CHARACTERISATION OF THE ITS3 ANALOGUE PIXEL TEST STRUCTURES PRODUCED IN THE 65 nm TPSCo PROCESS

Rebekka Wittwer on behalf of **ALICE**

19th TREDI Workshop on Advanced Silicon Radiation Detectors

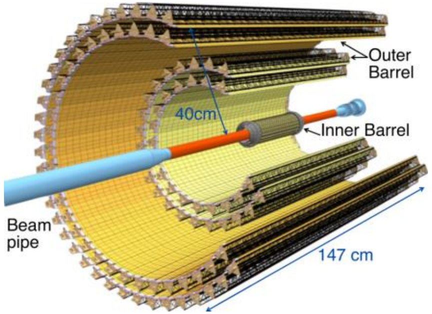
ALICE Inner Tracking System

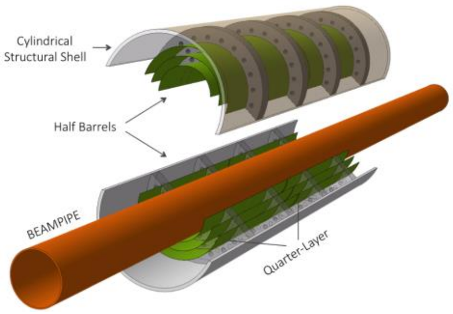
ITS2

- **Largest pixel detector in high energy physics**
- 7 Layers
- 10 m^2 active area

- 24k 180 nm CMOS MAPS
- 12.5 GPixel **ALPIDE** chip
- Stable, **> 99 % functional**

- Material budget: **0.35 % X/X_0**
- Beam pipe radius: 18.2 mm
- Radial position: 24 mm
- Water cooling





ITS3

- Replace three innermost layers of ITS2
- **Ultra thin** (50µm) **and bendable** → half-cylindrical detection layers with self-supported arched structure

- Commercial **65 nm CMOS** imaging technology and stitching

- Material budget: **0.05 % X/X_0**
- Beam pipe radius: 16 mm
- Radial position: 18 mm
- Air cooling

ALICE Inner Tracking System

ITS2

- **Largest pixel detector in**
  energy physics
- 7 Layers
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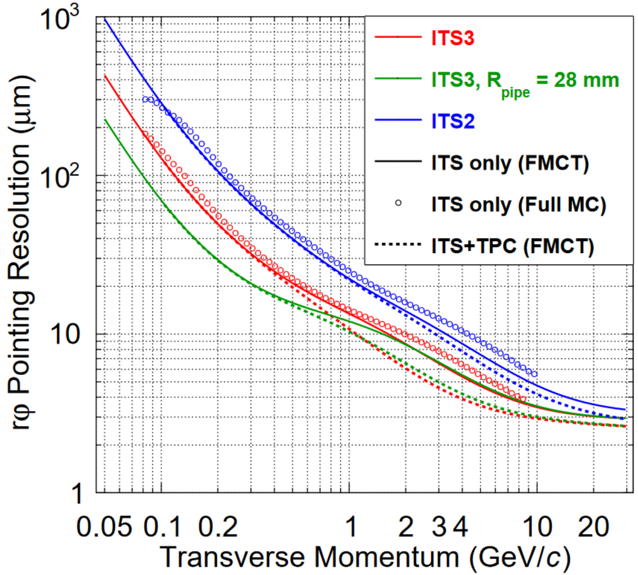
- Water cooling

Improvement of factor 2 over all momenta



3

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Synergy with Lepton Colliders

How can FCC-ee benefit from ALICE ITS3 developments?

ALICE ITS3 is a stepping stone for lepton colliders with similar requirements:

- Moderate radiation environment
- Low material budget and high spatial resolution is crucial
- First layer closer to the beam pipe for better IP resolution

	ALICE ITS3	FCC-ee
Position Precision	5 µm	3 µm
Low X/X_0	0.05 %	0.3 %
Radiation Tolerance NIEL	$< 10^{13}$	$< 10^{13}$

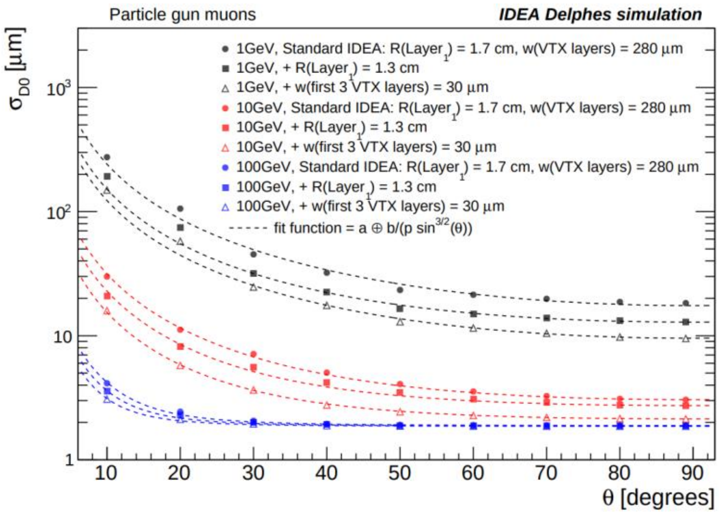
Future collider groups joined the ITS3 efforts:

M. Mager, FCCW2023

D. Contardo, FCCW2023

F. Palla, FCCPW2024

A. Ilg, FCCPW2024



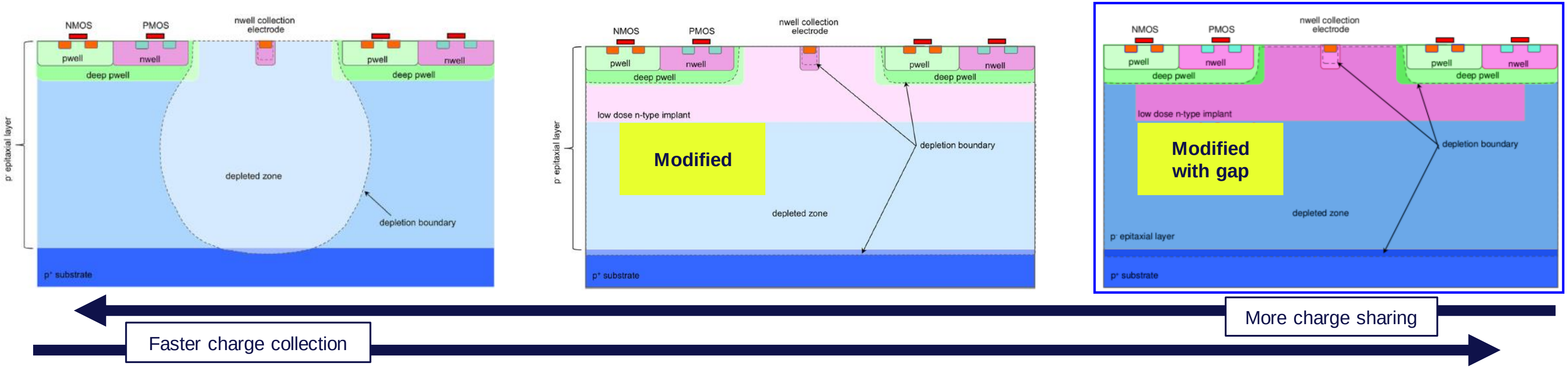
L. Freitag & A. Ilg, FCCPW

L. Freitag, Bachelor Thesis

ECFA Detector R&D Roadmap

TPSCo 65 nm Process and Modifications

How do we characterise this process?

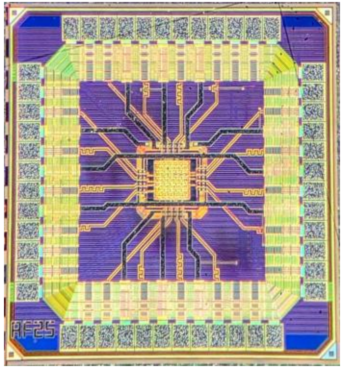


- **Deep p-well** shields the CMOS circuitry from collecting charge
- Low capacitance of the **small collection electrode** results in lower power consumption
- Applying substrate bias increases depletion and improves radiation tolerance

- Further modifications needed for the full depletion of the sensitive layer:
  - **Modified**: to reach full depletion
  - **Modified with gap**: more control over charge sharing

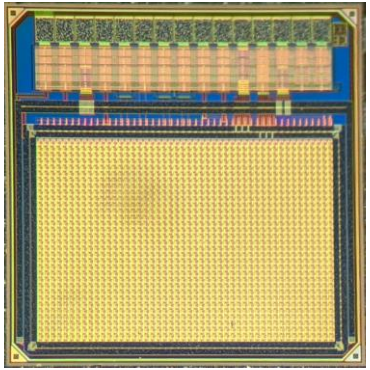
180 nm CMOS Pixel Sensors

ITS3: Pixel Prototype Chips



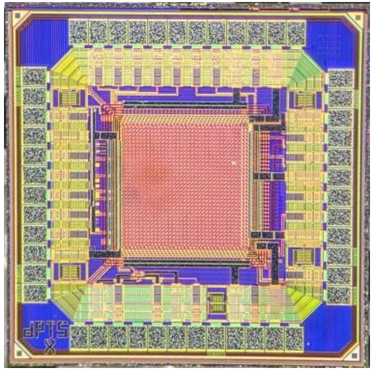
APTS

- 6x6 pixel matrix
- Direct analog readout of central 4x4 pixels
- Pitch: 10, 15, 20, 25 μm



CE65

- 64x64 [v1], 48x32 [v1], 48x24 [v2] pixel matrix
- Rolling shutter analog readout
- Pitch: 15, 25 μm



DPTS

- 32x32 pixel matrix
- Asynchronous digital readout with ToT
- Pitch: 15 μm

APTS, CE65, DPTS

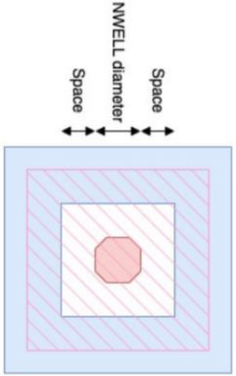
Variants of APTS

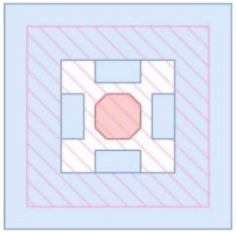
To study the influence on capacitance and charge collection, different variance of the geometry and size of p-well and n-well collection electrode were produced:

- **Reference**
- **Larger n-well collection electrode**
- **Finger-shaped p-well enclosure**
- **Smaller p-well enclosure**

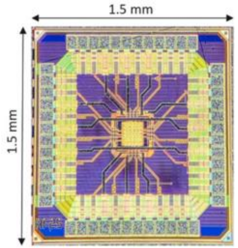
P-Type: only reference variant on chip
Multiplexer: all four variants on same chip

Comparison of: pitches, variants and irradiation damage

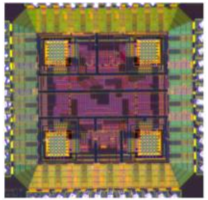




P-Type



Multiplexer



TESTING APTS

Lab Measurements

Lab Measurement Setup with Fe-55 Source

Fe55
radioactive source

DAQ Board
hosts the FPGA

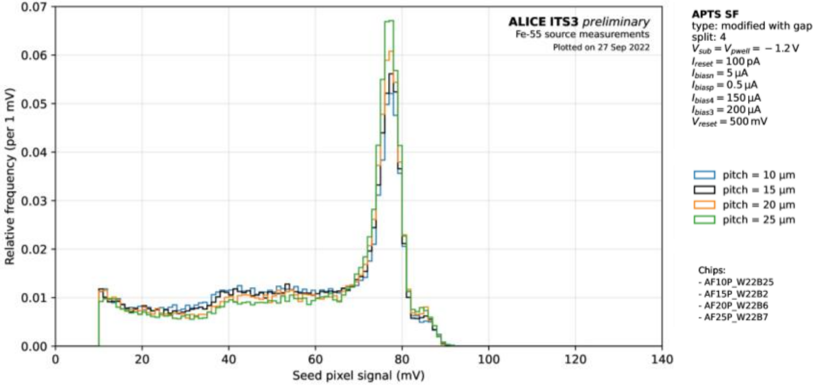
Proximity Board
sets voltages &
hosts ADCs

Carrier Board
hosts the chip

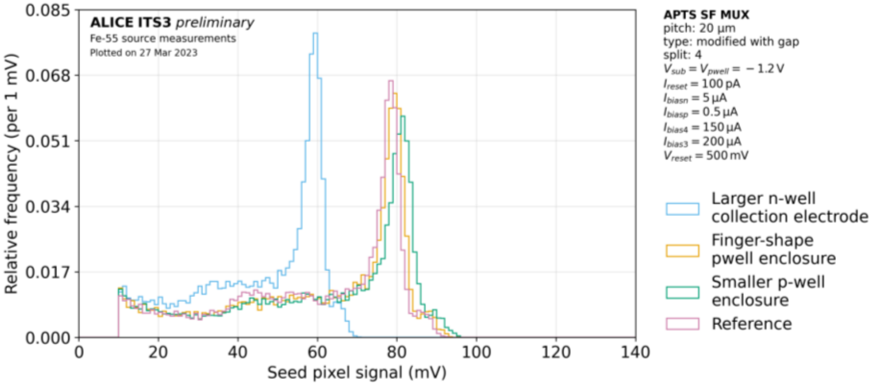
- Water cooling used to set a **standard temperature** during tests (16°-20°C)
- The measurement of the **Fe-55 spectrum** is used to **calibrate** the sensor readout to the collected charge at different **bias voltages**

Charge Collection

Pitch Comparison



Variant Comparison

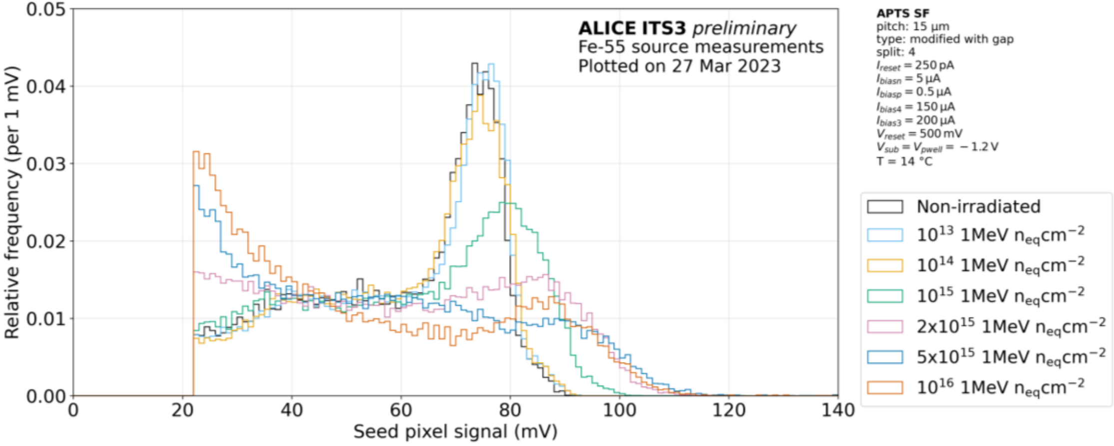


- The entire generated charge is collected pointing to the **near-full depletion** of the sensitive layer
- All pitches and variants show similar results indicating **efficient charge collection**
- Freedom to choose pitch depending on application

- Sensor variant with **higher capacitance** leads to **lower signal** in mV

Charge Collection

Irradiation Comparison

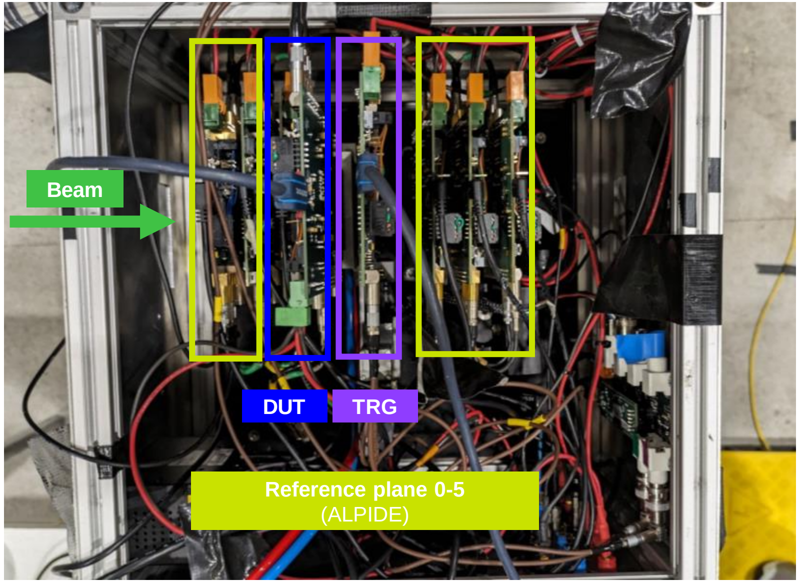


- Up to 10^{14} 1MeV $n_{eq}cm^{-2}$ all similar behaviour (ALICE ITS3 radiation tolerance requirement < 10^{13} NIEL)
- After 10^{14} 1MeV $n_{eq}cm^{-2}$ performance worsens, less charge gets collected and Fe-55 peak becomes less visible

TESTING APTS

Test Beam Measurements

Test Beam Measurement Setup

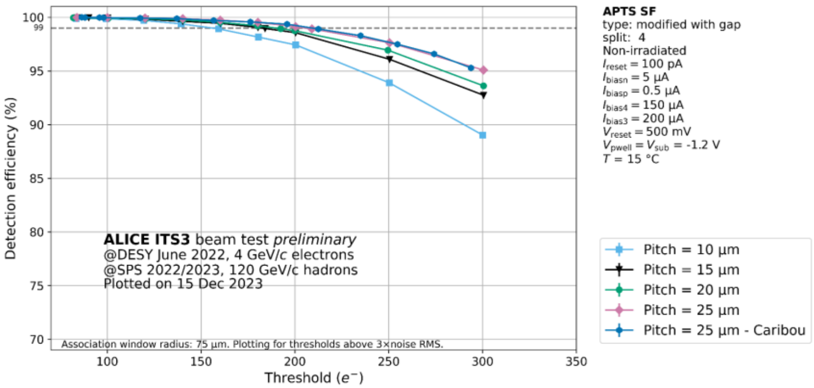


- **6 ALPIDEs** (ITS2) as **reference planes** (not cooled)
- **1 APTS** sensor as **DUT** at standard temperature (~16°C)
- **1 APTS** as **trigger**
- Tested at
  - SPS with **120 GeV hadrons**
  - PS with **10 GeV hadrons**
  - DESY with **0.8-5 GeV electrons**

- The test beam measurements are used to determine the **detection efficiency** and the **spatial resolution**.
- All plots show points above 3 x RMS noise

Pitch Comparison

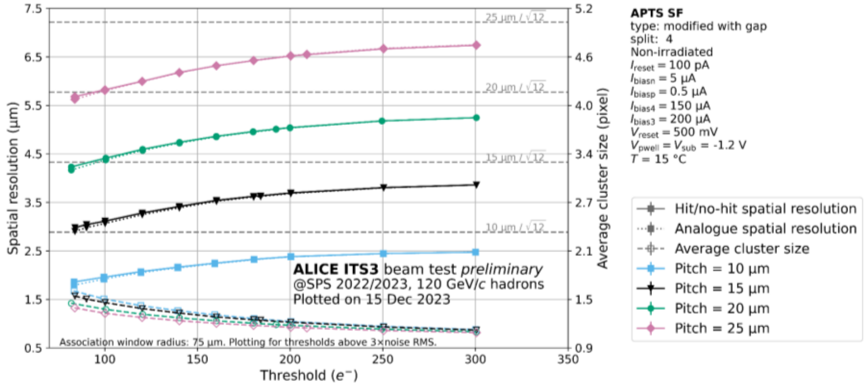
Detection Efficiency



99% efficiency reached for all pitches

- Worse efficiencies at higher thresholds due to more charge sharing
- **Smaller pitches → less range of operation** due to more charge sharing

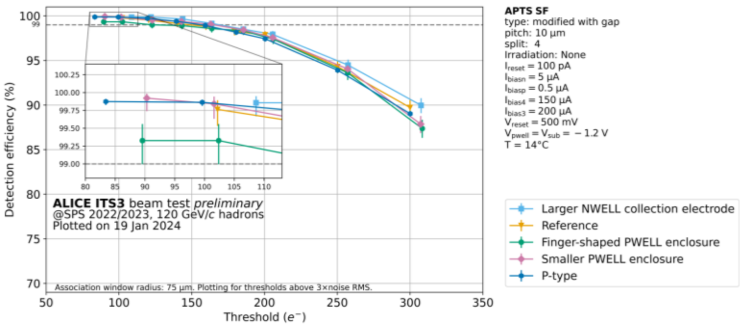
Spatial Resolution



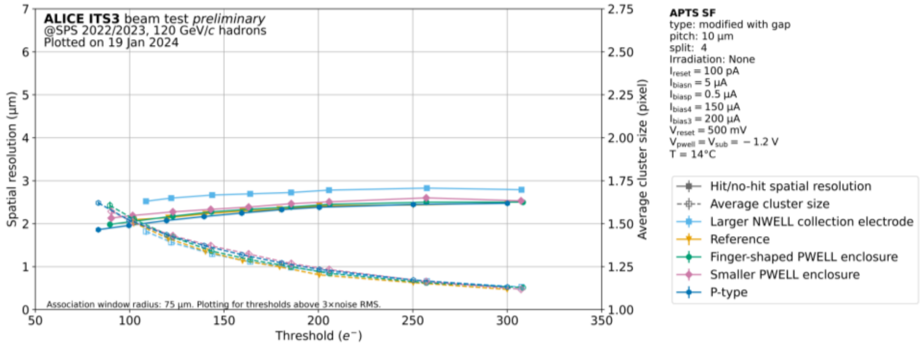
- Spatial resolution better than pitch/$\sqrt{12}$ thanks to charge sharing
- 10 µm pitch sensor: extremely good resolution (<3 µm)

Variant Comparison

Detection Efficiency



Spatial Resolution



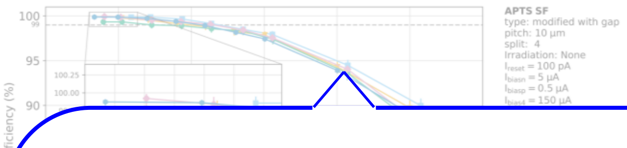
99% efficiency reached for all variants

- RMS noise for multiplexer ~ 13-14% higher than P-type in all cases due to higher currents

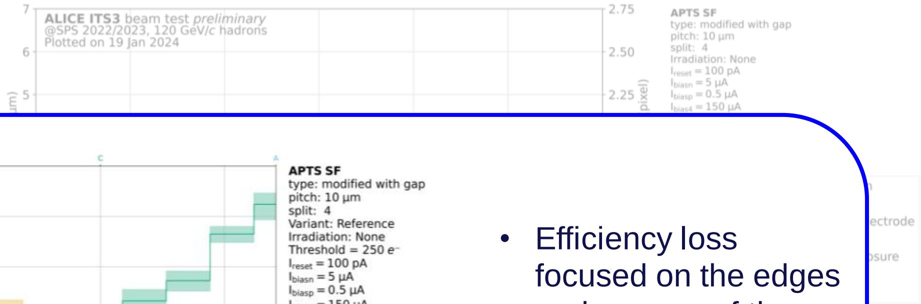
- More **charge sharing improves** the **spatial resolution**
- Little to no impact of sensor geometry except for large n-well variant

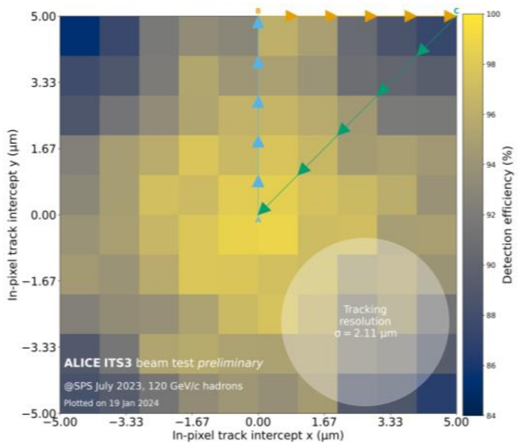
Variant Comparison

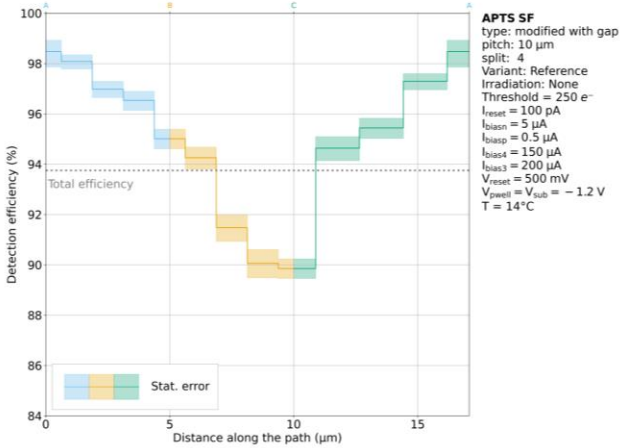
Detection Efficiency



Spatial Resolution





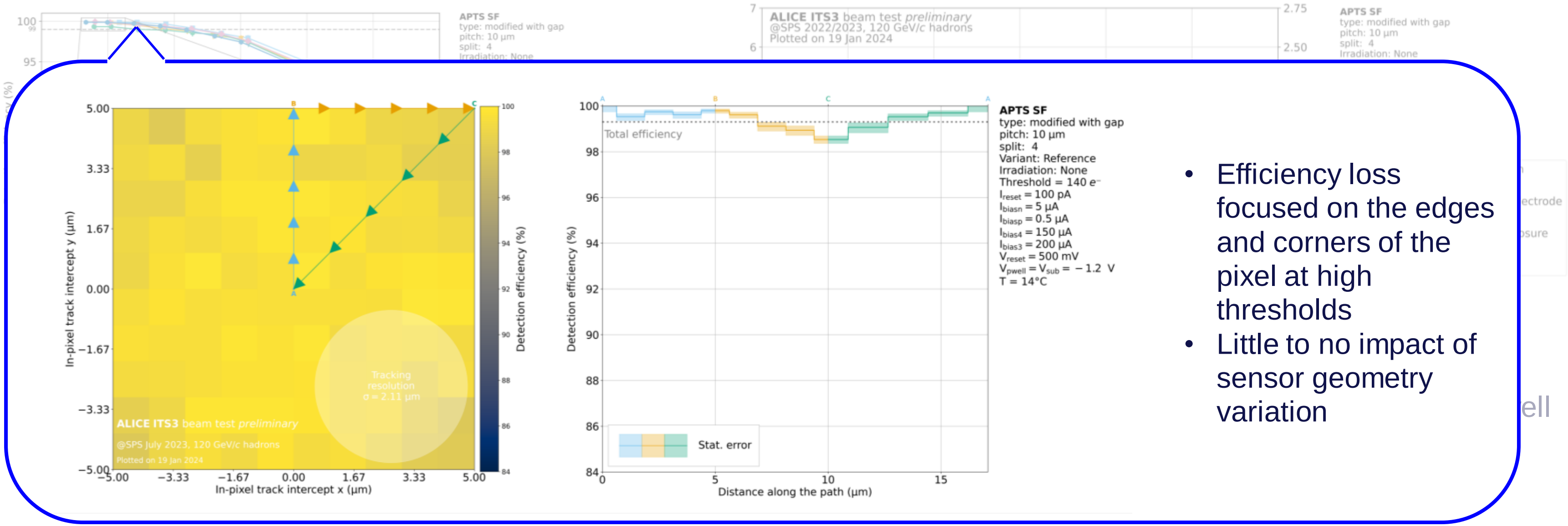


- Efficiency loss focused on the edges and corners of the pixel at high thresholds
- Little to no impact of sensor geometry variation

Variant Comparison

Detection Efficiency

Spatial Resolution



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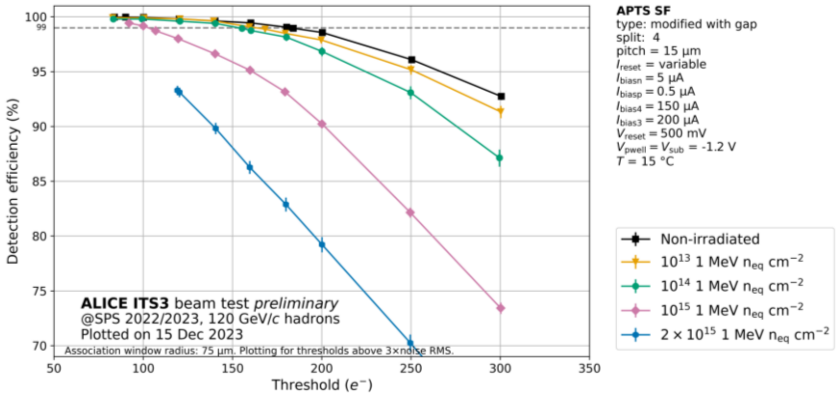
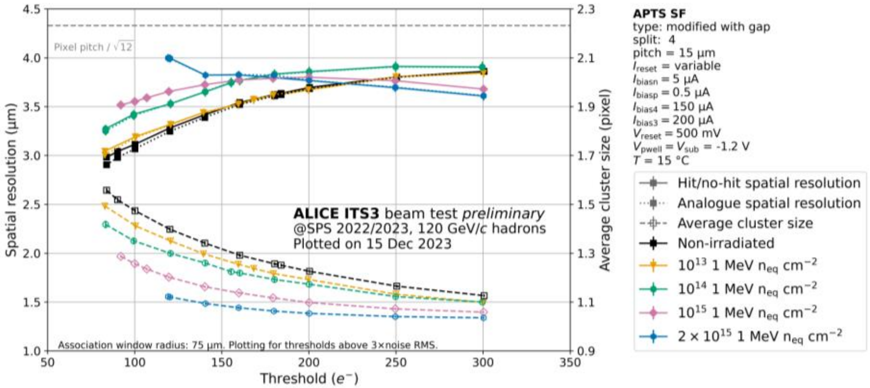
Irradiation Comparison

Detection Efficiency



99% efficiency reachable with irradiation **up to 10^{14} 1MeV $n_{eq}cm^{-2}$** with the application of bias voltage

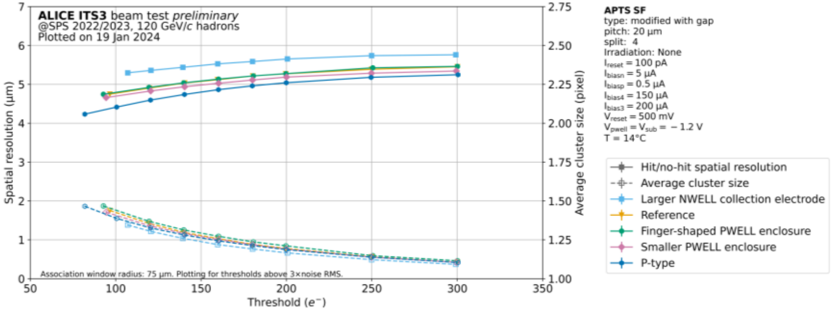
Spatial Resolution



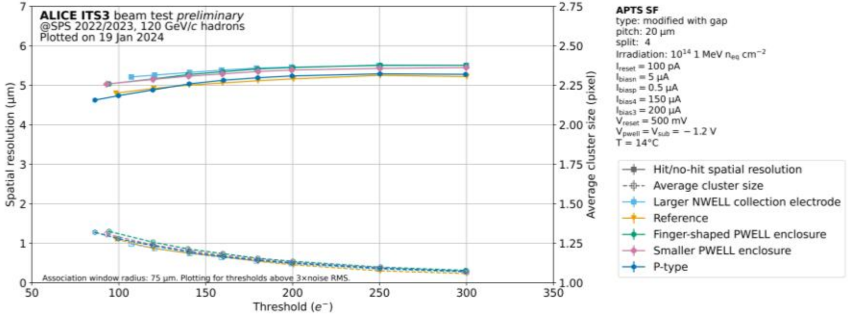
Resolution worsens after a irradiation of 10^{14} 1MeV $n_{eq}cm^{-2}$

Irradiation Comparison

Not Irradiated



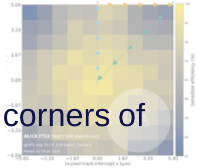
Irradiation: 10^{14} 1MeV $n_{eq}cm^{-2}$



Spatial resolution of **larger n-well less affected by irradiation** thanks to larger collection area but not surpassing performance of other sensor geometries

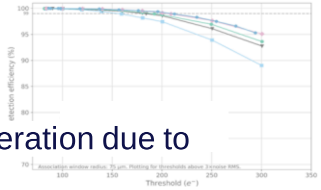
SUMMARY AND OUTLOOK

Summary and Outlook



Charge Collection:
- All pitches and variants very similar
- The entire generated charge is collected pointing to **near-full depletion** of sensitive layer

In-pixel study:
- Efficiency loss focused on the edges and corners of the pixel at high thresholds
- Little to no impact of sensor geometry variation



Efficiency:
- All pitches and variants very similar
- Over **99% efficiency** reached
- Smaller pitches → less range of operation due to charge sharing

Radiation Tolerance:
- All variants very similar, good performance (operation over 99% efficiency) up to the irradiation level of 1e14 NIEL

APTS results show that sensor performance required by ITS3 detector design is feasible

Resolution:
- Effect of charge sharing/cluster size visible
- 10 µm pitch sensor: extremely good resolution (<3 µm)

- Testing of stitched design started
- Assembly of wafer-scale sensors defined
- TDR now with LHCC

Thank you
for your attention.

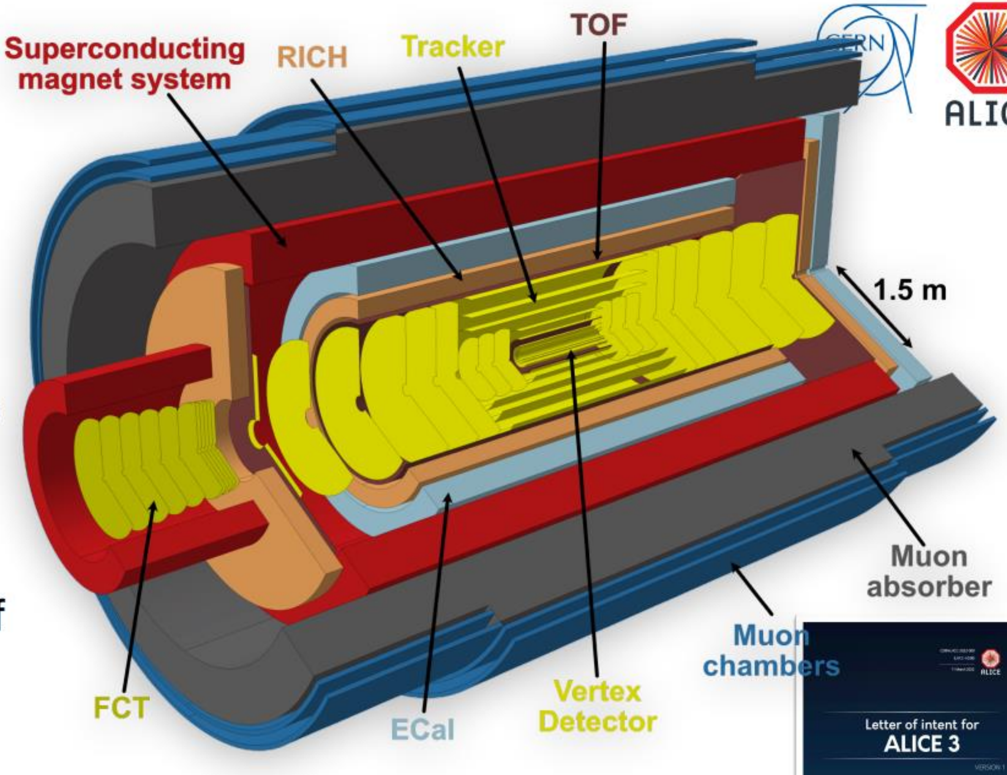
This project has received funding from the European Unions Horizon Europe research and innovation programme under grant agreement No 101057511

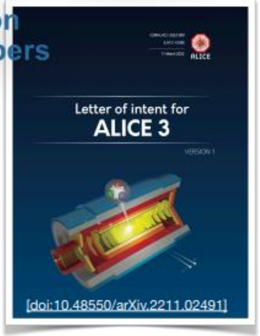
Back-up

ALICE 3

LHC LS4 2033/34

- ALICE 3 is centred around a 60 m² MAPS tracker
  - innermost layers will be based on wafer-scale Silicon sensors "iris tracker", similar to ITS3 (but in vacuum)
  - outer tracker will be based on modules like ITS2 (but order of magnitude larger)
- *This is the next big and concrete step for this technology*

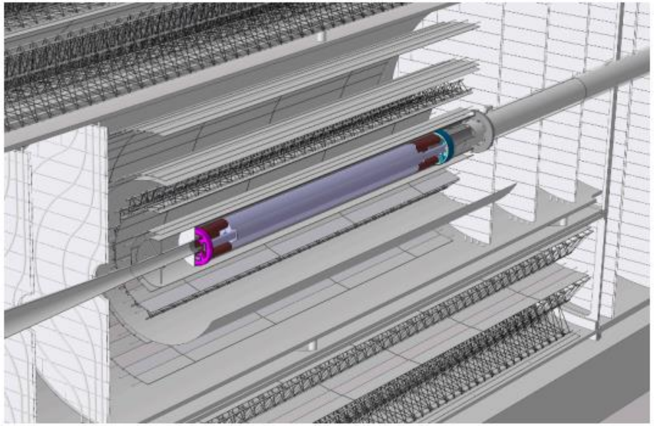


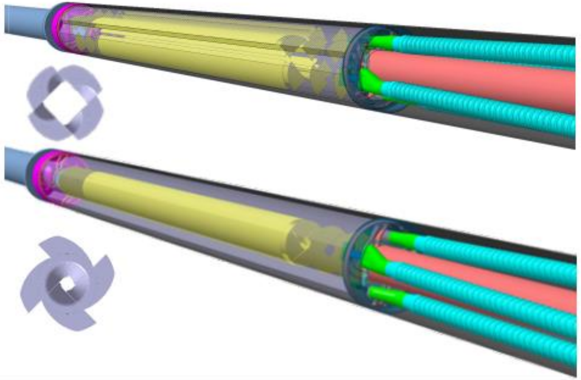


Magnus Mager (CERN) | Si detector development for ALICE ITS3 and ALICE 3 | FCC week, London | 08.06.2023 | 31

ALICE 3

vertex detector



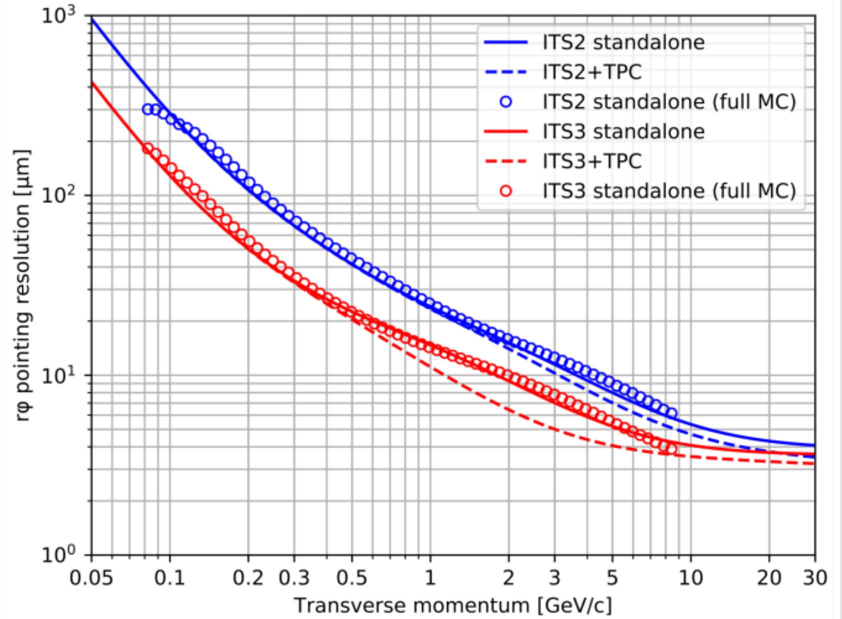


- Based on wafer-scale, ultra-thin, curved MAPS
  - radial distance from interaction point: 5 mm (inside beampipe, retractable configuration)
  - unprecedented spatial resolution: ≈ 2.5 µm
  - … and material budget: ≈ 0.1% X_0/layer
  - at radiation levels of: ≈ 10^{16} 1MeV n_{eq}/cm^2 + 300 Mrad
  - and hit rates up to: 94 MHz/cm^2
- Unprecedented performance figures
  - largely leverages on the ITS3 developments
  - pushes improvements on a number of fronts

ALICE ITS3

Performance improvement

pointing resolution



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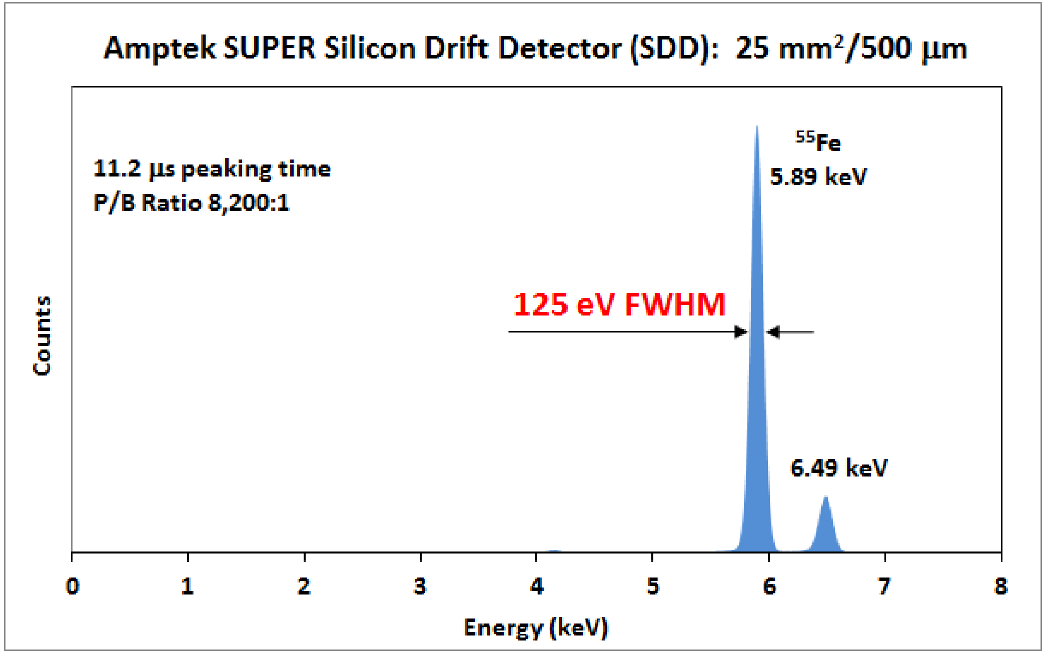
improvement of factor 2 over all momenta

- Improvement of pointing resolution by:
  - drastic reduction of **material budget** (0.3 → 0.05% X_0/layer)
  - being **closer** to the interaction point (24 → 18 mm)
  - thinner and smaller **beam pipe** (700 → 500 µm; 18 → 16 mm)
- Directly boosts the ALICE core physics program that is largely based on:
  - low momenta
  - secondary vertex reconstruction
- E.g. Λ_c S/B improves by factor 10, significance by factor 4

Fe55 Spectrum



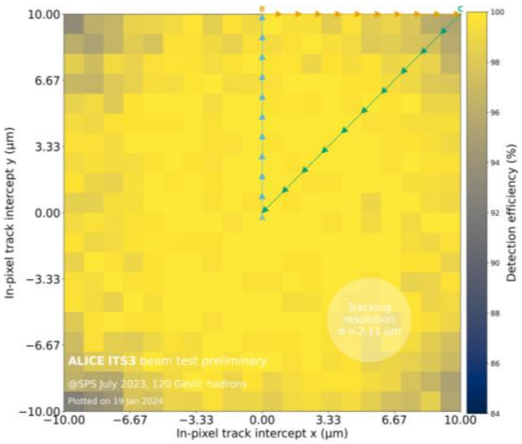
The measurement of the Fe55 spectrum is used to calibrate the sensor readout to the collected charge

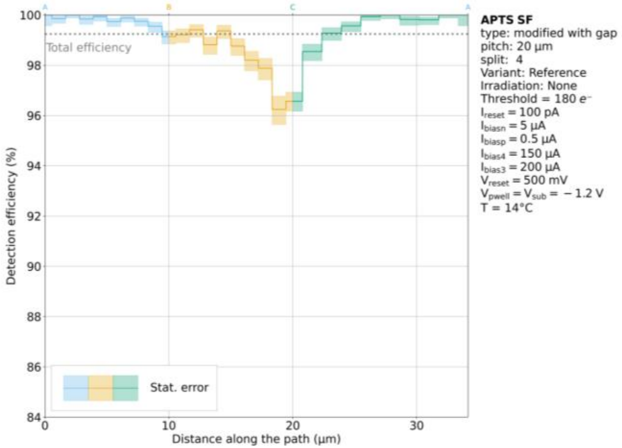
- Number of electrons generated by Kα : 1640
- Number of electrons generated by Kβ : 1800

Variant Comparison

Detection Efficiency

Spatial Resolution





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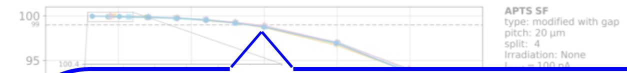
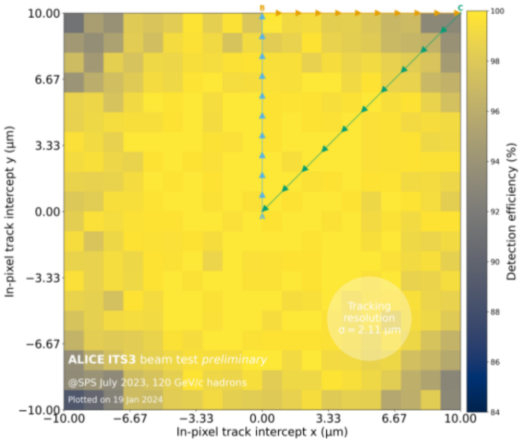
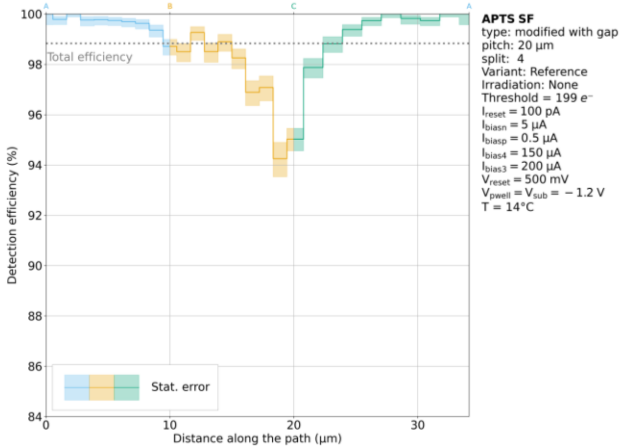
Variant Comparison

Detection Efficiency



Spatial Resolution





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