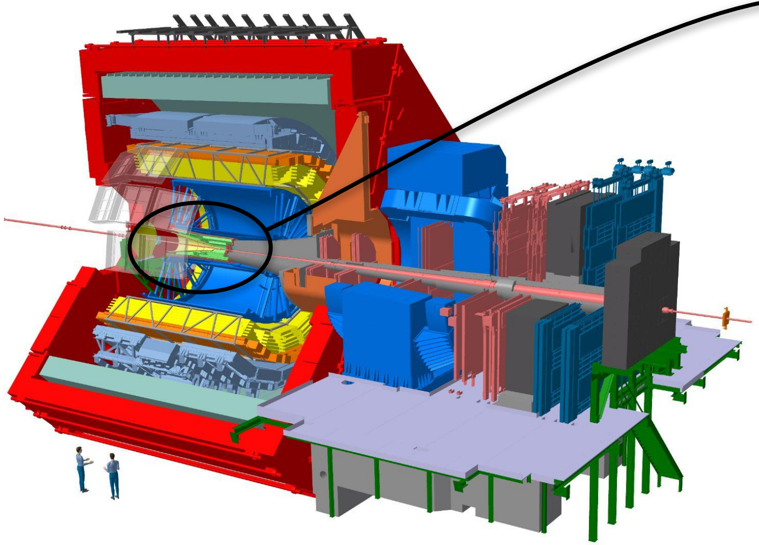
BTTB11, 17-21 April 2023

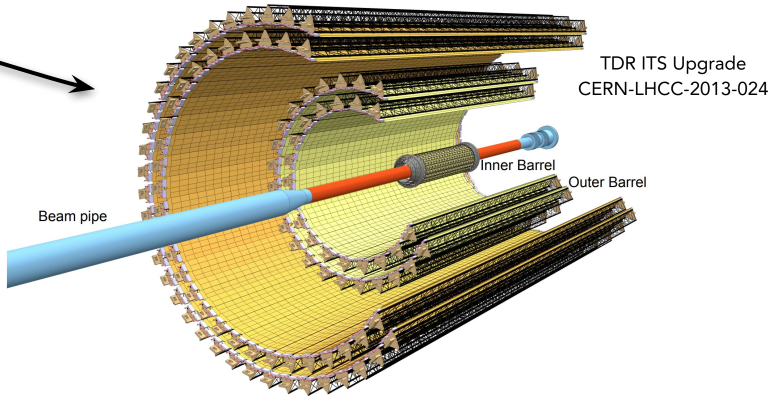
Implementation of bent pixel sensors analysis in the Corryvreckan framework

Bogdan Mihail Blidaru
on behalf of the ALICE collaboration

20.04.2023

ALICE detector





- ALICE is **the** heavy-ion physics focussed experiment at the LHC
- Main goal: study of the quark-gluon plasma in heavy-ion collisions
- Need **high resolution vertexing** and **low momentum tracking** in a **high multiplicity environment**
  → must update tracker

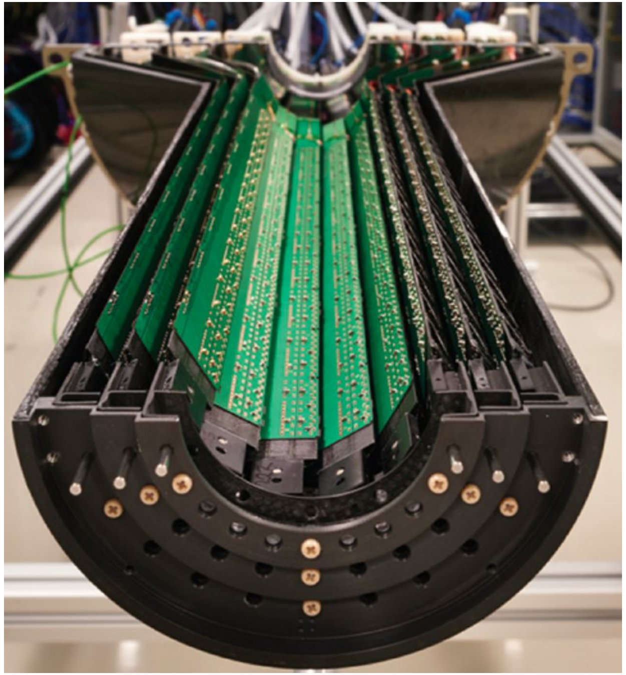
ITS2: a **full CMOS MAPS detector**

- installed during LHC Long Shutdown 2 (2021)
- 10 m^2 active silicon area, 12.5 Gpx
- 7 layers of **ALPIDE** sensors (3 inner + 4 outer)
- low material budget: **0.36% X_0/layer** (innermost layer)
- sensors with high detection efficiency: **≫ 99%**
- good intrinsic position resolution: **~5 µm**

ALICE - The Inner Tracking System

ITS2 inner barrel (3 layers)

- 9 ALPIDE sensors / layer



ALICE - The Inner Tracking System upgrade(s)

ITS3 upgrade
➠ LHC LS3 (2026-2028)
- replaces the 3 inner layers of the ITS2
- ultra light, wafer scale, curved sensors in 65nm

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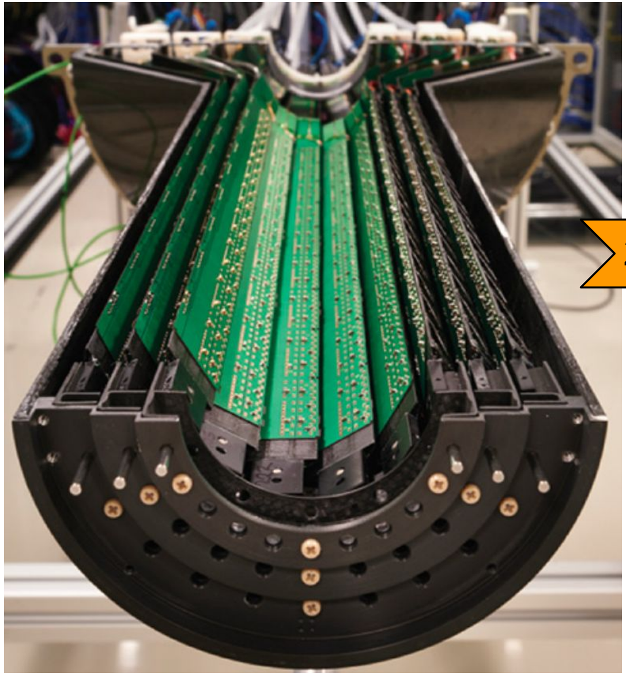
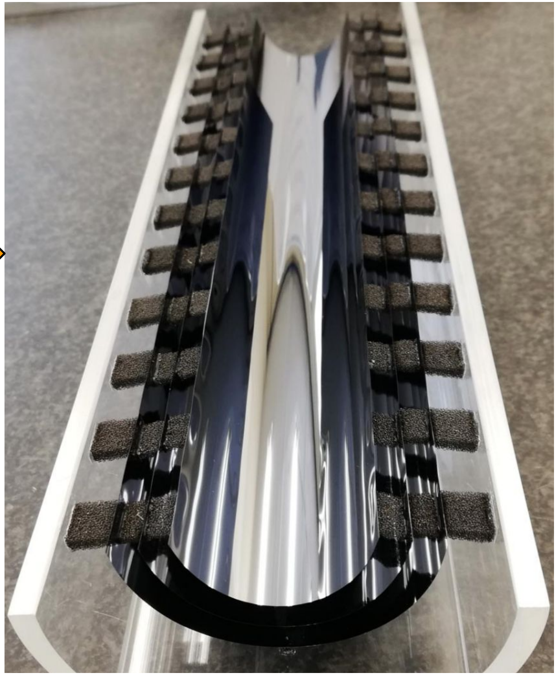


2028

ITS3
- 0.36% → 0.05% X0/layer (Si-only)



First prototype integration with dummy silicon

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Selected R&D topics
‣ 65 nm testing & qualification
G. Alocco ➠ talk on Thu
‣ wafer scale sensors
‣ bending of sensors

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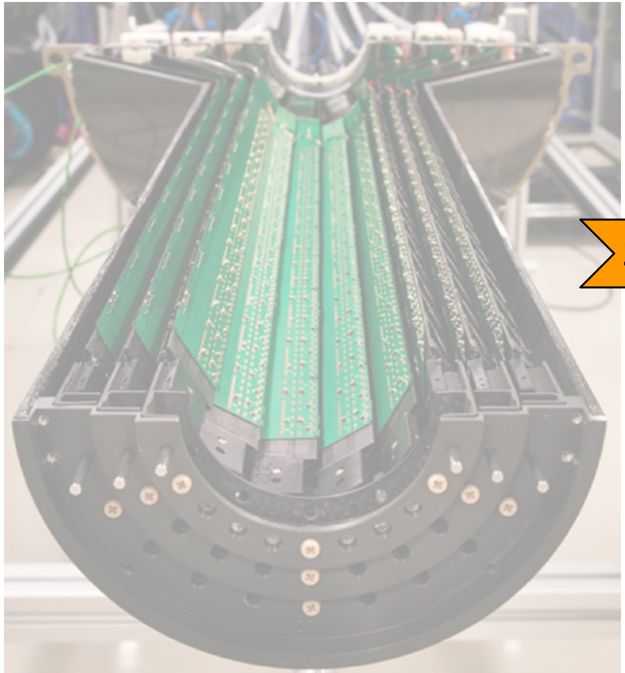

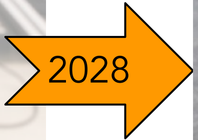

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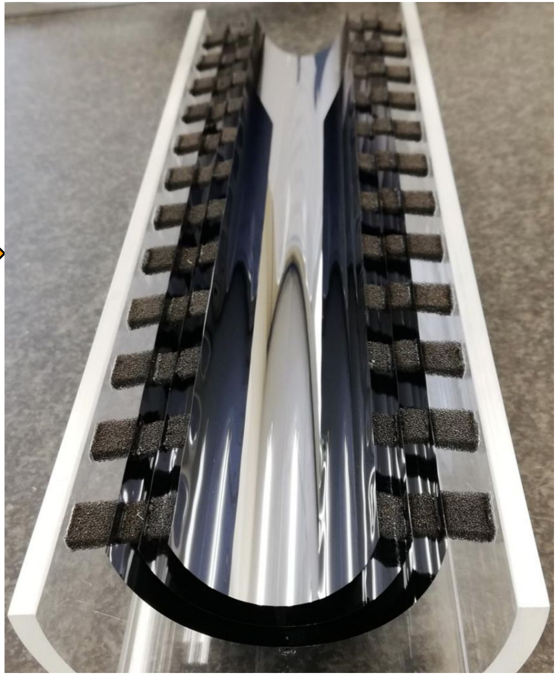

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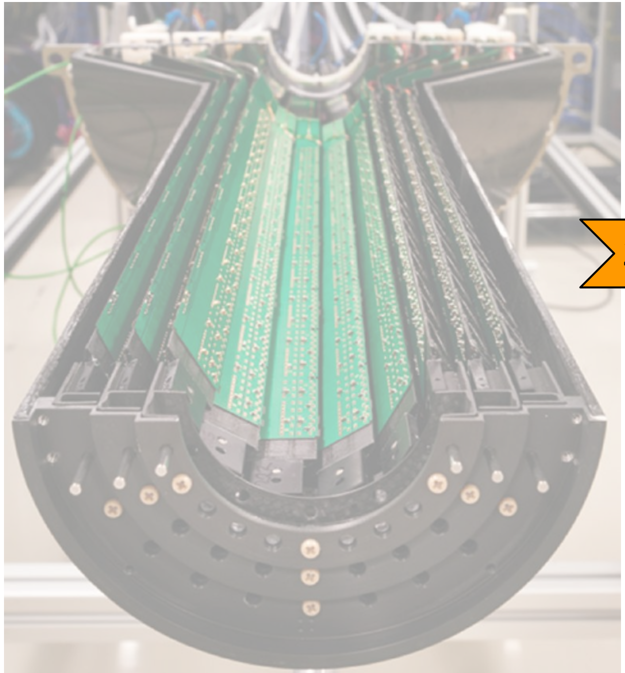

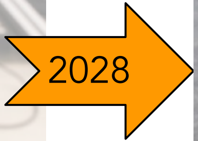

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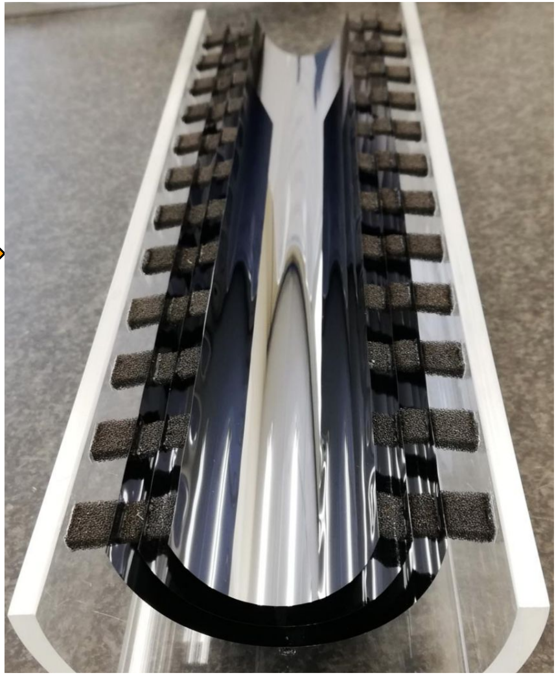
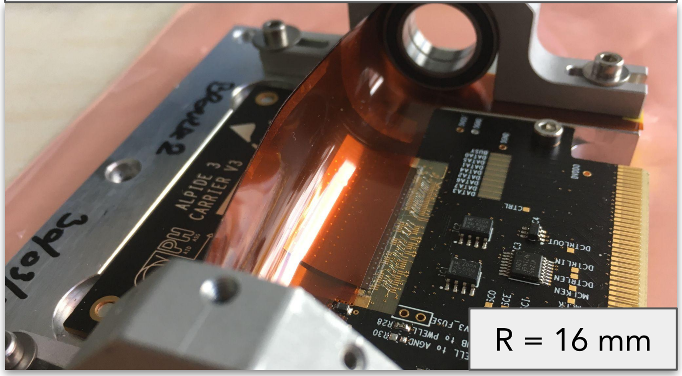


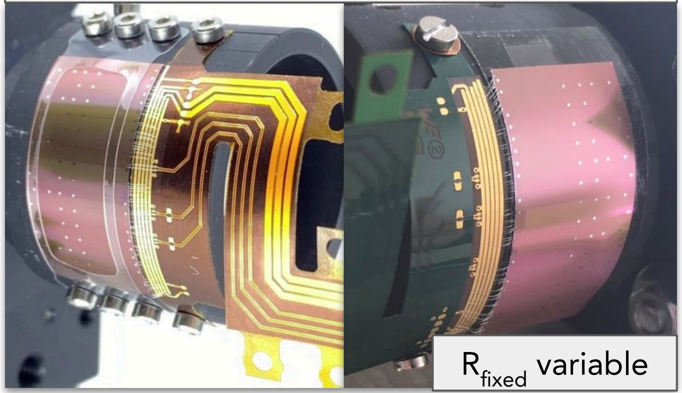
First prototype integration with dummy silicon

Bending ALPIDEs

Along the short edge, compressed circuitry



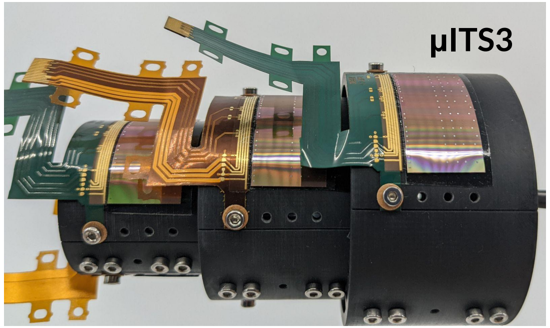
Along the long edge, stretched circuitry



Bending of ALPIDE sensors

- ➠ Functional chips bent routinely
- ➠ Electrical operation consistent (wrt flat state)
  - threshold, noise, dead pixels **unaffected**
- ➠ Setups that mimic the **radii** of the **future ITS3** (18, 24, 30 mm)
  - proven to function effectively
  - efficiency, position resolution, stability unchanged

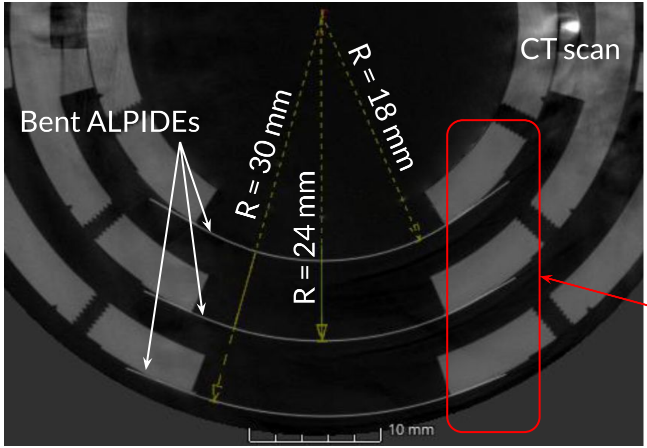
Bent MAPS working well! Performance unchanged!



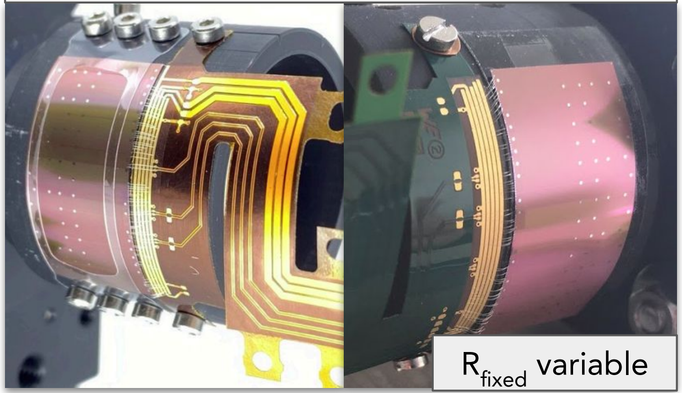
opening in the jig behind the sensor for beam tests (no material)

More details:
10.1016/j.nima.2021.166280

Radius control



Along the long edge, stretched circuitry



Issues observed with bending

➠ with first prototype, sagging (Si relaxation) was observed

- $R_{initial}$ = 16mm → R_{data} = 22 mm → R_{final} = 26mm

➠ consequent versions built on 3D-printed jigs

- v1: sensor glued with tape → can detach
- v2: kapton sleeve keeps the sensor on the jig

Radius control

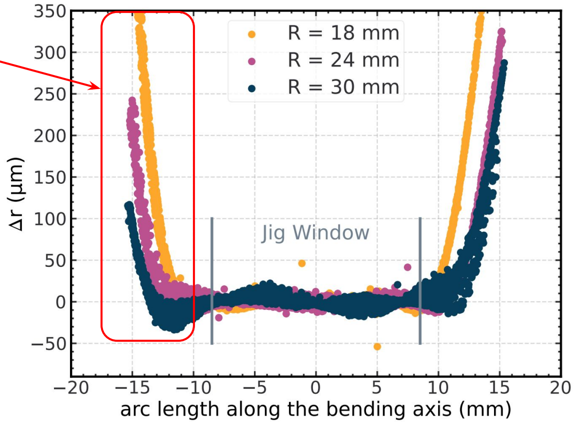
➠ CT and 3D profilometer scans of sensors to assess possible deviations

➠ Good radius control

- inside the jig window

at most 30 μm deviation from R_{fixed}

3D profilometer scan

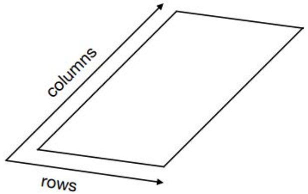


Software analysis

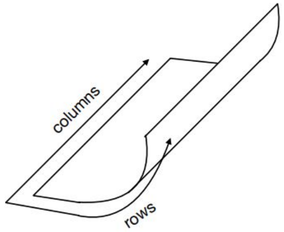
Bent sensors in code

- ➠ Corryvreckan framework used for testbeam data analysis
- ➠ New class **`BentPixelDetector`** defined
  - ‣ new coordinate system: **`cartesian-bent`**
  - ‣ possibility to bend along rows or columns
  - ‣ **`Local`** to **`Global`** and **`Global`** to **`Local`** transformations redefined to account for bending
  - ‣ fixed **`radius`** of a perfect cylinder
  - ‣ rotation of sensor around the center
  - ‣ **`radius`** sign controls the orientation wrt beam axis

The Maelstrom for Your Test Beam Data

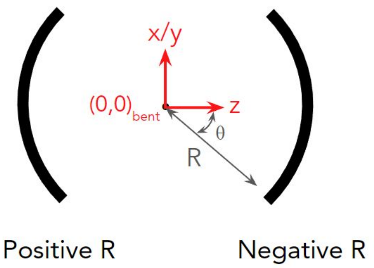


Flat sensor

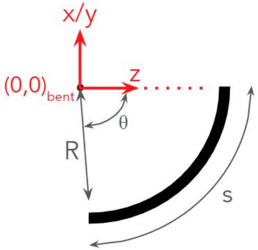


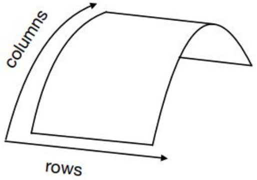
Bent along the rows

Bending along rows/columns



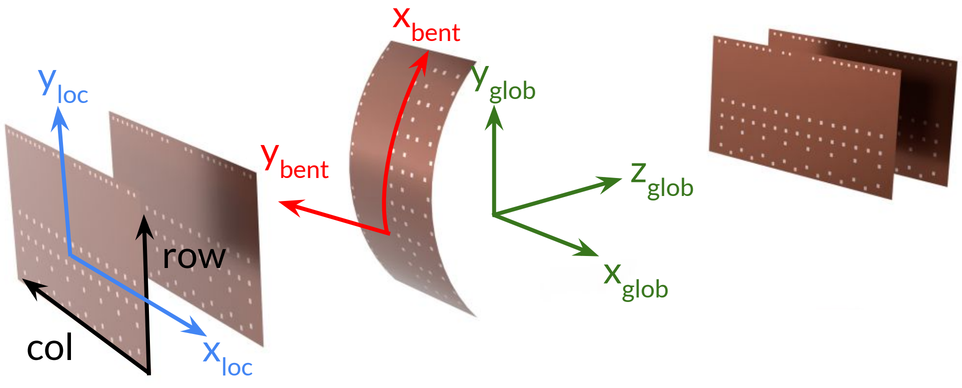
Rotated sensor (by θ/2)

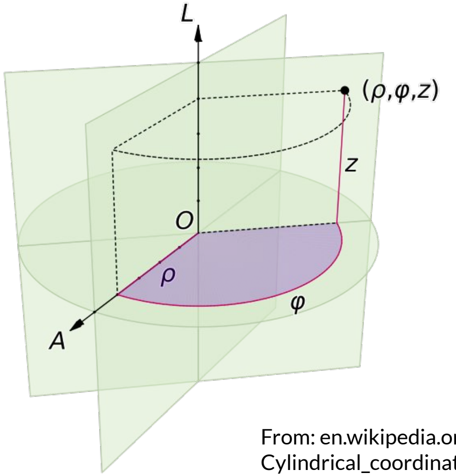




Bent along the columns

Coordinate system changes





From: en.wikipedia.org/wiki/
Cylindrical_coordinate_system

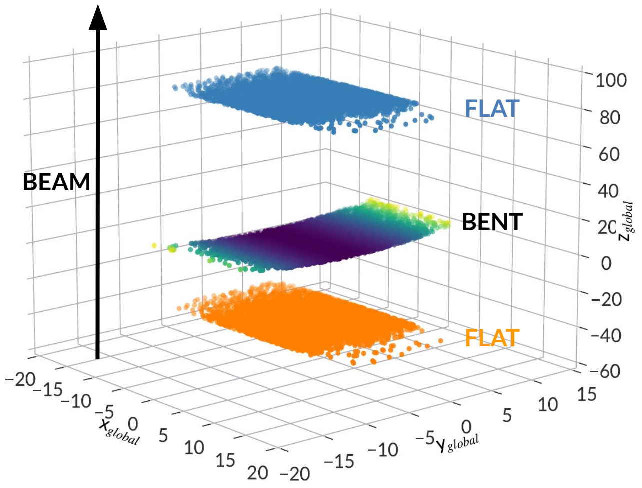
➠ Local position defined as a `ROOT::Math::RhoZPhiVector`

- fixed radius (input from the user)
- one direction (column/row) is bent, the other one is not sensitive to bending effects (along z in cylindrical coordinates)
- only one bending direction is possible in the code

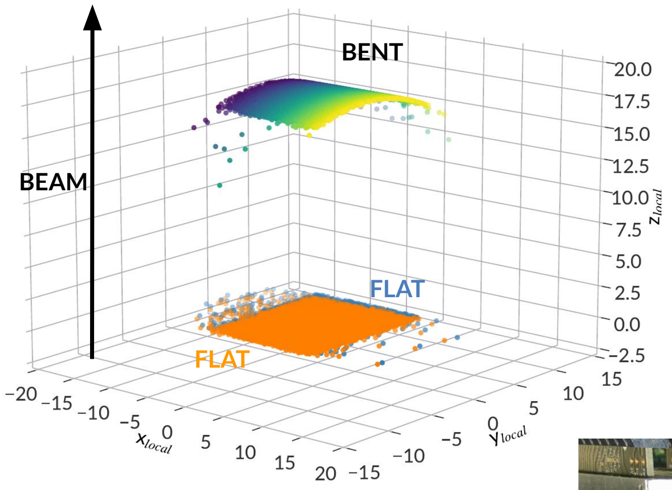
Local vs global coordinates

ALICE

Clusters in global coordinates



Clusters in local coordinates



Local coordinate system

- ➠ Flat sensors fixed at `z=0`
- ➠ Bent sensor has cylinder center at `z=0`

Global coordinate system

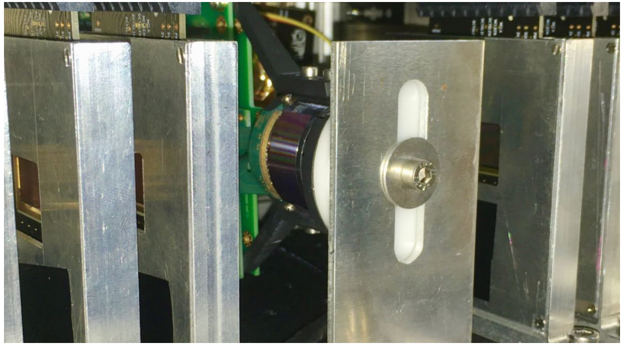
- ➠ Flat sensors have the z position from the geometry file (measured)

```
bent_axis   = "column"
coordinates = "cartesian-bent"
position    = 0mm,0mm,18mm
orientation = 0deg,90deg,0deg
radius      = 18mm
```

This example

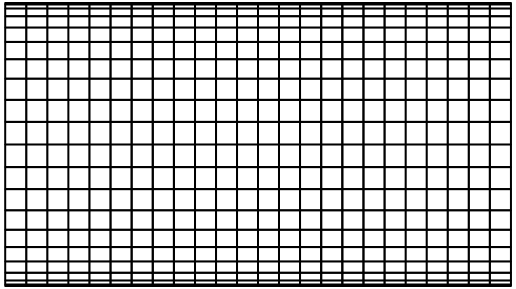
- ➠ Bent sensor with R=18 mm
- ➠ Facing the beam
- ➠ Rotated by 90°

(motivated by mechanics)

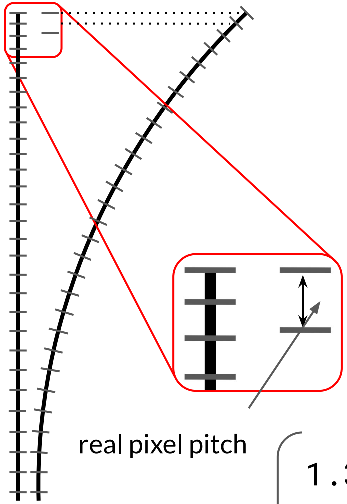


NB: sensors are aligned

Coordinate system changes



Pixel matrix as seen by an incoming track



➠ **Interplay of resolution** along bent direction and z direction

- as one grows, the other shrinks

➠ Global error matrix used for straight line fit

- must take z correctly into account

➠ Small uncertainty if clusters close to $z_{global}=0$, and increasing up to $resolution^2$ for the most bent part

$$\begin{pmatrix} \sigma_x^2 & & 0 \\ & \sigma_y^2 & \\ 0 & & \sigma_z^2 \end{pmatrix}$$

For 5 μm resolution of the sensors:

$$\begin{pmatrix} 1.3e\text{-}5 & 0 & 0 \\ 0 & 2.5e\text{-}5 & 0 \\ 0 & 0 & 1.1e\text{-}5 \end{pmatrix}$$

Example of global spatial resolution error matrix for a hit near the most bent part

- if hit is at a large angle, the uncertainty in z is comparable with the one in x

$$\begin{pmatrix} 2.3e\text{-}5 & 0 & 0 \\ 0 & 2.5e\text{-}5 & 0 \\ 0 & 0 & 4.9e\text{-}7 \end{pmatrix}$$

Example of global spatial resolution error matrix for a somewhat central hit (flat-like sensor error matrix)

- if hit is perpendicular on surface, there is almost no uncertainty in z

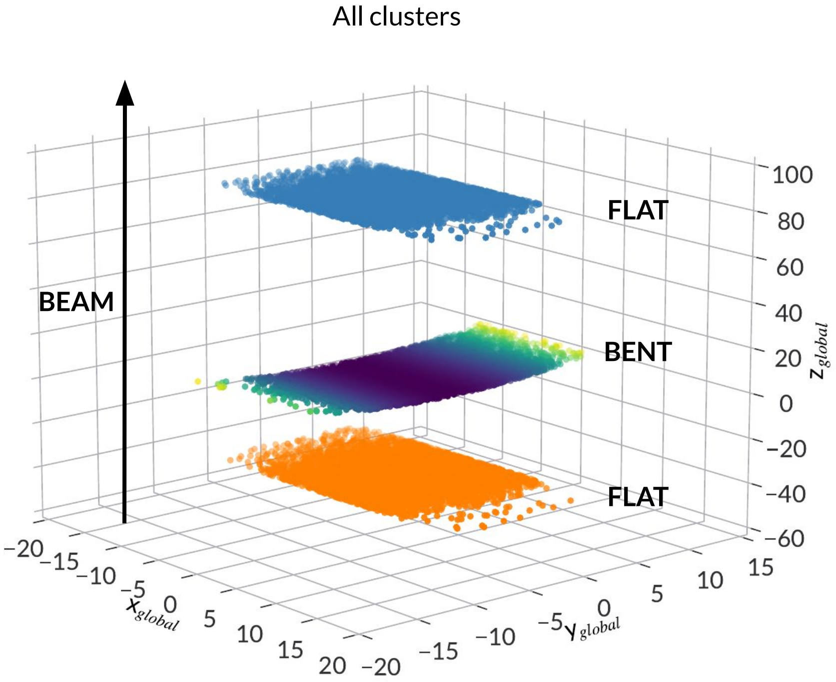
Bent sensors in code

➠ **Intersection** of tracks with the sensor happens at a **different z** position

➠ Non-zero residuals along z

➠ The incoming track sees "*contracted*" pixels where the sensor is bent

Clustering



NB: sensors are aligned

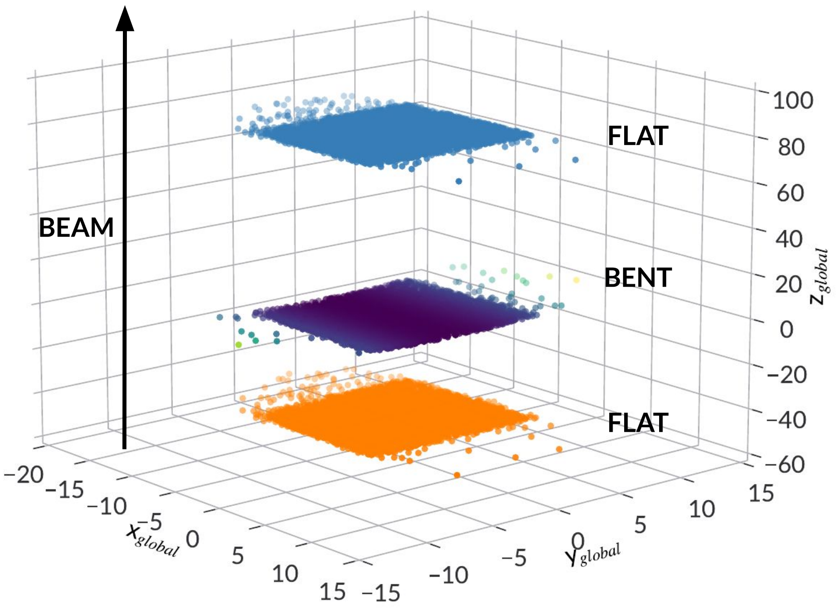
How does this actually look

➠ Plotting all clusters on all planes

- ‣ trigger given by scintillator coincidence (area > sensor surface)

Clustering

One cluster per plane per event



NB: sensors are aligned

How does this actually look

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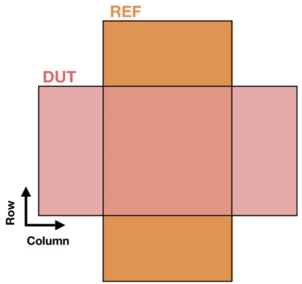
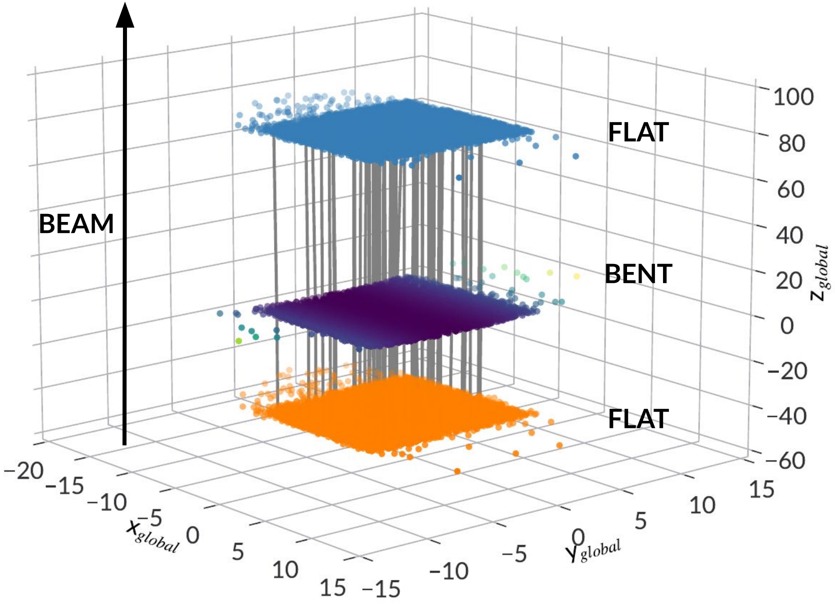
➠ Since bent sensor is 90° rotated wrt flat sensors, fiducial area is a square



Tracking

All cluster combinations from the different planes (only 50 shown)



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How does this actually look

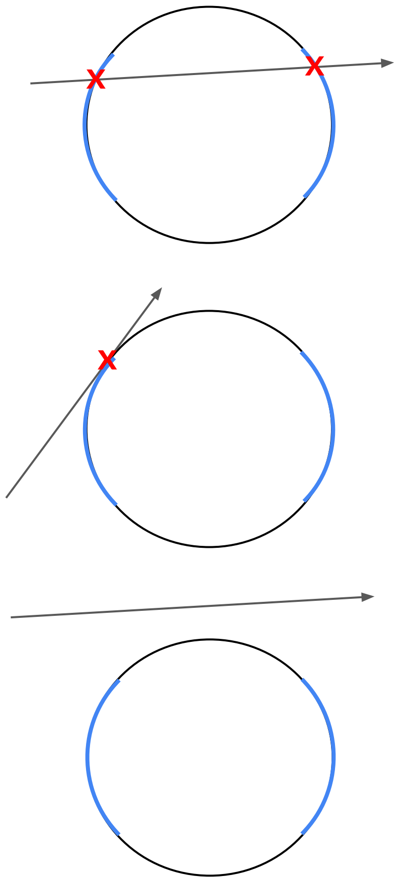
➠ Plotting all clusters on all planes

‣ trigger given by scintillator coincidence (area > sensor surface)

➠ Since bent sensor is 90° rotated wrt flat sensors, fiducial area is a square

➠ Tracking done with straight-line fit → line intersection with a cylinder:

Intersection of tracks with sensors

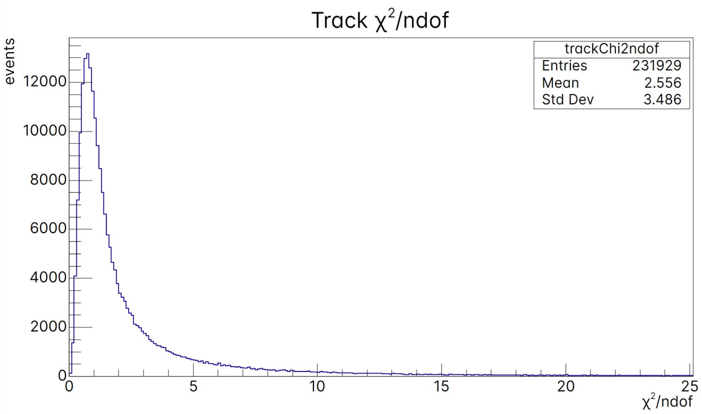


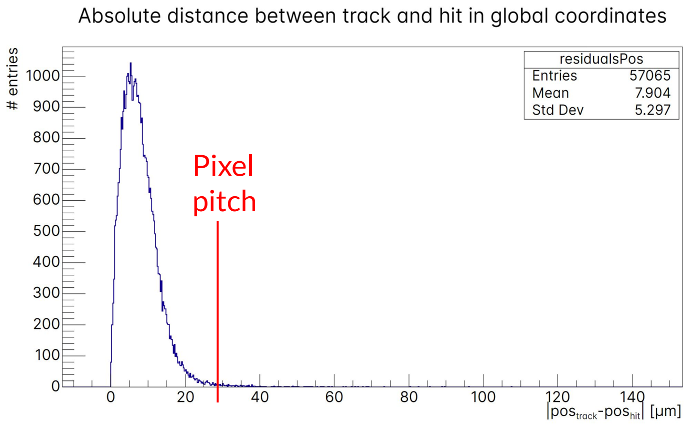
Line intersection with a cylinder

- ➠ two intersection points
  - ▸select the one according to how the sensor is bent (positive R vs negative R)
  - ▸not considering cases with grazing angle geometry
- ➠ one intersection point
  - ▸tangent on the surface
- ➠ no intersection points

- ➠ further checks for finite sensor length
  - ▸if sensors have limited extent and intercepts are found outside, throw an error
  - ▸not yet implemented

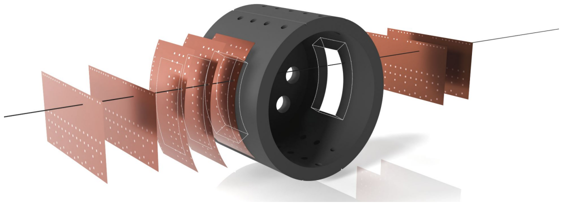
A few checks





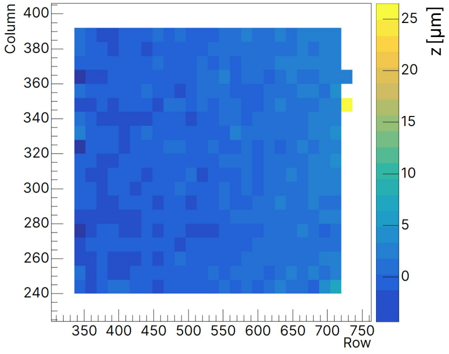
Control plots

- ➠ **Good alignment** (straight tracks)
- ➠ Distance between track intercept and hit position is **less than a pixel pitch**
- ➠ Residual mean is **uniform** and less than 10 μm over the surface
- ➠ Detachment of the sensor is remarked as increased values of the residual mean

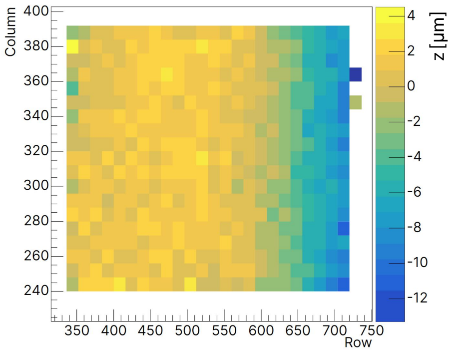


NB: 5.4 GeV e^- (DESY)

Residuals mean in the non-bent direction (y)



Residuals mean in the bent direction (x)



Merging with Corryvreckan code

Until now

➠ Merge request submitted to Corryvreckan master

➠ Work ongoing (thanks Lennart!)

So far implemented

➠ Coordinate transformations

➠ Resolution in z and correct covariance matrix of spatial resolution

➠ Straight-line tracking and track intercept with the bent sensor

Work in progress

➠ General Broken Line (GBL) fit

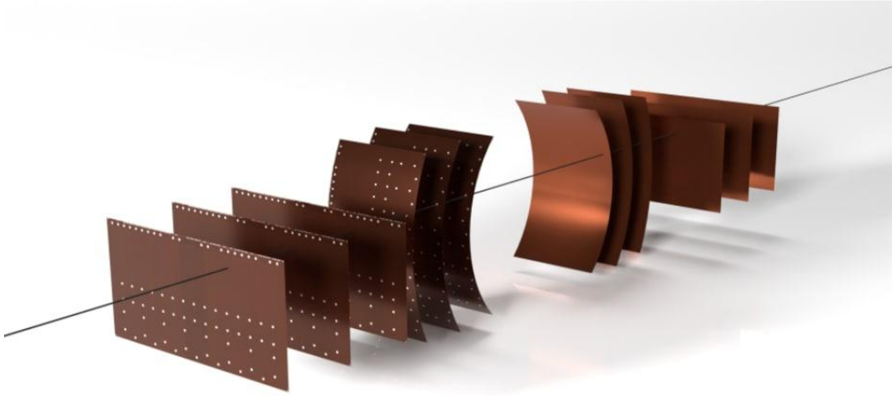
- calculation of the Jacobian between planes
  assumes planar detector at position z

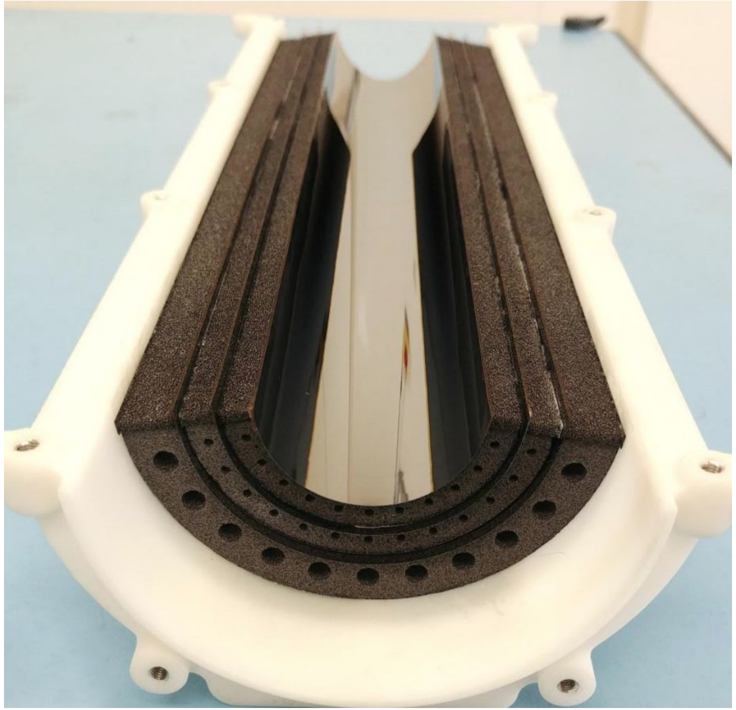
➠ Understand how degrees of freedom affect the alignment

Conclusion and outlook

➠ In the near future, bent sensors will be available in Corryvreckan
➠ Currently working on the merge request; few more checks needed

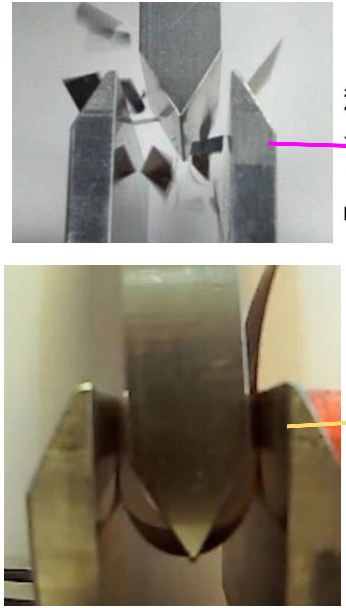
➠ Work ongoing on tracking with GBL and alignment validation
➠ Input and suggestions are appreciated!

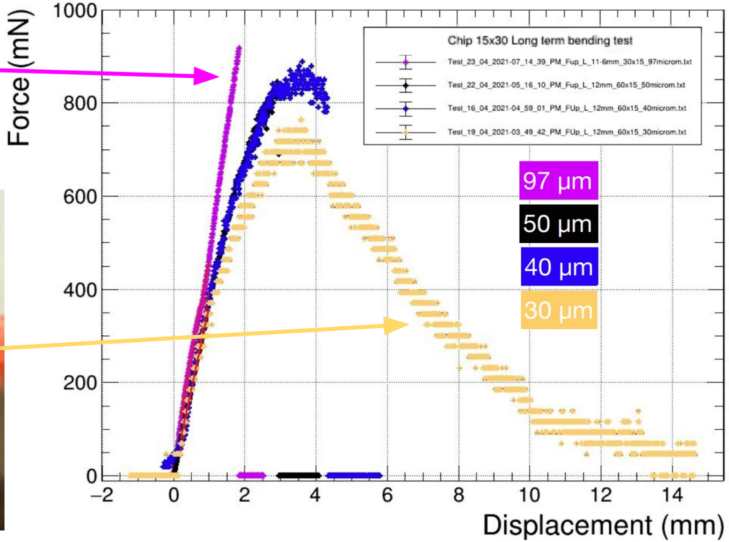


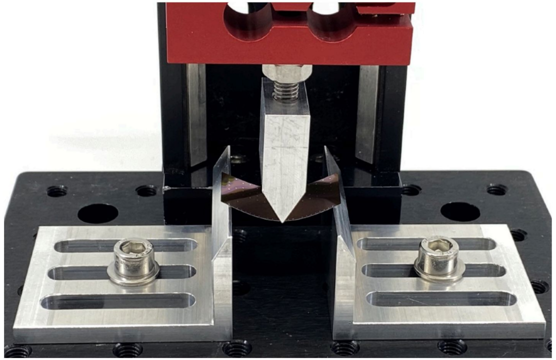


Backup

Bending tests

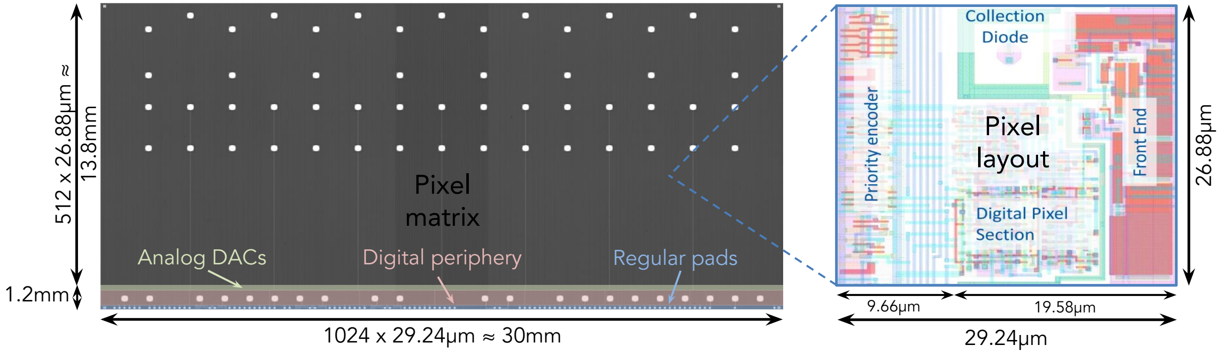


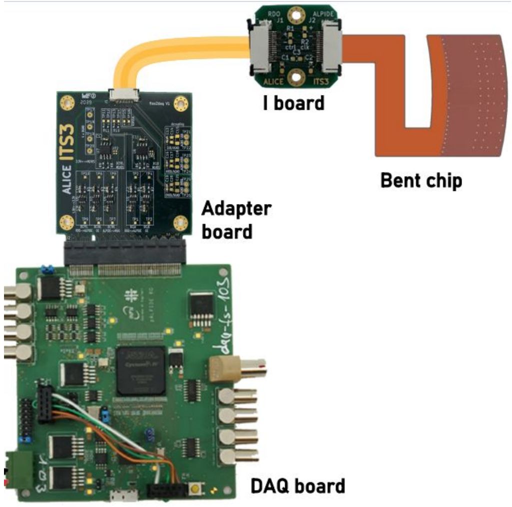




- ALPIDEs are in the right order of thickness: 50/100 µm vs 20-30 µm (ITS3)
- Thinner is better: silicon behaves like paper
- ITS3 target radii: 18, 24, 30 mm

ALPIDE





Design

- TowerJazz 180 nm CMOS Imaging Process
- High resistivity (>1 kΩcm) p-type epitaxial layer (25 µm)
- Small NWELL diode (2 µm) diameter (pixel: 29×27 µm^2)

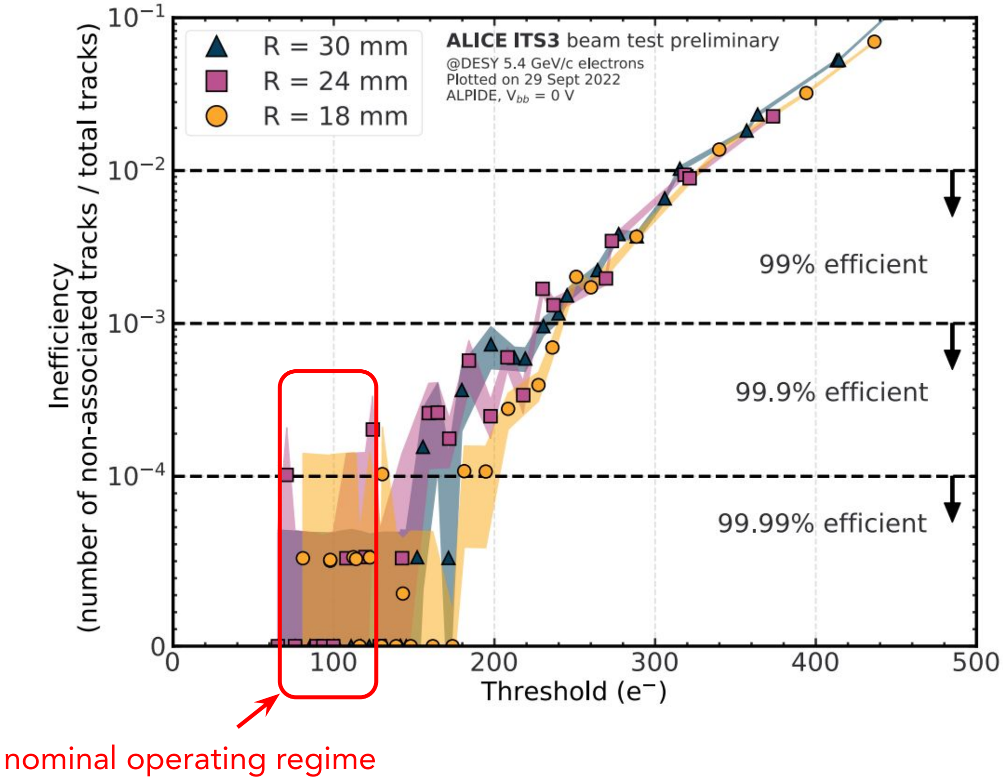
→ low capacitance (~fF) → low noise

- Reverse bias (up to -6V) used to increase depletion

Specifications

- 0.5 Mpx sensor
- 50 / 100 µm thick (IB/OB)
- >99.9% efficient
- ≪ 10^{-6} fake hits/ px/ event
- ~5 µm position resolution

Performance of bent ALPIDEs



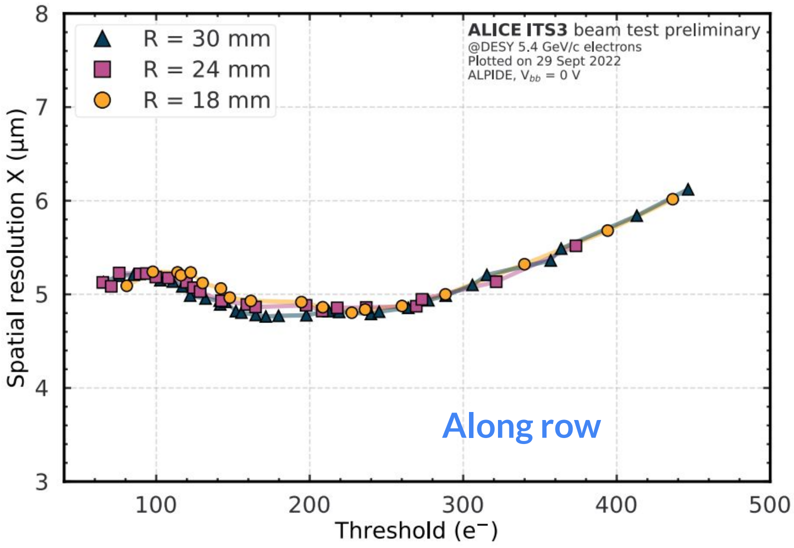
➠ No effects on the bending radius

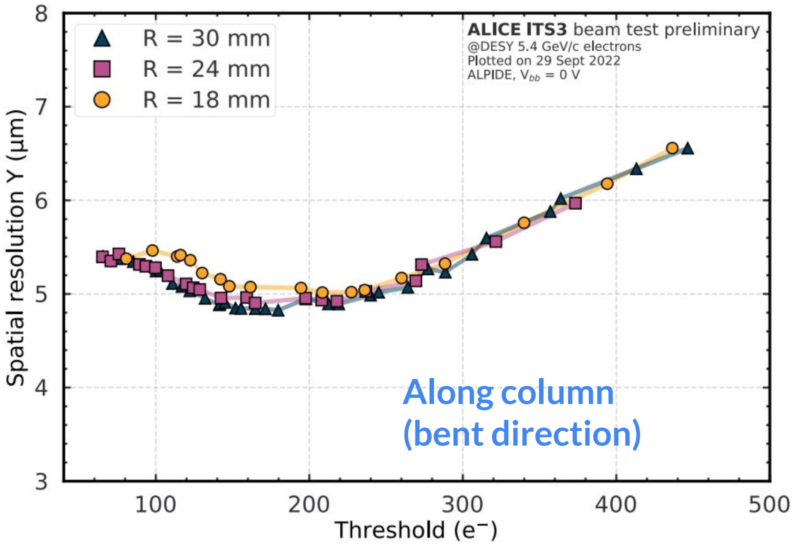
➠ Efficiency > 99% for nominal operating regime

➠ Compatible with flat ALPIDE

➠ Consistent with published results where the other bending direction was investigated

Performance of bent ALPIDEs

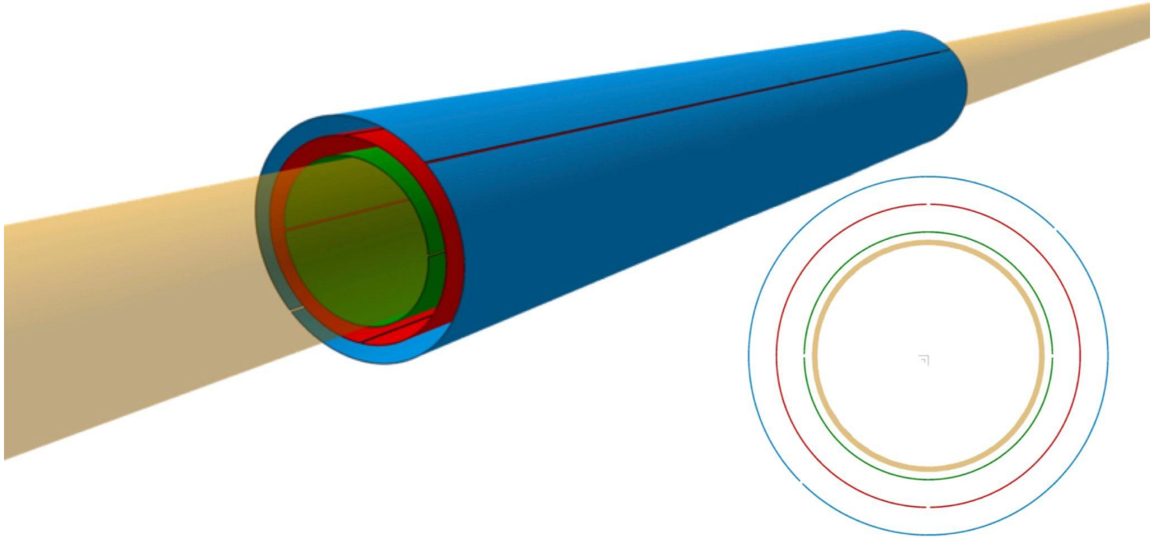




➠ No effects on the bending radius

➠ Spatial resolution consistent with ALPIDEs in flat state (~5 µm)

ITS3 details



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/layer (beampipe: 500 μm Be 0.14% X_0)
- Uniformly distributed material (no systematic errors)

➠ Wafer scale ← stitching

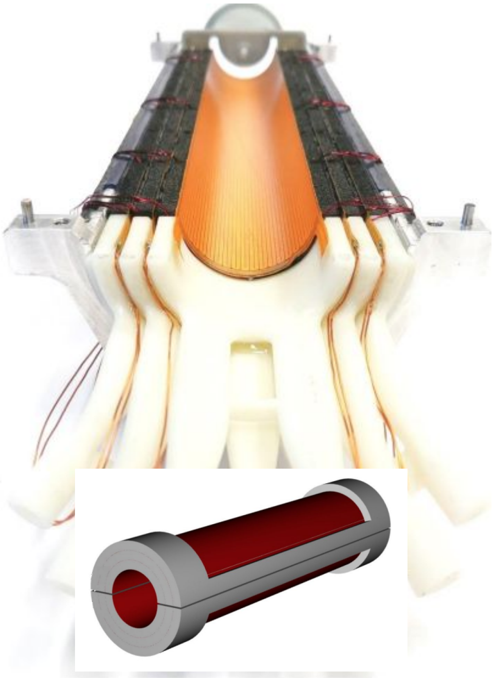
➠ Layout based on air cooling

Carbon foam and cooling structures

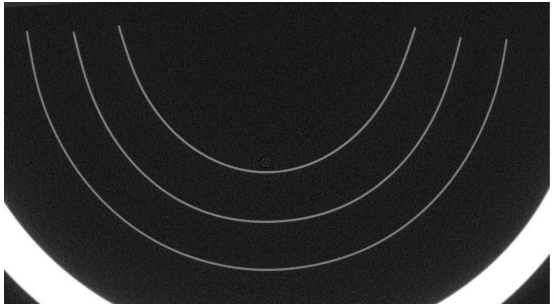
EM1

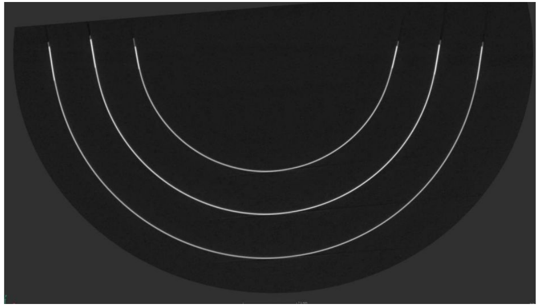
EM2

EM3



NB: EM = Engineering Model

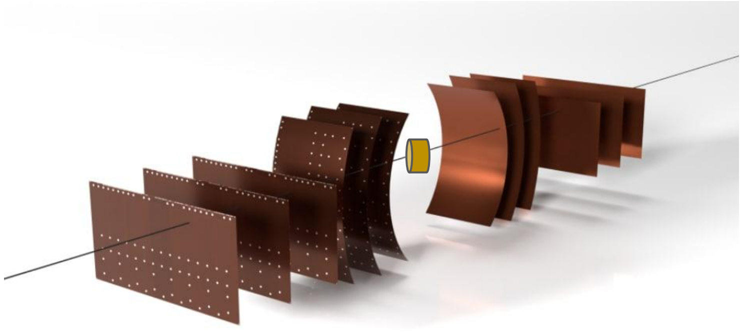




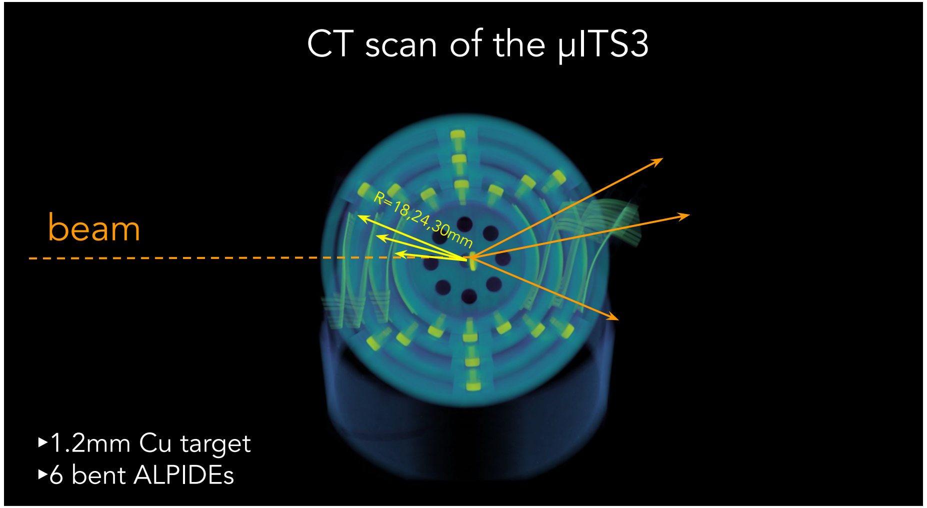
→ footprint
→ imperfect radius

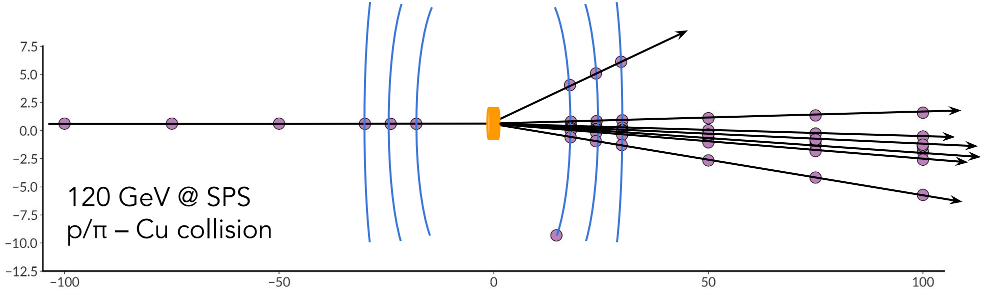
→ nominal radius
→ need to add services

Exotic geometries



➠ 6 reference flat ALPIDE (3+3 up/downstream)
➠ μITS3: probably the most compact beam telescope (6 sensors, ITS3 radii: 18, 24, 30 mm)





➠ tracking with GBL (incl. multiple scattering)
➠ investigation of standalone tracking and DCA (distance of closest approach) measurements