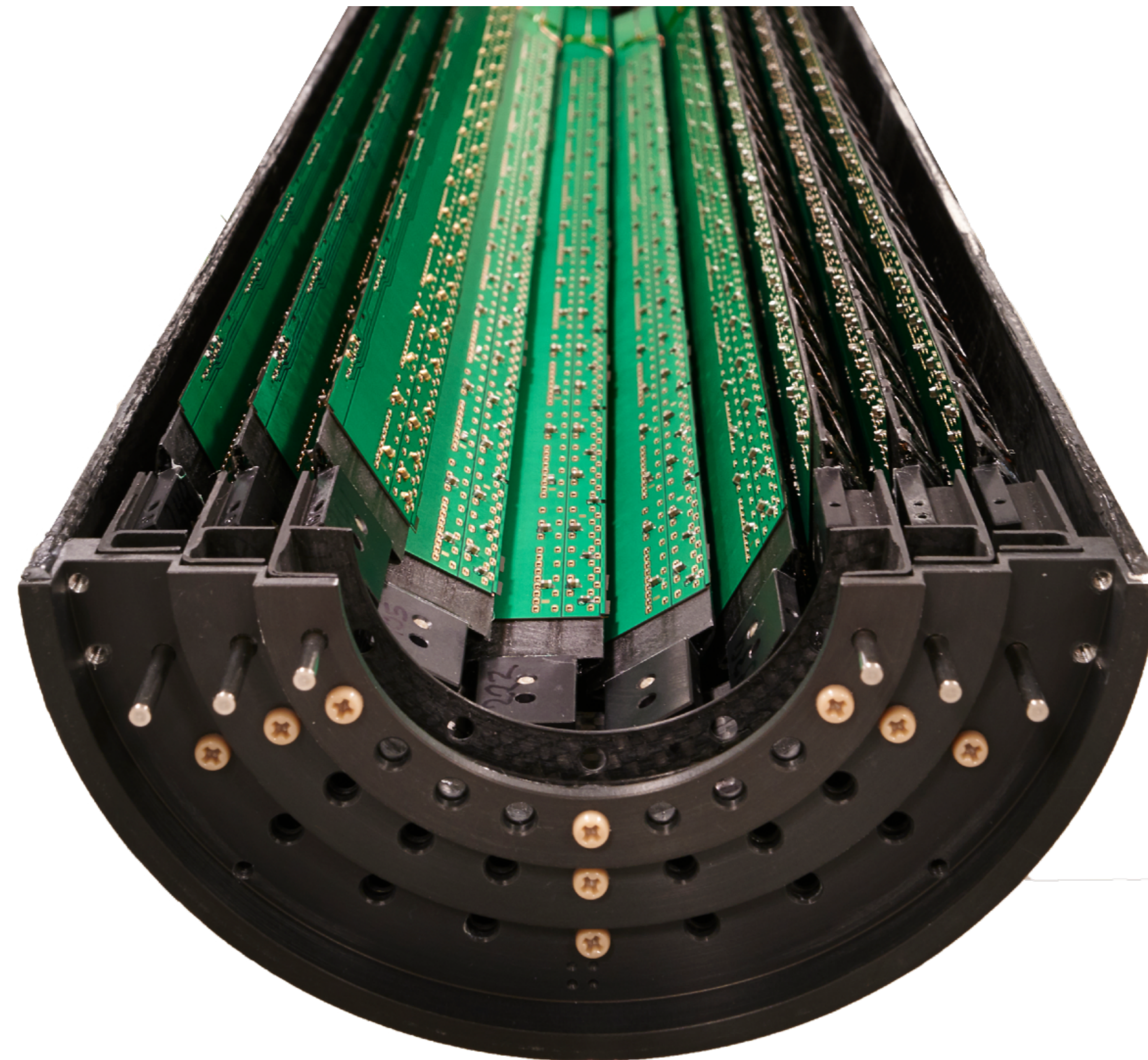

ITS half IB

ALICE, CERN-LHCC-2019-018, 2019

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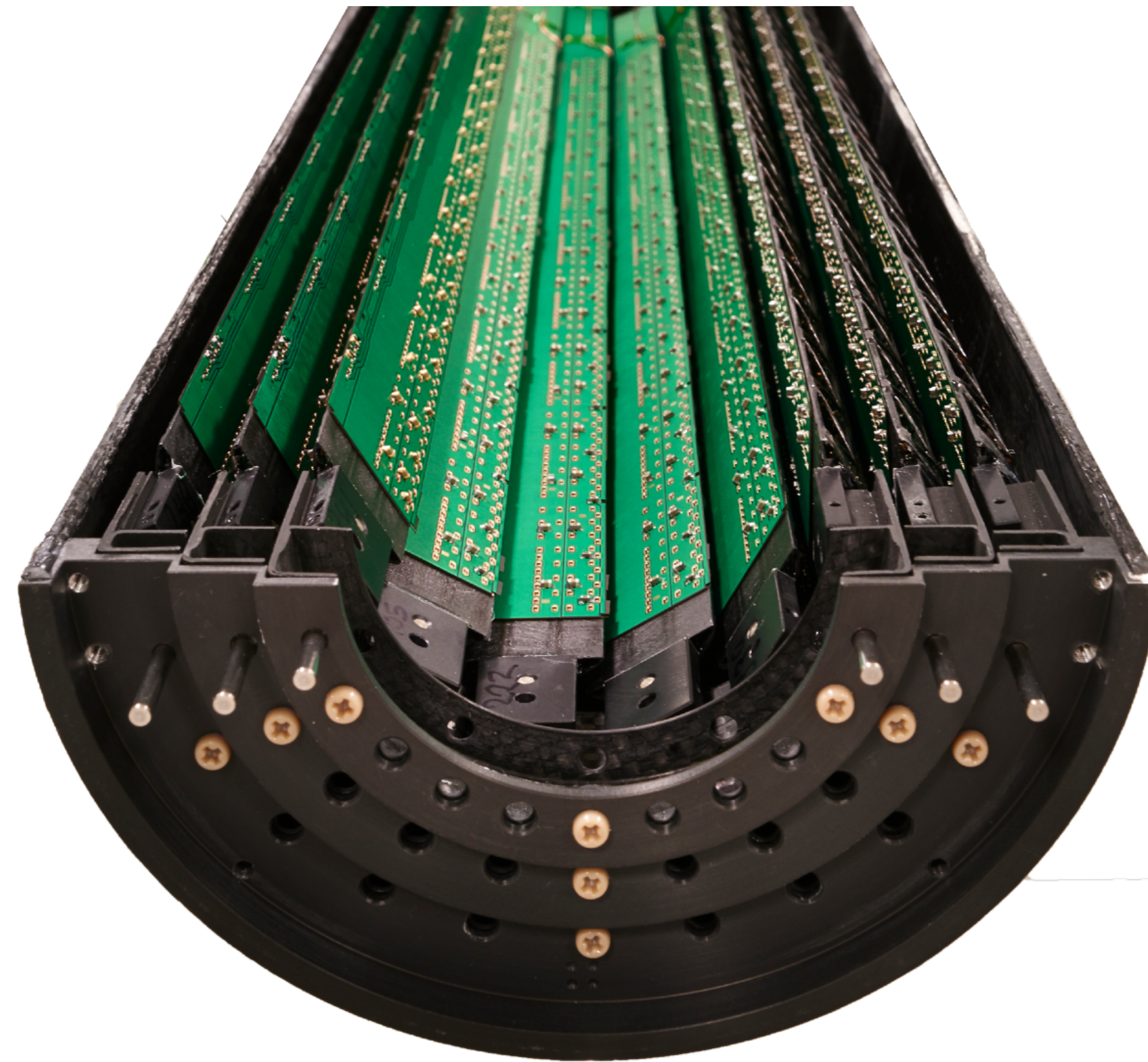

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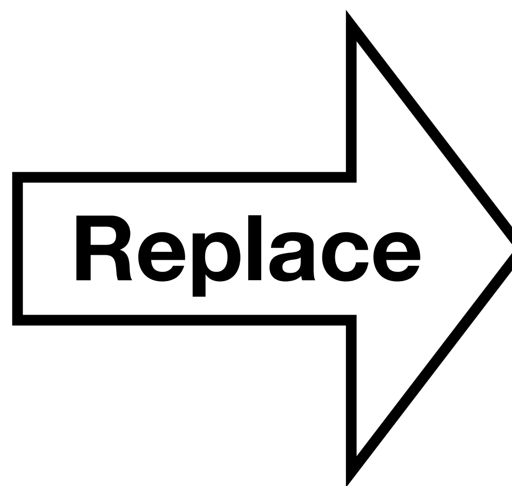

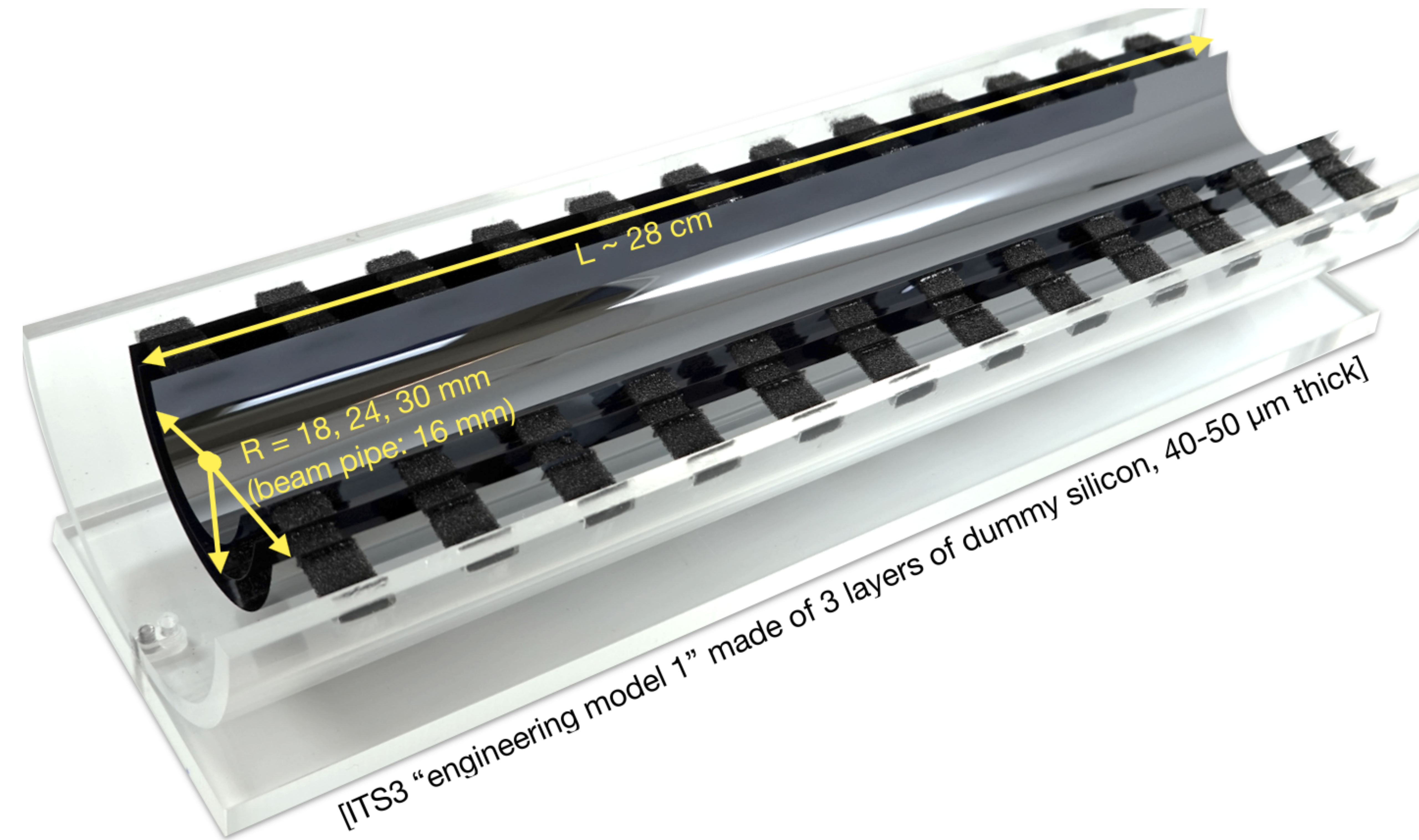

- Replace the inner barrel (3 layers) of the current ITS → new 3 layers of ITS3 (wafer-scale size one chip)

ALICE, CERN-LHCC-2019-018, 2019

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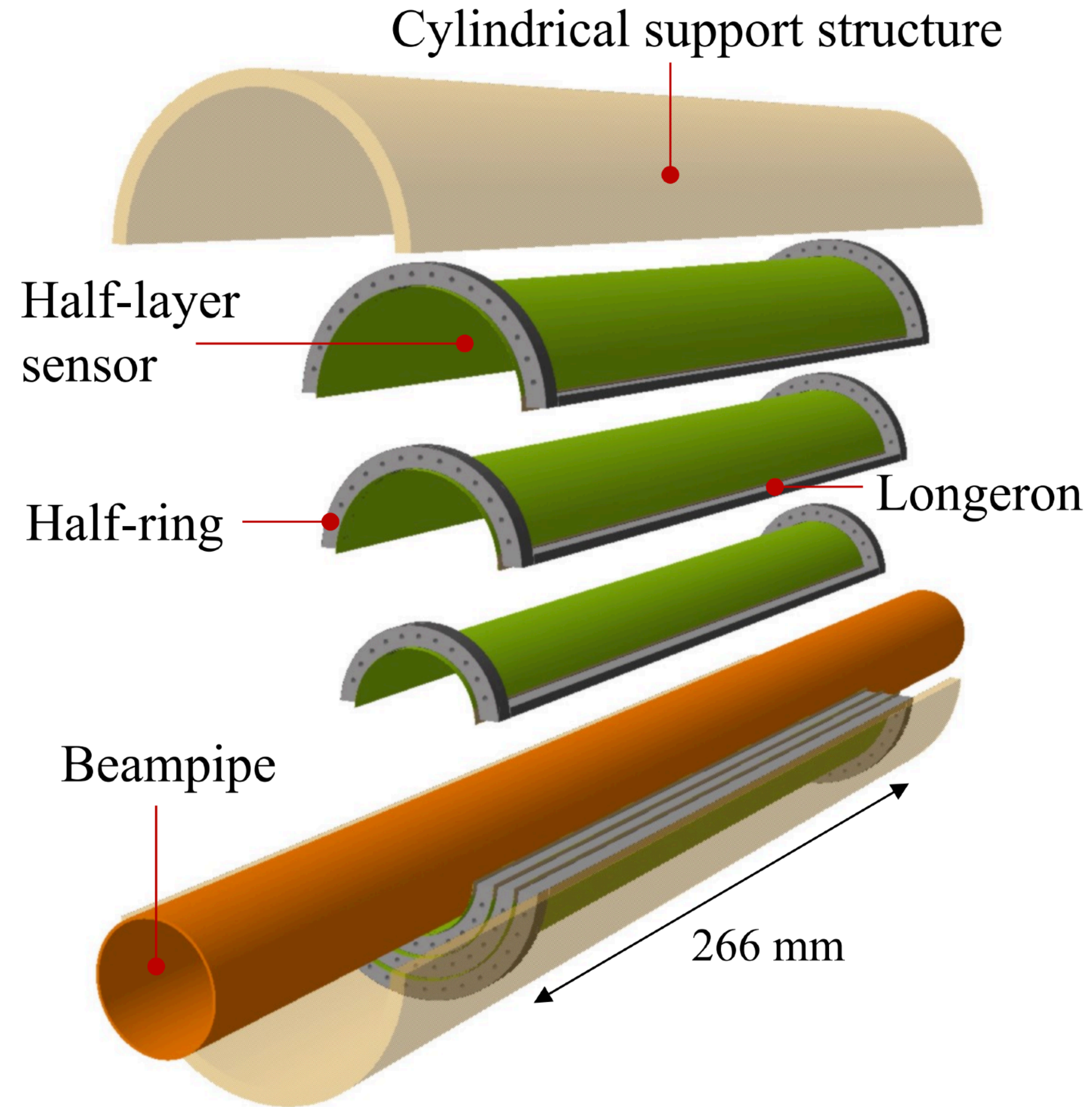

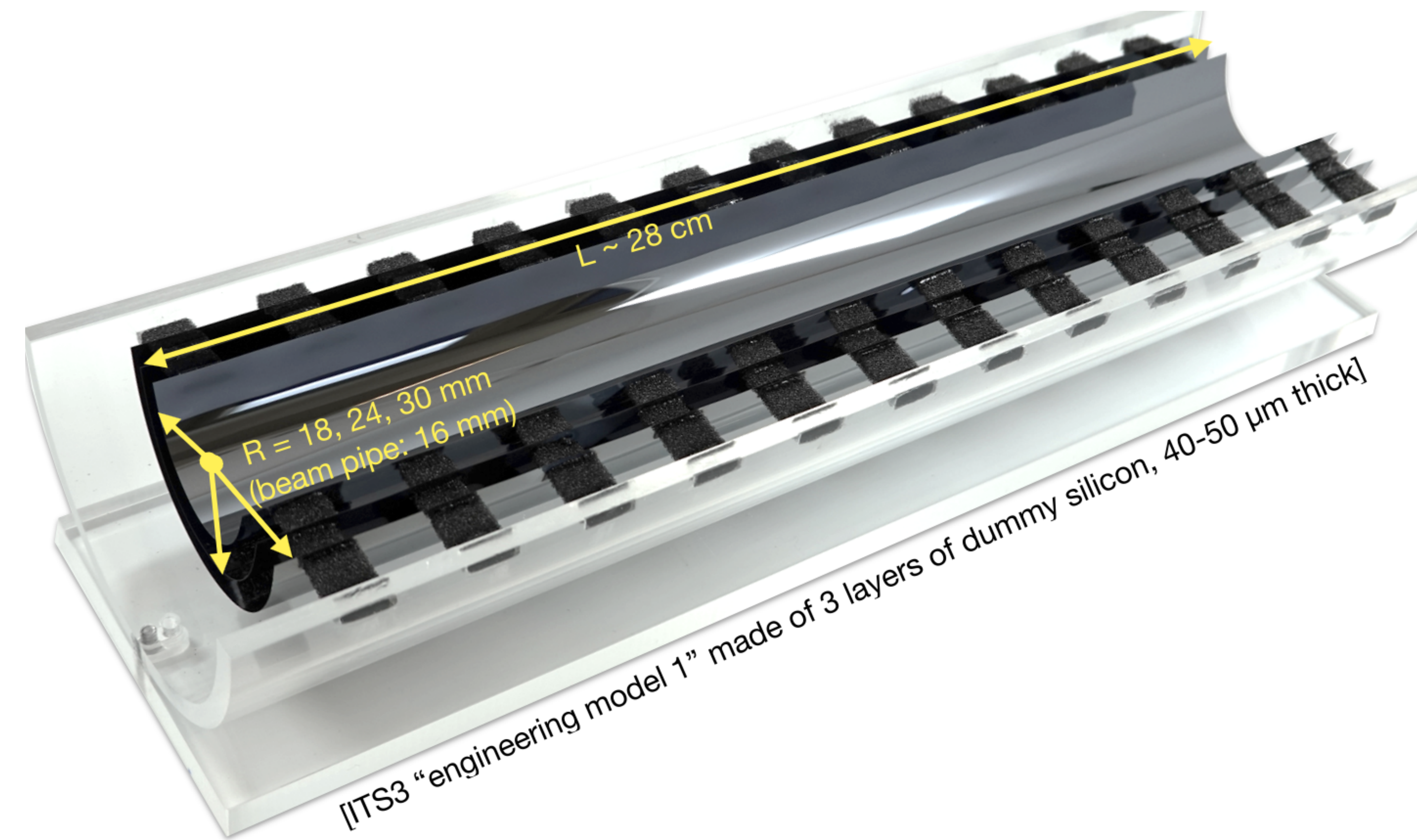

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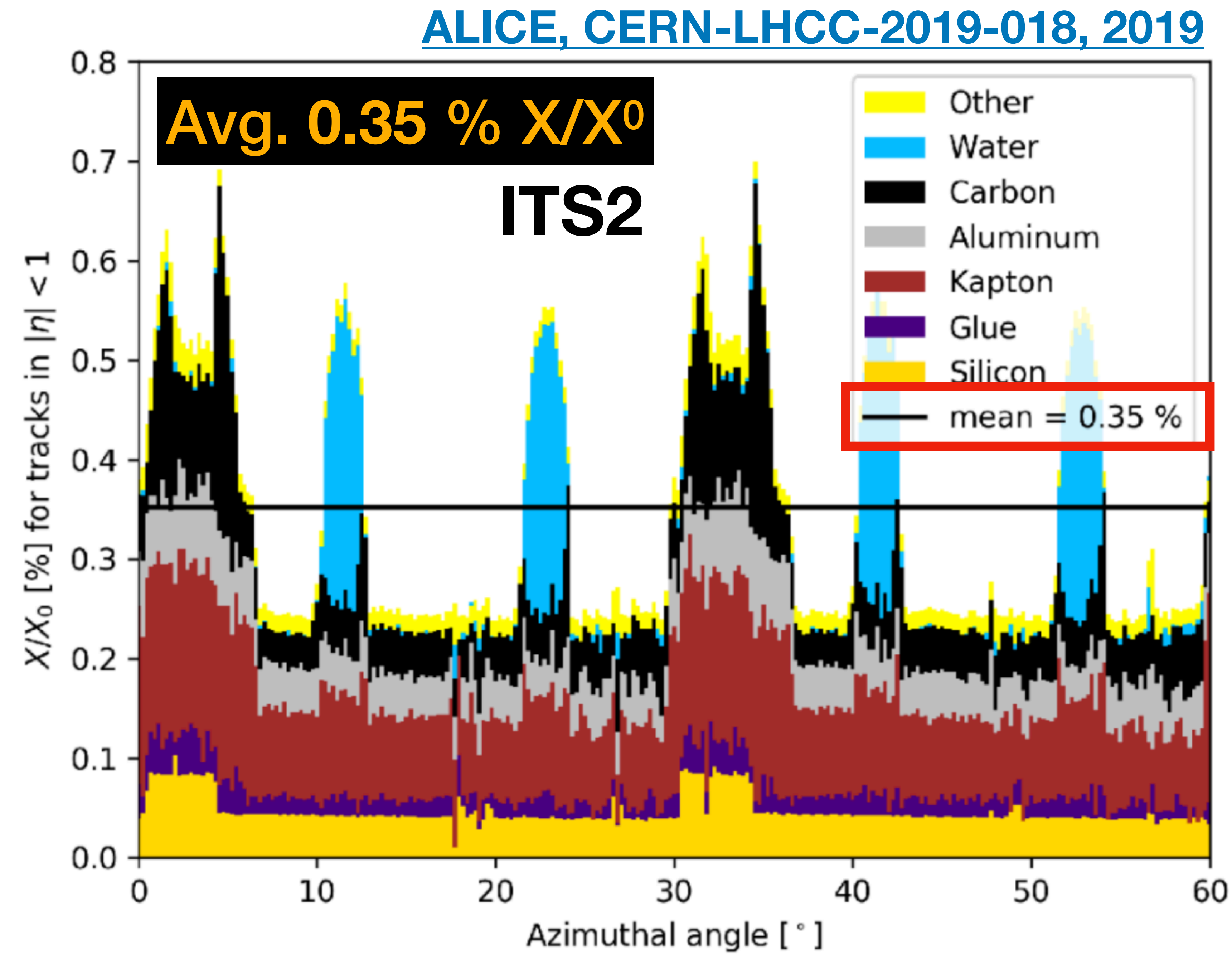
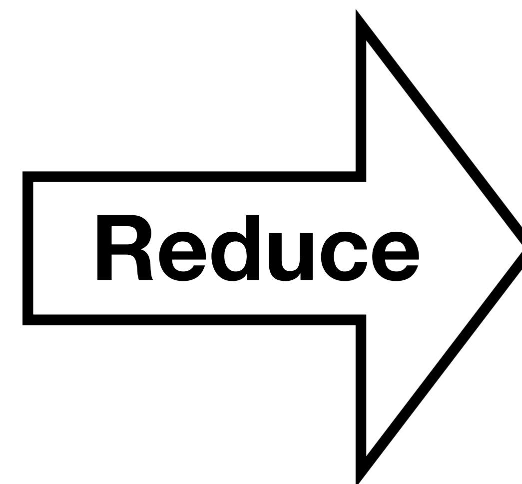
ALICE, CERN-LHCC-2019-018, 2019

How can we achieve?

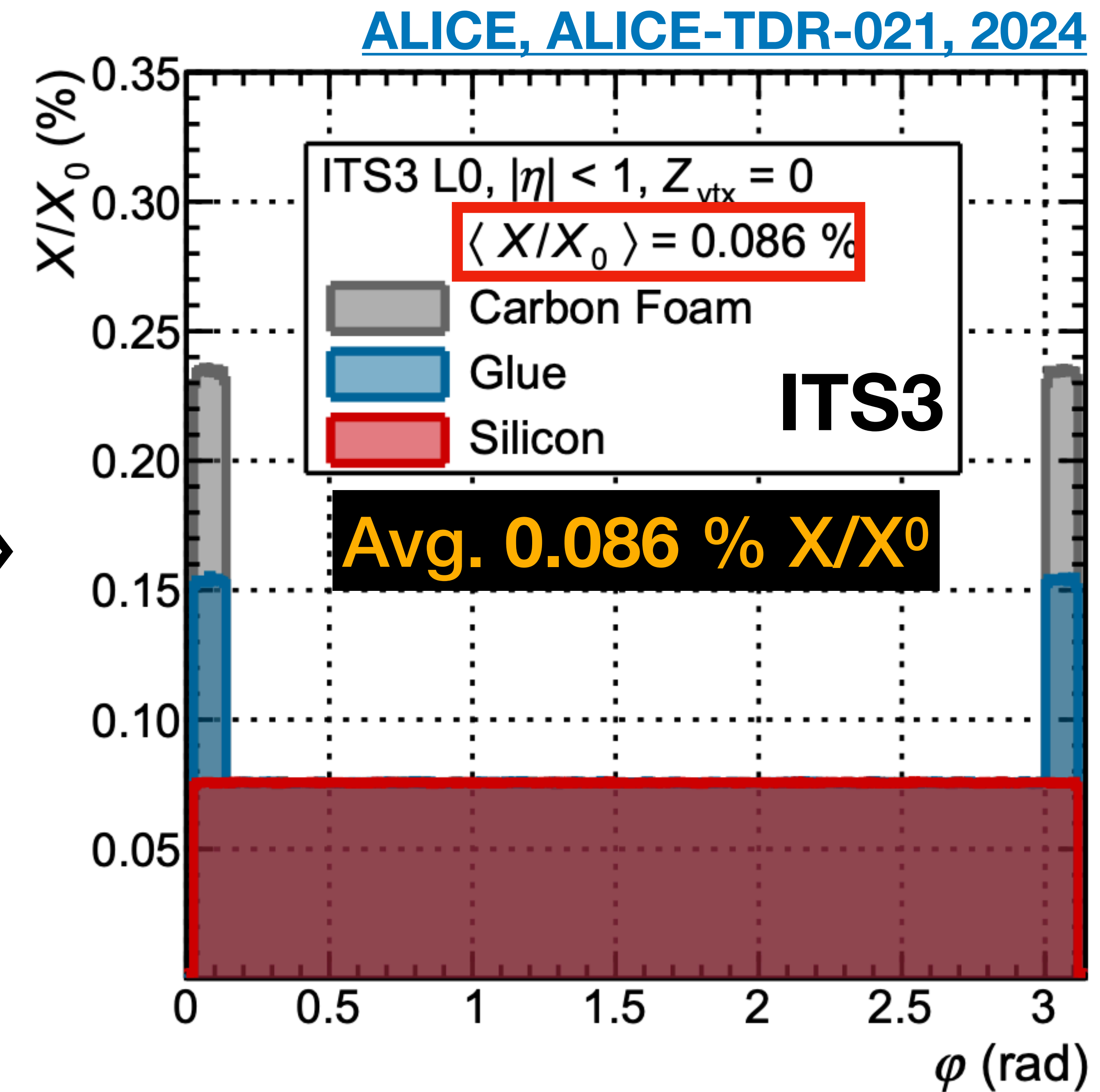
Possible improvements

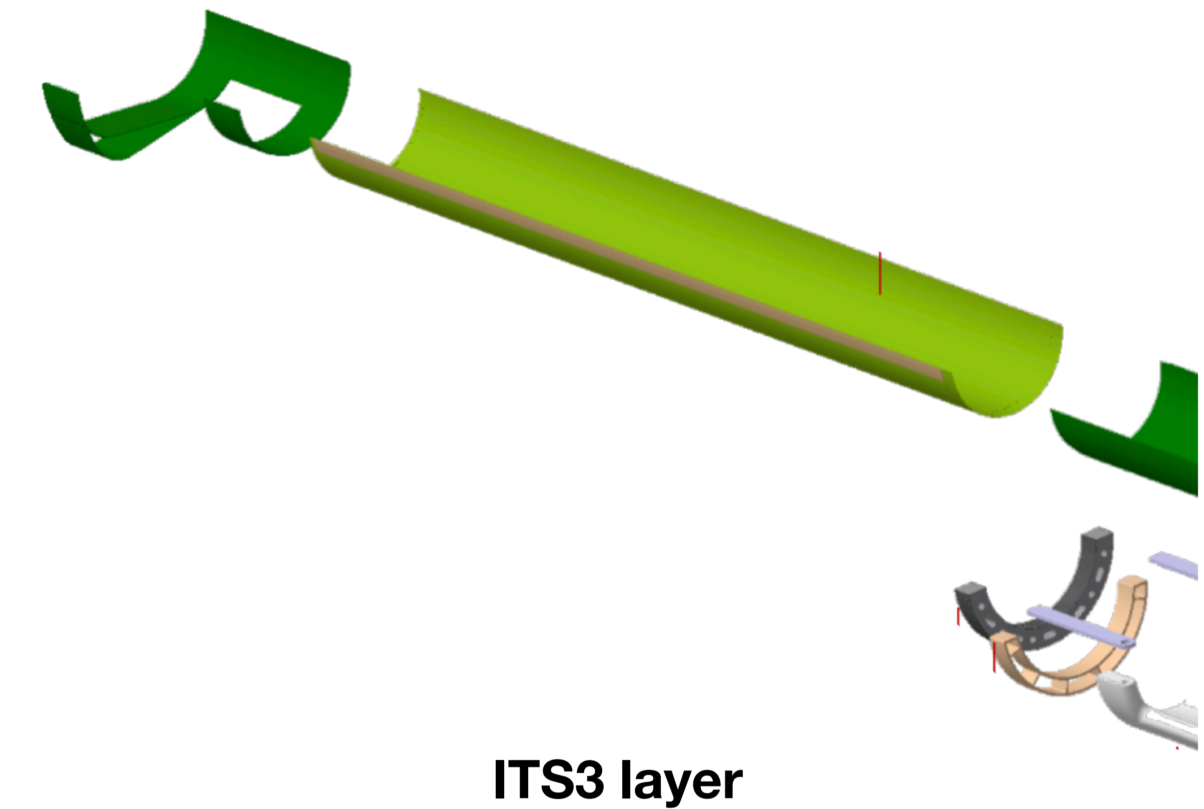
ALICE, CERN-LHCC-2019-018, 2019



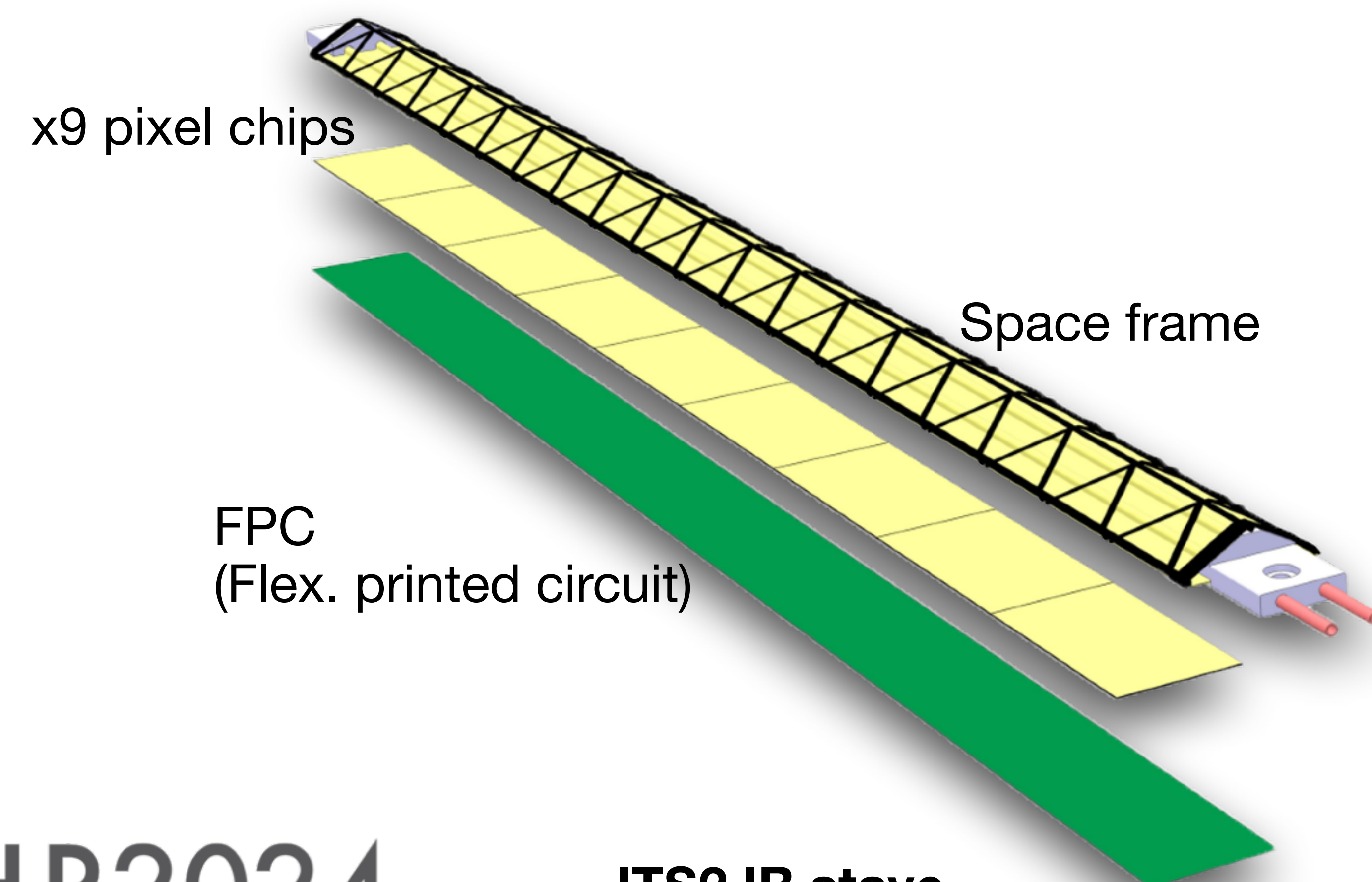


ALICE, ALICE-TDR-021, 2024





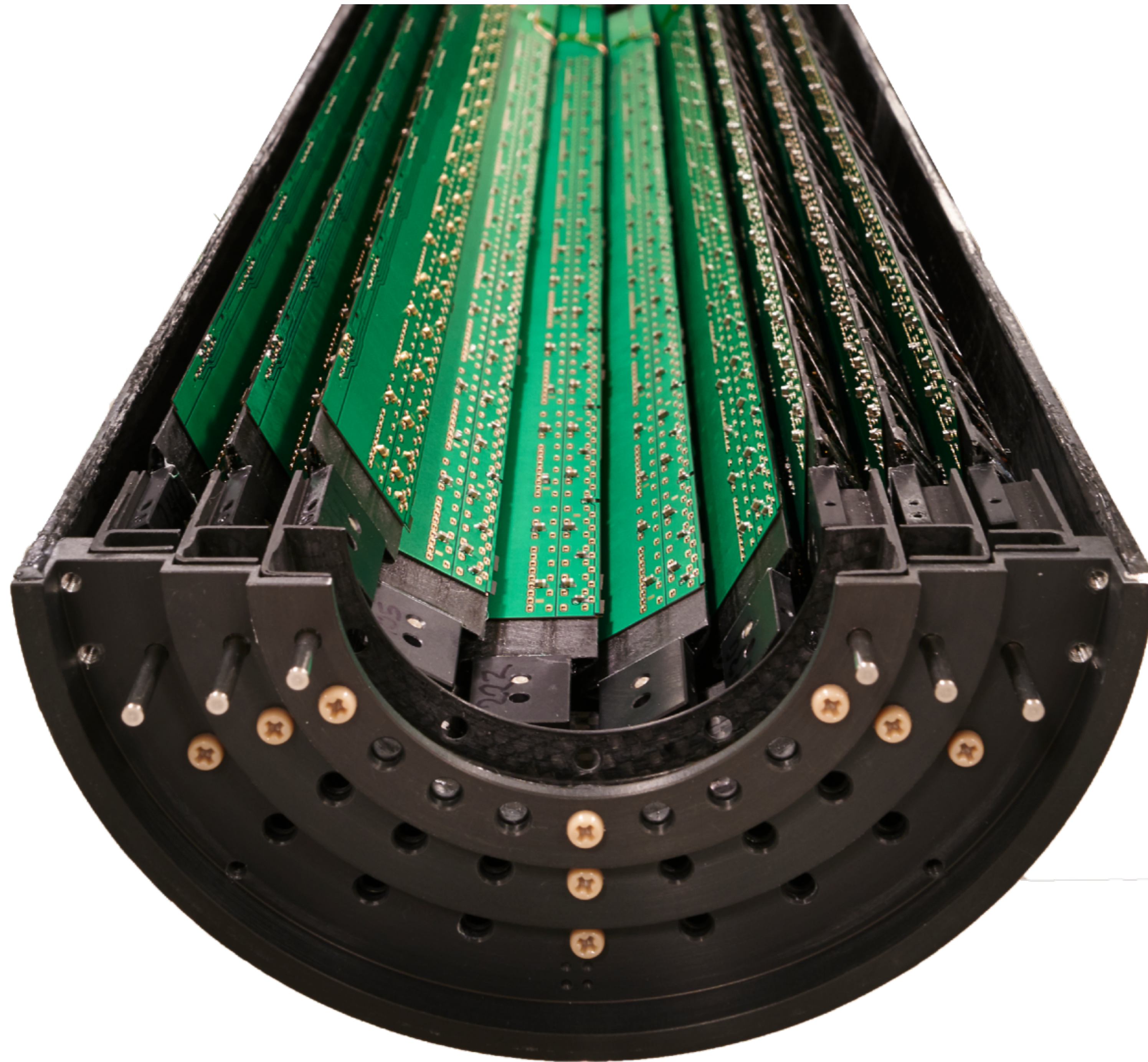
ITS3 layer

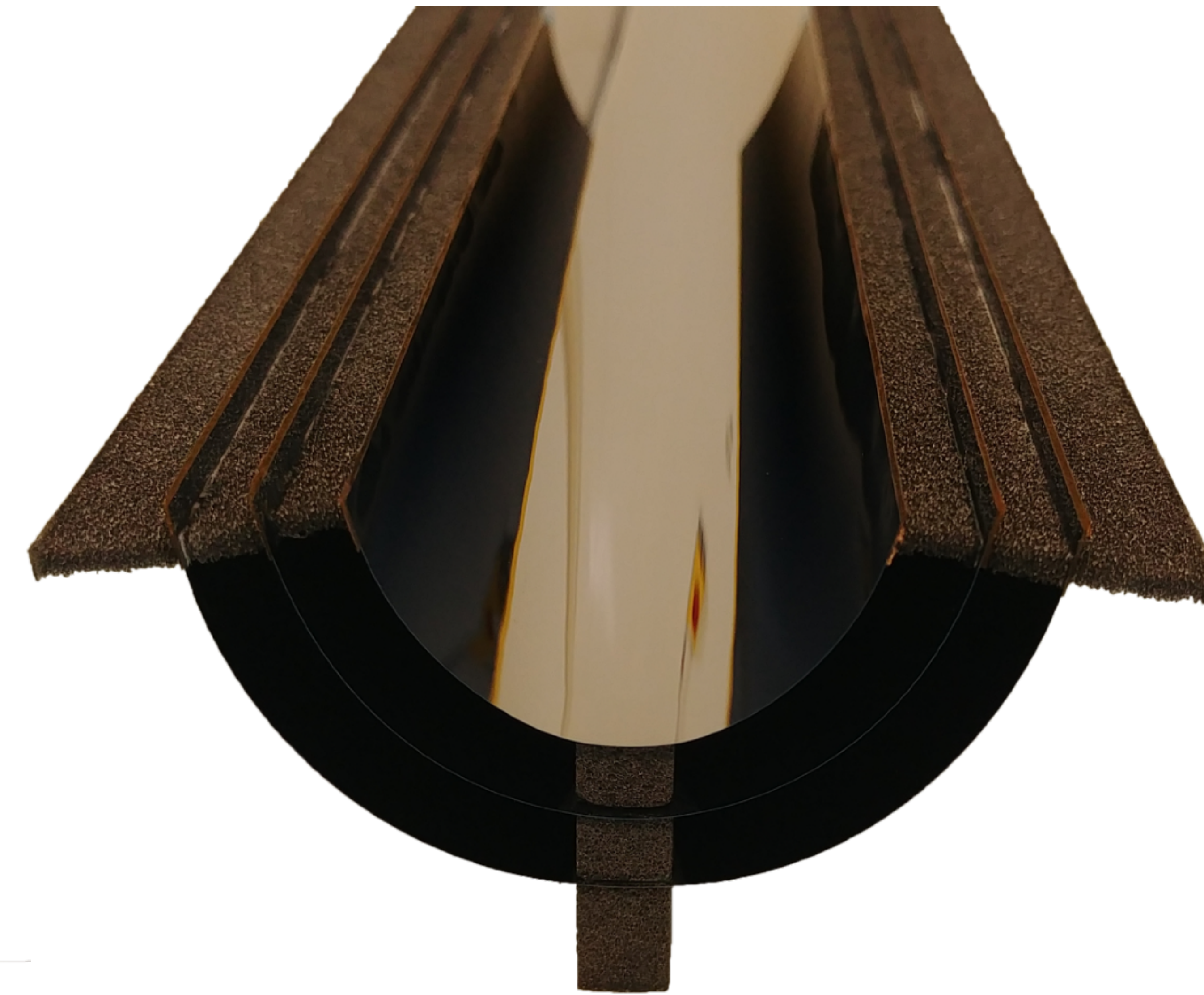


ITS2 IB stave

1. **Removal of water cooling:**
   - Possible if reduction of **power consumption < 40 mW/cm²**
2. **Removal of the Flexible Printed Circuit (FPC)**
   - **Integrate** it on the chip (data & power)
3. **Removal of the mechanical support**
   - Thinned silicon [≤ 50 μm] → **bending**

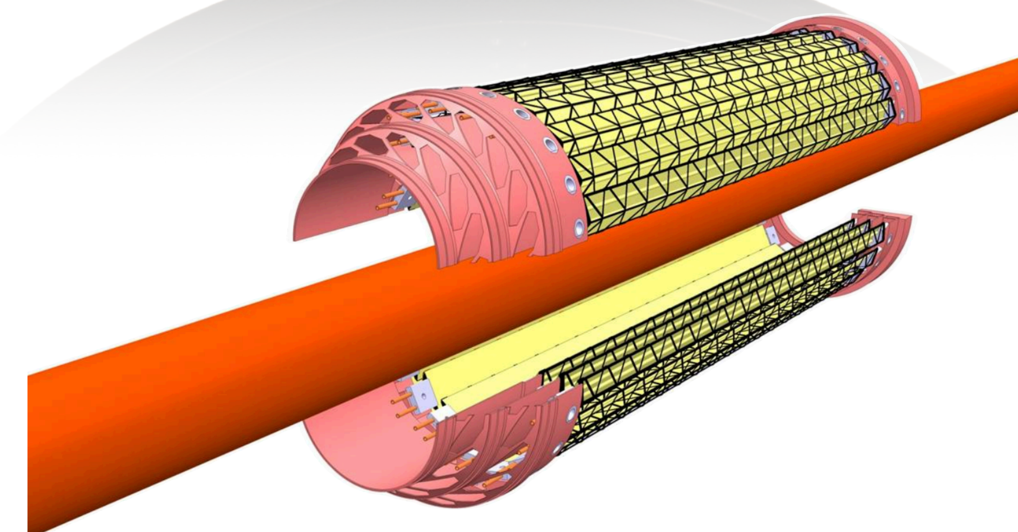
Some key points
of ITS3 upgrade

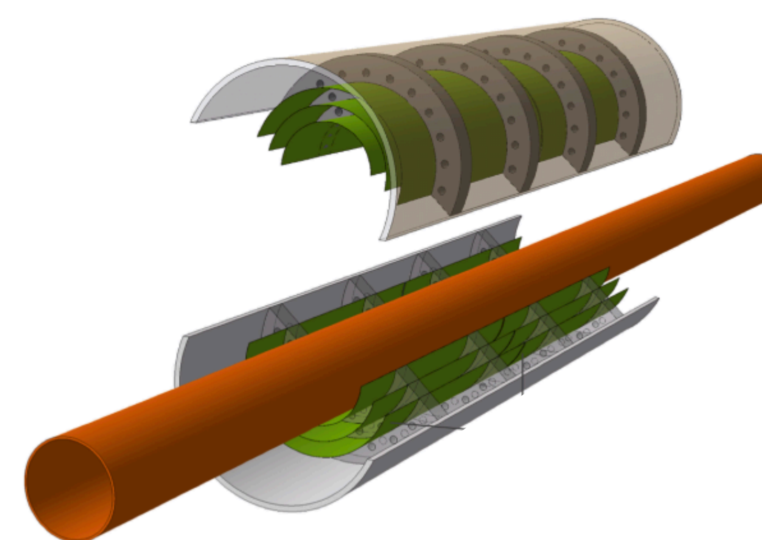




ITS half IB

ITS3 engineering model





	ITS2	ITS3
Technology	180 nm	65 nm
Chips	432	6
Pixel size	29 x 27 μm²	20.8 x 22.8 μm²
Material budget / layer	0.35 % x/X_0	0.086 % x/X_0
r_{L0}	24 mm	19 mm
$r_{\text{Beam pipe}}$	18.2 ± 0.8 mm	16 + 0.5 mm

- **3 wafer-scaled** bent CMOS active silicon **sensor** for half barrel
  - **~26 x ~10 cm size for last layer**

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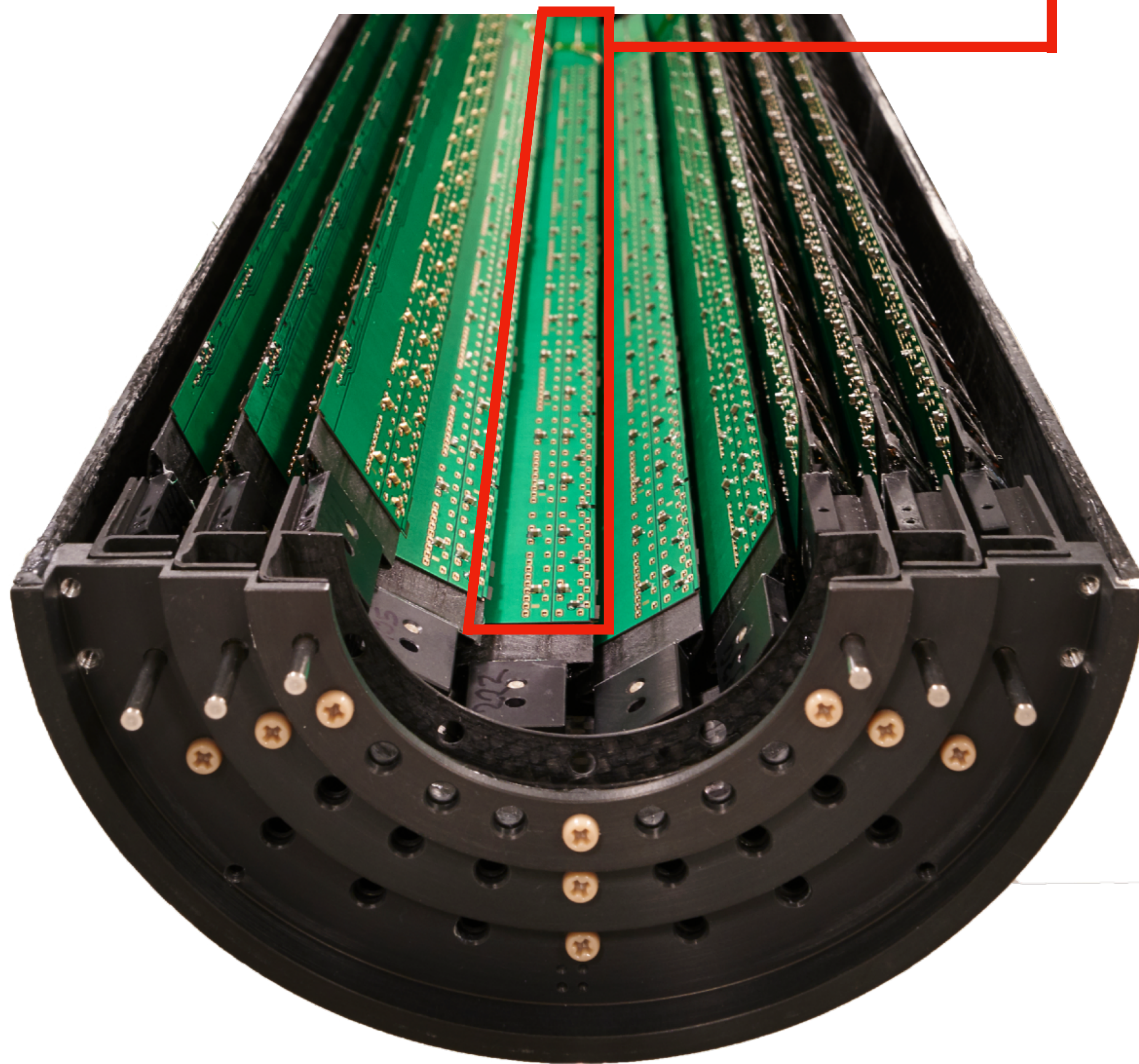

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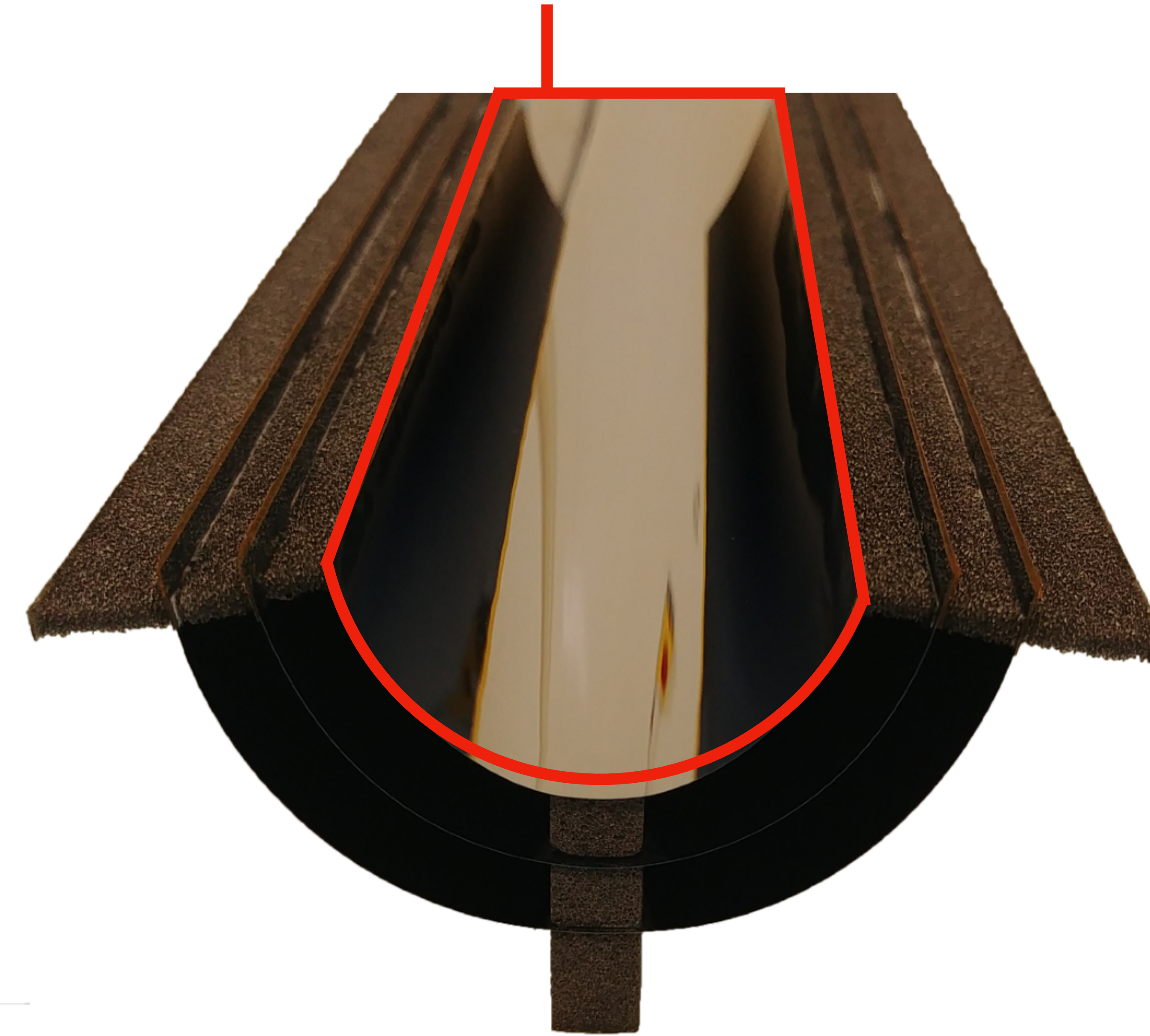

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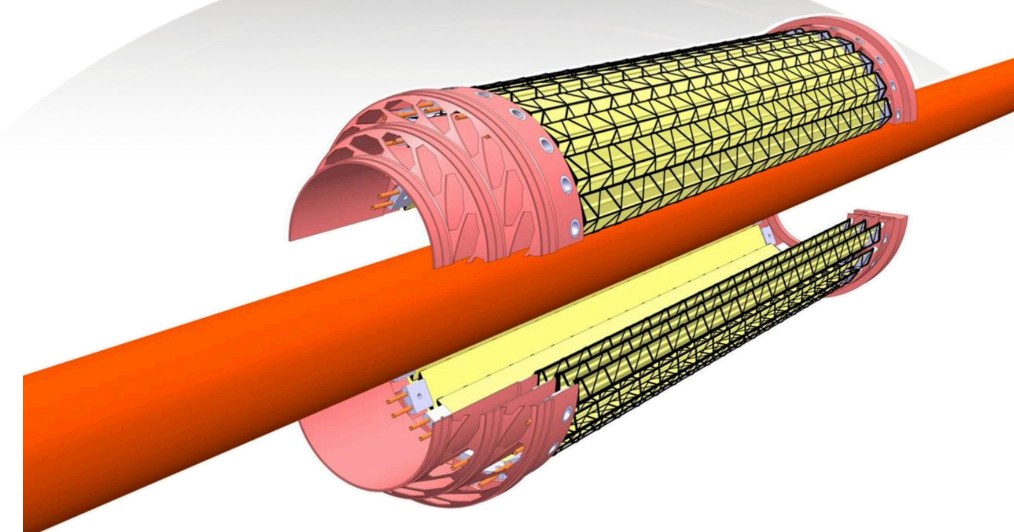

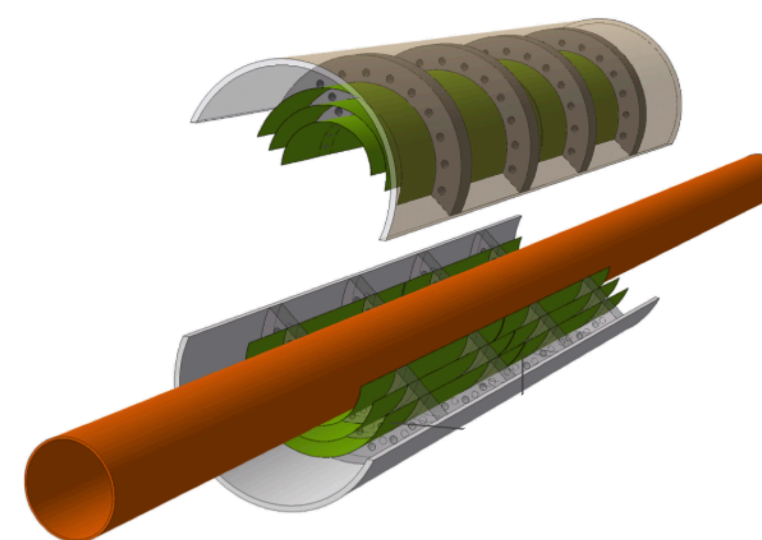

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Some key points
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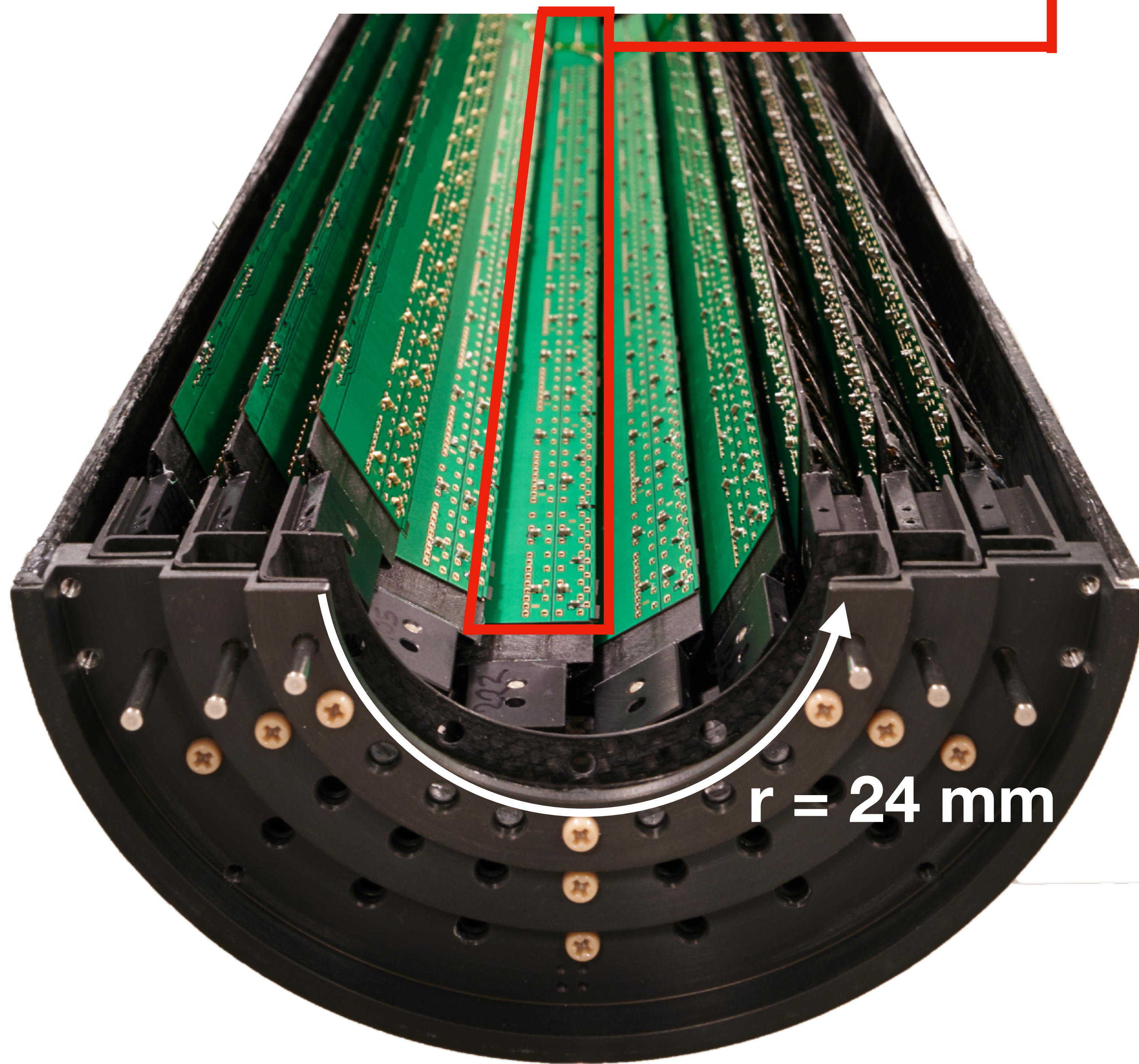
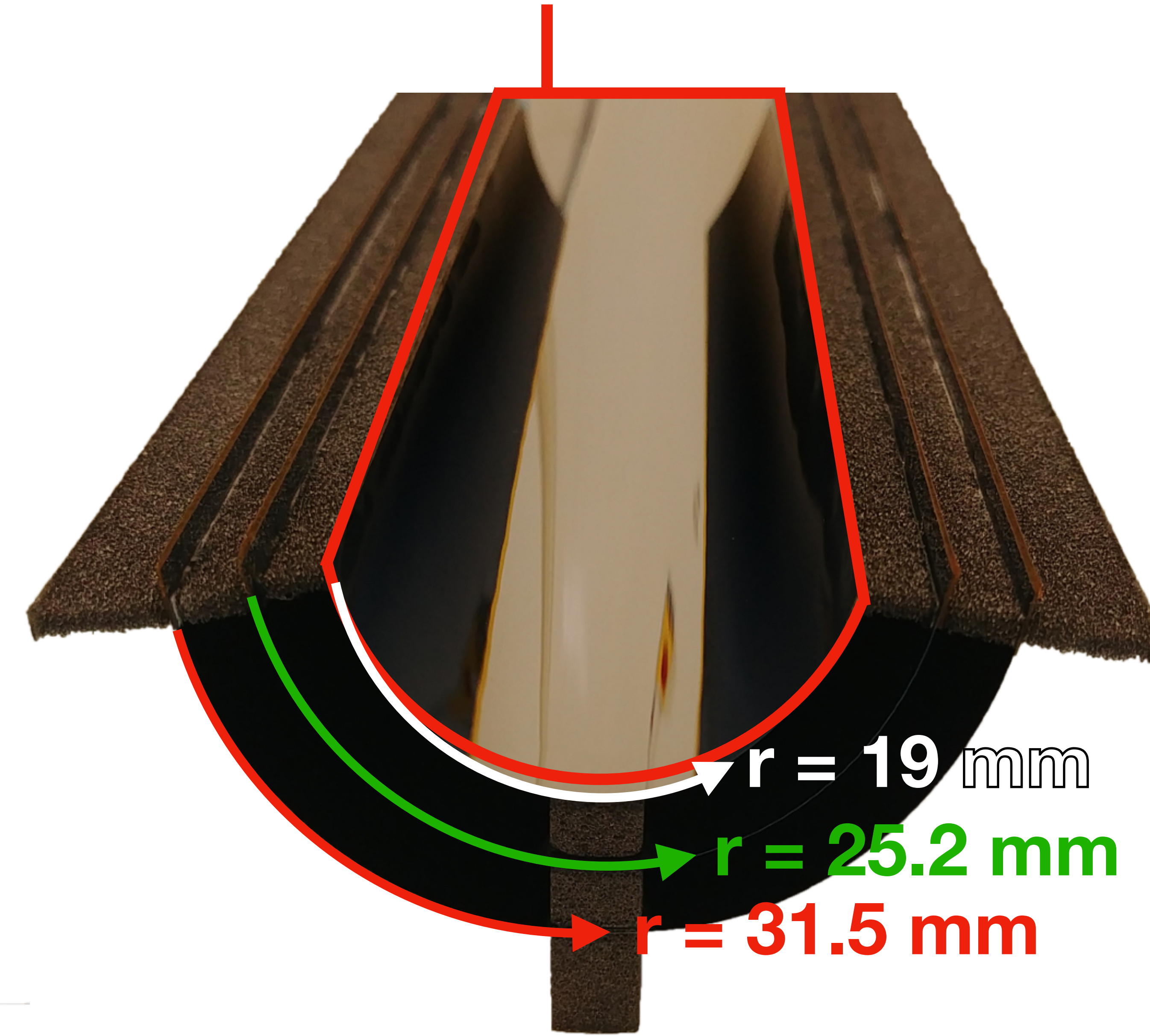
Module structure (stave)

Wafer-scaled sensor (1chip)





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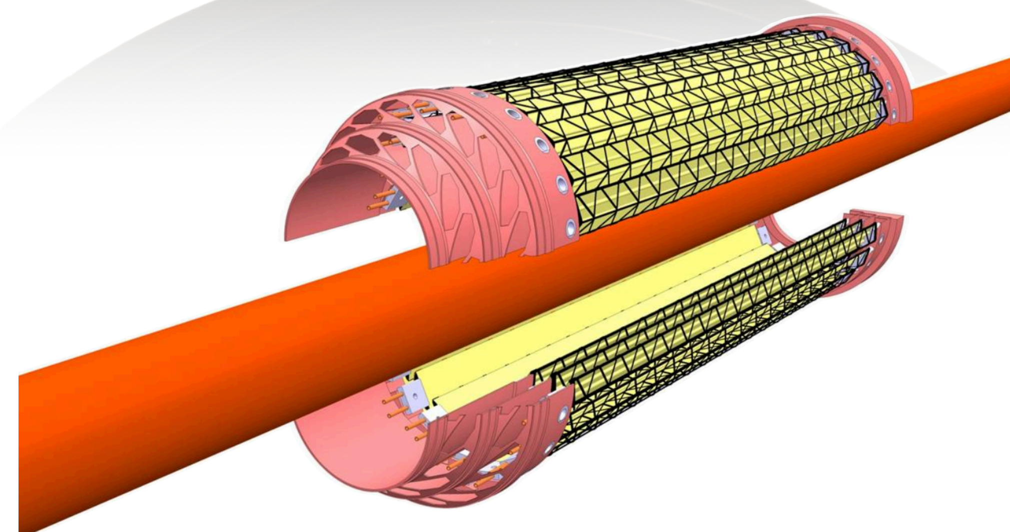

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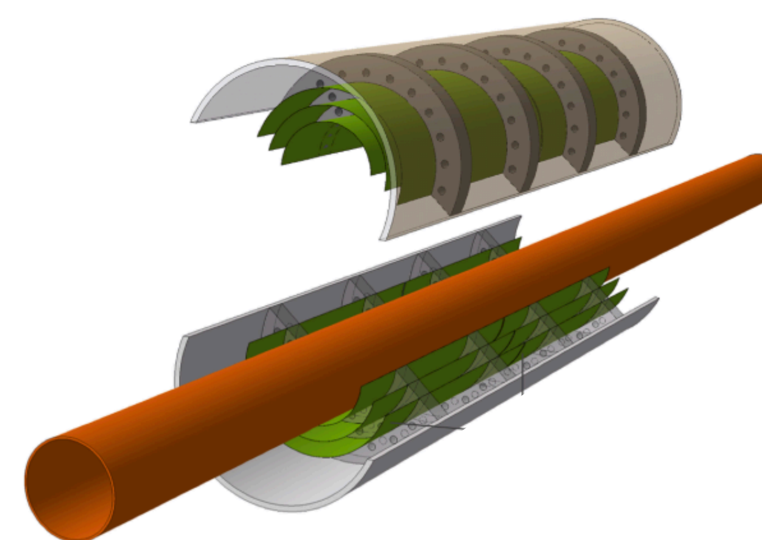

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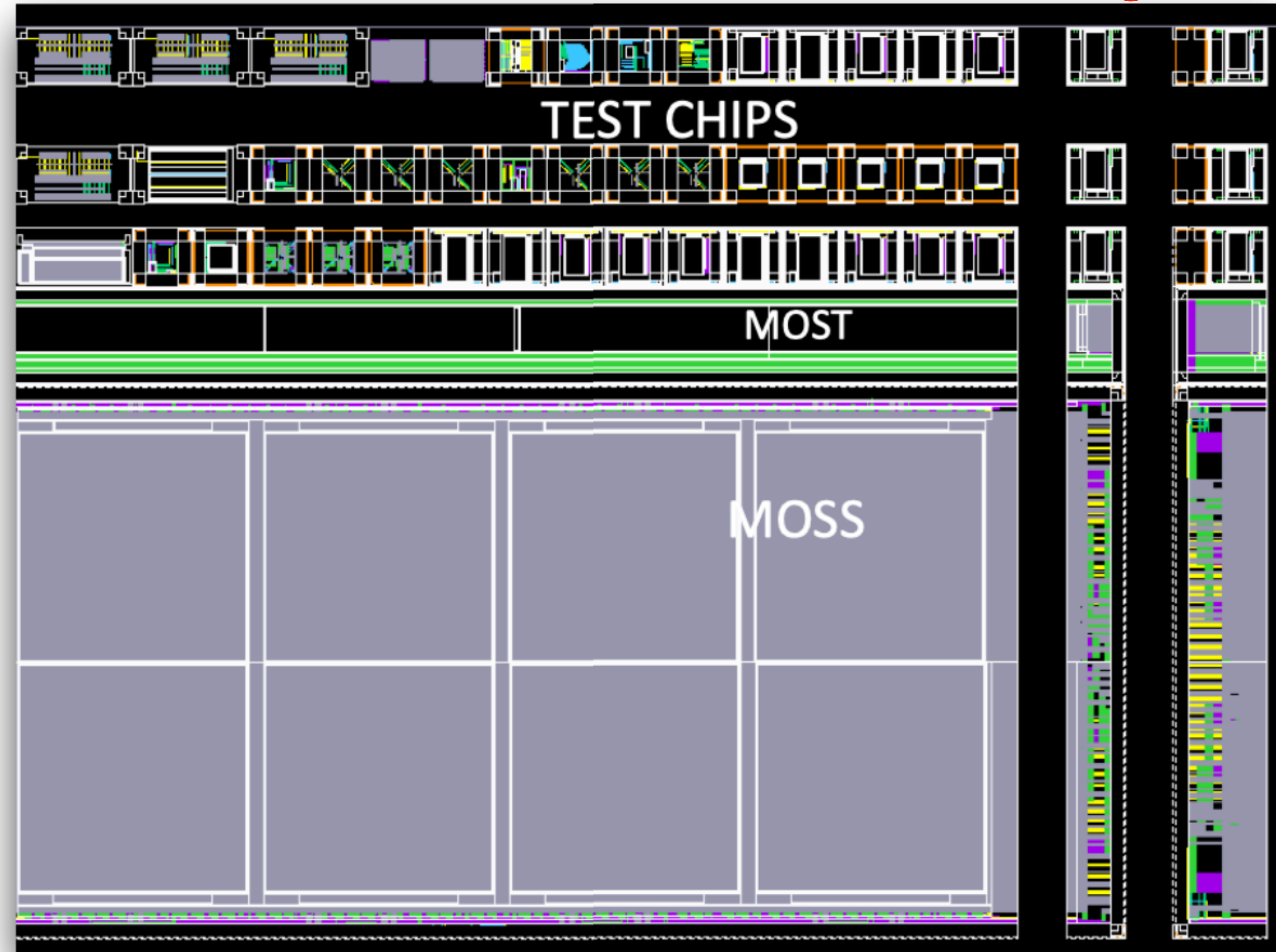
How can we make such a large sensor?

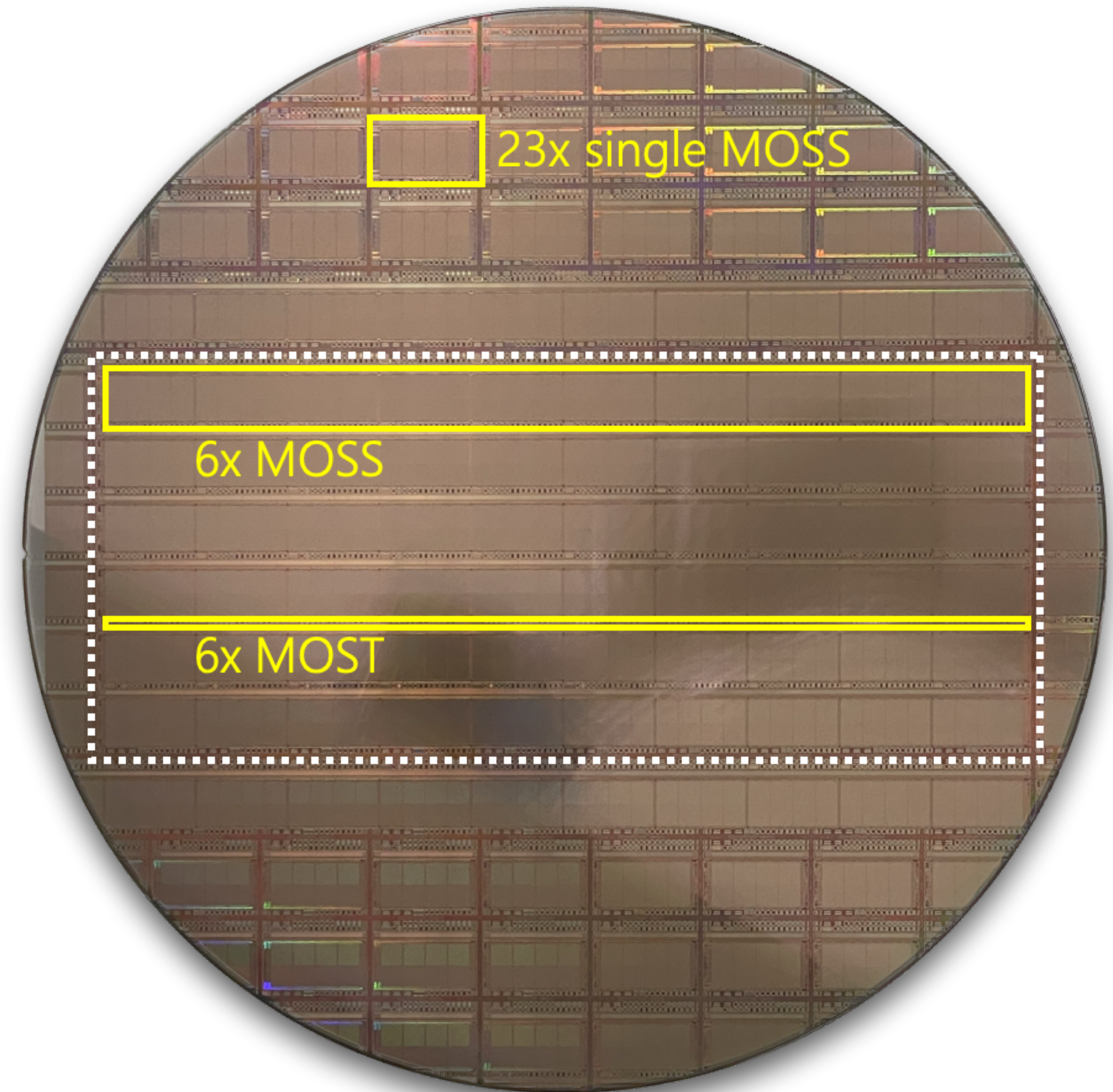
Stitching (simplified)

"What we designed"



Reticle (mask)

"What we want to fabricate"



Wafer (ϕ=300mm)

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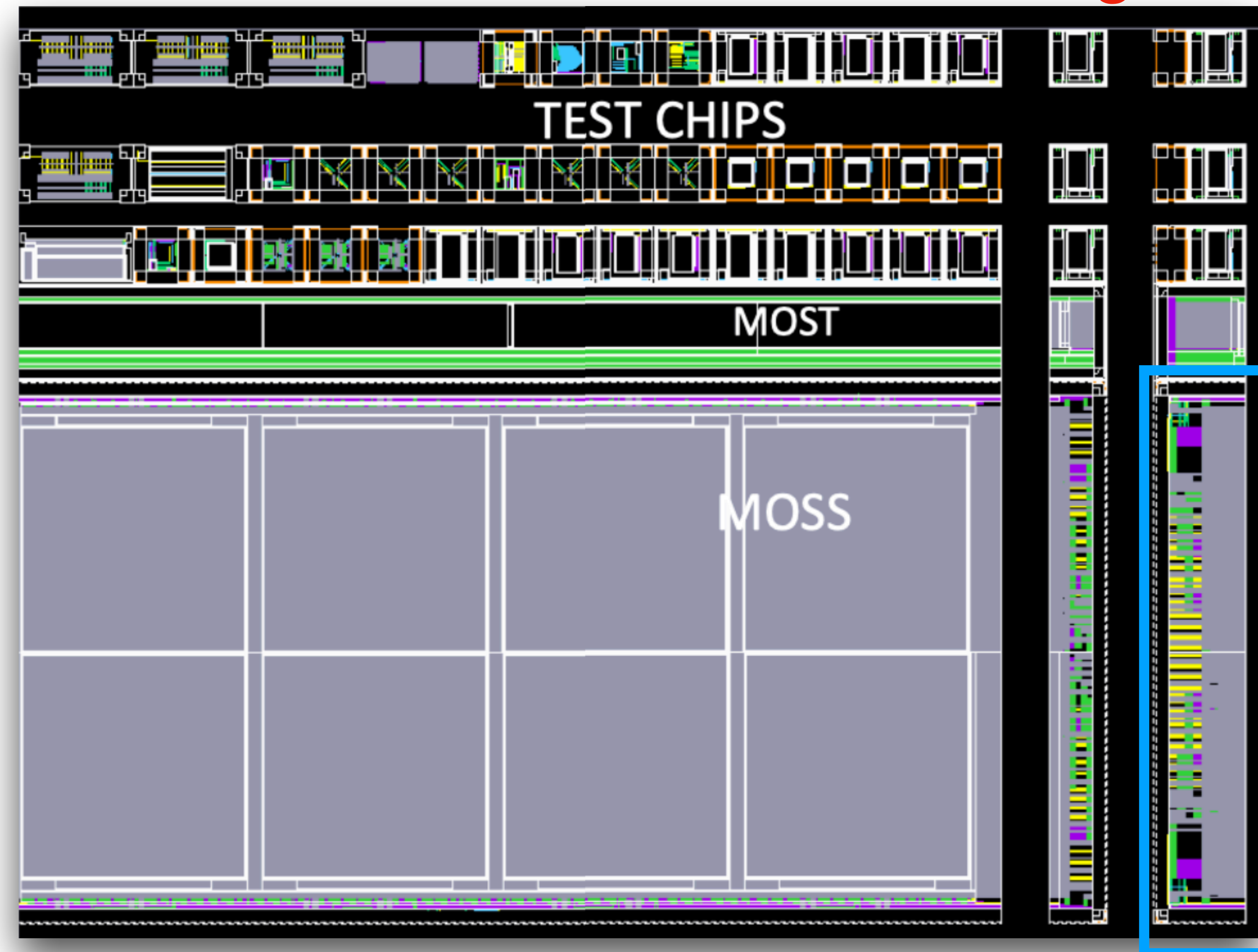
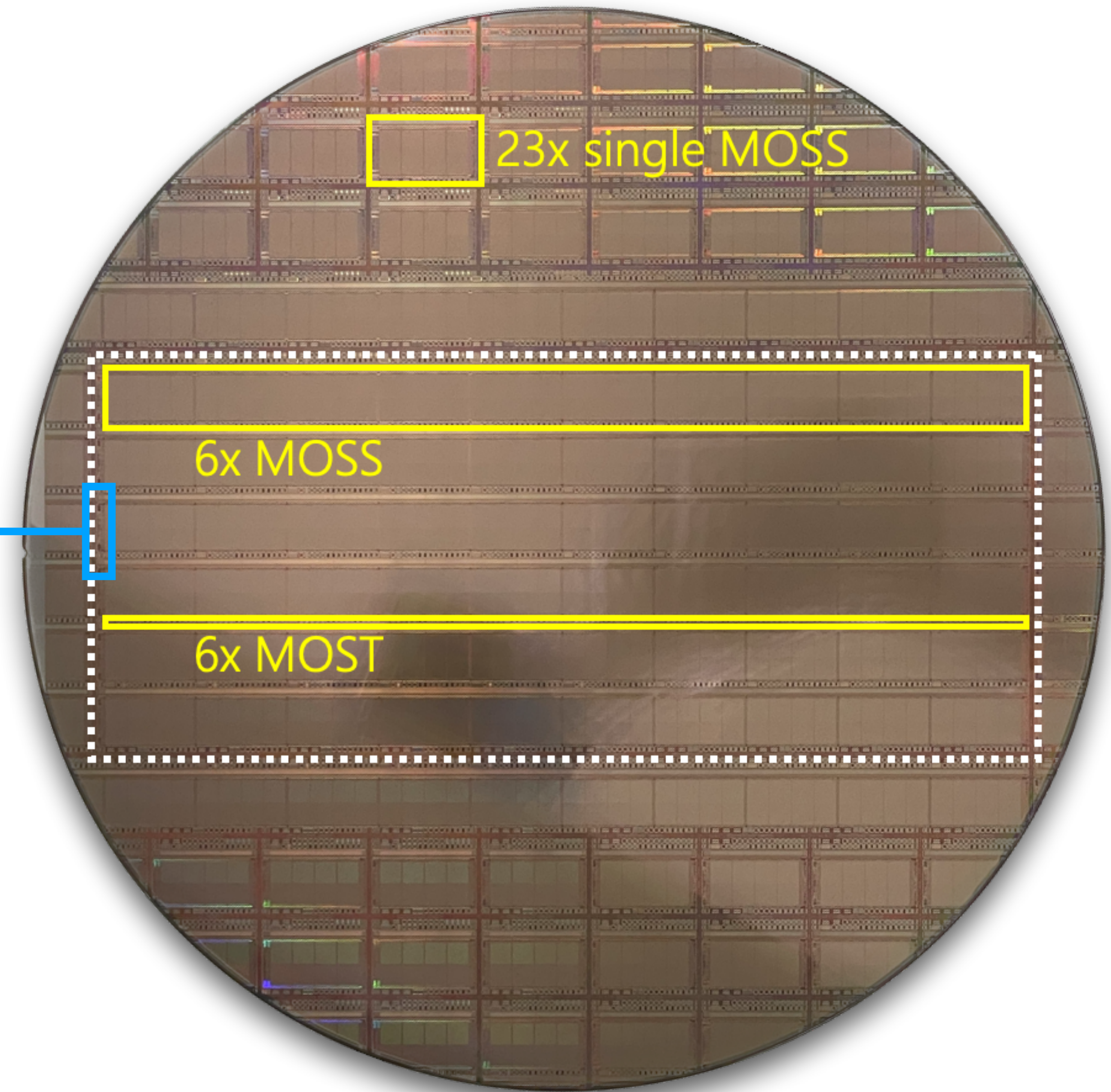


Reticle (mask)

Left endcap

"What we want to fabricate"



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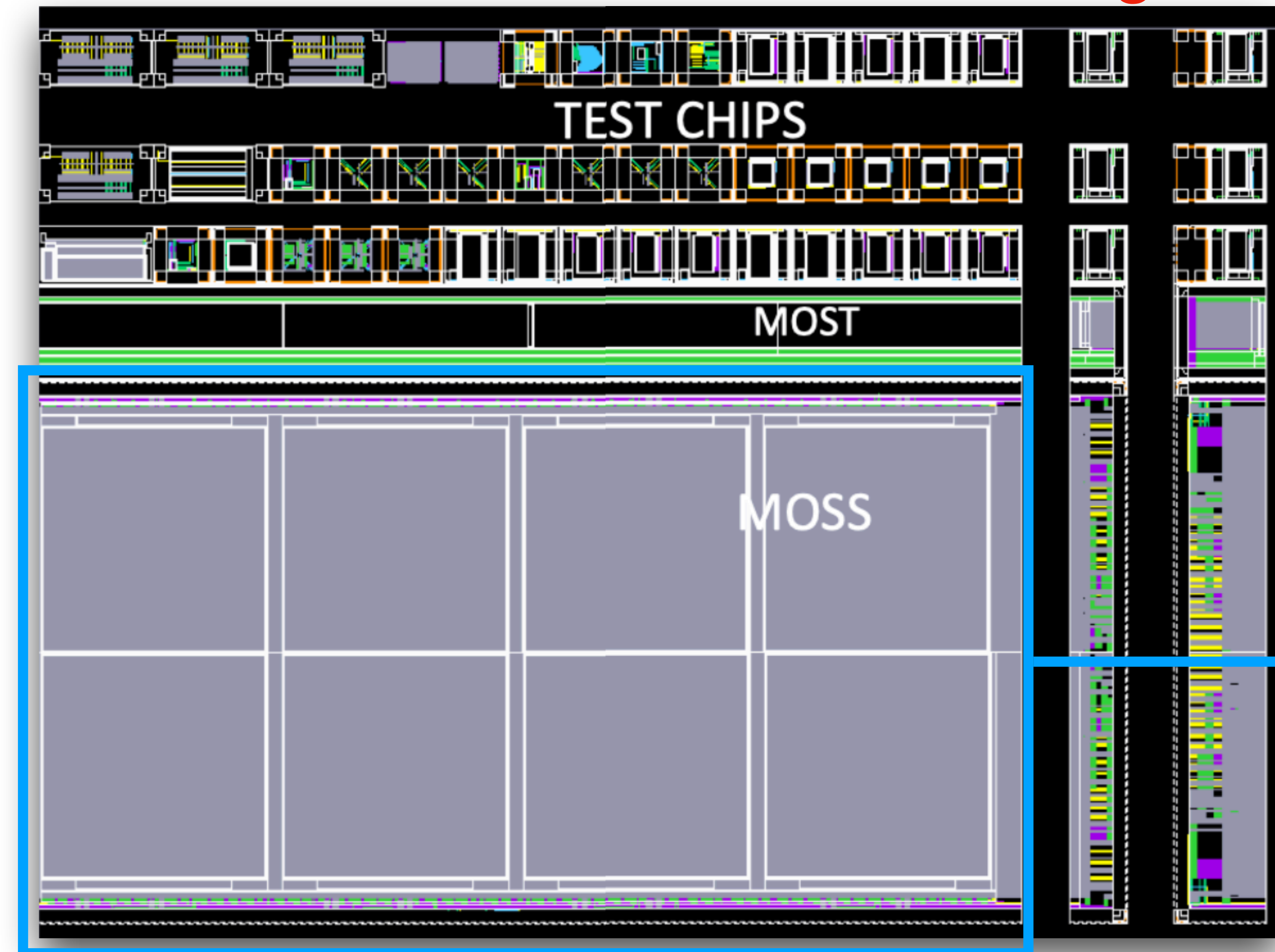

Reticle (mask)

Repeated part

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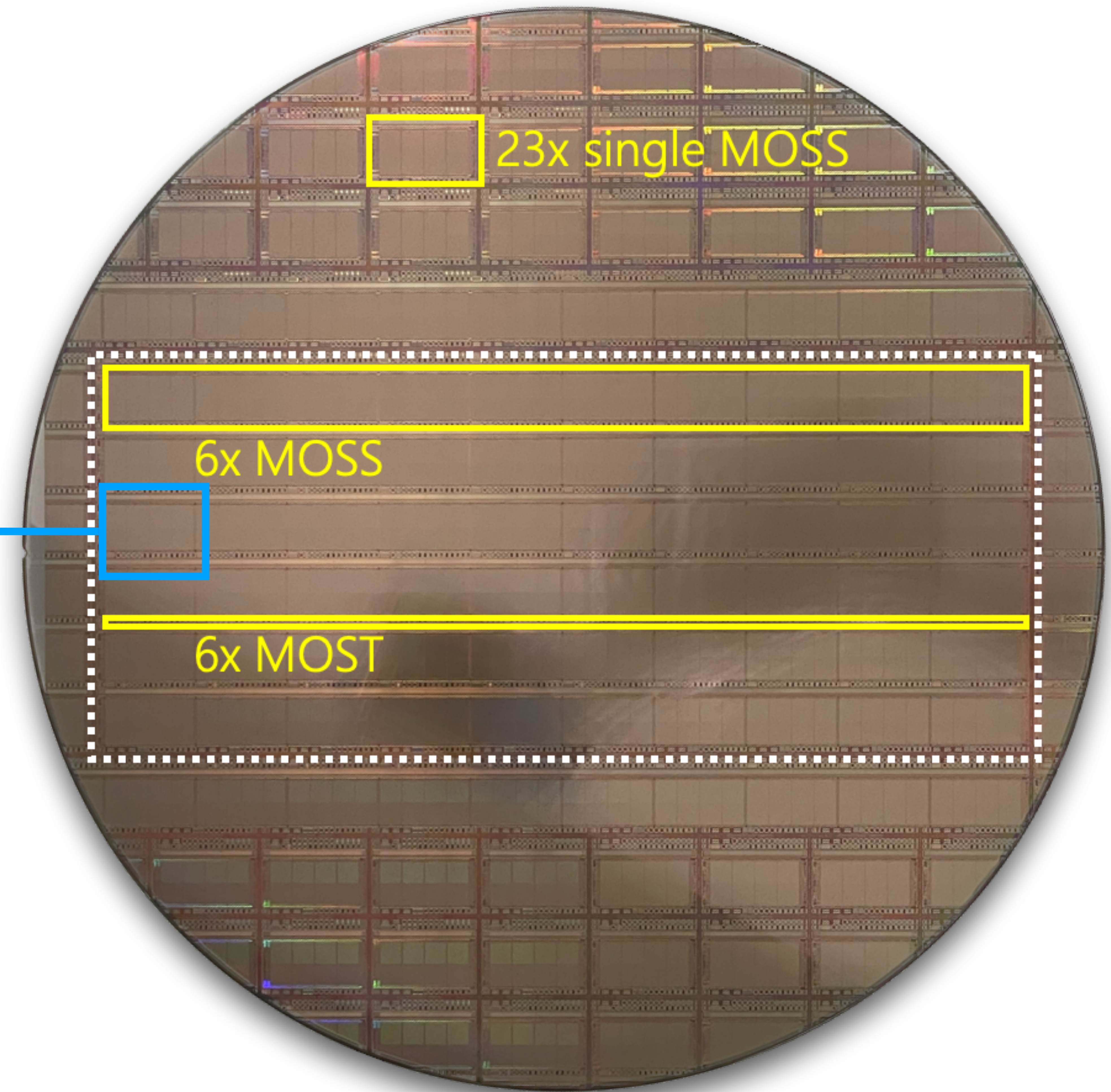

Wafer (ϕ=300mm)

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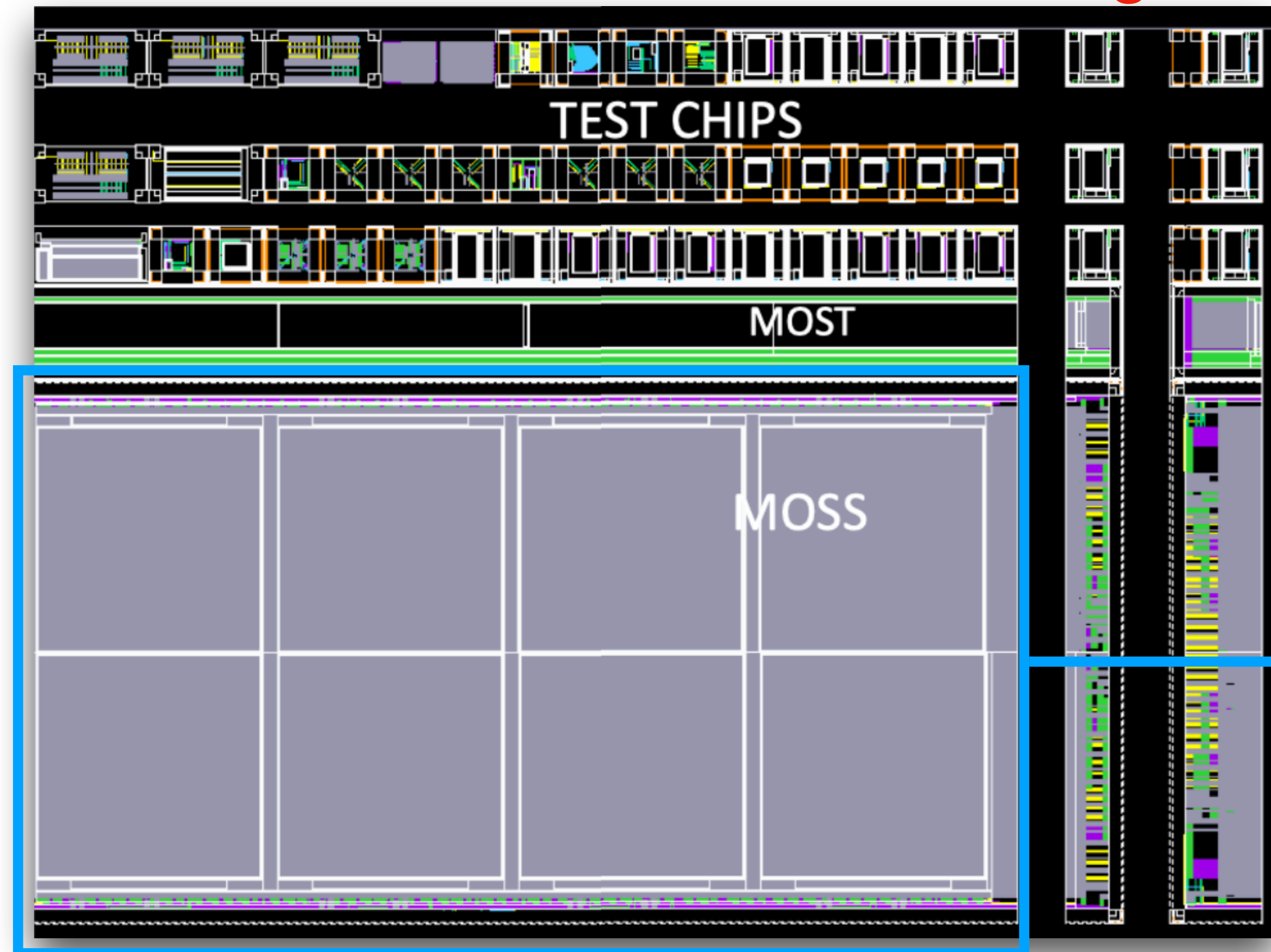

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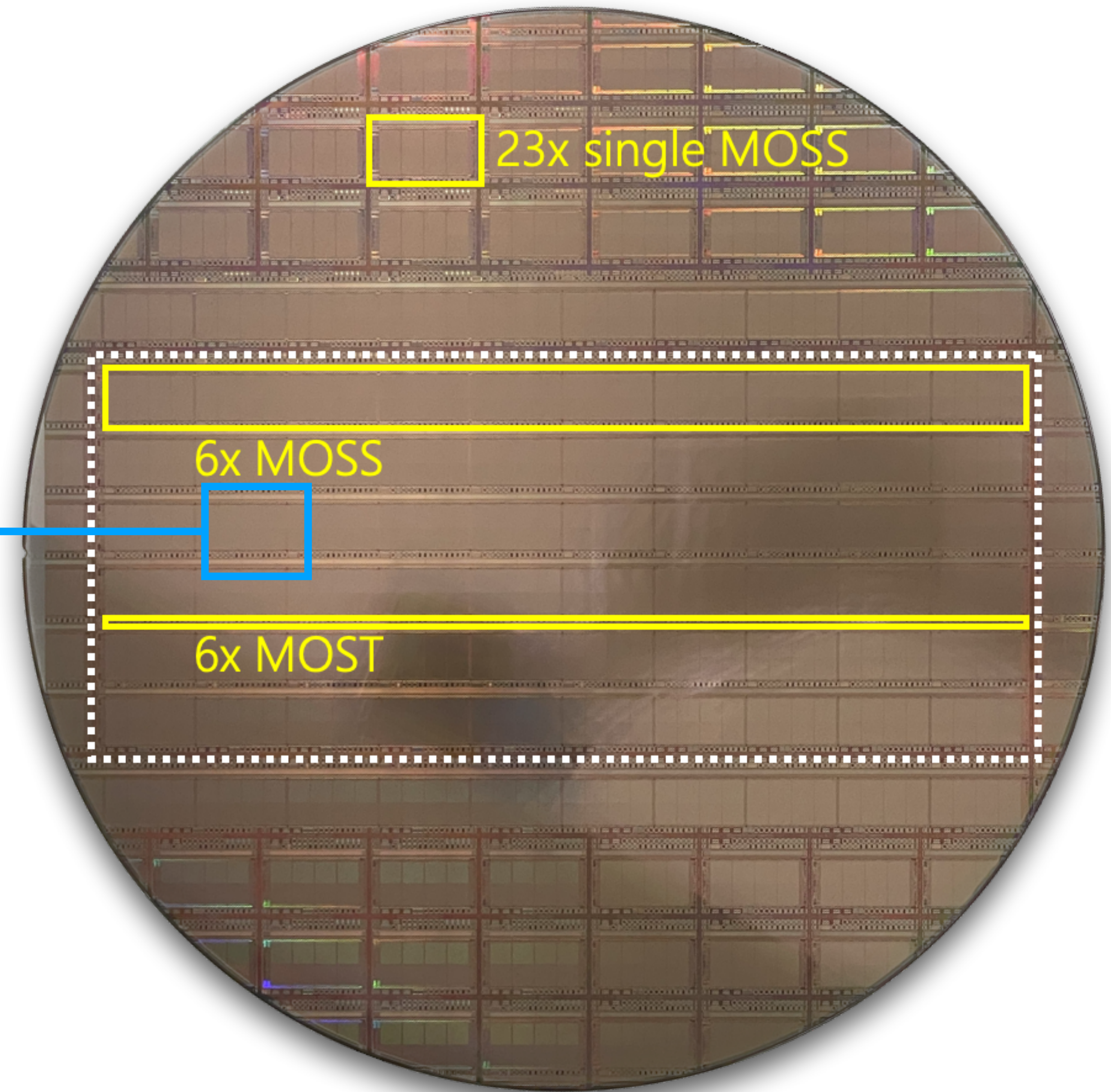

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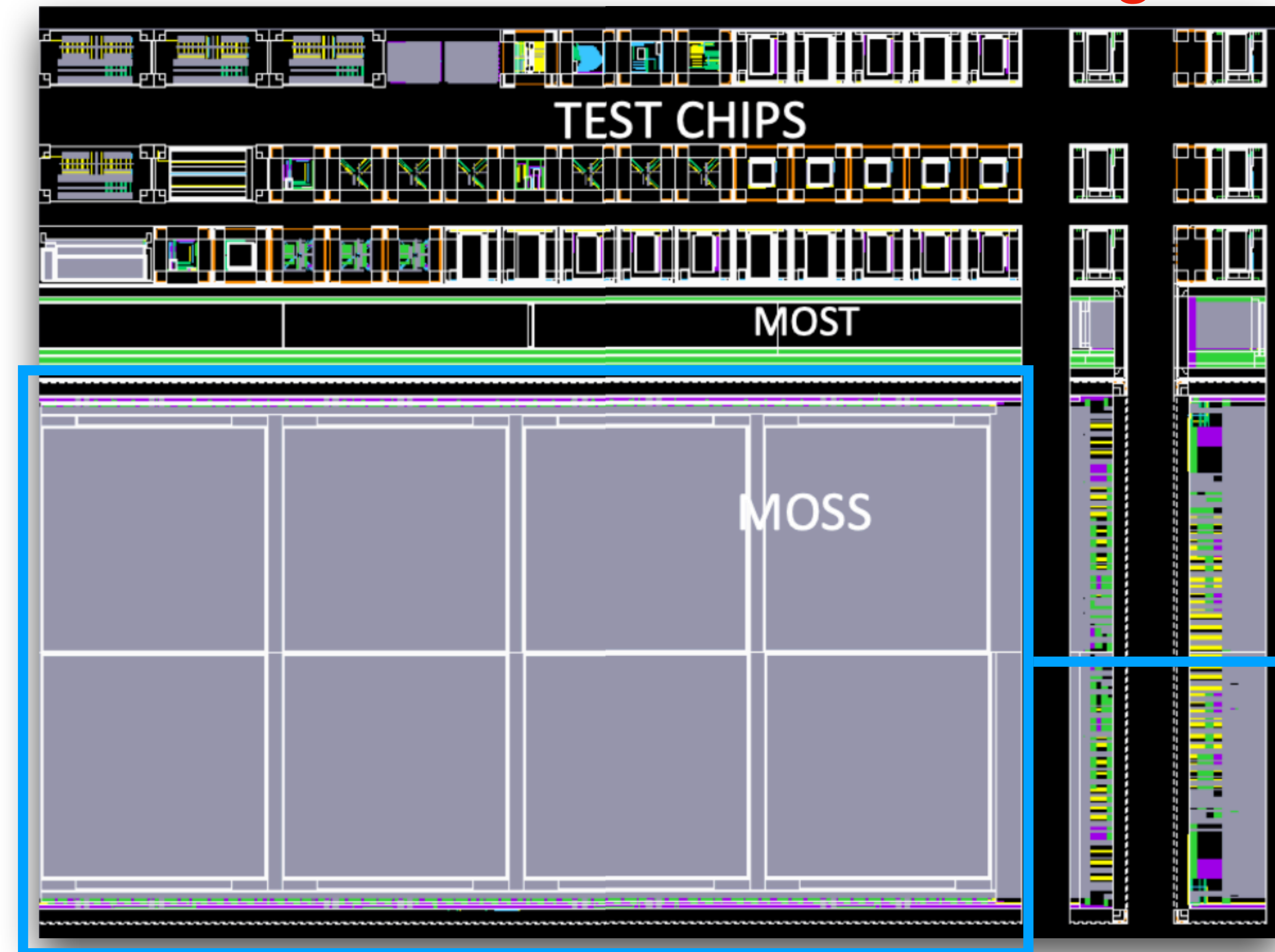

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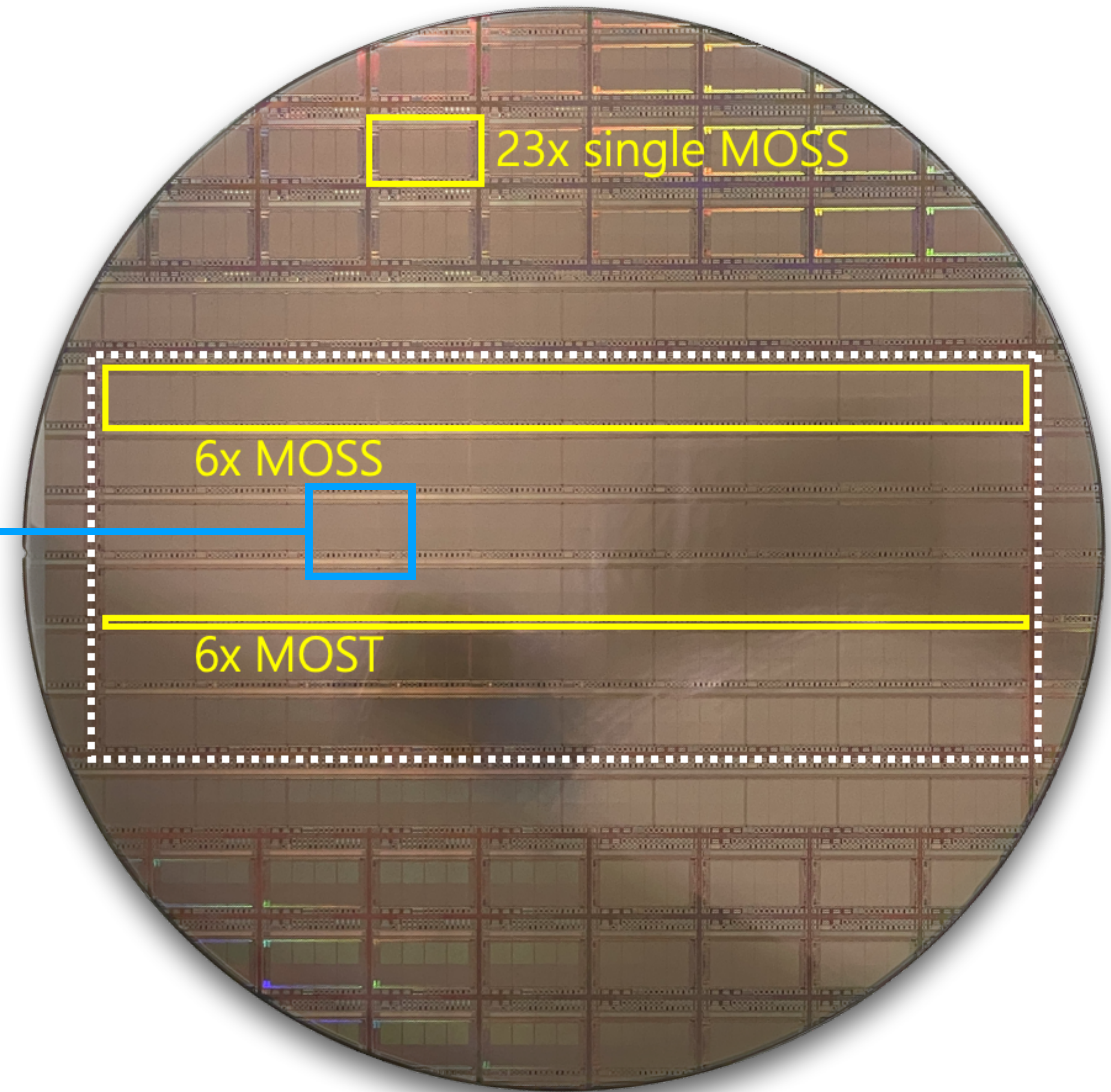
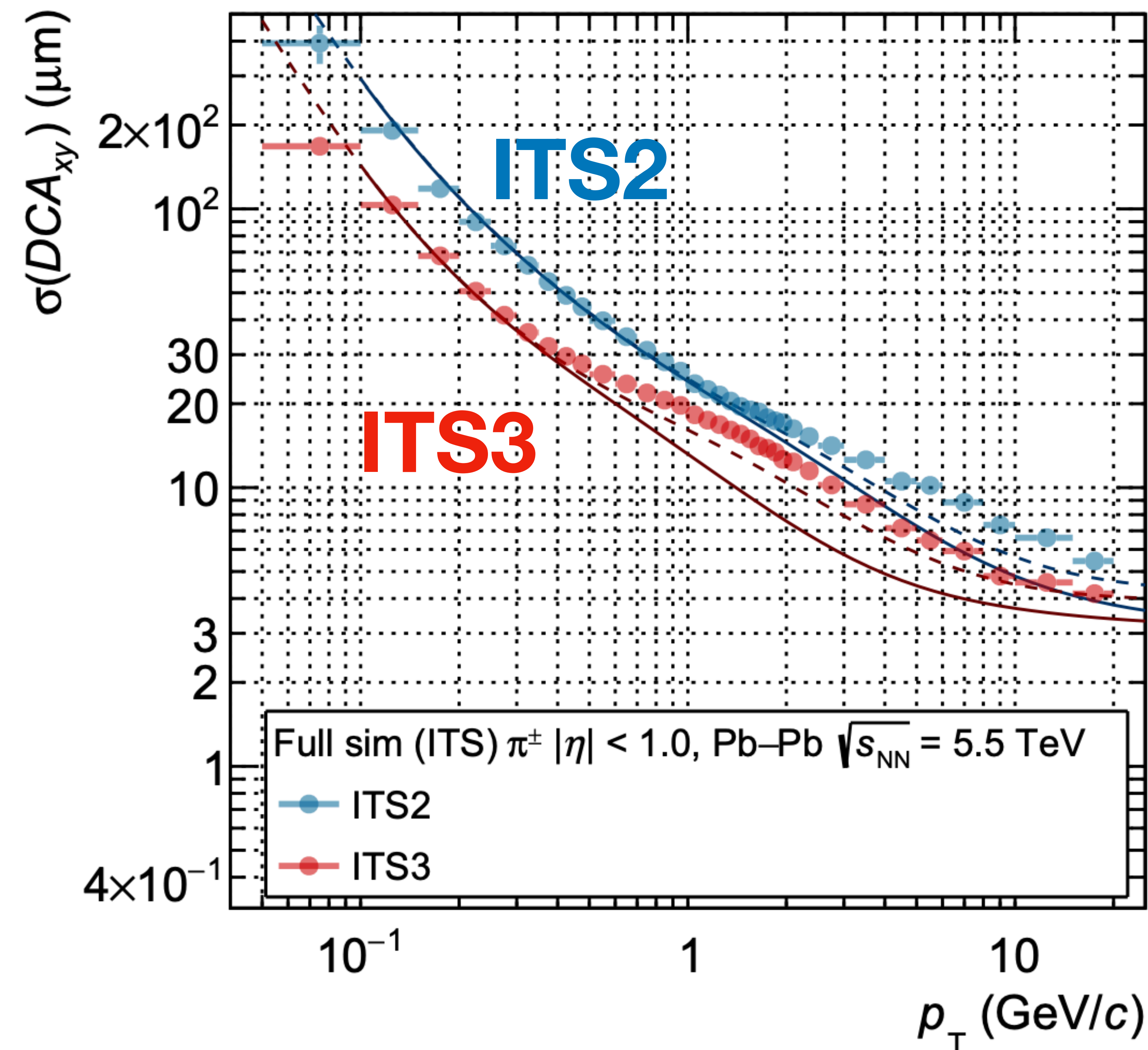


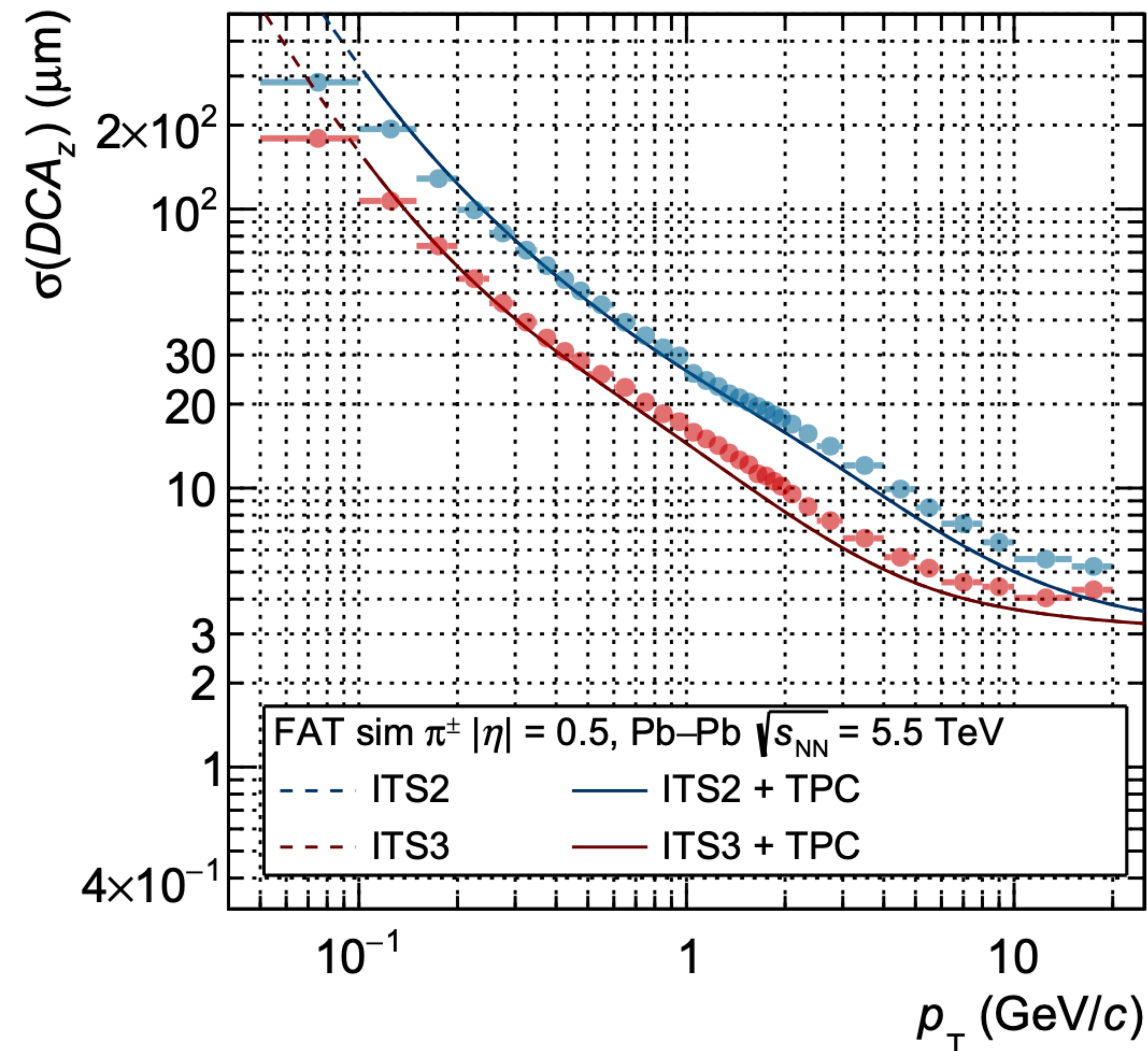
Wafer (ϕ=300mm)

What we can get?

ITS3 performance improvements

ALICE, ALICE-TDR-021, 2024





- **2x improvement** in the pointing resolution (left: $r\varphi$, right: z) of primary charged pion
  - Drastic reduction of material budget (0.35 → 0.086% X_0/layer)
  - Being closer to the interaction point (24 → 19 mm)
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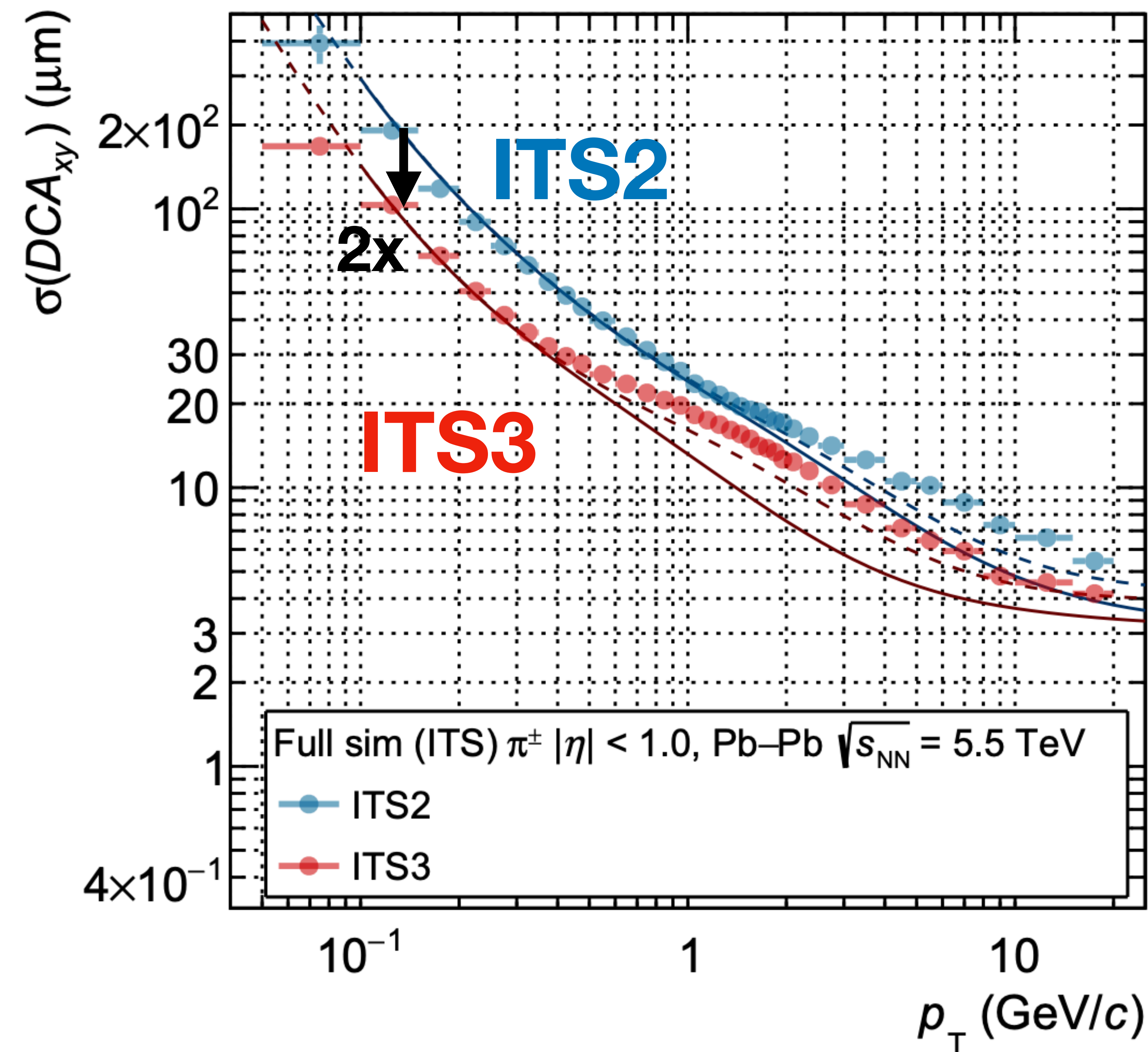

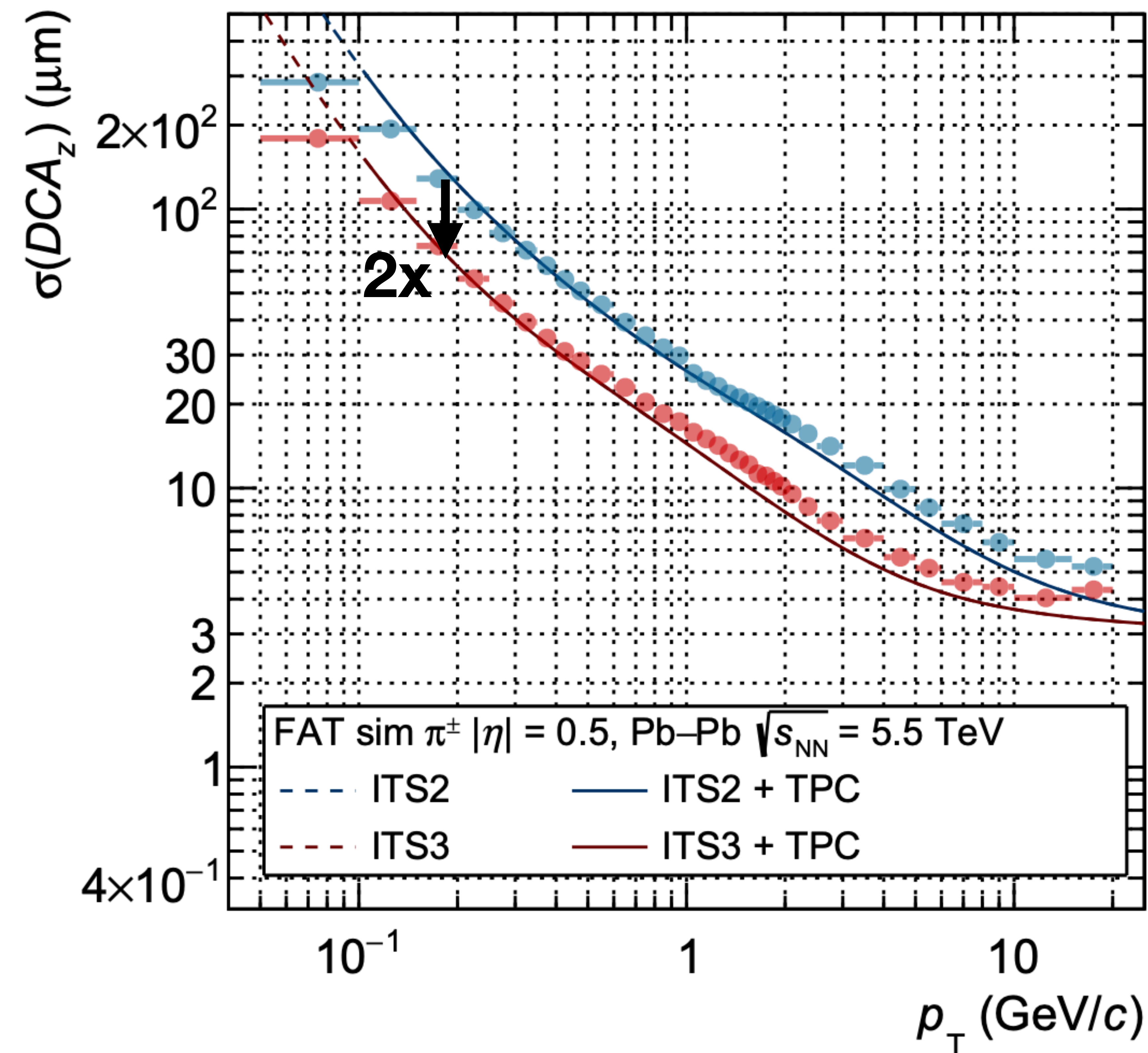

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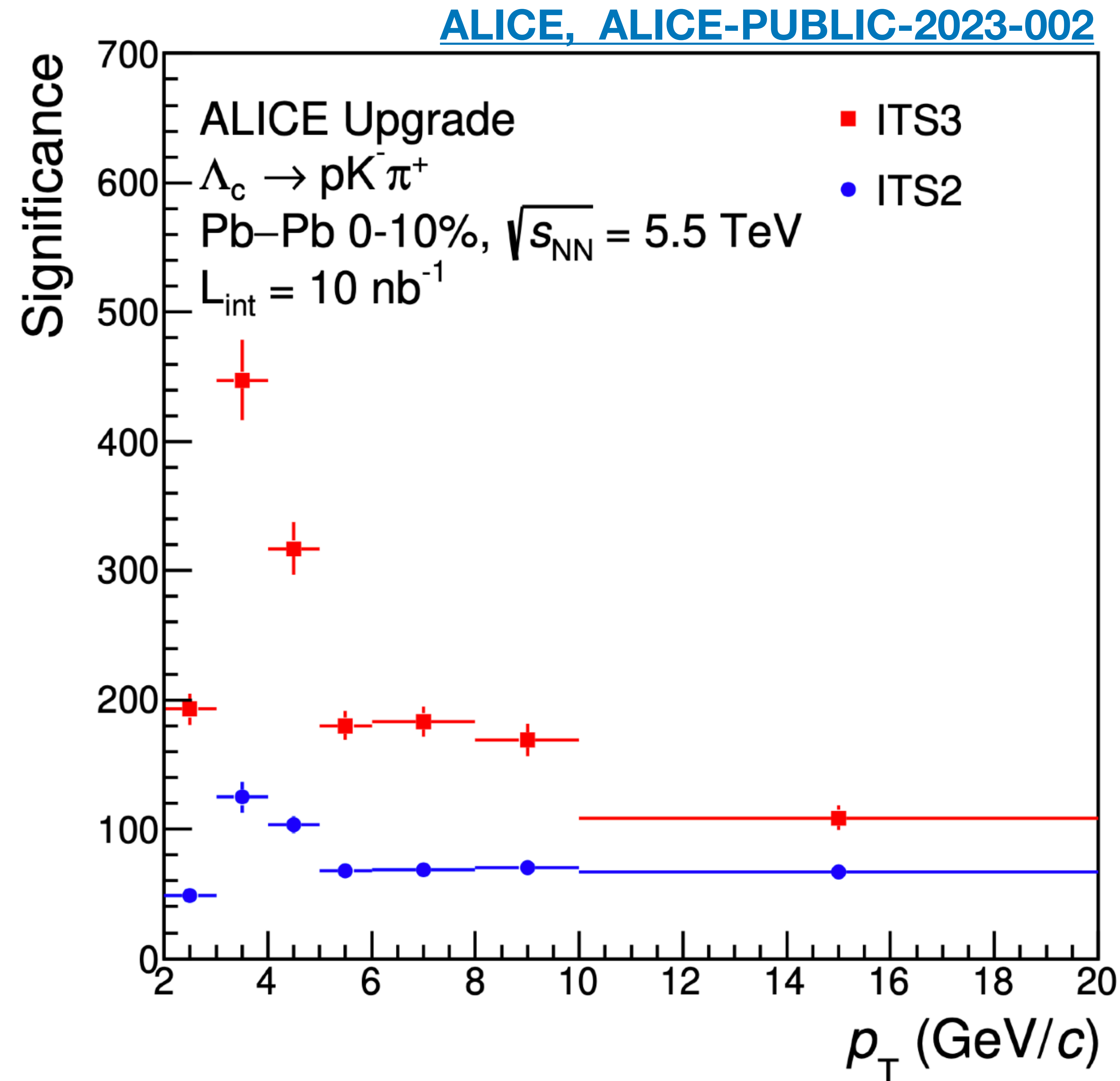
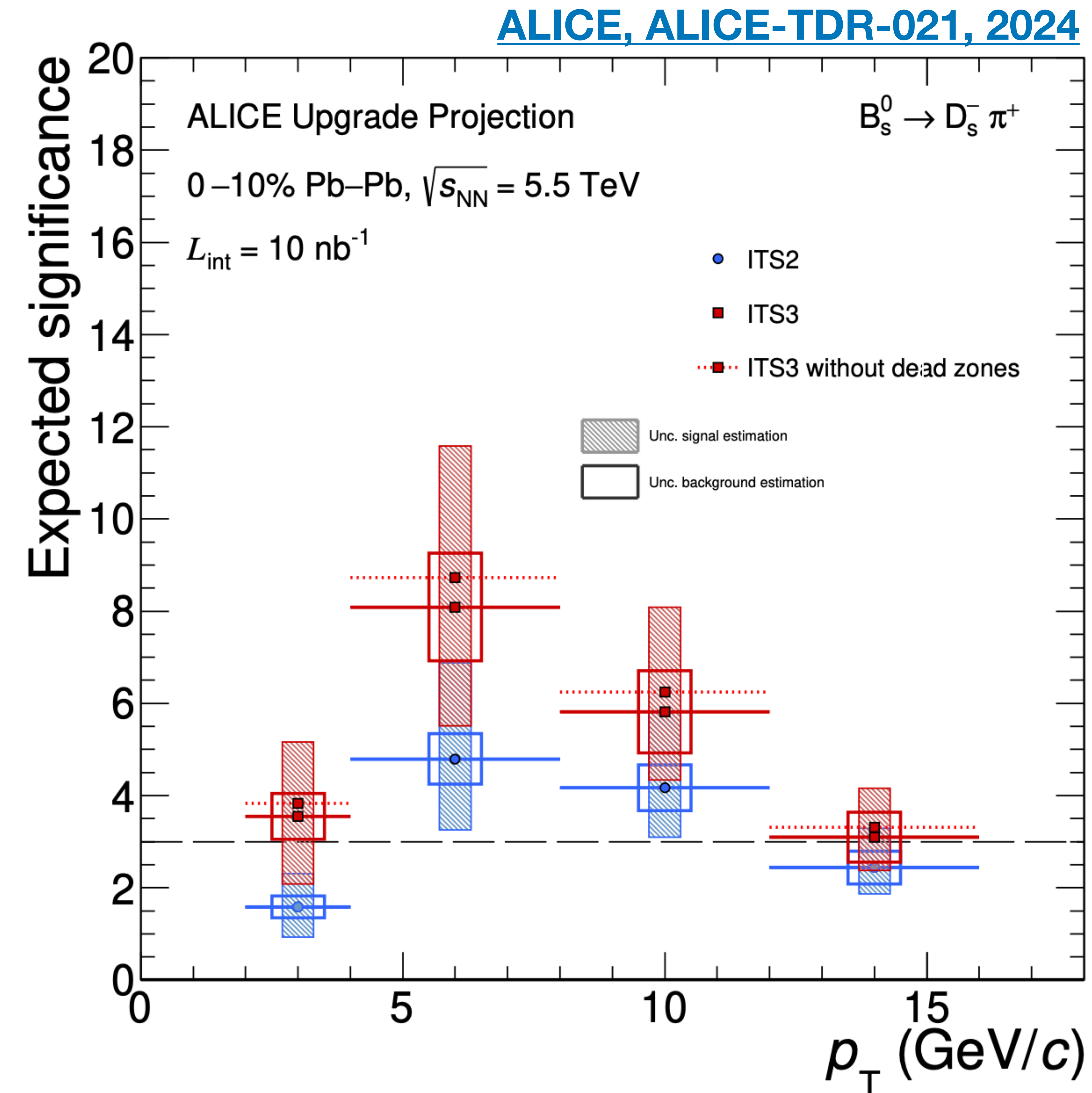
Measurements benefitting from ITS3



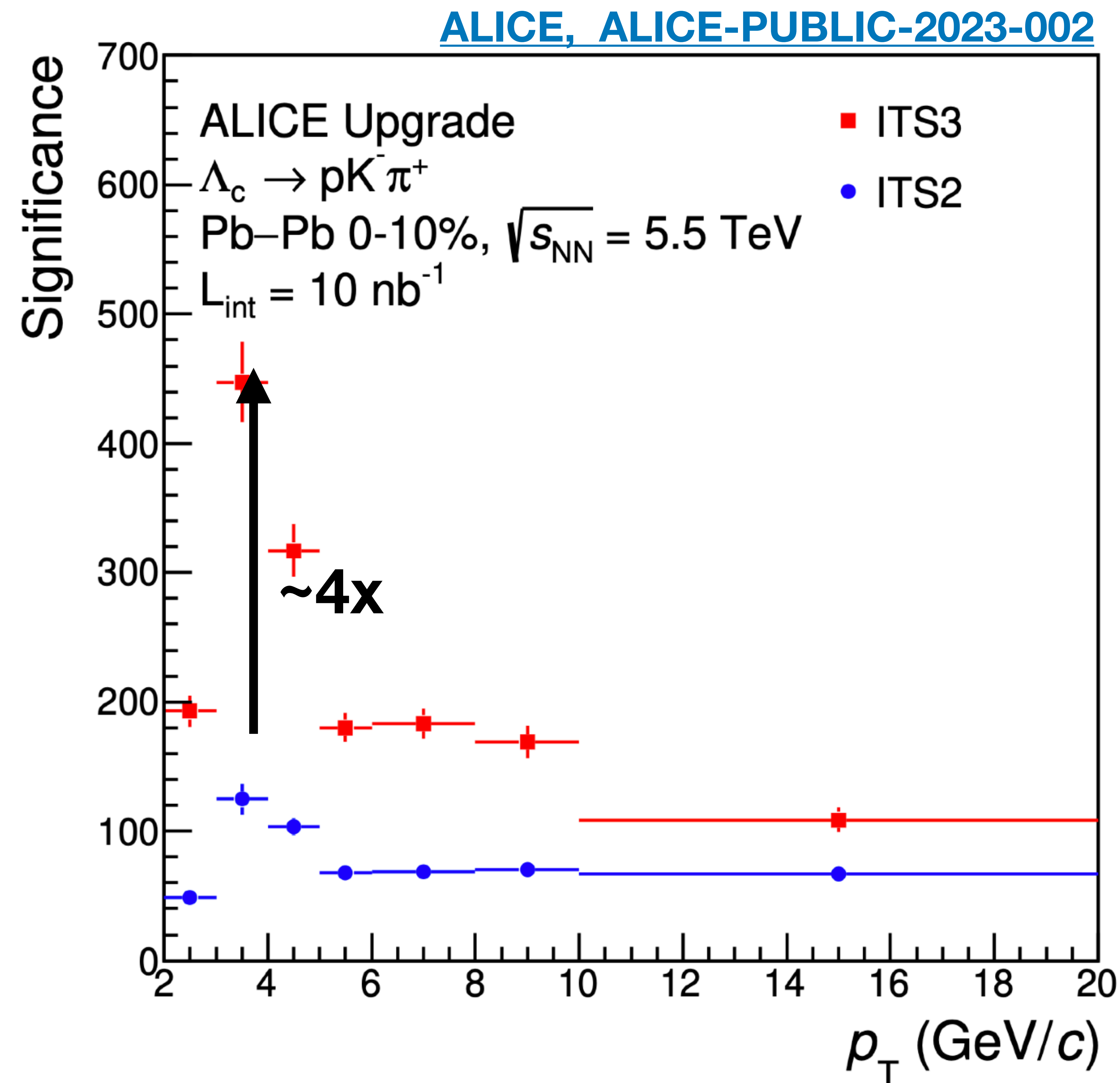


- Directly boosts the **ALICE core physics program** that is largely based on:
  - Low momenta
  - Secondary vertex reconstruction

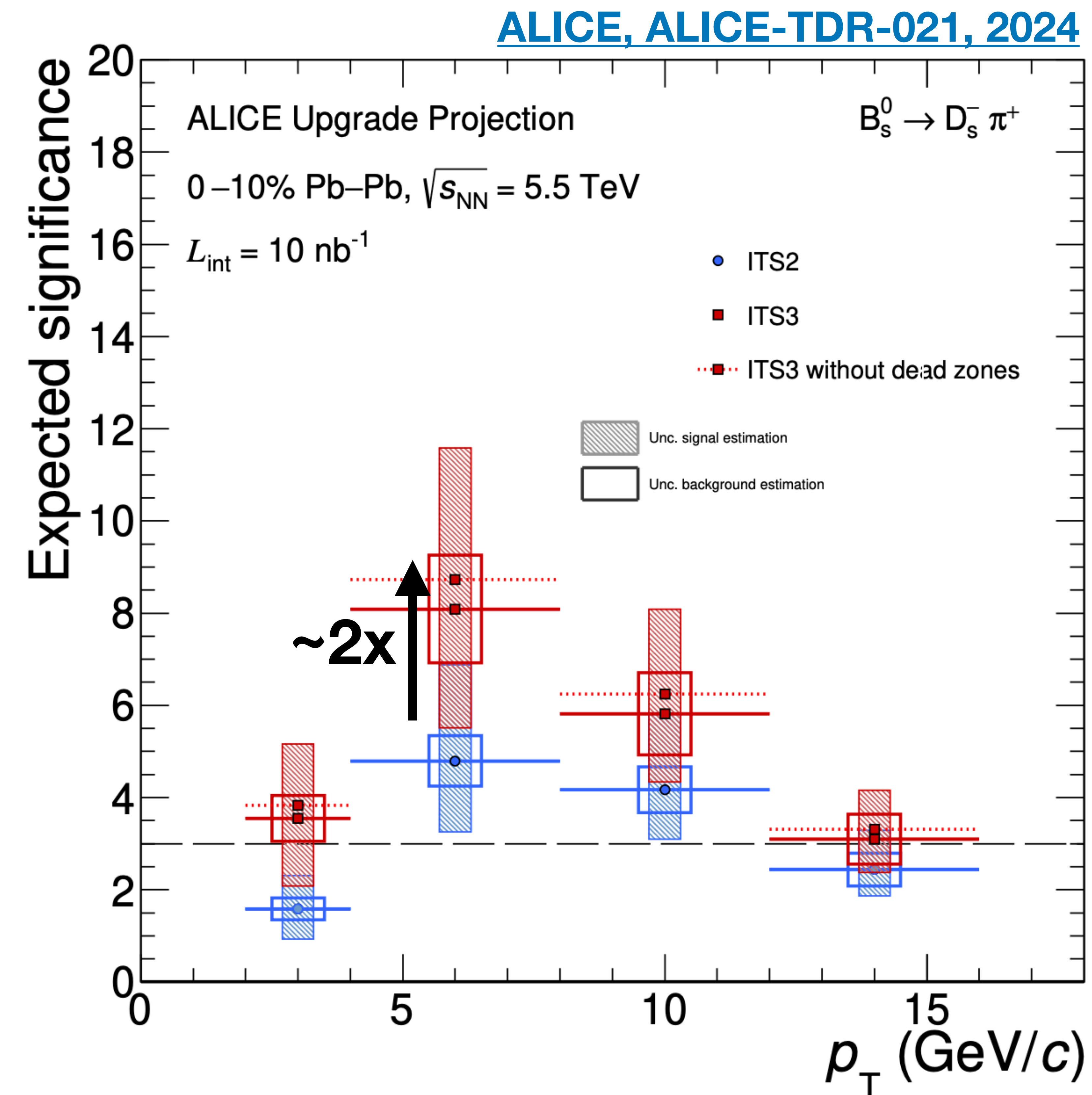
What we can get?

Measurements benefitting from ITS3

ALICE, ALICE-PUBLIC-2023-002



ALICE, ALICE-TDR-021, 2024



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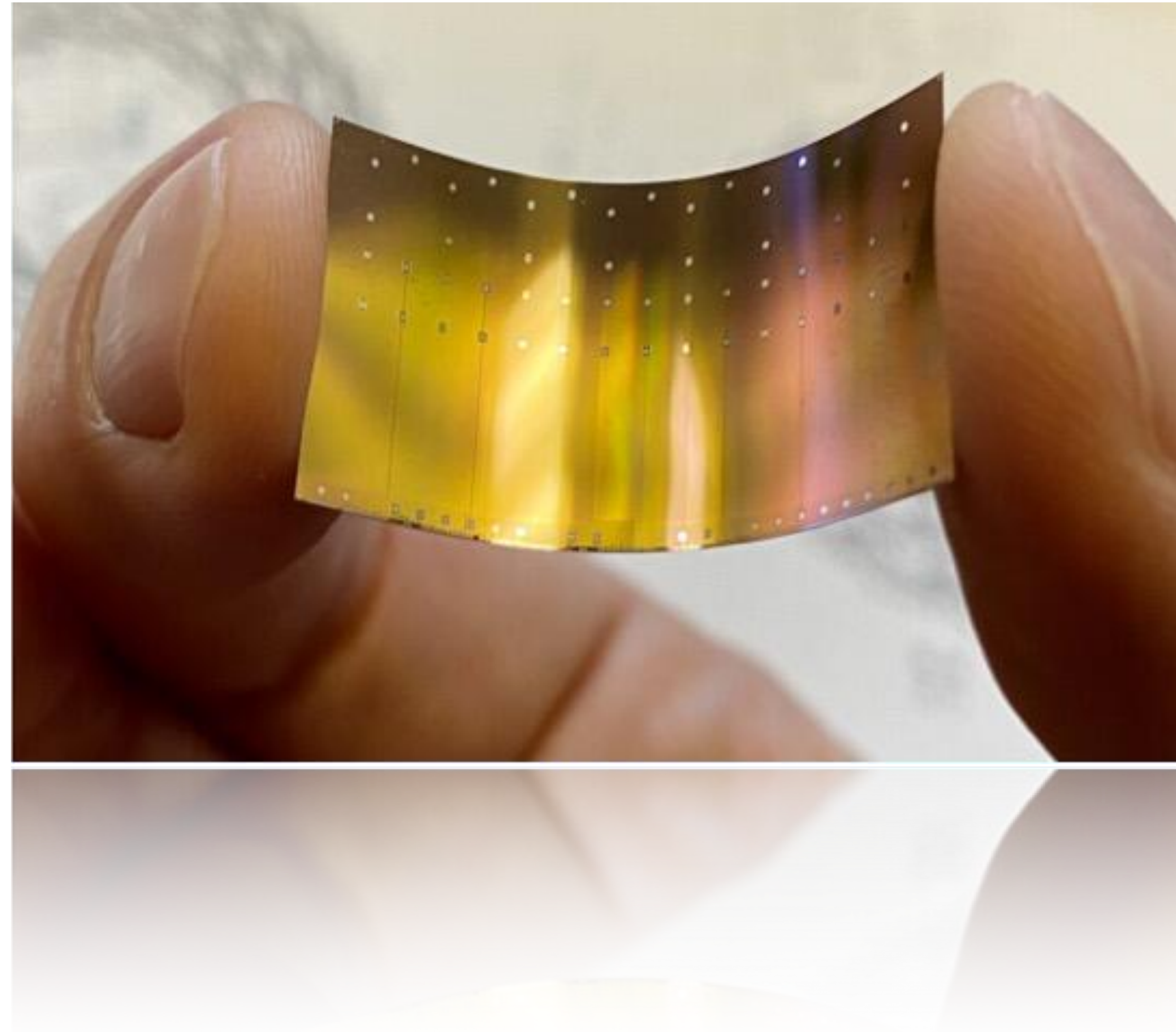
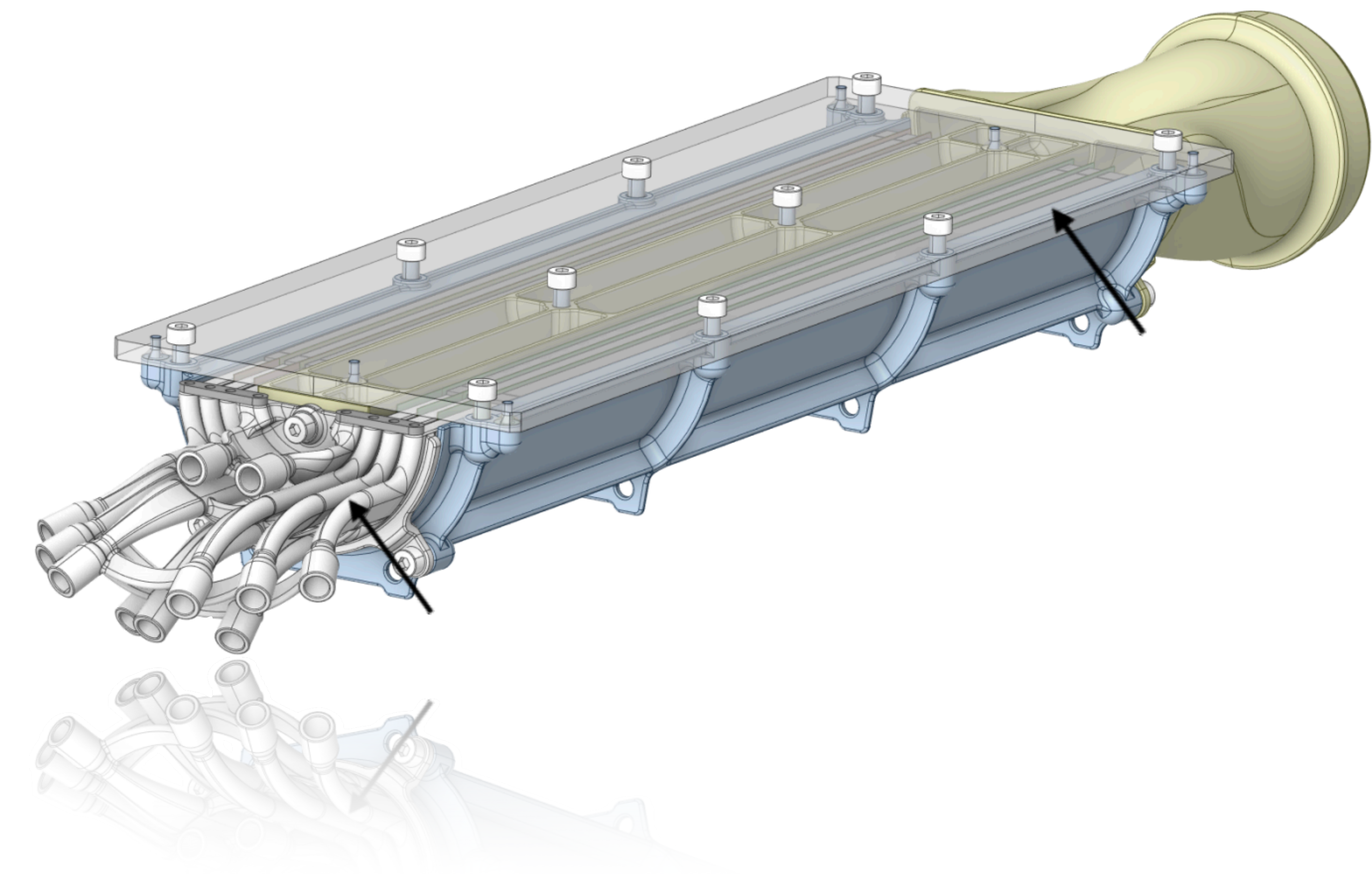


ITS3 design and R&D Activities

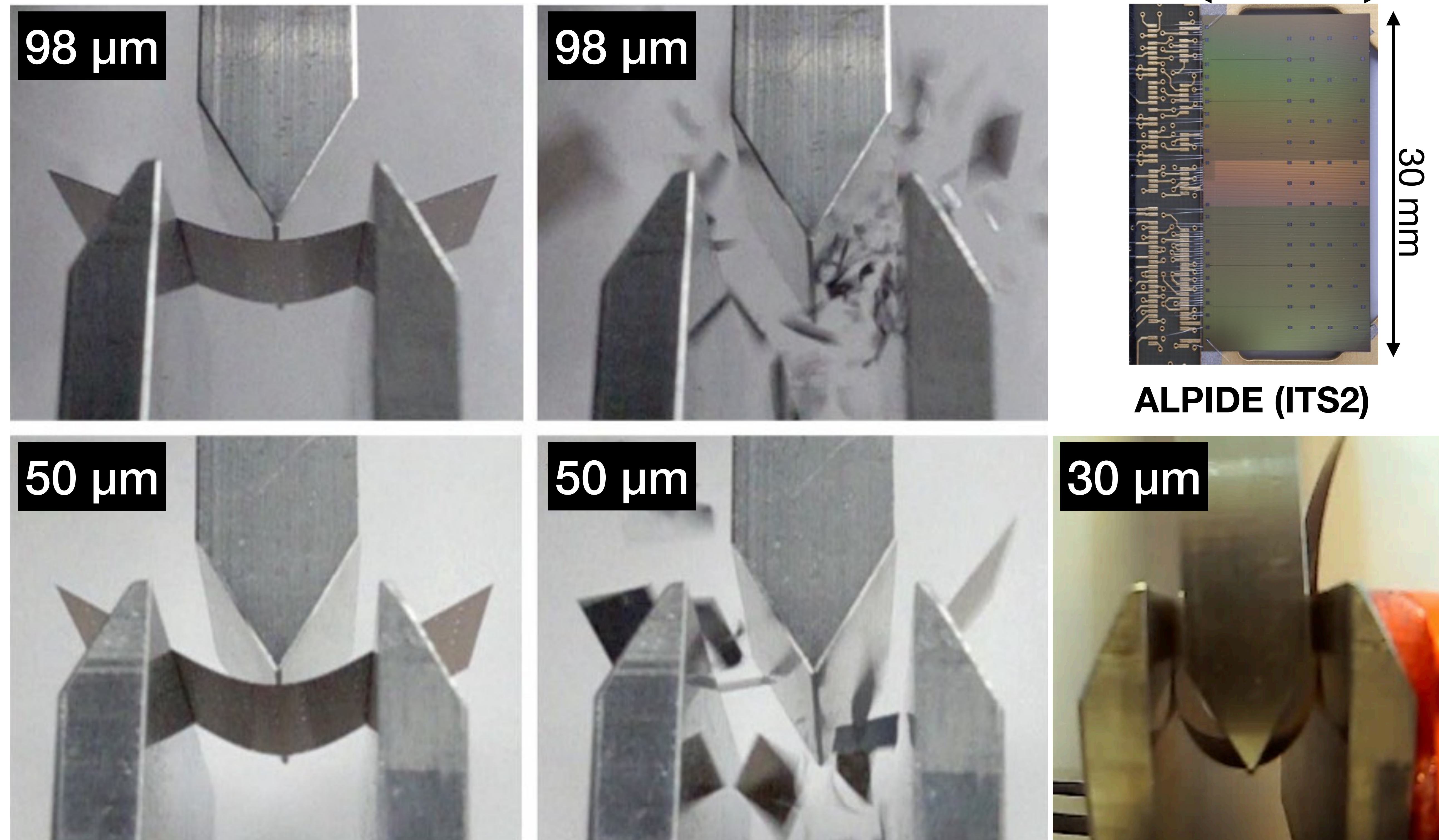
- Can we **bend it?**
- Can we **cool it down?**
- Can it **withstand vibration from cooling?**
- Can we use **65 nm technology?**
- Can we **do the stitching?**

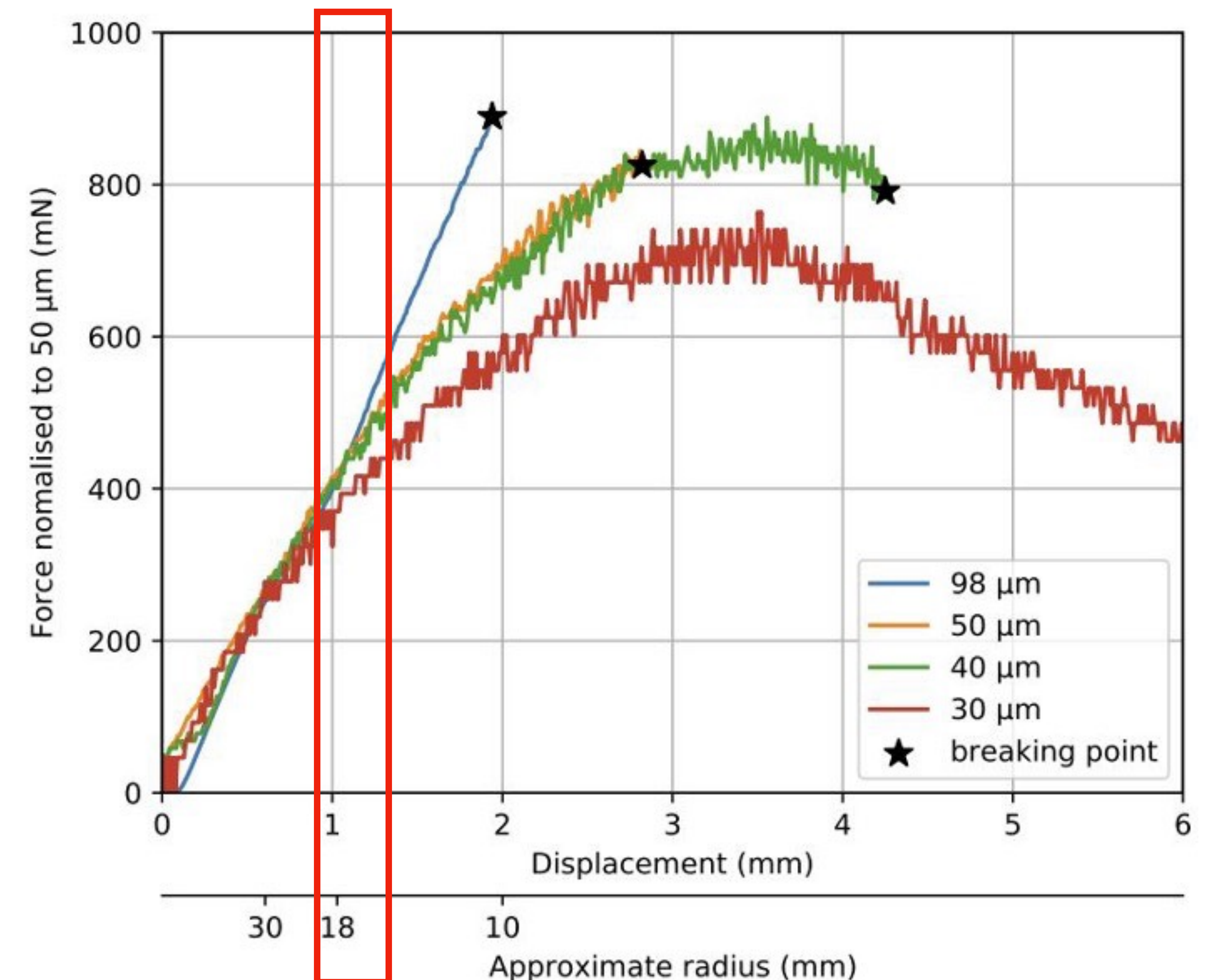


ITS design and R&D

Flexibility of silicon

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

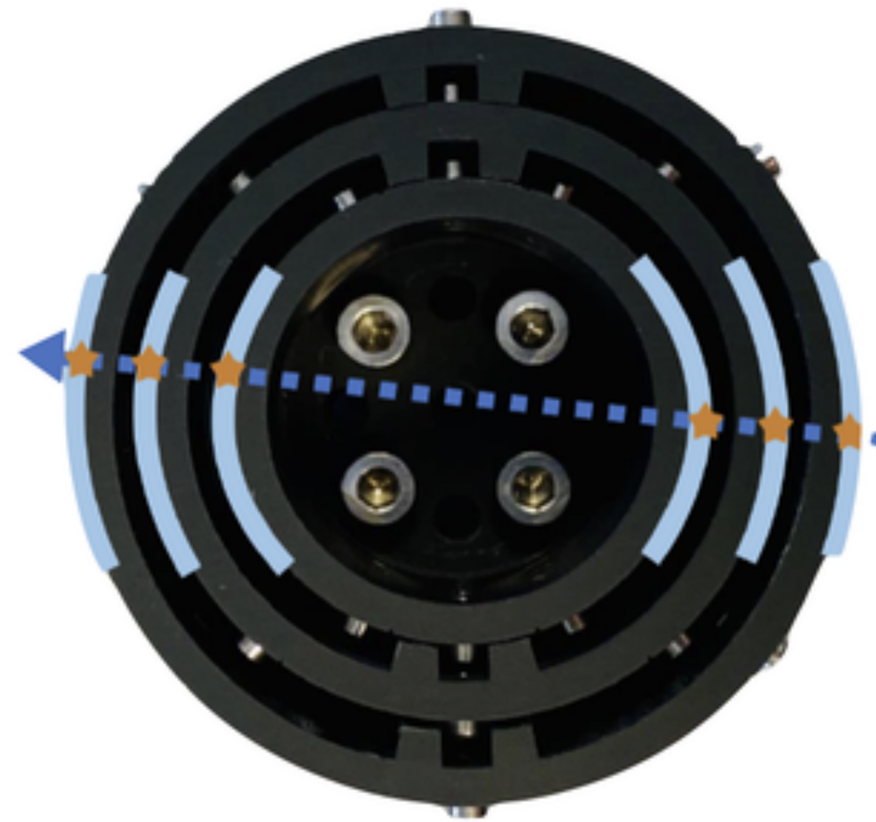


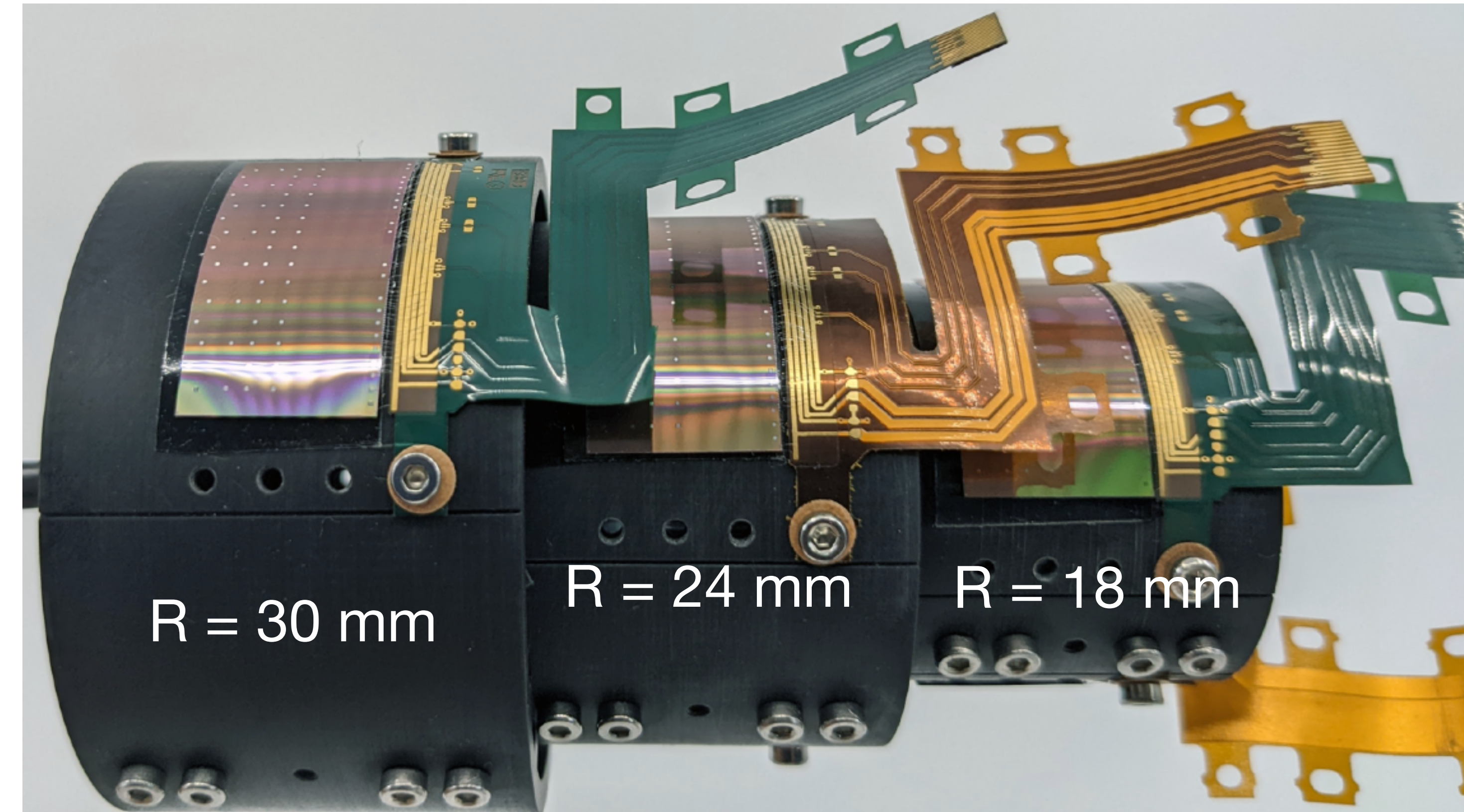


- **Bending test with ITS2 sensor:** Target radii (19 mm) easily achievable

ITS design and R&D

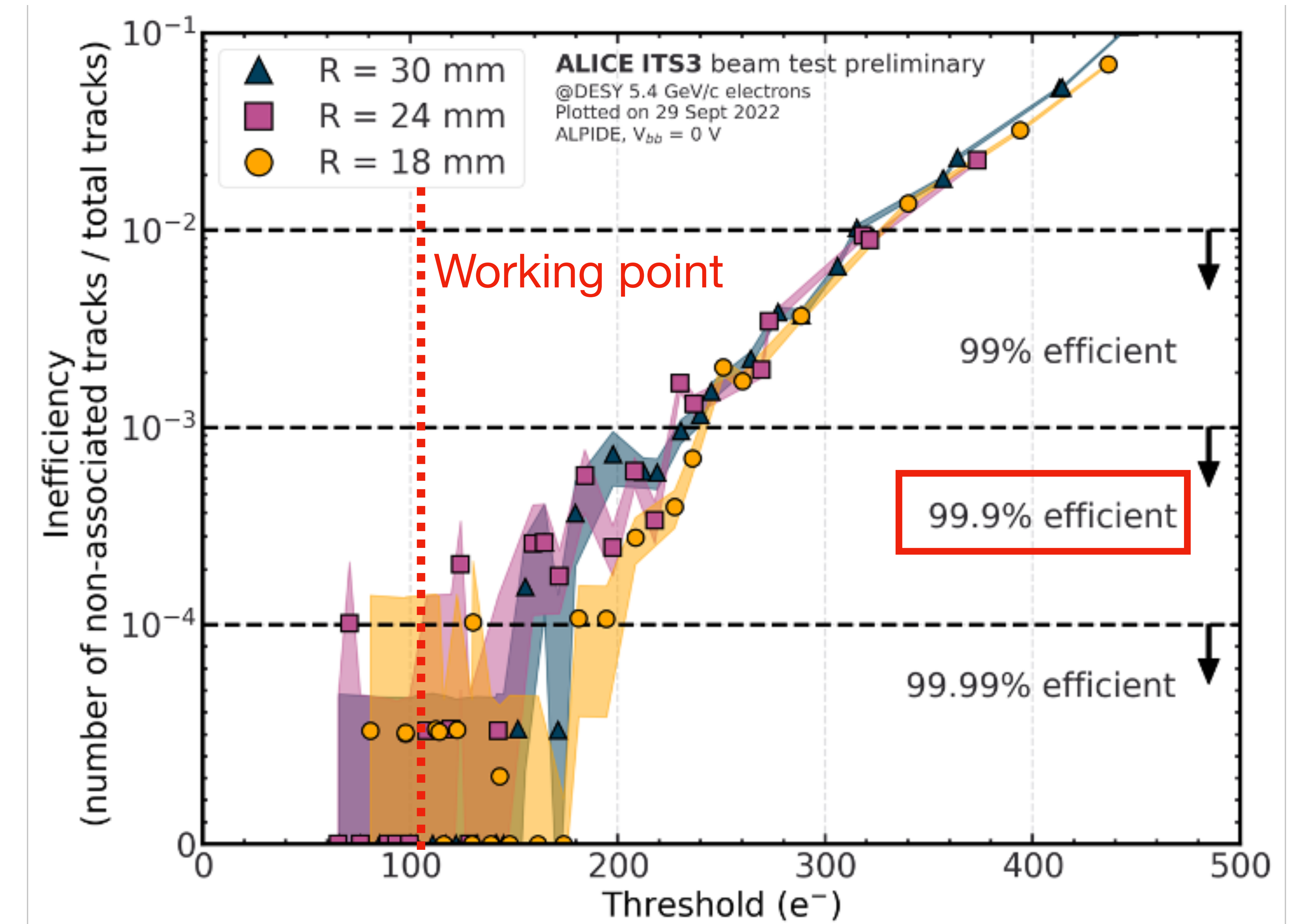
Bending ALPIDEs (ITS2) performance





ALICE, NIM.A 1028 (2022) 166280

μITS3



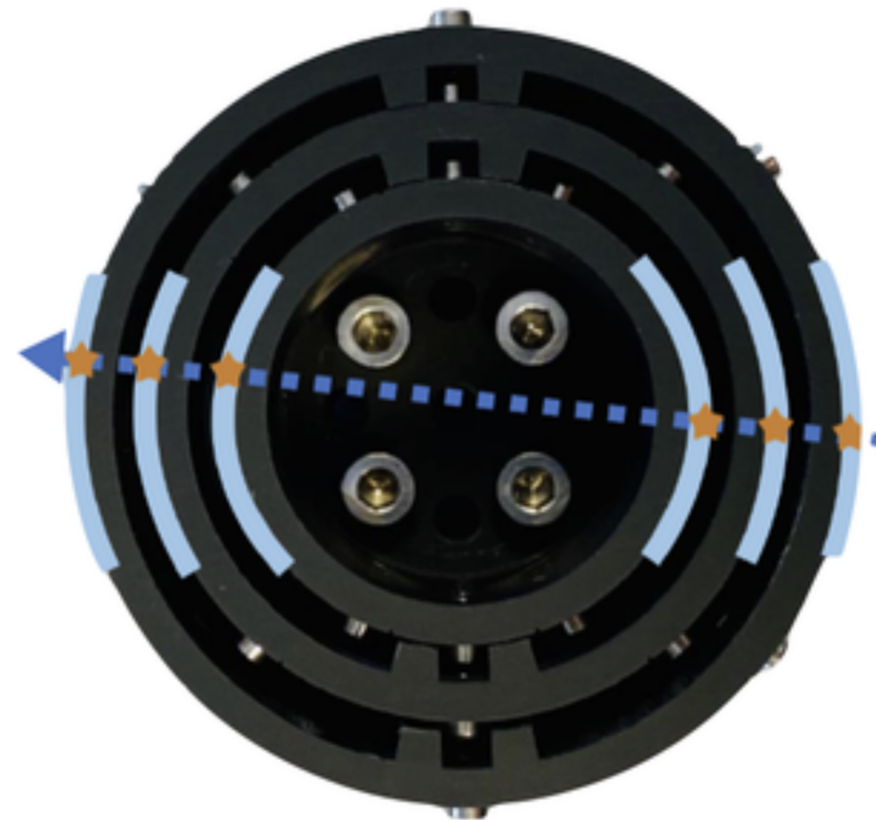
Inefficiency test results

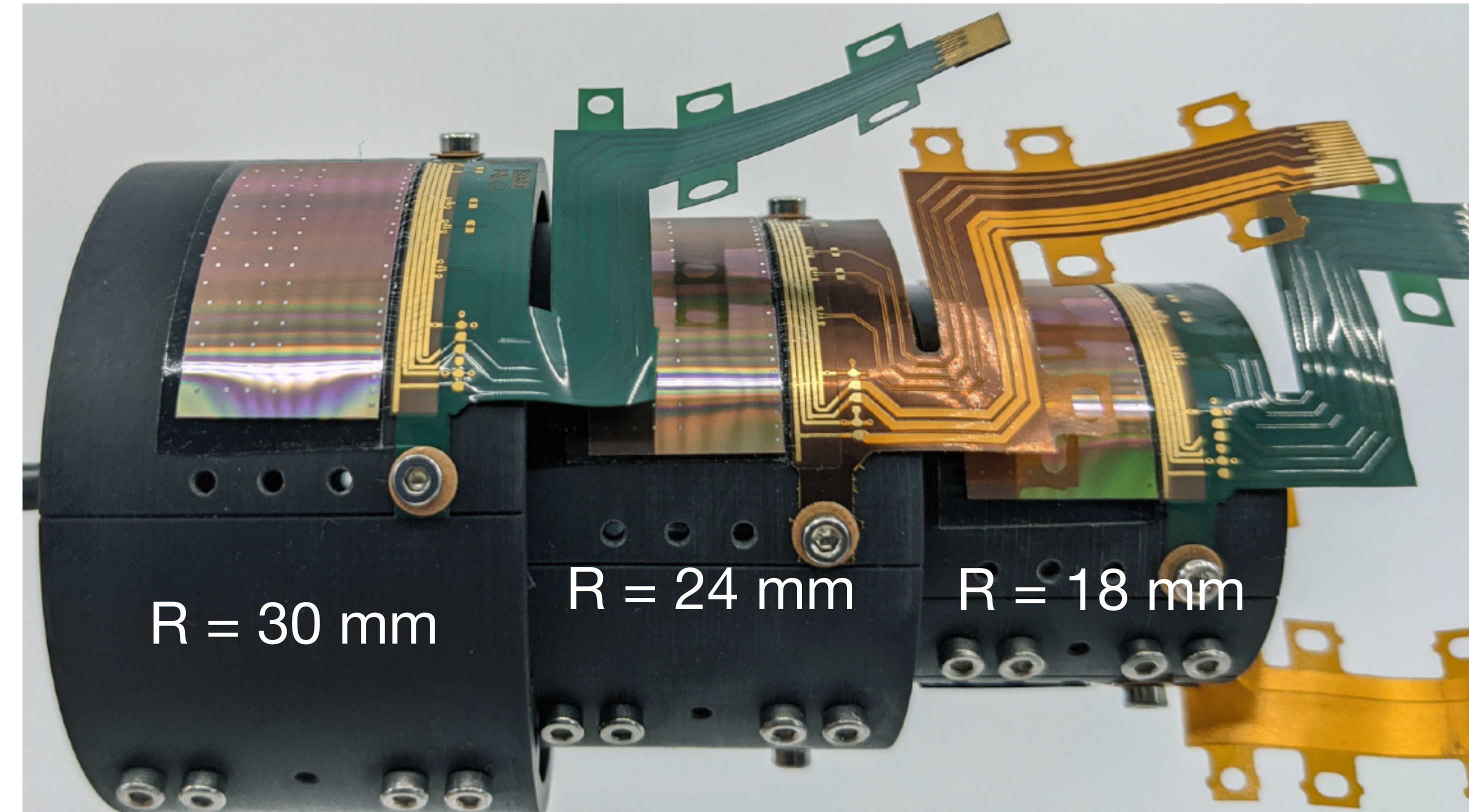
- **"μITS3": 6 ALPIDEs (180 nm) bent to ITS3 target radii**
- No degradation of detection efficiency observed
- Results validated on bent 65 nm pixel test structures
- Electrical interconnections to FPC after bending through wire bonding tested

65 nm sensor with FPC

ITS design and R&D

Bending ALPIDEs (ITS2) performance





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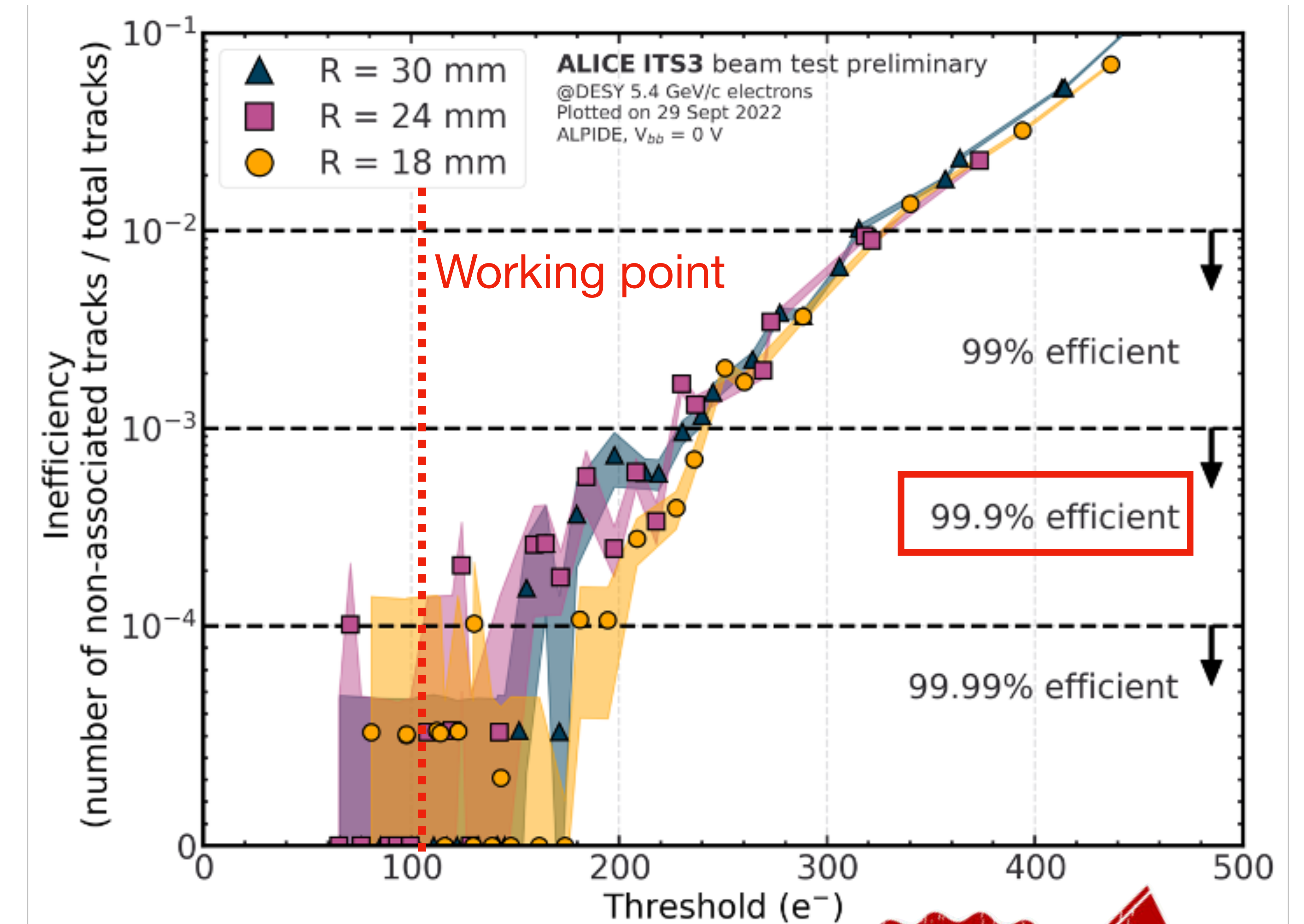

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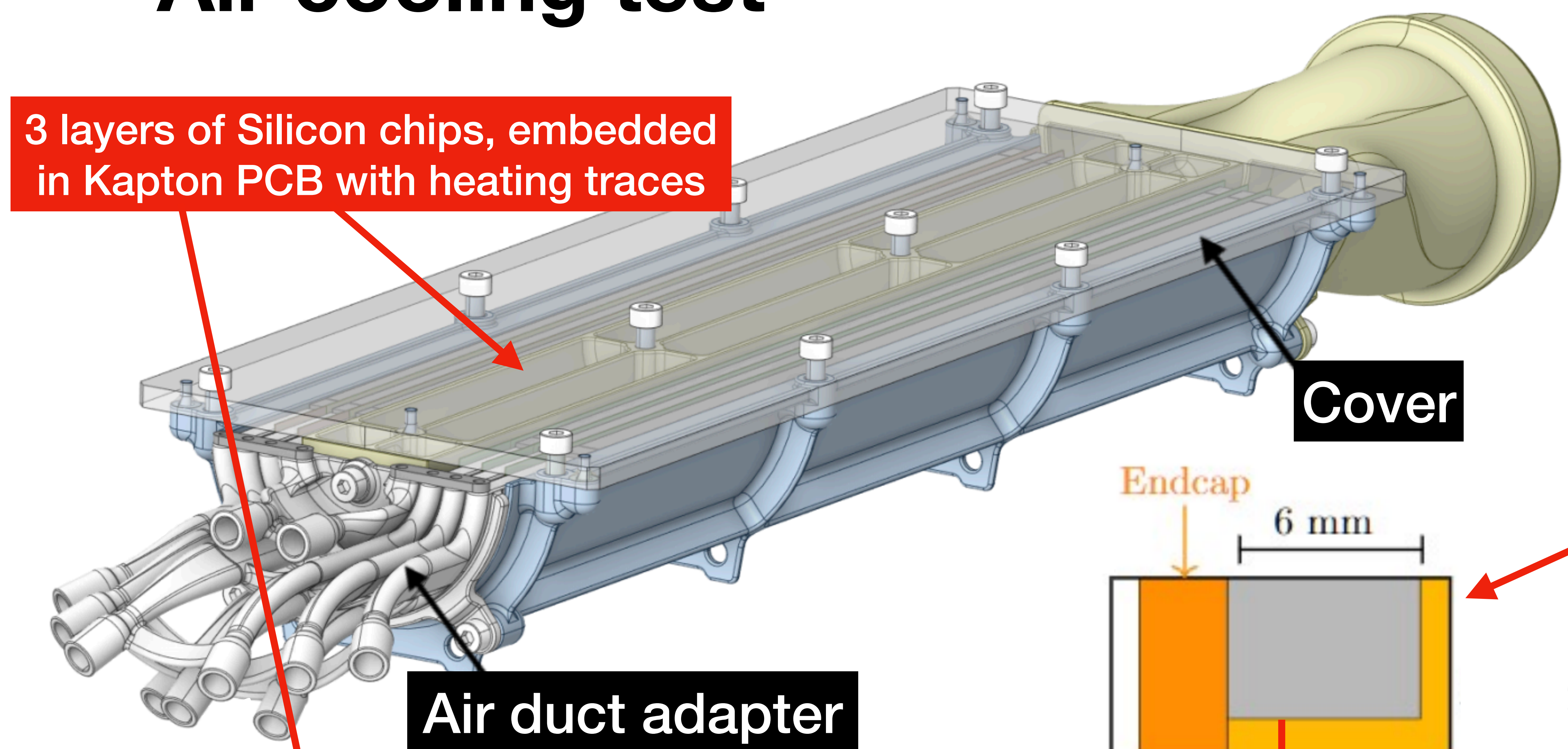
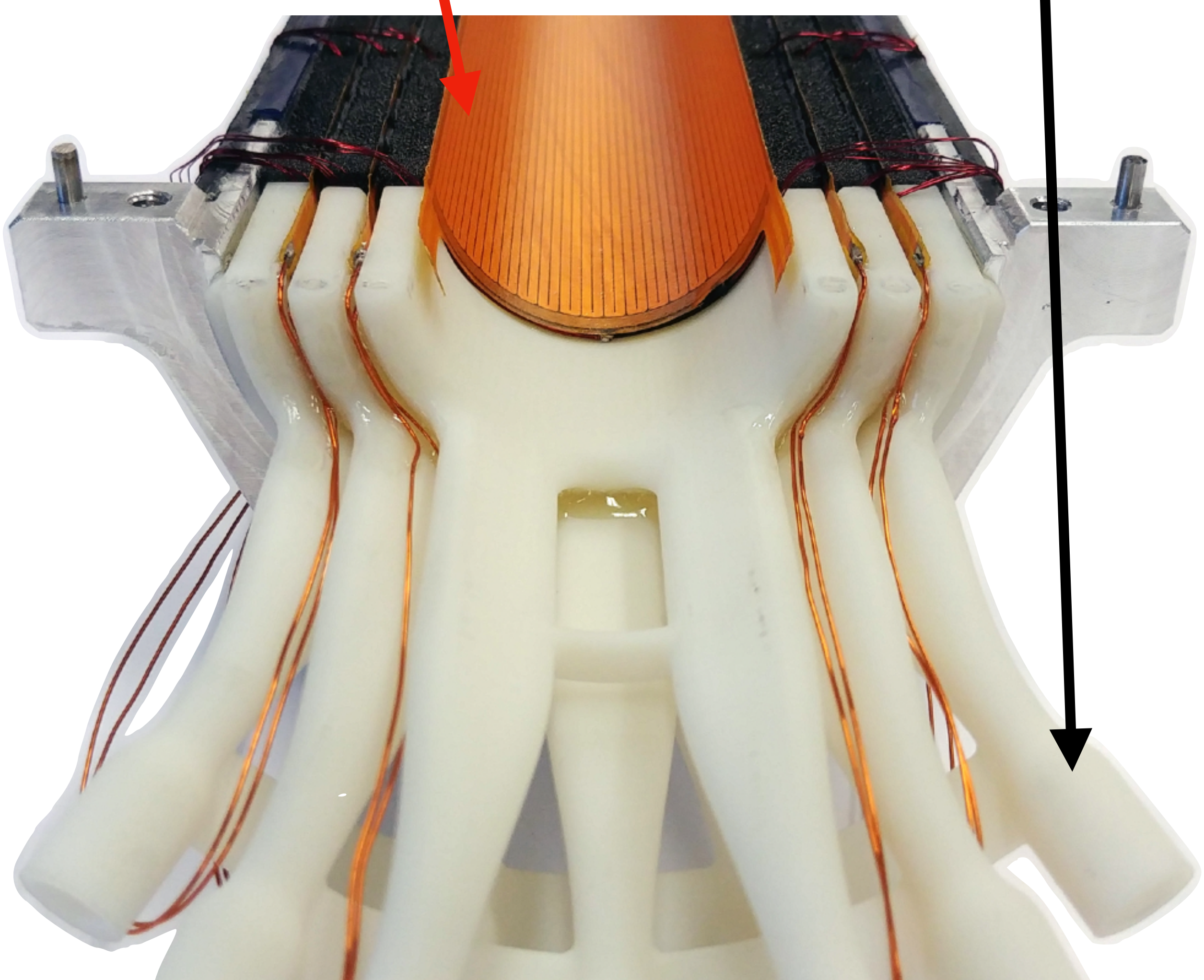
- **"μITS3": 6 ALPIDEs (180 nm) bent to ITS3 target radii**
- No degradation of detection efficiency observed
- Results validated on bent 65 nm pixel test structures
- Electrical interconnections to FPC after bending through wire bonding tested

We can make the bent detector !

ITS design and R&D

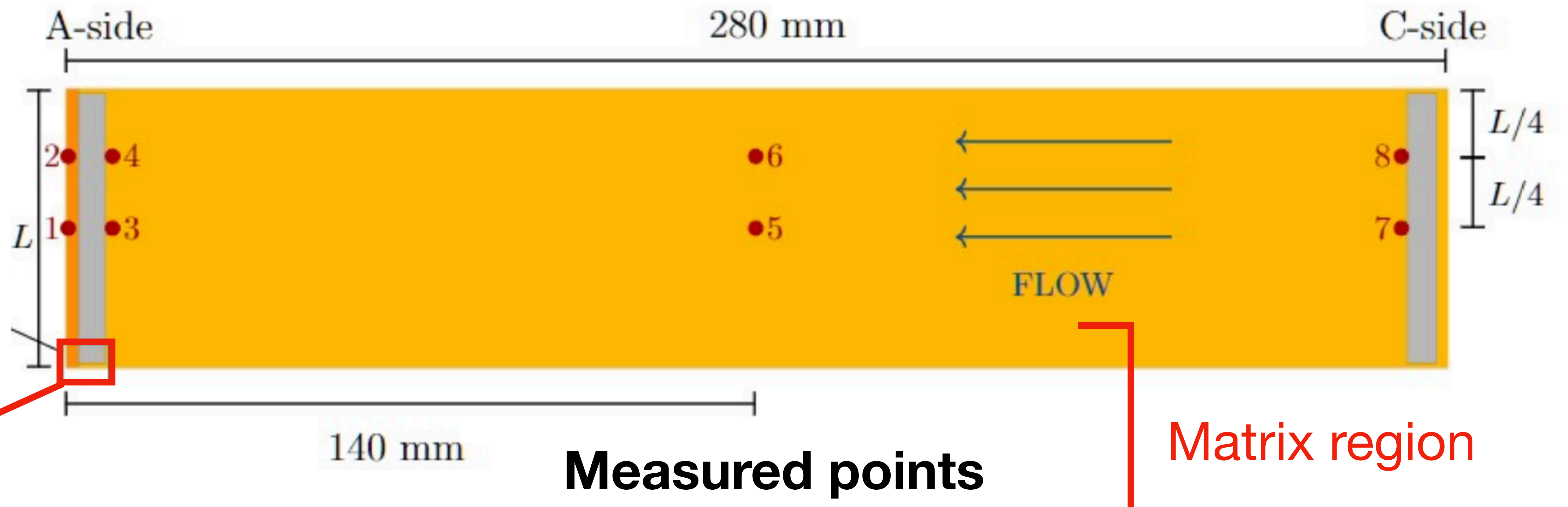
Air cooling test



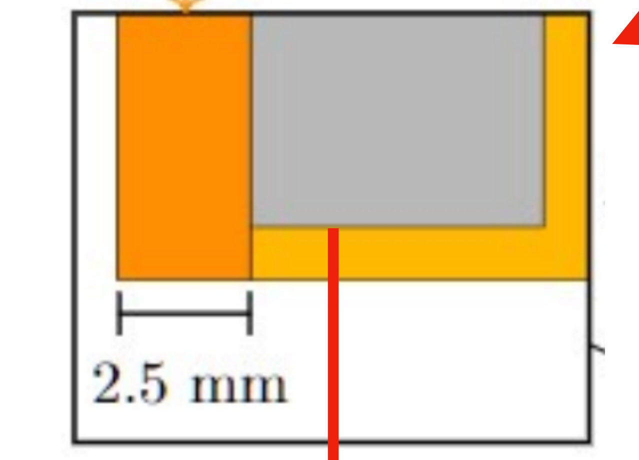


ITS3 "bread board" model 3

Power consumption tested:
Endcap: 1000 mW/cm2, Matrix 25 mW/cm2

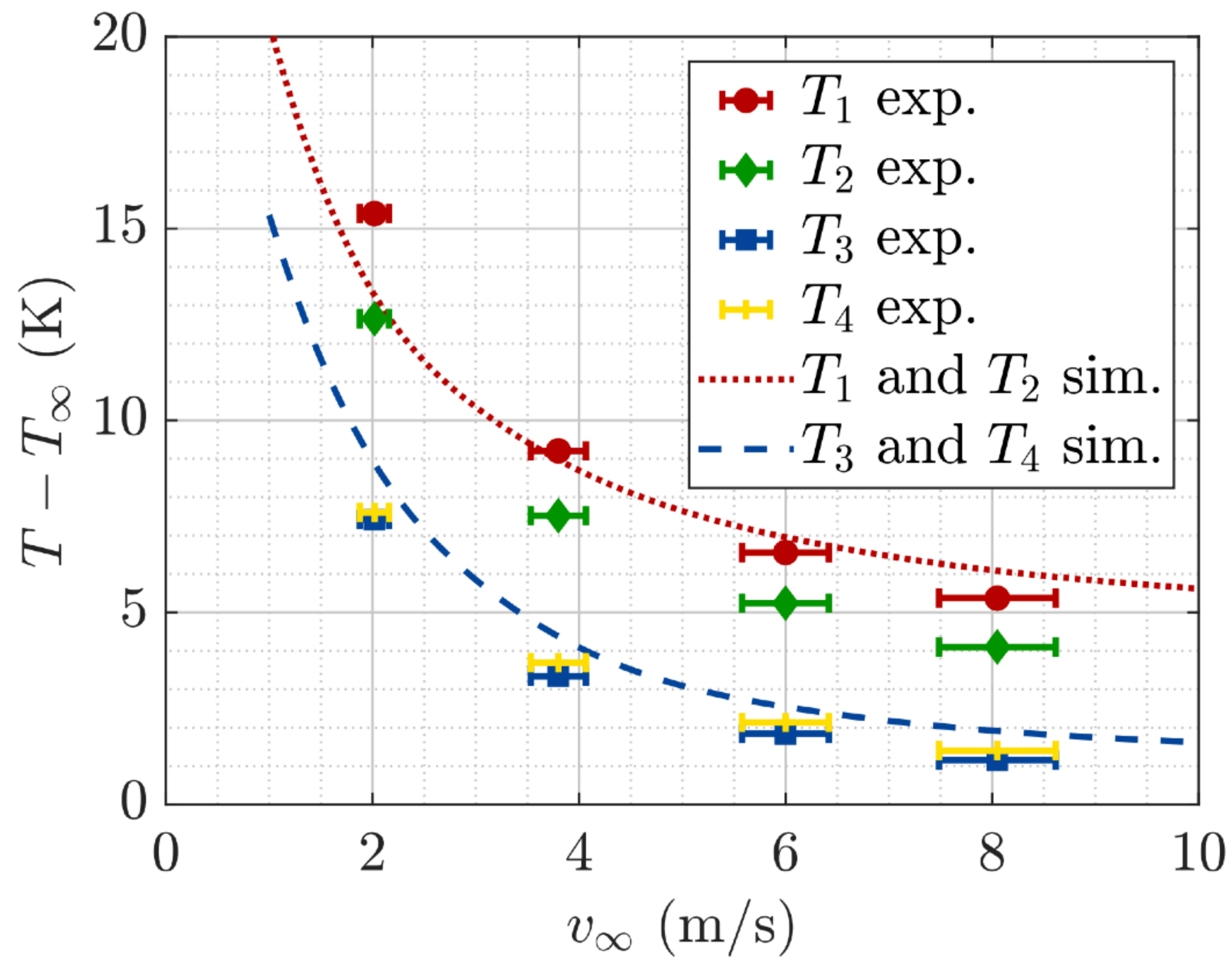


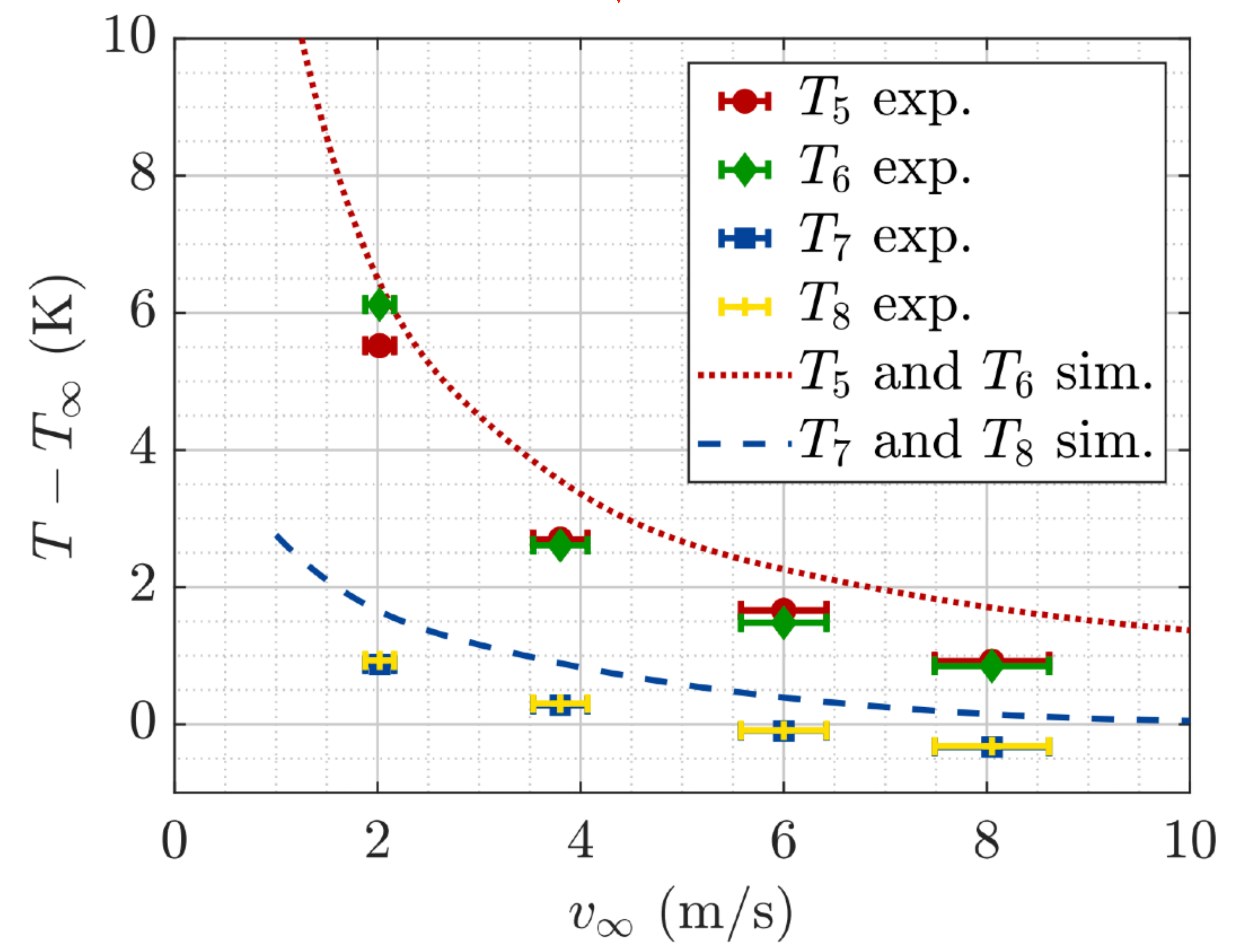
Measured points



Endcap region

Matrix region



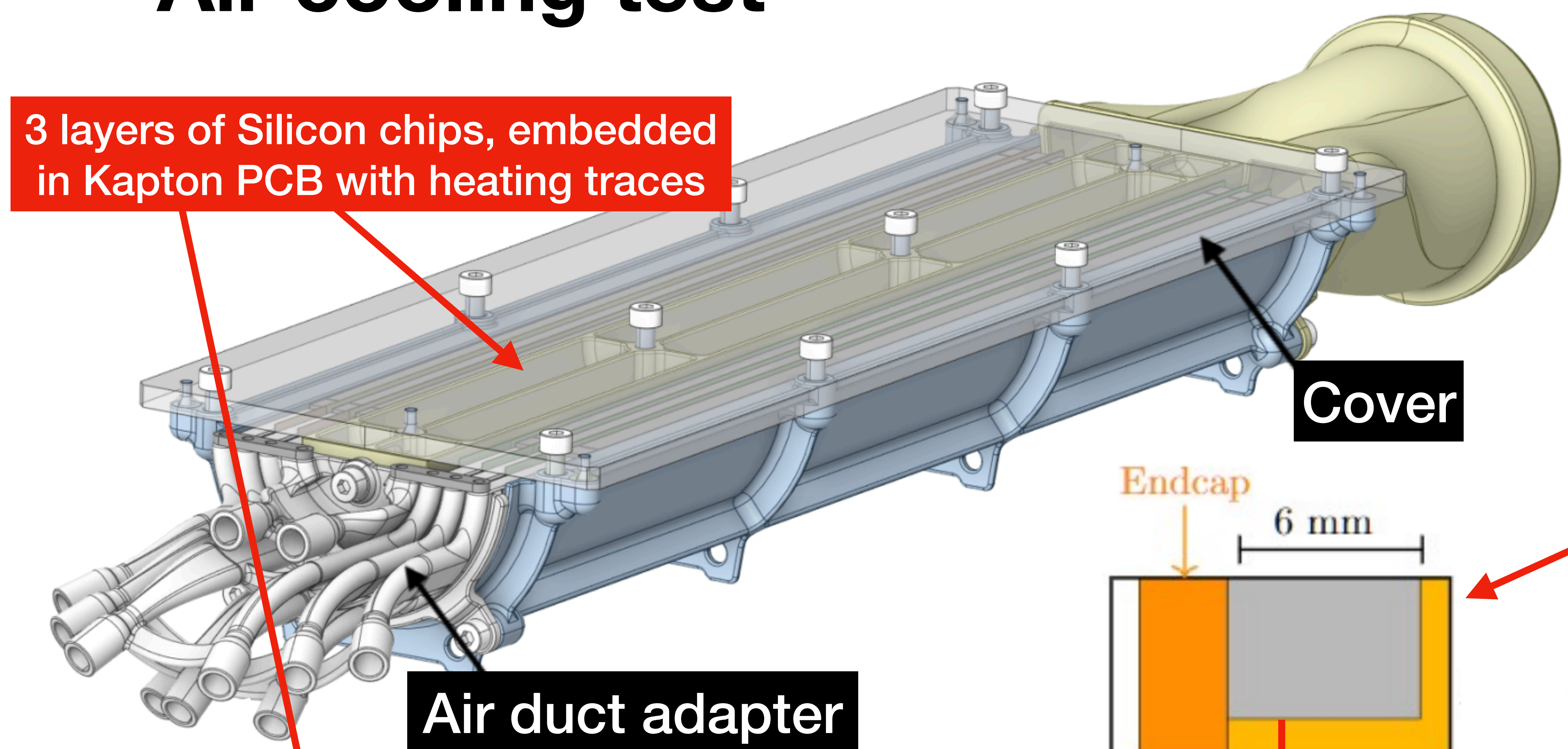


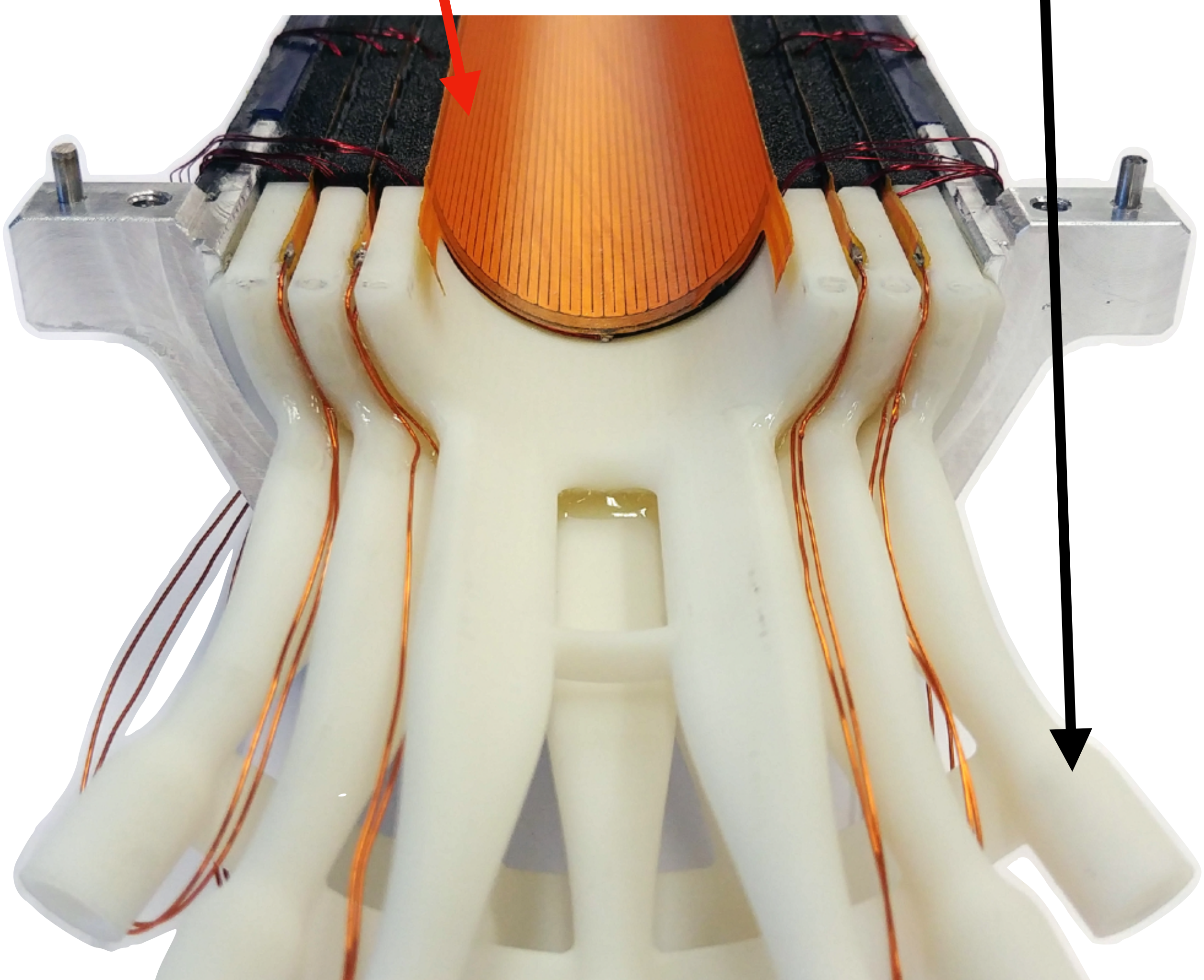
- The CFD simulations and the experimental results agree well
  - The simulations slightly over-predict the values in all cases.

ITS design and R&D

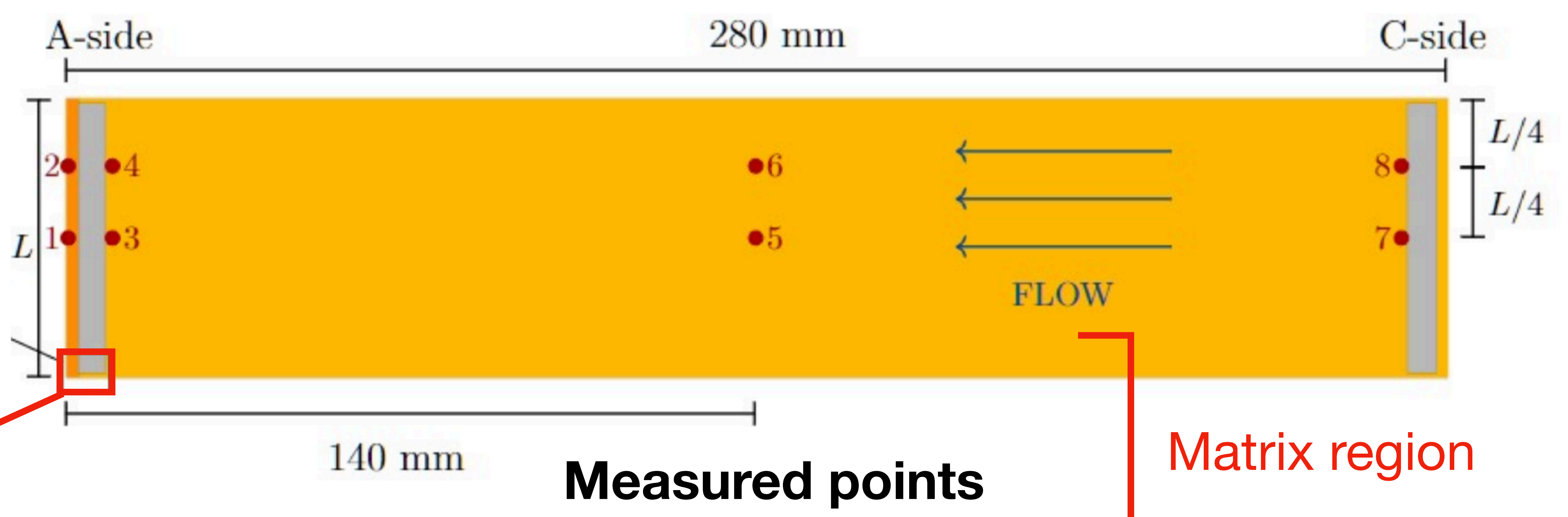
Air cooling test

Power consumption tested:
Endcap: 1000 mW/cm2, Matrix 25 mW/cm2

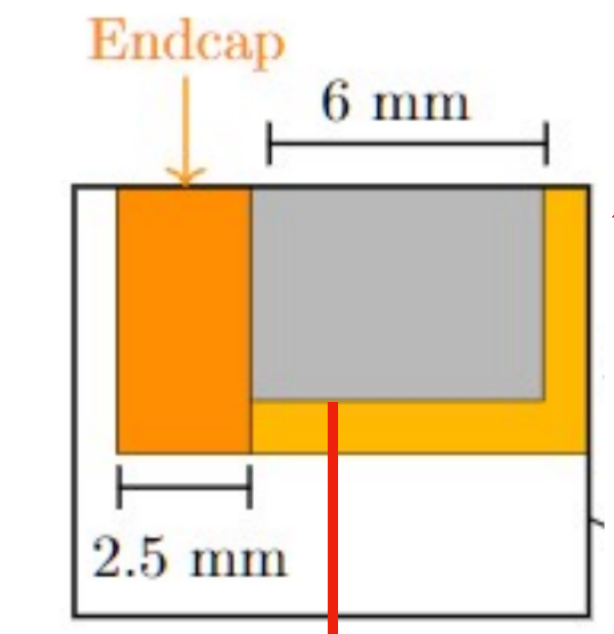




ITS3 "bread board" model 3

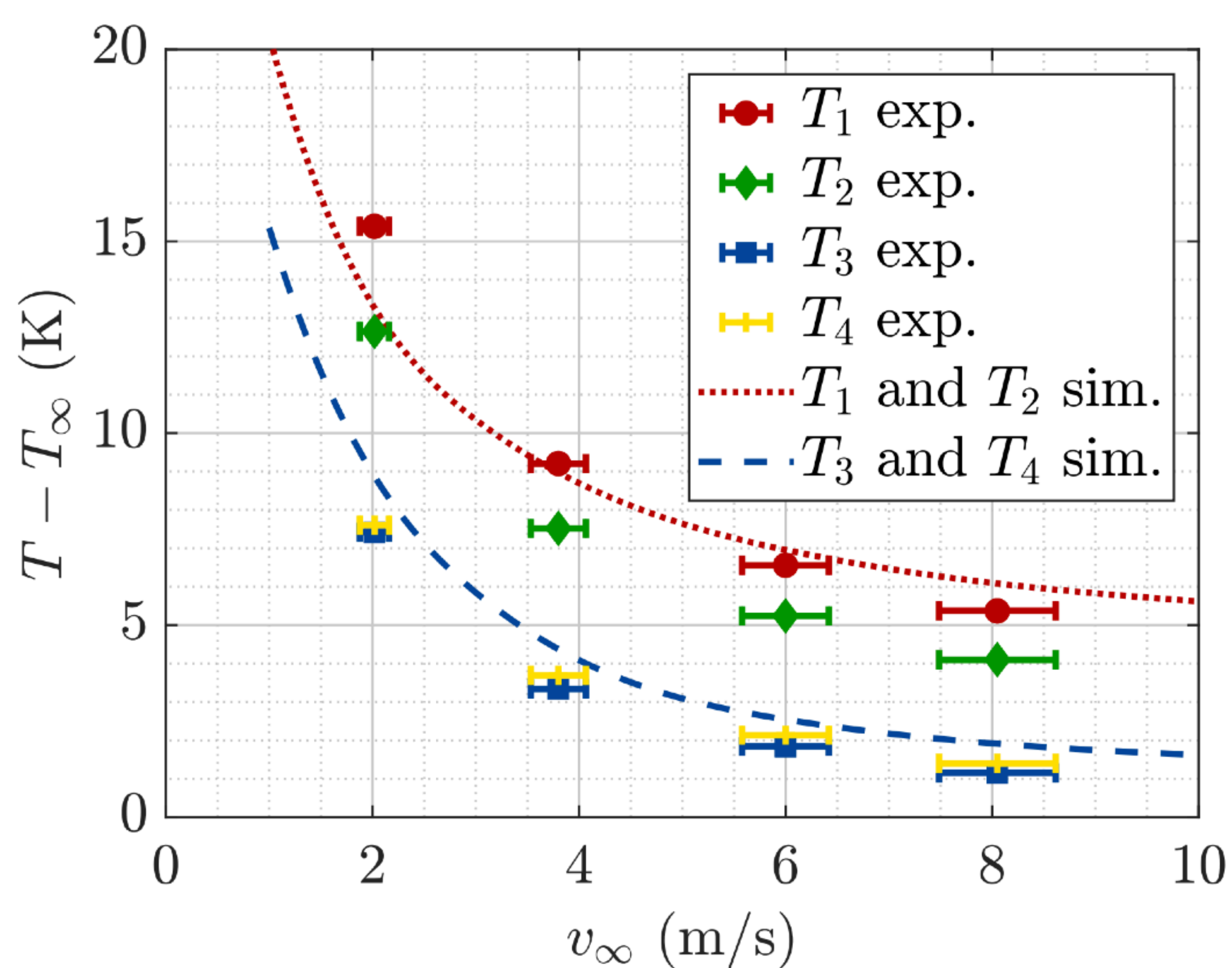


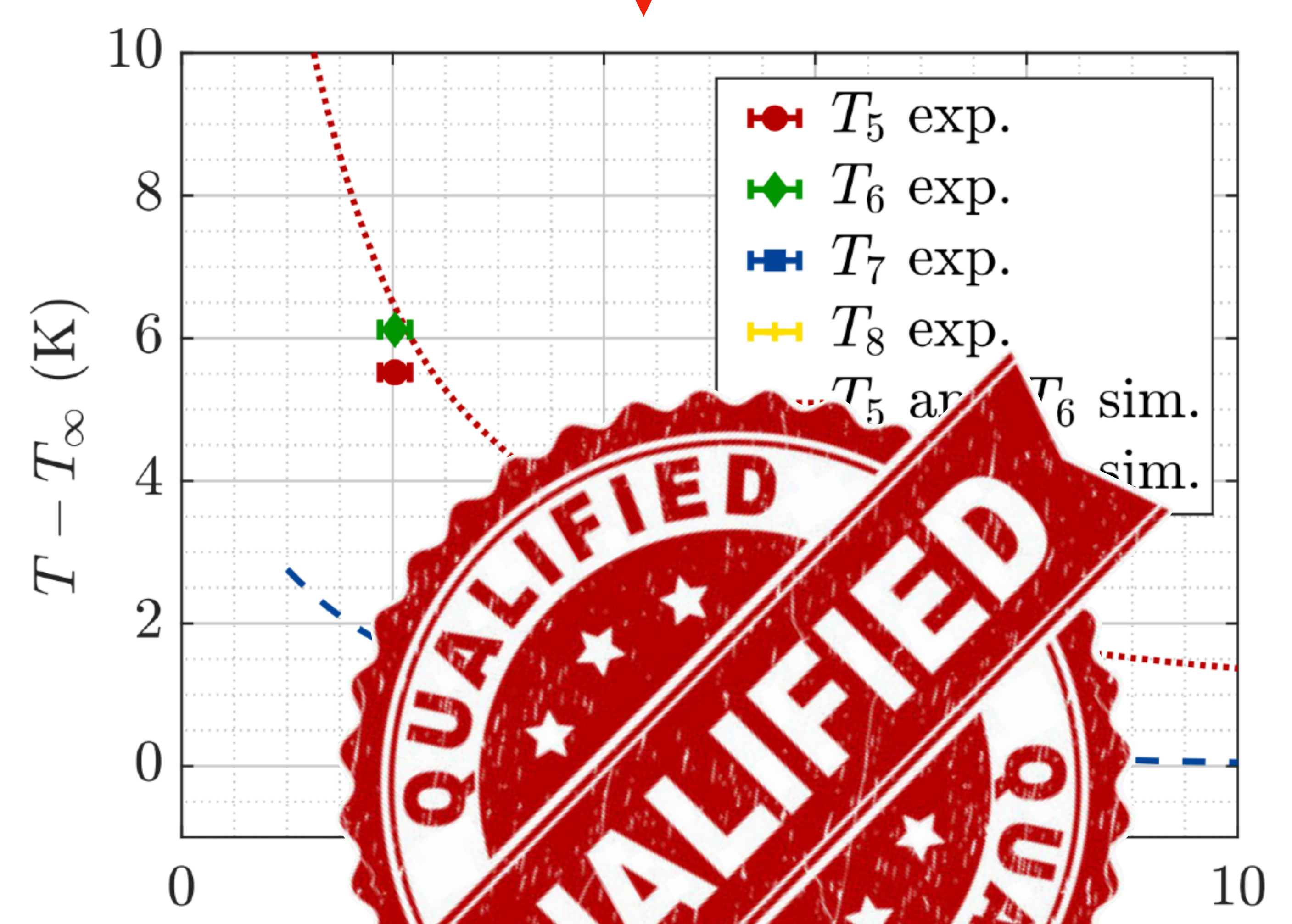
Measured points



Endcap region

Matrix region



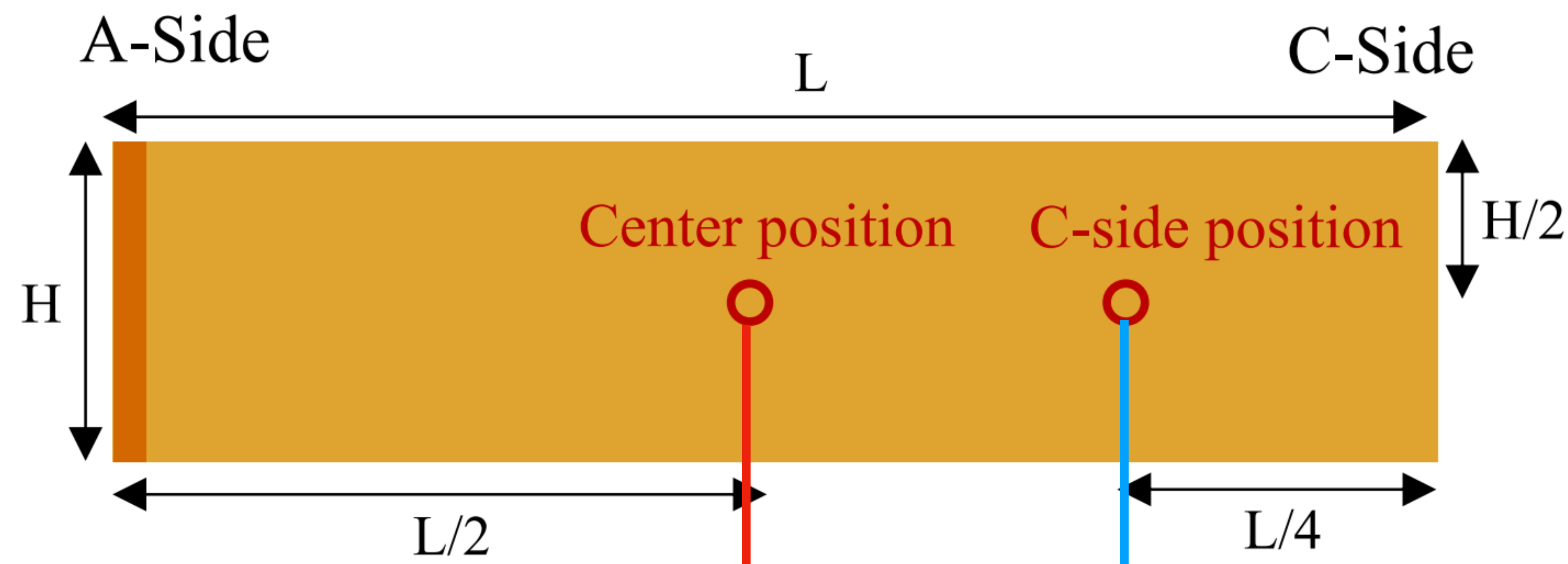


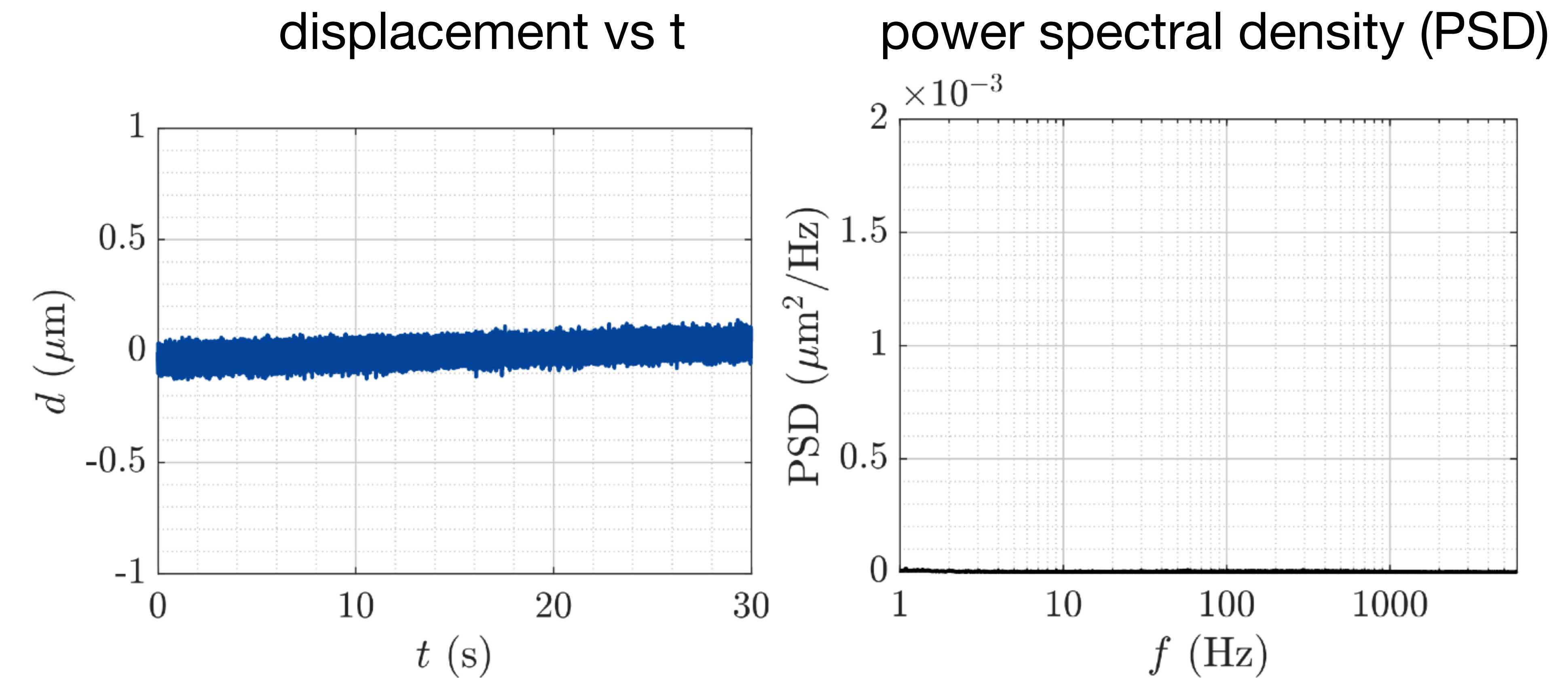
- The CFD simulations and the experimental results agree
  - The simulations slightly ove... ses

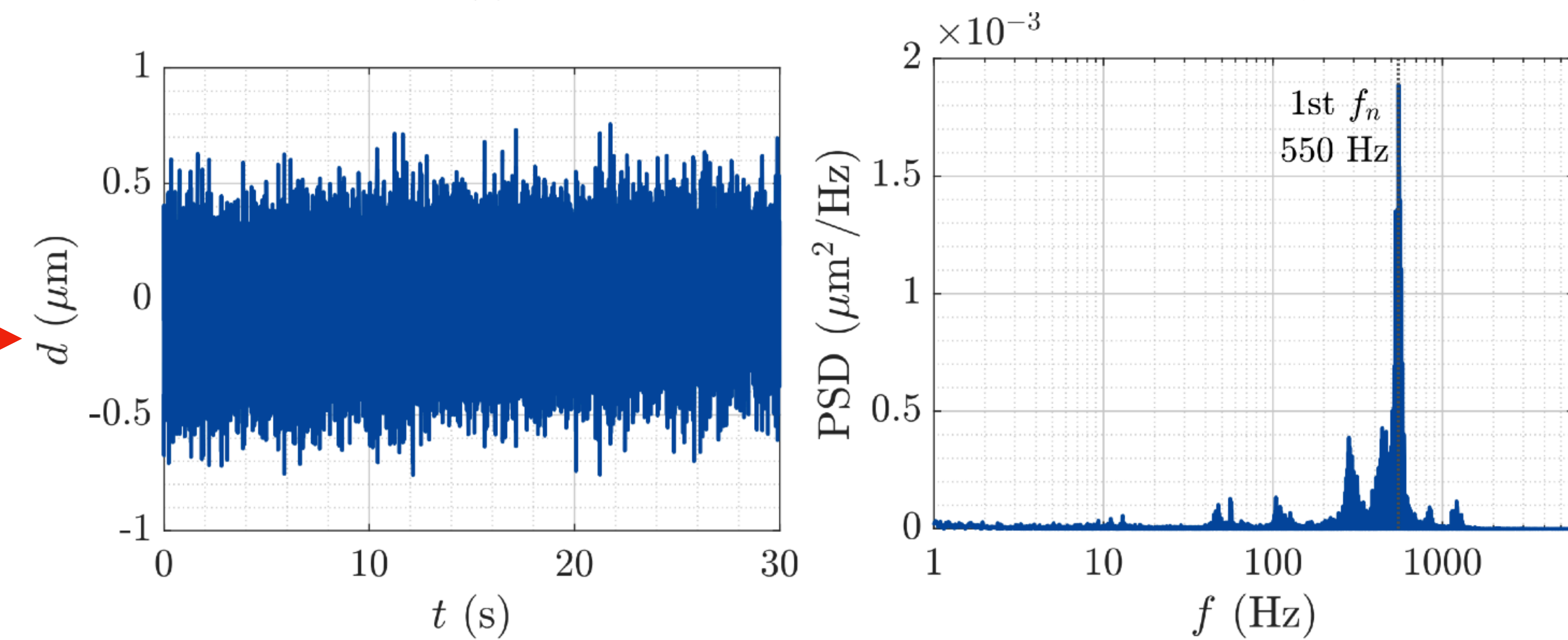
Air cooling works well !

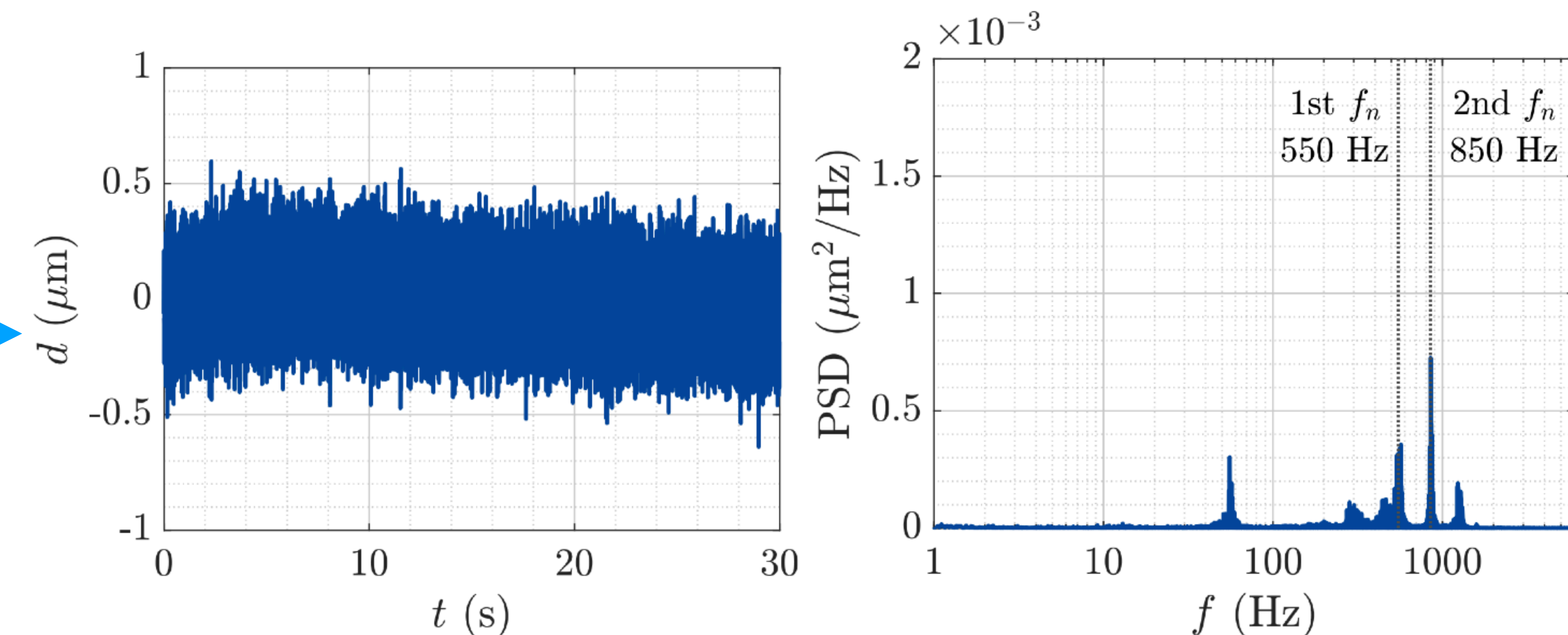
ITS design and R&D

Aeroelastic test





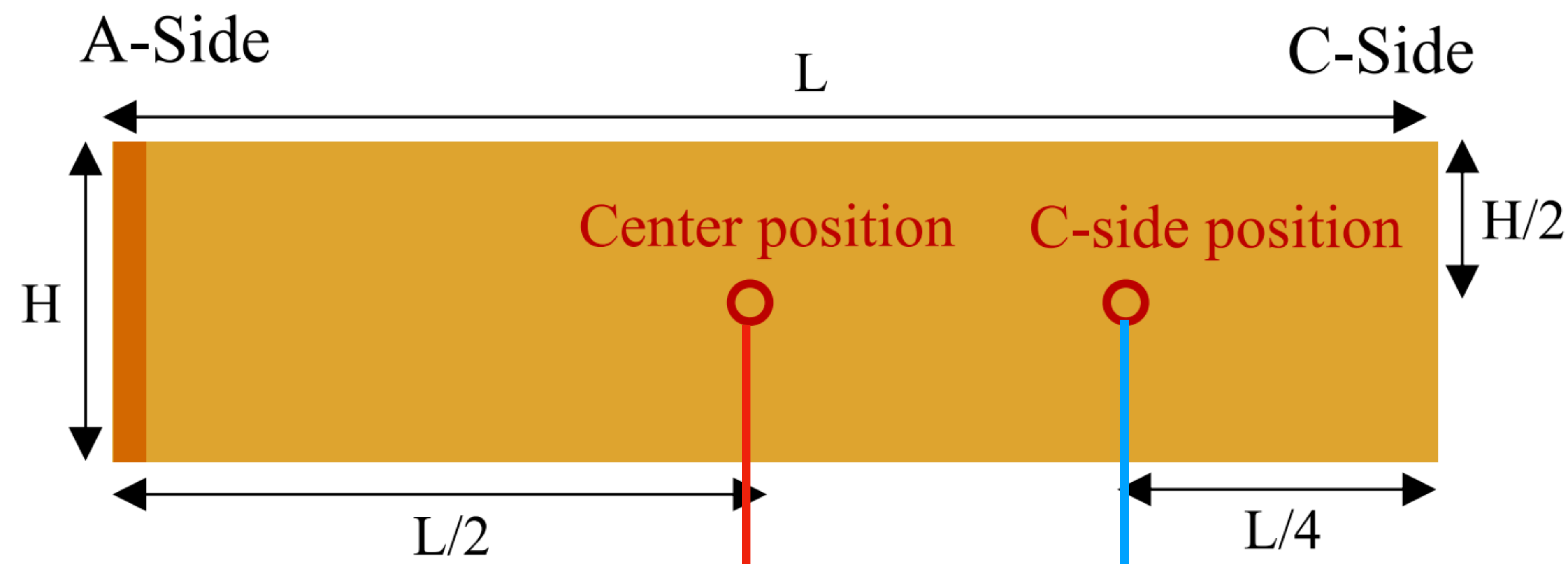




- **Air flow: 8 m/s**
- **Measured displacement:**
  - $RMS_{airflow}$: < 0.4 μm
  - Maximum: ~1.1 μm
  - Requirement: < 2 μm

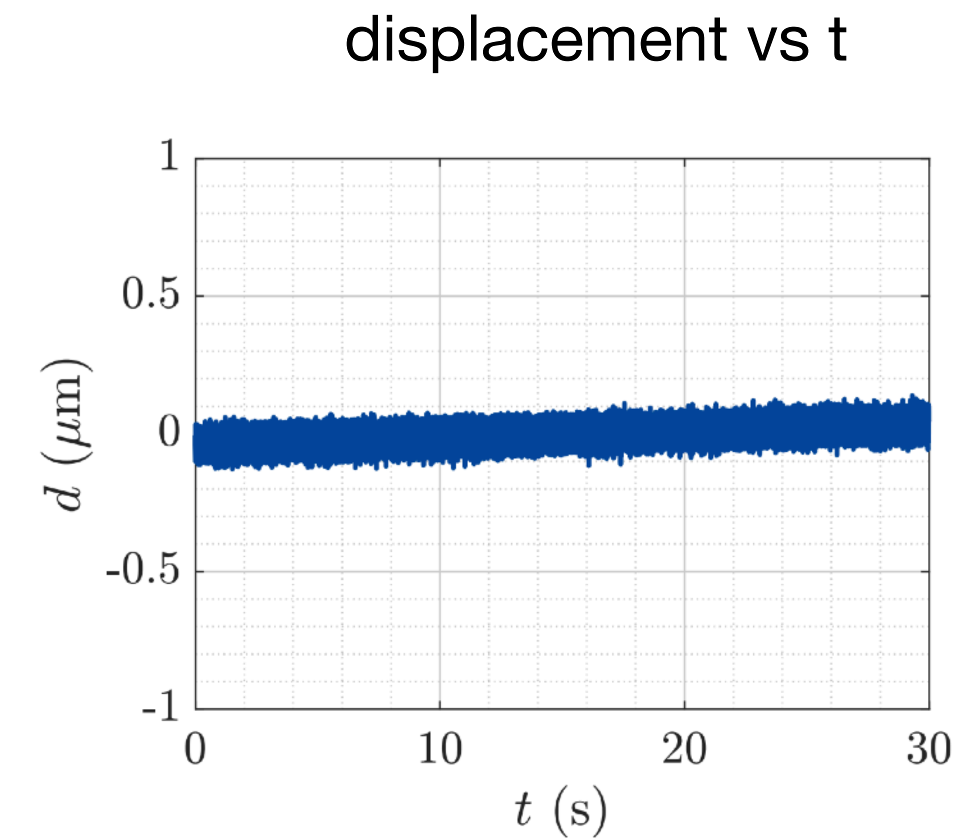
ITS design and R&D

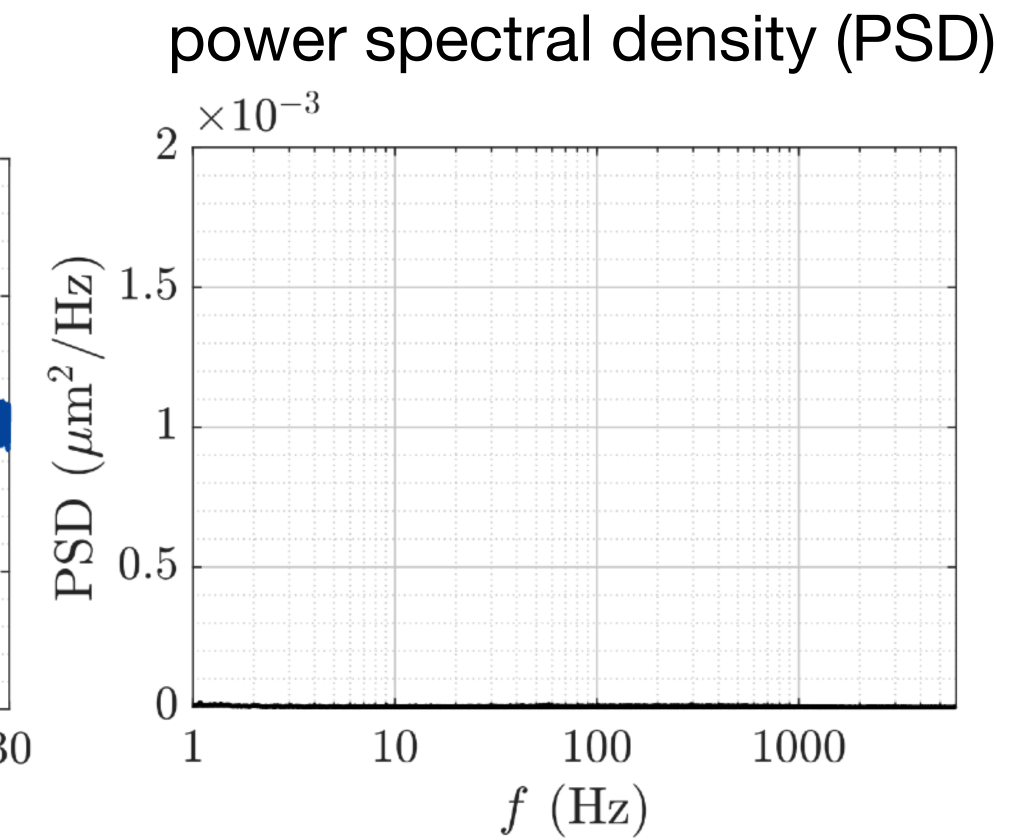
Aeroelastic test

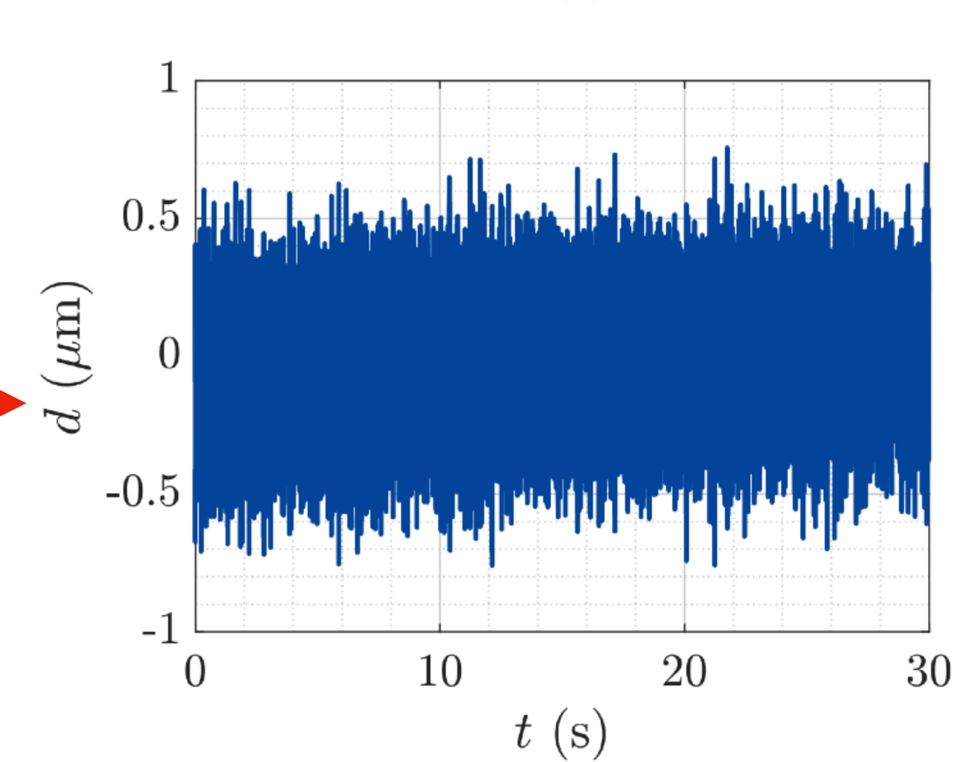


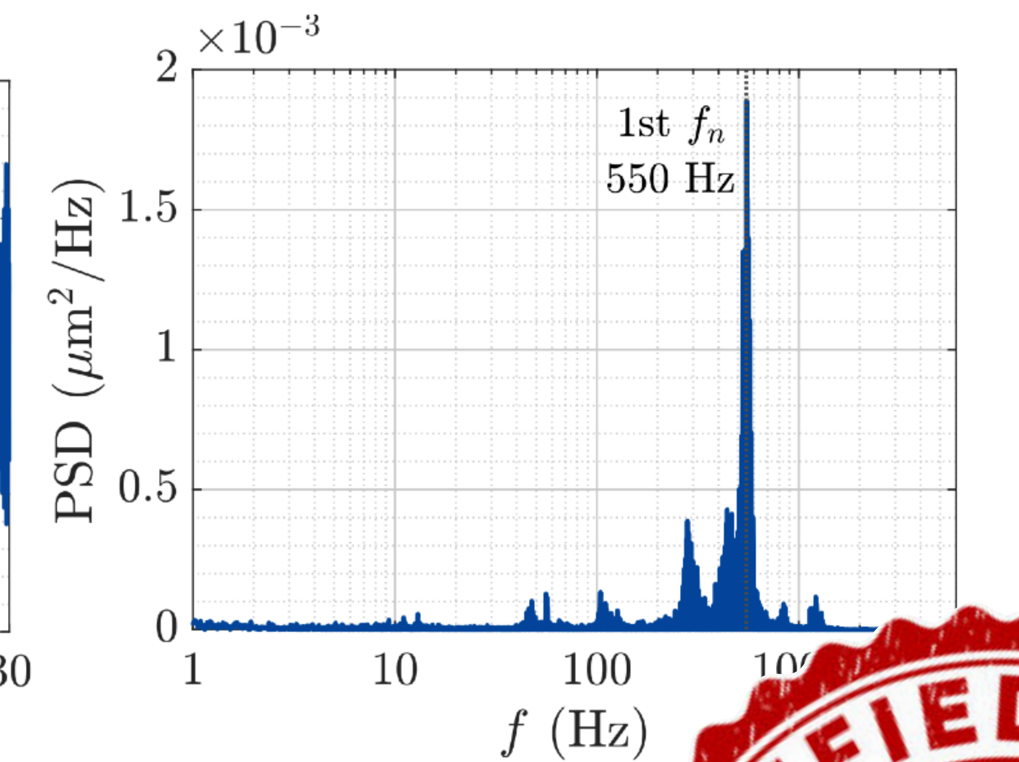
displacement vs t

power spectral density (PSD)









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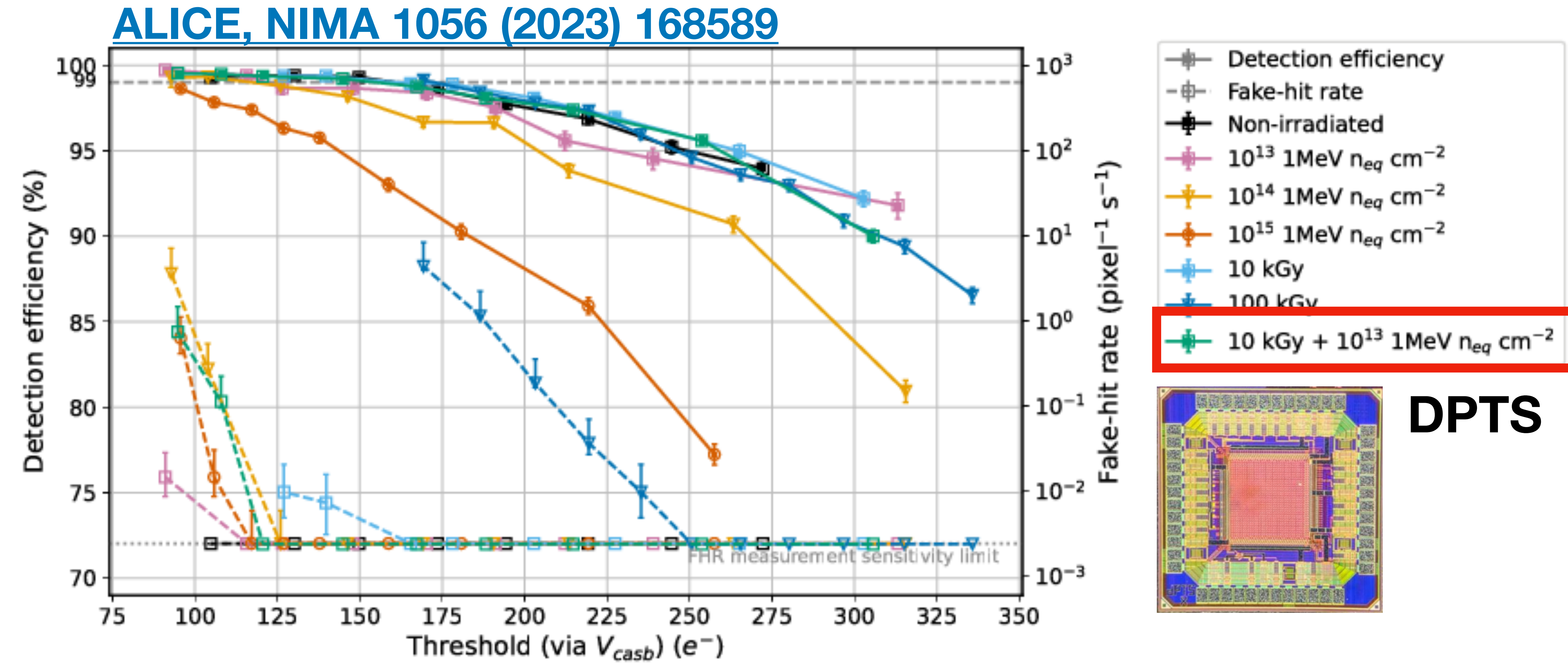
Aeroelastic test seems okay !

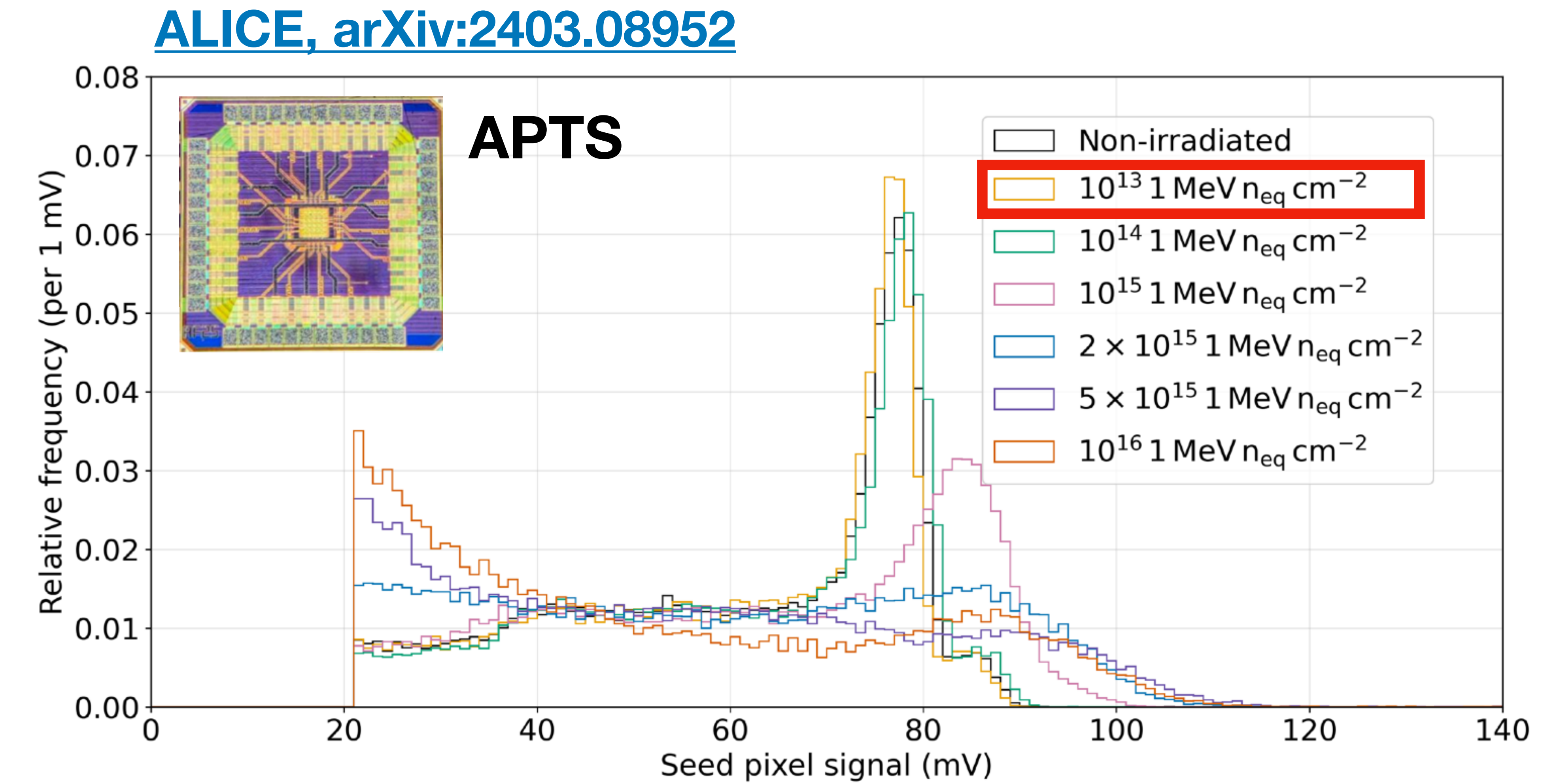
ITS design and R&D

Qualification of 65nm CMOS

ALICE, NIMA 1056 (2023) 168589



ALICE, arXiv:2403.08952



- Concentrated effort **ALICE ITS3** together with **CERN EP R&D**
- **Prototype sensors:** APTS (Analogue pixel test structure), DPTS (Digital pixel test structure), CE65
  - **DPTS (left):** Efficiency (> 99%) with low fake-hit rate (< 2×10^{-3} pixel^{-1}s^{-1})
  - **APTS (right):** Charge collection not deteriorated by irradiation

ITS design and R&D
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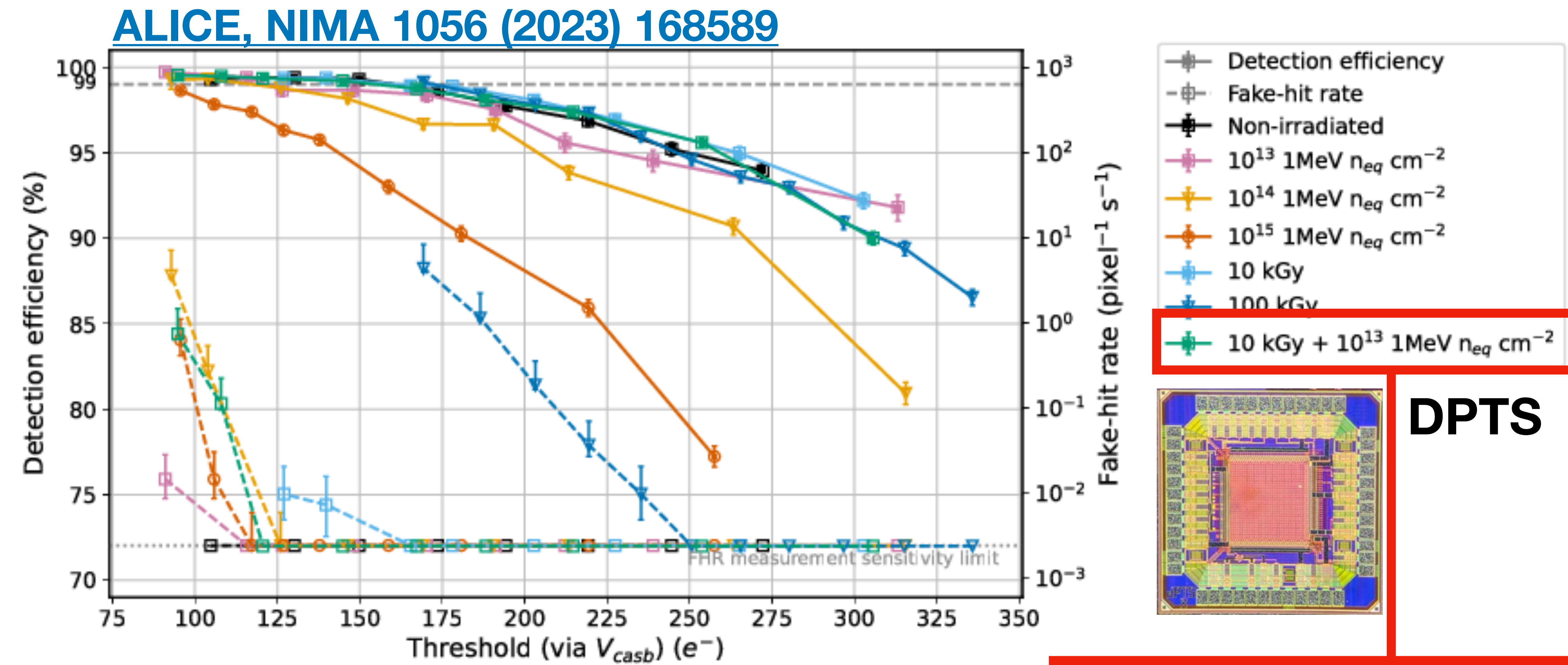
ALICE, NIMA 1056 (2023) 168589



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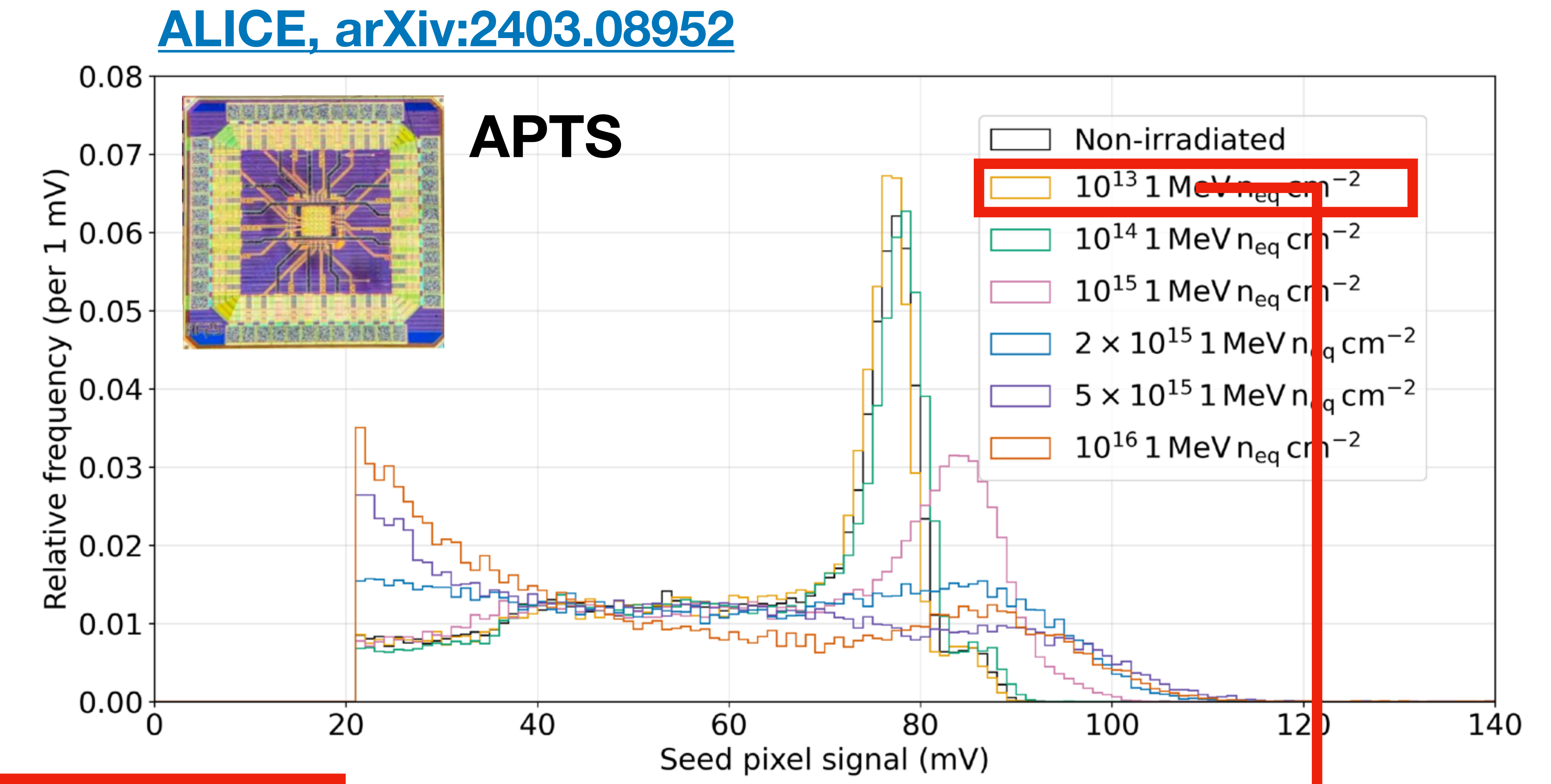

Irradiation ITS3 requirements

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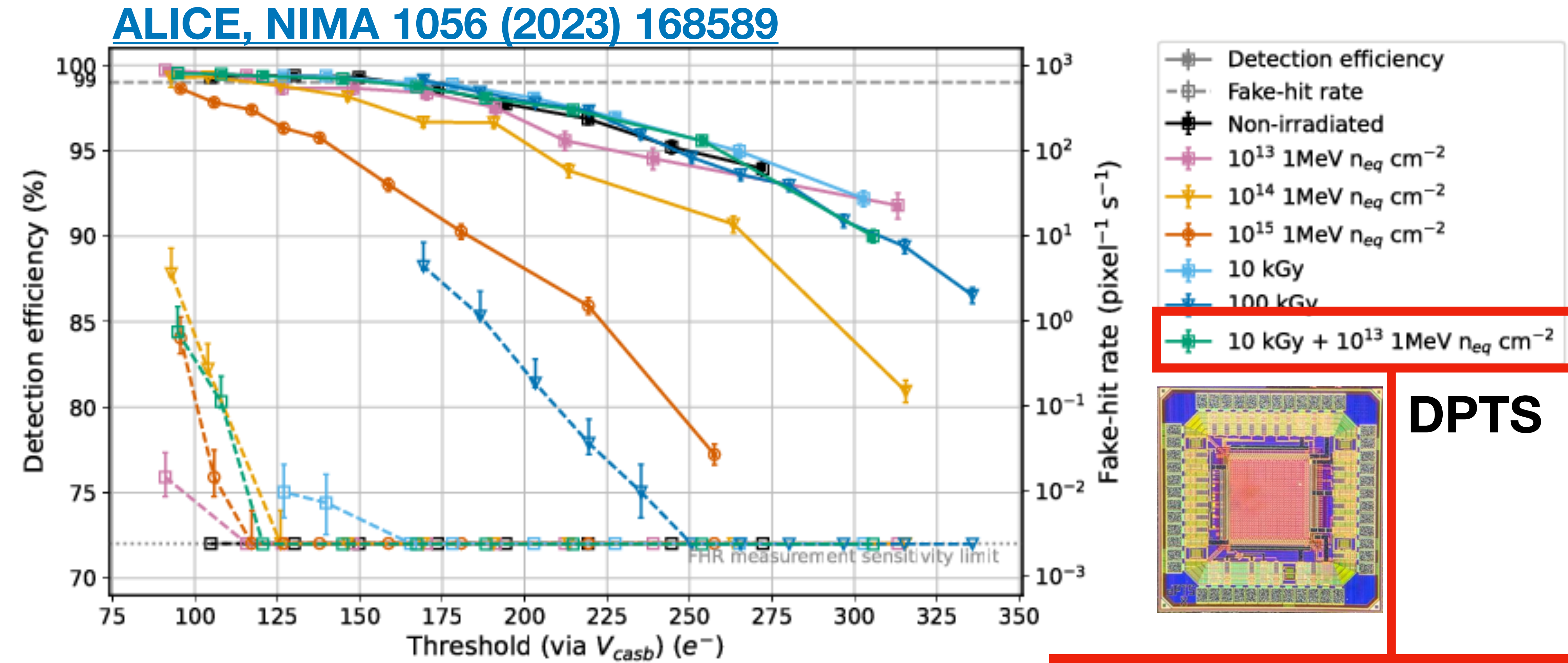
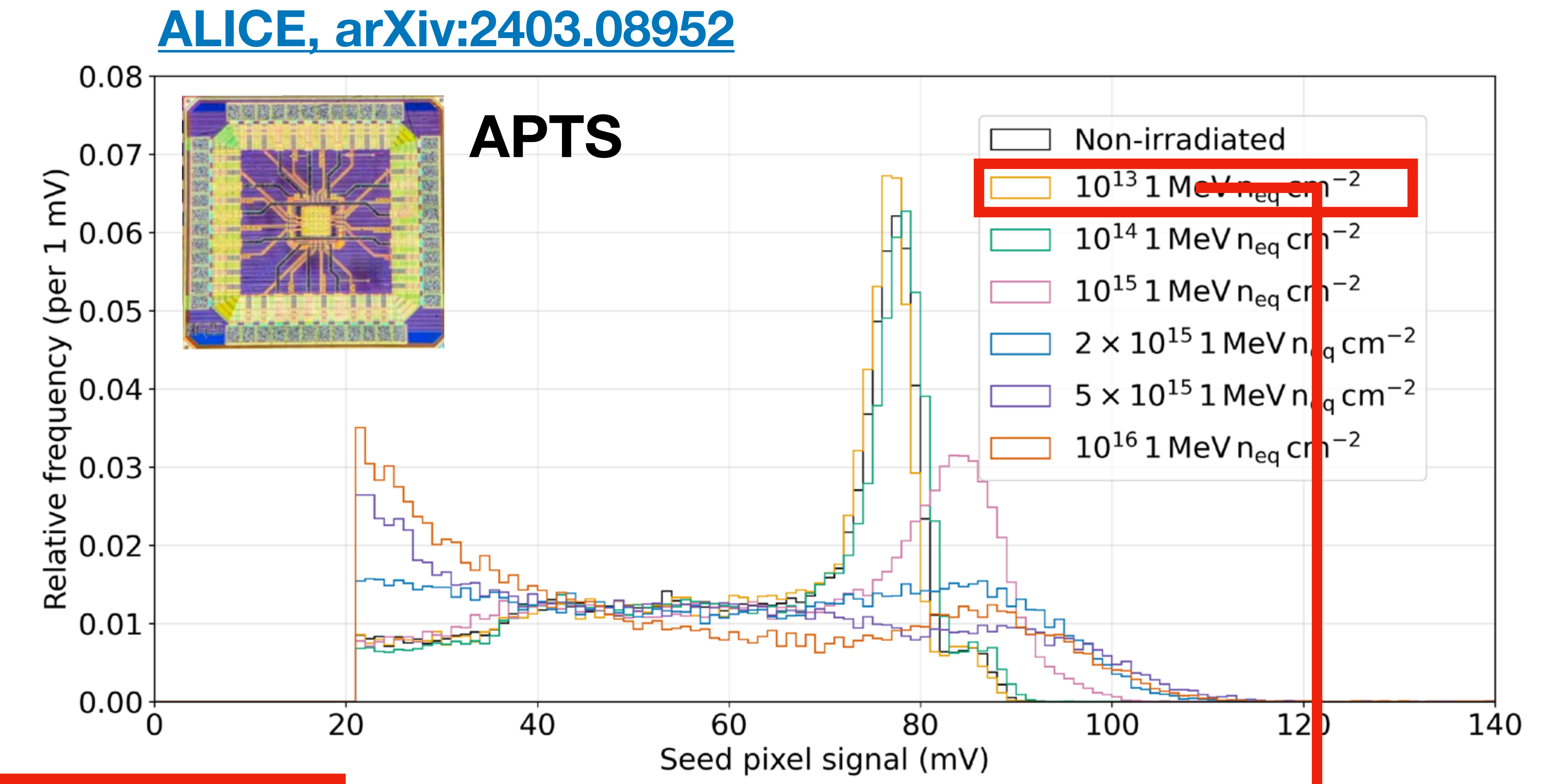
ITS design and R&D

Qualification of 65nm CMOS

ALICE, NIMA 1056 (2023) 168589



ALICE, arXiv:2403.08952



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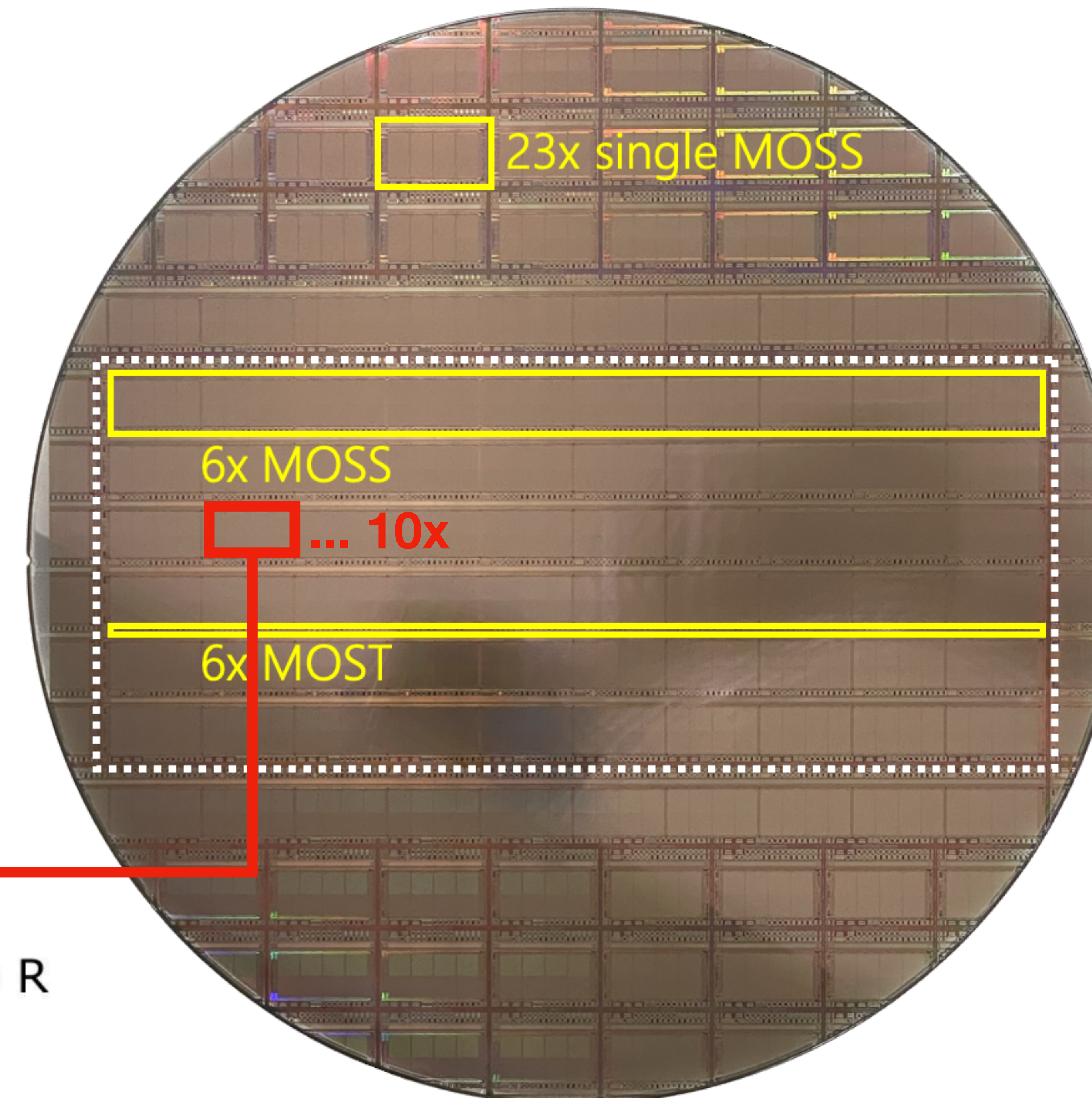
We can make the pixel sensor with this technology !

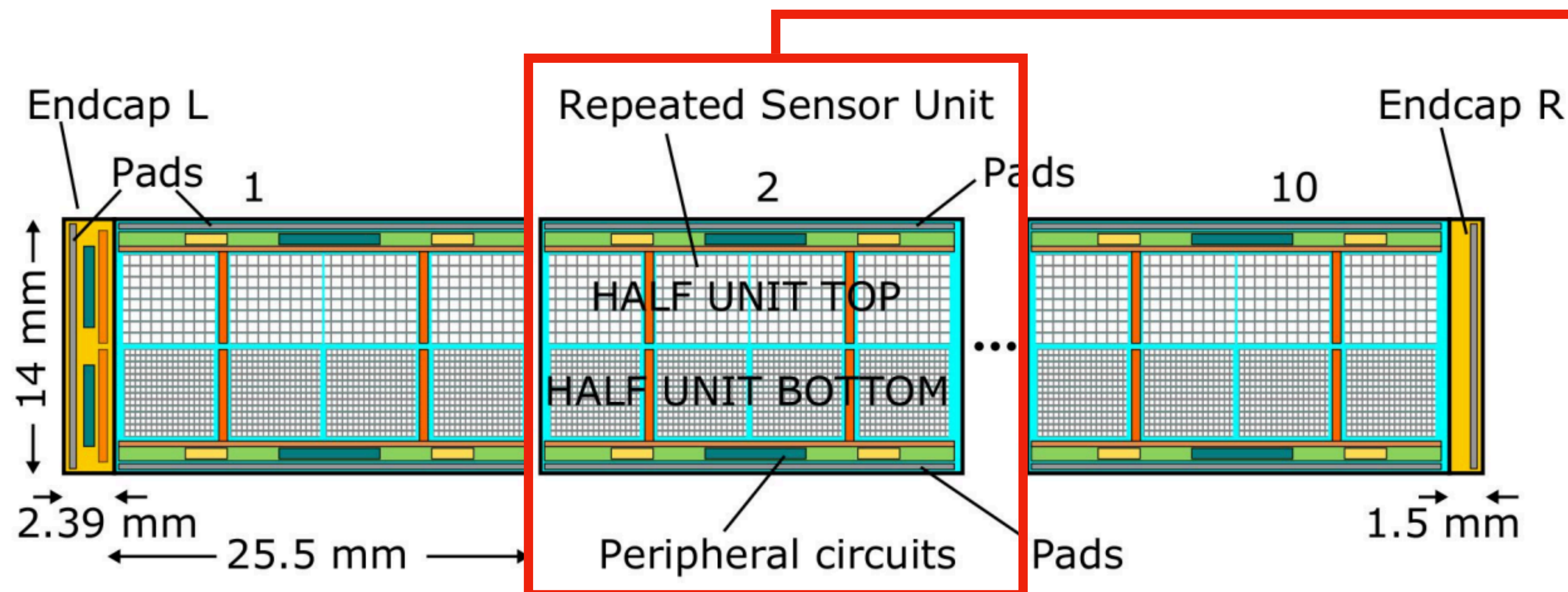
ITS design and R&D

Stitched MAPS

- **Goal:** Feasibility of stitching process
- **MOnolithic Stitched Sensor (MOSS):**
  - 10 Repeated Sensor Units stitched together: 259 mm x 14 mm per sensor
  - 2 pixel pitches (18 μm and 22.5 μm) and 5 front-end variants



300 mm ER1 wafer



- **MOSS is operational and reaches full efficiency**
  - Yield: currently under study with extensive characterization campaign with wafer prober.
  - **First beam tests performed at PS@CERN**
    Detection efficiency: in line with expectations from MLR1 study

ITS design and R&D

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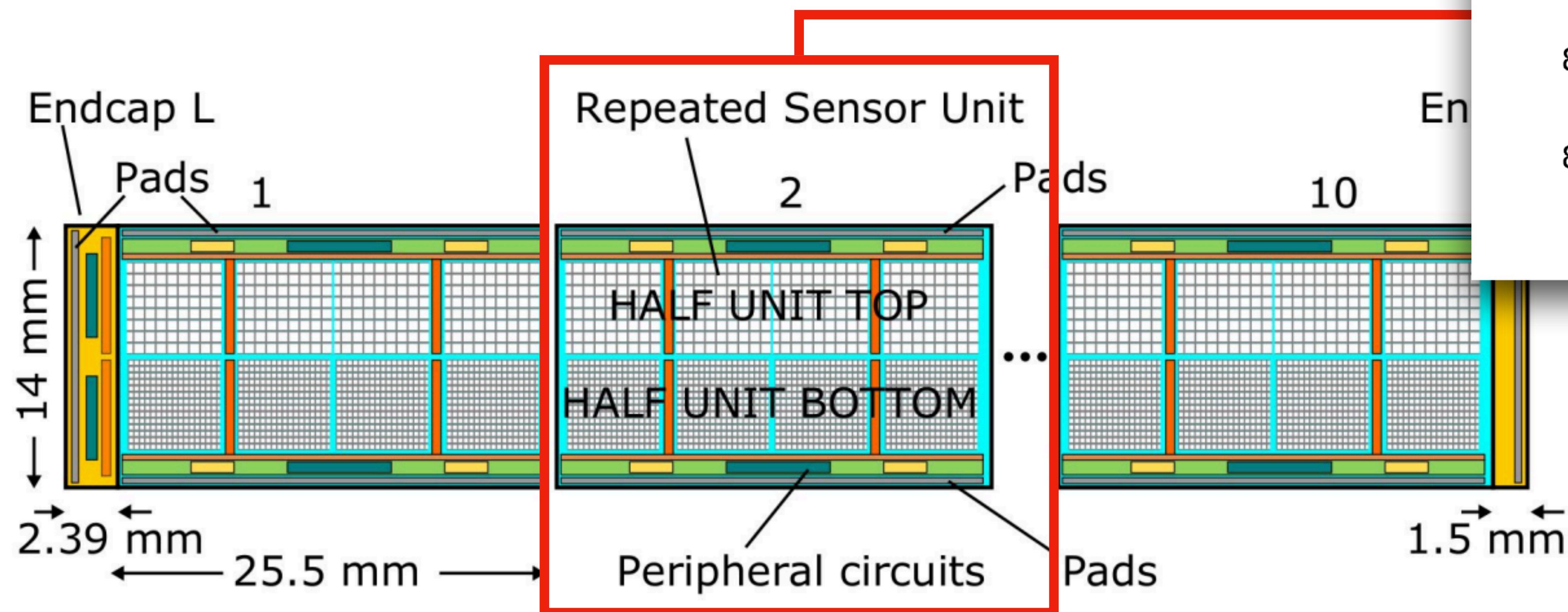

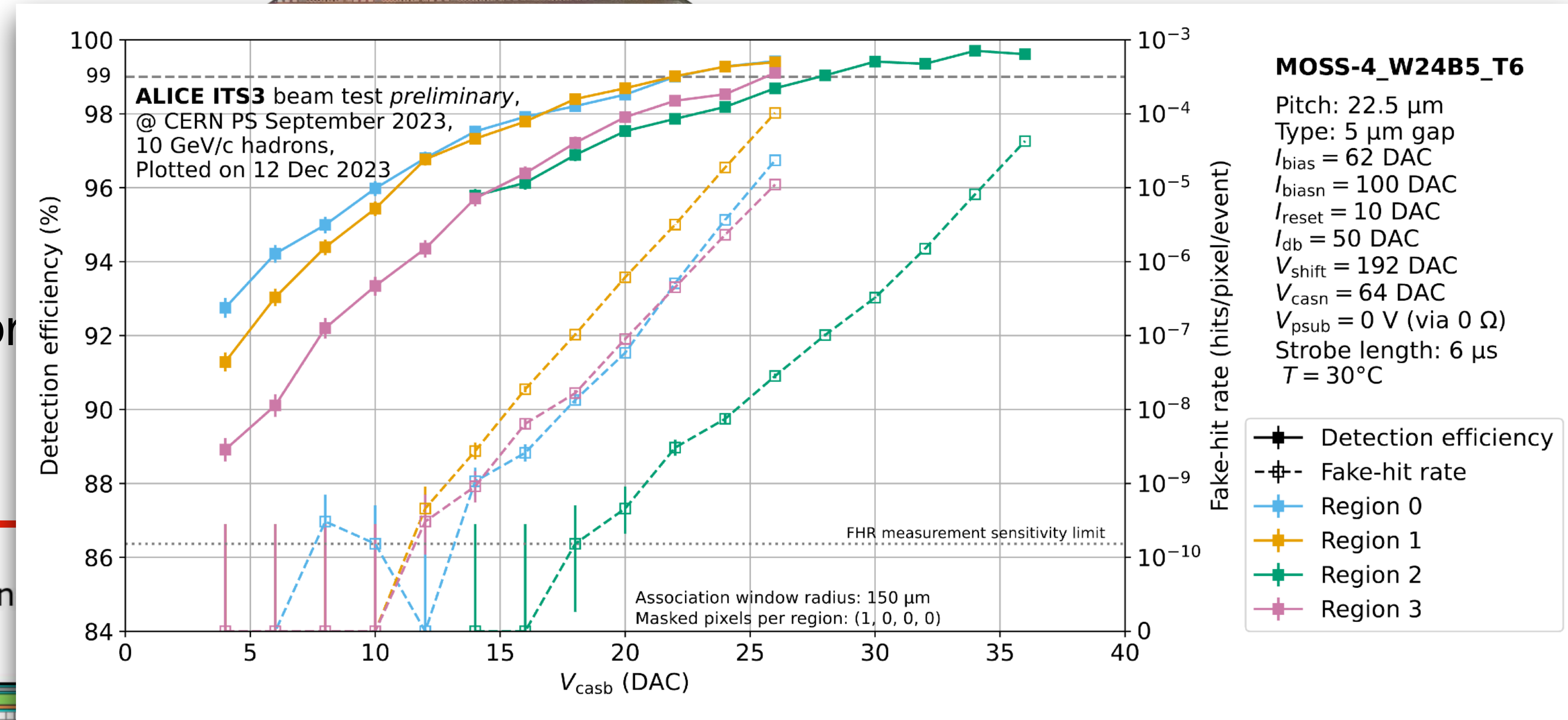

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ITS design and R&D

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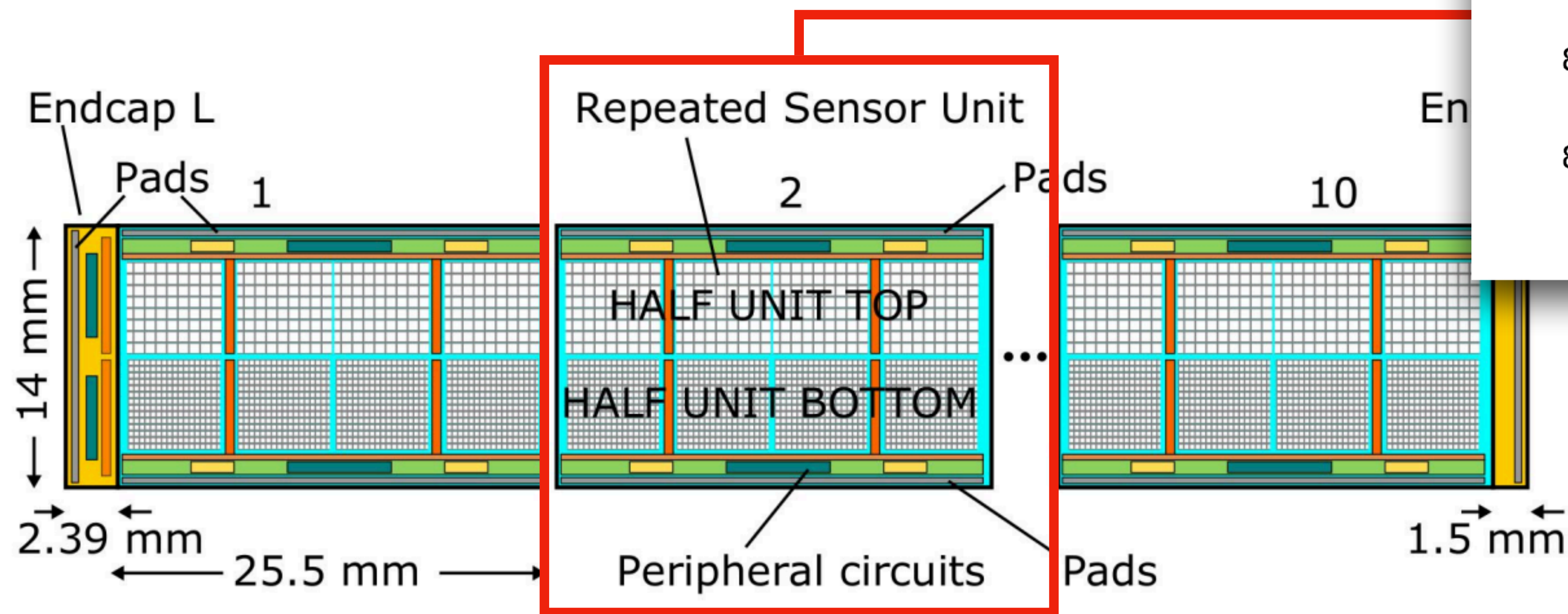

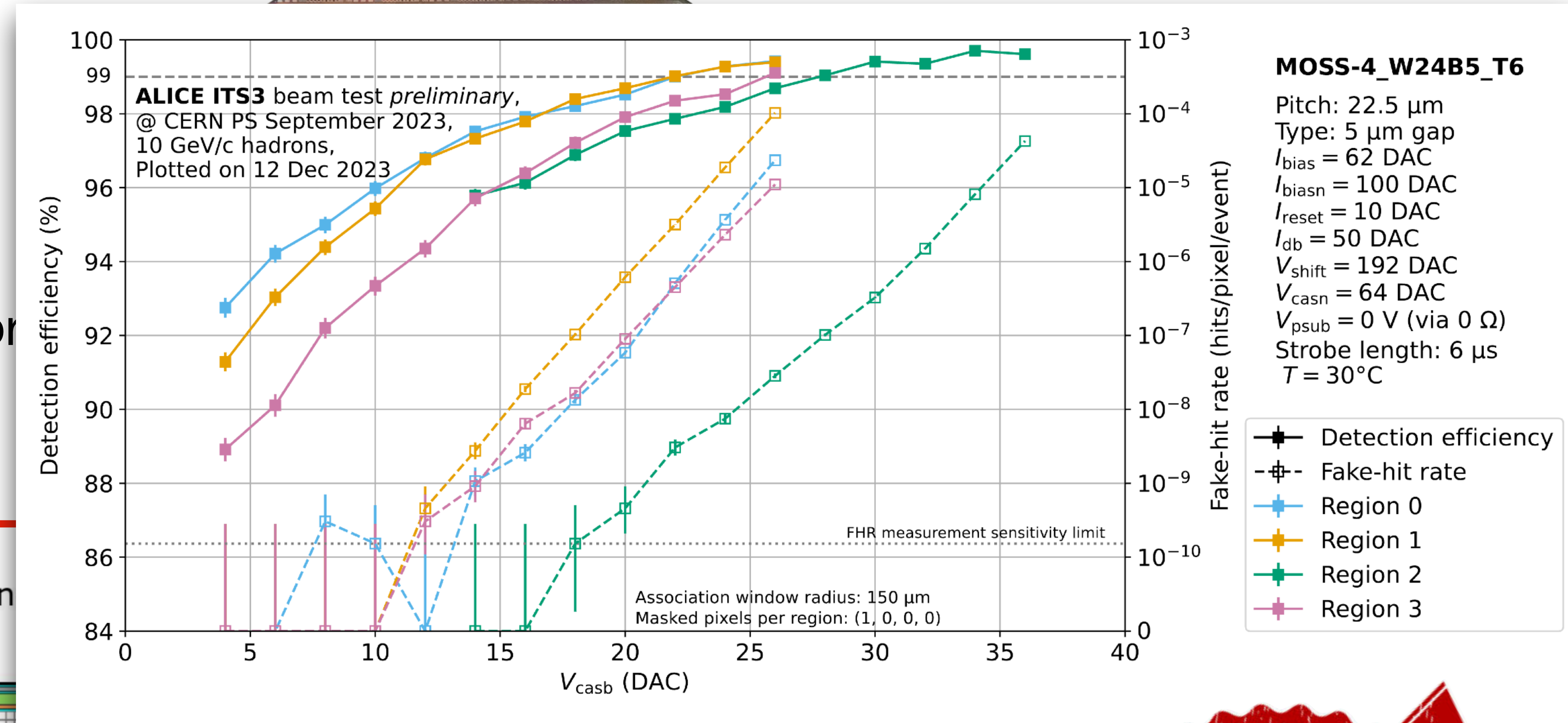

300 mm ER1 wafer

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We can readout the stitched sensor !

Sensor development

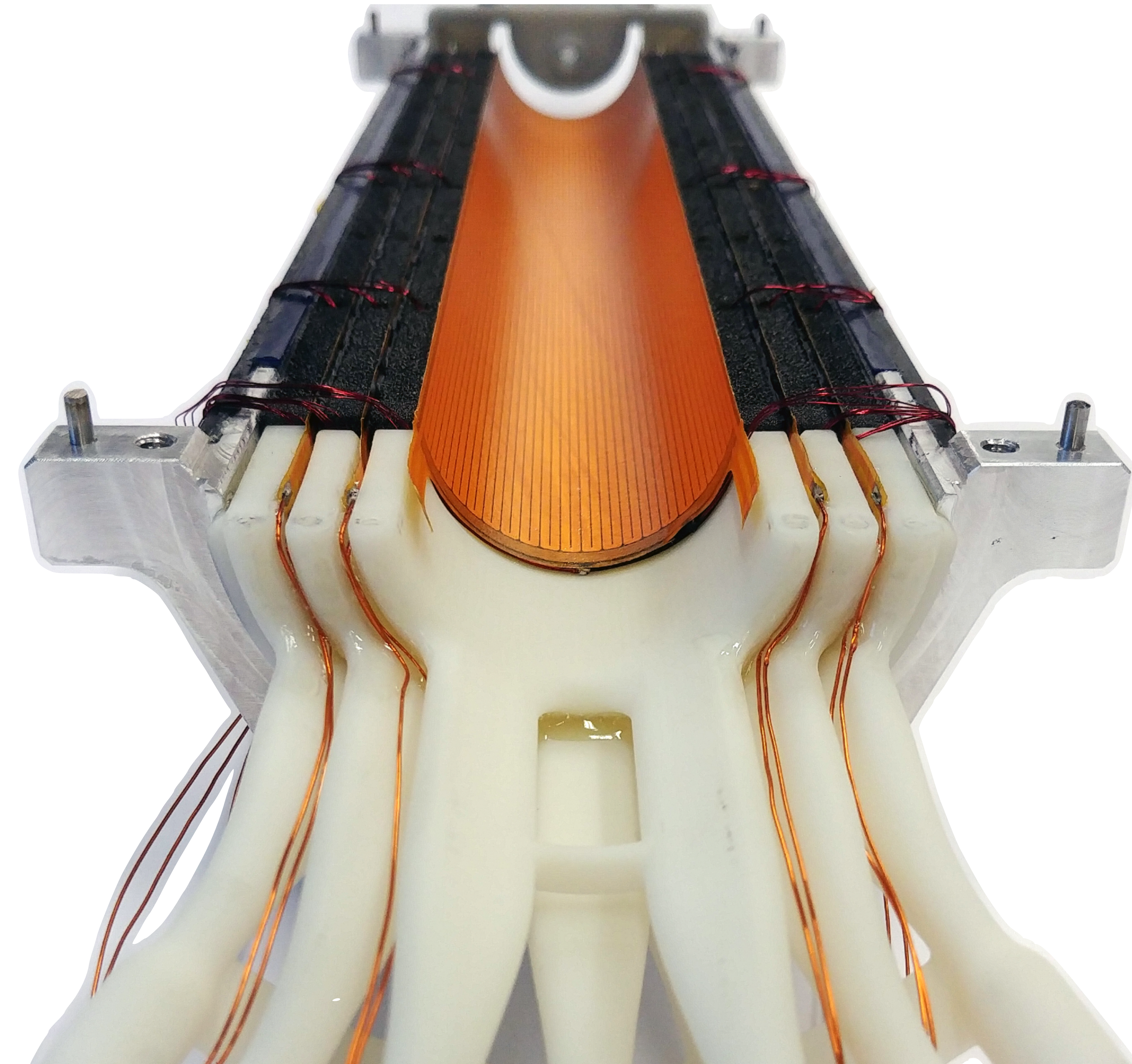
Outlook

- **MOSAIX:** Final size 2D stitched sensor
- **Modular design:** each sensor is divided into 3, 4, or 5 **segments** with 12 RSUs.
- Each RSU is divided in turn in 12 fully independent tiles (powering, control and readout)
- **Currently working to submission !**

Summary

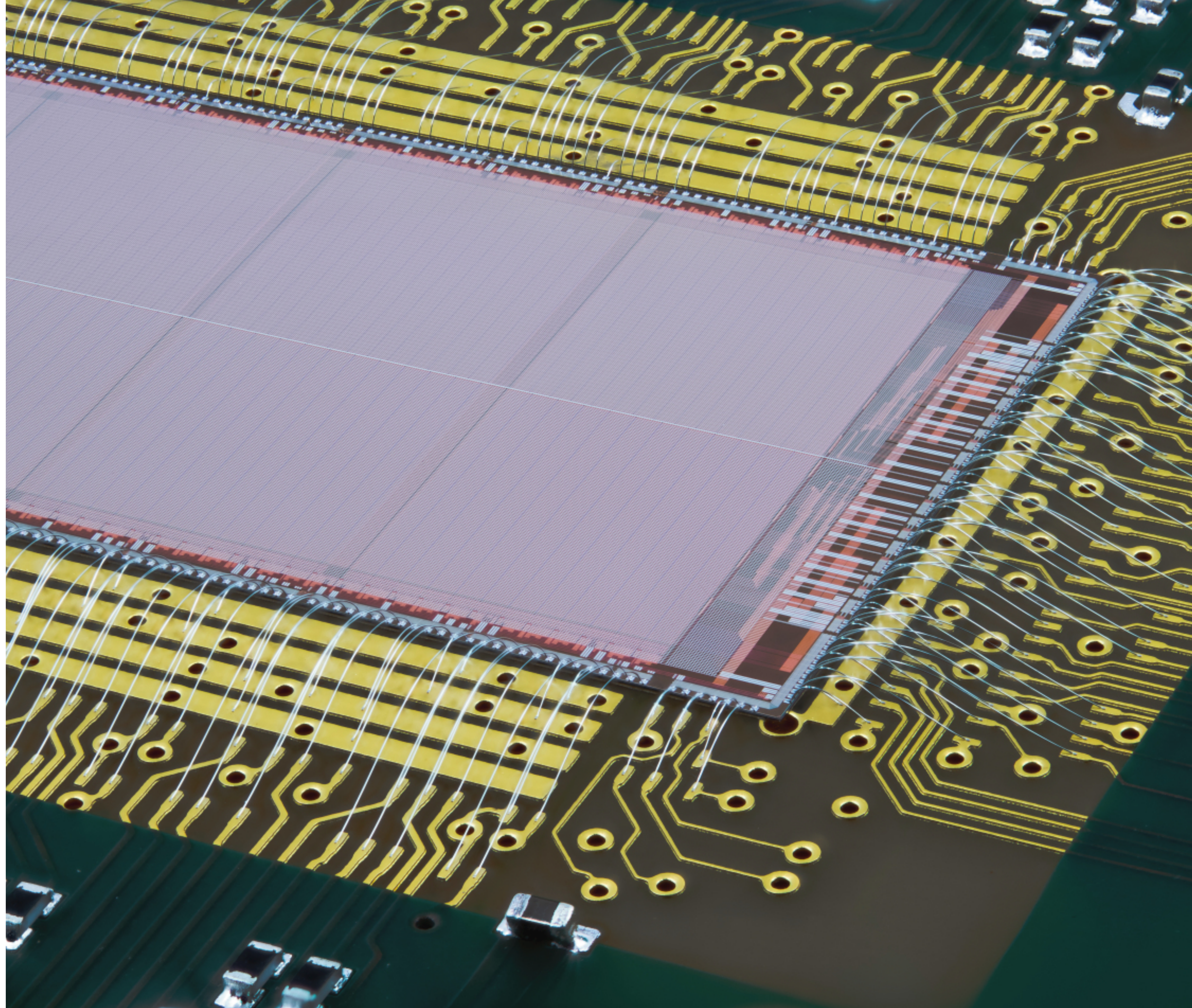
ALICE INFN TORINO

- **ALICE is preparing the new ITS upgrade:**
  Truly cylindrical wafer-scale MAPS
- **ITS3 key R&D questions answered:**
  - Can we **bent it?**
    → Bent MAPS demonstrated in beam
  - Can we **cool it down?**
    Can it **withstand vibration from cooling?**
    → Air cooling tested with aeroelastic
  - Can we use **65 nm technology?**
    → 65nm process qualified with radiation
  - Can we **do the stitching?**
    → Stitching (MOSS) qualified
- **Next steps:**
  - Finalisation of the design and production of final prototype sensor (ER2)
- **ALICE ITS3 on track for installation in LS3 (2026-2028)**



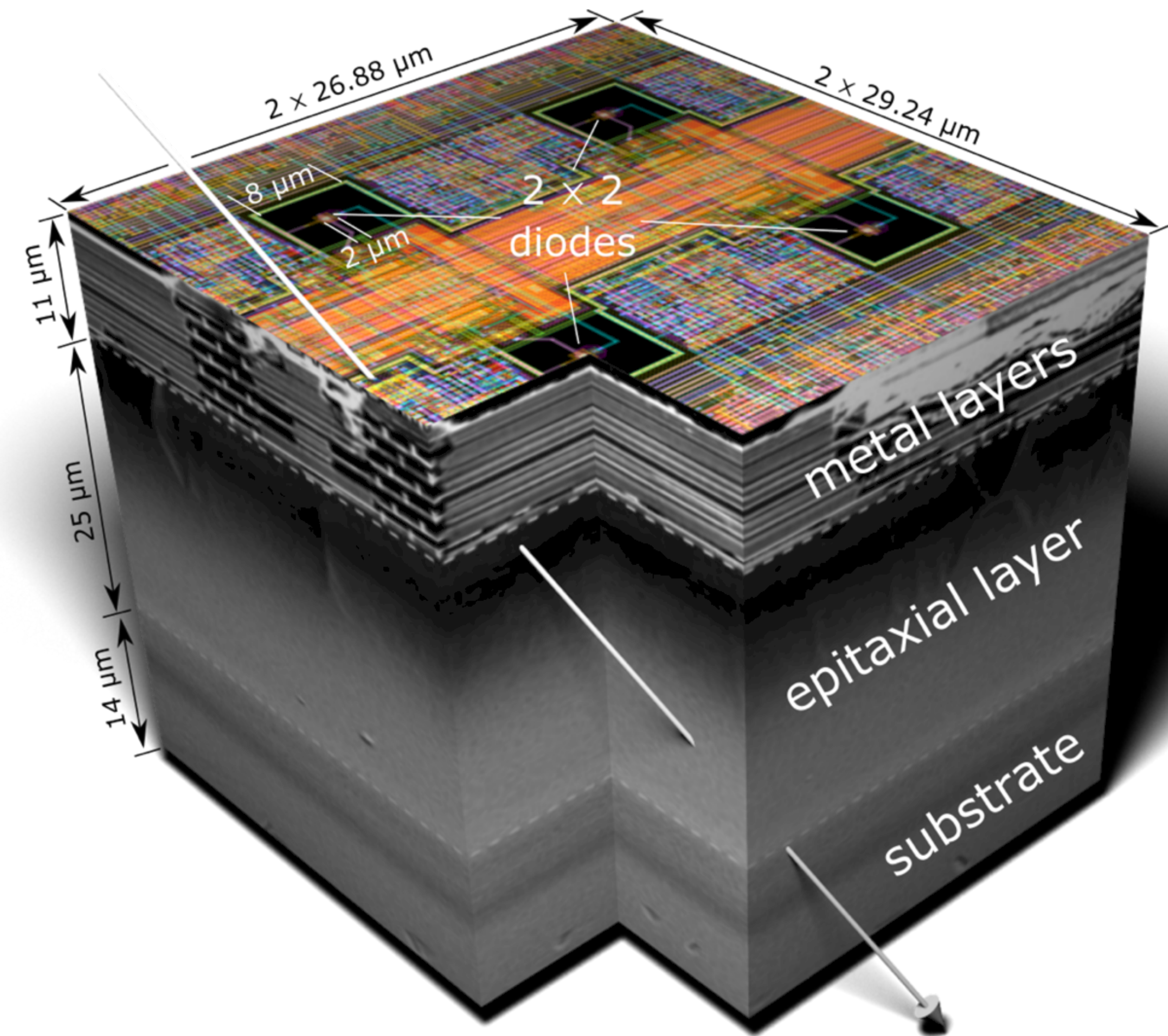
ITS3 "bread board" model 3

Back up

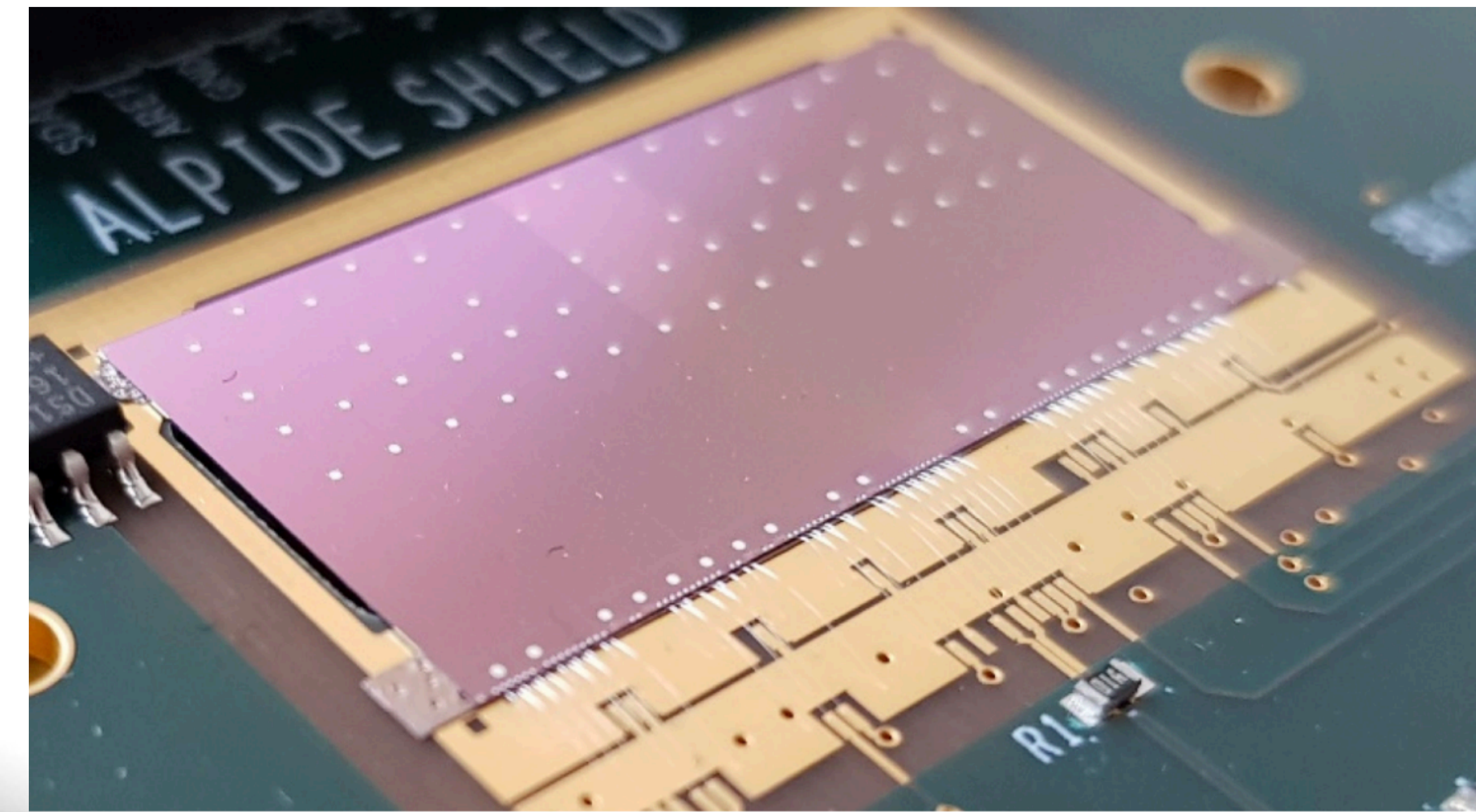


Monolithic Active Pixel Sensor (MAPS)

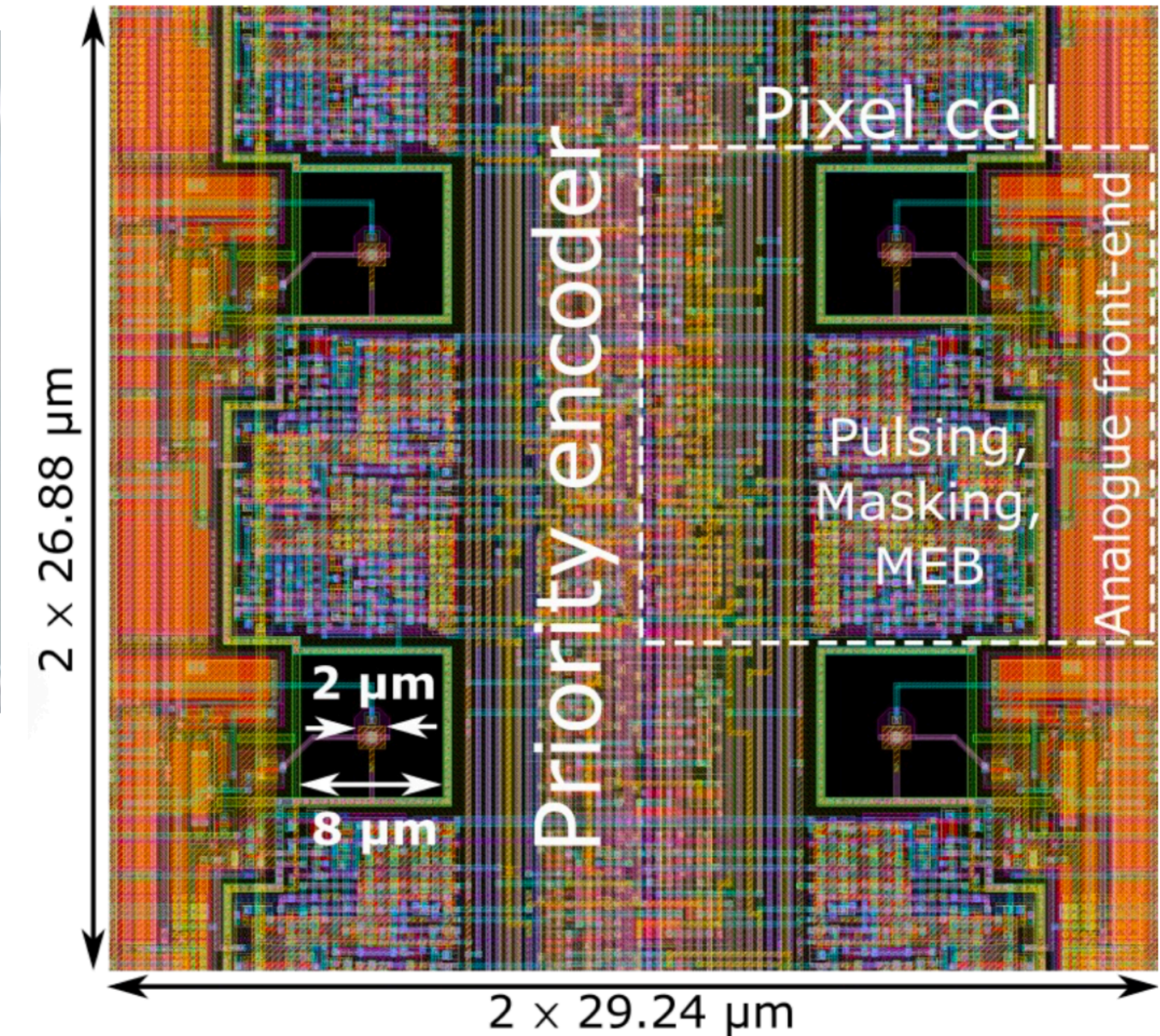
CMOS MAPS



ALPIDE (MAPS)



ALPIDE chip



Layout of 4 pixels

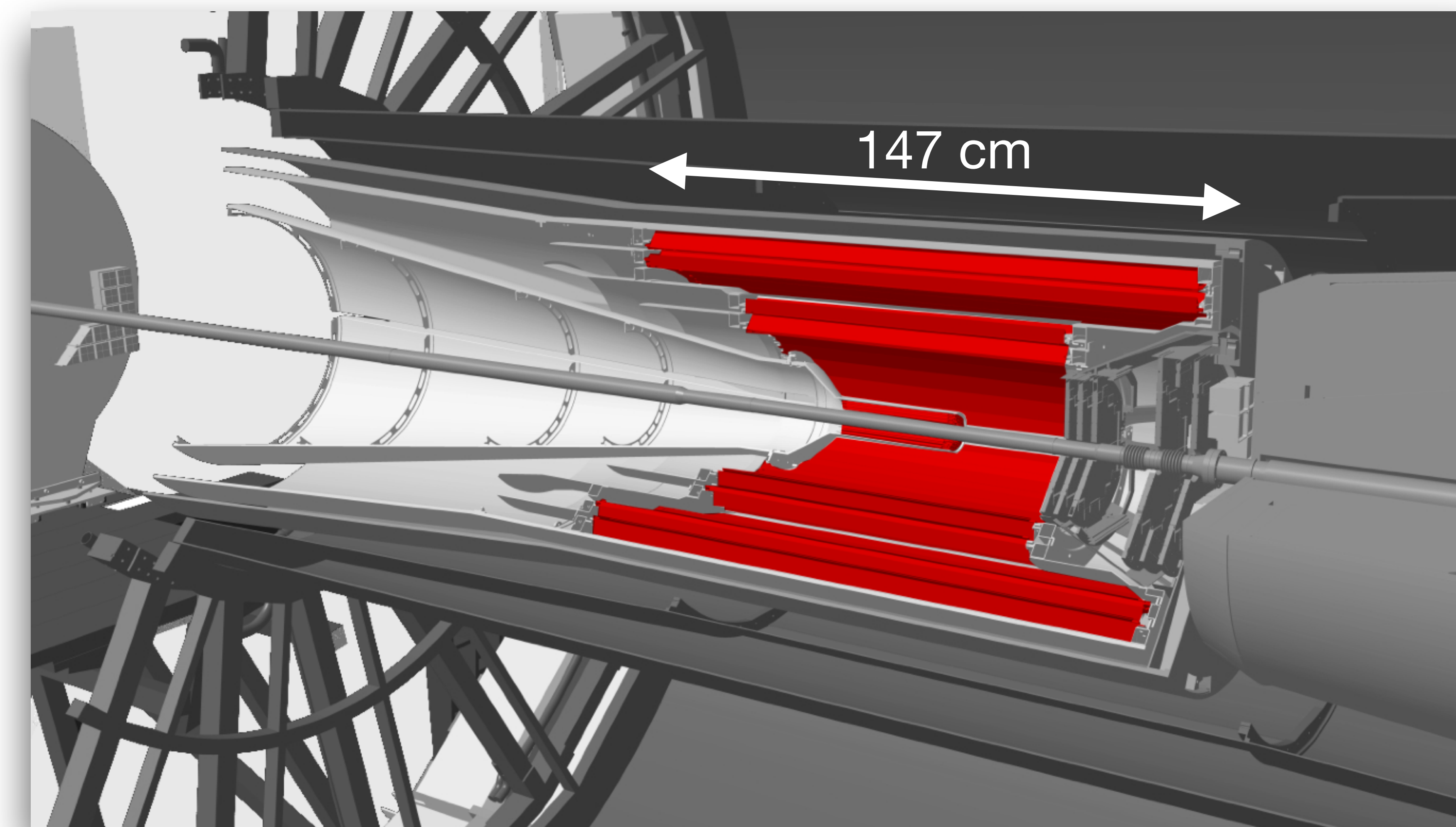
- **Single silicon chip** contains both **the detection volume and the readout electronics**
  - as opposed to hybrid pixel sensors, which use two chips that need to be interconnected
- 180 nm CMOS imaging process by TowerJazz
- 3 cm x 1.5 cm (1024 x 512 pixels) with thickness 50 μm for IB
- Size of pixel pitch: 29 μm x 27 μm

ITS; Inner Tracking System

40 cm

27 cm

147 cm



ALICE, J. Phys. G 41 (2014) 087002

- **7 layers** as barrel structure
- New ITS2 for ongoing Run3, fully operational (installed 2021, LHC LS2)
- **Largest MAPS** and pixel detector ever built
  - ~10 m^2, 24k chips, 12.5 Giga-pixels
- Fast readout rate: **100 kHz (Pb-Pb)**

ITS2 in operation (2023 Pb-Pb)

CERN COURIER
Reporting on international high-energy physics
July/August 2021 cerncourier.com

PIXEL PERFECT

Exploring the Hubble tension
A CERN for climate change
Medical technologies

Run 3 Pb-Pb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV

27 September 2023, 04:50

What can we achieve?

Observation on the current ITS

ITS half IB

ITS Inner Barrel Stave

material

Coldplate

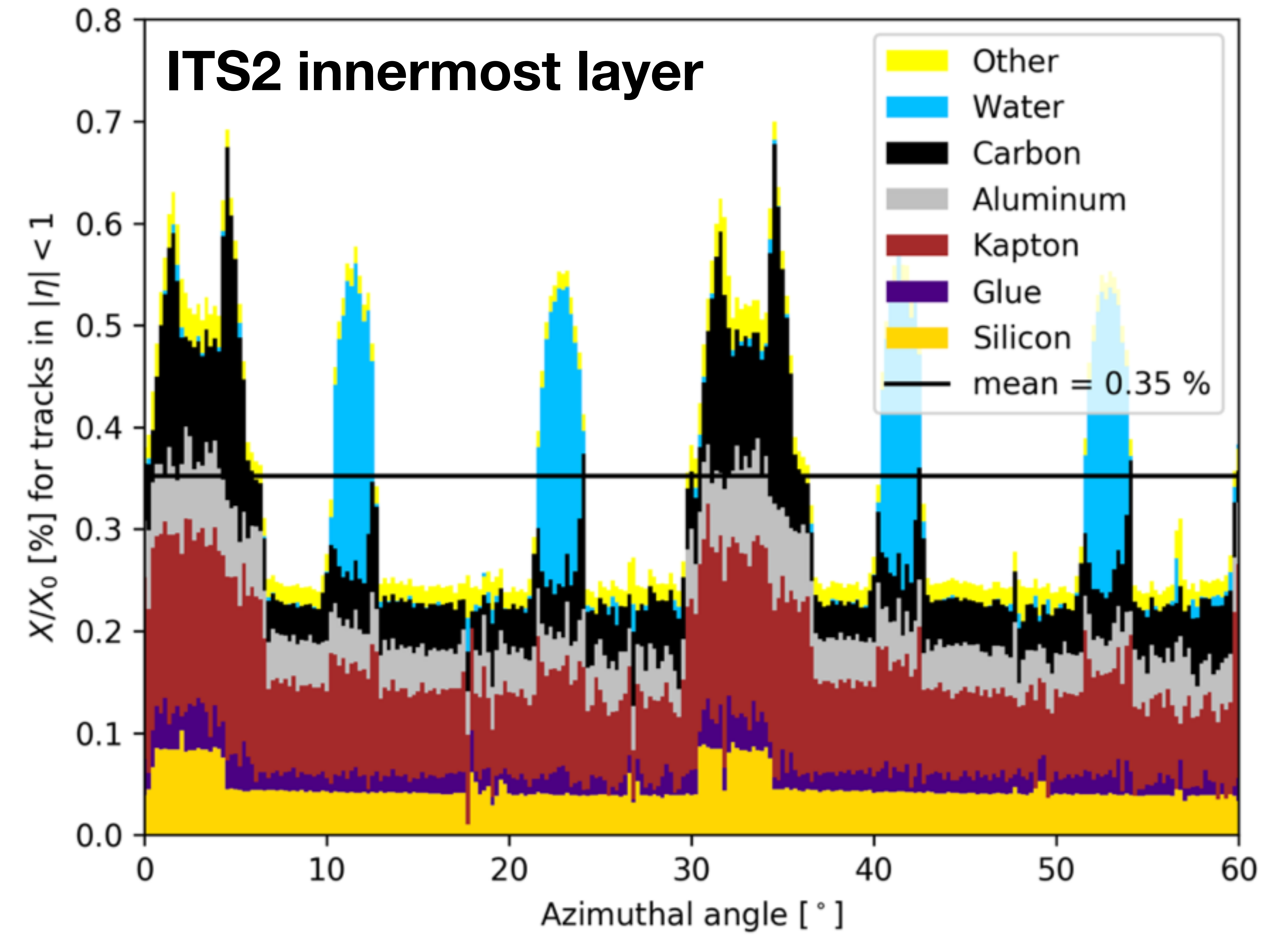
Spaceframe

29 cm , 1.7 gram

High Modulus fibres

High Thermal Conductive fibres

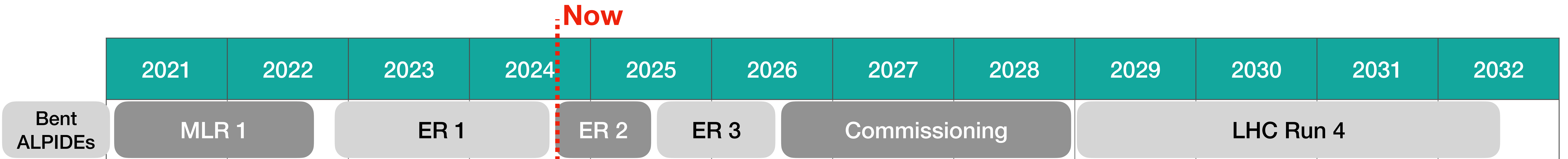
Polyimide pipes



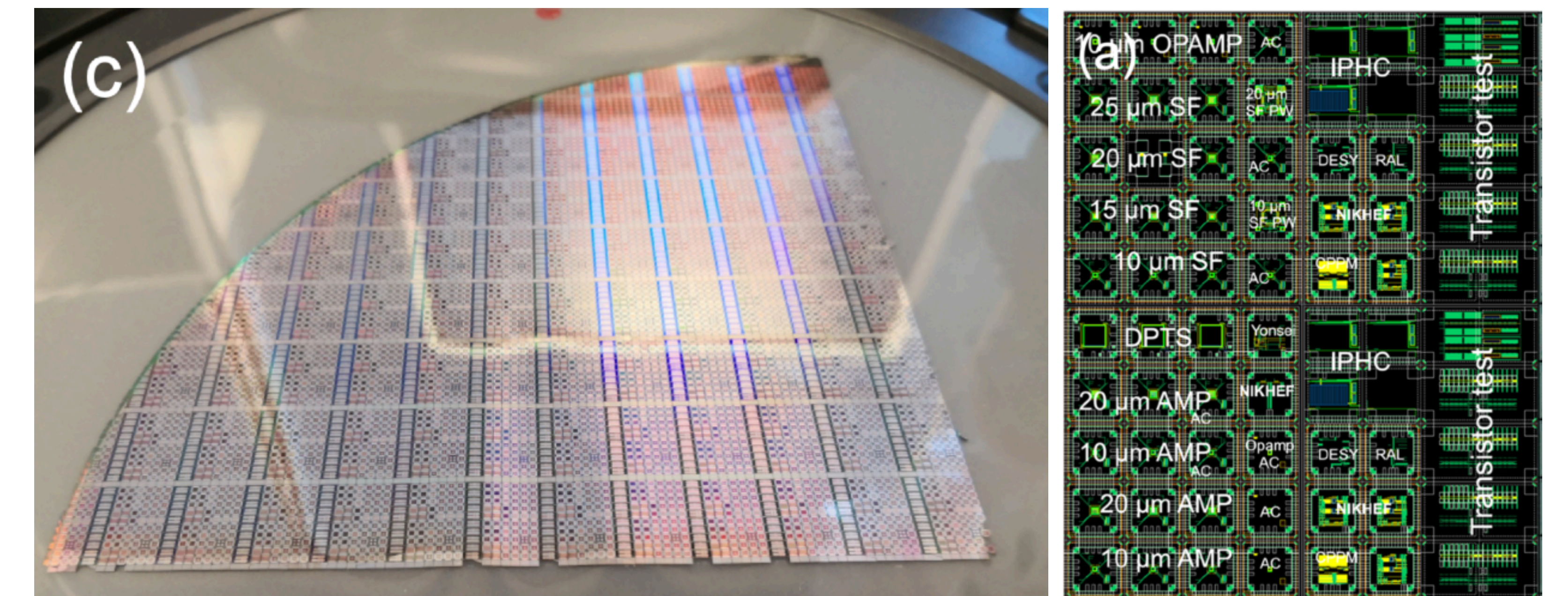
- **ITS2 IB one layer material budget**
  - Silicon makes only **~15%** of the material.
  - Irregularities: support structures, cooling, and overlaps

ITS3 upgrade project

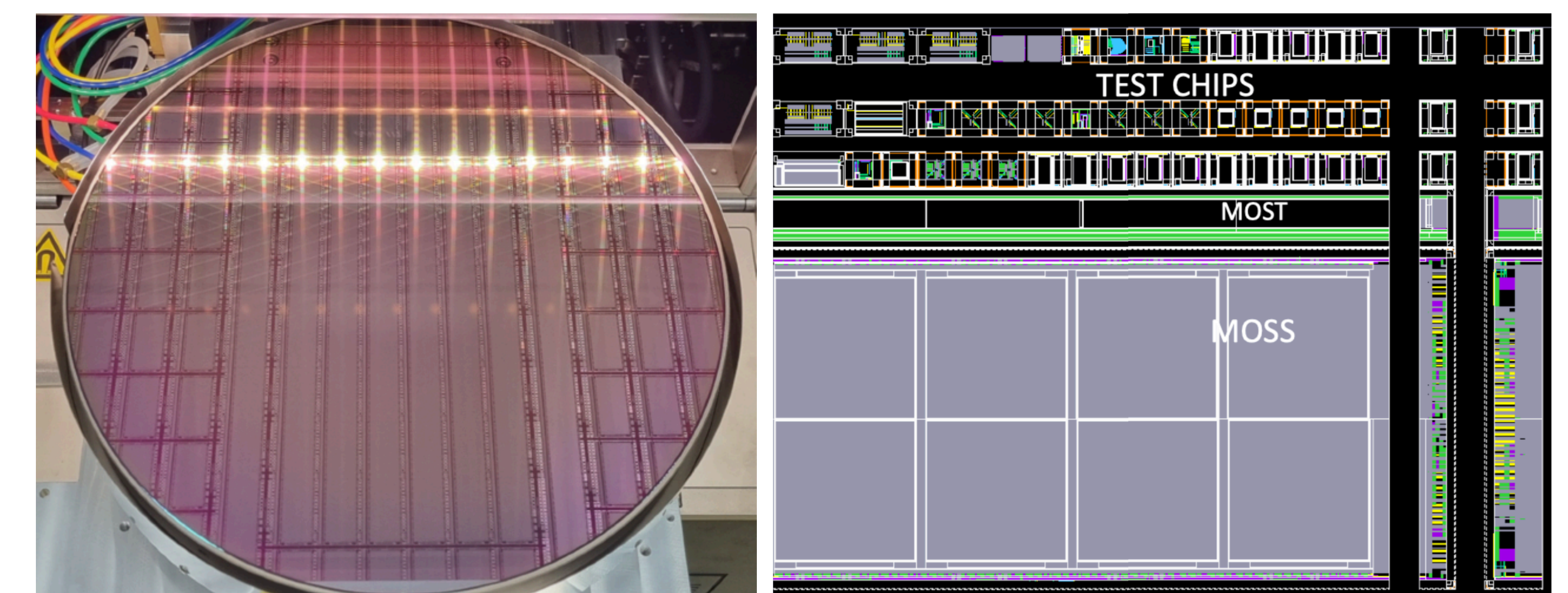
Milestones of prototype sensor submission



- **Tower Partners Semiconductor (TPSCo) 65 nm CMOS Imaging Technology:**
  - Smaller transistors: higher integration density
  - Lower power consumption
  - Larger wafers 300 mm
- **MLR 1 tape out (2020-12):**
  Qualify the 65 nm process MAPS with 3 prototypes: APTS, CE65, DPTS
- **ER1 tape out (2022-11):**
  Stitching 1D (+ assess yields by the foundry) with 2 large sensors: MOSS, MOST
- **ER2 tape out (2024-fall):** ITS3 full-size prototype with full functionalities (power, readout, etc)
- **ER3 tape out (2025-middle):** ITS3 sensor production



MLR1 wafer (1/4) and layout



ER1 wafer and layout

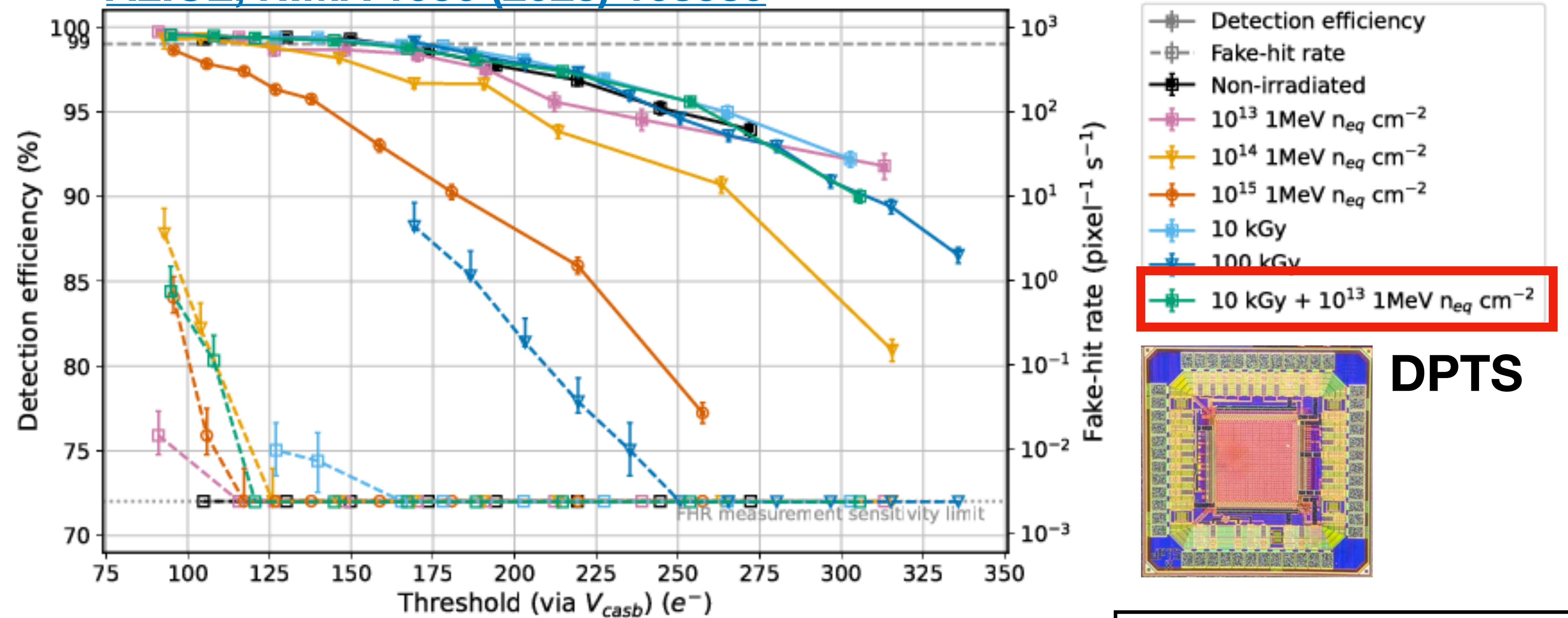
ITS design and R&D

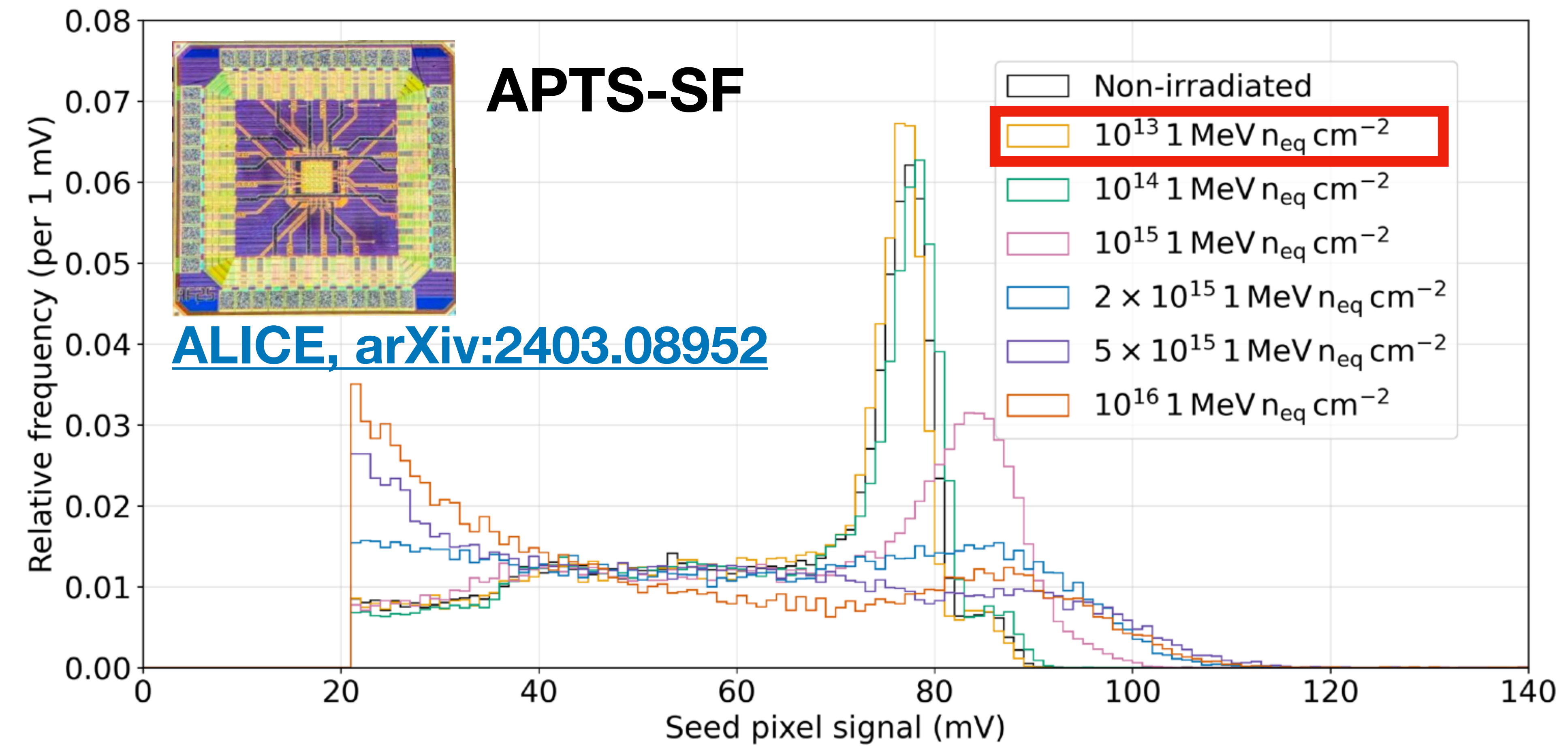
Qualification of 65nm CMOS: MLR1

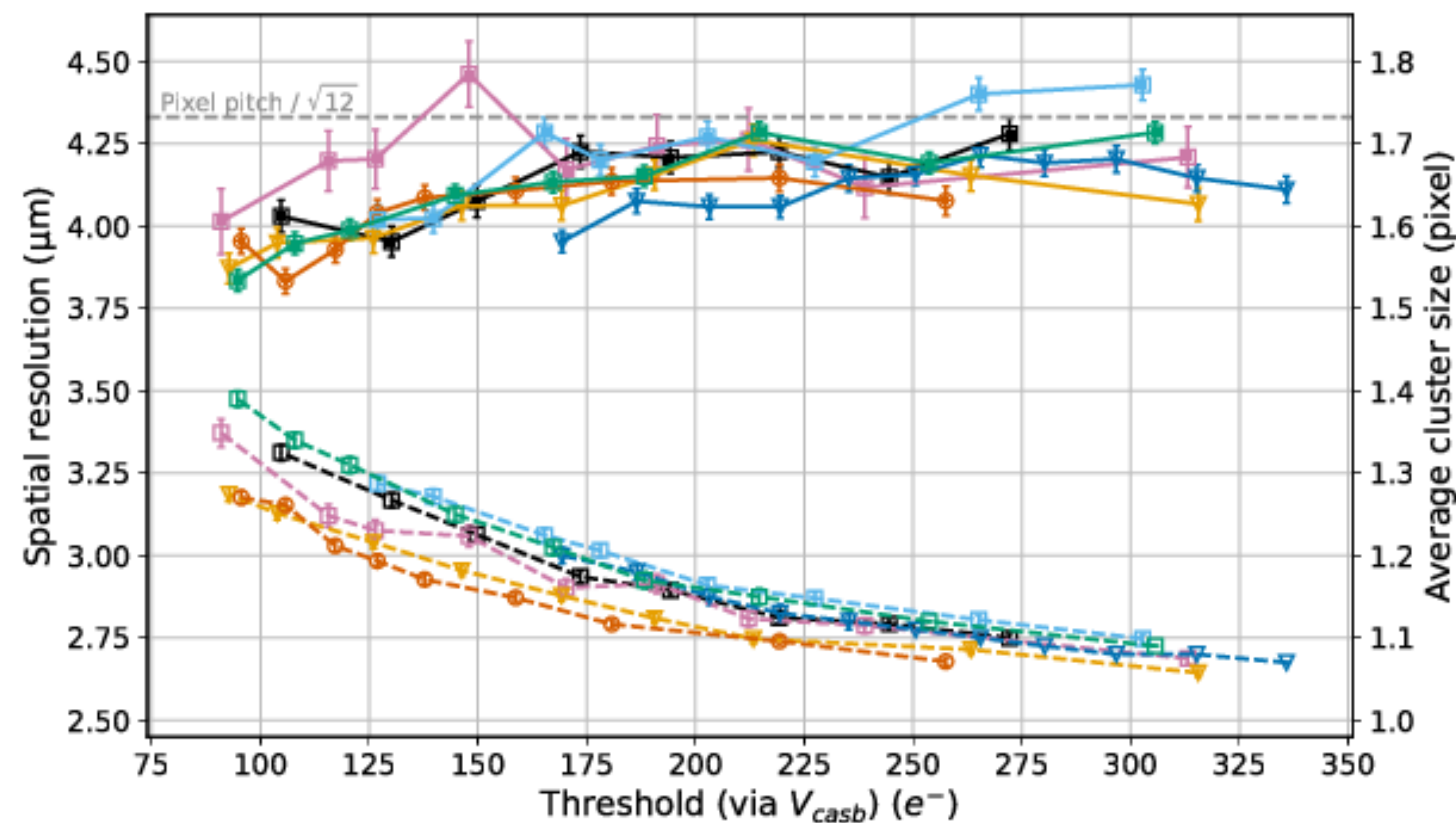
- Concentrated effort **ALICE ITS3** together with **CERN EP R&D**
- **Prototype sensors:** APTS, CE65, DPTS

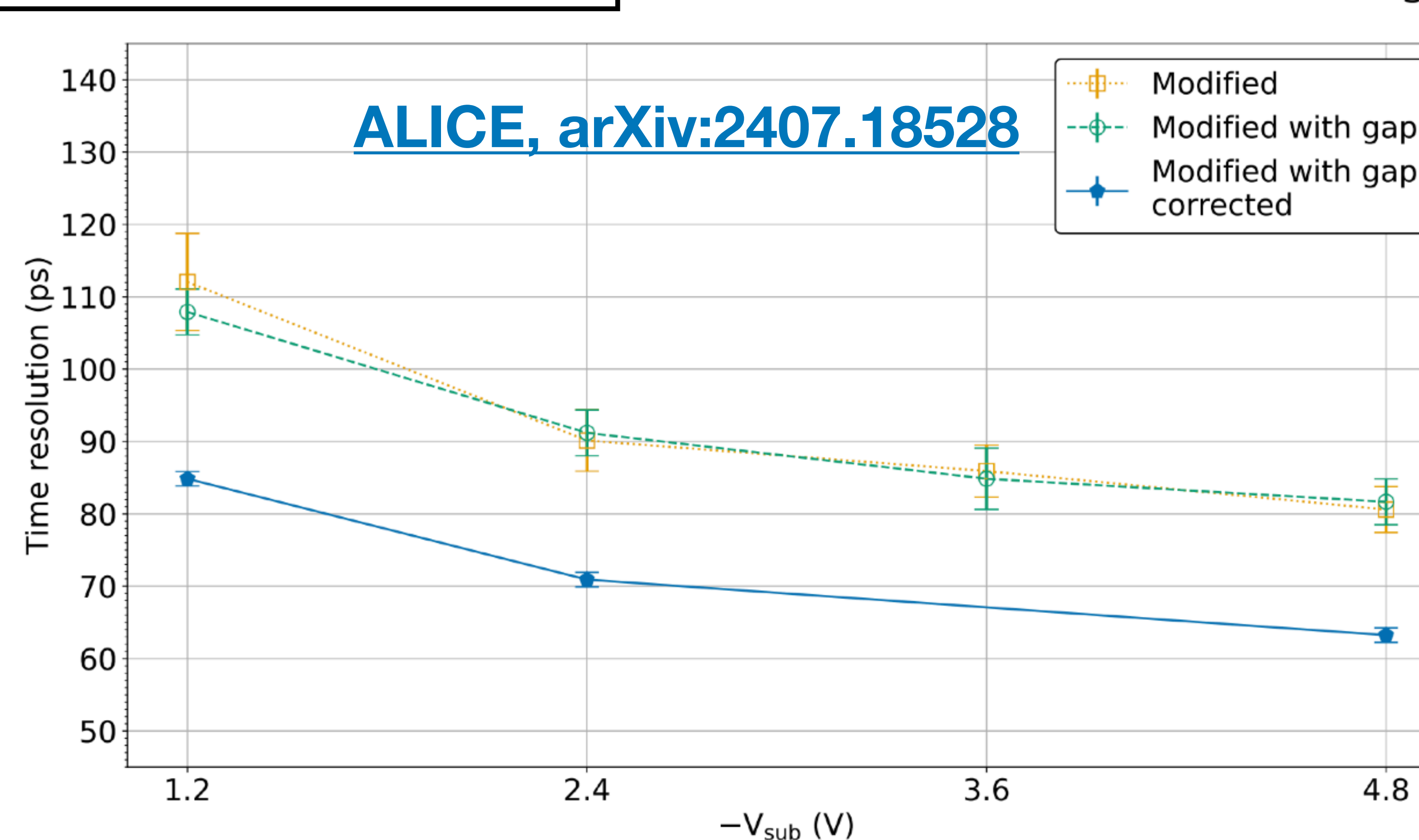
Irradiation ITS3 requirements

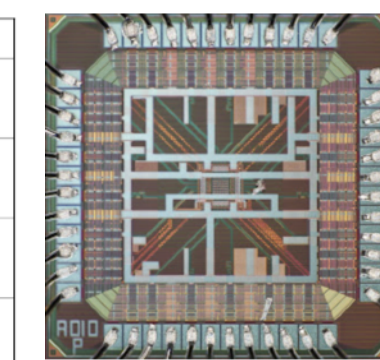
ALICE, NIMA 1056 (2023) 168589











APTS-OA

- **DPTS:**
  - Efficiency (>99%) and spatial resolution (< 5µm) matches **ITS3 requirements**
  - matrix power consumption 40mW/cm²
- **APTS:**
  - **SF:** Charge collection not deteriorated by irradiation
  - **OA:** Sensor time resolution ≤ 70 ps