HighRR seminar
21.04.2021

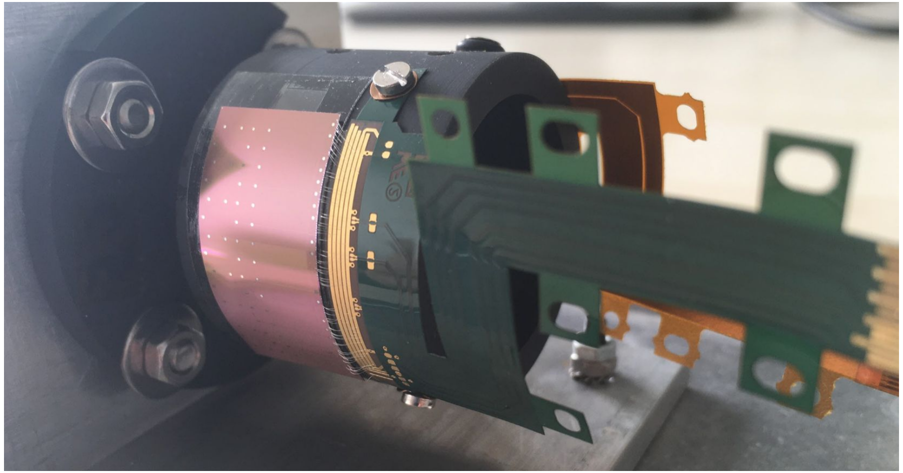
Towards a novel, truly cylindrical, ultra-thin silicon detector for the ALICE Inner Tracker System

Bogdan Mihail BLIDARU

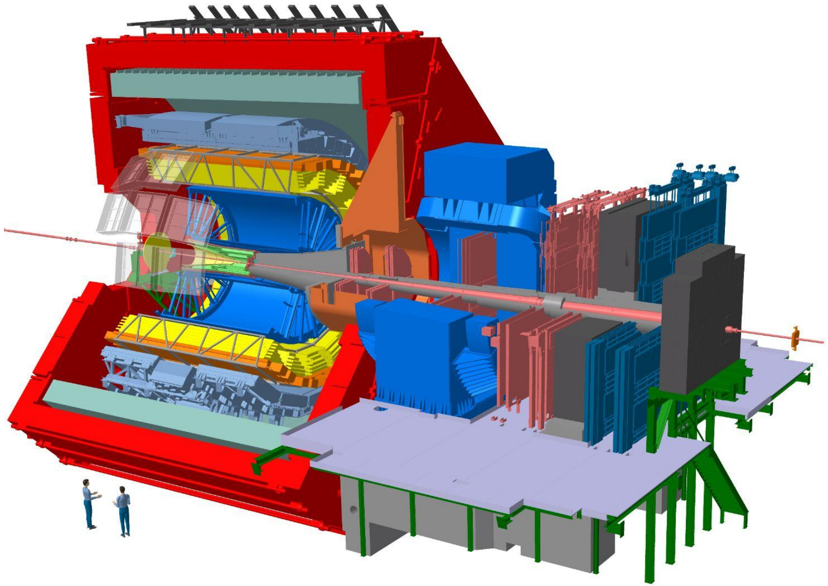
Overview

- ALPIDE @ ITS2, ALICE
- Motivation & design for ITS3
- R&D highlights

  → testbeam characterization of bent ALPIDEs

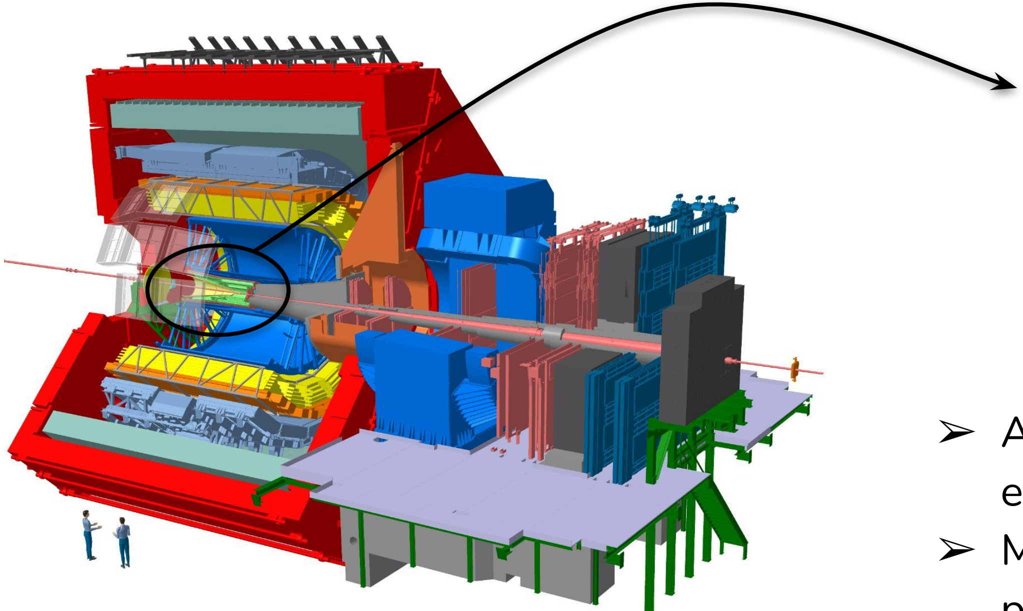


ALICE detector

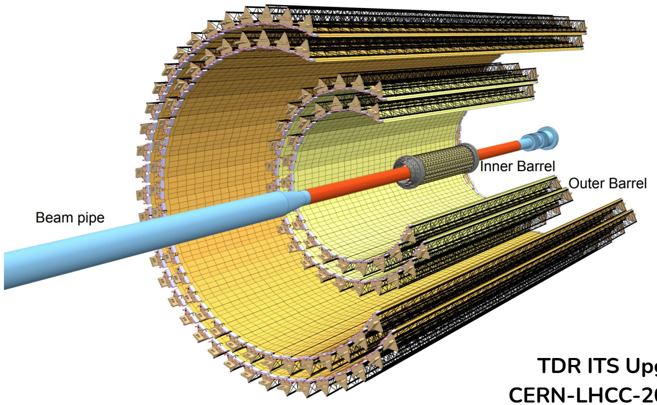


- ALICE is the heavy-ion physics focused experiment at the LHC
- Main goal: study of the quark-gluon plasma in heavy-ion collisions
- Currently LHC LS2 → detector upgrades
- Inner Tracking System 2 (ITS2)

ALICE detector - the Inner Tracking System (ITS2)



ALICE figure repository



TDR ITS Upgrade
CERN-LHCC-2013-024

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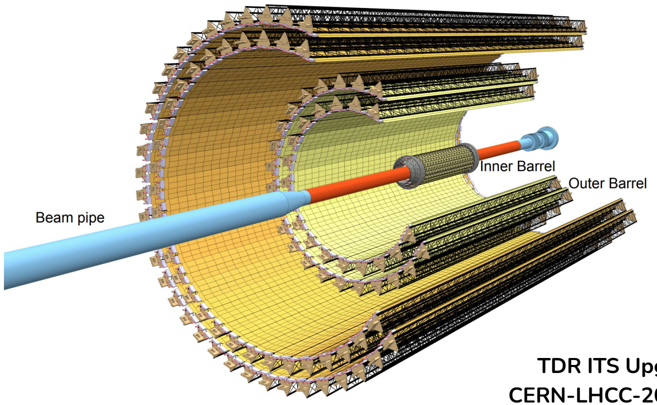
ALICE detector - ITS2

- ➢ ITS2 (LHC LS2, currently under installation)
  - ○ Novel, MAPS based, detector design
  - ○ Seven layers of ALPIDE sensors
  - ○ Increased vertexing and tracking performance with respect to ITS

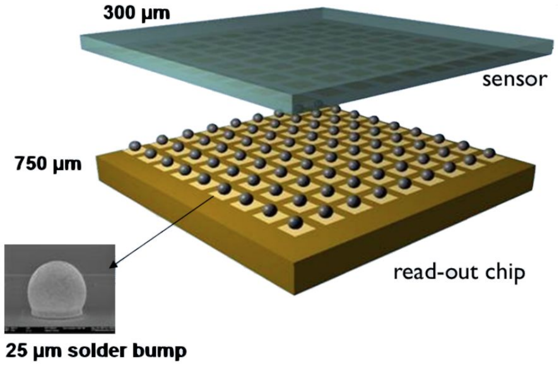


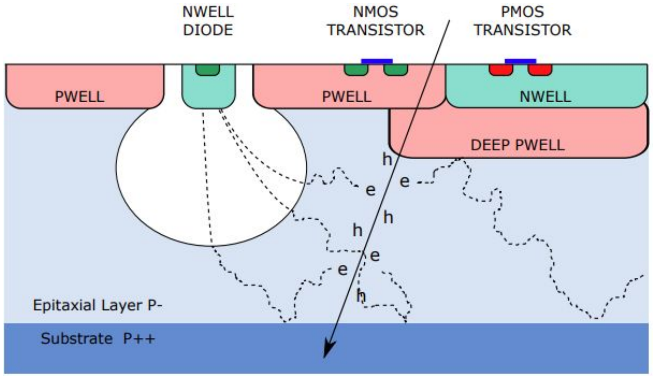
TDR ITS Upgrade
CERN-LHCC-2013-024

- Layer 0 closer to IP: 39mm → 23mm
- Reduced material budget (x/X_0) per layer: 1.14% → 0.3%
- Rate capability: 1kHz → 100 kHz (Pb-Pb)
- Higher granularity (pixel size): 50×425 μm^2 → 29×27μm^2

Hybrid vs monolithic pixel sensors

ITS



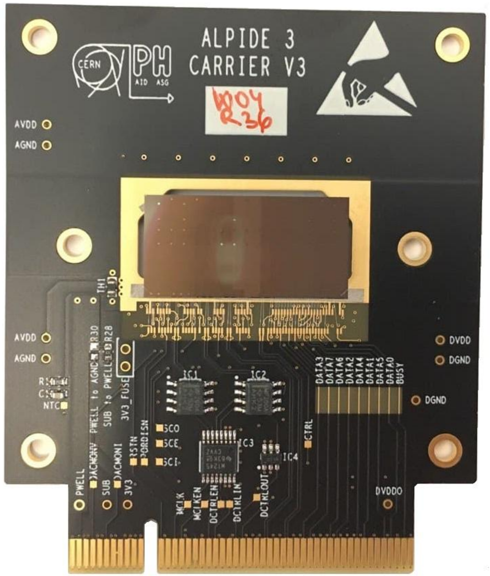


ITS2

$50{\times}425\ \mu m^2$

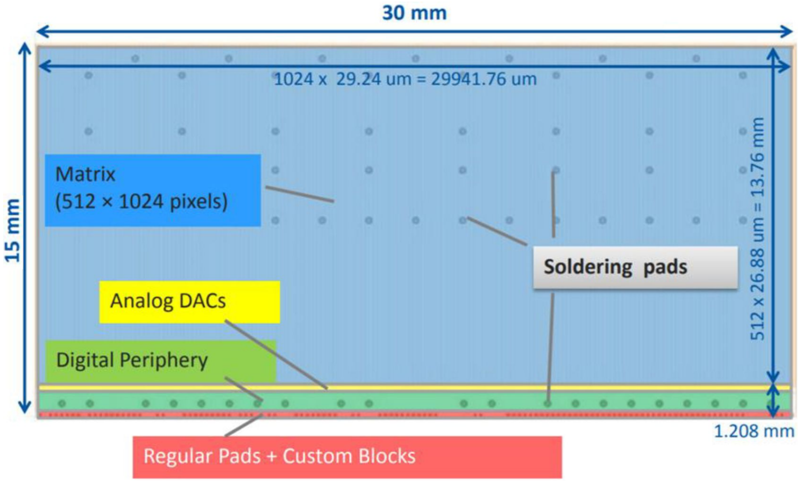
$29{\times}27 \mu m^2$

ALPIDE - a closer look

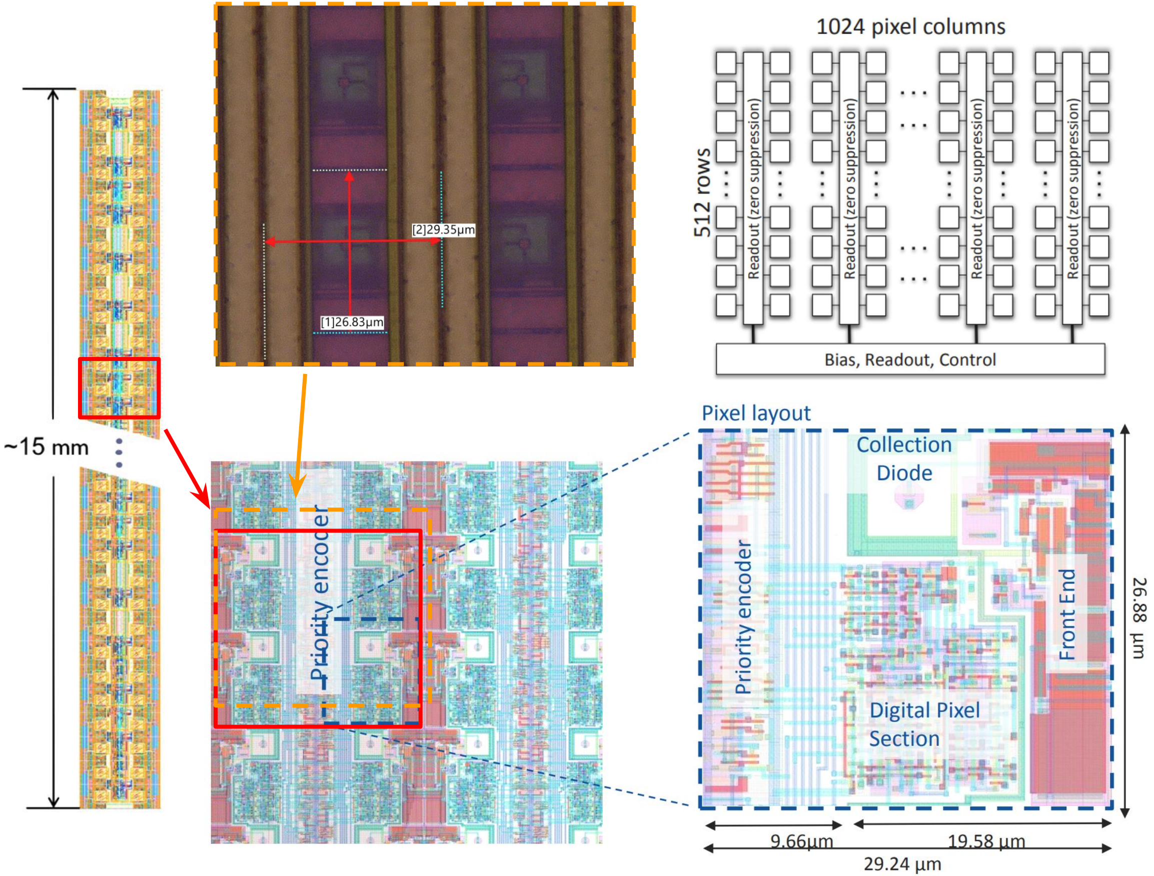


Alpide on carrier card

- MAPS produced in the 180nm TowerJazz CMOS IP
- 30 × 15 mm^2 matrix of pixels
- Pixel pitch 29.24 × 26.88 μm^2 (1024 × 512 px)
- Silicon thickness 50μm
- Spatial resolution ~5μm (required: 5μm)
- Time resolution ~1μs
- Detection efficiency ≫99% (req: >99%)
- Fake hit rate ≪ req. 10^{-6} /px /event
- Power consumption ($7mW/cm^2$ matrix, $150mW/cm^2$ periphery) ~$40mW/cm^2$



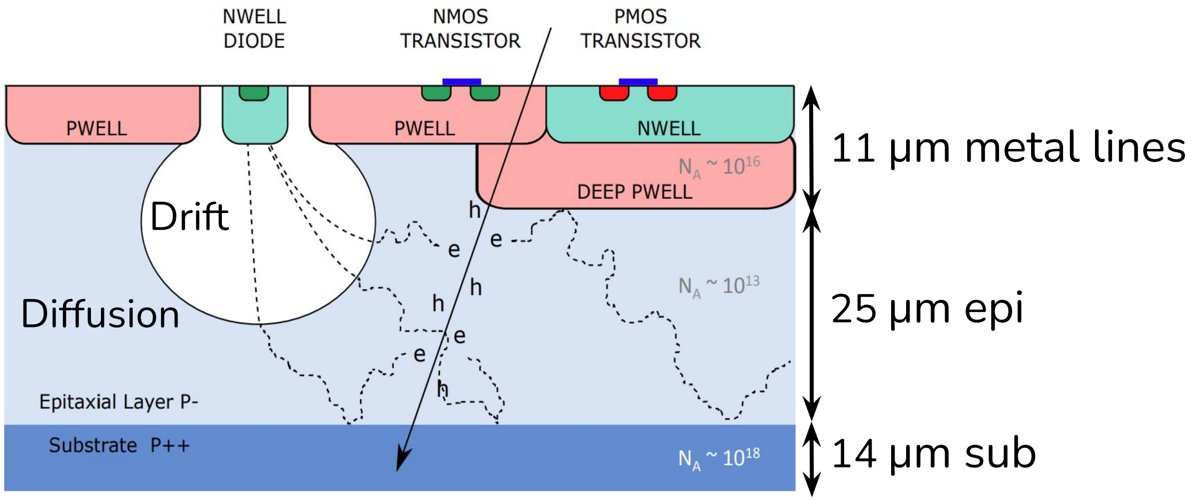
ALPIDE layout features



- ➢ Readout of the pixel data from the matrix based on combinatorial readout
- ➢ ALPIDE readout is binary (hit / no hit information)
- ➢ Data transfer from matrix to periphery is zero suppressed via a priority encoder circuit
- ➢ No free running CLK distributed in the matrix, no signaling activity if no hits to read

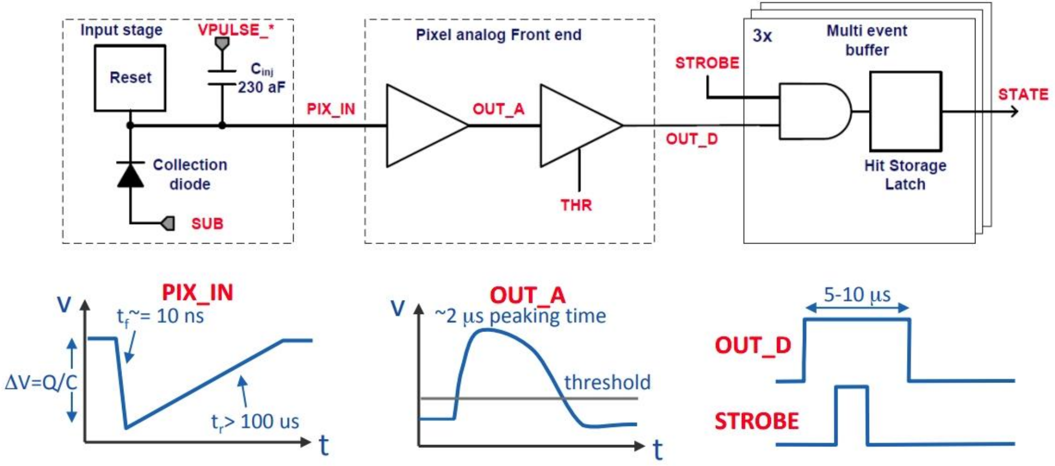
Very low power consumption!

ALPIDE - the pixel



- ➢ Charge is created in the high resistivity (>1kΩcm) epitaxial layer (half the sensor thickness)
- ➢ Highly doped P substrate and PWELLs act as reflective barriers and contain the charge
- ➢ Deep PWELL shields NWELLs, allowing PMOS transistors (full CMOS within active area)
- ➢ Small NWELL diode (2µm diameter) → low capacitance (2fF) → large S/N
- ➢ Reverse bias (-3V) used to increase depletion of the diode

ALPIDE - the pixel; signal processing



- ➢ Charge is collected, amplified, discriminated and strobed to in-pixel memory
- ➢ The analogue front-end is continuously active (non-linear response);
  it acts as analogue delay line; rise-time (<2µs) - defines time resolution
- ➢ Global shutter (STROBE) latches discriminated hits to memory

ALICE detector - ITS2

- ➢ ITS2 (LHC LS2, currently under installation)
  - Novel, MAPS based, detector design
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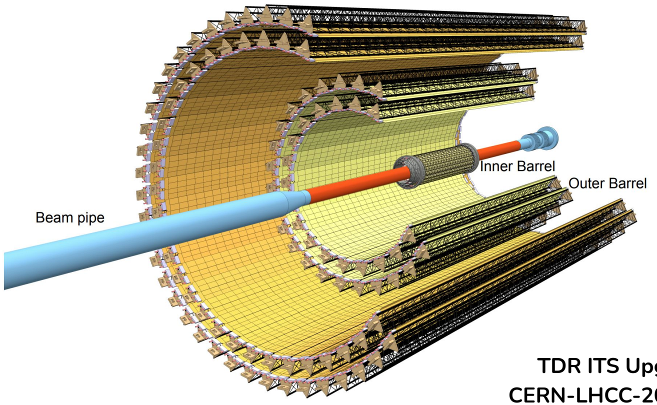

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- Rate capability: 1kHz → 100 kHz (Pb-Pb)
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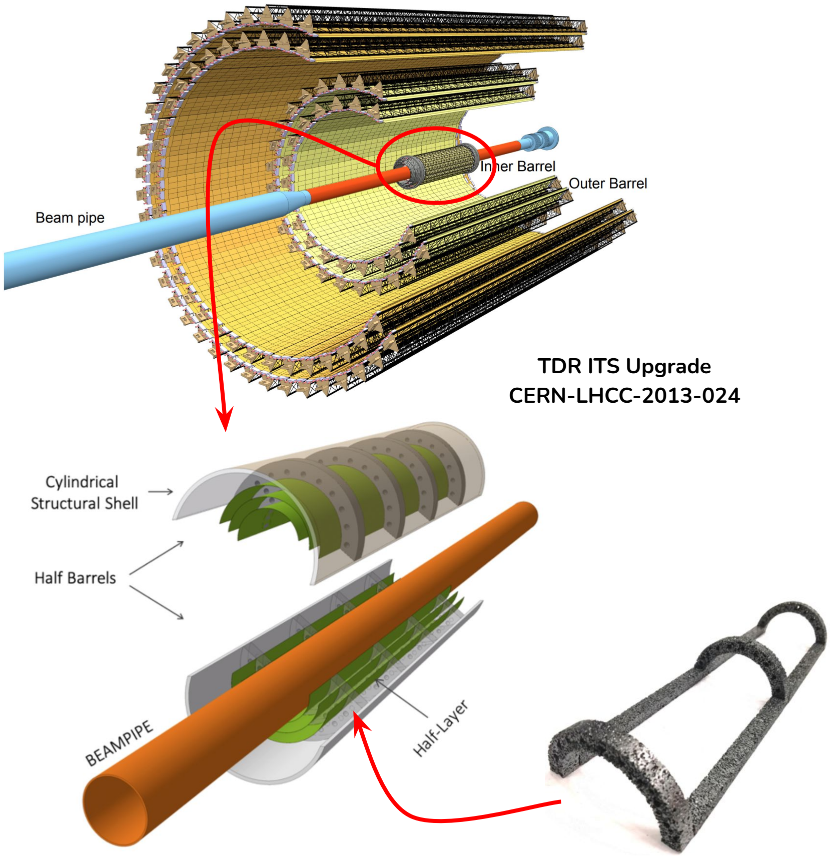
- ➢ ITS2 is a state of the art MAPS detector
- ➢ Further improvements are possible

ALICE detector - ITS3

- ➢ ITS2 (LHC LS2, currently under installation)
  - Novel, MAPS based, detector design
  - Seven layers of ALPIDE sensors
  - Increased vertexing and tracking performance with respect to ITS

- ➢ ITS3 (LHC LS3, 2025-2027)
  - Aim: replace the three ITS2 IB layers
  - Ultra-light, wafer-scale, curved sensors

  - Currently: R&D based on bent ALPIDE
  - First testbeam results with bent ALPIDE



TDR ITS Upgrade
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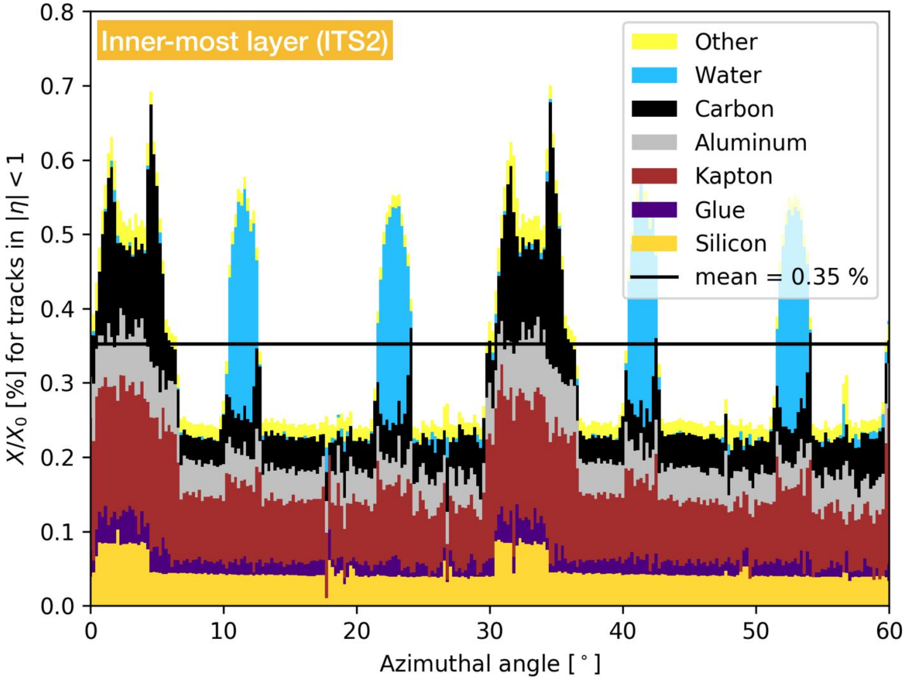
Motivation for the ITS3



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LoI for ITS3, CERN-LHCC-2019-018

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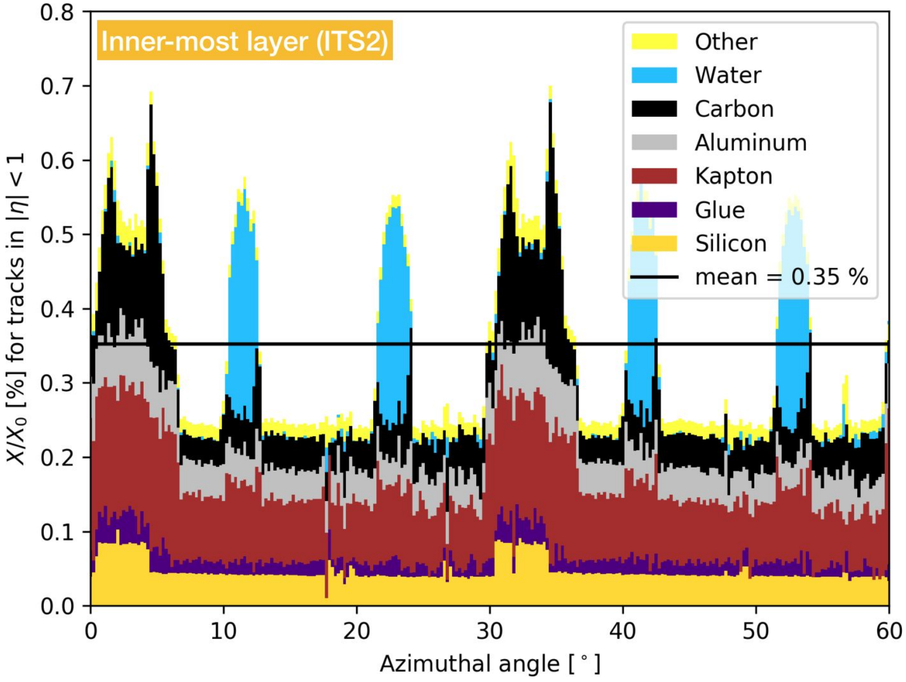

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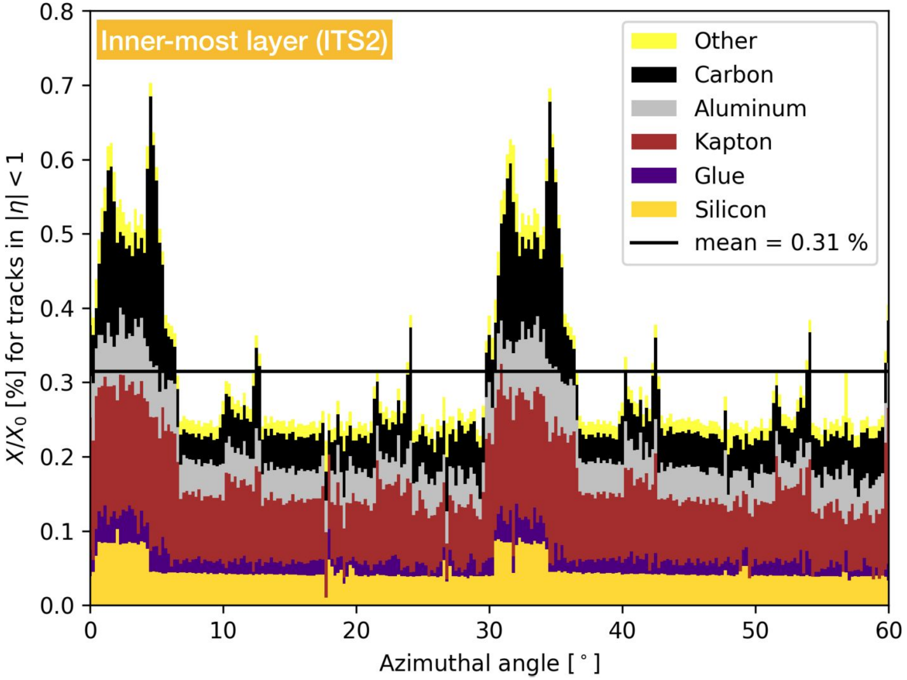

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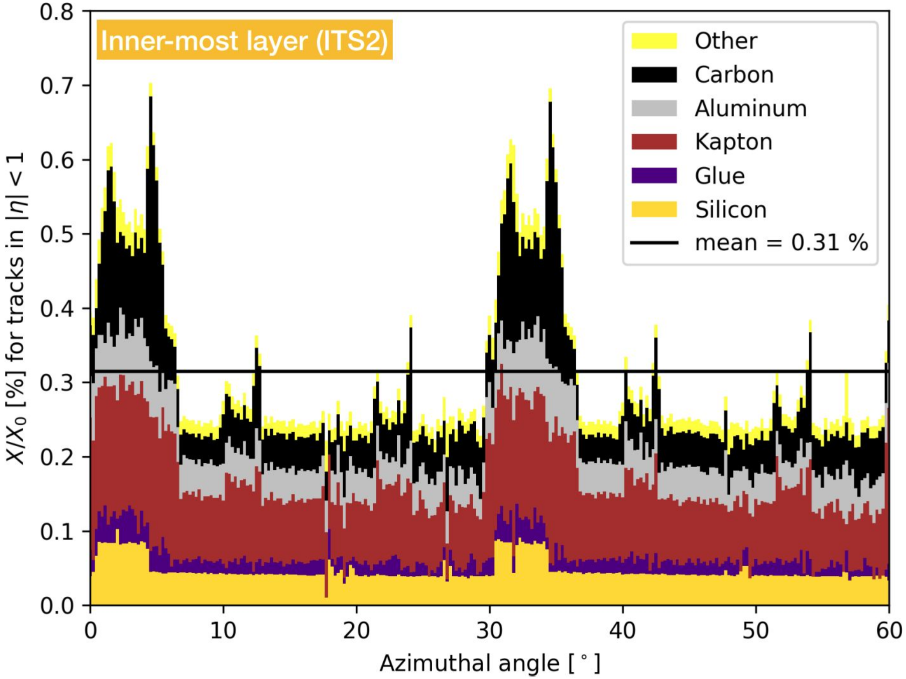

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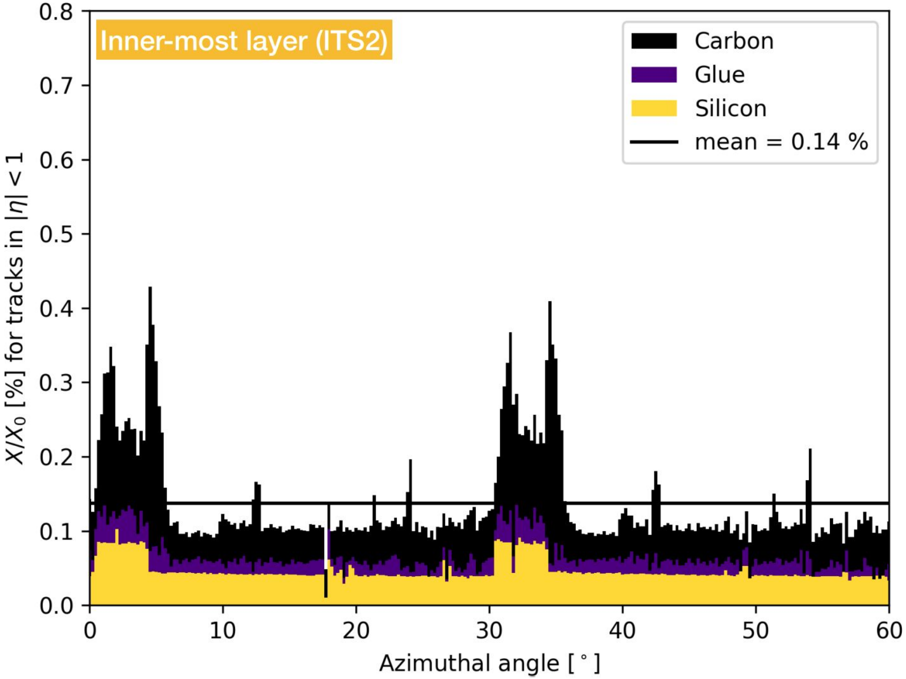

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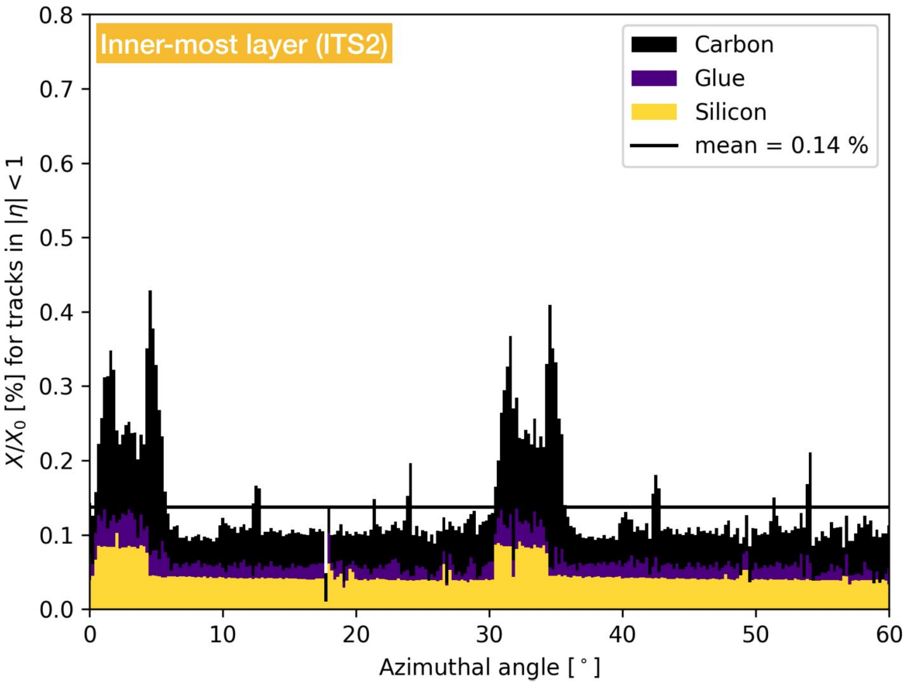

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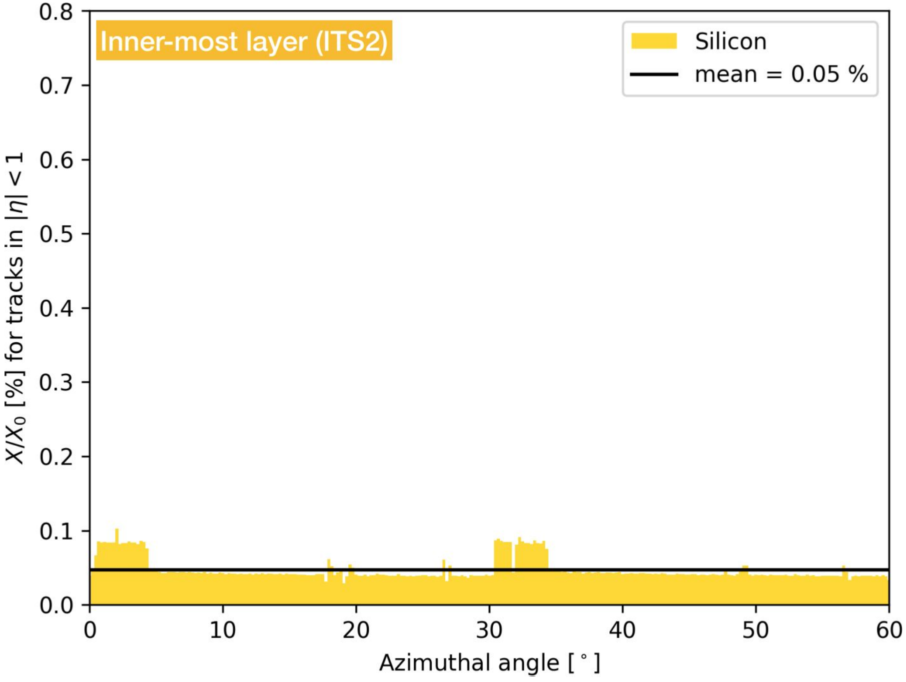

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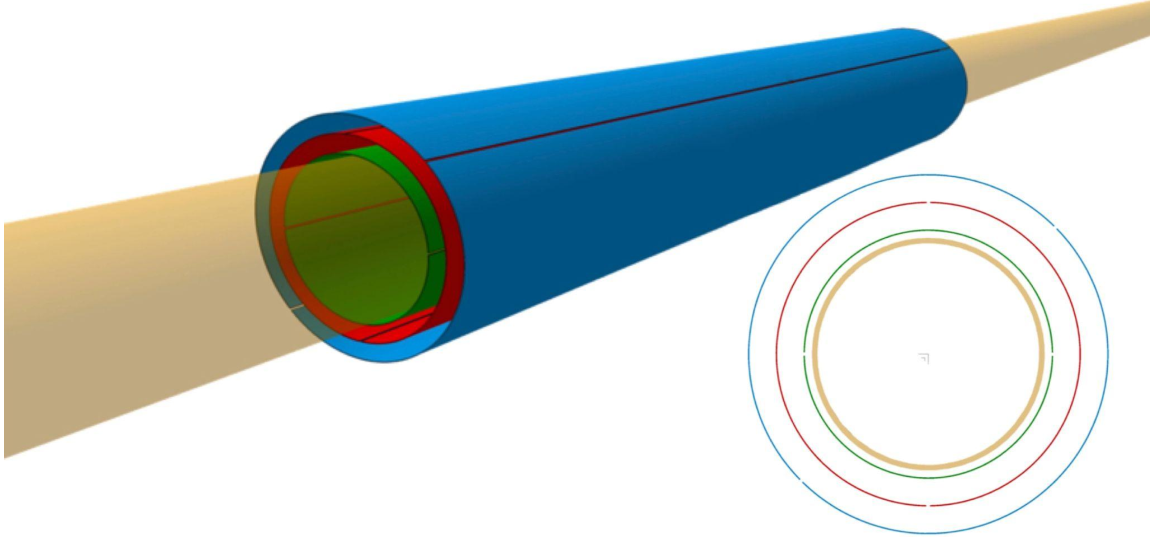
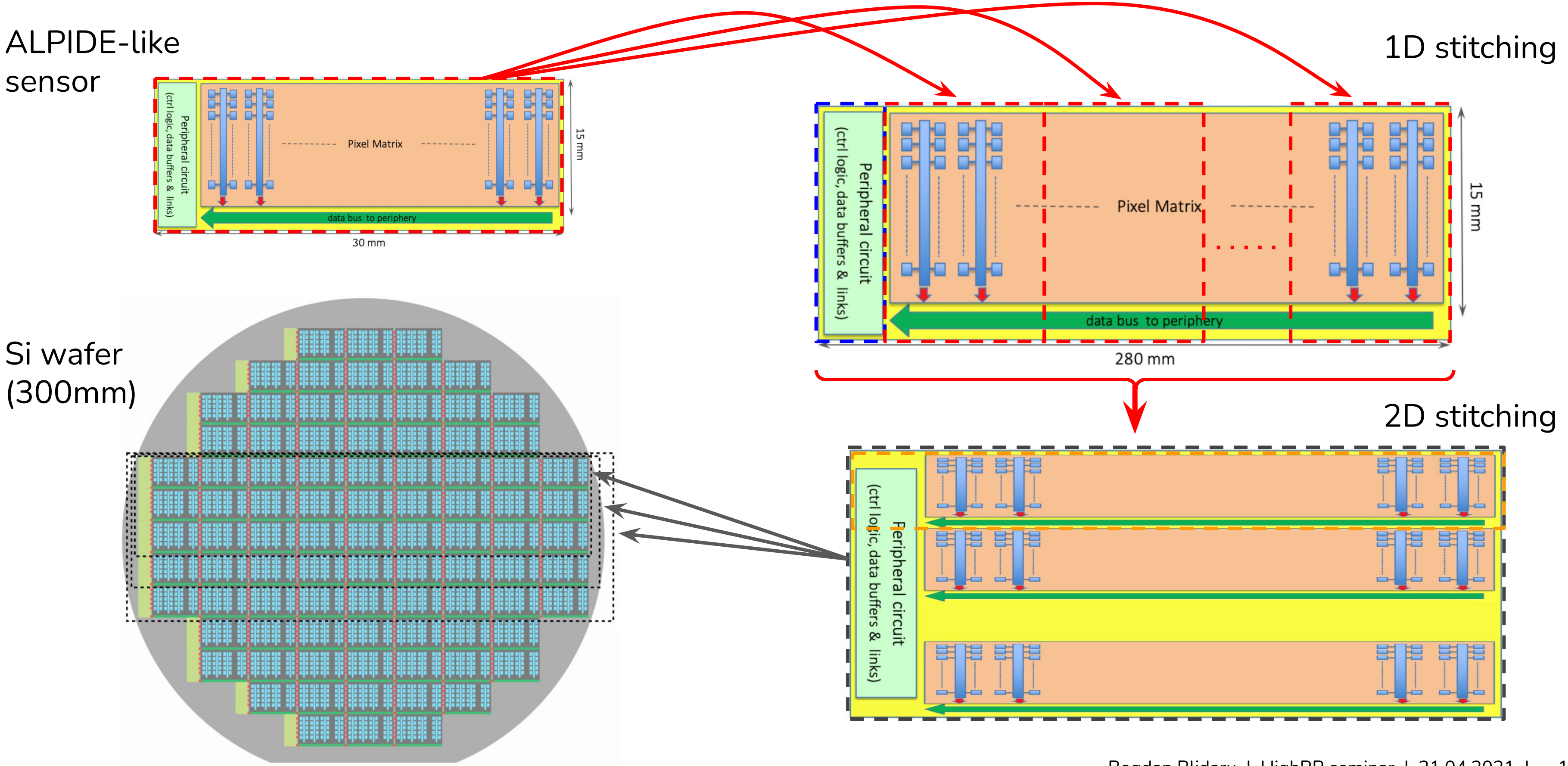
ITS3 detector concept



Beam pipe inner/outer radius (mm)	16.0 / 16.5		
	Layer 0	Layer 1	Layer 2
Radial distance from IP (mm)	18	24	30
Pixel sensor dimensions (mm^2)	280×56.5	280×75.5	280×94
Sensitive area length (mm)	300		
Pixel size (μm^2)	O(10×10)		

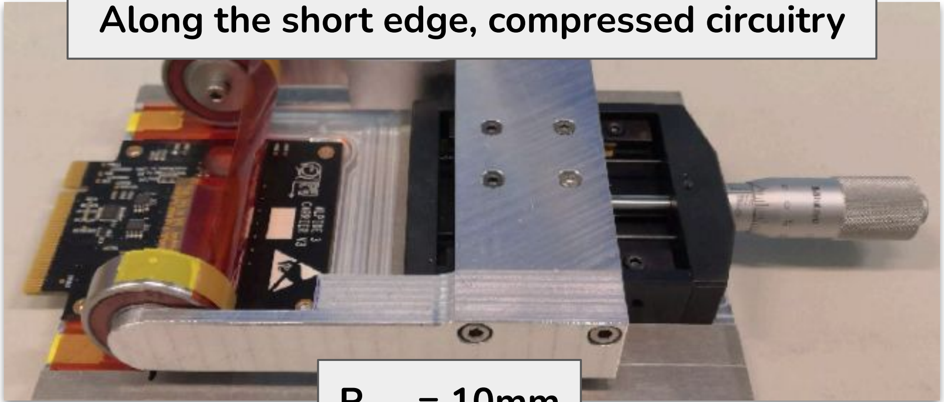
- ➢ Ultra thin and closer to the interaction point
  - Layer 0: 23 → 18 mm
  - Layer thickness: 0.35 → < 0.05% X_0 (beampipe: 500µm Be 0.14% X_0)
  - Uniformly distributed material (no system. errors)
- ➢ Wafer scale ← stitching
- ➢ Layout based on air cooling

Architecture & stitching

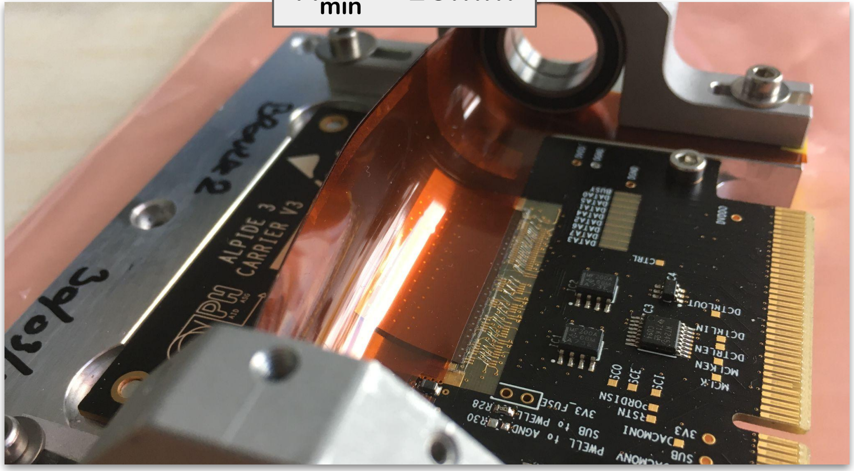


Bending ALPIDEs

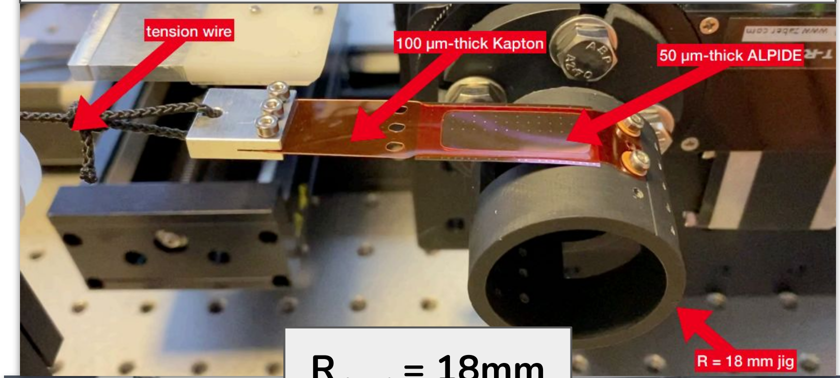
Along the short edge, compressed circuitry



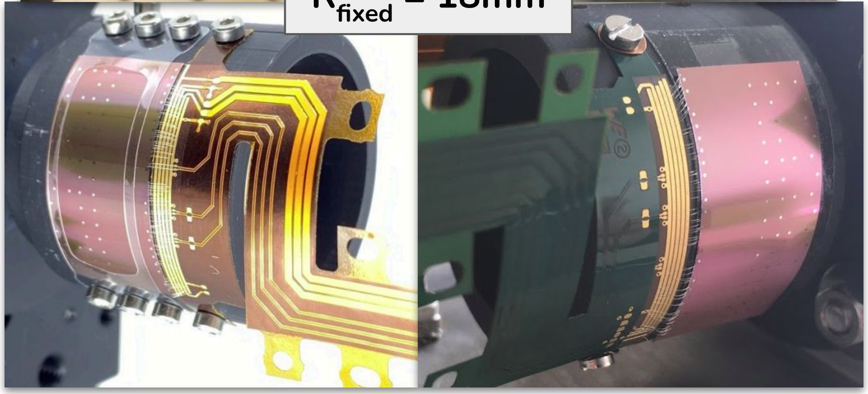
R_{min} = 10mm



Along the long edge, stretched circuitry

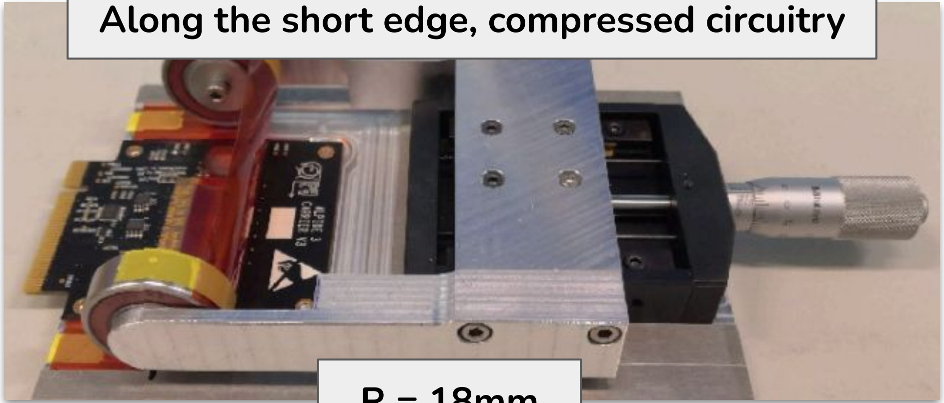


R_{fixed} = 18mm



Bending ALPIDEs - part I

Along the short edge, compressed circuitry



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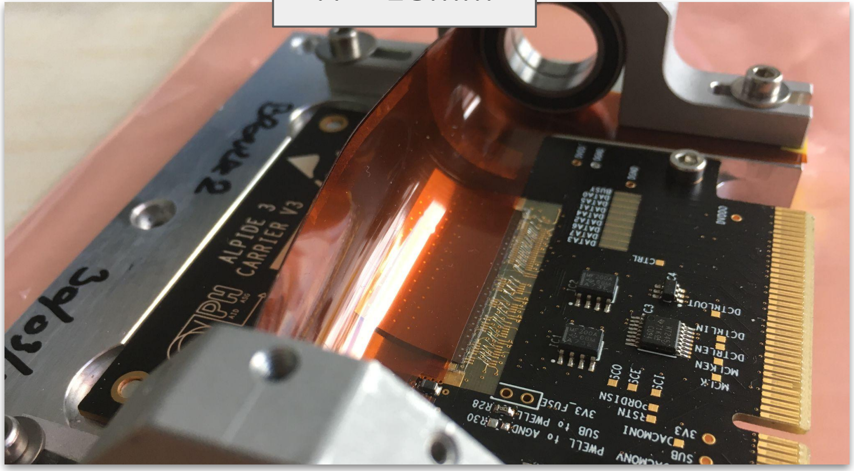

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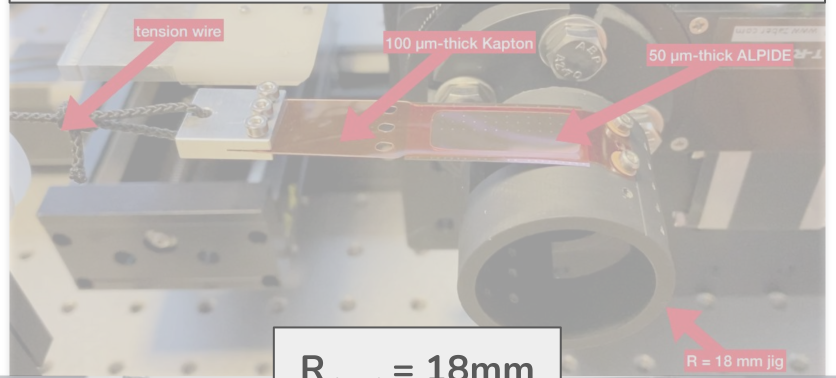

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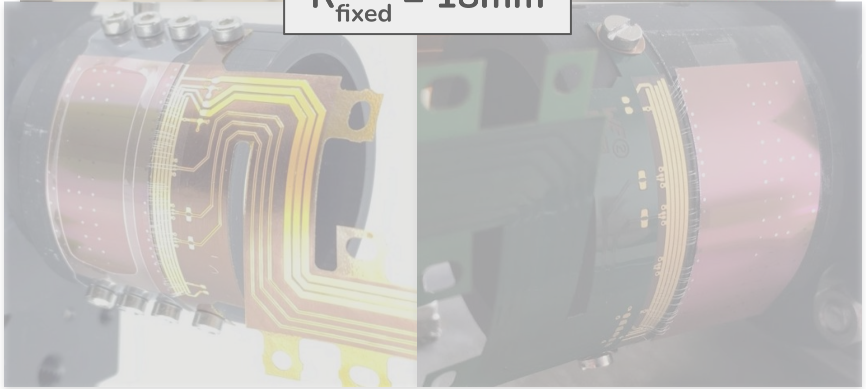
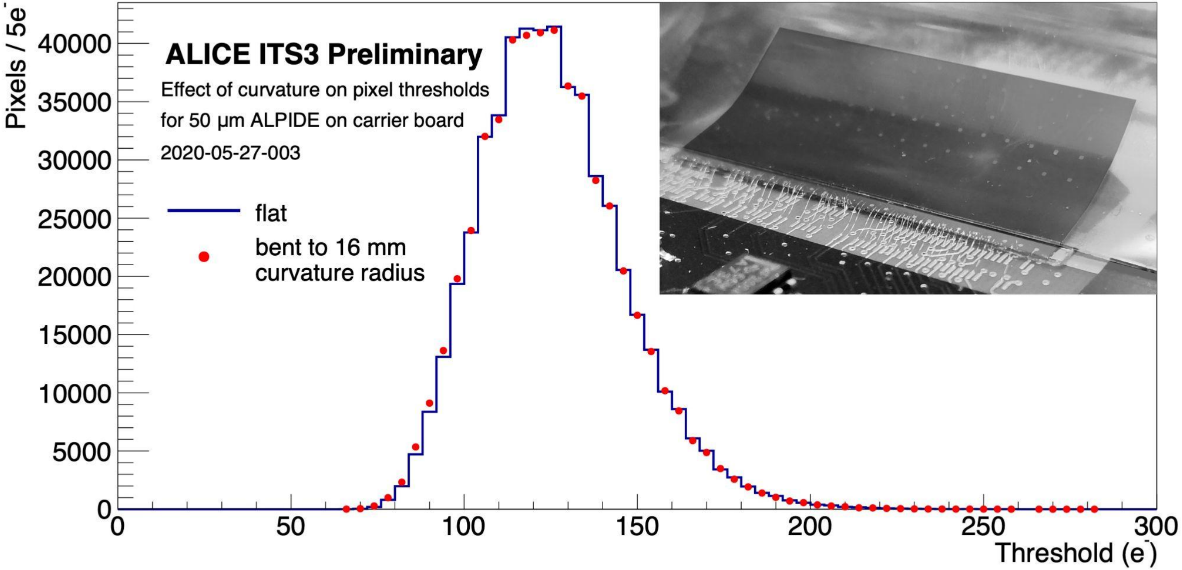
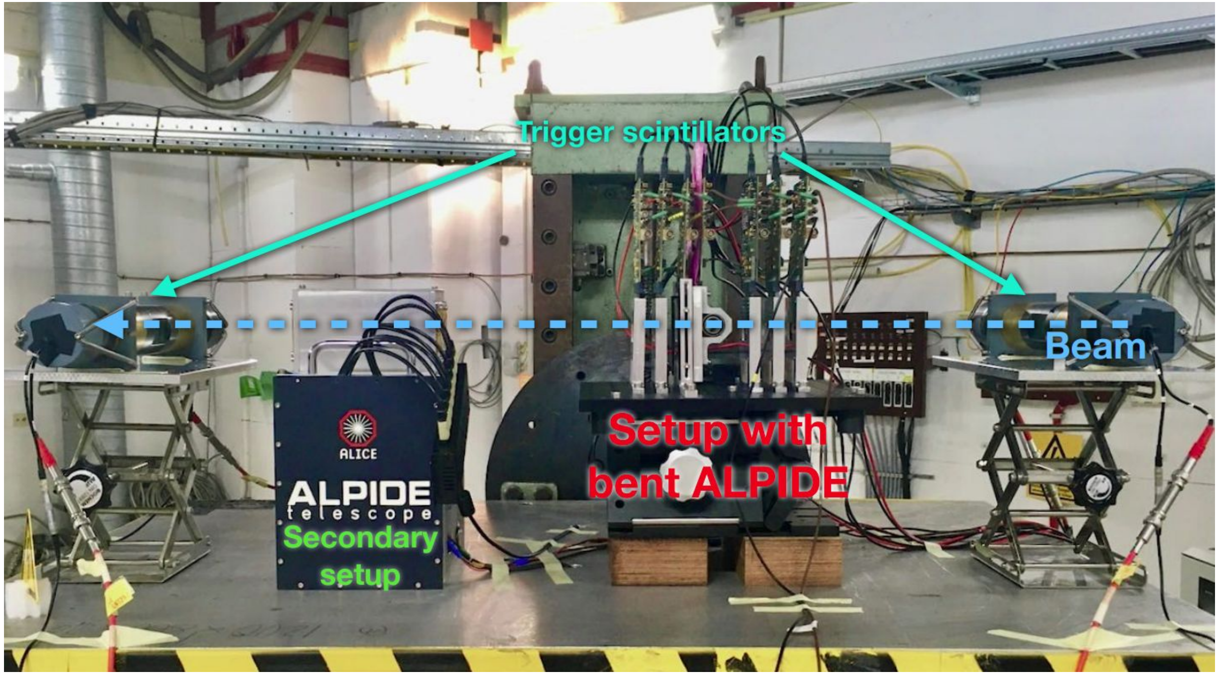


Bent ALPIDE - part I - electrical characterization



- **Electrical performance of the chip is unchanged with respect to the flat state**
- Threshold and noise unchanged
- No variation in the number of dead pixels

Bent ALPIDE - part I - testbeam

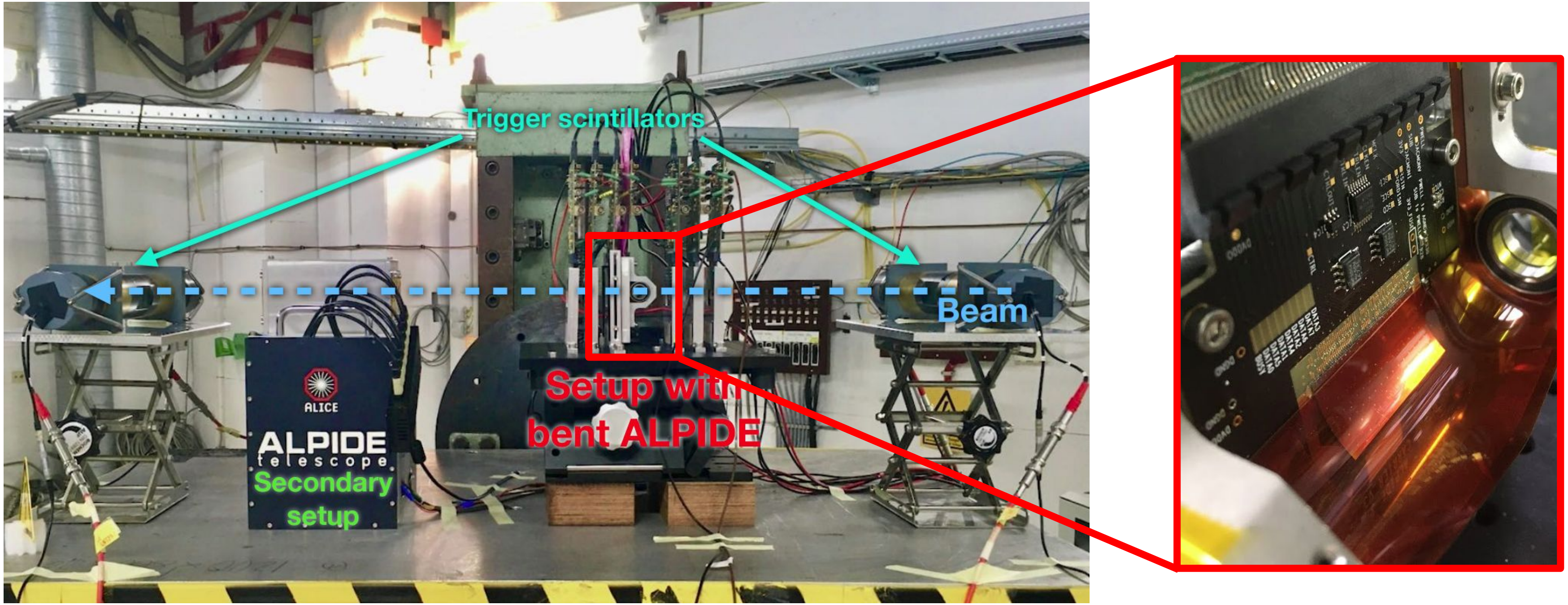


- First ever testbeam with bent silicon pixel sensors
- 5.4 GeV e^-, DESY
- 6 flat ALPIDEs as reference planes (track reconstruction)
- Determine: efficiency of bent sensor, position resolution

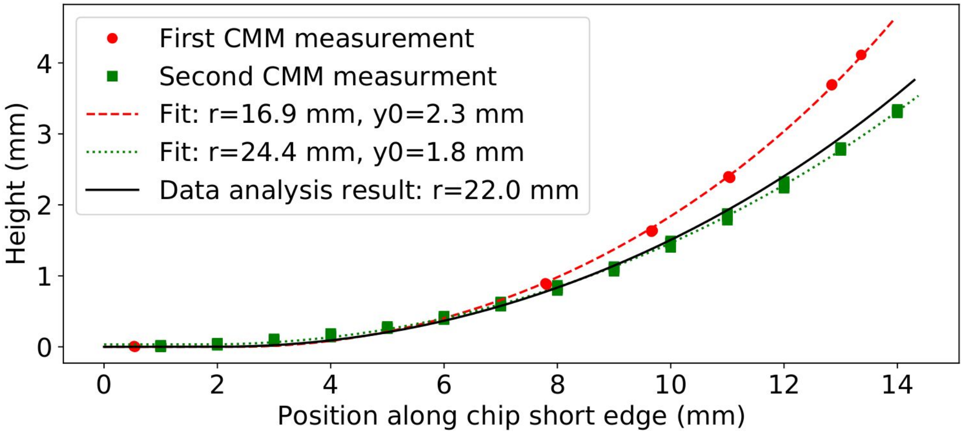
- Corryvreckan* used for data analysis

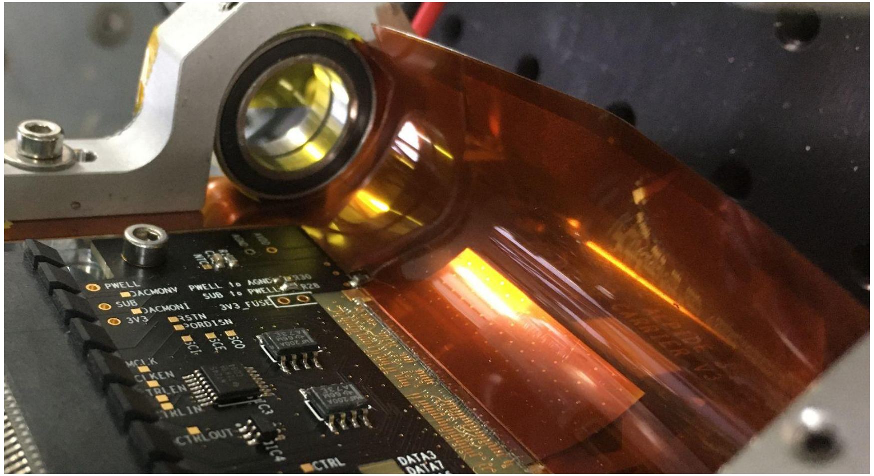
* https://cern.ch/corryvreckan

Bent ALPIDE - part I - testbeam



Bent ALPIDE - part I - radius assessment

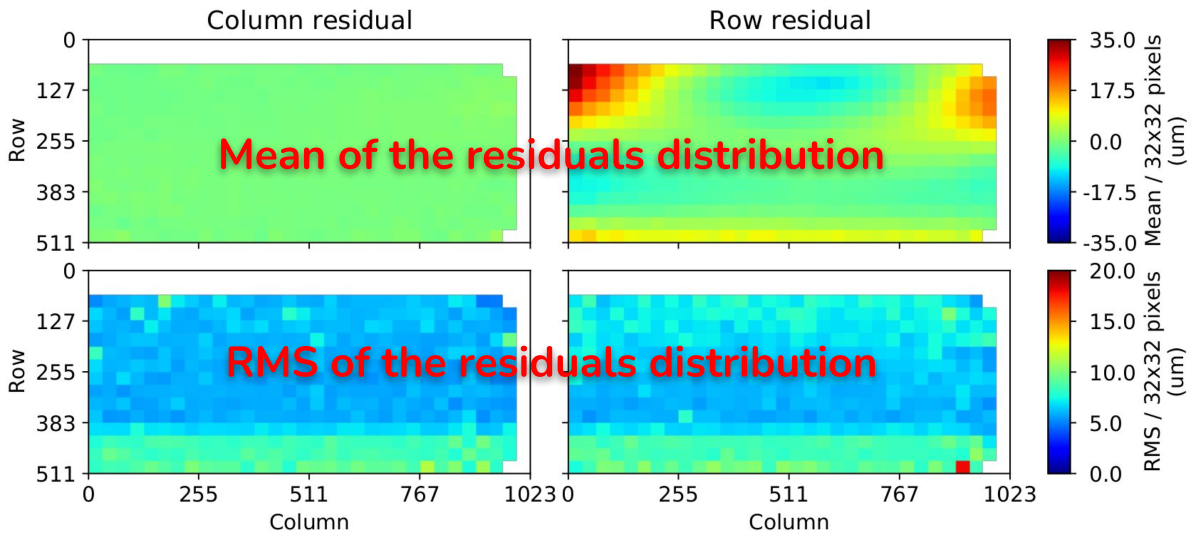


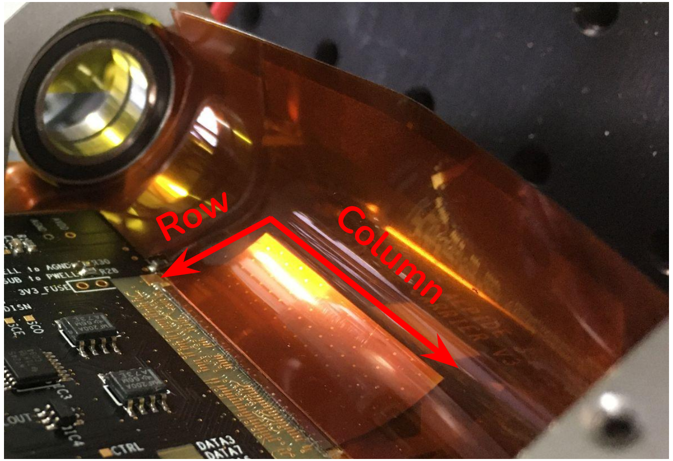


- Sensor bent to 16.9 mm - measured with Coordinate Measurement Machine (CMM) before the testbeam
- Re-measured after testbeam: observed relaxation (R_{new}=24.4mm)

- Results of the testbeam analysis show a radius of 22 ± 1 mm
- Cylindrical geometry model used to describe the bent chip
- Radius free parameter ← minimization of the residuals

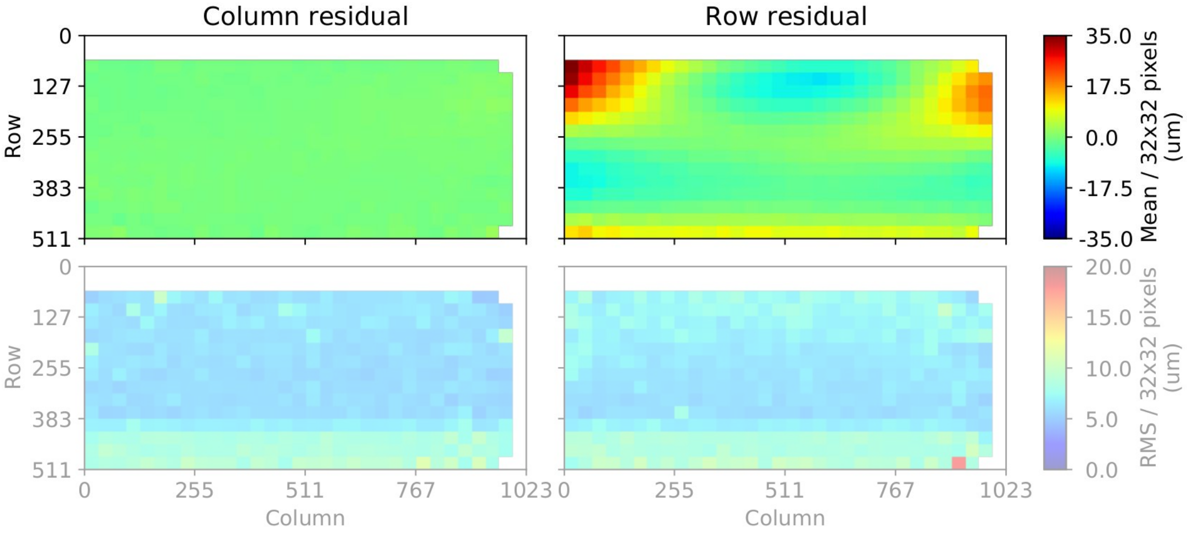
Bent ALPIDE - part I - spatial residuals

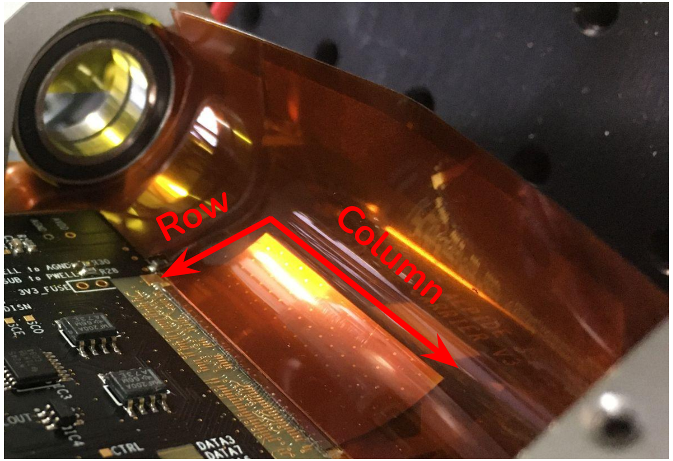




Bent ALPIDE - part I - radius assessment

- **Mean of the residuals distribution**
  - Invariant to rotation around column axis
  - Row direction - compatible with cylindrical geometry model up to 35 µm





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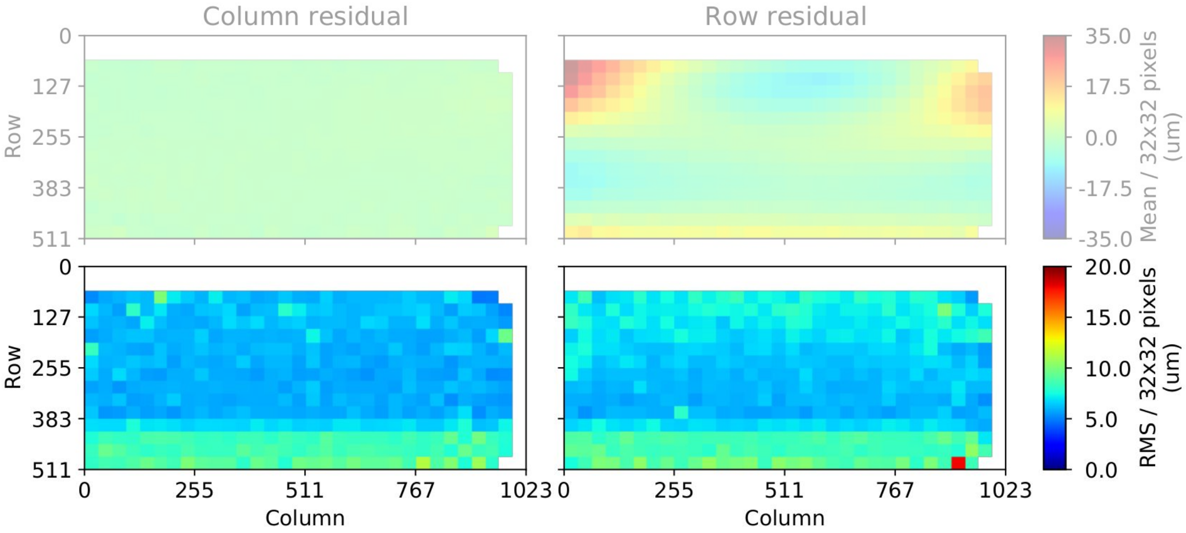

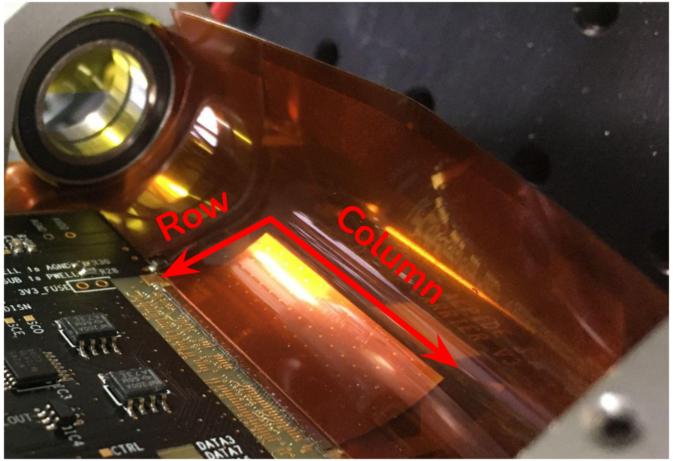

- **RMS of the residuals**
  - Larger where the chip is glued to PCB (due to scattering)
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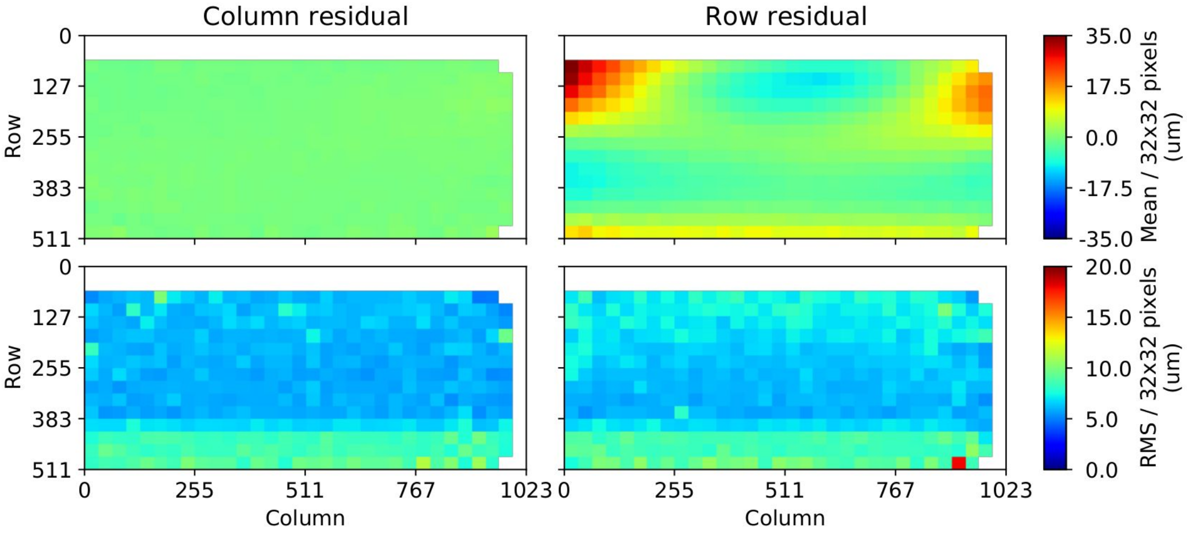

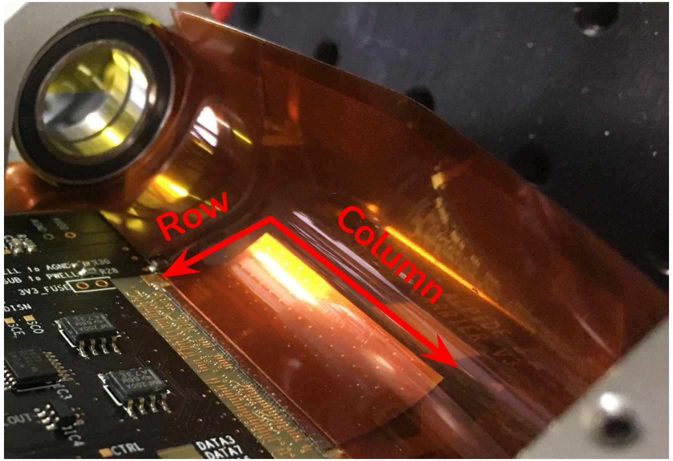

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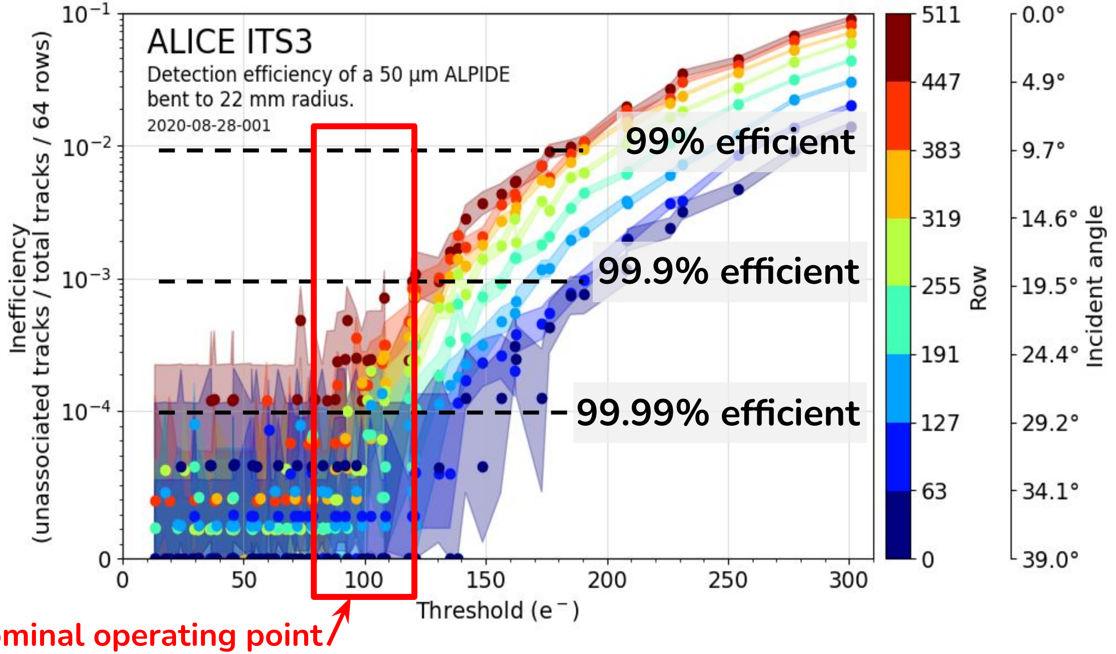
Bent ALPIDE - part I - efficiency of bent sensor

- **Inefficiency** as a function of pixel threshold for various chip rows (= incident angles)
- Linear-logarithmic plot



- Only 0V back-bias!
- More than 8000 tracks per data point

- Below a threshold of 100 e^-, only 1 in 10^4 tracks is inefficient
- Above 100 e^-, the inefficiency increases with decreasing beam incident angle (increasing row number)

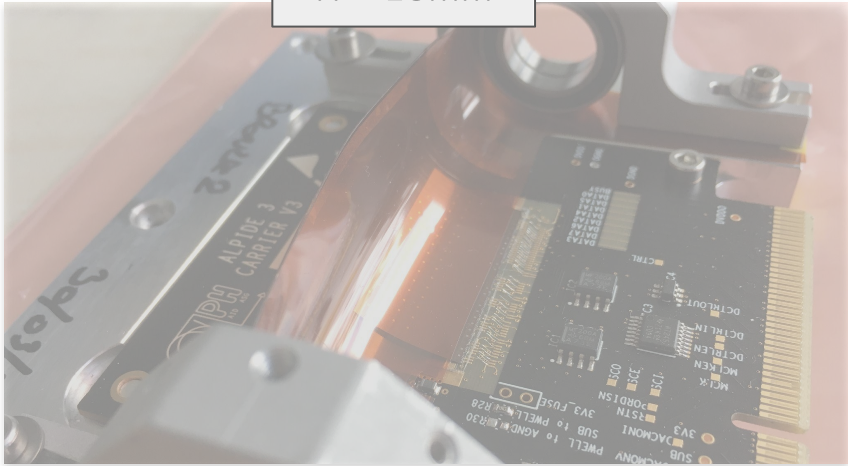
- **Excellent detection performance retained!**

- Publication under internal review

Bending ALPIDEs - part II

Along the short edge, compressed circuitry

R = 18mm



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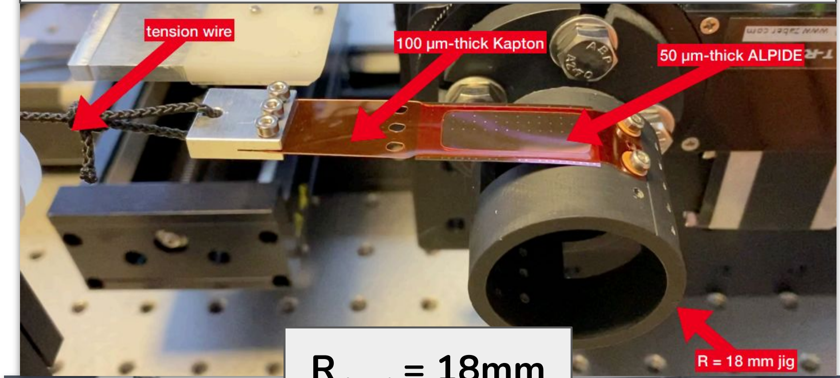

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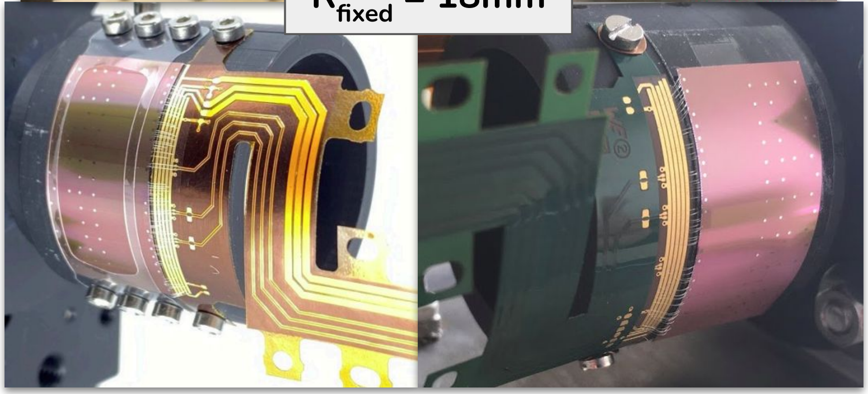


Bending ALPIDEs - part II

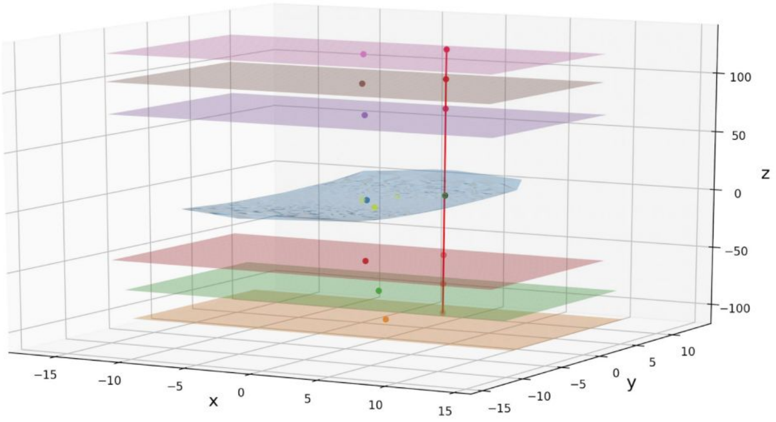
- ➢ More rigid construction
- ➢ Bent along the long side (decompressed circuitry) → piezoresistive effect (change in electrical resistivity)
- ➢ Connection to DAQ board done via flex-print-cable (FPC)
- ➢ Bonded after bending
- ➢ Multiple radii (18,24,30 mm), corresponding to ITS3 layers

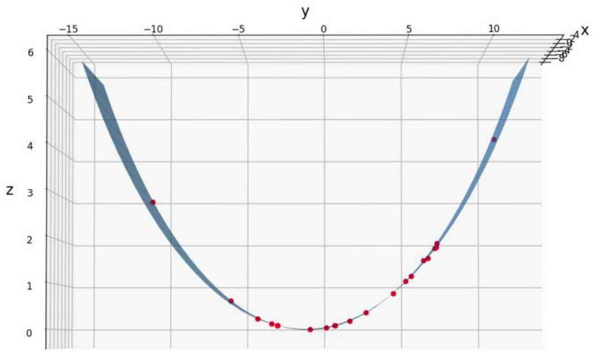
Bending ALPIDEs - part II - new geometry

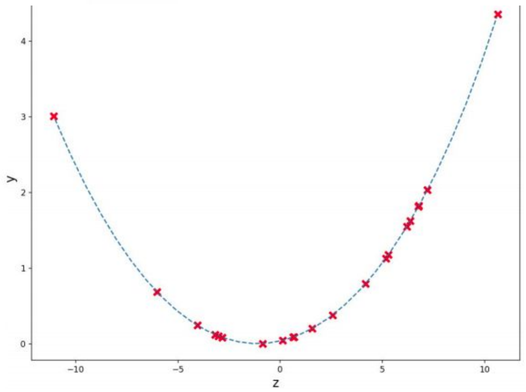
- ➢ Include cylindrical geometry in code
- ➢ Account for change of coordinate transformation (local → global)

- ➢ Correct for different z track intercept (no curved detectors previously studied)

- ➢ Ensure all DOFs are accounted for
- ➢ Check that tracks/clusters lie on the same plane

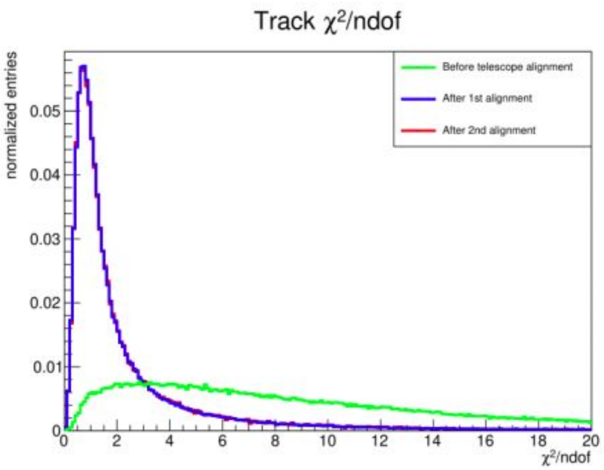


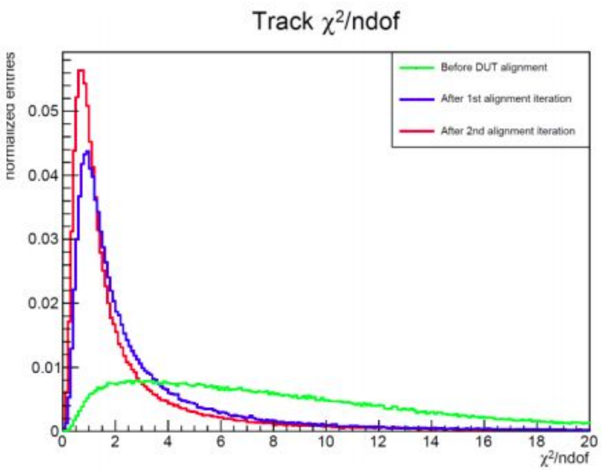


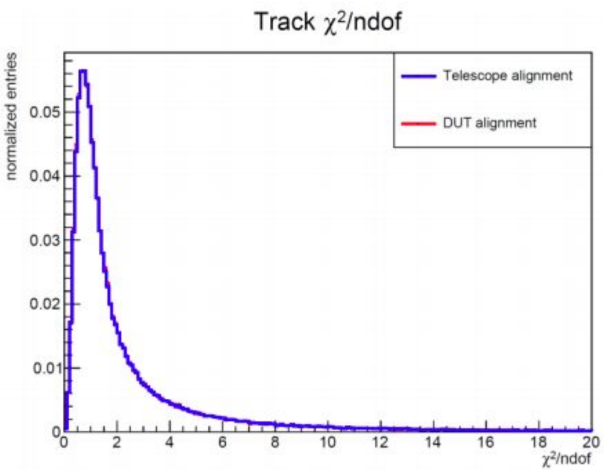


Bending ALPIDEs - part II - tracking

- ➢ Align telescope planes with tracks from the reference planes only
- ➢ Include and align the DUT with respect to the telescope
- ➢ Straight tracks only (not accounting for scattering)

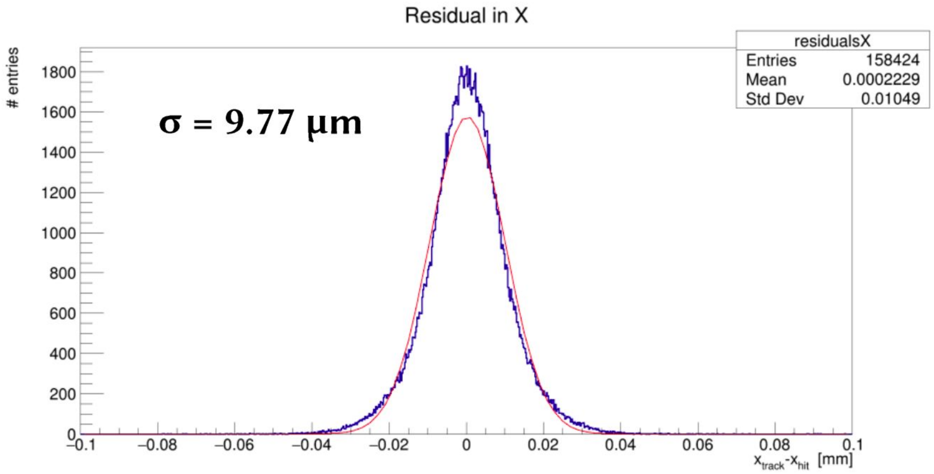


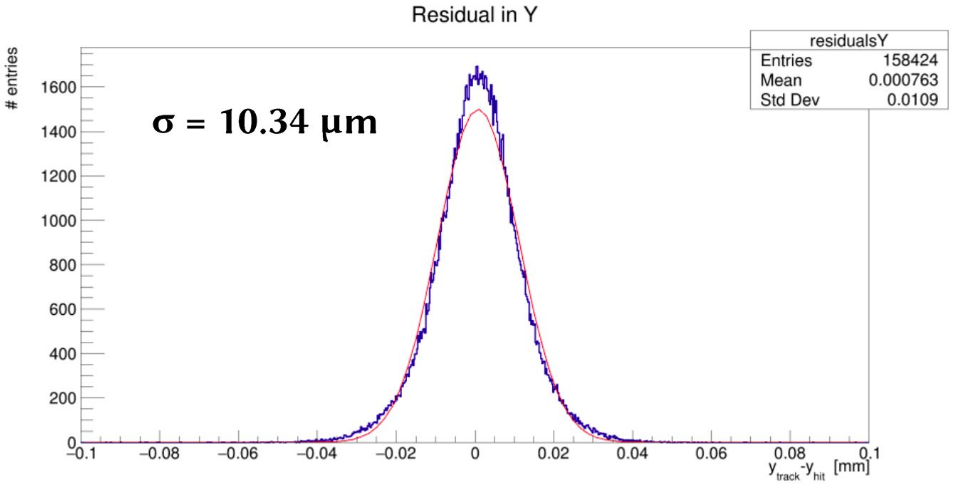




Bending ALPIDEs - part II - spatial residuals

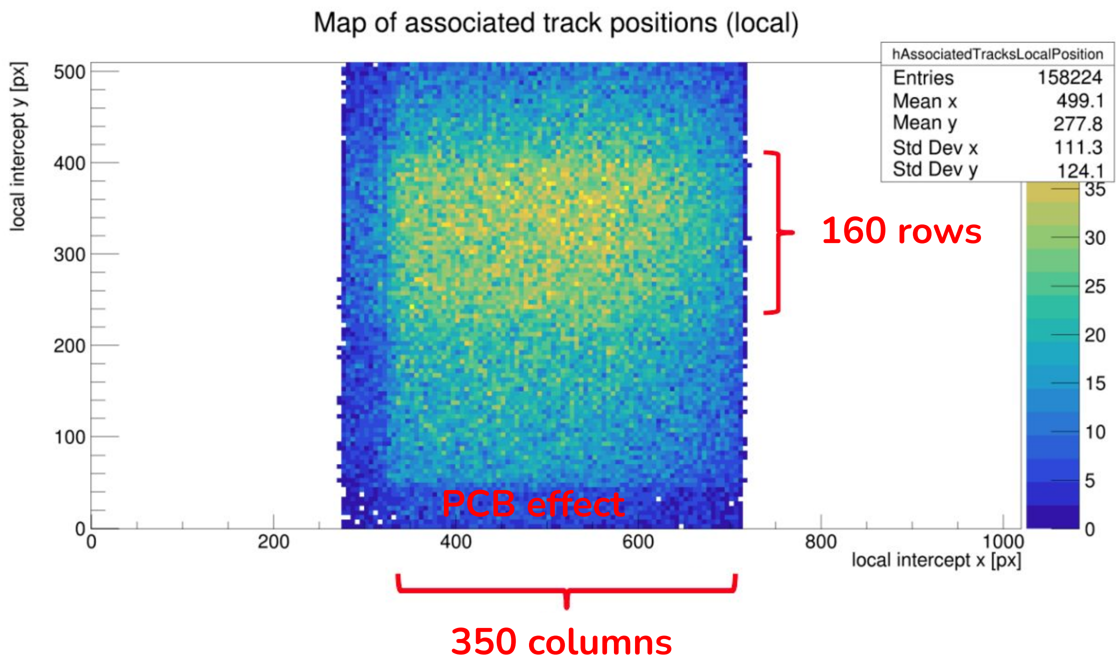
- ➢ Broad residuals
- ➢ Convolution of effects?

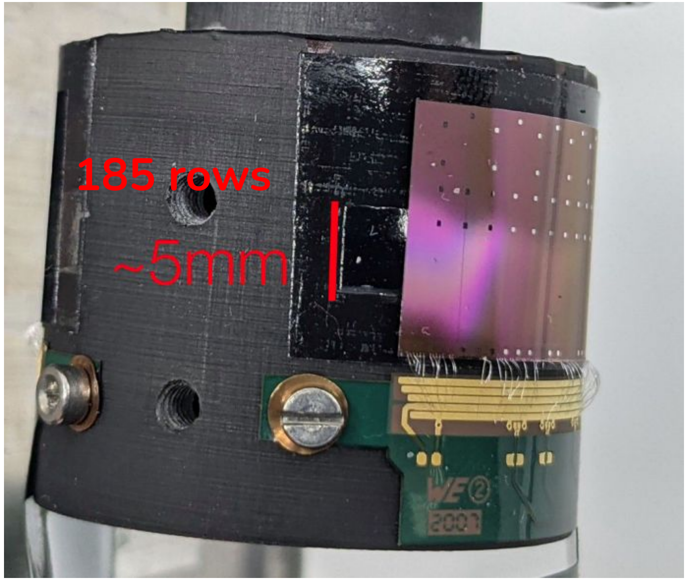




Bending ALPIDEs - part II - ROI definition

- ➢ Tracks associated to clusters on DUT
- ➢ Region of interest (ROI) selection - chose part of the sensor to characterize





Bending ALPIDEs - part II - ROI definition

- ➢ Tracks associated to clusters on DUT
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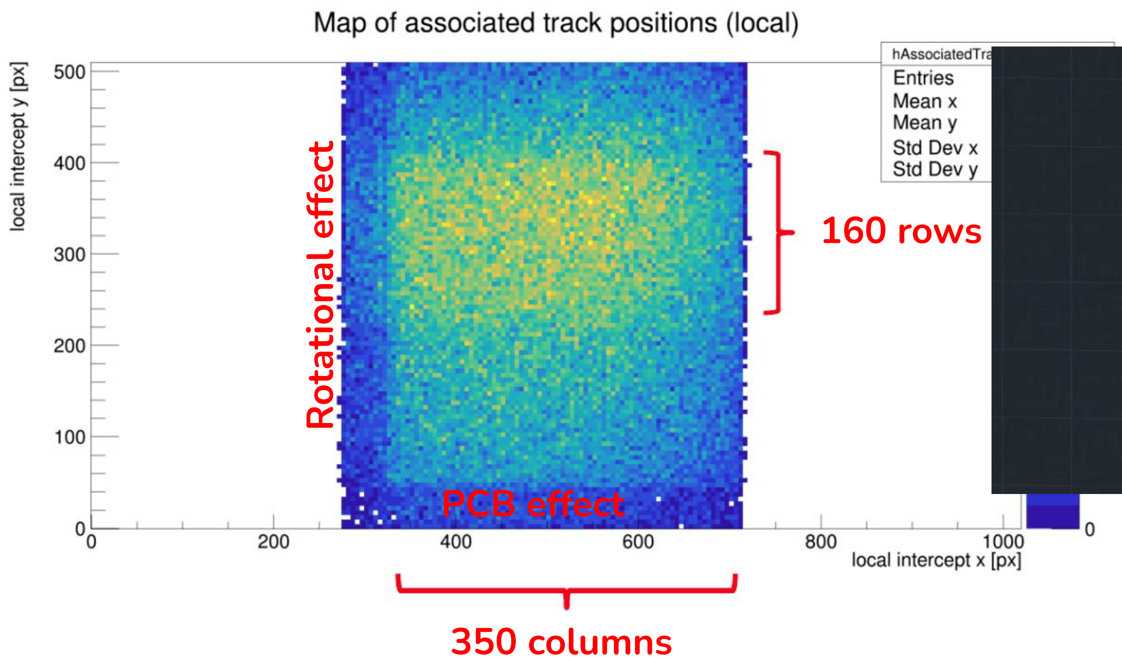
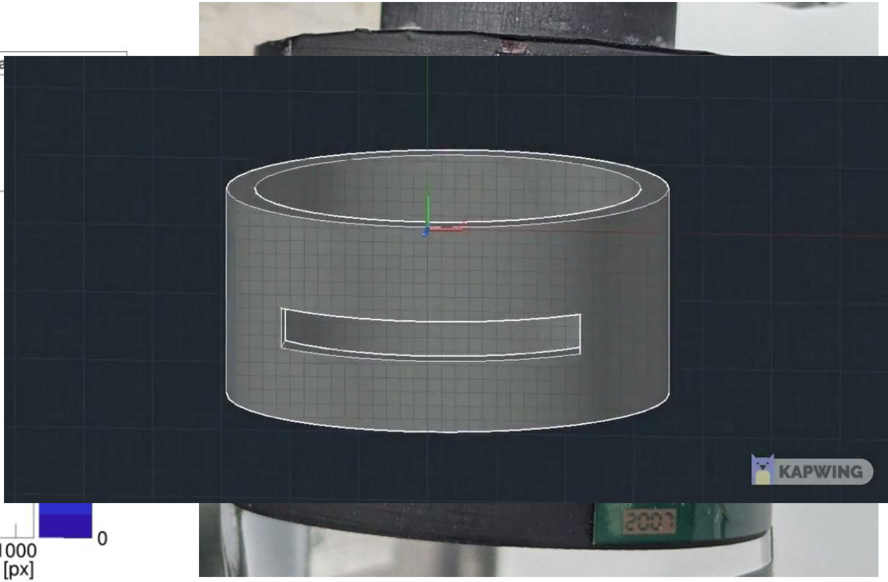
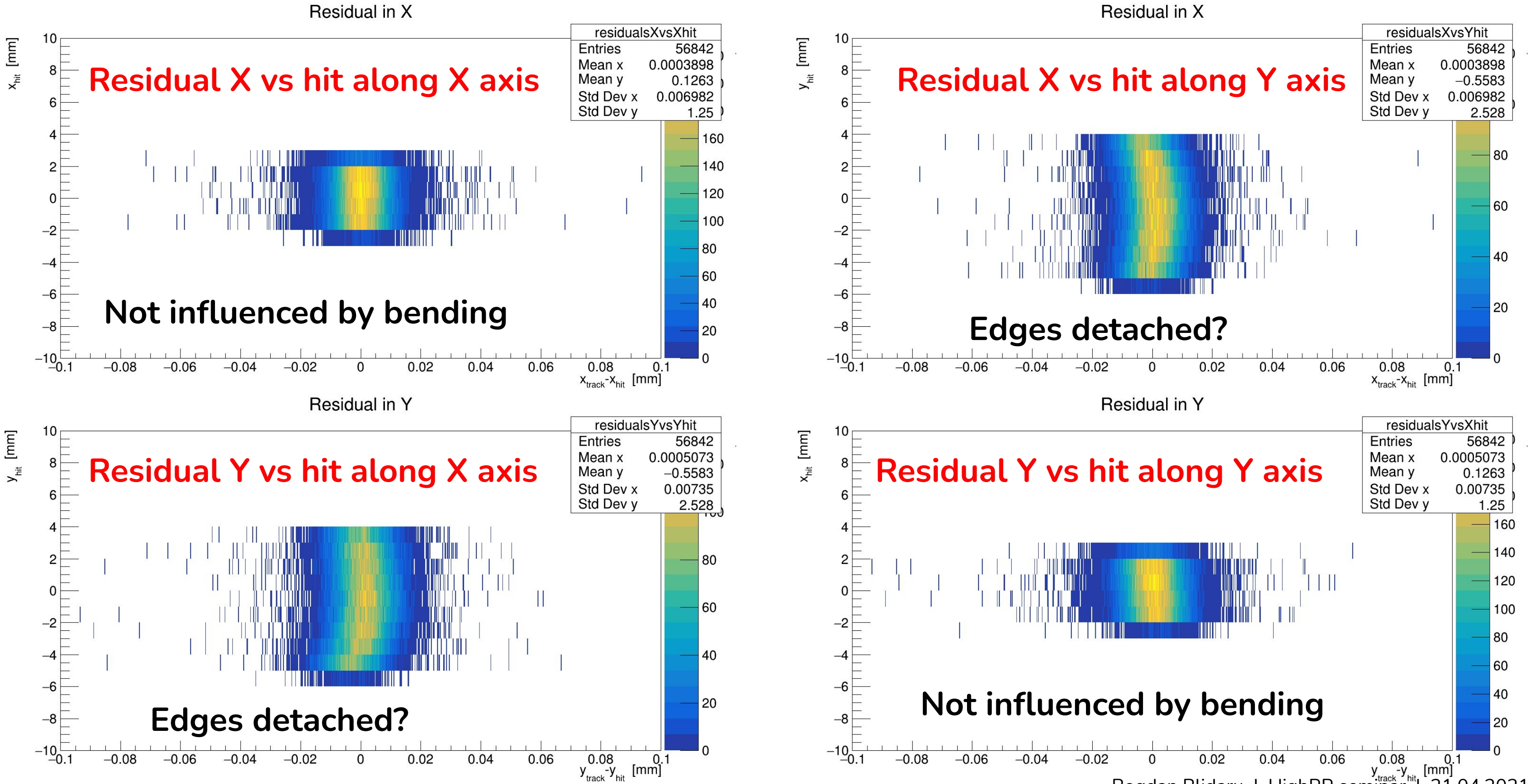


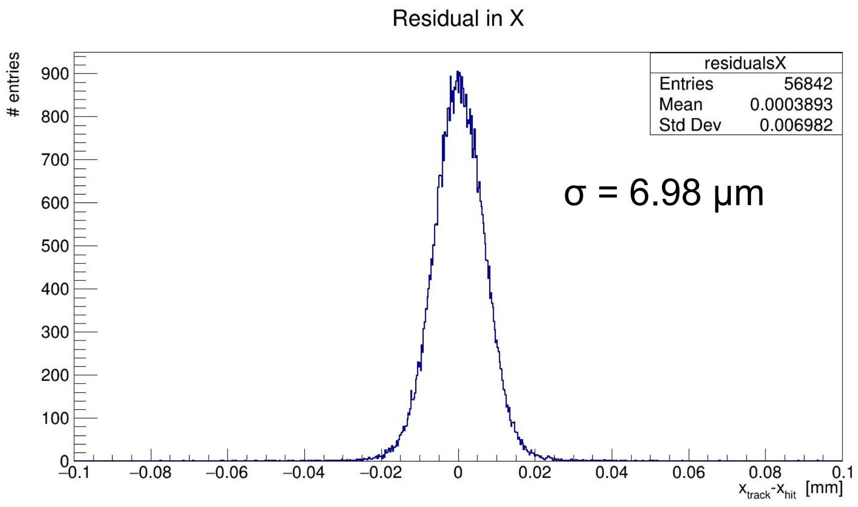


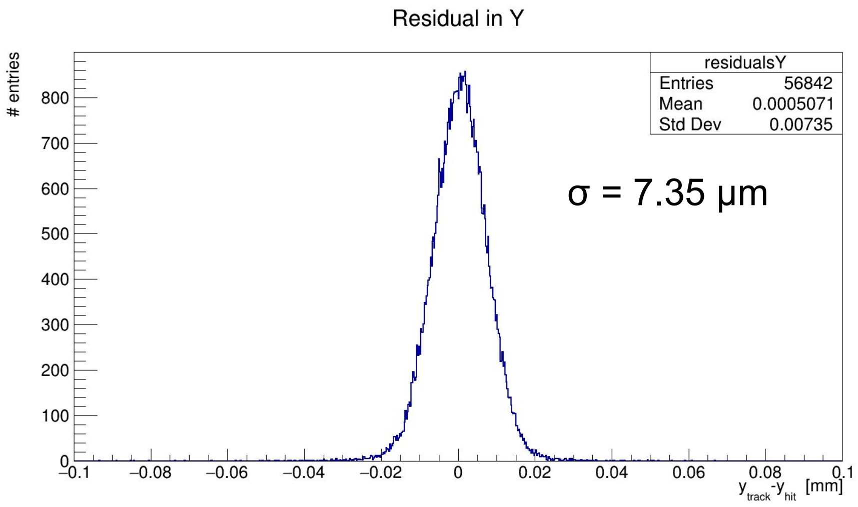
Bending ALPIDEs - part II - residuals



Bending ALPIDEs - part II - residuals

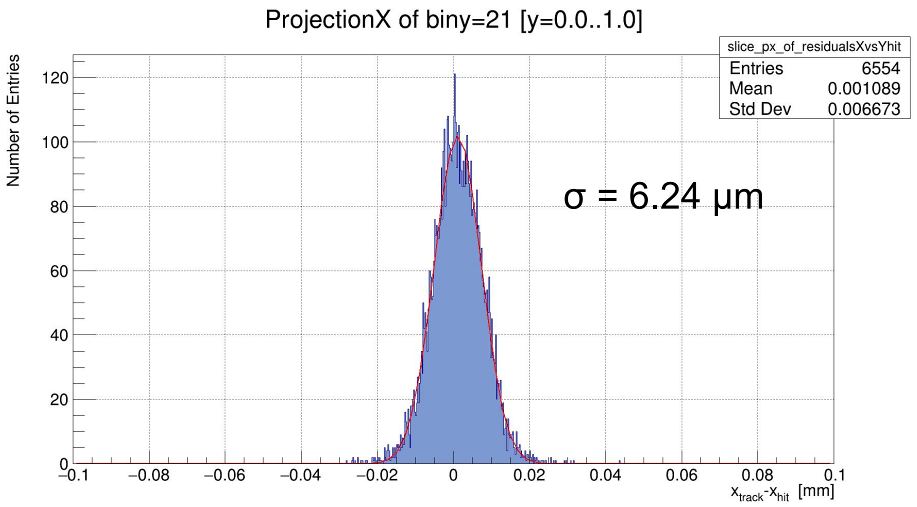
- Residuals are still a convolution of Gaussians, due to curvature effect

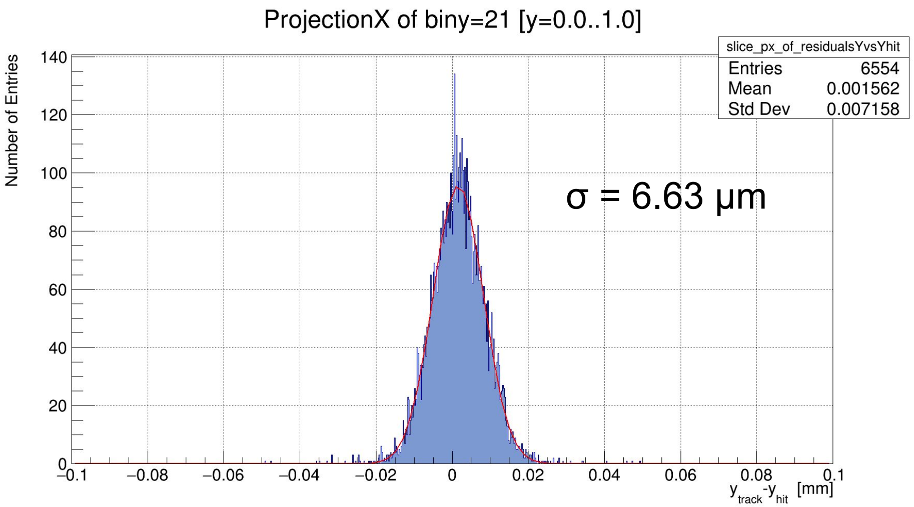




Bending ALPIDEs - part II - residuals

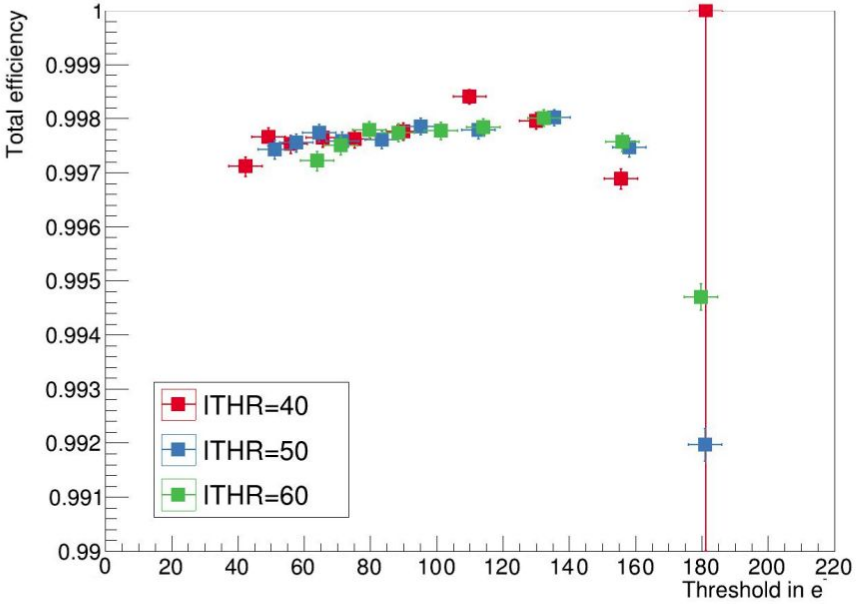
- ➢ Residuals are still a convolution of Gaussians, due to curvature effect
- ➢ A single bin, deconvoluted ~6-7 μm
- ➢ Need to subtract telescope resolution (tracking) → resolution ~5 μm

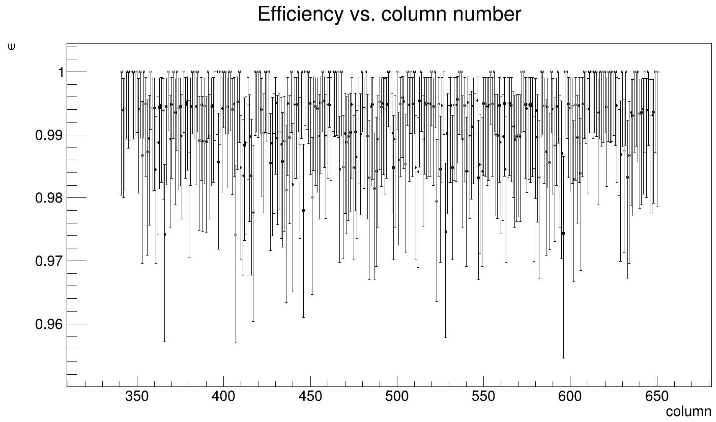


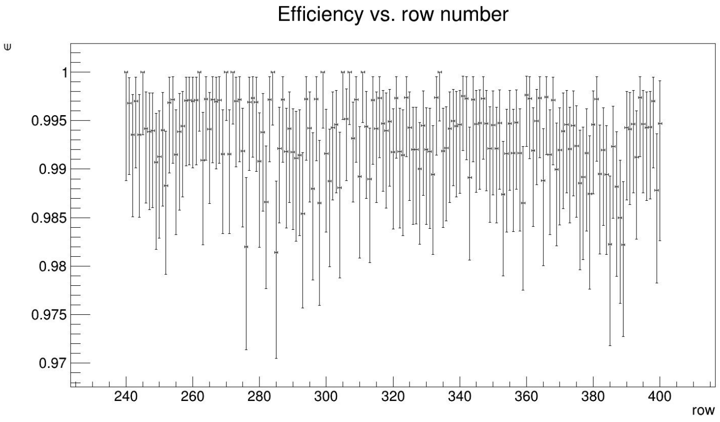


Bending ALPIDEs - part II - efficiency

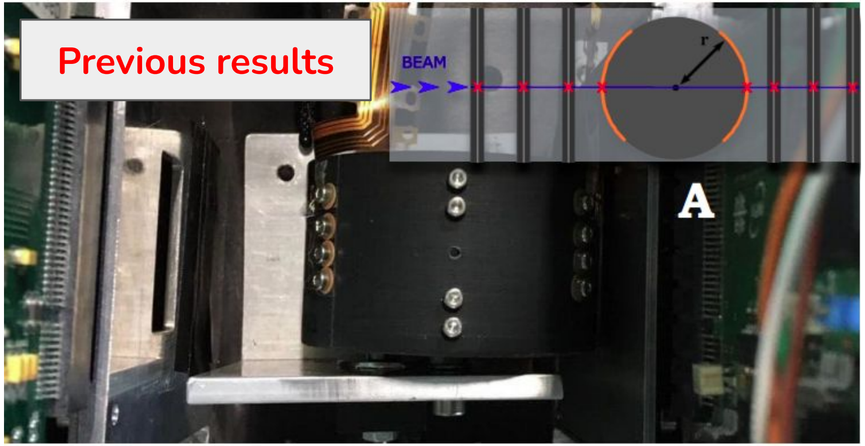
- Still highly efficient (@ 0V back bias)
- Efficiency decreases as a fc. of threshold (increasing number of inefficient pixels)

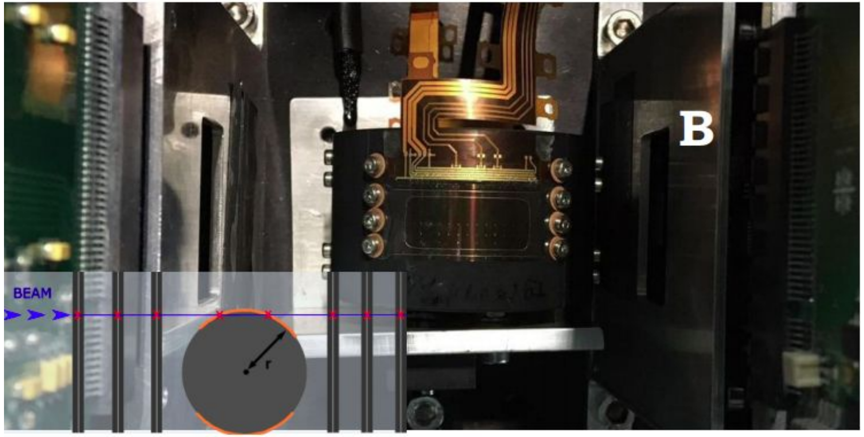






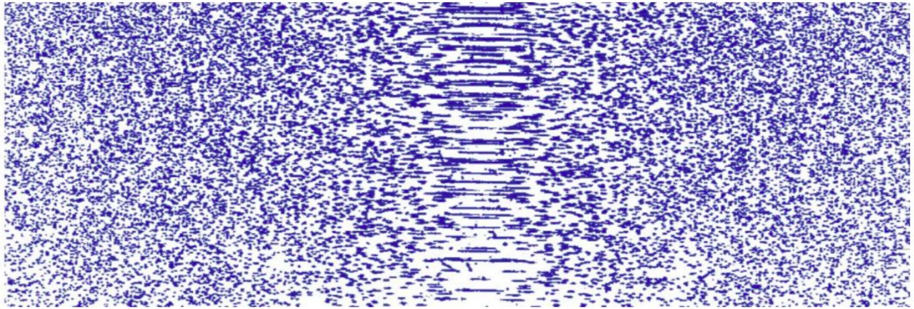
Bending ALPIDEs - part II - configurations





- More than one configuration possible
  - A - single crossing per sensor
  - B - double crossing / grazing

- Example hitmap - grazing events
- Can probe epitaxial layer



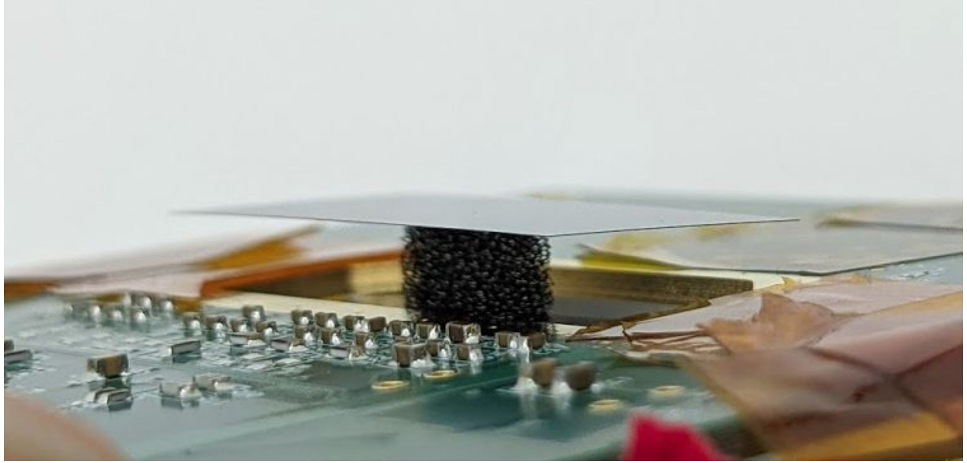
Conclusion

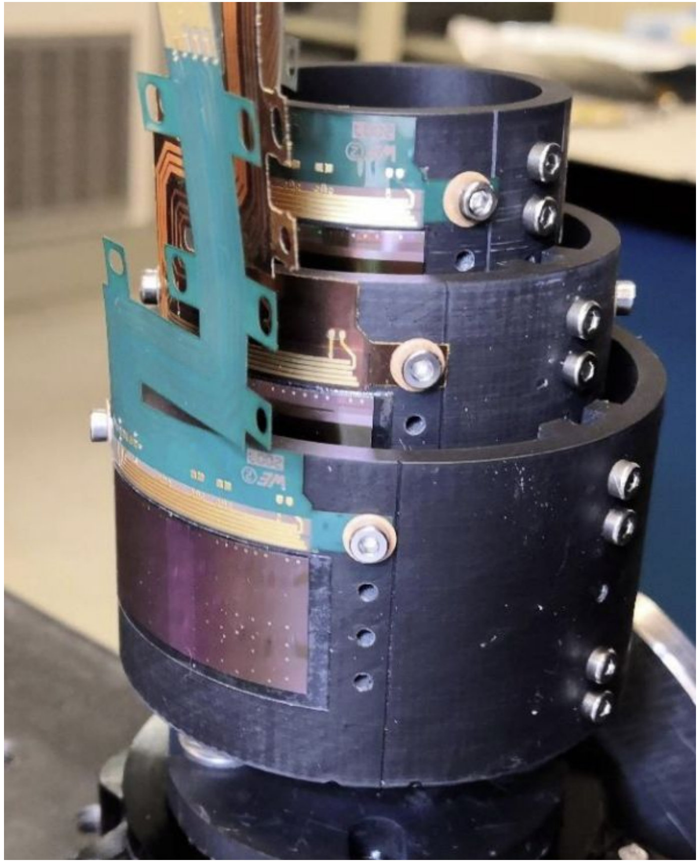
- ➢ ALICE proposes to build a next-generation Inner Tracking System in LHC LS3
- ➢ Based on 300mm wafer scale, ultra-thin bent MAPS → ITS3 will push the technology even further, approaching a massless detector

- ➢ R&D started with bending current ALPIDE sensors and testing them in beam
- ➢ Laboratory and testbeam results show **no performance deterioration** of the sensors after bending

Outlook - now!

- ➢ µITS3
  - → mimics ITS3 - same radii (18, 24, 30 mm)
  - → 4 out of 6 layers bonded, operational
- ➢ Carbon foam X_0 measurement
  - → measure scattering on foam, determine X_0





Outlook - further out

➢ MLR1 (Multi Layer Reticle 1)

→ chip submitted in 65 nm technology node

→ back end of May, then testing starts

➢ Super ALPIDE

→ 18 ALPIDE dies/ superchip

→ not stitched, but interconnected