Monolithic Active Pixel Sensors for High-Energy Physics applications

Giacomo Contin

Università di Trieste & INFN Sezione di Trieste

24th iWoRiD - International Workshop On Radiation Imaging Detectors

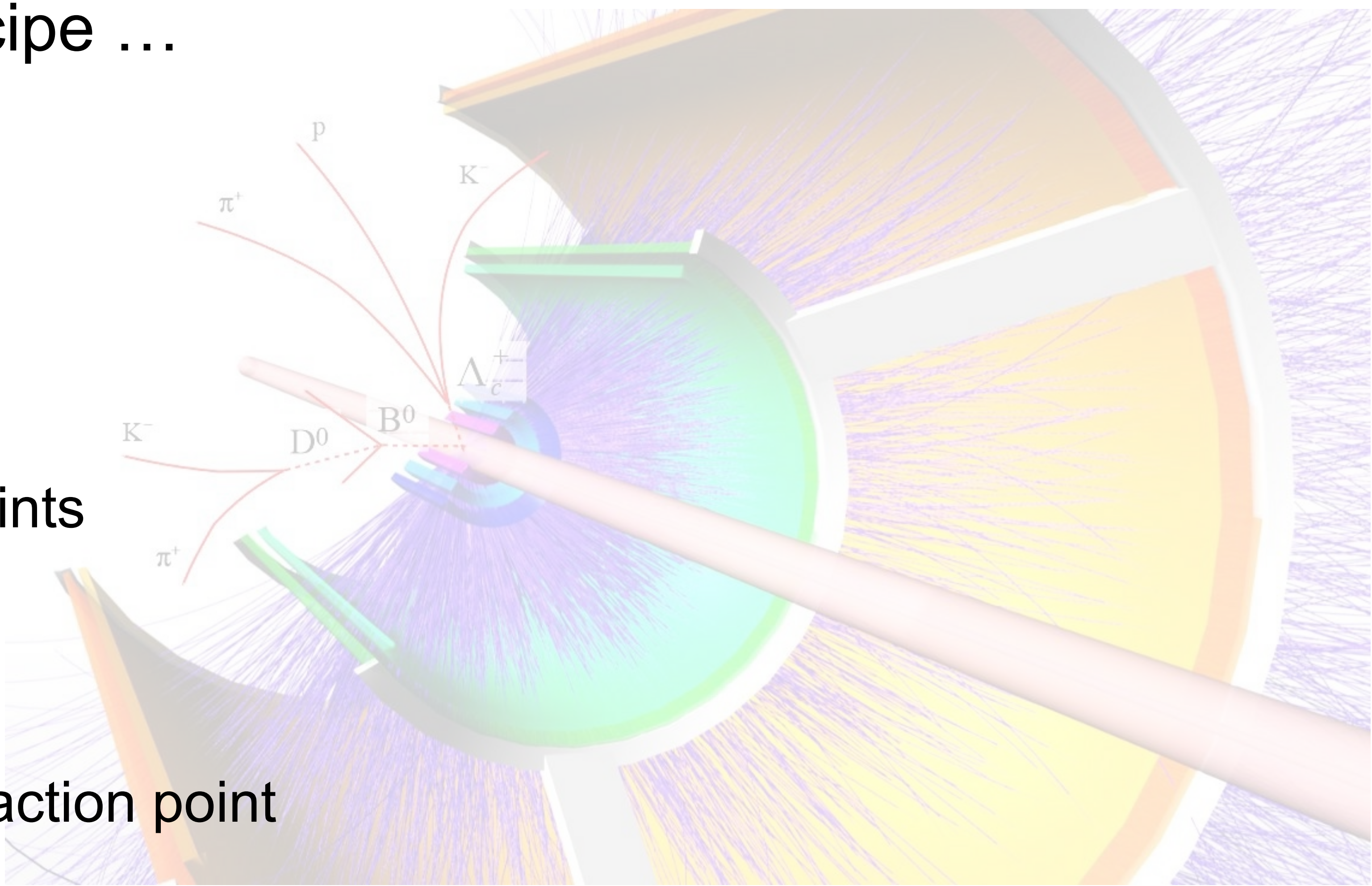
25-29 June 2023 – Oslo (Norway)

Outline

- **M**onolithic **A**ctive **P**ixel **S**ensor technology
- Successful experiences: **STAR HFT** and **ALICE ITS2**
- The future: **ALICE ITS3** and further plans

High-precision tracking in High-Energy Physics

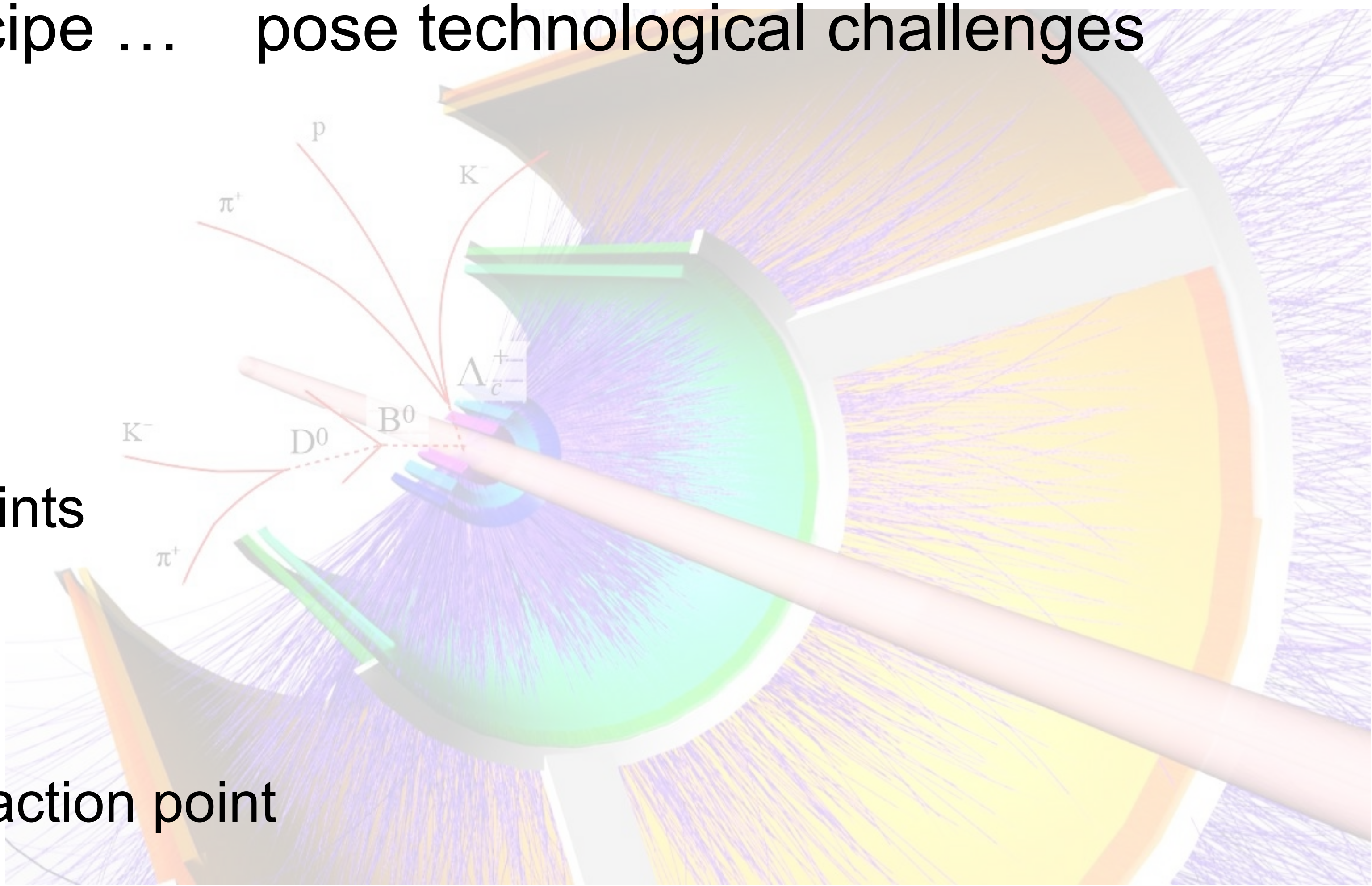
The ingredients for the recipe …



- Low material budget
- Large number of track-points
- Small distance from interaction point

High-precision tracking in High-Energy Physics

The ingredients for the recipe …   pose technological challenges



- Low material budget
- Large number of track-points
- Small distance from interaction point

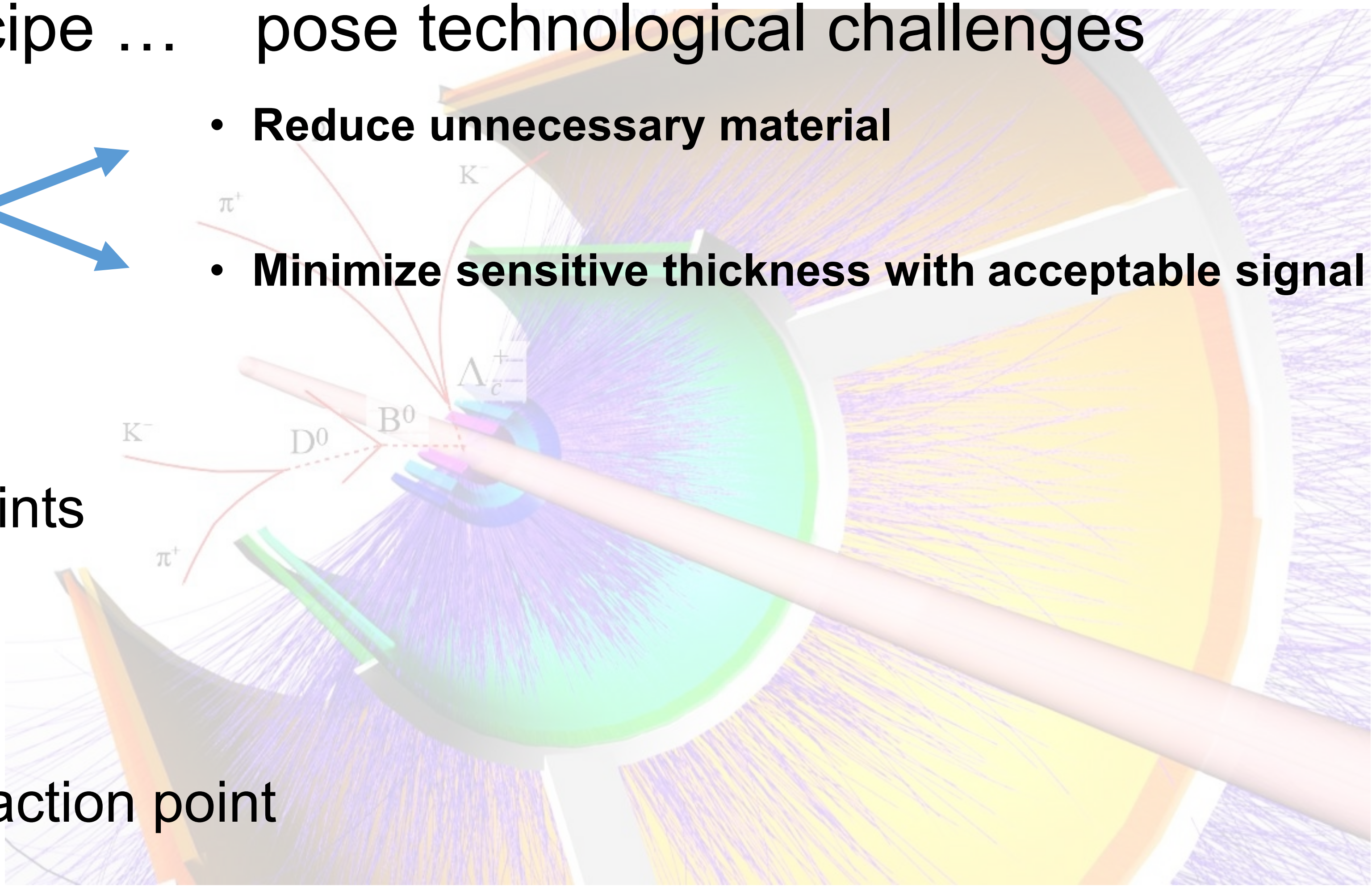
High-precision tracking in High-Energy Physics

The ingredients for the recipe …

- Low material budget
- Large number of track-points
- Small distance from interaction point

pose technological challenges

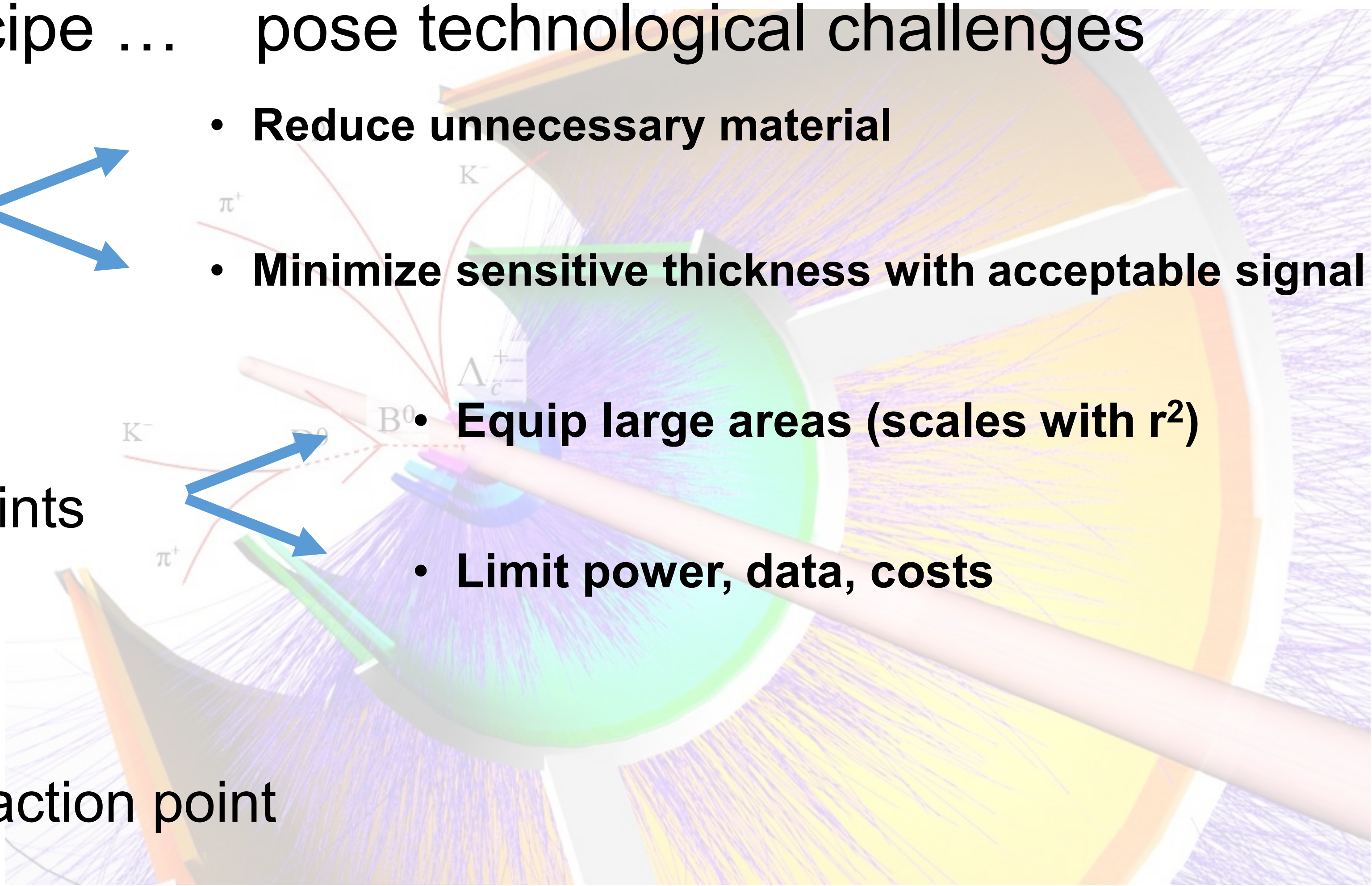
- **Reduce unnecessary material**
- **Minimize sensitive thickness with acceptable signal**



High-precision tracking in High-Energy Physics

The ingredients for the recipe … pose technological challenges

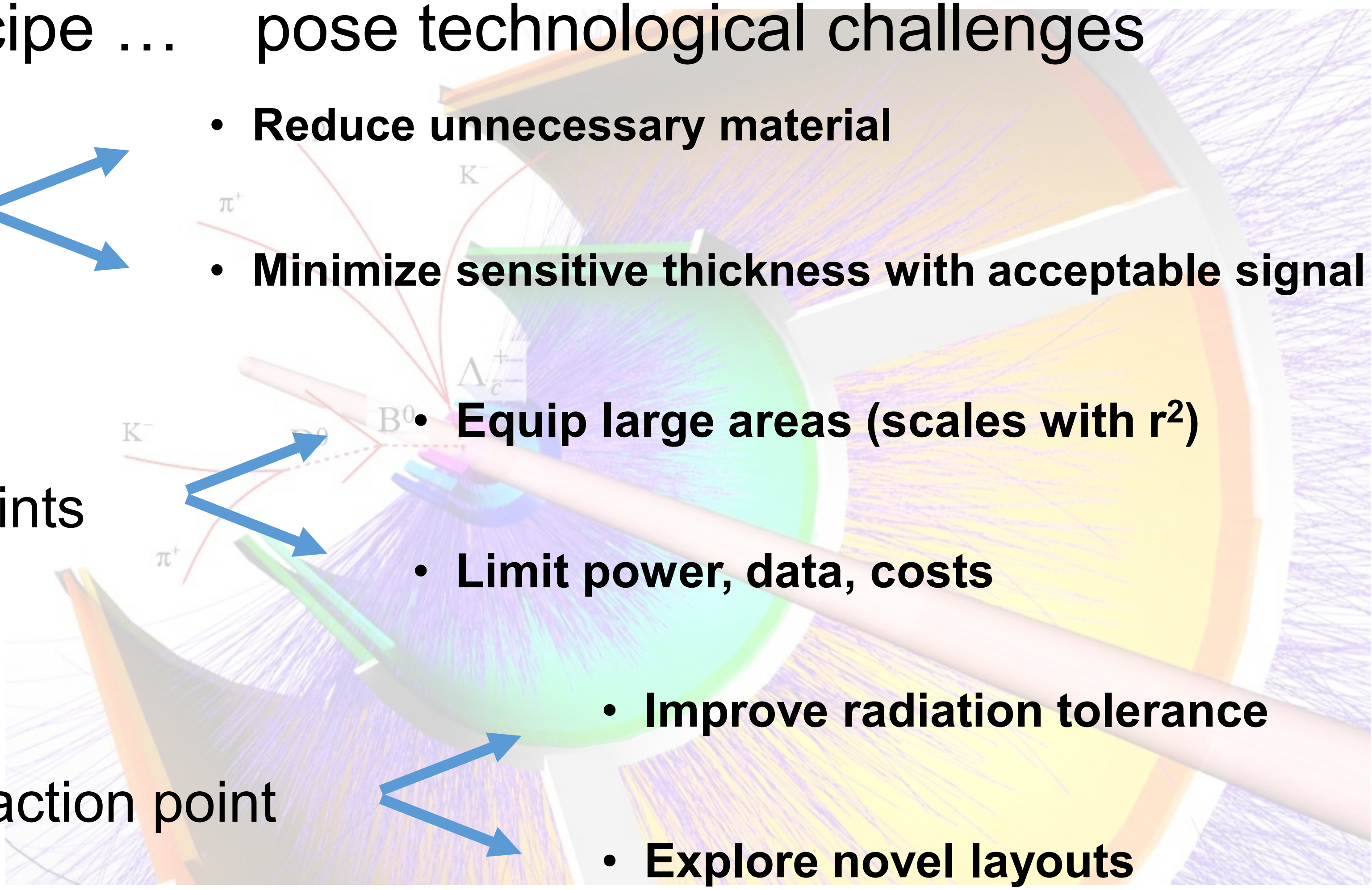
- Low material budget
  - **Reduce unnecessary material**
  - **Minimize sensitive thickness with acceptable signal**
- Large number of track-points
  - **Equip large areas (scales with r^2)**
  - **Limit power, data, costs**
- Small distance from interaction point



High-precision tracking in High-Energy Physics

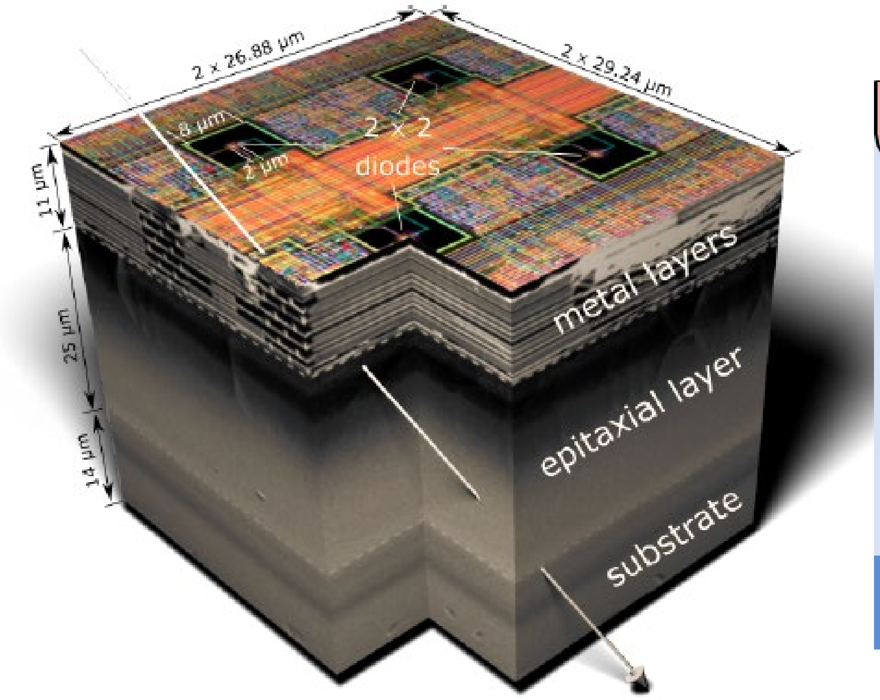
The ingredients for the recipe … pose technological challenges

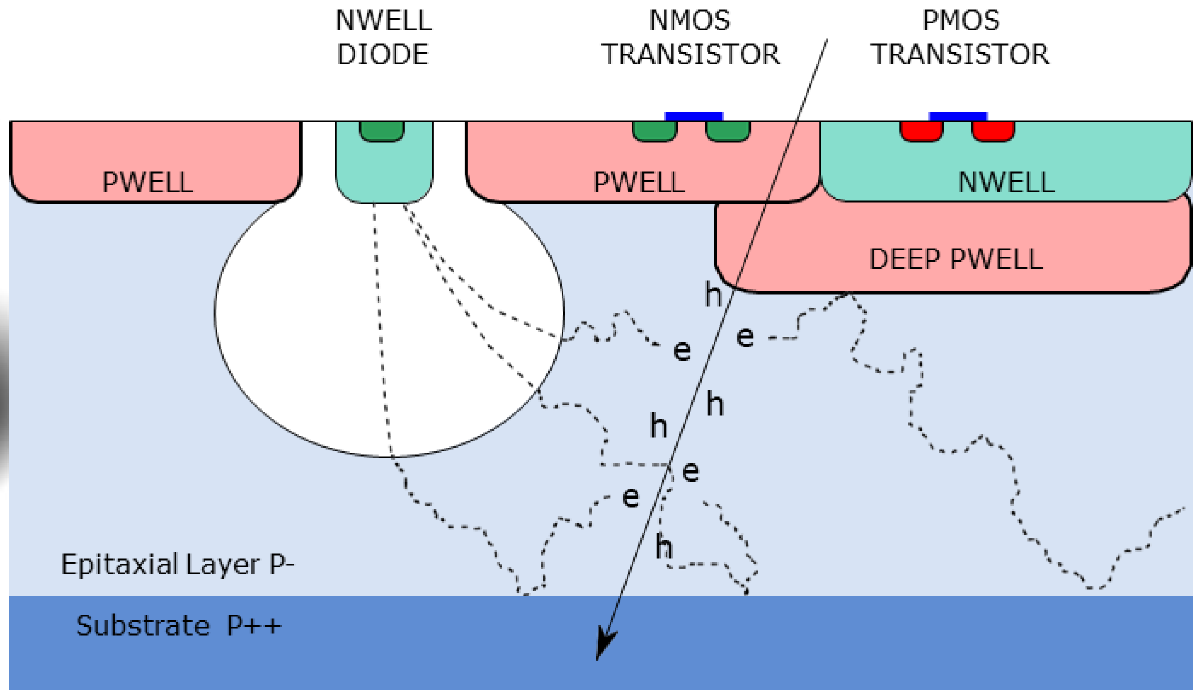
- Low material budget
  - **Reduce unnecessary material**
  - **Minimize sensitive thickness with acceptable signal**
- Large number of track-points
  - **Equip large areas (scales with r^2)**
  - **Limit power, data, costs**
- Small distance from interaction point
  - **Improve radiation tolerance**
  - **Explore novel layouts**



Monolithic Active Pixel Sensor technology

- Combines sensitive volume and front-end readout CMOS logic in the same piece of silicon





Front-end logic ~ 10 μm

High resitivity epi-layer ~ 20 μm

Substrate: can be thinned!

Minimizes the material budget + simplifies the construction

MAPS: the origins

- Invented in the ’90s for the detection of visible light
  - Soon became leader technology for cameras
  - Later reached performance required by scientific imaging applications
  - Active area is just a fraction of the pixel; the standard substrate has low resistivity
- Only in the early 2000s proposed for charged particle tracking in HEP
  - Need larger fill factor and better charge collection (higher resistivity substrate)

[doi:10.1016/S0168-9002(00)00893-7](https://doi.org/10.1016/S0168-9002(00)00893-7)

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 458 (2001) 677–689

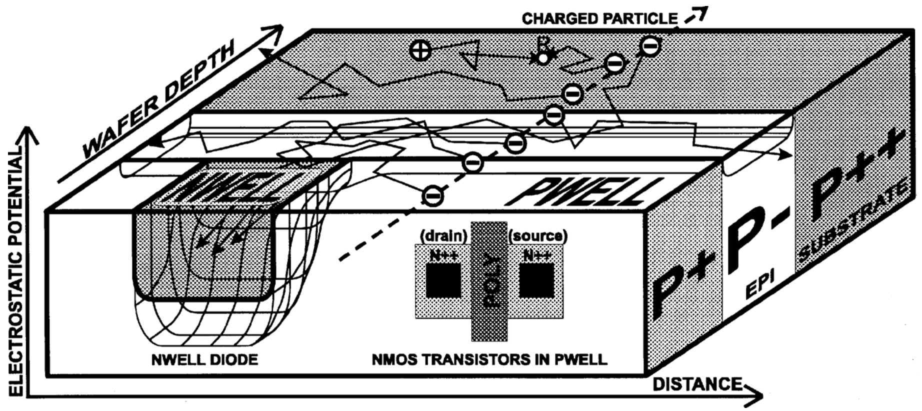
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology

R. Turchetta[a,*], J.D. Berst[a], B. Casadei[a], G. Claus[a], C. Colledani[a], W. Dulinski[a], Y. Hu[a], D. Husson[a], J.P. Le Normand[a], J.L. Riester[a], G. Deptuch[b,1], U. Goerlach[b], S. Higueret[b], M. Winter[b]

[a]LEPSI, IN2P3/ULP, 23 rue du Loess, BP20, F-67037 Strasbourg, France
[b]IReS, IN2P3/ULP, 23 rue du Loess, BP20, F-67037 Strasbourg, France



First MAPS for collider experiment: STAR HFT

Requirements for the MAPS layers	
Operate in a moderate radiation environment	20 to 90 kRad / year $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
DCA pointing resolution	≤ 30 µm for 750 MeV/c kaons
Integration time	< 200 µs
Sensor efficiency	≥ 99% with accidental rate ≤ 10^{-4}
Installation and maintenance	Quick insertion and extraction from one side

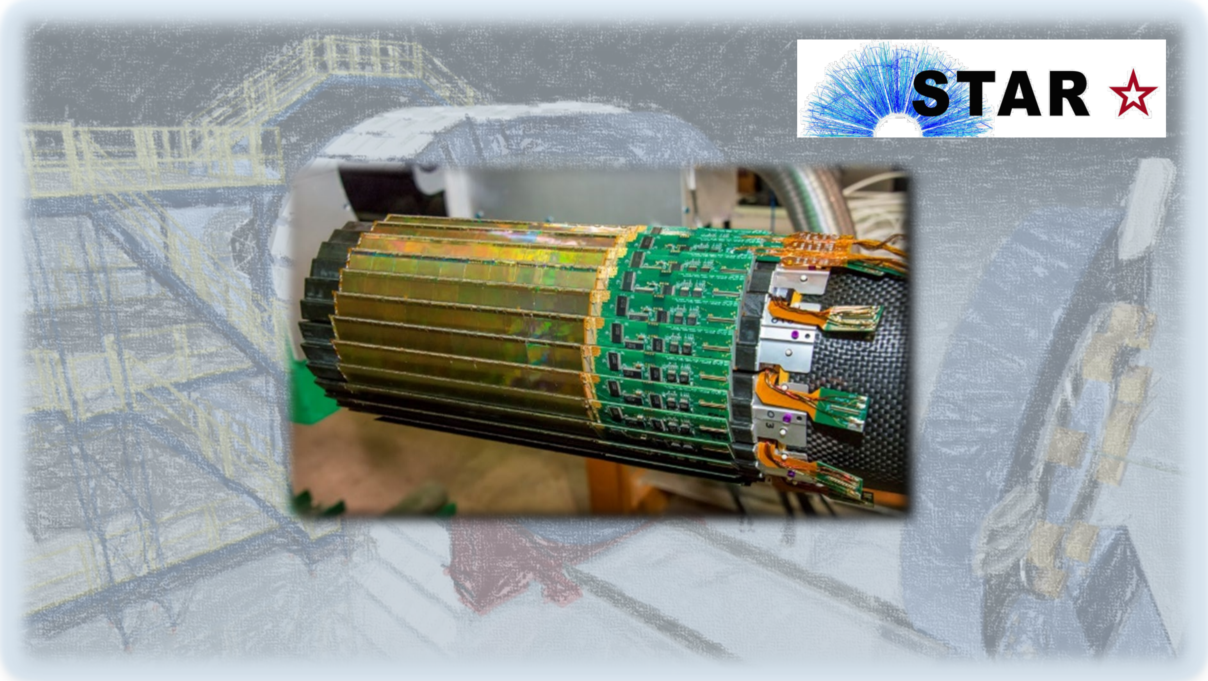
The STAR Experiment at RHIC (BNL)

Goal: Detect charm decays with small $c\tau$ in Au-Au collisions at 200 GeV

First MAPS for collider experiment: STAR HFT

Requirements for the MAPS layers	
Operate in a moderate radiation environment	**20 to 90 kRad / year** **$2*10^{11}$ to 10^{12} 1MeV n eq/cm^2**
DCA pointing resolution	**≤ 30 µm for 750 MeV/c kaons**
Integration time	**< 200 µs**
Sensor efficiency	**≥ 99% with accidental rate ≤ 10^{-4}**
Installation and maintenance	**Quick insertion and extraction from one side**

A new Heavy Flavor Tracker (HFT)

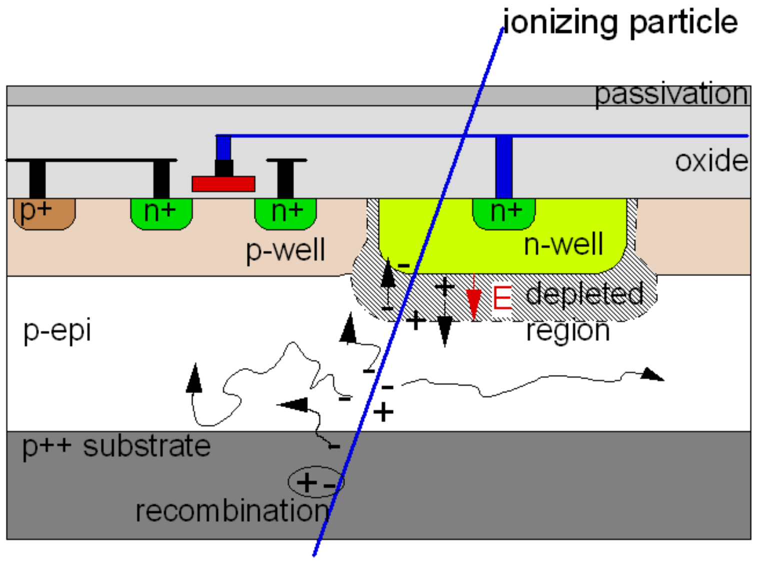


Two vertexing layers based on thin, low-power, small-pitch MAPS sensors

The MIMOSA *Ultimate-2* sensor for STAR HFT

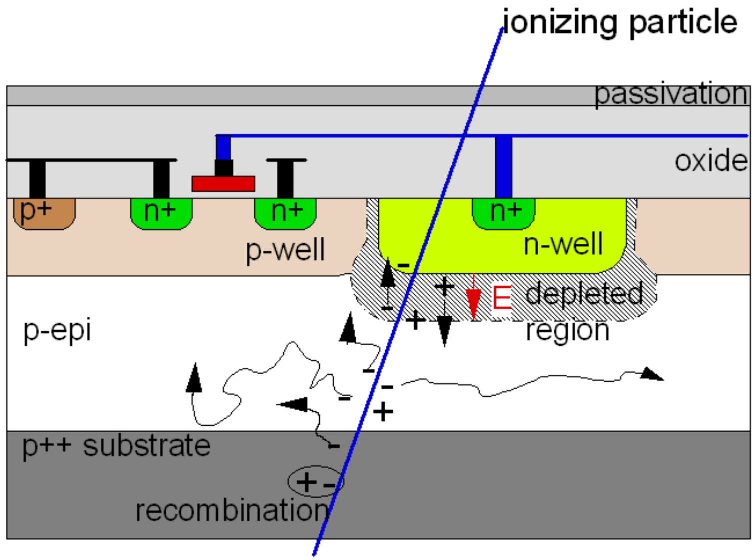
MIMOSA-family sensor developed for HFT at IPHC, Strasbourg

- AMS 0.35 μm CMOS, Twin-well process
  - **Only NMOS transistors** to avoid competition in charge collection
- 'High' resistivity (≥ 400 Ω·cm) p-epi layer (~ 15 μm)
  - Reduced **charge collection time** and improved **radiation hardness**
- Charge collection mostly by **diffusion**
  - **Shallow depletion** region formed between n-well and p-epi
  - **High-potential difference** between epi and substrate acts as a mirror



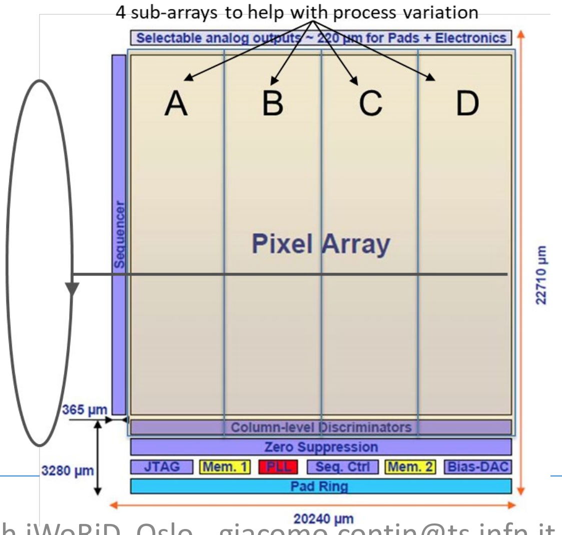
The MIMOSA *Ultimate-2* sensor for STAR HFT

MIMOSA-family sensor developed for HFT at IPHC, Strasbourg



- AMS 0.35 μm CMOS, Twin-well process
  - **Only NMOS transistors** to avoid competition in charge collection
- 'High' resistivity (≥ 400 Ω·cm) p-epi layer (~ 15 μm)
  - Reduced **charge collection time** and improved **radiation hardness**
- Charge collection mostly by **diffusion**
  - **Shallow depletion** region formed between n-well and p-epi
  - **High-potential difference** between epi and substrate acts as a mirror

- **Rolling-shutter** readout architecture
- 185.6 μs integration time
- ~170 mW/cm² power dissipation
  - Clock distributed across the matrix



- Pixel matrix
  - 20.7 μm pitch
  - 928 rows * 960 columns = ~1M pixel
  - In-pixel amplifier
  - In-pixel Correlated Double Sampling (CDS)
- Digital section
  - Ping-pong memory
  - 160 MHz LVDS data output

The STAR HFT PXL Layers

See G. Contin @ iWoRiD 2014

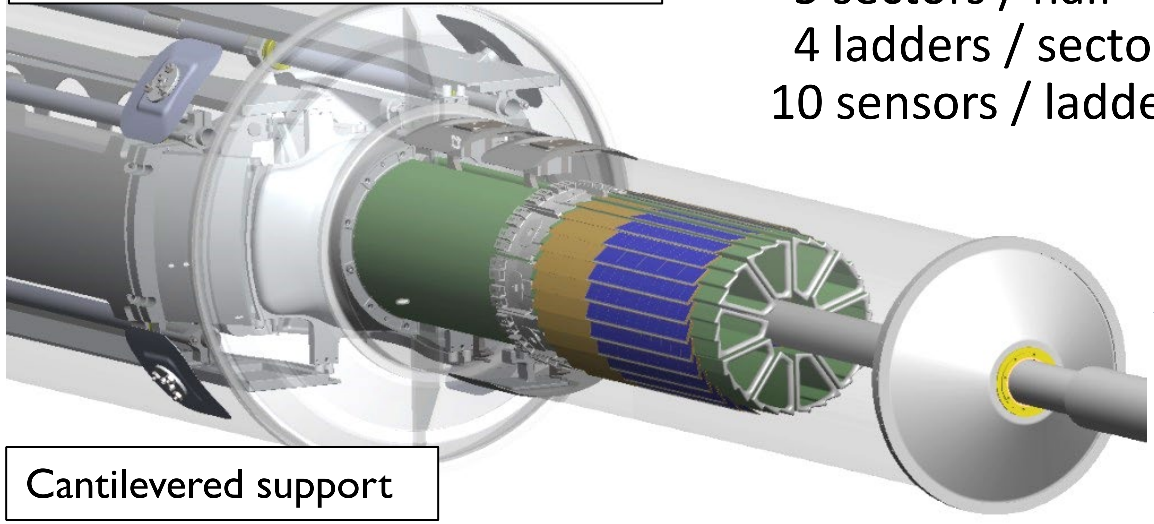
Ladder with 10 MAPS sensors (~ 2×2 cm each)

Highly parallel system

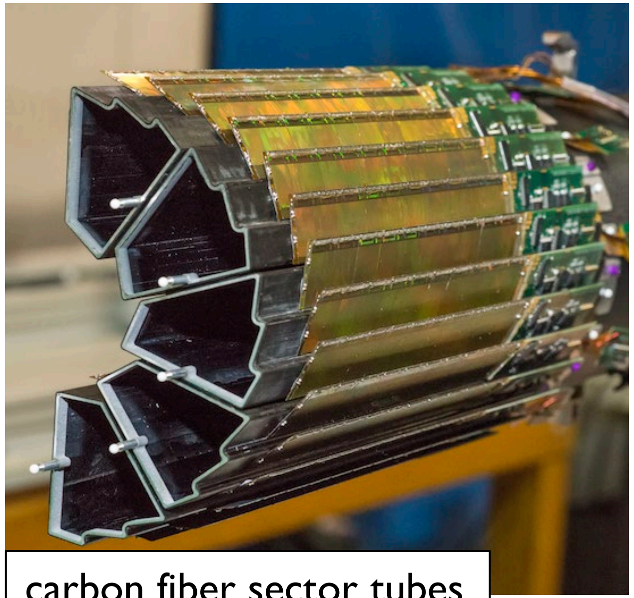
10 sectors total
5 sectors / half
4 ladders / sector
10 sensors / ladder

~356 M pixels over ~0.16 m^2

Mechanical support with kinematic mounts (insertion side)



Cantilevered support

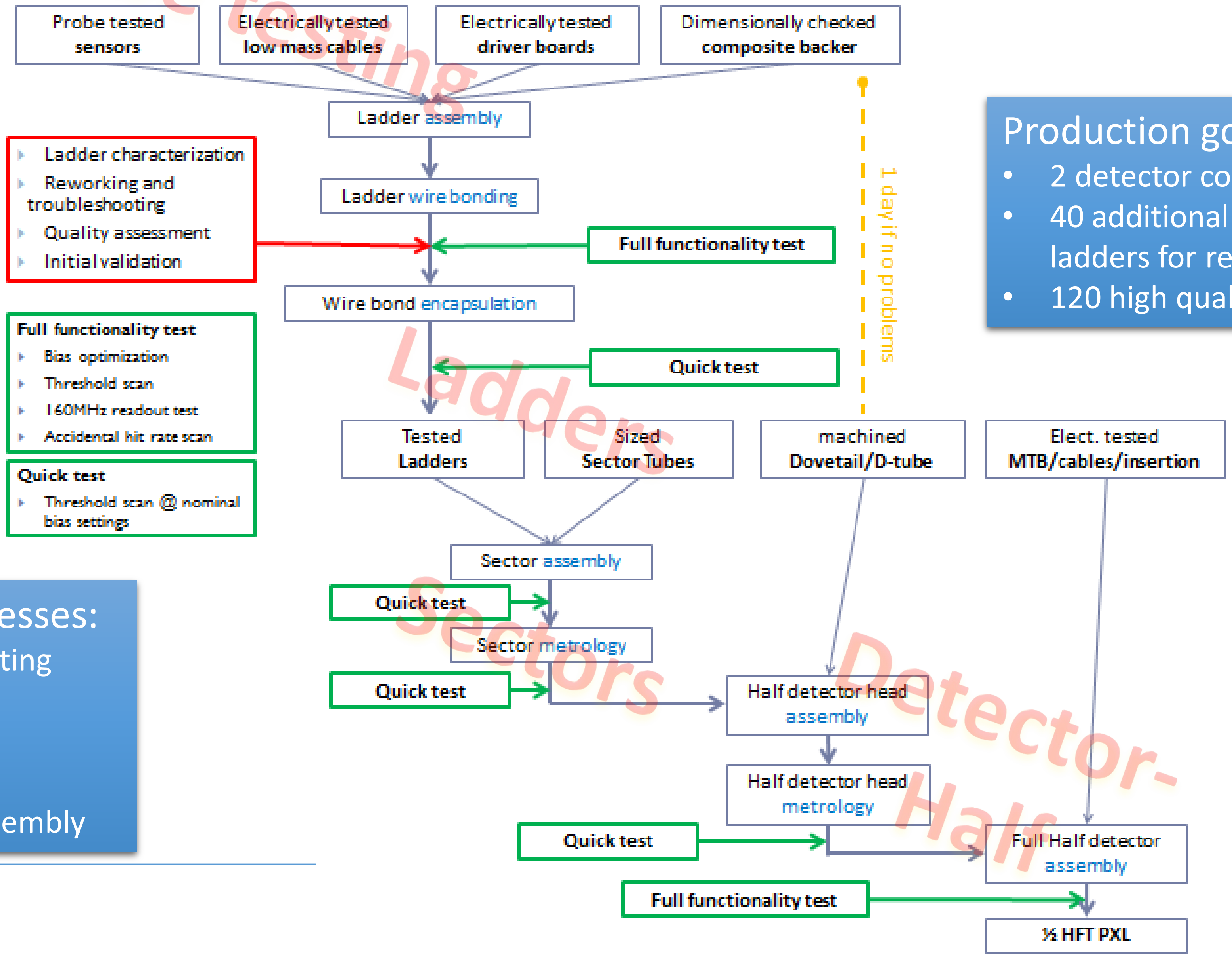


carbon fiber sector tubes

Untested technology in a collider environment

- Plan for a way to quickly replace malfunctioning components
- Produce spare replica and components ready to plug in

HFT Production, Assembly and QA workflow



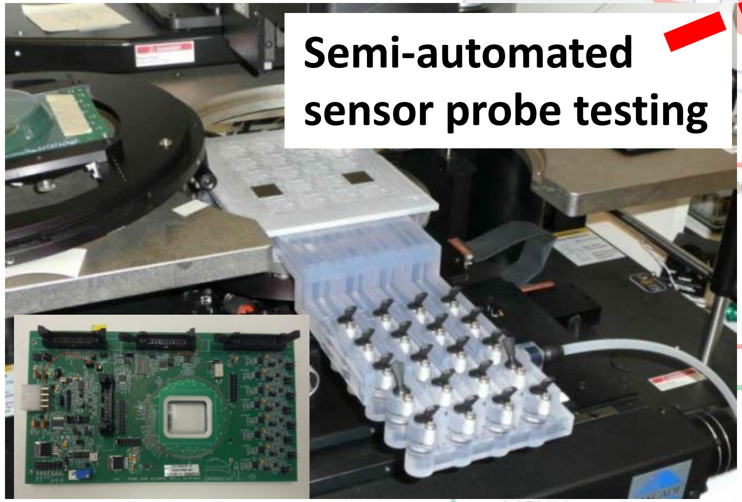
Production goals:

- 2 detector copies
- 40 additional spare ladders for refurbishment
- 120 high quality ladders

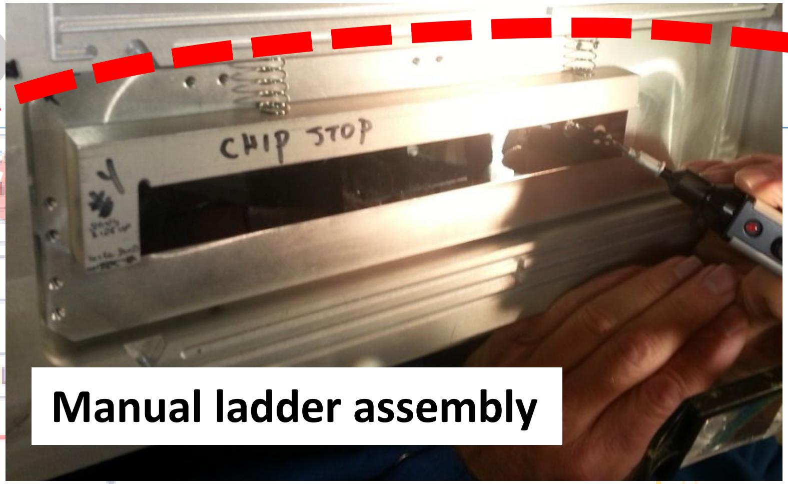
Production processes:

- Sensor probe testing
- Ladder assembly
- Ladder testing
- Sector assembly
- Detector-half assembly

HFT Productio… QA workflow



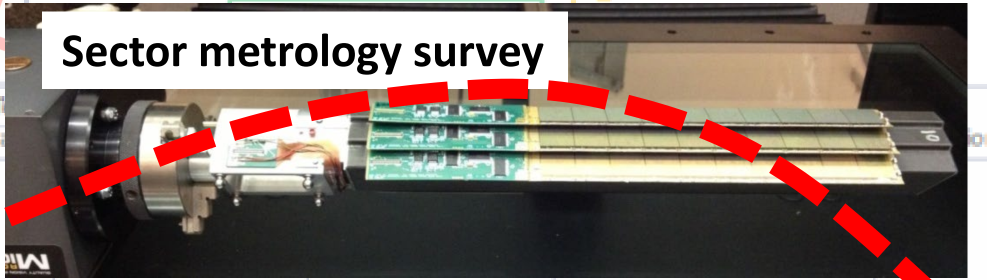
Semi-automated sensor probe testing



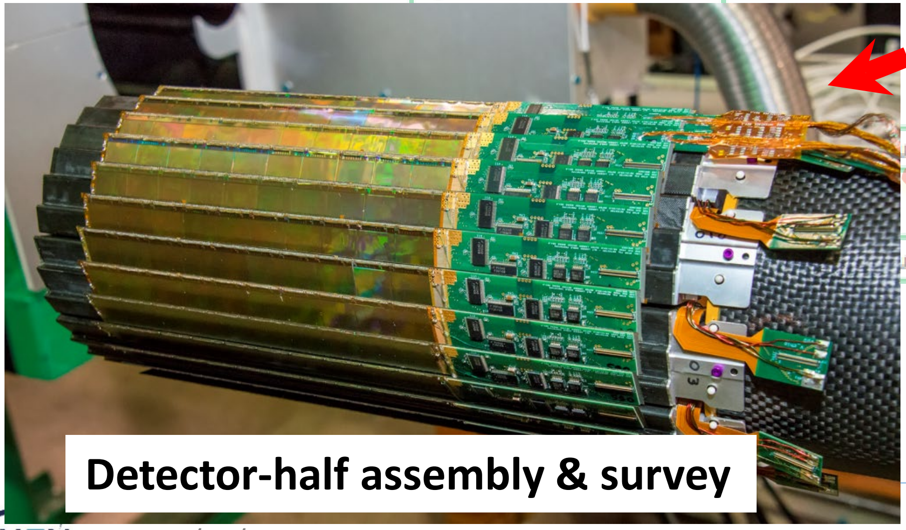
Manual ladder assembly

Production goals:

- 2 detector copies
- 40 additional spare ladders for refurbishment
- 120 high quality ladders

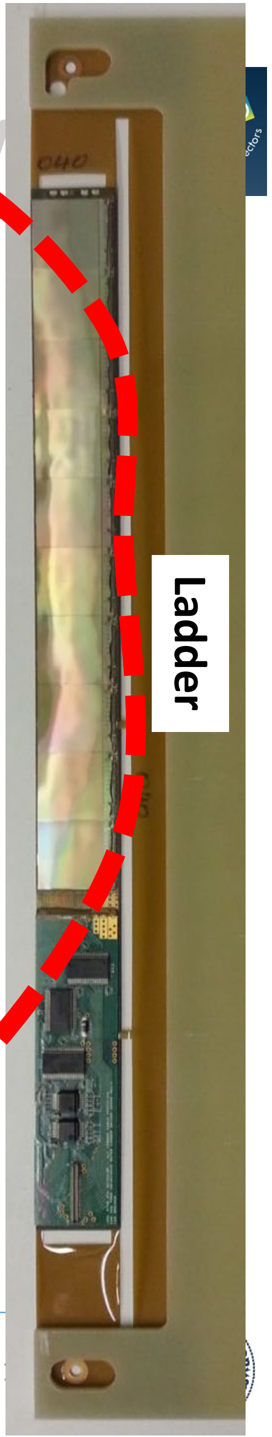


Sector metrology survey



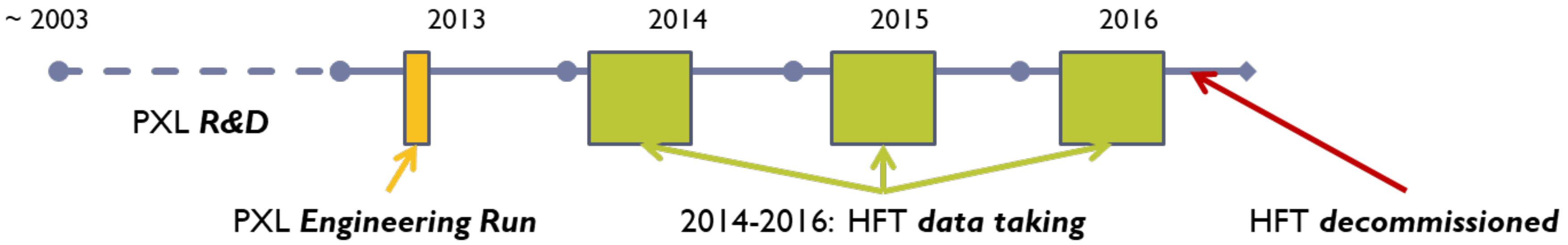
Detector-half assembly & survey

Manual sector assembly



Ladder

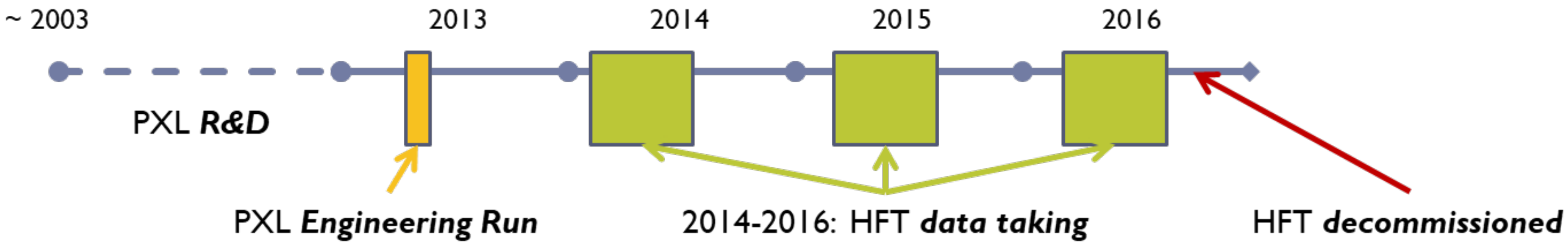
HFT PXL timeline and operations



- **2013 Engineering Run** (3 sectors in actual STAR environment) crucial to solve:
  - **Electrical shorts, mechanical interference, missing functionalities**
  - Power control, monitoring and overcurrent thresholds were made available

- **2014-2016 Physics Runs** operations: up to 1000hits/sensor; Trigger rate: 0.8-1 kHz

HFT PXL timeline and operations

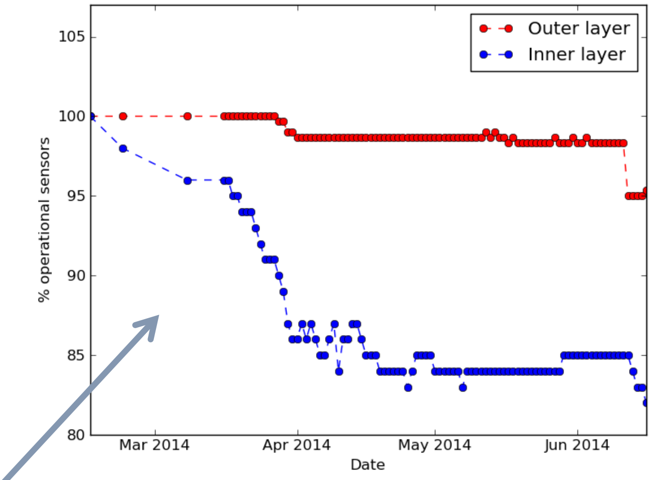


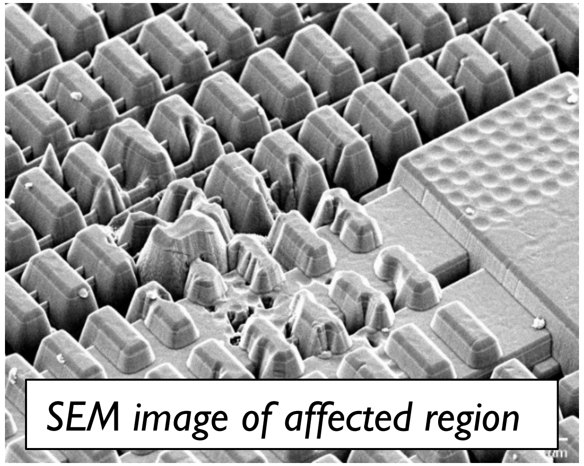
- **2013 Engineering Run** (3 sectors in actual STAR environment) crucial to solve:
  - **Electrical shorts, mechanical interference, missing functionalities**
  - Power control, monitoring and overcurrent thresholds were made available

- **2014-2016 Physics Runs** operations: up to 1000hits/sensor; Trigger rate: 0.8-1 kHz

- **SEL (Single Event Latch-up) induced damage**
  - Current limited latch-up states (typically ~300 mA) **permanently damaging the thin sensor**
  - Affected mostly high-density logic in the digital section: **local power dissipation** melting the metal layers
  - Mitigated with **latch-up detection and automatic power cycling**: dead time up to ~6%

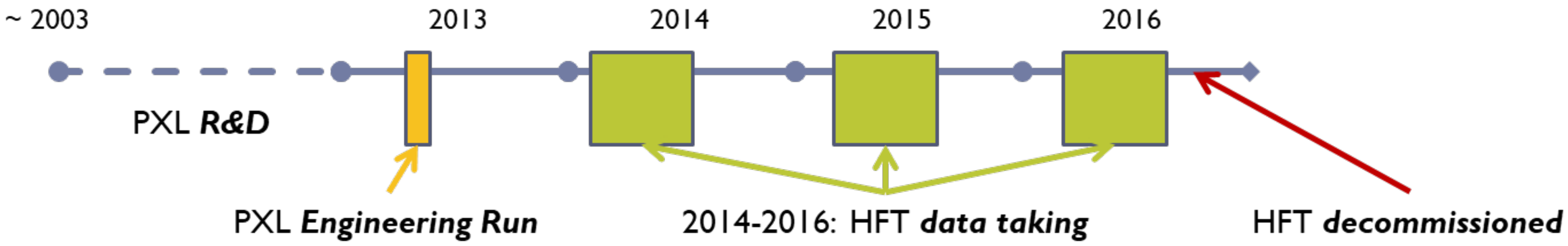
Operational sensor % trend



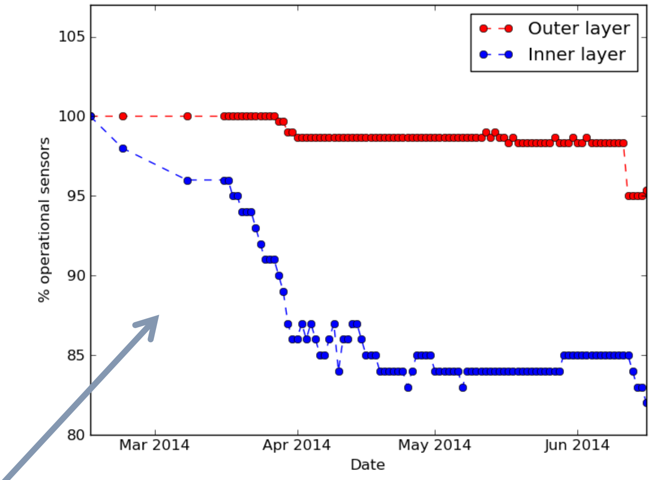


SEM image of affected region

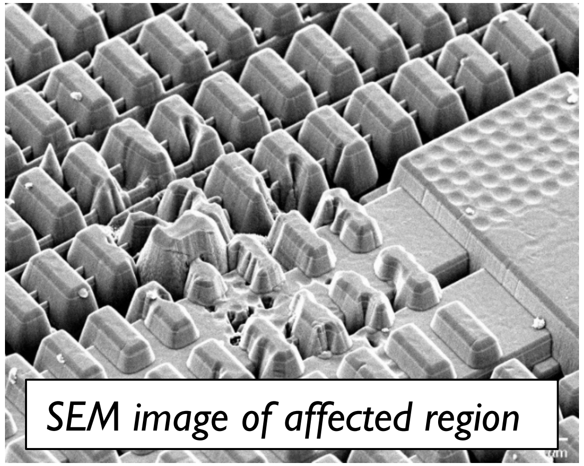
HFT PXL timeline and operations



Operational sensor % trend

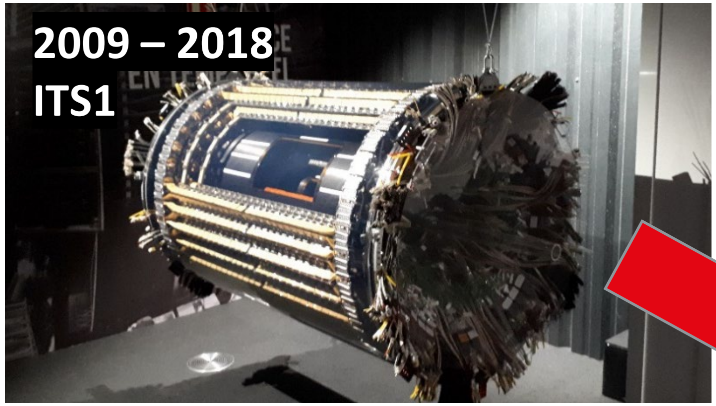


- **2013 Engineering Run** (3 sectors in actual STAR environment) crucial to solve:
  - **Electrical shorts, mechanical interference, missing functionalities**
  - Power control, monitoring and overcurrent thresholds were made available
- **2014-2016 Physics Runs** operations: up to 1000hits/sensor; Trigger rate: 0.8-1 kHz
- **SEL (Single Event Latch-up) induced damage**
  - Current limited latch-up states (typically ~300 mA) **permanently damaging the thin sensor**
  - Affected mostly high-density logic in the digital section: **local power dissipation** melting the metal layers
  - Mitigated with **latch-up detection and automatic power cycling**: dead time up to ~6%
- **MAPS technology proved to be suitable for a collider experiment!**



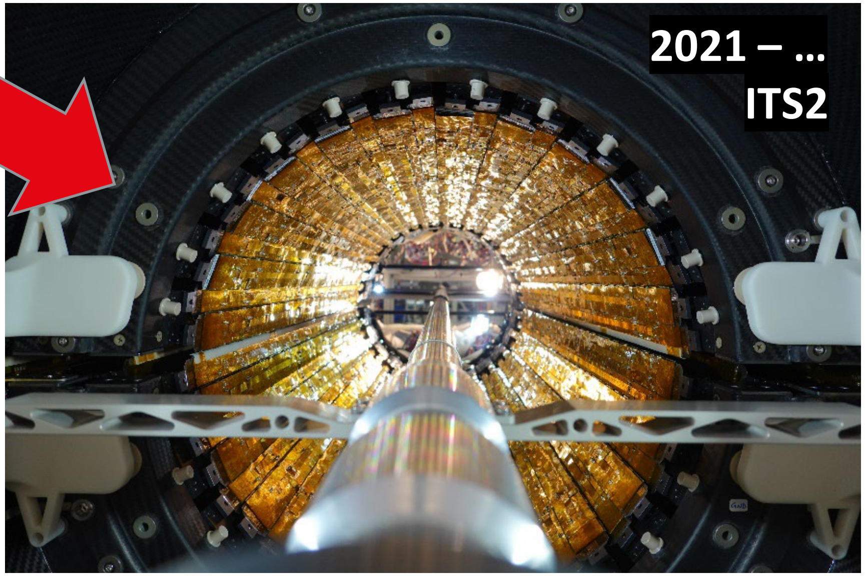
SEM image of affected region

ALICE ITS2: first large-area MAPS-based tracker



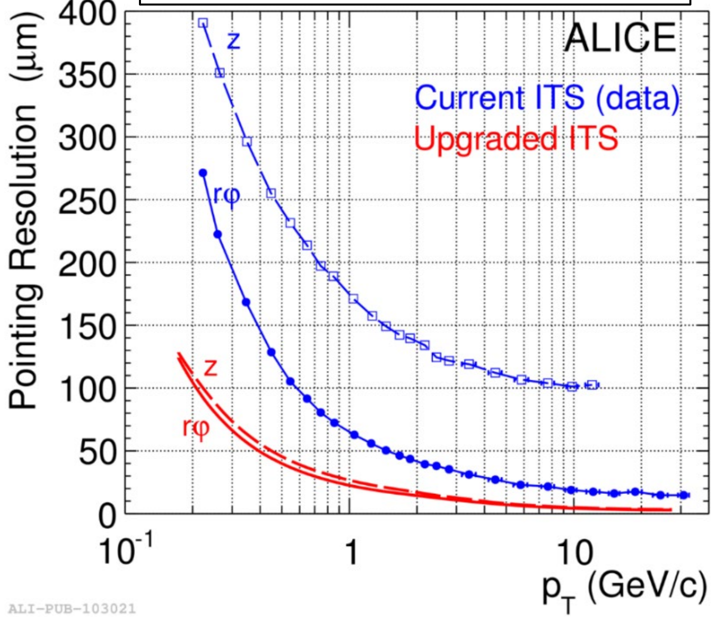
- **ITS1**: three silicon technologies
  - Hybrid pixels
  - Drift chambers
  - Micro-strips
- Operated for 10 years in ALICE
  - Secondary vertex reconstruction: essential ingredient for its physics output

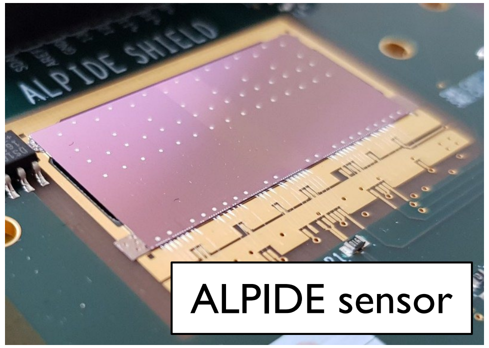
- **ITS2**: a large-scale MAPS detector
- **Goal**: a dramatic improvement in the detector performance, especially at low p_T



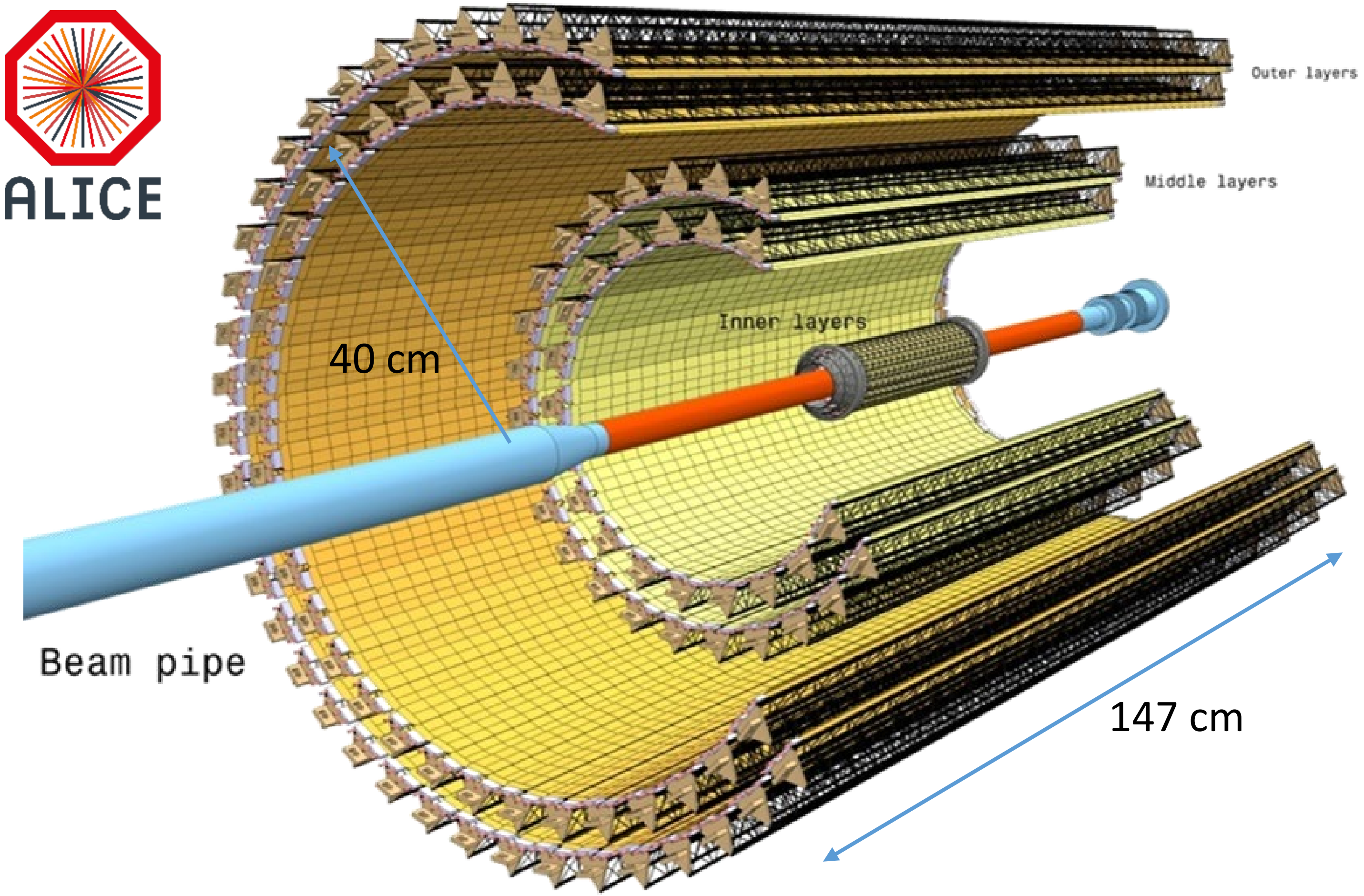
- **Single technology**: MAPS sensor developed within the Collaboration in TowerJazz 180nm CMOS process

Simulated ITS2 performance





ALICE ITS2: 12.5 Gpixels on ~10 m^2 of silicon



- Monolithic Active Pixel Sensor
- Pixel pitch: **~30 μm**
- **7 cylinders** covering **~10 m^2**
- Innermost radius: **23 mm**
- **~0.35% X_0** material budget
- ~24k chips = **12.5G pixels**

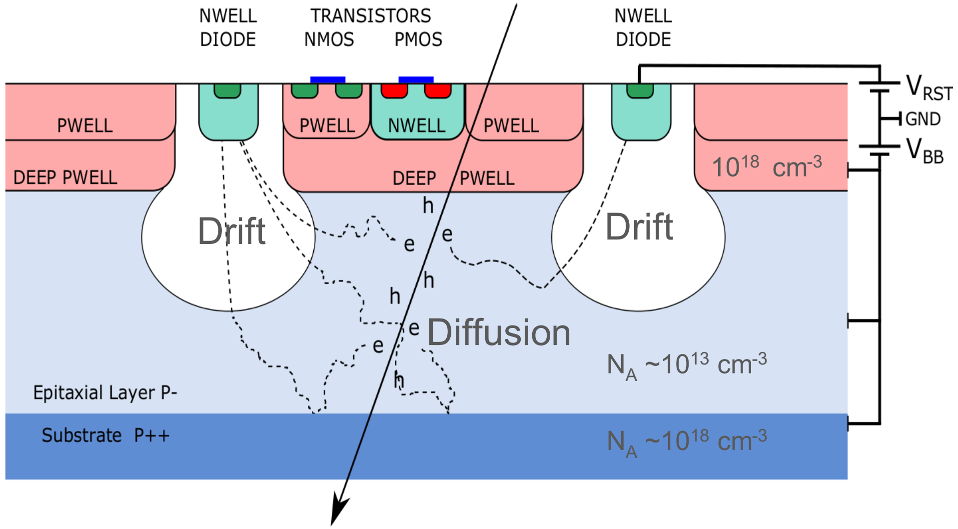
"Technical Design Report for the Upgrade of the ALICE Inner Tracking System"
ALICE Collaboration, J.Phys. G41 (2014) 087002, CERN-LHCC-2013-024

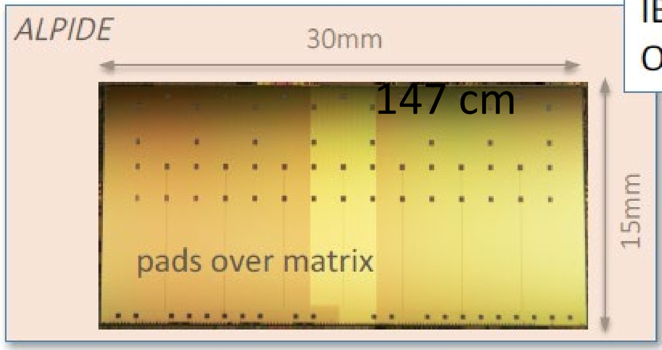
The ALPIDE sensor for ALICE ITS2

MAPS produced using TowerJazz 0.18μm CMOS Imaging Process

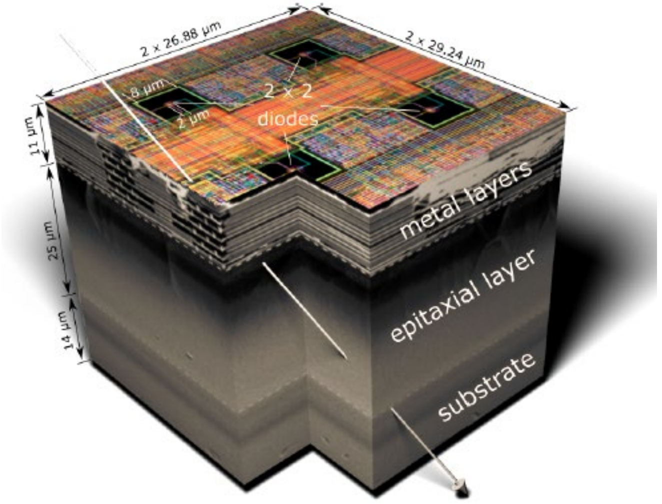
- Deep P-well allows in-pixel **full CMOS**
- Low-power (~40mW/cm^2)
- ~30 μm pitch → high granularity
- **50 μm thickness→** low material budget
- >1 kΩ·cm p-type epitaxial layer (25 μm)
- Possibility of **reverse biasing** to expand drift region
- **TID** ~ 0.3 Mrad
- **NIEL** ~ 3 · 10^{12} 1 MeV n_{eq}/cm^2

- 27x29x25 μm^3
- 1024 x 512 pixels
- Spatial resolution: ~5 μm
- Priority Encoder Readout





IB: 50μm thick
OB: 100μm thick

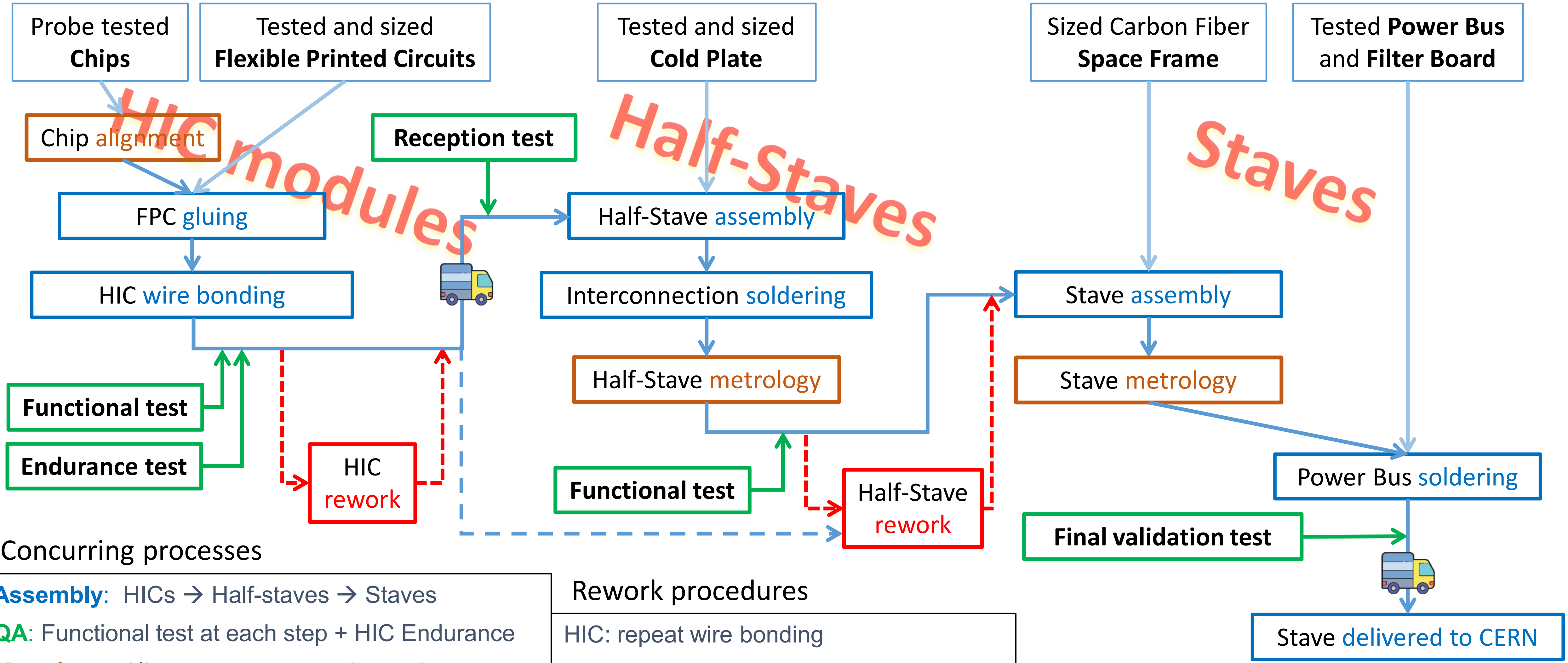


- Integration time: < 20 μs
- Read out up to 1.2 Gbit/s
- Continuous or triggered read-out
- Final testing yield: 64%

ALICE ITS2

~4 days → ~2 weeks

Assembly and Quality Assurance workflow



Concurring processes

Assembly: HICs → Half-staves → Staves

QA: Functional test at each step + HIC Endurance

Metrology: Align components and map the sensitive volume positions

Rework procedures

HIC: repeat wire bonding

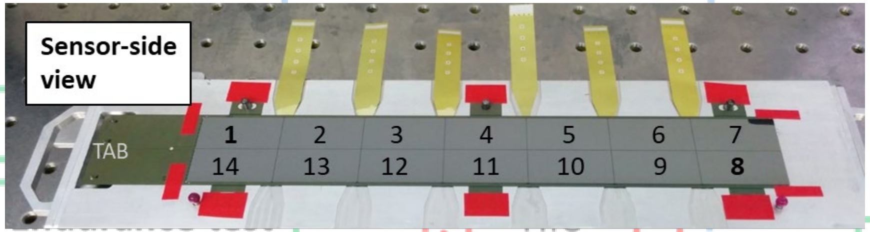
Half-Stave: replace HIC

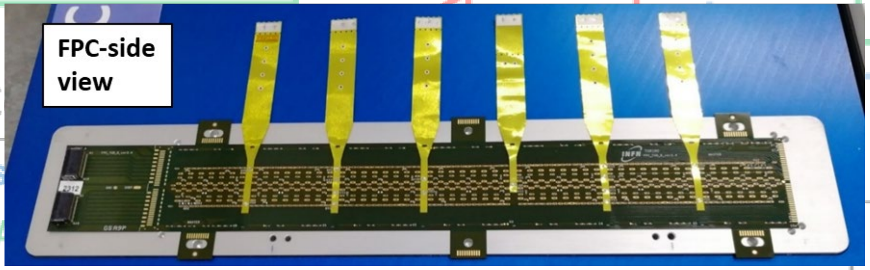
Stave: Disconnect and rework Half-Stave

Quality Assurance workflow

~2 weeks

Custom-made module assembly machine for **automated** placing, alignment, inspection, gluing





HIC wire bonding

Tested and sized **Cold Plate**

Half-Staves

Half-Stave assembly

Interconnection soldering

Half-Stave metrology

Functional test

Half-Stave rework

Sized Carbon Fiber **Space Frame**

Tested **Power Bus** and **Filter Board**

Staves

Stave assembly

Stave metrology

Power Bus soldering

Final validation test

Stave delivered to CERN

Metrology: Align components and map the sensitive volume positions

Rework procedures

HIC: repeat wire bonding

Half-Stave: replace HIC

Stave: Disconnect and rework Half-Stave

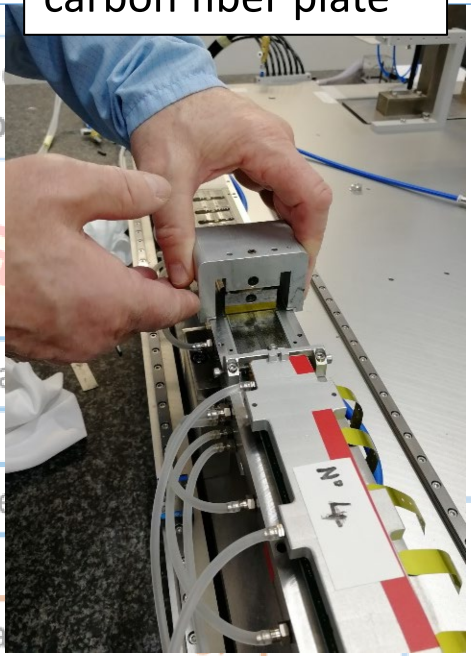
INFN TRIESTE

~2 weeks

Quality Assurance workflow

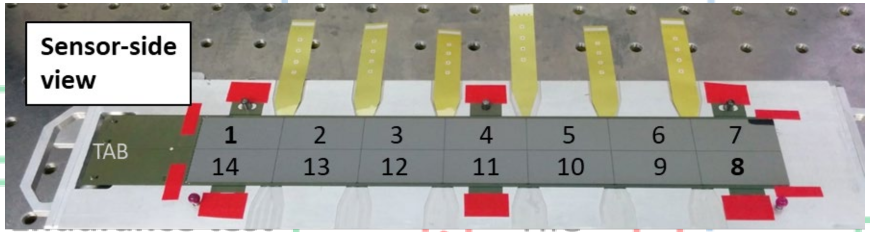
Custom-made module assembly machine for **automated** placing, alignment, inspection, gluing

Manual gluing on carbon fiber plate

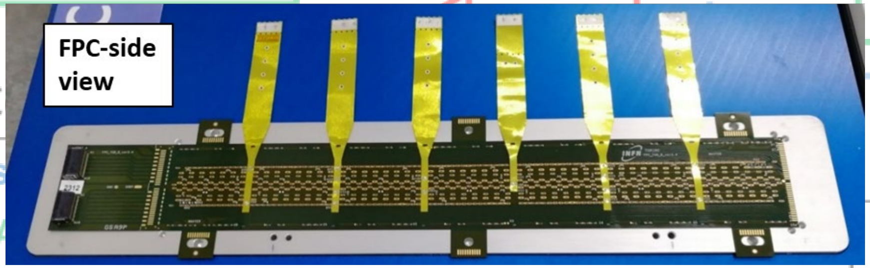


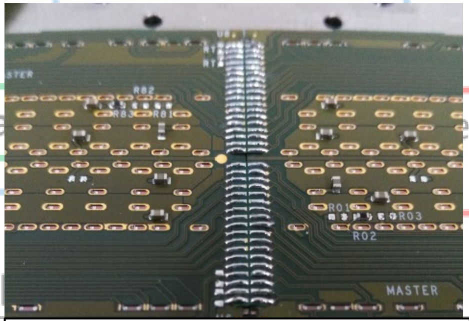
HIC wire bonding

Sensor-side view



FPC-side view





Manual module connection soldering

Rework

Stave: Disconnect and rework Half-Stave

Sized Carbon Fiber Space Frame

Tested Power Bus and Filter Board

Staves

Stave assembly

Stave metrology

Power Bus soldering

Final validation test

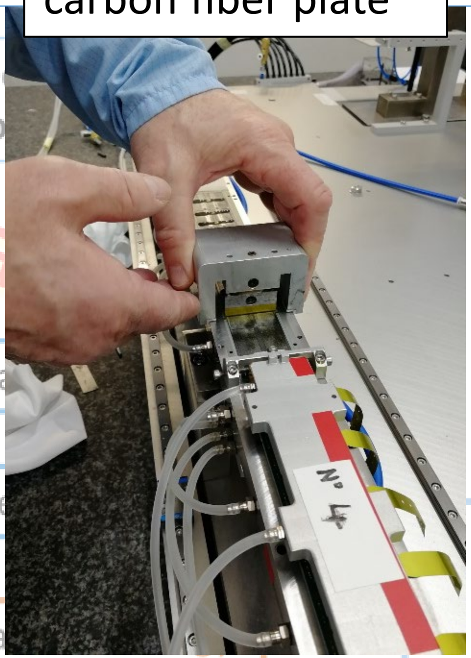
Stave delivered to CERN

Metrology: Align components and map the sensitive volume positions

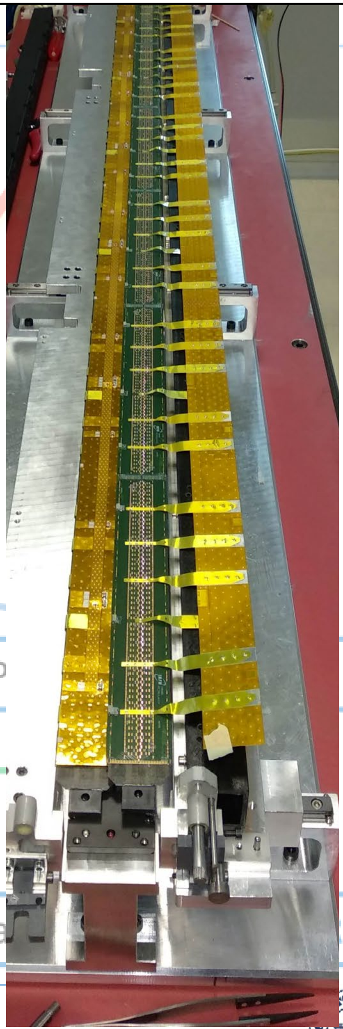
See G. Contin @ Vertex 2019

Custom-made module assembly machine for **automated** placing, alignment, inspection, gluing

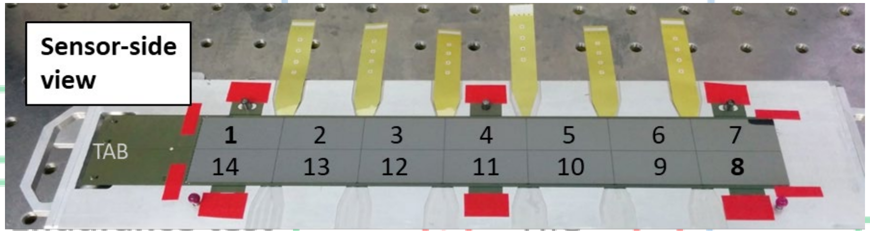
Manual gluing on carbon fiber plate



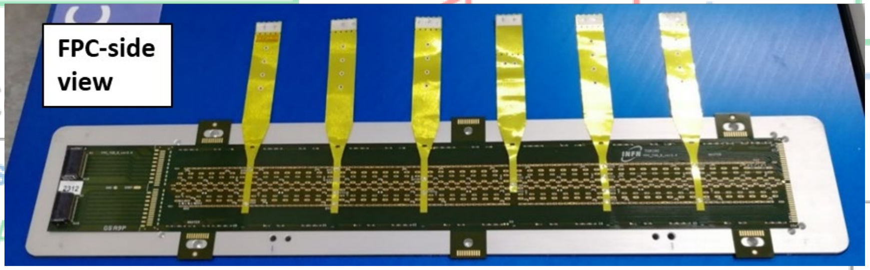
Manual power-bus application and folding

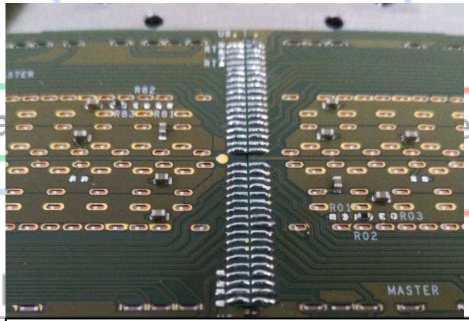


Sensor-side view

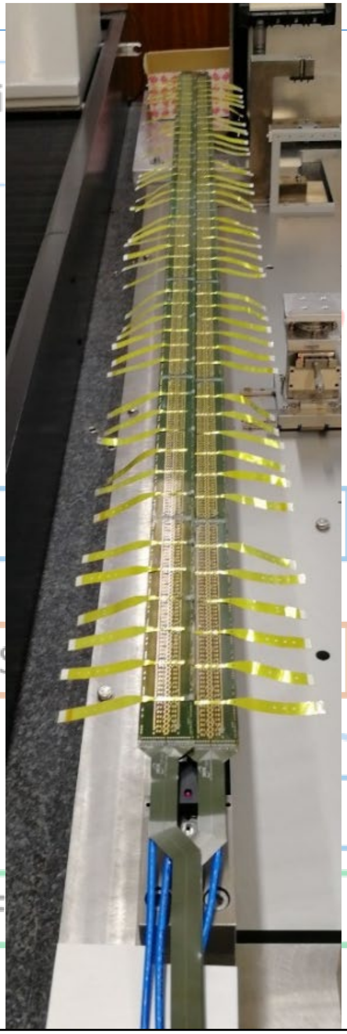


FPC-side view





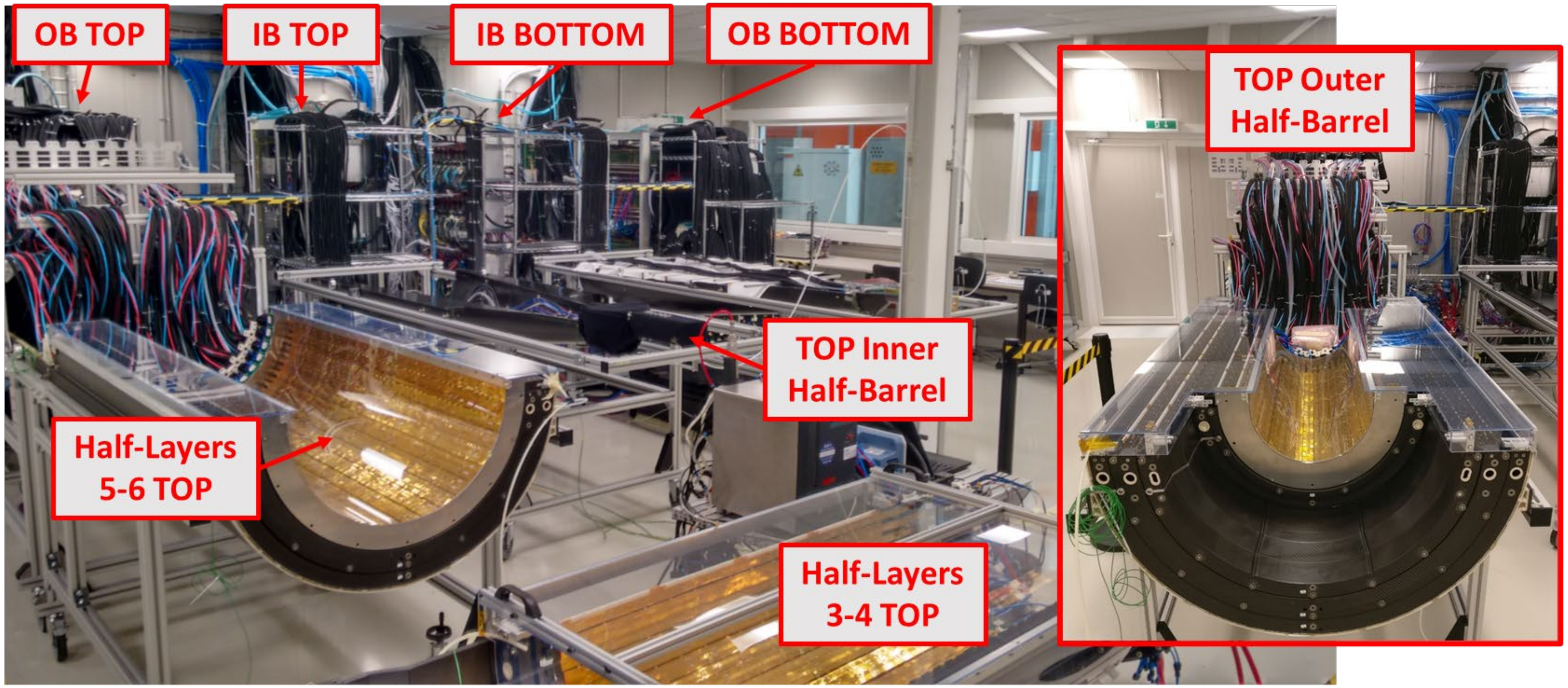
Manual module connection soldering



Surveyed manual stave assembly

More than 10 Institutes for a few years!

1-year commissioning at the surface

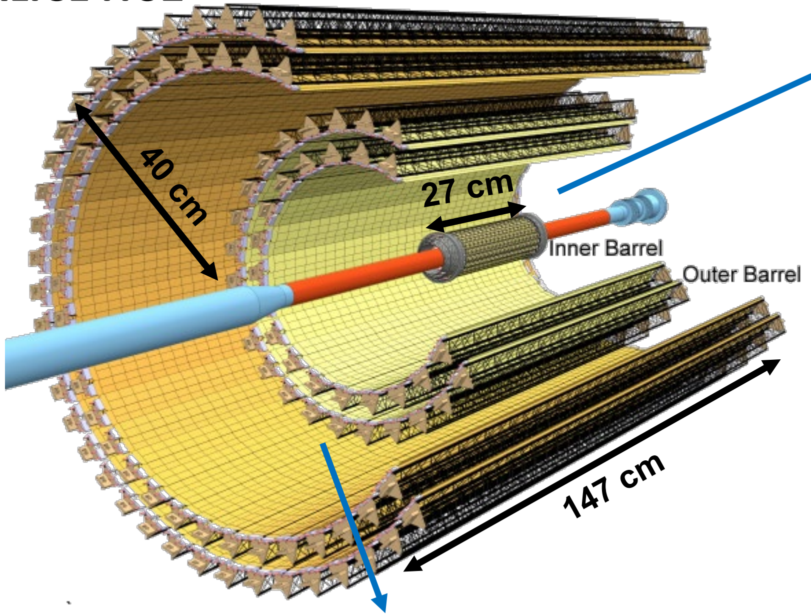


- ITS2 included in ALICE Data Taking since 2022:
  - Extremely quiet ($<10^{-7}$ hits/event/pixel), meeting performance expectations

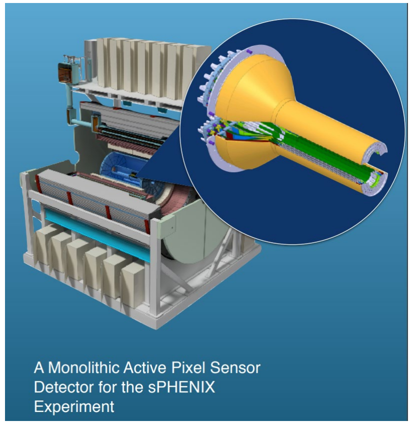
See J. Liu's poster @ this conference!

ITS2 technology transfer to other projects

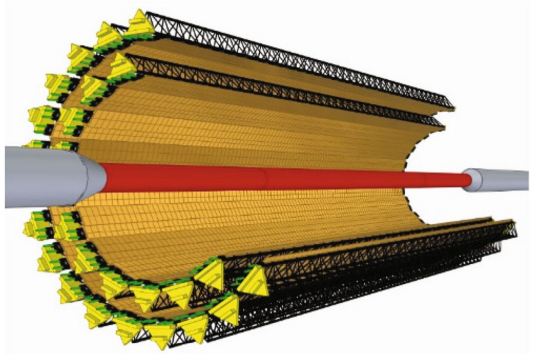
ALICE ITS2



sPHENIX MVTX @RHIC

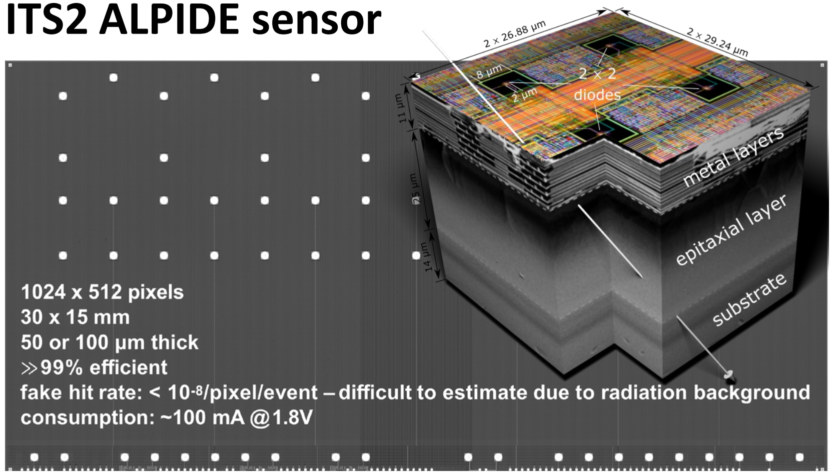


MPD Inner Tracker @NICA

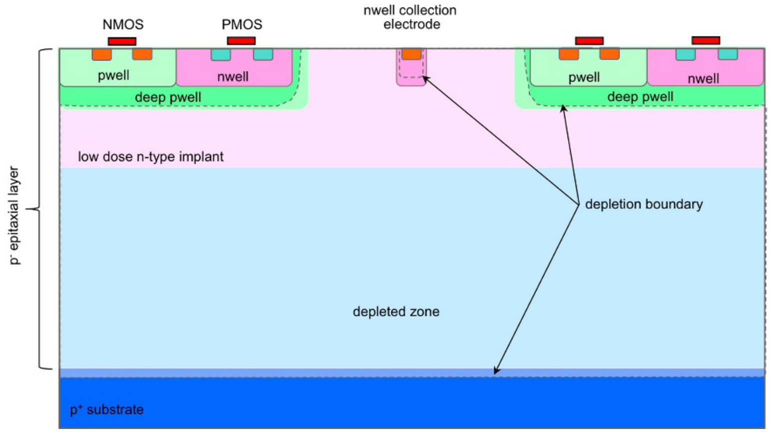


- **Detector replicas** for new experiments

ITS2 ALPIDE sensor



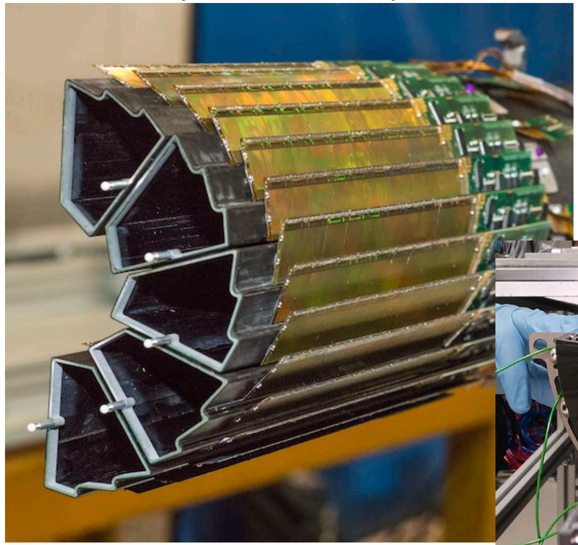
- **Modified process** developed and prototyped within ALPIDE R&D for better timing and radiation hardness



- Now adopted or considered by future experiments...
  - HADES, CBM, PANDA, NUSTAR, NA61, CSES2-Limadou, iMPACT, COMPASS++/AMBER, pCT, ePIC ...
- & chip developments:
  - MALTA,
  - CLICpix,
  - FastPix, ...

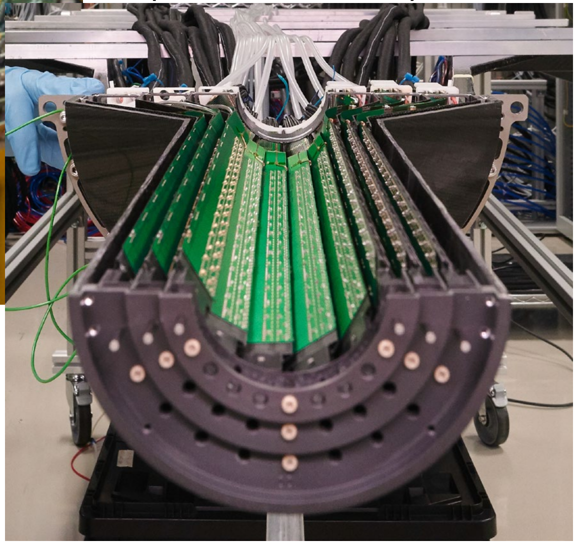
The next MAPS development for HEP

STAR HFT
(2014-2016)



Material: 0.4%X_0
Minimum radius: 2.8 cm
Pixel pitch: ~ 21 μm

ALICE ITS2
Inner Barrel
(2021 - 2025?)

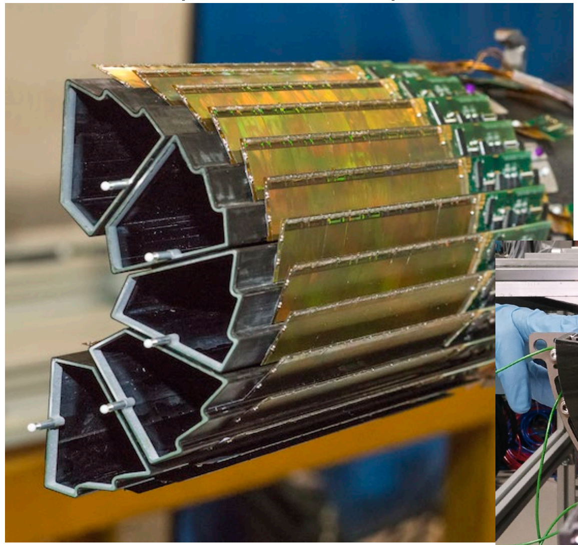


Material: 0.3%X_0
Minimum radius: 2.3 cm
Pixel pitch: ~ 30 μm

How can we do better than this?

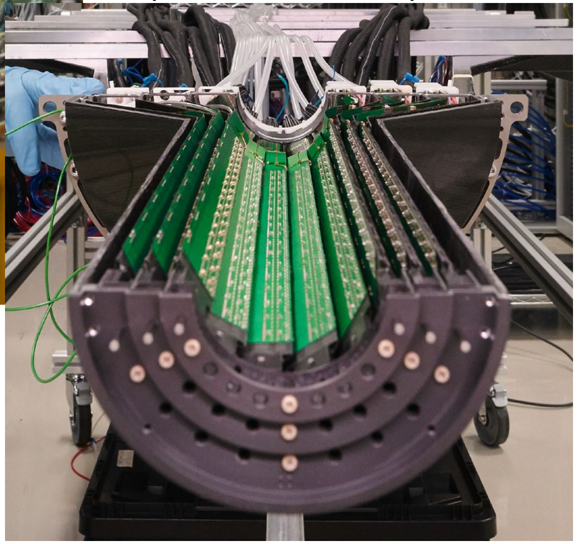
The next MAPS development for HEP

STAR HFT
(2014-2016)



Material: 0.4%X_0
Minimum radius: 2.8 cm
Pixel pitch: ~ 21 μm

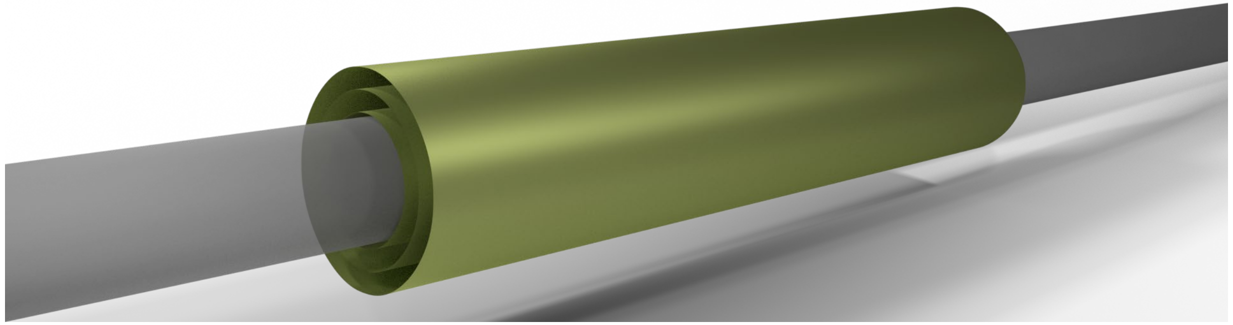
ALICE ITS2
Inner Barrel
(2021 - 2025?)



Material: 0.3%X_0
Minimum radius: 2.3 cm
Pixel pitch: ~ 30 μm

A truly-cylindrical, 'silicon-only' detector to achieve unprecedented tracking performance at low transverse momenta.

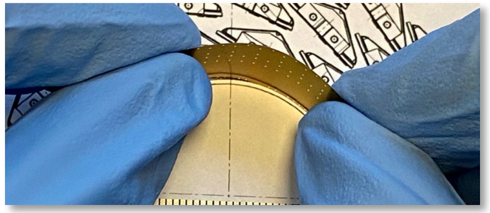
ALICE ITS3
(2027 - ?)

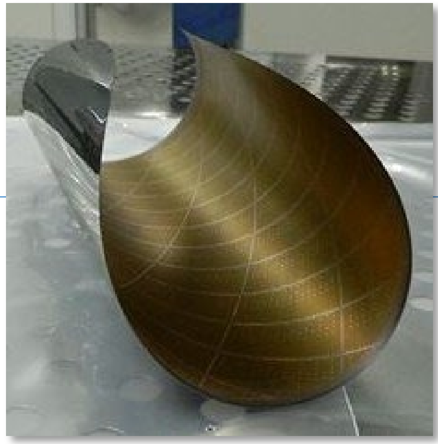


Material: < 0.05%X_0
Minimum radius: ~1.8 cm
Pixel pitch: < 25 μm

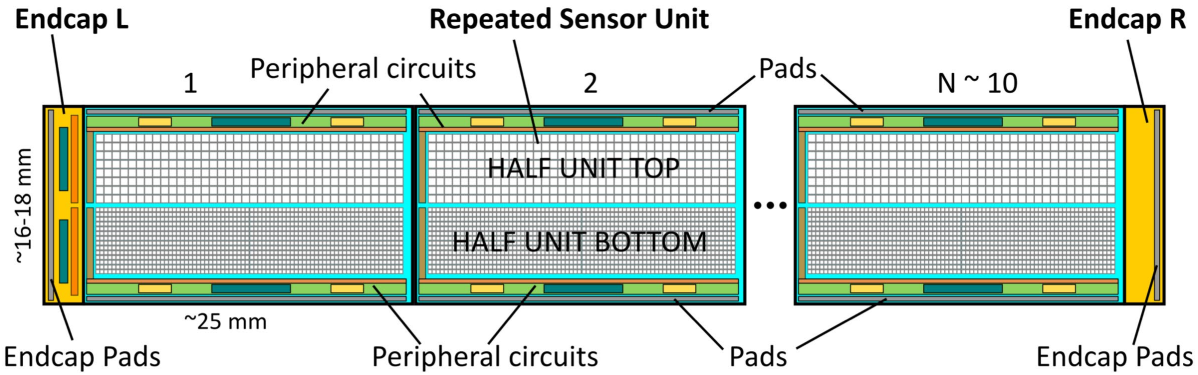
See M. Suljic's talk @ this conference!

ITS3 silicon-only layers





- **Curved geometry**
  - Silicon becomes flexible below 50 µm thickness
- **Large area** chips to reduce segmentation and interconnections
  - 30 cm wafers
  - Stitched design: *possible architecture* →
    - abutting identical but functionally independent units
    - connect metal traces for power distribution and long range on-chip interconnect busses
    - repeat in vertical direction to match layer size



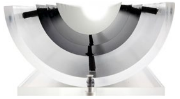
- **TPSCo 65 nm CMOS process** exploration
  - First submission containing test structures now characterised
  - Performance meeting ITS3 requirements

featuring: →

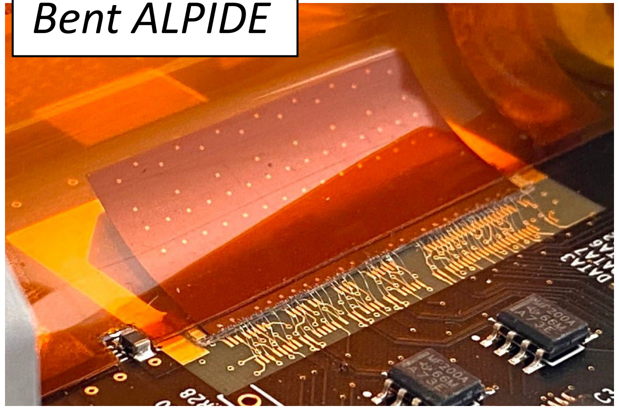
- ❖ 30 cm wafers (vs 20 cm in 180 nm)
- ❖ 2D stitching experience
- ❖ Smaller feature size → smaller pixels

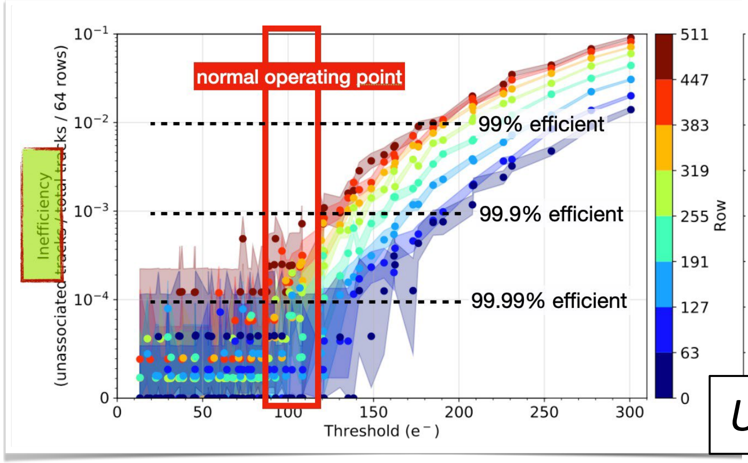
Bent silicon validation

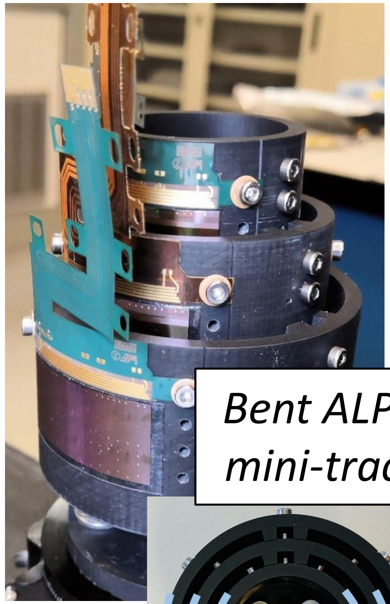
ALICE ITS3

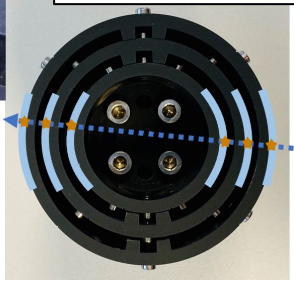


Bent ALPIDE









Bent ALPIDE mini-tracker

Unchanged efficiency

doi:10.1016/j.nima.2021.166280

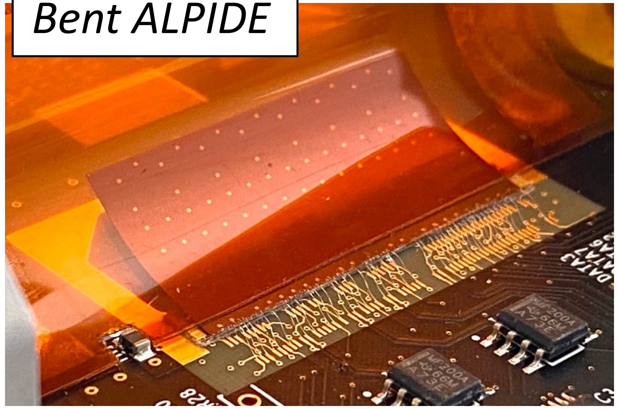
Bent silicon works!

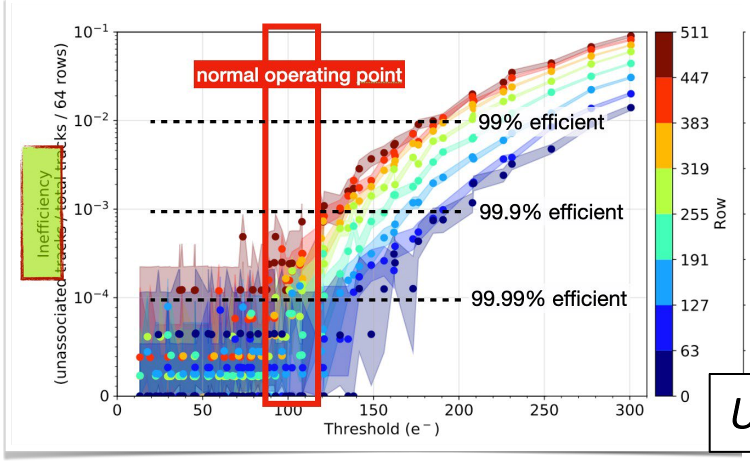
ALICE ITS3

Bent silicon validation

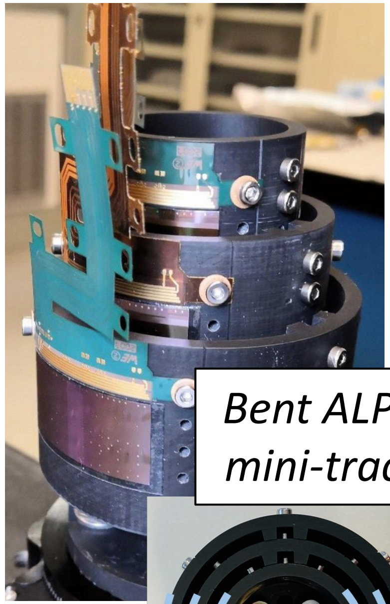
Process validation

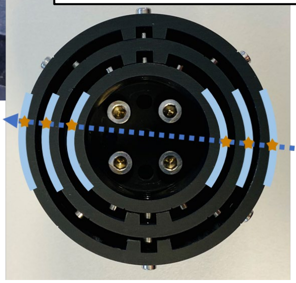
Bent ALPIDE





Bent ALPIDE mini-tracker

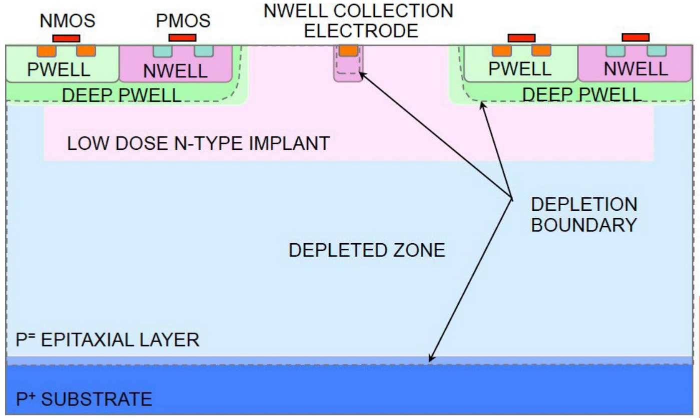




Unchanged efficiency

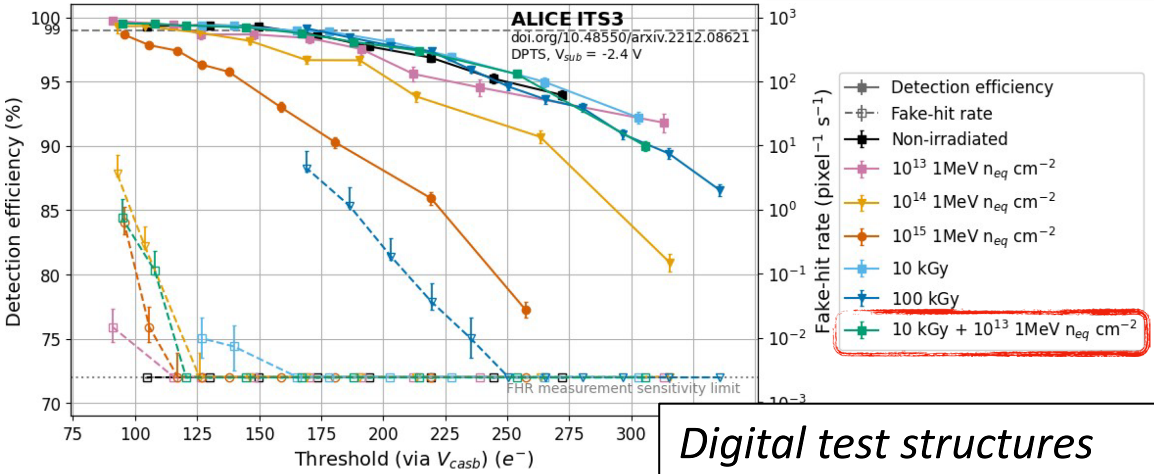
doi:10.1016/j.nima.2021.166280

Bent silicon works!



65 nm CMOS modified process with gap

M. Buckland's poster @ this conference!



Digital test structures efficient after irradiation

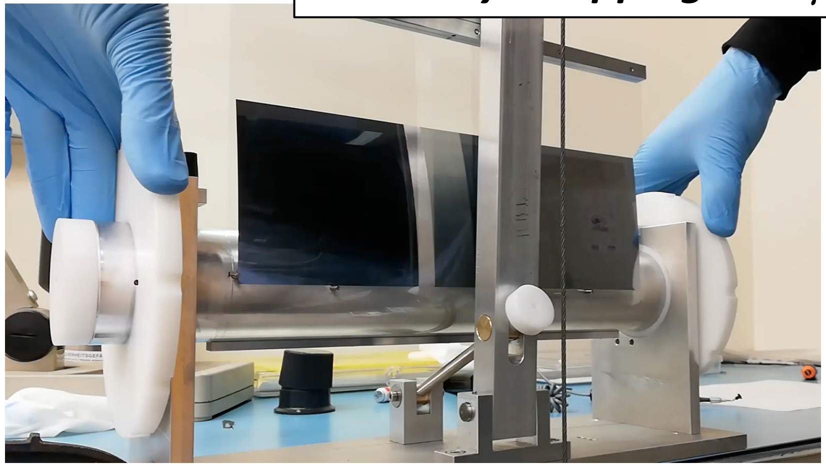
doi:10.48550/arXiv.2212.08621

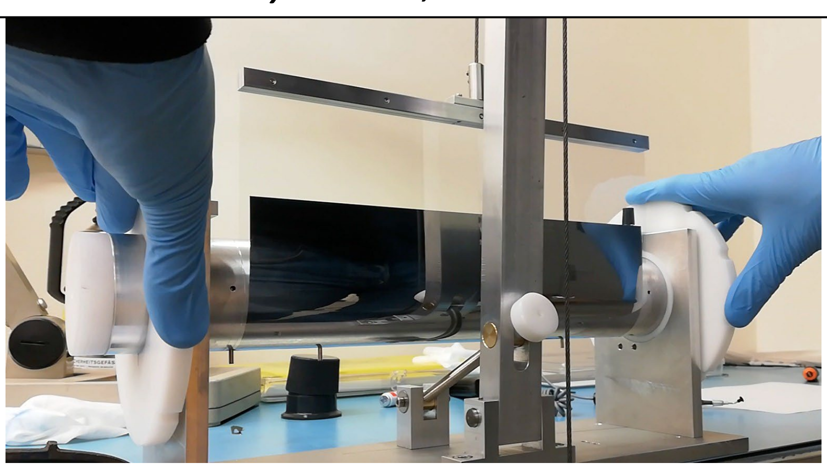
65 nm CMOS meets ITS3 requirements!

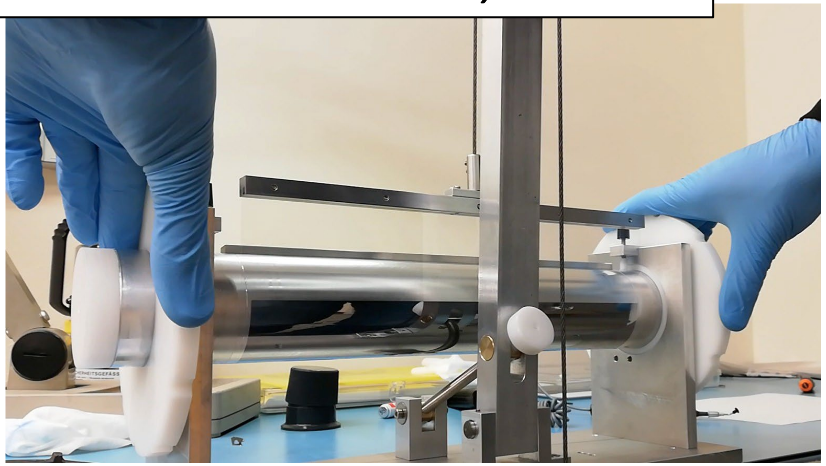
Manual bending and assembly

ALICE ITS3

***Manually wrapping** a 50 μm thick dummy sensor, ~10 x 28 cm^2 around the 3 cm radius assembly mandrel*







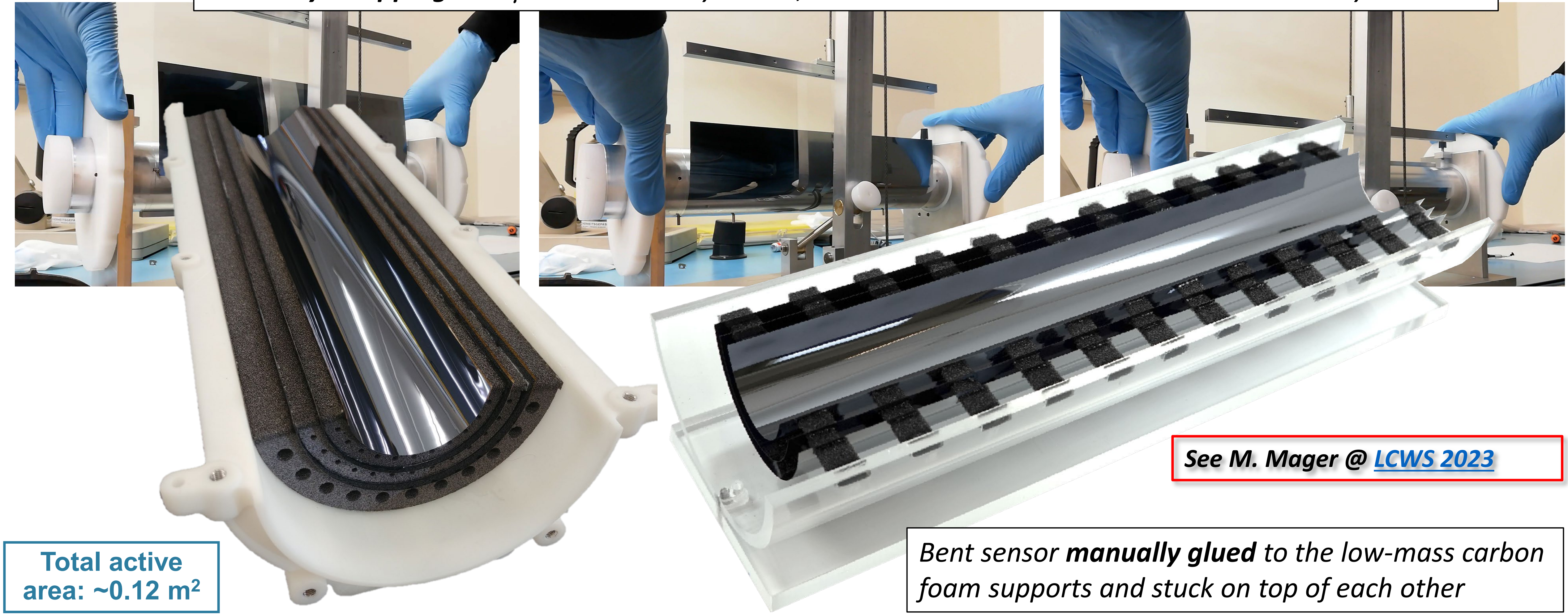
See M. Mager @ LCWS 2023

Total active area: ~0.12 m^2

Manual bending and assembly

ALICE ITS3

Manually wrapping *a 50 μm thick dummy sensor, ~10 x 28 cm^2 around the 3 cm radius assembly mandrel*



See M. Mager @ LCWS 2023

Bent sensor ***manually glued*** *to the low-mass carbon foam supports and stuck on top of each other*

Total active area: ~0.12 m^2

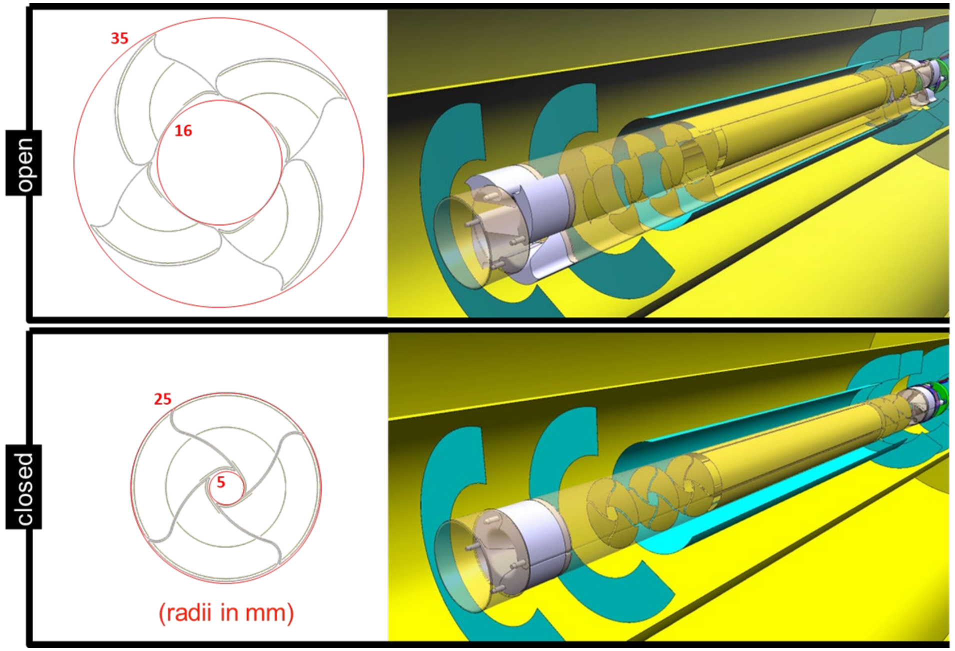
Future challenges for MAPS-based trackers - 1

- Improve radiation tolerance and develop mechanics to place the detector directly ‘in the beam’

→ **ALICE 3 Experiment,** proposed for LHC LS4 (2034)

- **ALICE 3 Vertex Layers**: curved sensors at 5 mm from the interaction point
  - Expected **NIEL**: 10^{16} 1MeV n_{eq} / cm^2 **~1000x ITS3 level**
    - Improve doping profiles in modified process
  - Expected **TID**: 300 Mrad **~300x ITS3 level**
    - Extend tests to understand limitations
  - **Retractable mechanics** inside the beam pipe
  - **Vacuum-compatible** services and interconnections

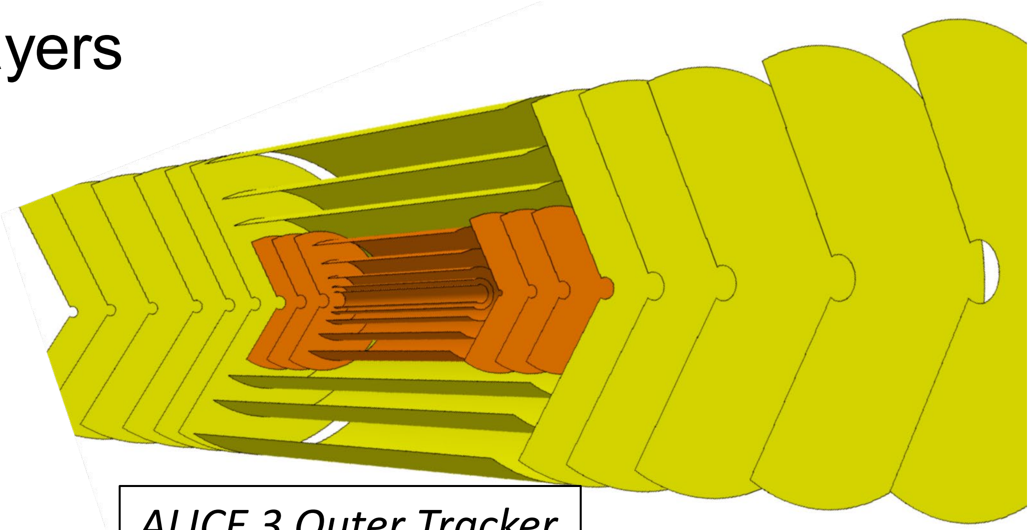
See M. Mager @ FCC Week 2023



Future challenges for MAPS-based trackers - 2

- Cover **extra-large areas** on barrel and disk layers
  - **ALICE 3 Outer Tracker ~60 m^2**
    - **Industrialisation** of the production
      - Module layout complying with industrial standards
    - **Specific sensor** development
      - Extremely low power consumption (≈ 20 mW/cm^2)
      - Larger pixel pitch to reduce data and power

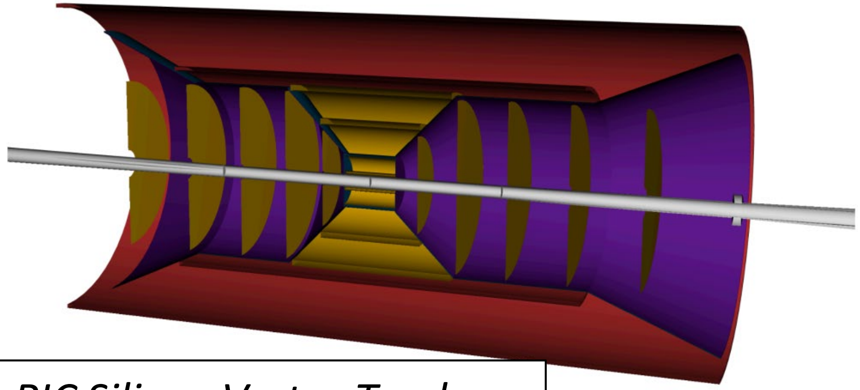
See M. Mager @ FCC Week 2023



ALICE 3 Outer Tracker

  - **ePIC Silicon Vertex Tracker, proposed for EIC (2034)**
    - Based on ALICE ITS3 sensor
    - Stitched sensor size adapted for **yield optimisation**

See X. Li @ Vertex 2022



ePIC Silicon Vertex Tracker

Summary: the sensor

MIMOSA Ultimate-2

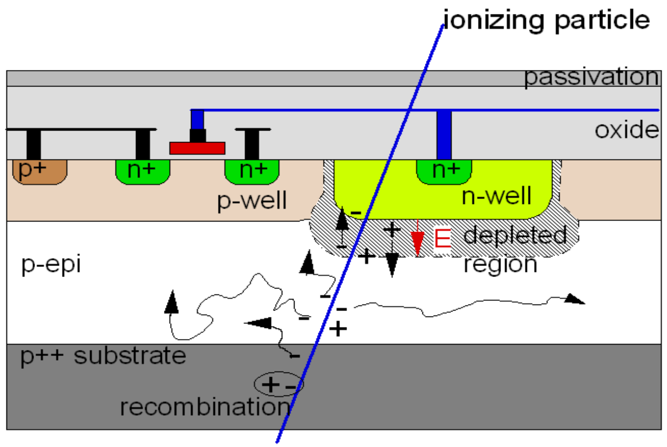
- **AMS 350 nm** CMOS
- Twin-well process
- In-pixel **NMOS** transistors only
- **Rolling-shutter** readout
- (ρ > 0.4kΩ·cm) p-type epitaxial
- **Collection mostly by diffusion** + drift in the built-in depletion

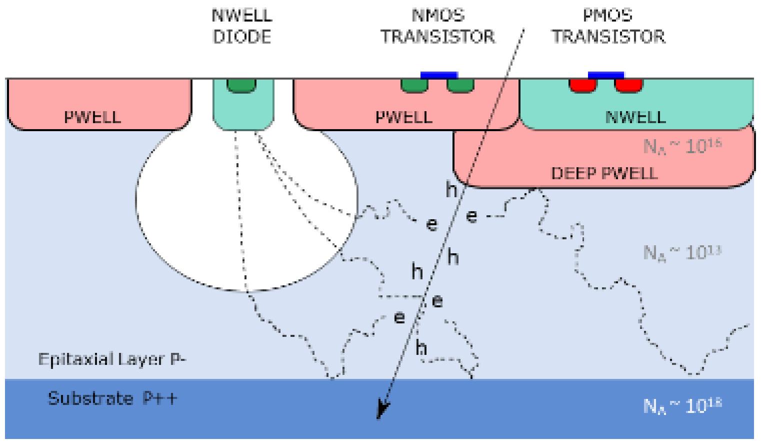
ALPIDE

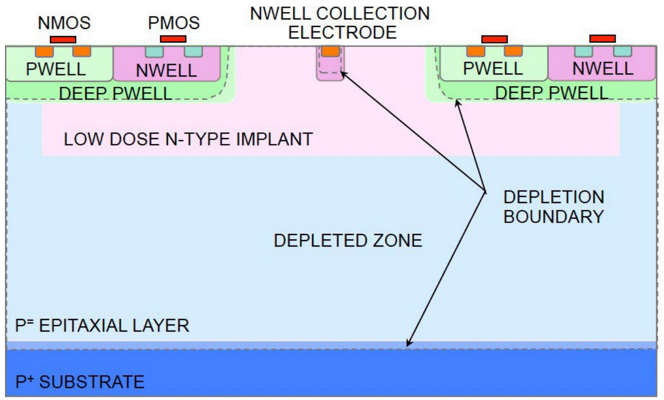
- **TowerJazz 180 nm** CMOS
- Quadrupole-well technology
- Deep-pwell for in-pixel **full CMOS**
- **Hit-driven** readout
- (ρ > 1kΩ·cm) p-type epitaxial (~25μm) on p-type substrate
- Depleted **drift region expanded** through reverse bias (0-6V)

ITS3 sensor

- **TPSCo 65 nm** CMOS
- Deep-pwell for in-pixel **full CMOS**
- **Hit-driven** readout
- **Modified process** for planar depletion + **gaps** for efficient collection from the edges
- **Uniformly and fully depleted** epi-layer







Summary: the sensor

MIMOSA Ultimate-2

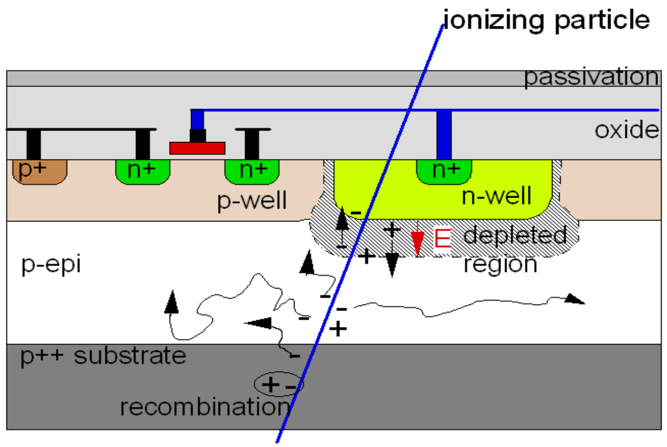
- **AMS 350 nm** CMOS
- Twin-well process
- In-pixel **NMOS** transistors only
- **Rolling-shutter** readout
- (ρ > 0.4kΩ·cm) p-type epitaxial
- **Collection mostly by diffusion** + drift in the built-in depletion

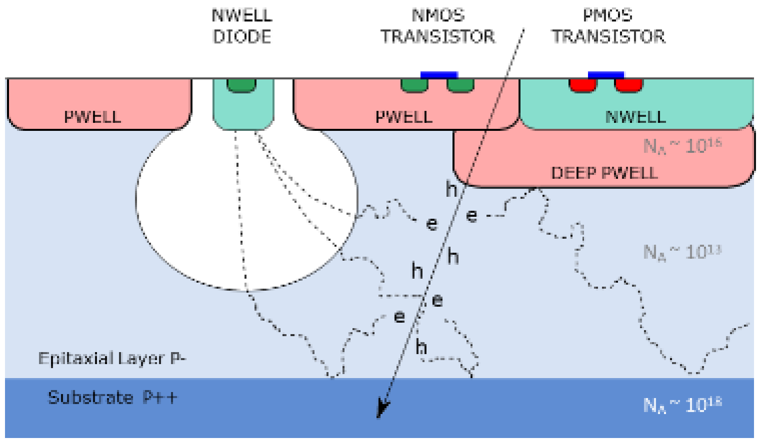
ALPIDE

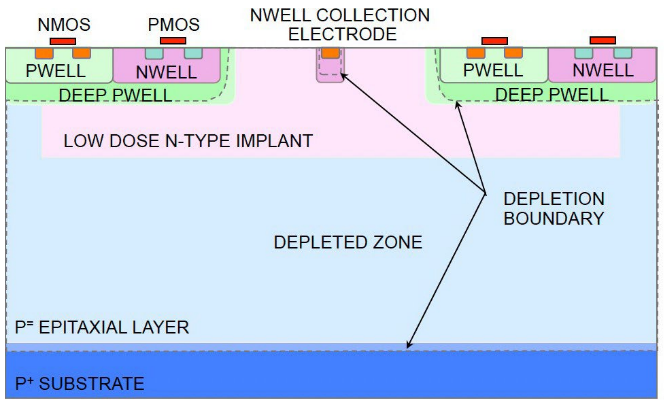
- **TowerJazz 180 nm** CMOS
- Quadrupole-well technology
- Deep-pwell for in-pixel **full CMOS**
- **Hit-driven** readout
- (ρ > 1kΩ·cm) p-type epitaxial (~25μm) on p-type substrate
- Depleted **drift region expanded** through reverse bias (0-6V)

ITS3 sensor

- **TPSCo 65 nm** CMOS
- Deep-pwell for in-pixel **full CMOS**
- **Hit-driven** readout
- **Modified process** for planar depletion + **gaps** for efficient collection from the edges
- **Uniformly and fully depleted** epi-layer



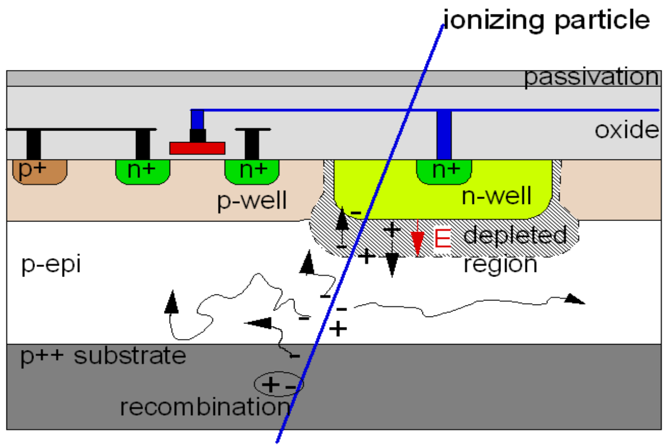




Summary: the sensor

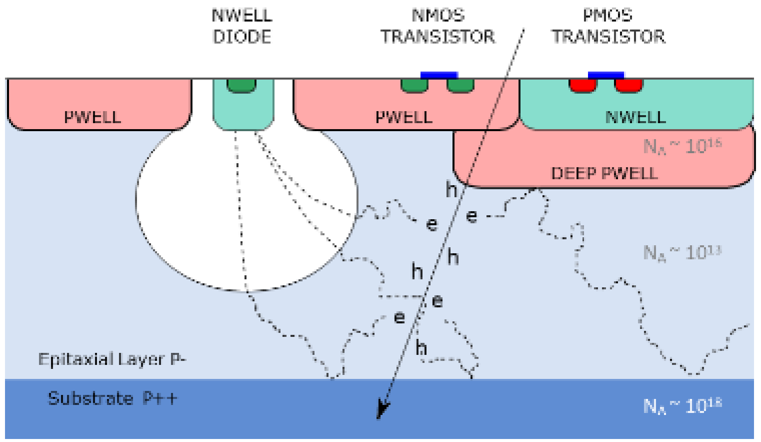
MIMOSA Ultimate-2

- **AMS 350 nm** CMOS
- Twin-well process
- In-pixel **NMOS** transistors only
- **Rolling-shutter** readout
- (ρ > 0.4kΩ·cm) p-type epitaxial
- **Collection mostly by diffusion** + drift in the built-in depletion



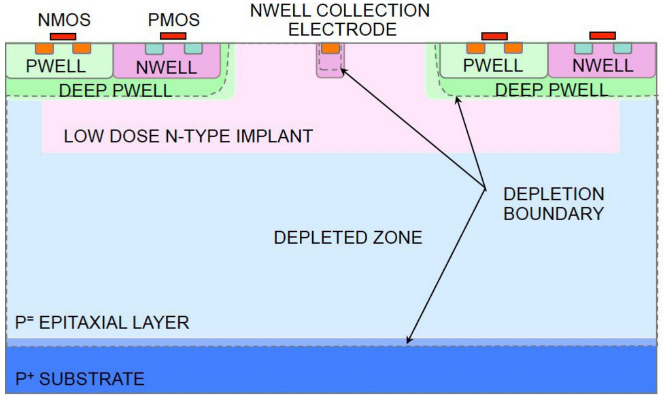
ALPIDE

- **TowerJazz 180 nm** CMOS
- Quadrupole-well technology
- Deep-pwell for in-pixel **full CMOS**
- **Hit-driven** readout
- (ρ > 1kΩ·cm) p-type epitaxial (~25μm) on p-type substrate
- Depleted **drift region expanded** through reverse bias (0-6V)



ITS3 sensor

- **TPSCo 65 nm** CMOS
- Deep-pwell for in-pixel **full CMOS**
- **Hit-driven** readout
- **Modified process** with low dose for planar depletion **+ gaps** for efficient collection from the edges
- **Uniformly and fully depleted** epi-layer



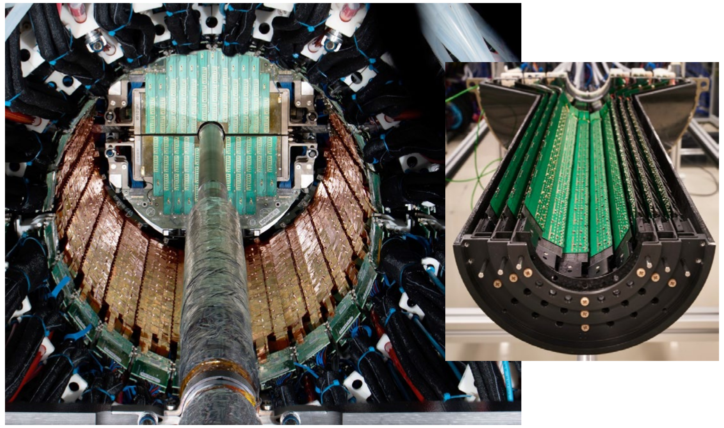
Summary: the apparatus

STAR HFT Pixel

- **2 vertexing layers**
- ~356 Mpixel on 0.16 m^2
- Traditional stave layout in turbo-like geometry
- 50 μm sensors on carbon fiber supports + FPC
- Air cooled
- Inner layer $X/X_0 = 0.39\%$

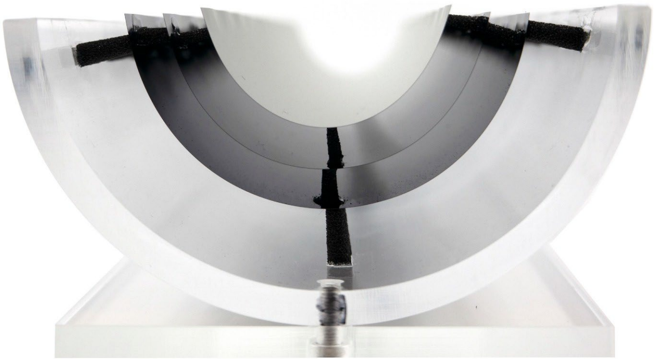
ALICE ITS2

- **7-layer tracker** – Inner(-Outer) layers
- ~12.5 Gpixels on 10 m^2
- Traditional (module-)stave layout in turbo-like or staggered geometry
- 50(/100) μm sensors on carbon fiber + FPC (+ power bus)
- Water cooled
- Inner layer $X/X_0 = 0.35\%$



ALICE ITS3

- **3 vertexing layers** (~0.12 m^2) integrated in ITS2 tracker
- Truly-cylindrical layer layout
- ~40 μm sensors on minimal carbon foam supports
- No in-acceptance data/power bus
- Air cooled
- Inner layer $X/X_0 = 0.05\%$



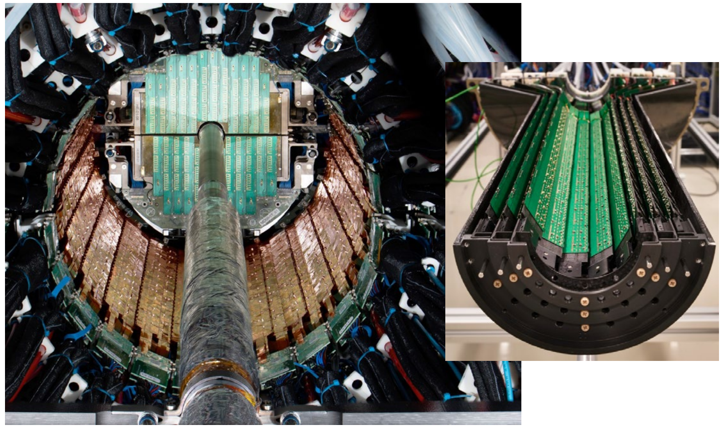
Summary: the apparatus

STAR HFT Pixel

- **2 vertexing layers**
- ~356 Mpixel on 0.16 m^2
- Traditional stave layout in turbo-like geometry
- 50 μm sensors on carbon fiber supports + FPC
- Air cooled
- Inner layer **X/X_0 = 0.39%**

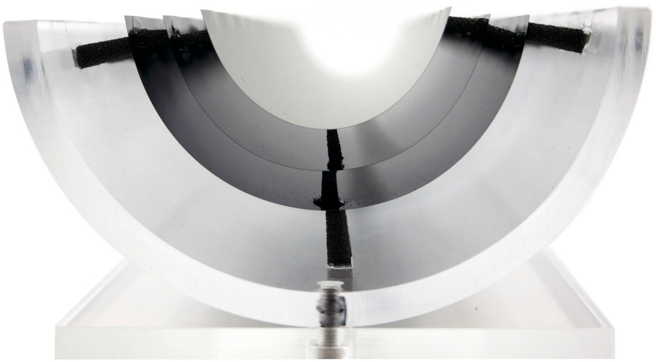
ALICE ITS2

- **7-layer tracker** – Inner(-Outer) layers
- ~12.5 Gpixels on 10 m^2
- Traditional (module-)stave layout in turbo-like or staggered geometry
- 50(/100) μm thin sensors on carbon fiber + FPC (+ power bus)
- Water cooled
- Inner layer **X/X_0 = 0.35%**



ALICE ITS3

- 3 vertexing layers (~0.12 m2) integrated in ITS2 tracker
- Truly-cylindrical layer layout
- ~40 μm thin sensors on minimal carbon foam supports
- No in-acceptance data/power bus
- Air cooled
- Inner layer **X/X_0 = 0.05%**



Final considerations

- The HEP experiment requirements **pushed the sensor technology** to the current specifications and performance
- Innovative solutions for sensor, layout and mechanics developed for HEP goals are now **enabling new detector concepts**, made available for any application

- The **construction approach** depends on detector area and layout complexity:
  - From manual to semi-automated, to fully industrialised procedure as the area increases
- **Novel technologies**, fresh from R&D, quickly embedded in operating detectors, **need risk mitigation strategies**:
  - Engineering run (HFT), long-period commissioning (ITS2), spare detector copies for relatively quick replacement in case of failure

- **Higher radiation tolerance** and **larger areas** are the next challenges for MAPS

Thank you for your attention!