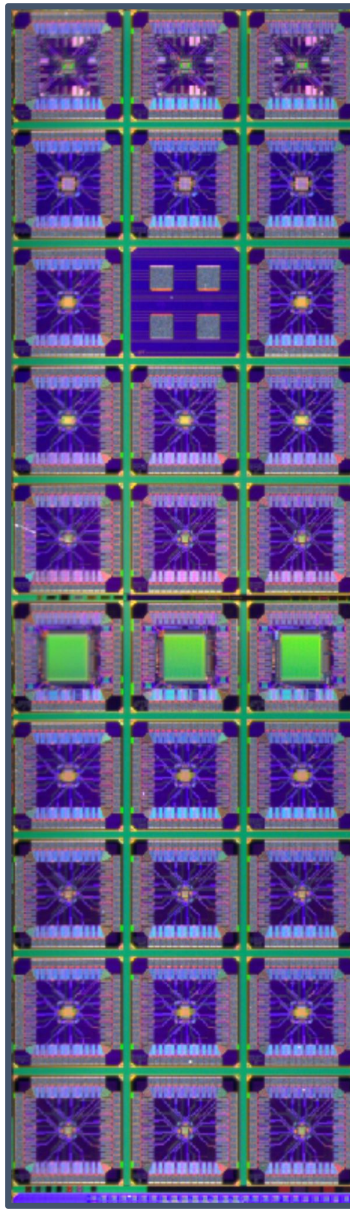
Study of MAPS prototypes for the ALICE ITS3 upgrade

Riccardo Ricci

INFN Bologna

ALICE-ePIC meeting
29/01/2025



The ALICE ITS3 - a bent vertex detector

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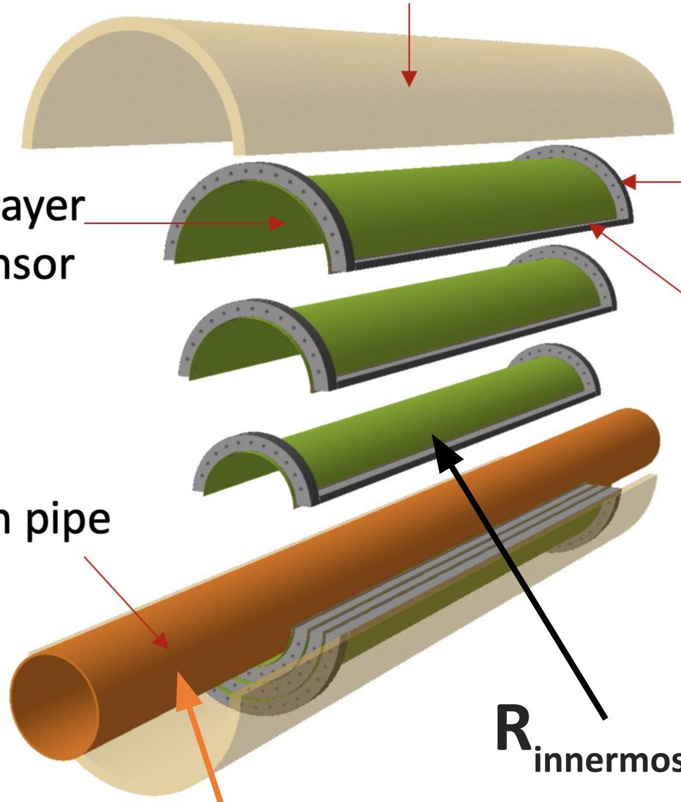
- Ready for LHC RUN 4 - mounted during LS3
- Built using **wafer-scale MAPS (Monolithic Active Pixel Sensors)**, produced using **stitching**
- **Thinner (≲ 50 µm)**
- Mechanically held in place by carbon foam ribs
- **Bent** to the target radius
  - 1st layer at 19 mm, **closer** to the Interaction Point
  - new beam-pipe at 16.5 mm
- Less material budget, less power consumption
- Better tracking efficiency and impact parameter resolution
- ITS3 will replace the 3 innermost layers with only **6 sensors** 26 cm long



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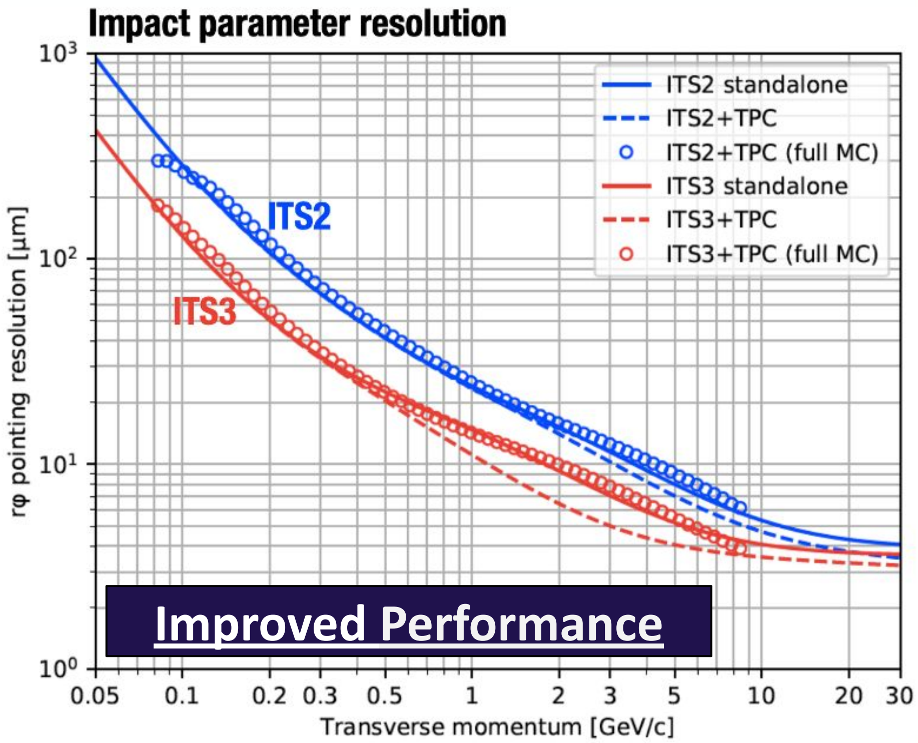
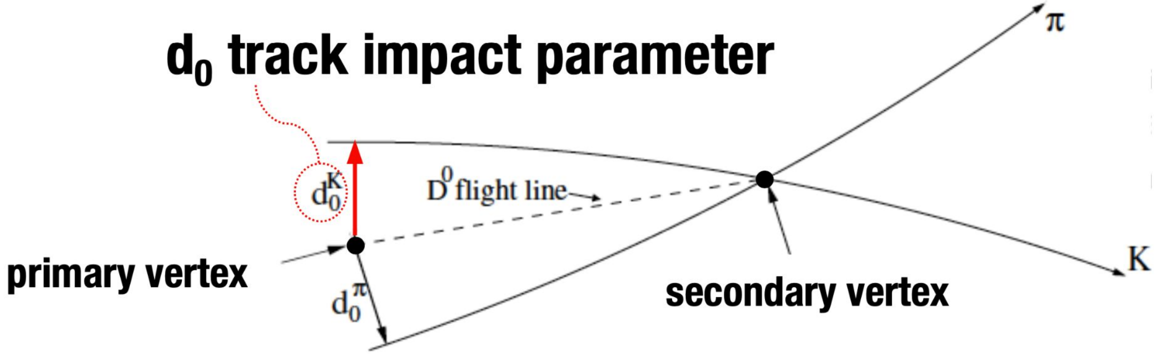
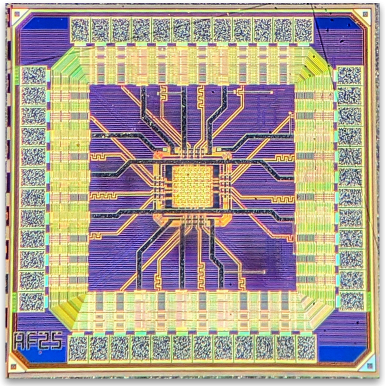




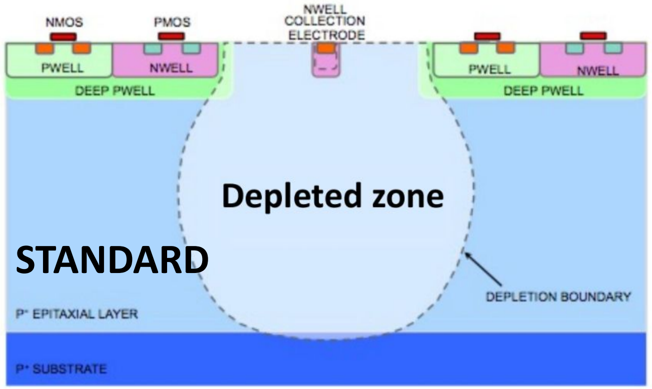
ITS3 prototypes and technology validation - MLR1

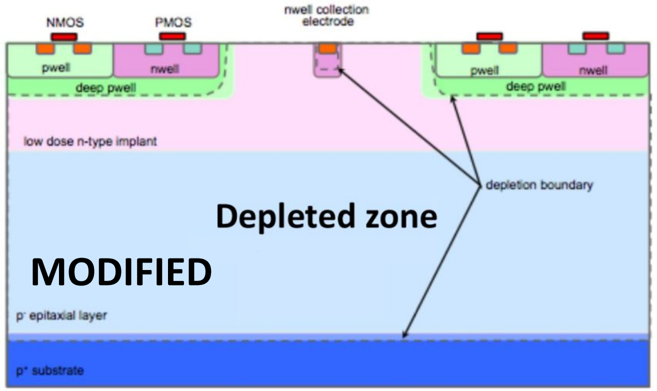
- **MAPS technology** provide sensor and electronics integration in one single chip reducing cost, power, material budget
- ITS2 features 180 nm MAPS technology (ALPIDE sensor), with **ALPIDE**
- **Multi Layer Reticle 1** - First submission with the TPSCo **65 nm** MAPS technology for the ITS3

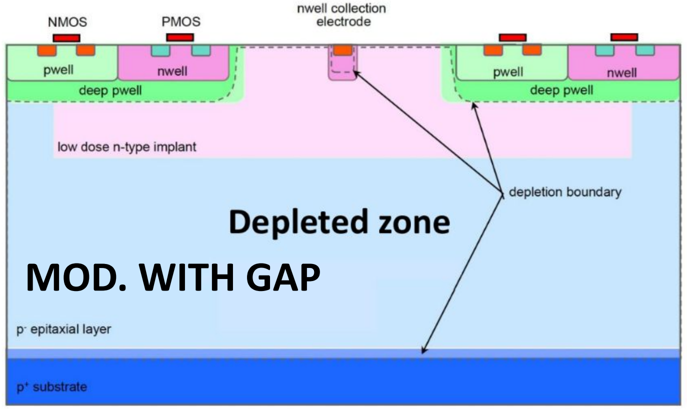
APTS - Analog Pixel Test Structure



- **matrix**: 6x6 pixels
- **readout**: direct analogue of central 4x4 pixels
- **pitch**: 10, 15, 20, 25 µm
- produced in three **designs**: standard, modified, modified-with-gap
- Validation in laboratory with ^{55}Fe source and at beam-tests (CERN SPS)







^{55}Fe source measurements @INFN-BO
APTS, Modified-with-gap type

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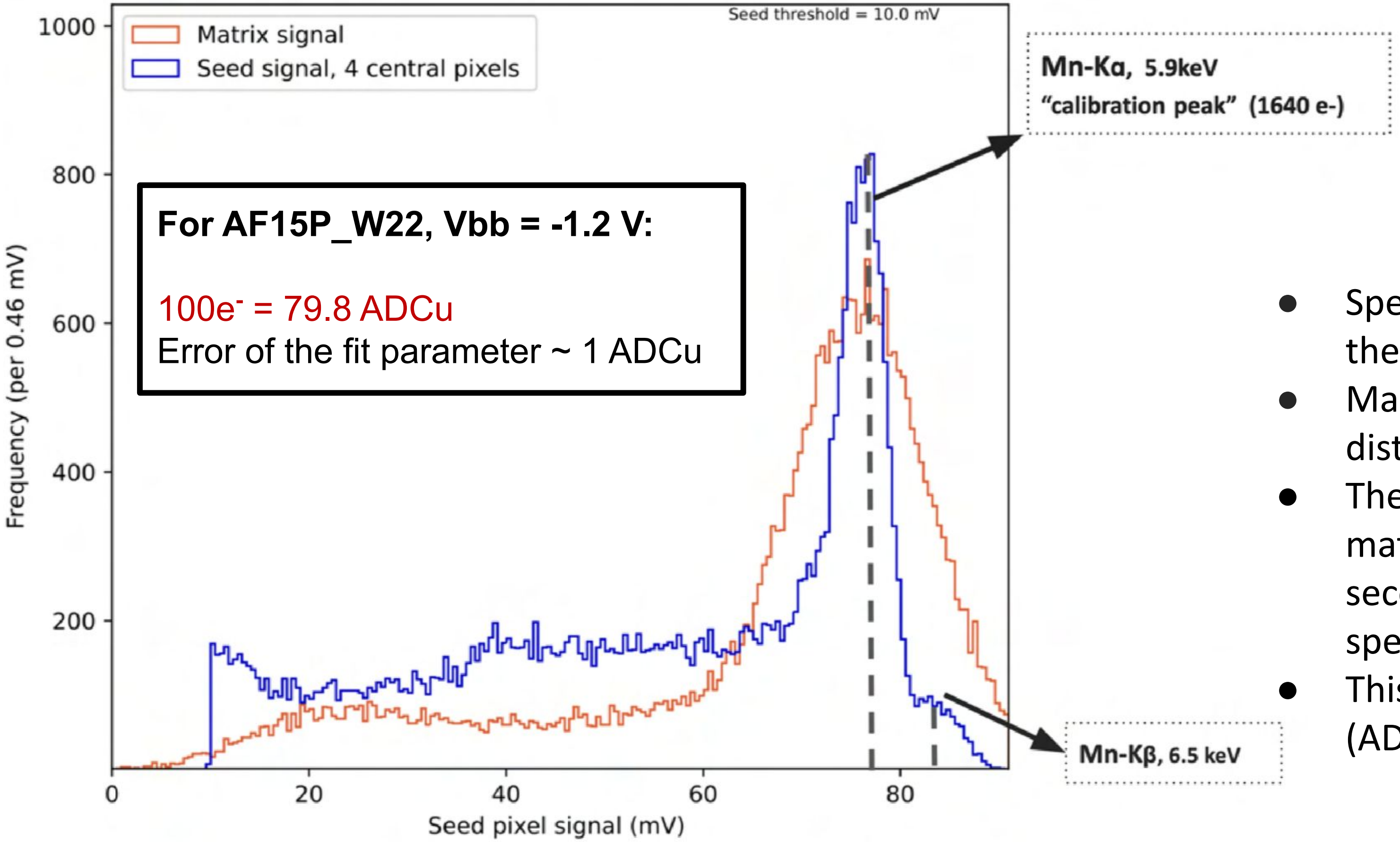
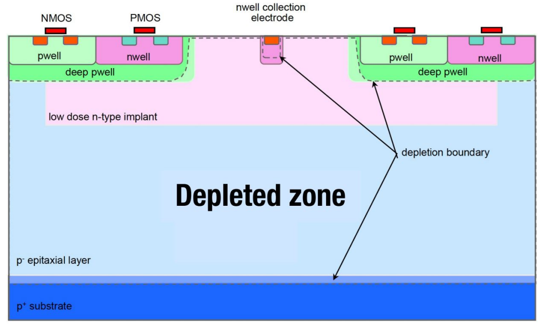


For AF15P_W22, Vbb = -1.2 V:

100e⁻ = 79.8 ADCu
Error of the fit parameter ~ 1 ADCu

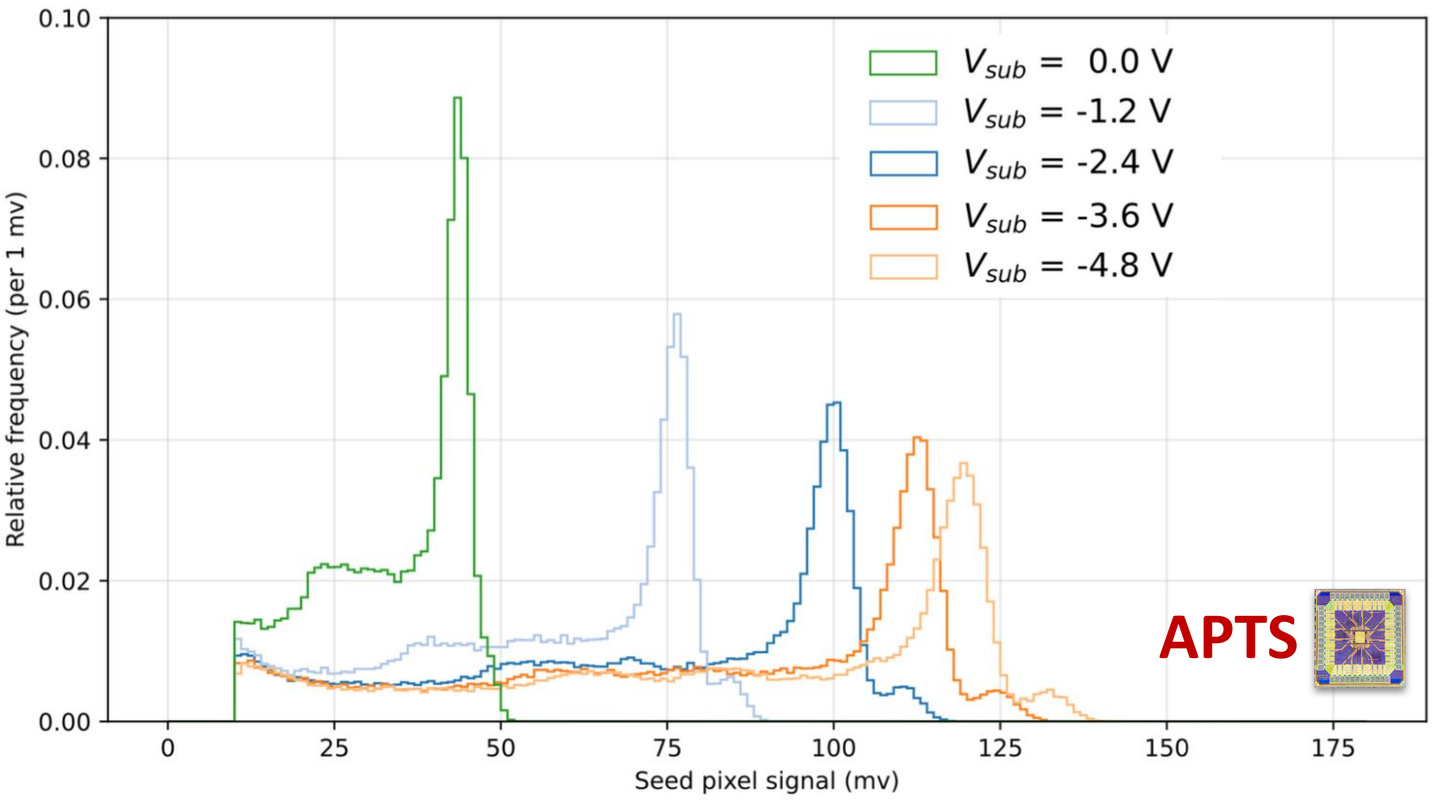


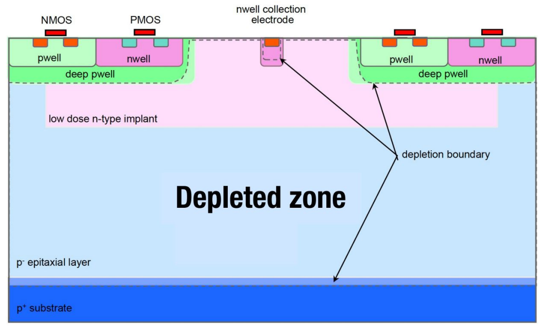
- Spectrum obtained by considering the distribution of the signals obtained from the **seed pixels**(1)
- Main peaks of the ^{55}Fe spectrum become distinguishable from 10^4 events
- The comparison between the **matrix signal**(2) and the matrix formed by the 4 central pixels shows that the second distribution reproduces better the ^{55}Fe spectrum
- This result is used for the sensor calibration (ADCu to e- conversion) via the following formula:

$$A_{\text{electrons}} = \frac{A_{\text{mV, ADC}} \times 1640}{\text{mean}}$$

(1) The **seed pixel** is the pixel with the largest amount of collected charge
(2) The **matrix signal** represents the total charge collected within an $N \times N$ matrix centered on the seed pixel

^{55}Fe source measurements @INFN-BO
APTS, Modified-with-gap design



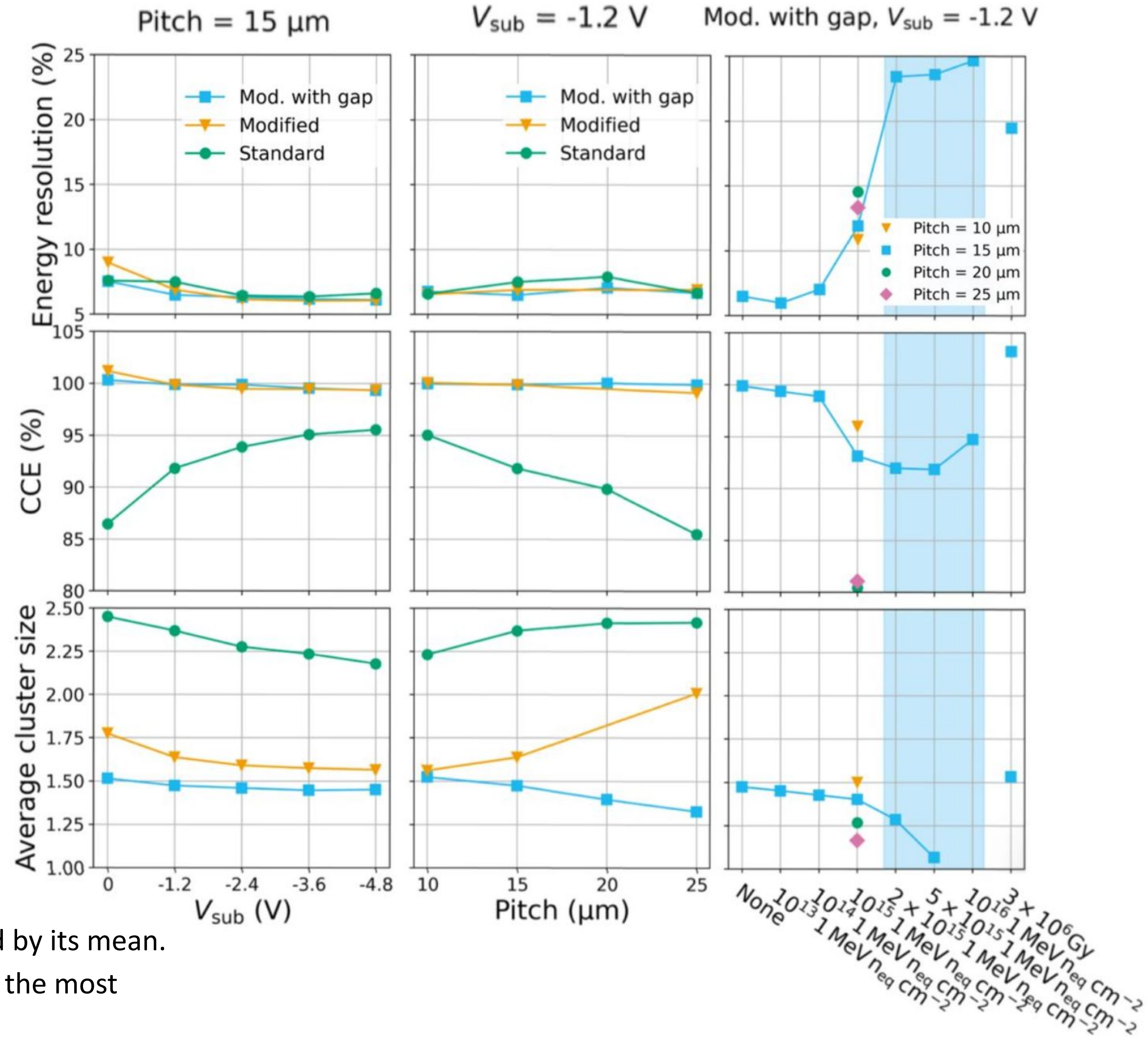


Pitch: 15 µm
Type: modified-with-gap design
Reverse-bias: from 0 to -4.8 V
Source: 37 MBq ^{55}Fe

- Seed pixel signal distribution of the 4 innermost pixel of APTS at different bias voltages, expressed in mV.
- The amplitude rises with increasing reverse-bias voltage → due to the expansion of the depletion region and the related decrease in capacitance.

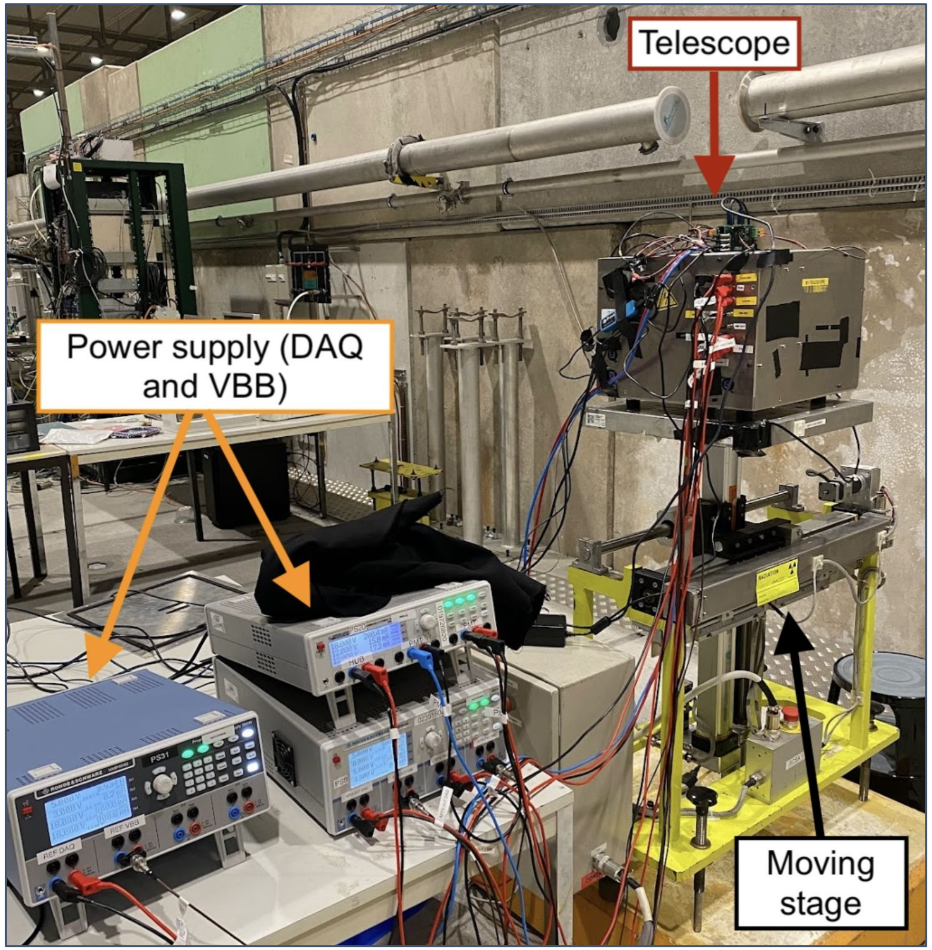
Resume of ^{55}Fe measurements

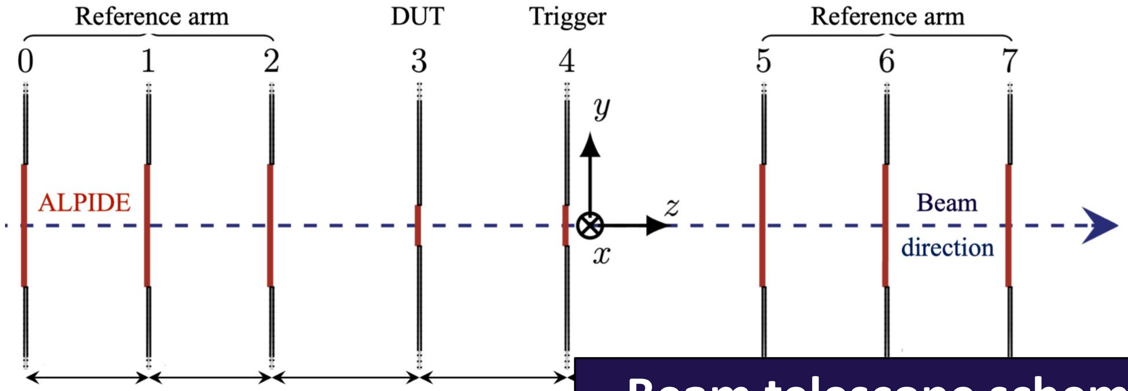
- The standard type shows a reduced Charge Collection efficiency (CCE) along with an increase in the average cluster size.
  Reduced CCE also at larger pitch (Vsub = -1.2 V)
- Modified types show in general a higher CCE, compared to the standard type
- The degradation in energy resolution[(1)] is more pronounced for larger pixel pitches, primarily due to increased noise, as leakage current is gathered from a greater sensor volume.
- DUT remains operational across all irradiation levels.



[(1)]The energy resolution is computed as the ratio of the FWHM of the Mn-Kα peak divided by its mean.
[(2)]CCE is the ratio of the most probable value of the 3x3-pixel matrix signal distribution to the most probable value of the signal distribution for cluster size of 1.

Beam test data taking and analysis





Beam telescope scheme

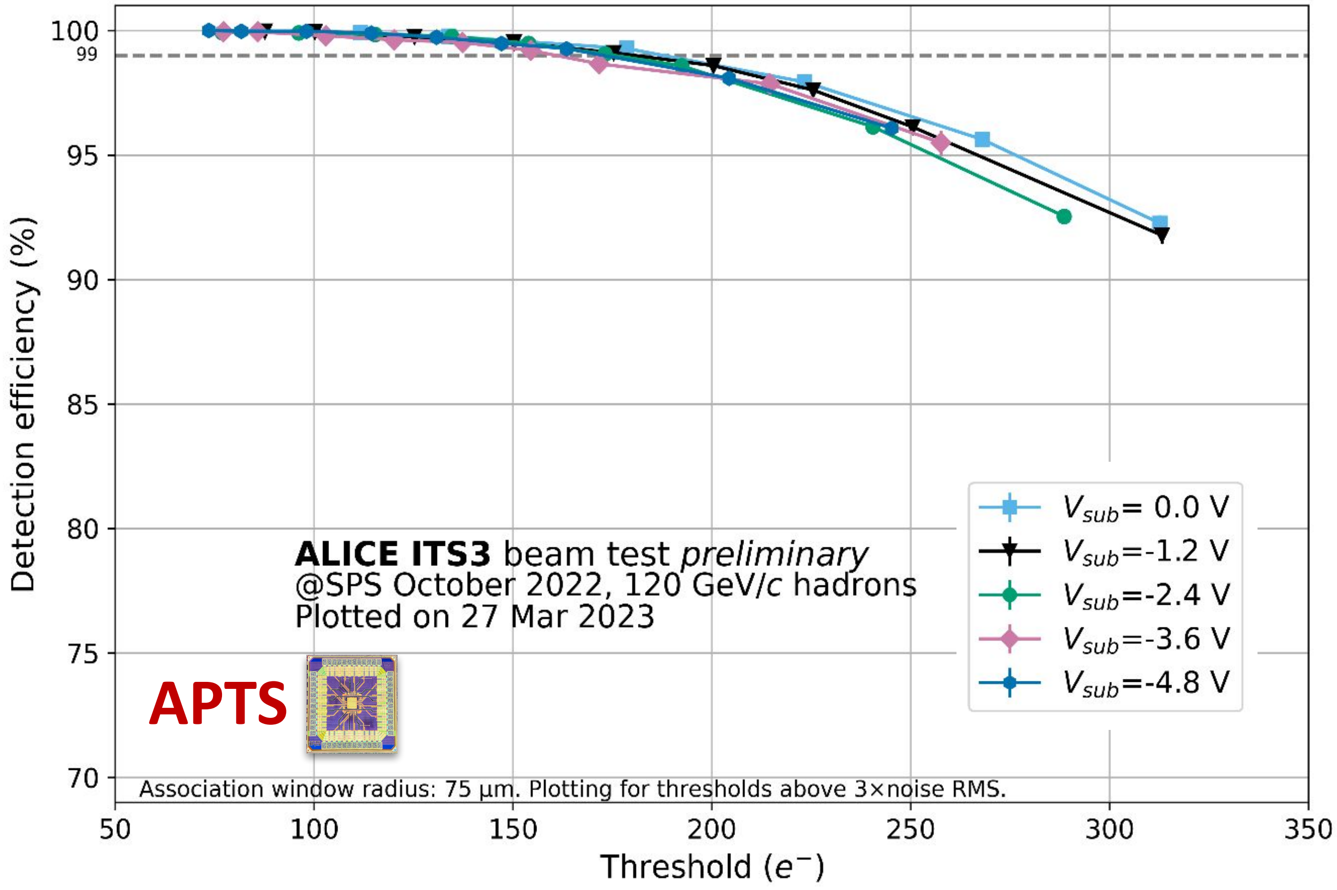
- DUT: APTS sensors differing for design, pitch and irradiation level
- telescope: 6 reference ALPIDE planes used for tracking
- trigger: APTS sensor (pixel pitch 25 um)
- Beam: 120 GeV positive hadrons @CERN SPS
- Beam test data analysis performed using ***Corryvreckan***[(1)]
  - software written in C++
  - offline event reconstruction and analysis (masking + pre-alignment, telescope alignment, DUT alignment, efficiency and spatial residuals analysis)

→goal: measure APTS efficiency and spatial resolution

(1) https://project-corryvreckan.web.cern.ch/project-corryvreckan/

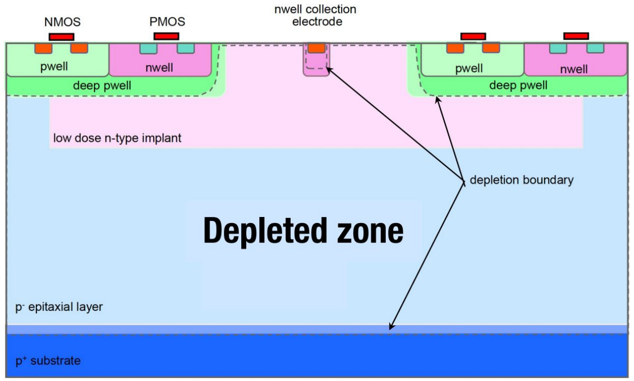
ITS3 beam tests - Efficiency results

Modified* with gap



Detection efficiency:

$$\epsilon = \frac{\#\ tracks_{1\ ass.cluster,\ DUT}}{total\ \#\ tracks_{DUT}}$$

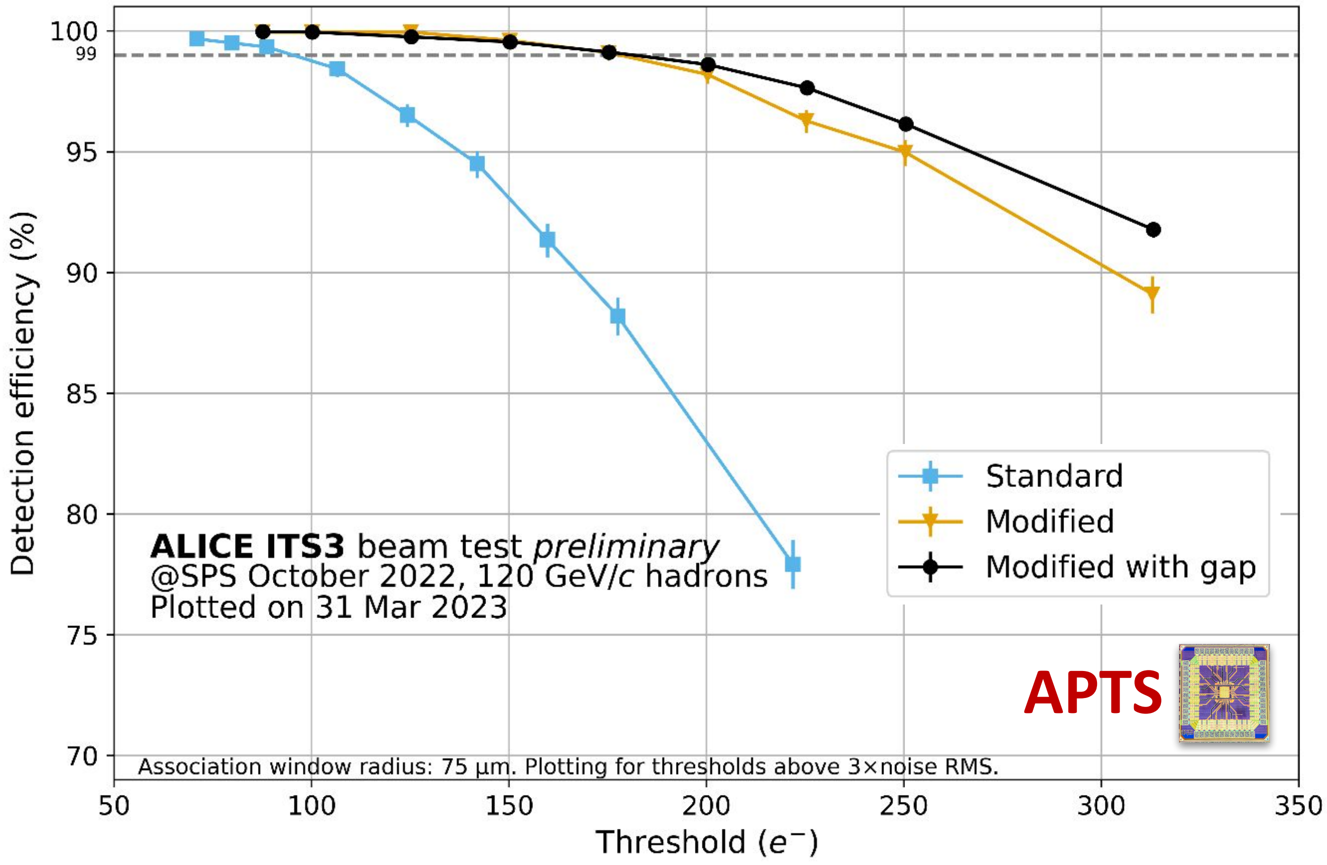


Chip fully efficient (> 99%) for a wide threshold range also at different voltages

*wrt ordinary MAPS design used for ALPIDE**: see here

ITS3 beam tests - Efficiency results

Design comparison



Detection efficiency:

$$\epsilon = \frac{\# \, tracks_{1 \, ass.cluster, \; DUT}}{total \, \# \, tracks_{DUT}}$$

Modified with gap shows also at at higher thresholds the best efficiency values

Design type (Vbb = 1.2 V)	Noise (e^-)
Standard	24
Modified	28
Mod.Gap	28

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Detection Efficiency - APTS
Modified with gap design - Irradiated

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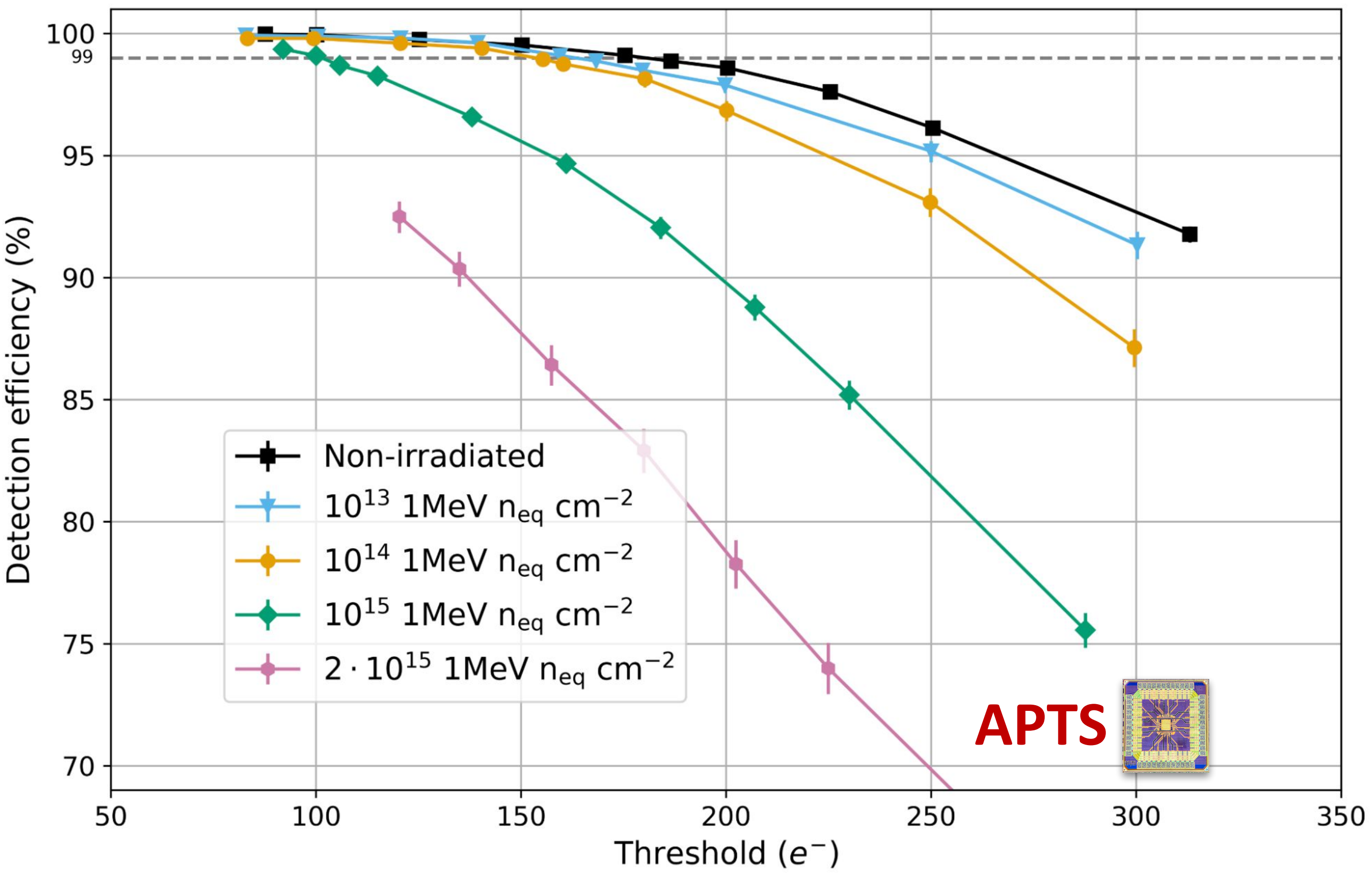
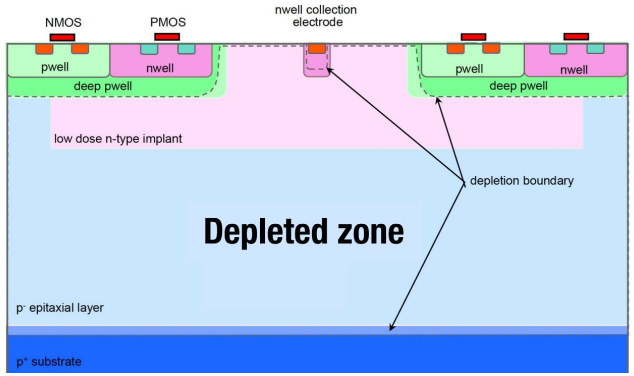




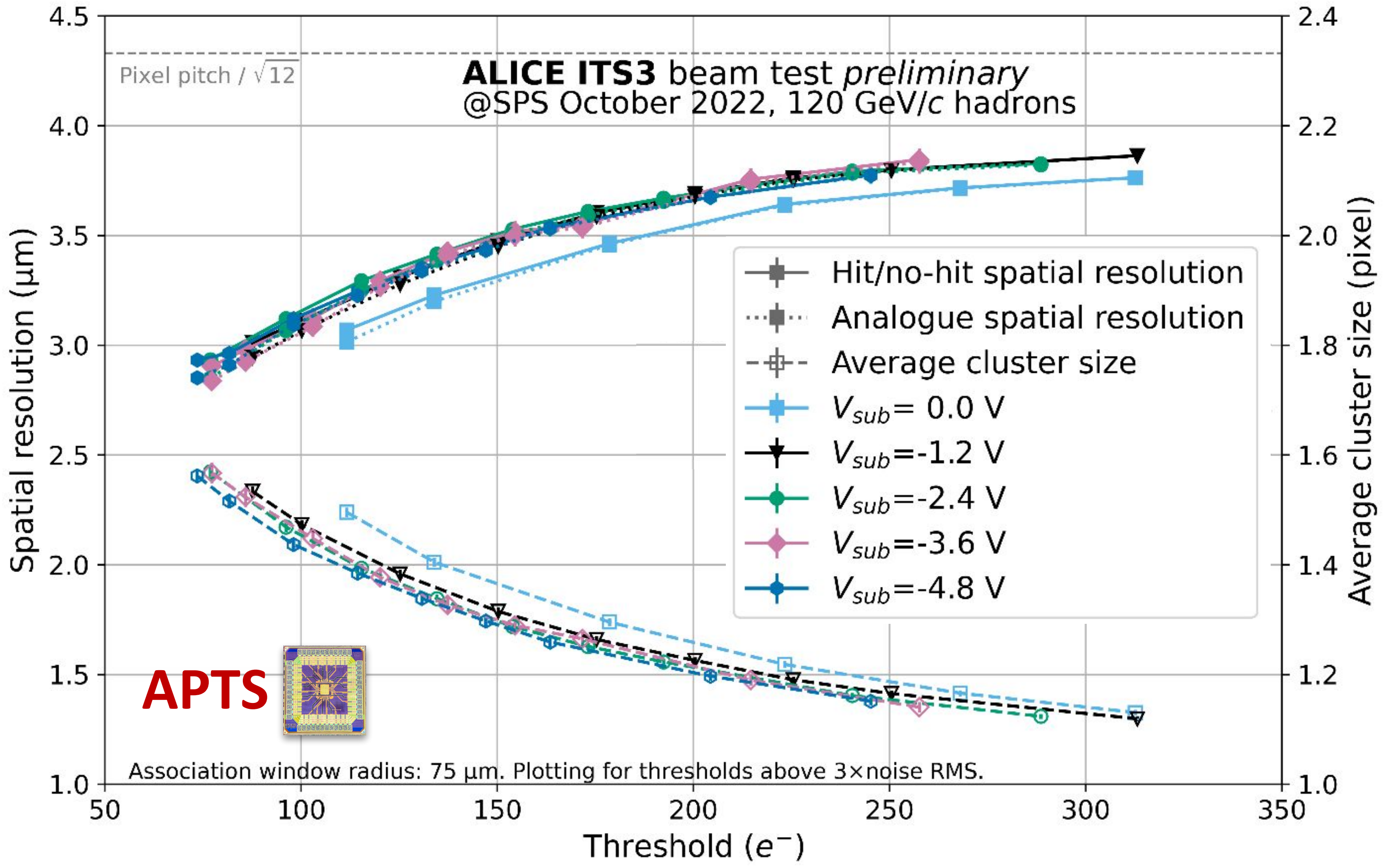
$$\epsilon = \frac{\#\ tracks_{1\ ass.cluster,\ DUT}}{total\ \#\ tracks_{DUT}}$$

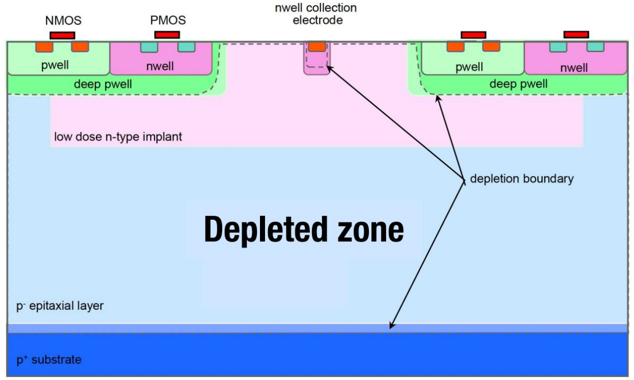
Detection efficiency drops significantly after THR=100 electrons, over 10^4 of NIEL[(1)]

(1) ITS3 requirement: 99% efficiency with radiation load of 10^3 NIEL for Layer 0 (19 mm from R = 0)

Spatial resolution - APTS

Modified with gap design - non irradiated





Spatial resolution computed as:

$$\sigma_{\mathrm{x(y)}} = \sqrt{\sigma^2_{\mathrm{DUT,x(y)}} - \sigma^2_{\mathrm{track}}}$$

Spatial resolution always under 4 μm also at different voltages

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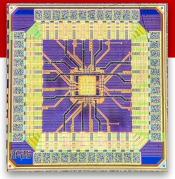
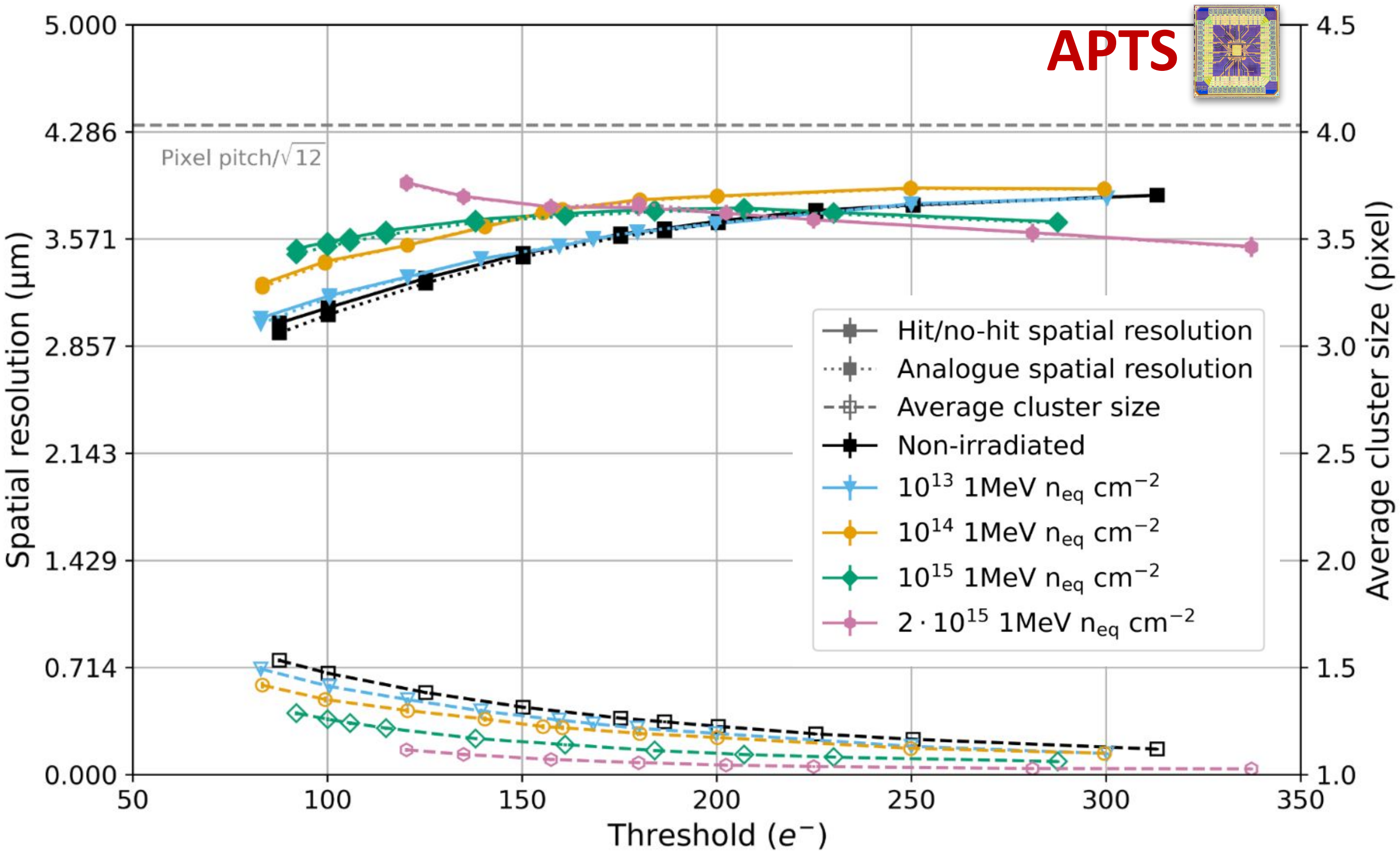
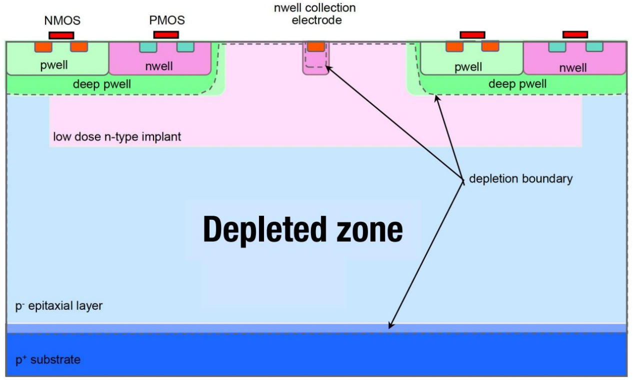
Spatial resolution - APTS

Modified with gap design - irradiated







Spatial resolution computed as:

$$\sigma_{x(y)} = \sqrt{\sigma^2_{DUT,x(y)} - \sigma^2_{track}}$$

A decrease in spatial resolution performance is observed over 10^{15} NIEL

APTS efficiency - resume

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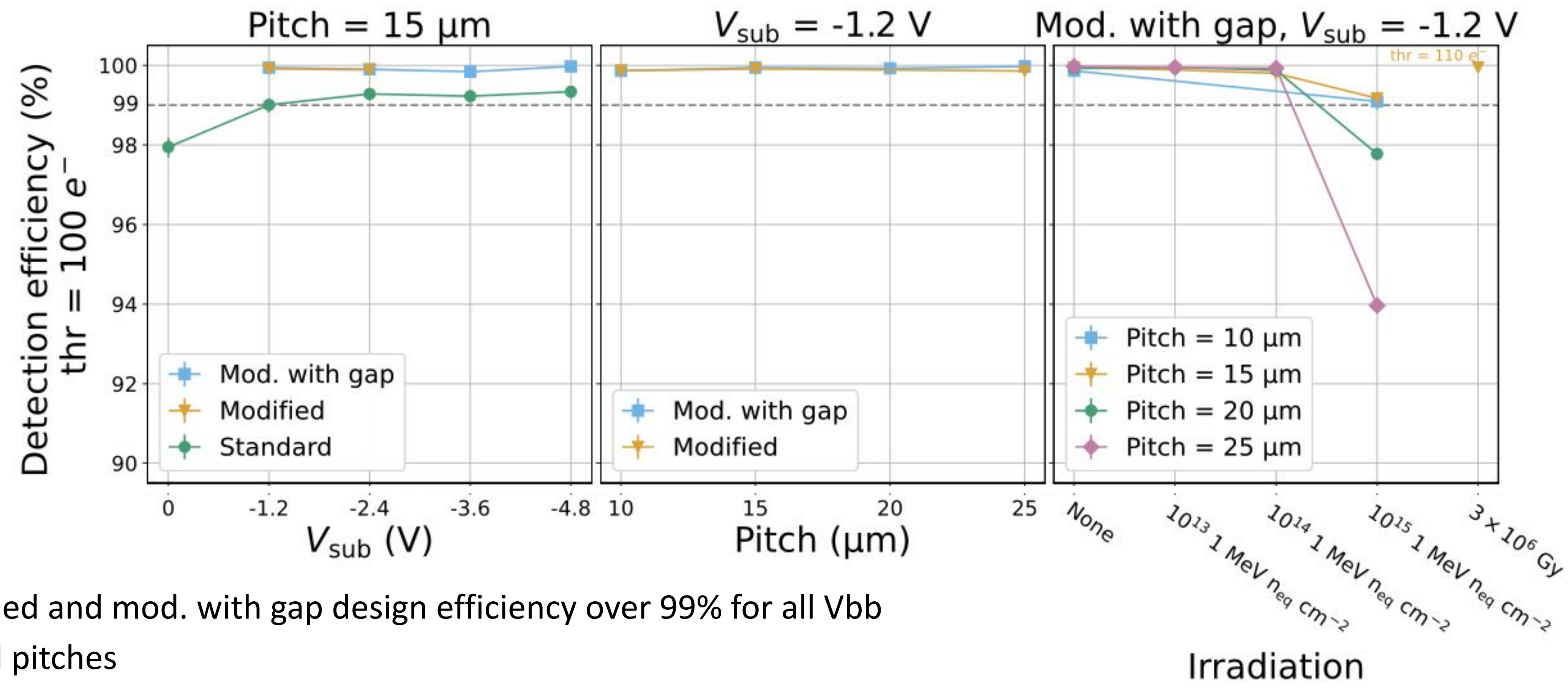
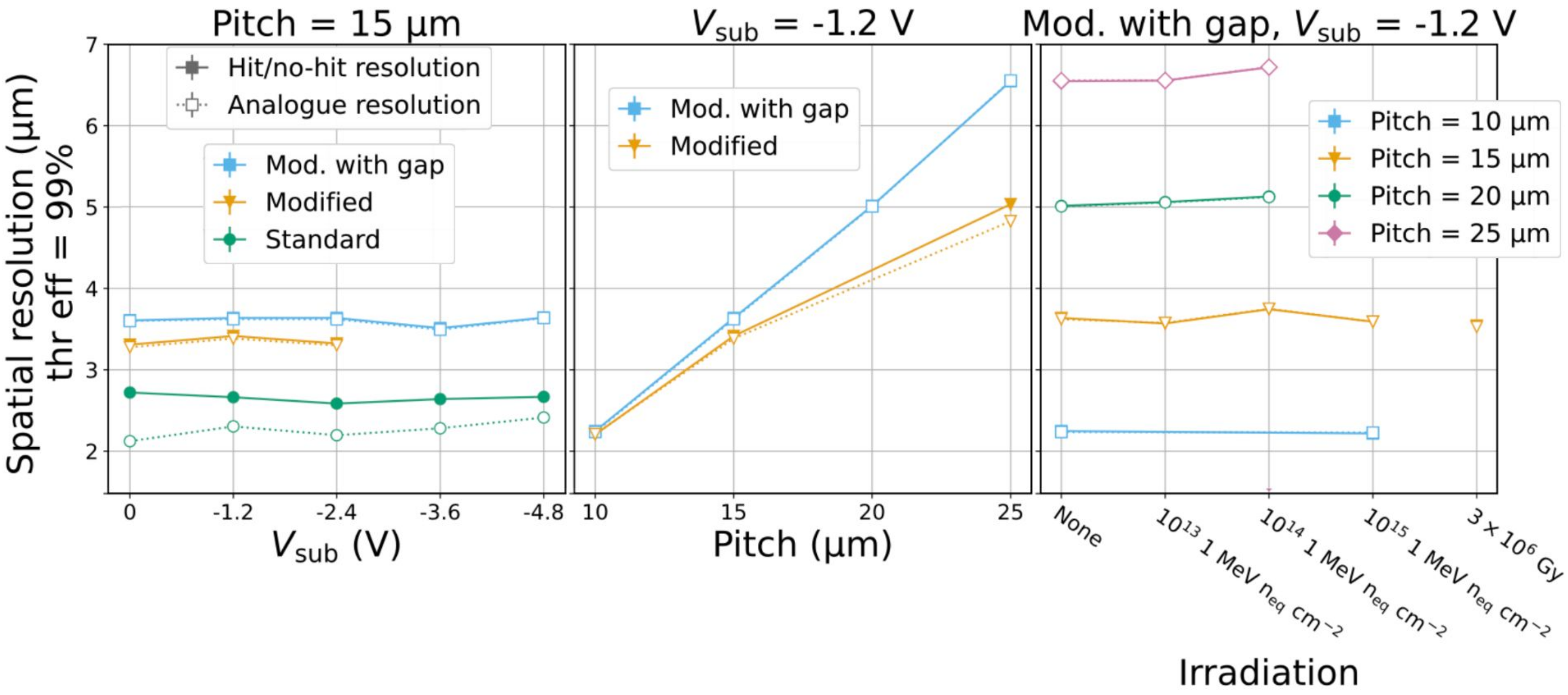


- Modified and mod. with gap design efficiency over 99% for all Vbb and all pitches
- irradiated APTS, mod. with gap: in general larger pitches are less efficient as the irradiation level gets higher

APTS resolution - resume



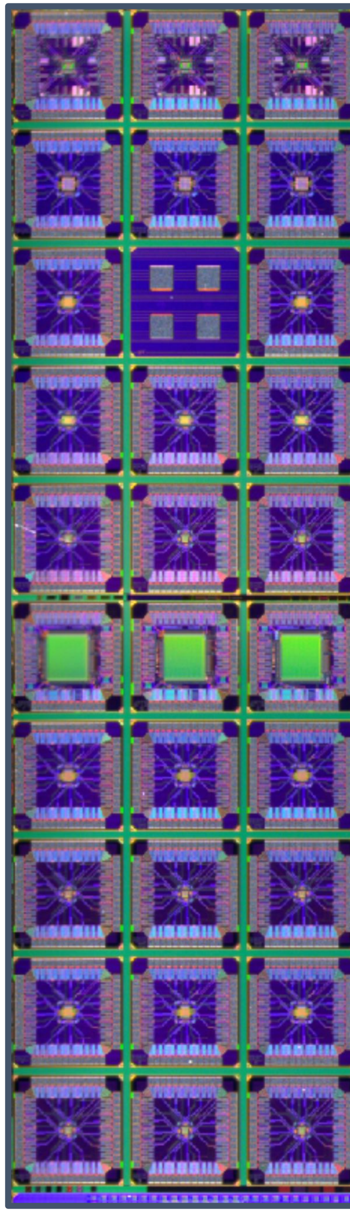
- Non irradiated chips: all the designs reach spatial resolution under 4 µm (ALPIDE~5 µm)
- Irradiated chips (modified-with-gap) maintain their resolution performance through all the irradiation levels

Summary and conclusions

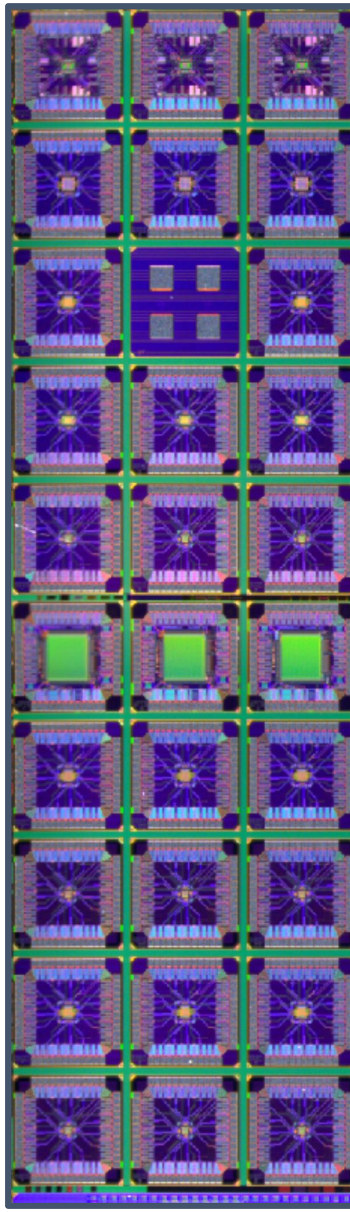
ITS3 will be installed during LS3 to be ready for LHC Run 4 (2029-2032).
The sensor qualification with the Analog Pixel Test Structure has shown that:

- **From the results of the APTS measurements with the ^{55}Fe source:**
  - modified and modified with gap APTS show higher charge collection compared to the standard design APTS
  - all the DUT remain operational across all irradiation levels (up to 10^{15} 1 MeV n_{eq} /cm).
- **Results of data analysis from the APTS beam tests show that:**
  - modified-with-gap design is the most efficient compared to the modified and standard design
  - all the tested modified-with-gap sensors show at least 99% detection efficiency over large threshold range, even surpassing (smaller pitches) the ITS3 radiation hardness requirements (10 kGy + 10^{13} 1 MeV n_{eq} /cm).
  - all the sensors show a spatial resolution under pitch/√12 (also irradiated chips - all pitches)
- **Modified-with-gap design has been chosen as the benchmark for the following steps of the ITS3 R&D (testing with wafer-scale sensors)**
- **Results on MLR1 chips qualified the 65 nm technology for the use in ITS3 and put the basis for studies on new wafer-scale sensors**

Thank you for your attention



Backup



ALICE and the ITS2

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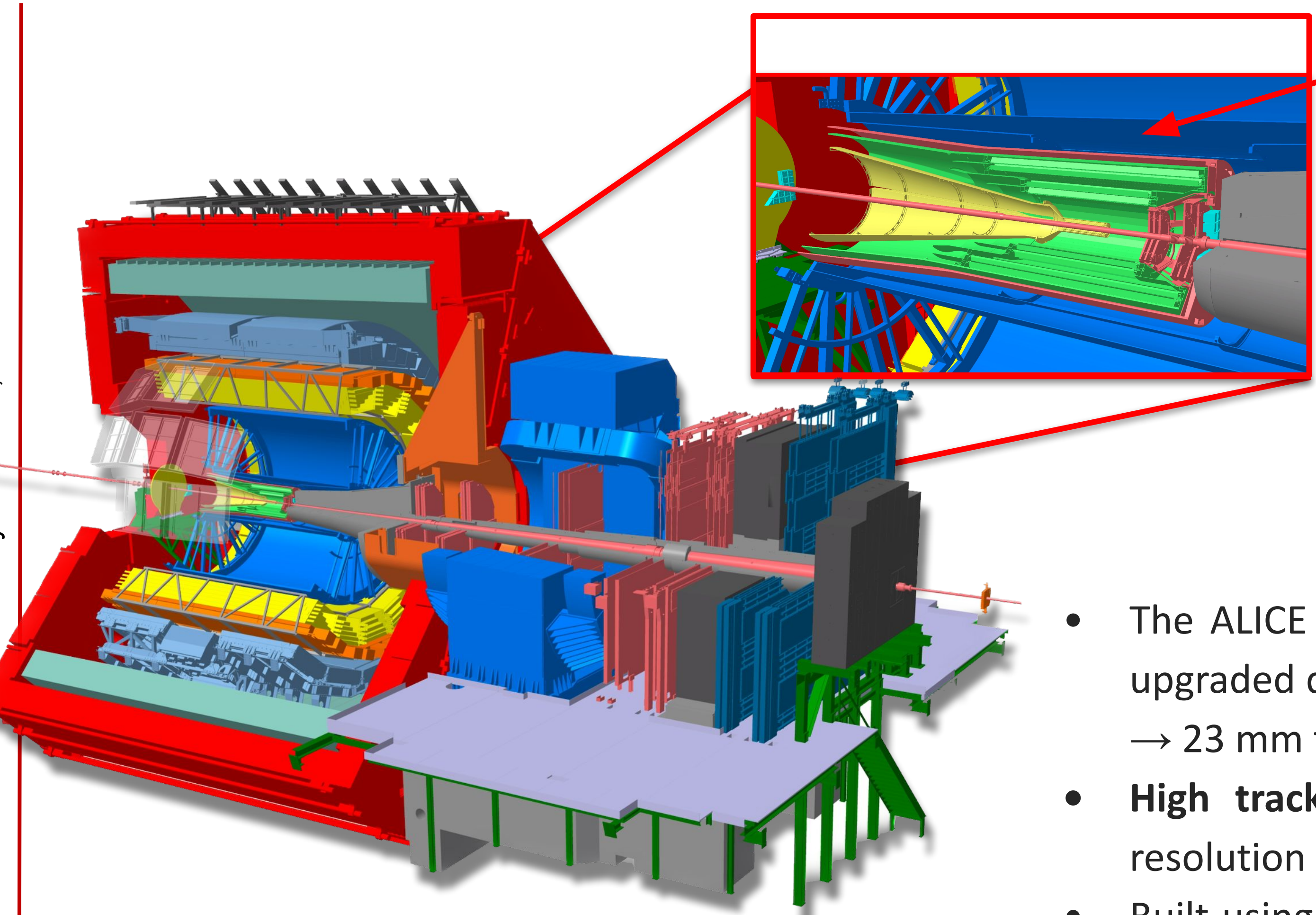
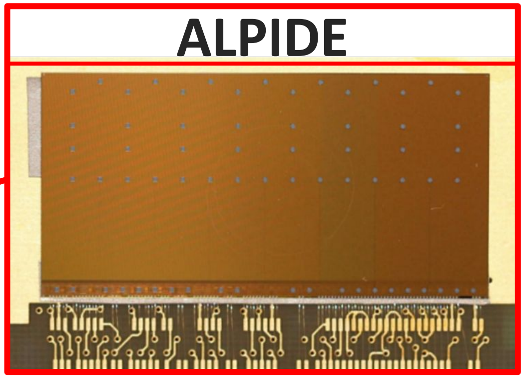
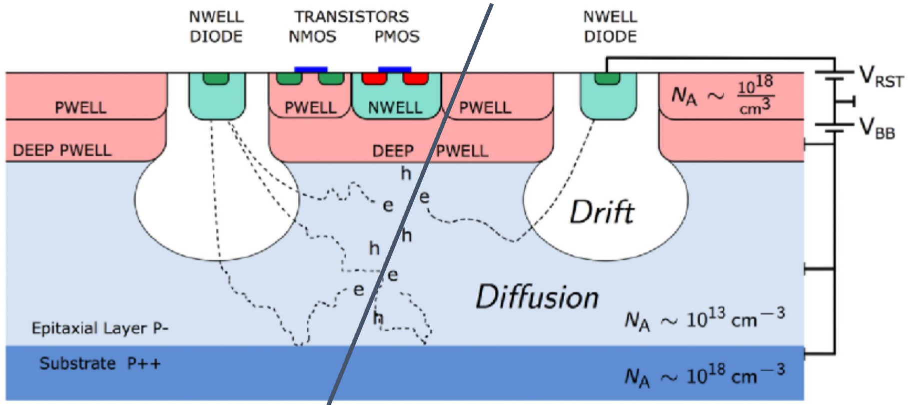
University and INFN, Salerno





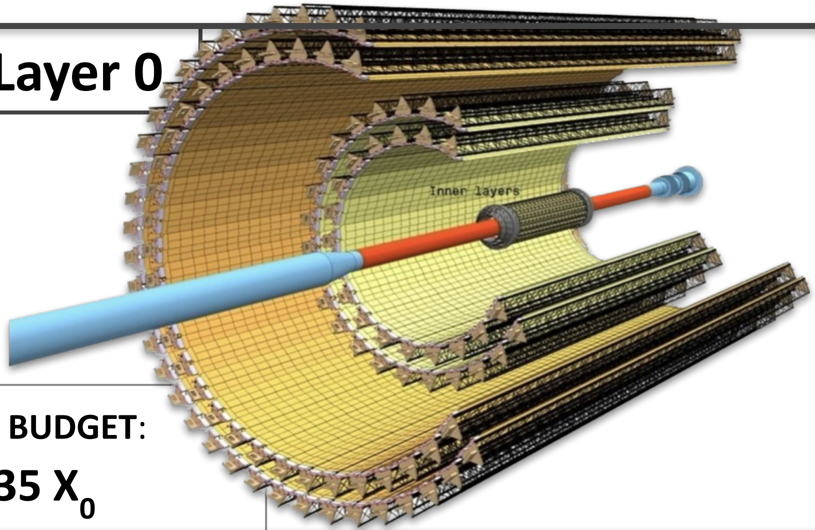


- The ALICE vertex detector (**ITS** = Inner Tracking System) has been upgraded during LHC Long Shutdown 2 (LS2) in preparation for Run3 → 23 mm from the Interaction Point (innermost layer)
- **High tracking performance** also at low p_T (100 µm pointing resolution at p_T = 200 MeV)
- Built using **ALPIDE**, a Silicon pixel chip based on 180 nm Monolithic Active Pixel Sensor (MAPS)

Material budget - ITS2 vs ITS3

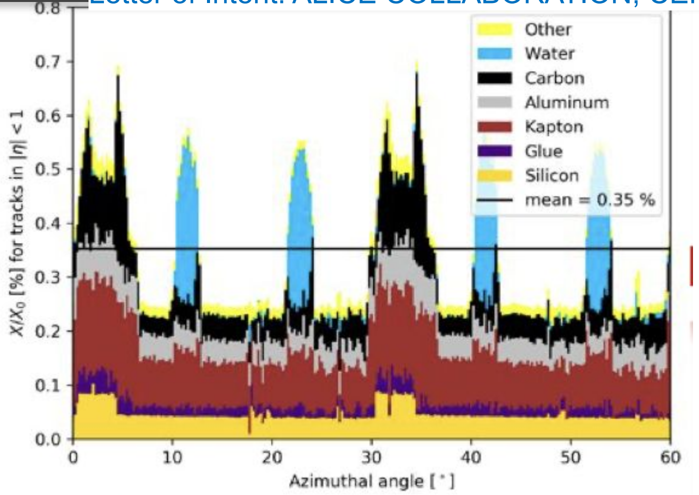
Letter of Intent: ALICE COLLABORATION, CERN-LHCC-2019-018. LHCC-I-034

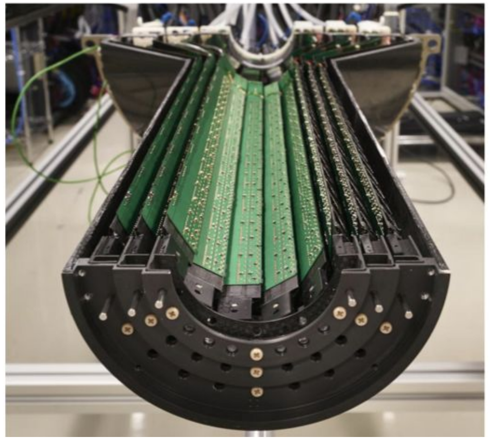
ITS2, Layer 0



MATERIAL BUDGET:

up to 0.35 X_0

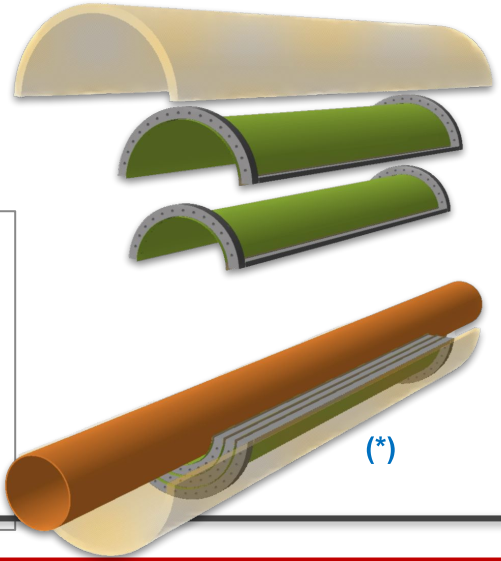


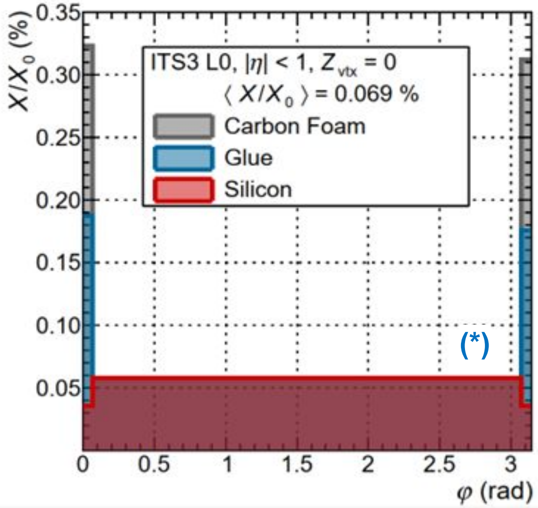


ITS3, Layer 0 Silicon-only contribution

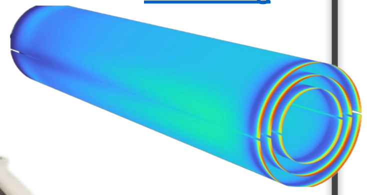
MATERIAL BUDGET

≲0.07 X_0, assuming
final sensor thickness ≤ **50 µm**,
implementing **air cooling**,
removing aluminum structure,
glue…





Temperature gradient simulation with air cooling



Carbon foam structure to keep the sensors in place

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Benefits in ALICE measurements from ITS3

- Low-mass dileptons
  Beauty-strange mesons
  - exclusive reconstruction of B_s^0
  - non-prompt D_s^+ (50% from $B^{0,+}$ and 50% from B_s^0)
- Beauty baryons
  - non-prompt Λ_c^+
  - exclusive reconstruction of Λ_b^0
- Charm strange and multi-strange baryons
  - Ξ_c^0 (cds), Ξ_c^+ (cus), Ω_c^0 (css)
- Searches for light charm hypernuclei
  - bound state of a Λ_c^+ and a neutron (c-deuteron)
  - bound state of a Λ_c^+ and a deuteron (c-triton)

ALICE

New Monolvthic Active Pixel Sensor designs

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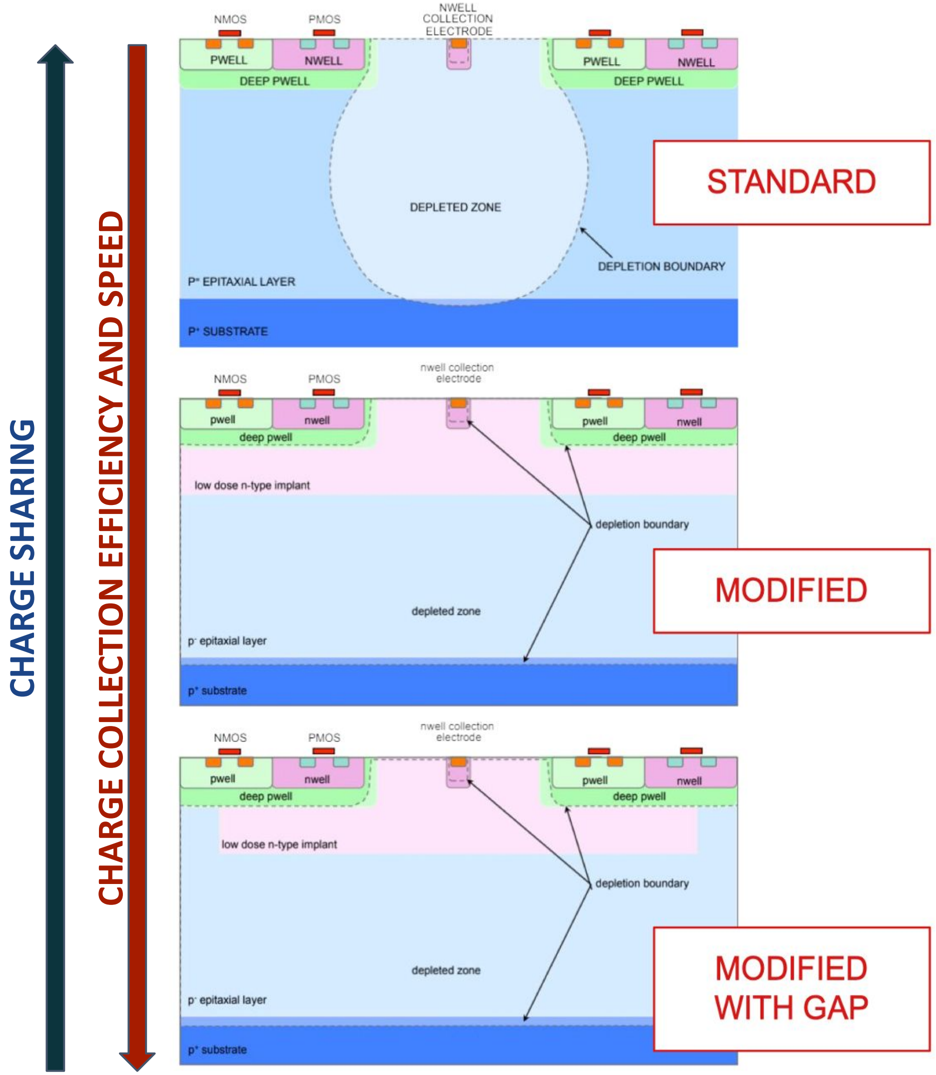


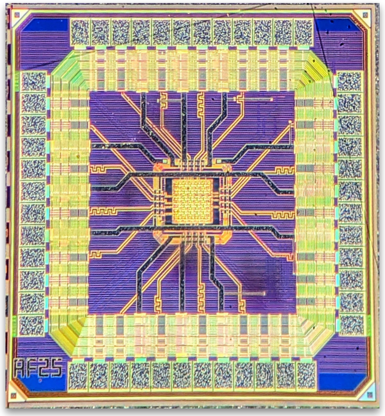
- Based on **MAPS** and **TPSCo 65 nm CMOS** technology
- 50 µm thick
- Three **different chip designs** for characterization and qualification purposes:
  1. Standard type
  2. Modified type
  3. Modified type with gap

ITS3 prototypes and technology validation - MLR1

Multi Layer Reticle 1 - First submission with the TPSCo **65 nm** MAPS technology for the ITS3

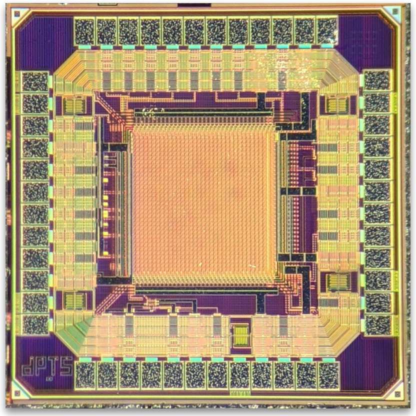
Goal → test and qualification (long R&D work done together with CERN EP R&D WP1, WP2)

APTS - Analog Pixel Test Structure



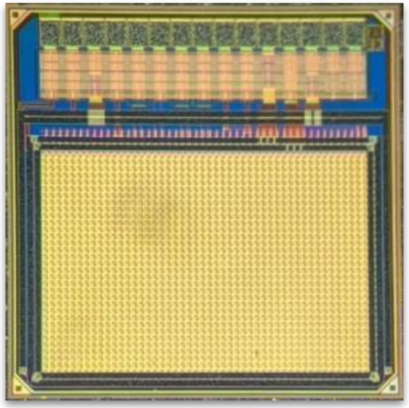
- **matrix**: 6x6 pixels
- **readout**: direct **analogue**
- readout of central 4x4
- **pitch**: 10, 15, 20, 25 µm
- **design**: standard, modified, modified-with-gap

DPTS - Digital Pixel Test Structure



- **matrix**: 32x32 pixels
- **readout**: **digital** with ToT
- **pitch**: 10, 15, 20, 25 µm
- **design**: modified with gap

CE65 - Circuit Exploratoire 65 nm



- **matrix**: 64×32 or 48×32
- **readout**: Rolling shutter readout (down to 50 µs integration time
- **pitch**: 15 µm or 25 µm
- **design**: standard, modified, modified with gap

Intensive characterization campaign:

Validation in terms of **charge collection efficiency**, **detection efficiency** and **radiation hardness**

Basic setup components
APTS laboratory setup

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DAQ board

- 5V power channel
- USB 3.0 interface to PC

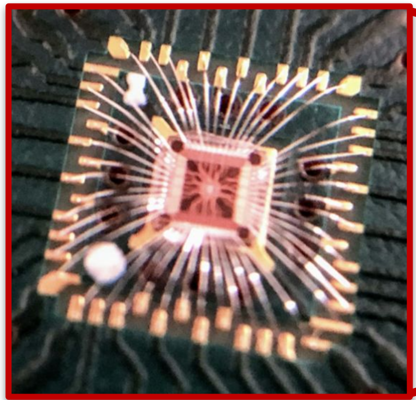
PROXIMITY board

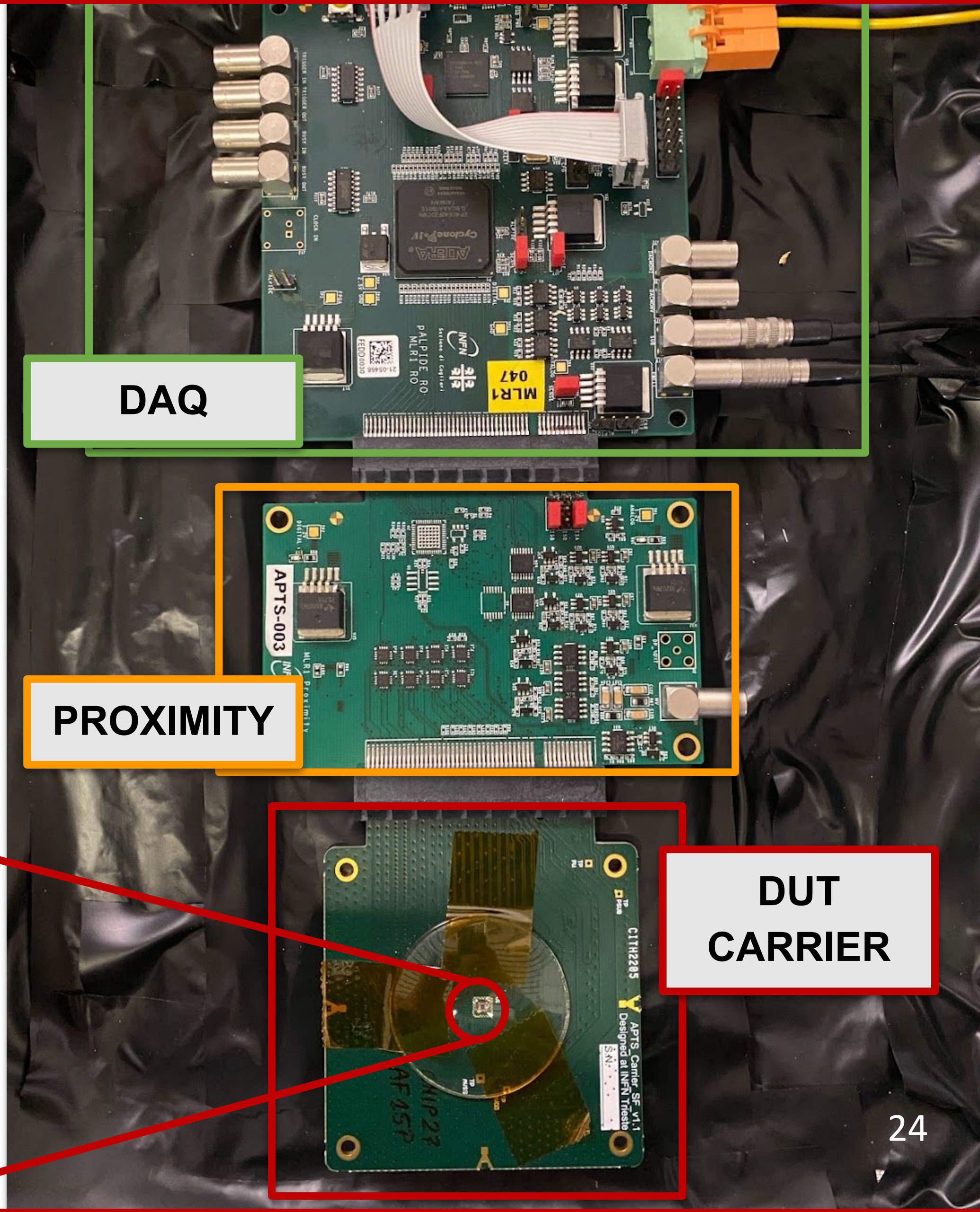
- communication between DAQ board and APTS

DUT CARRIER board

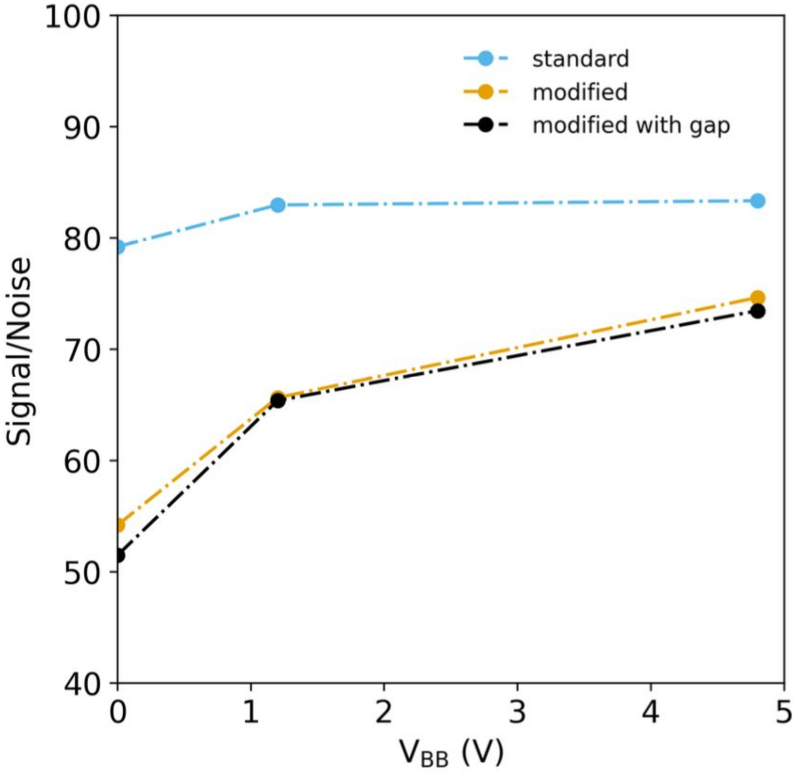
- chip_ID: AF15P_W22B20

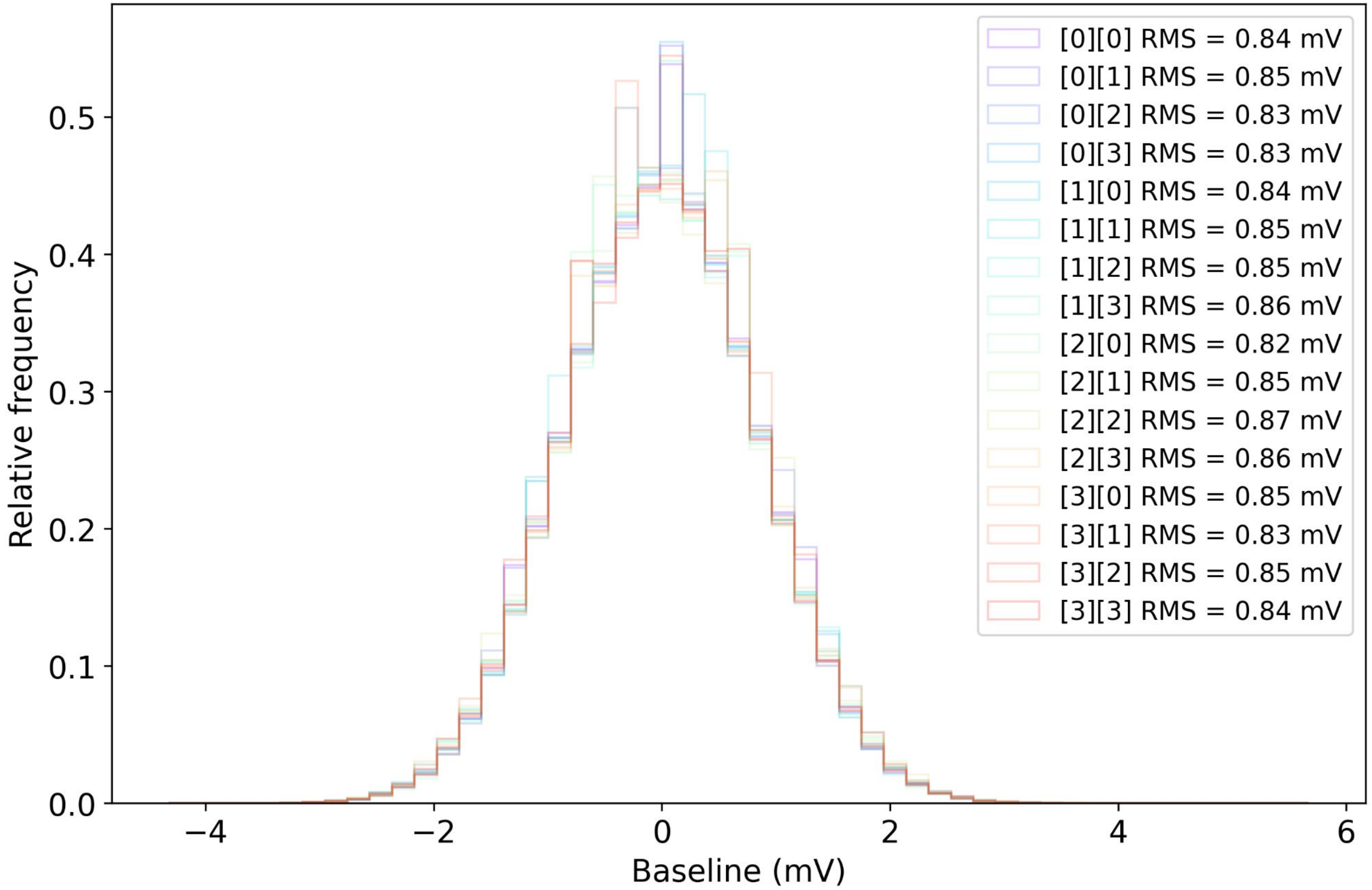
A → APTS
F → Source Follower
15 → pixel pitch (um)
W22 → wafer 22





APTS - noise

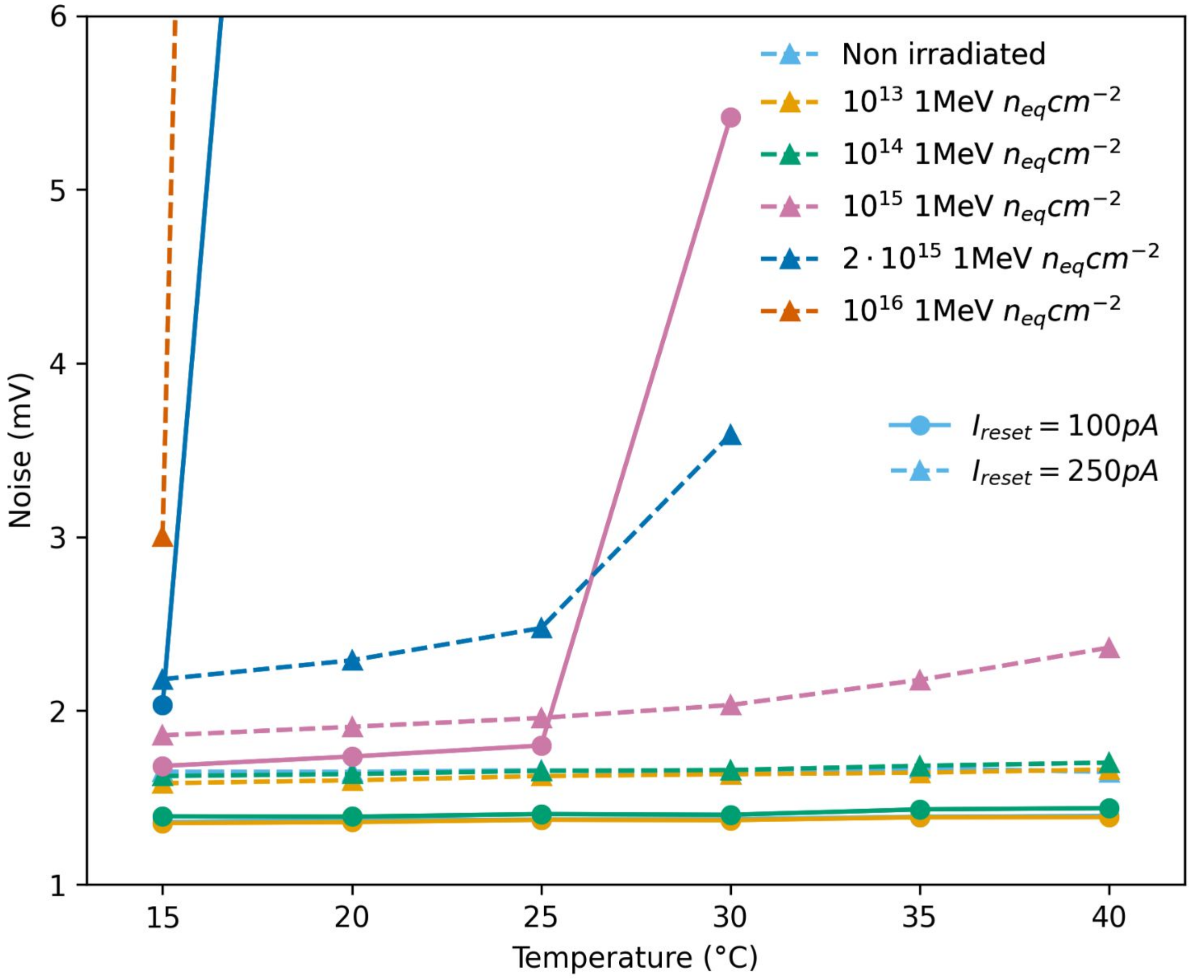




Noise	0 V	-1.2 V	-4.8 V
standard	25(0.95)	24(1.03)	23(1.11)
modified	34(0.58)	28(0.84)	24(1.13)
mod.gap	36(0.61)	28(0.85)	24(1.12)

Once the baseline is subtracted from the signal, the noise is evaluated as the **standard deviation** of the chip output at a frame located n samples before the frame used for the baseline estimation. The number *n* is chosen as the difference between the frame number where the waveform reaches its minimum (used for the signal extraction) and the frame number used for the baseline

APTS - noise
Modified with gap type



Irradiated sensors show good noise performance up to 10^{-15} 1MeV n_{eq}cm^{-2}

This has been confirmed with 99% efficiency reached during beam tests

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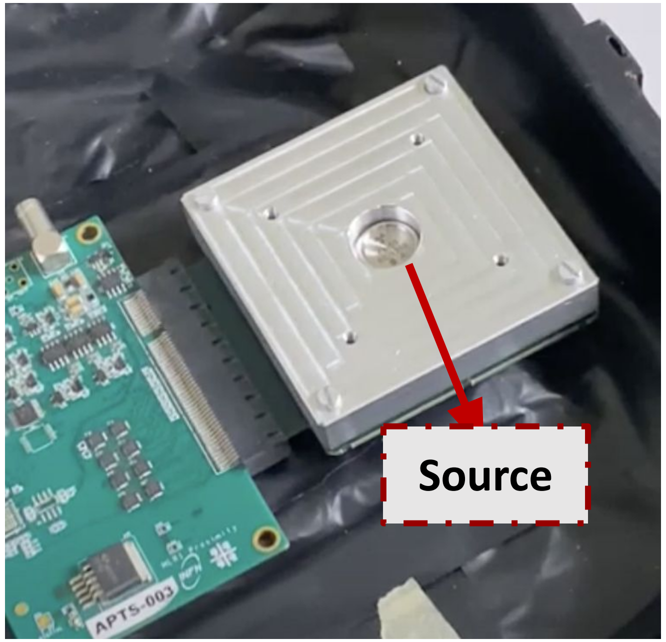
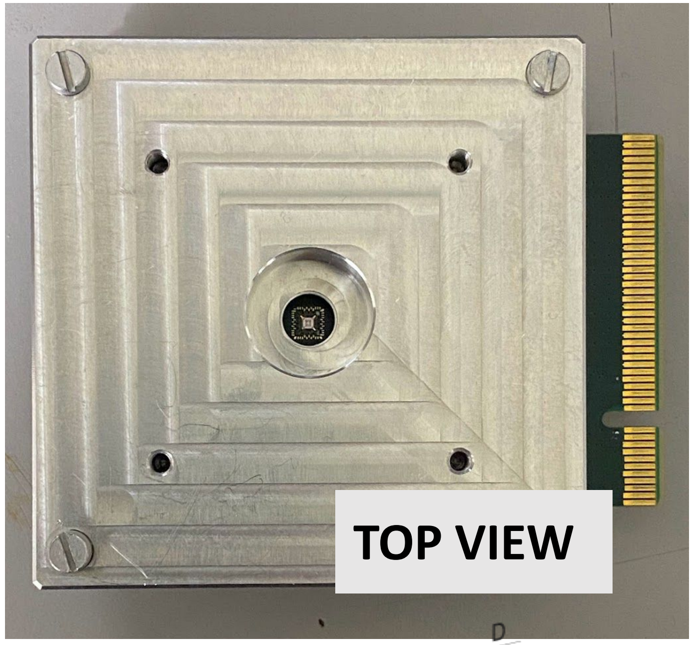
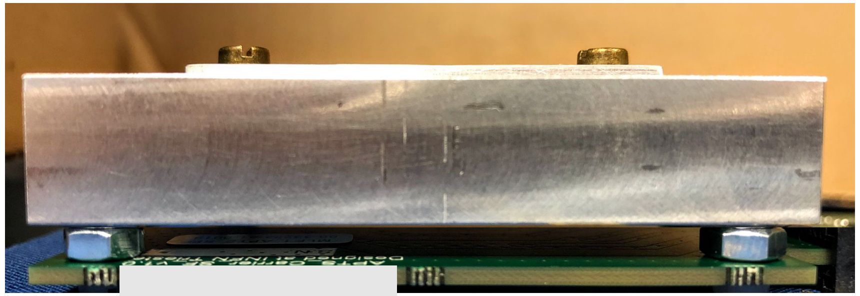
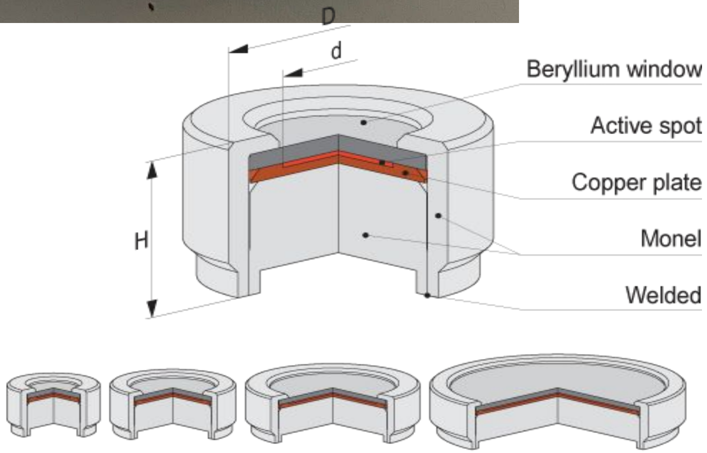
^{55}Fe source setup - INFN-BO

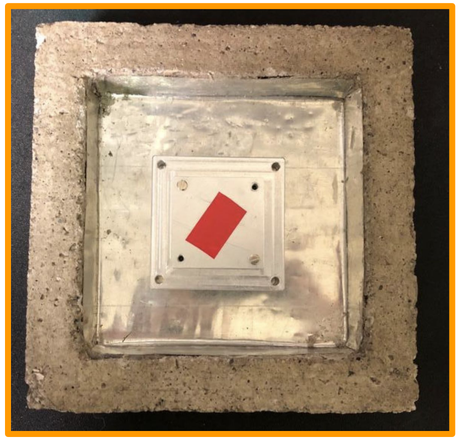




- Source housing diameter: 16 mm
- Hole: 5 mm
- Vertical distance source-chip: almost 3 mm
- when the source is not use, is inside a concrete holder







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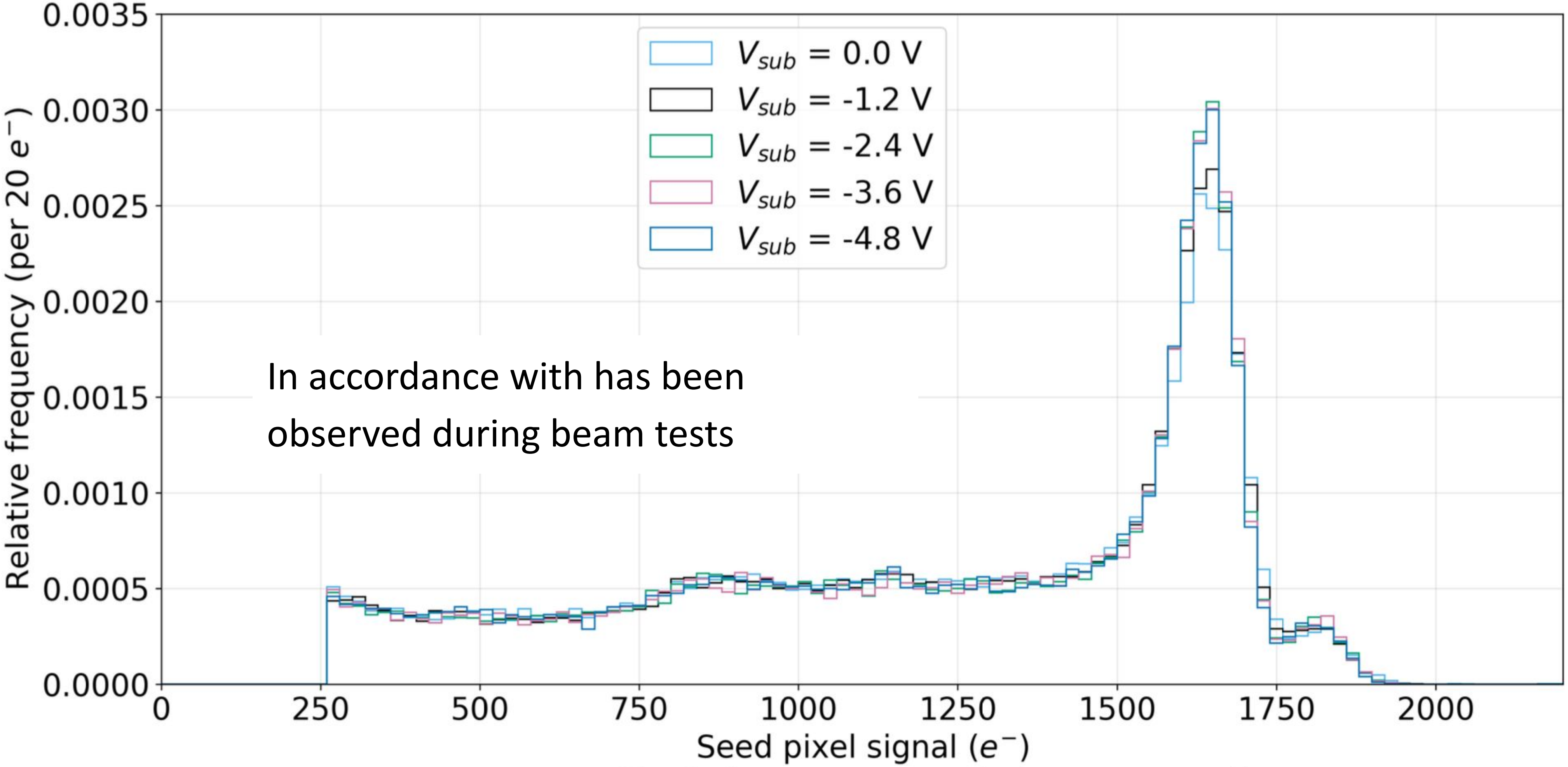
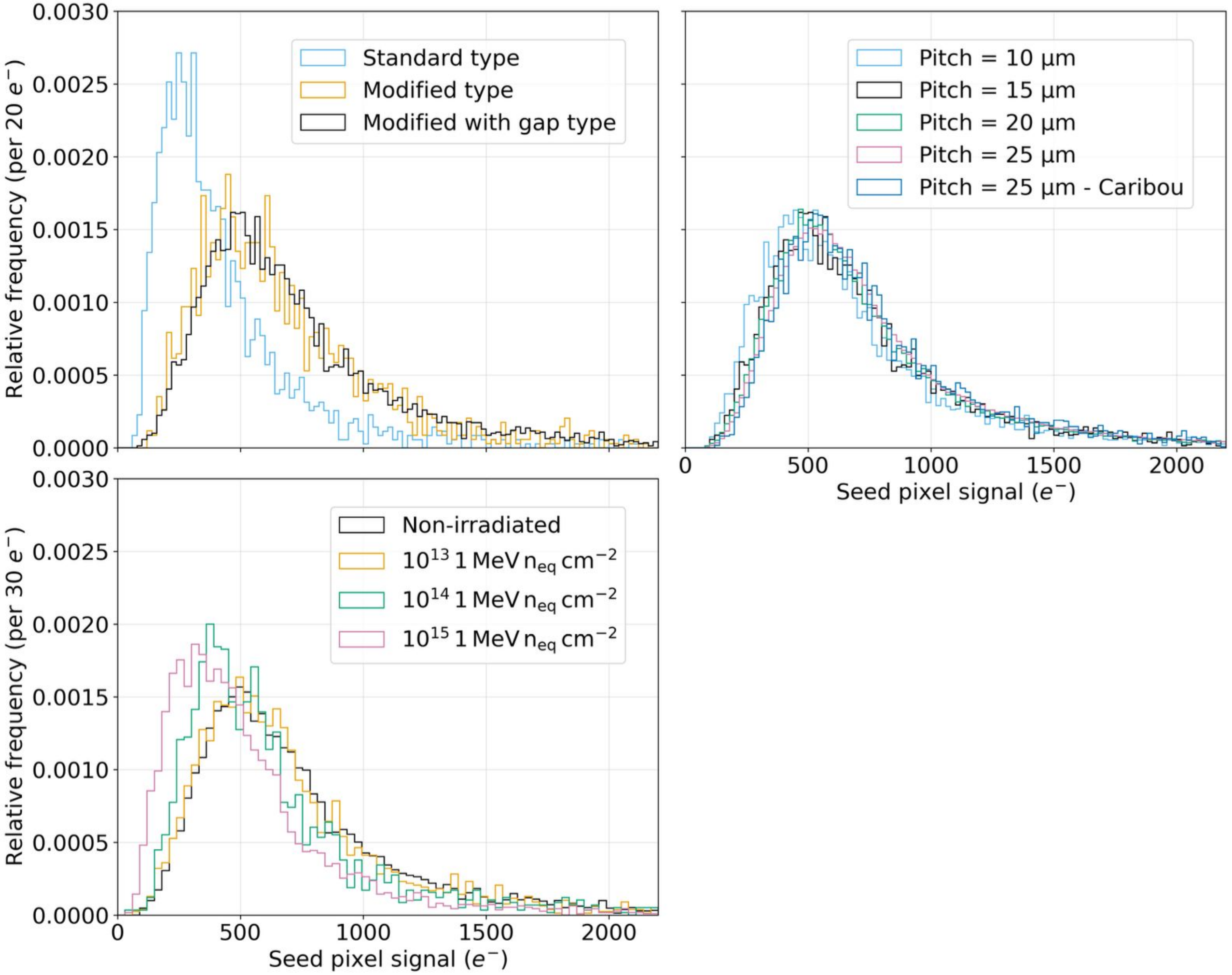
55Fe source results - spectrum with APTS

Modified-with-gap type - different voltages, INFN-BO



In accordance with has been observed during beam tests

55Fe source results - spectrum with APTS
Modified-with-gap type - different voltages, INFN-BO



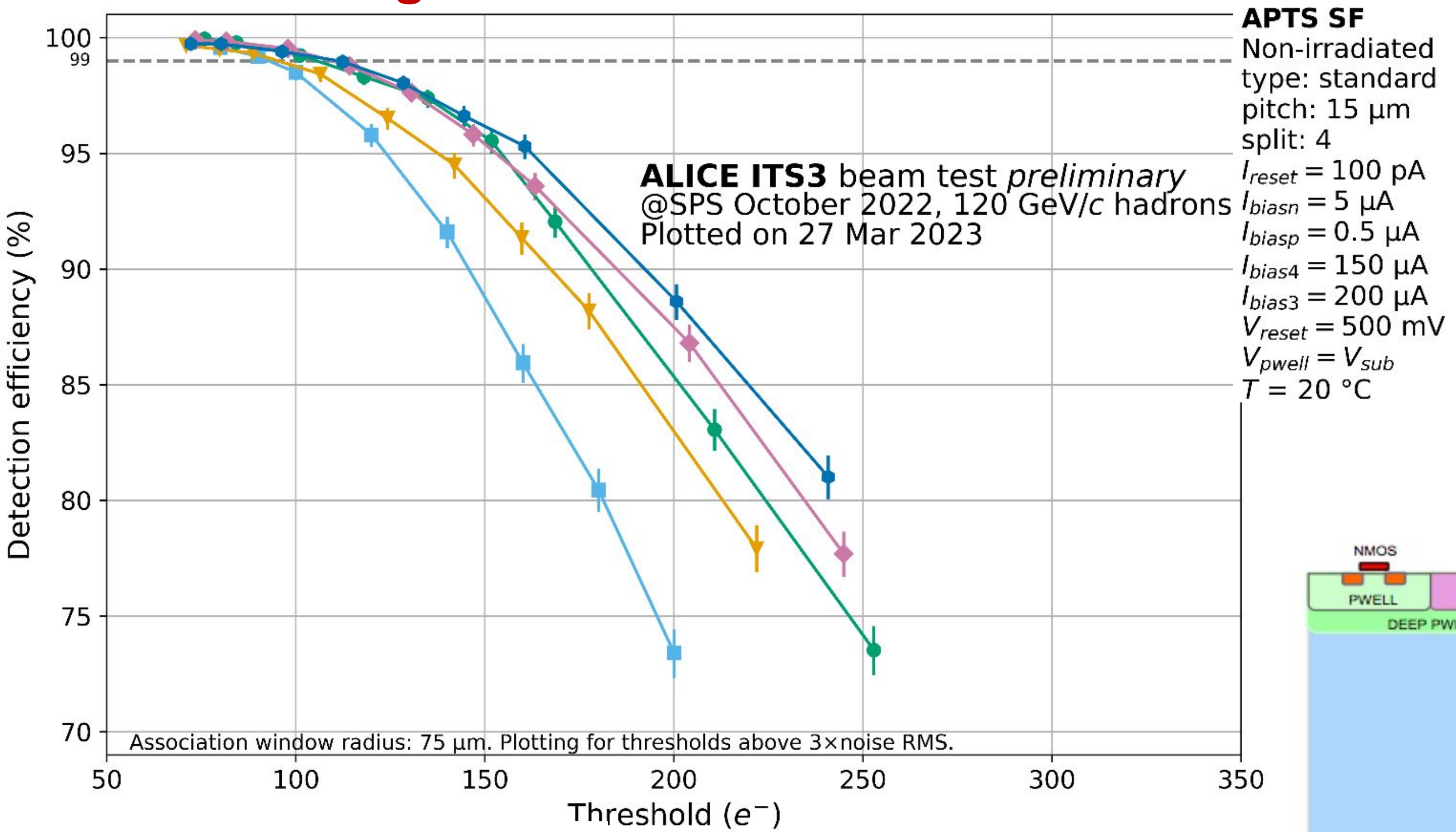
Moving from the standard design to the modified and modified with gap:

→the Most Probable Value (MPV)for the seed signal, increases to higher values

→ improvement in the signal to noise ratio, from 9 to 18

Detection Efficiency - APTS

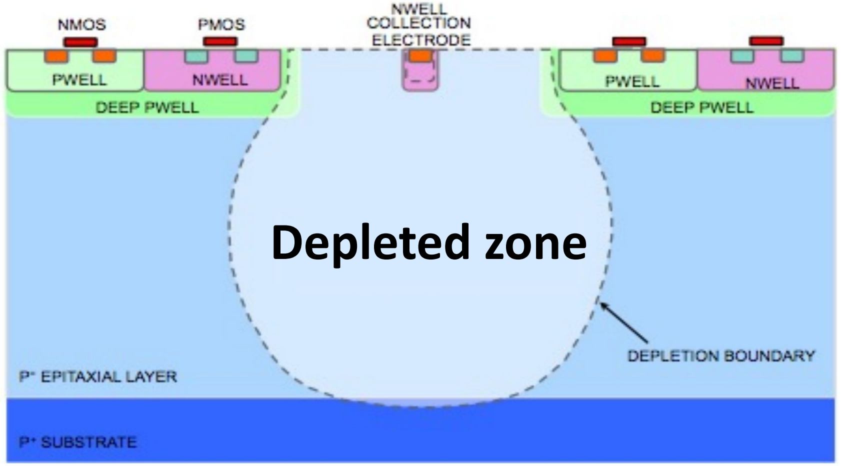
Standard design



$$\epsilon = \frac{\#\,tracks_{1\,ass.cluster,\ DUT}}{total\,\#\,tracks_{DUT}}$$

Efficiency changes depending on the applied reverse bias voltage

Vbb (V)	Noise (e^-)
0.0	25
1.2	24
2.4	24
3.6	23
4.8	23



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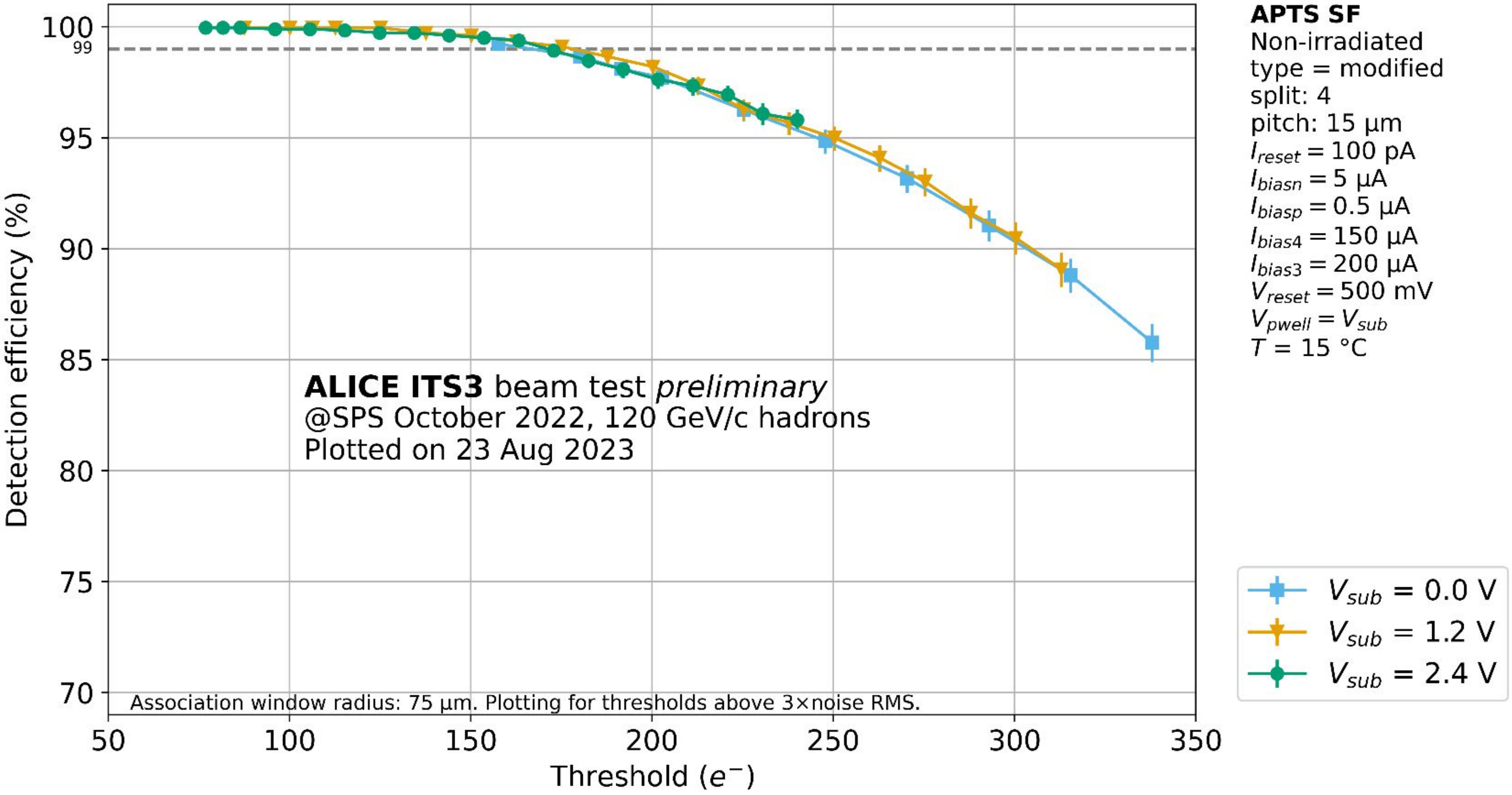
ITS3 - APTS Results - Resolution

Modified design



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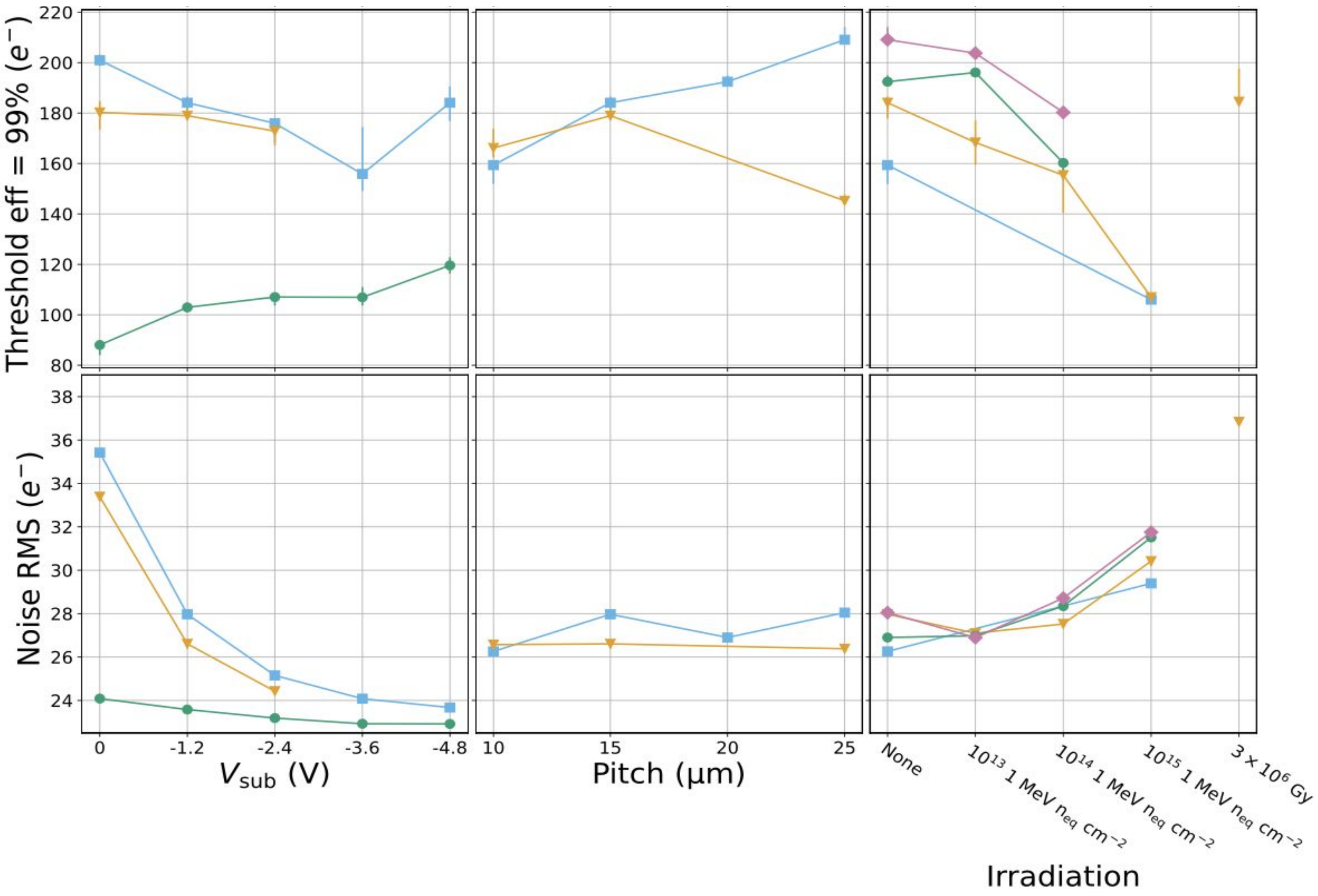
APTS efficiency - resume 2

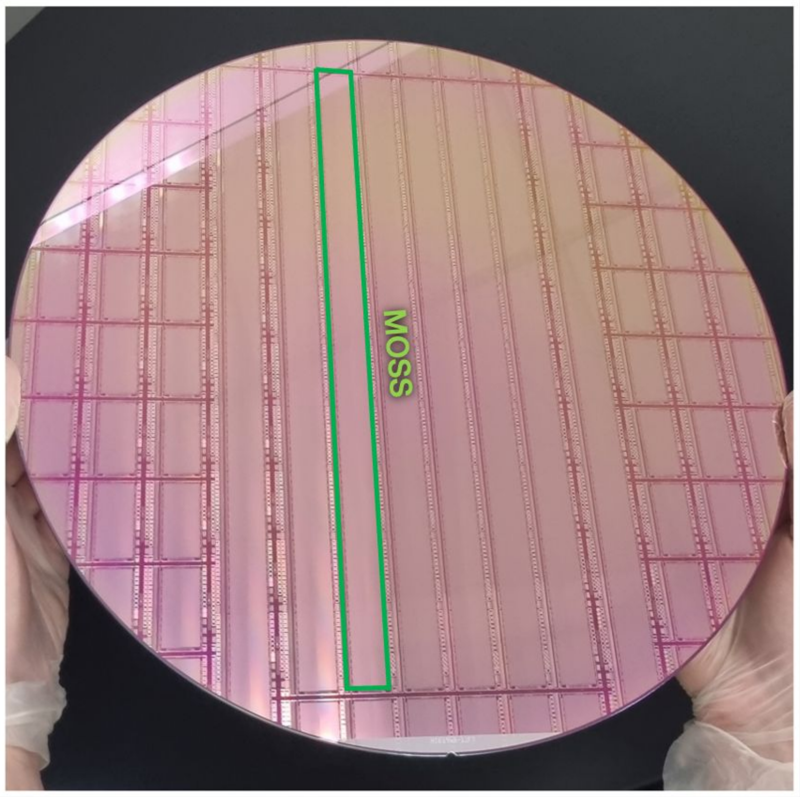


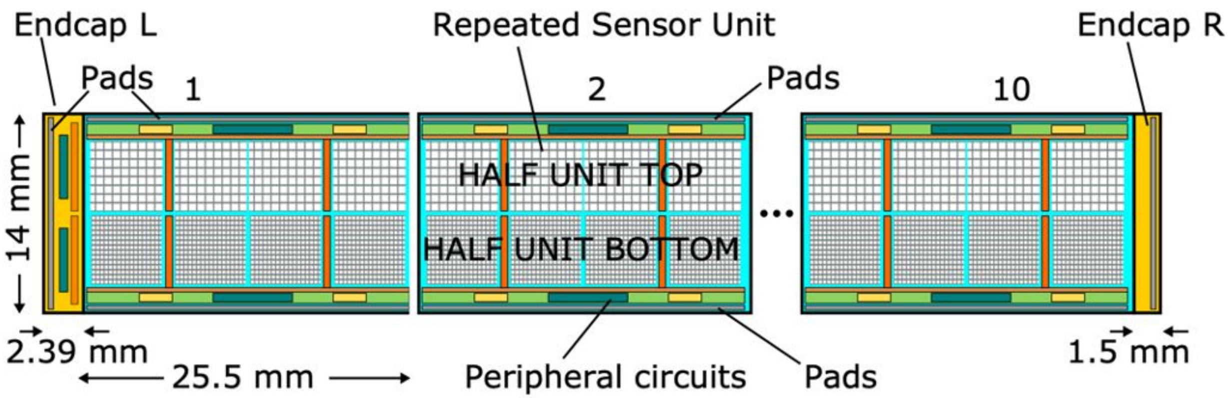
ITS3 - Wafer-scale sensors

MOSS

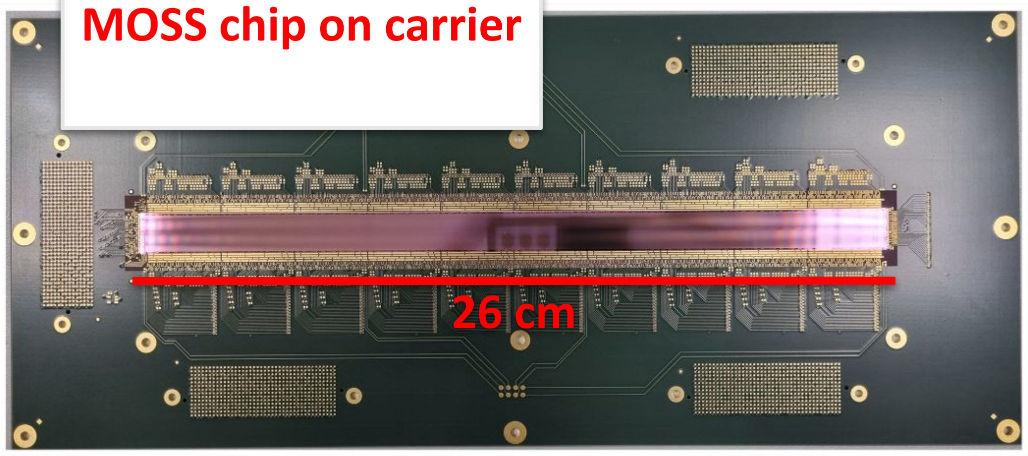
First **large-scale** stitched sensor, **MO**nolithic **S**titched **S**ensor (**MOSS**) received on April 2023:

- Repeated identical but functionally independent units, with **in-silicon** interconnections and peripheral structures of the sensor
- **Laboratory tests**: once checked the basic functionalities, full characterization to assess yield of different sensor sections



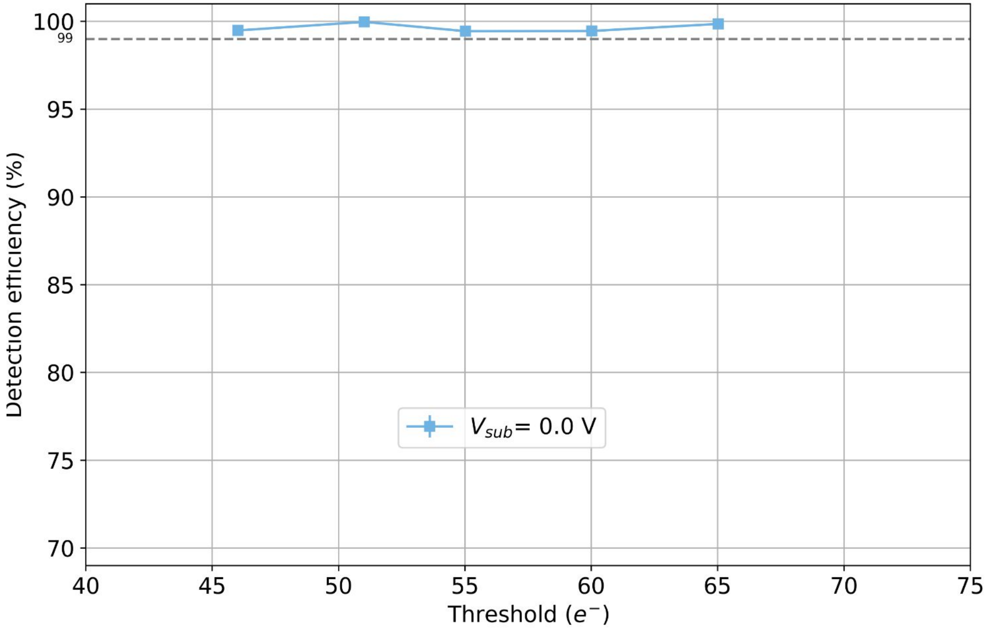


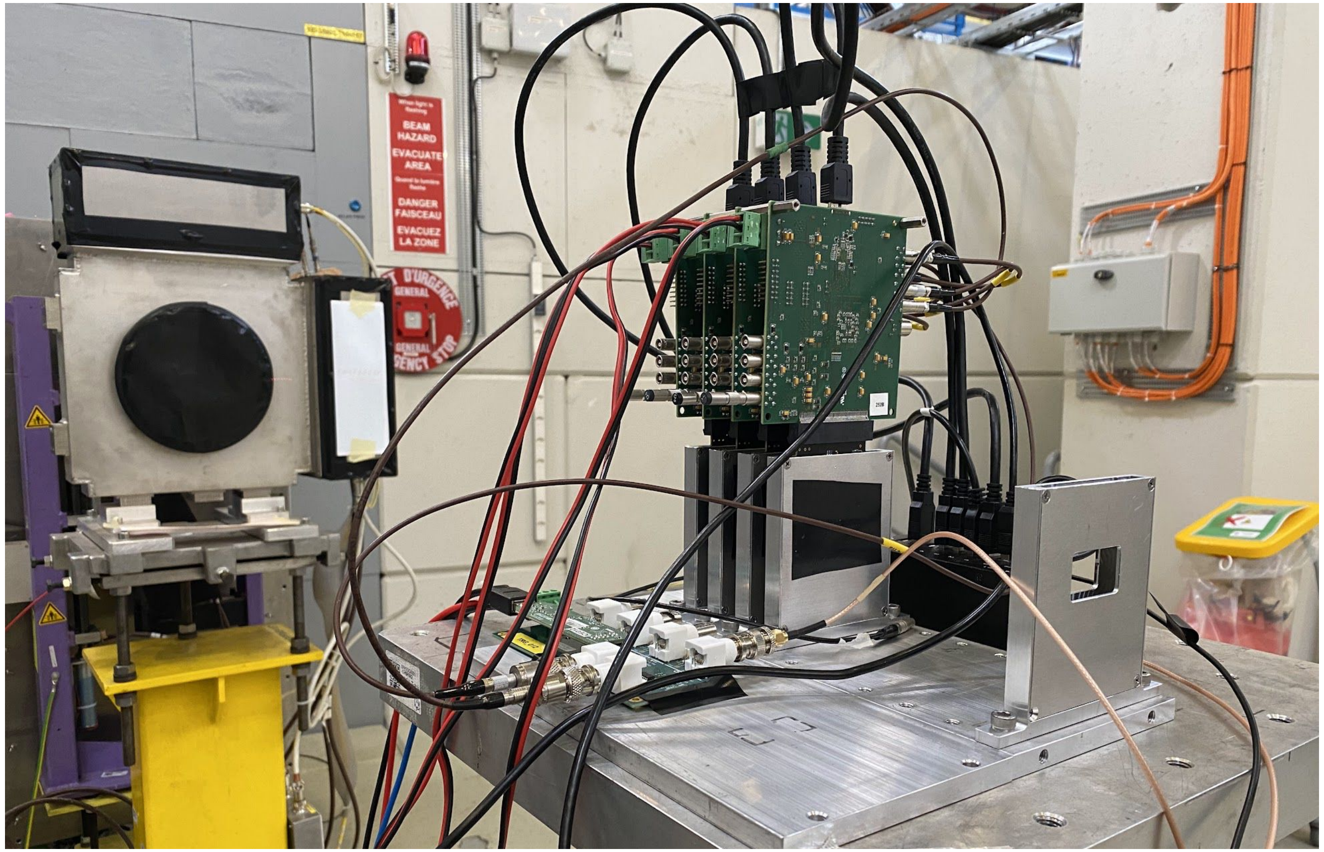
MOSS chip on carrier



Validation of a MAPS telescope for future use in beam test setup

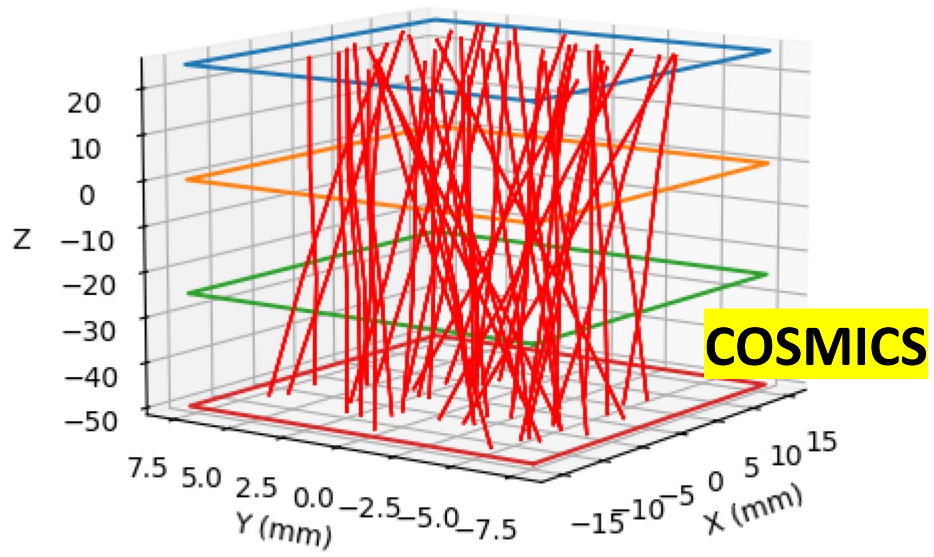
- Telescope with 4 MAPS (ALTAI, similar to the ALPIDE used in the current ALICE ITS2)
- Tested at CERN PS by June 2024
- Sensors are **fully efficient**

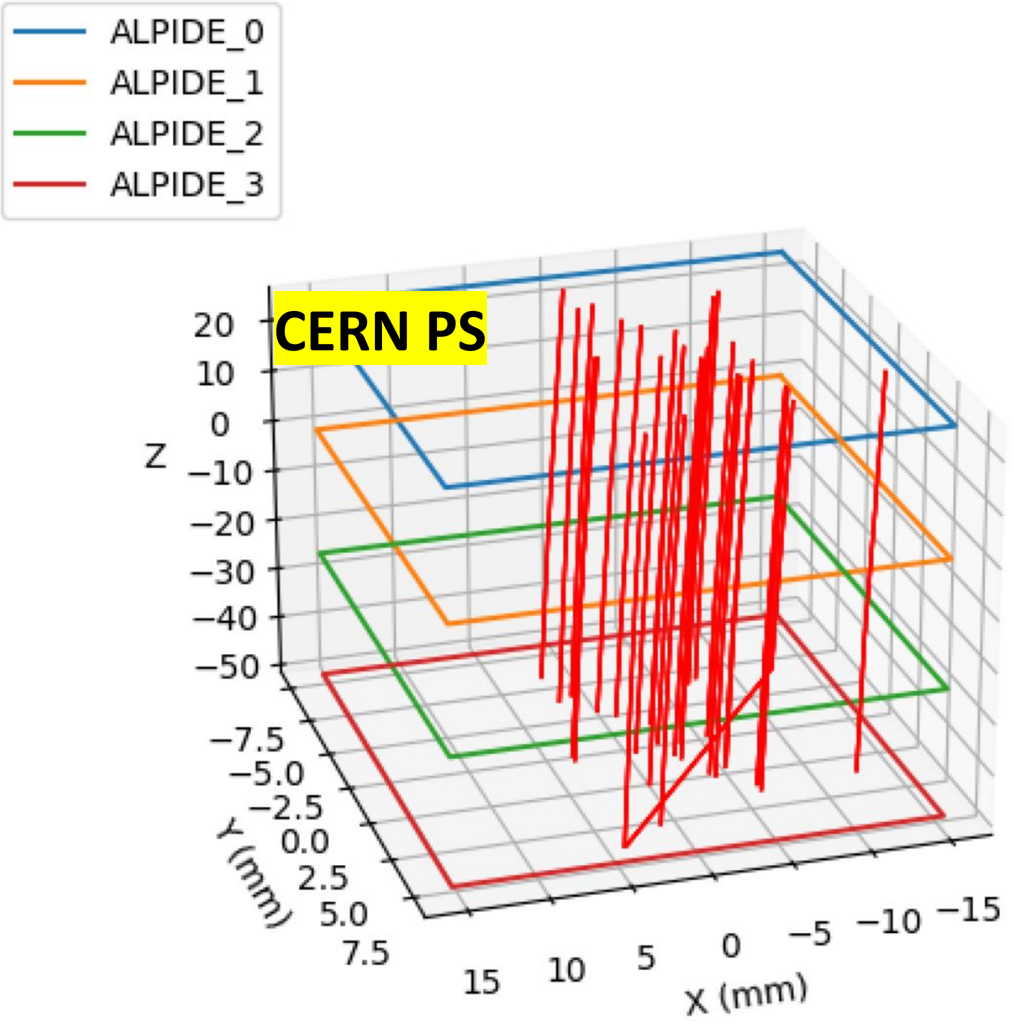




Validation of a MAPS telescope for future use in beam test setup

- Telescope with 4 MAPS (ALTAI, similar to the ALPIDE used in the current ALICE ITS2)
- Tested at CERN PS in June 2024
- Sensors are fully efficient
- **Event display** (WIP)





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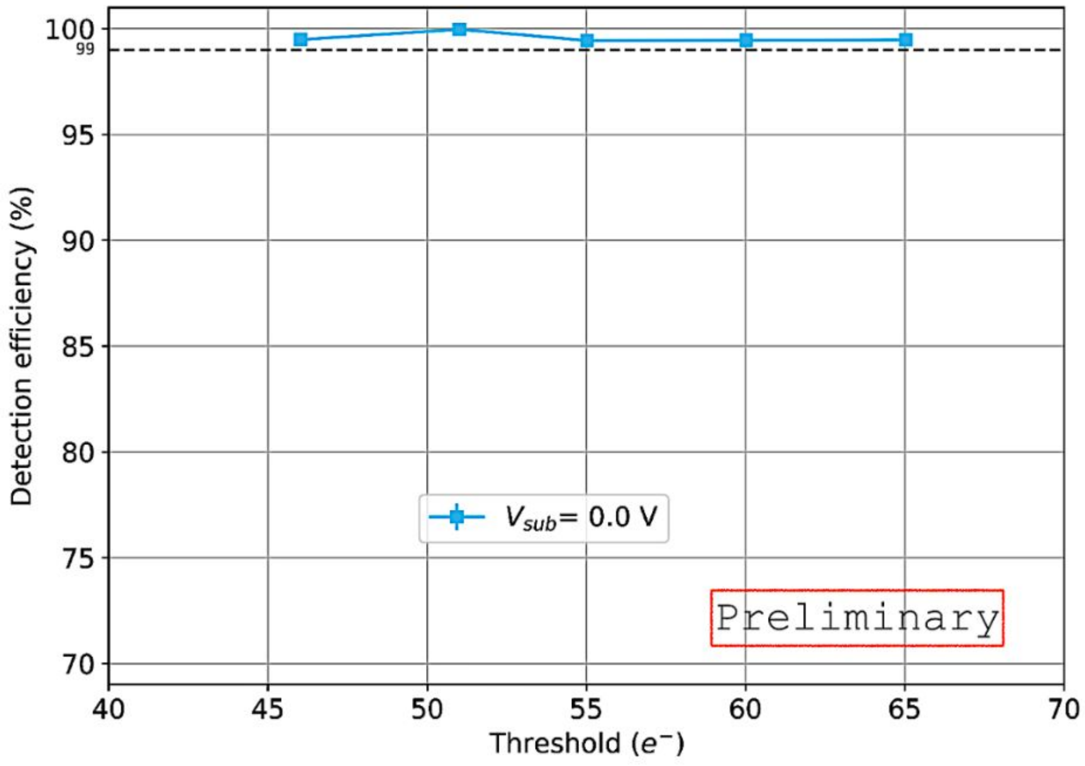
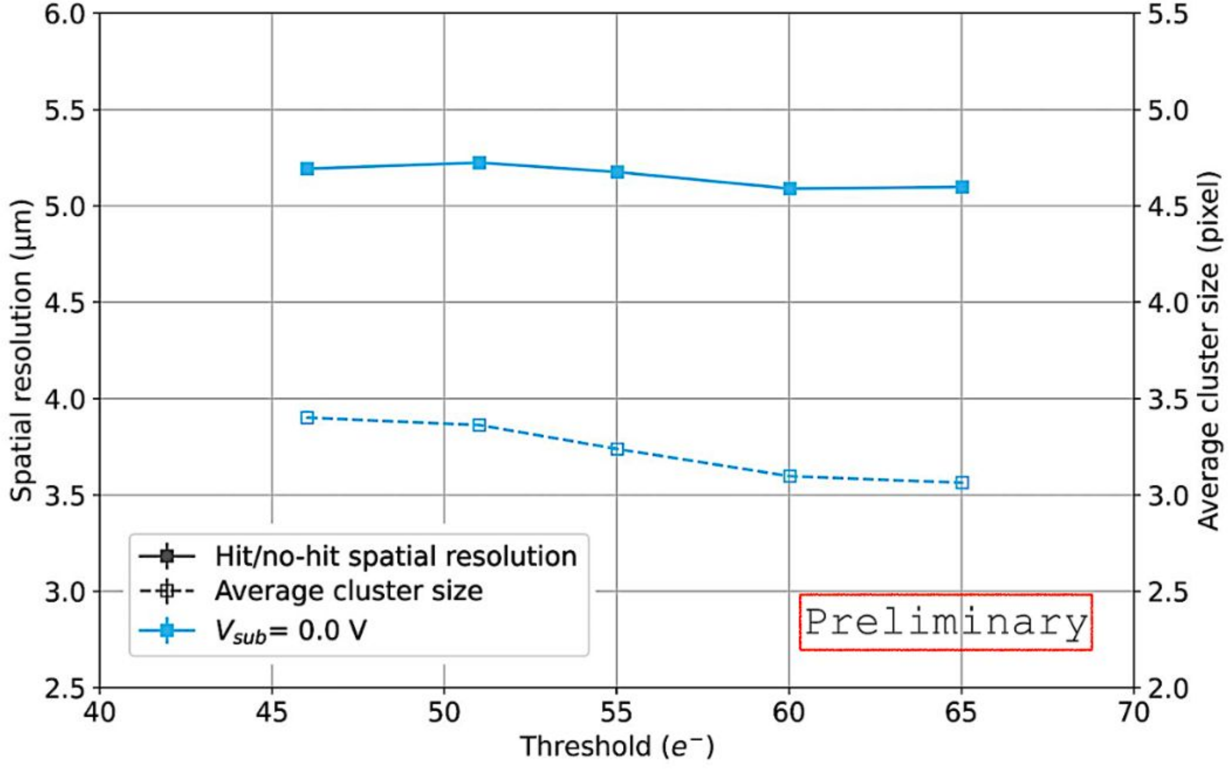
Validation of a MAPS telescope for future use in beam test setup

Efficiency and resolution





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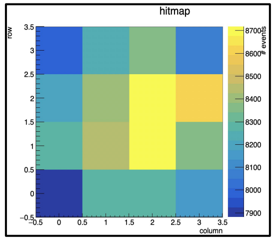
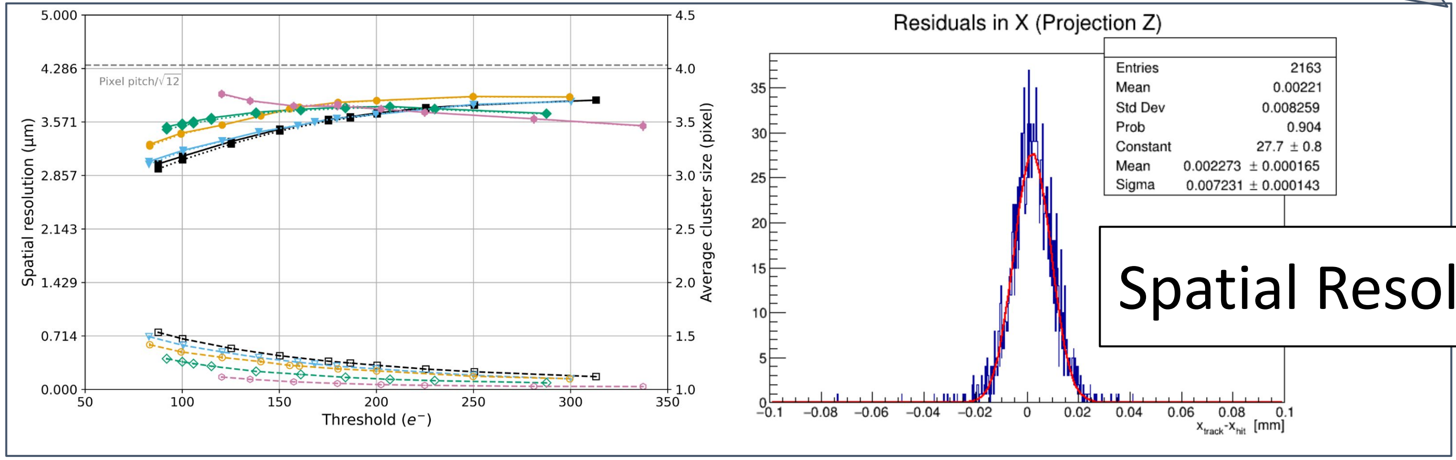
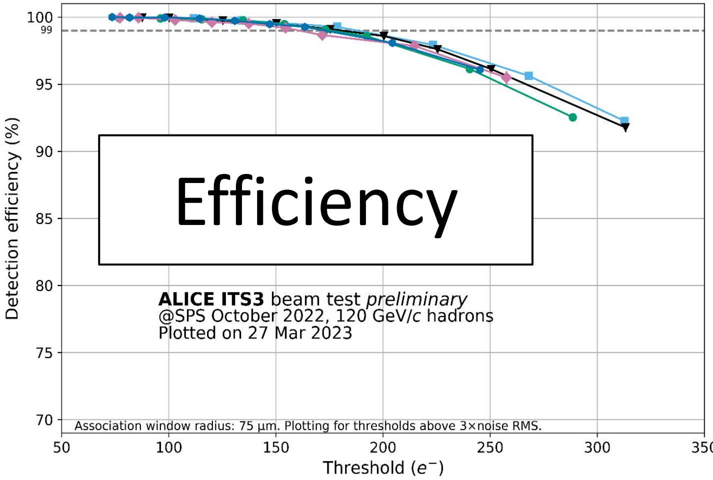
Typical analysis procedure with Corry



Masking → Prealignment → Telescope Alignment → DUT Alignment → Analysis



Spatial Resolution



Efficiency

Typical analysis procedure with Corryvreckan

Analysis flow:
- masking
- prealignment (telescope and DUT)
- alignment - telescope
- alignment - DUT
- analysis

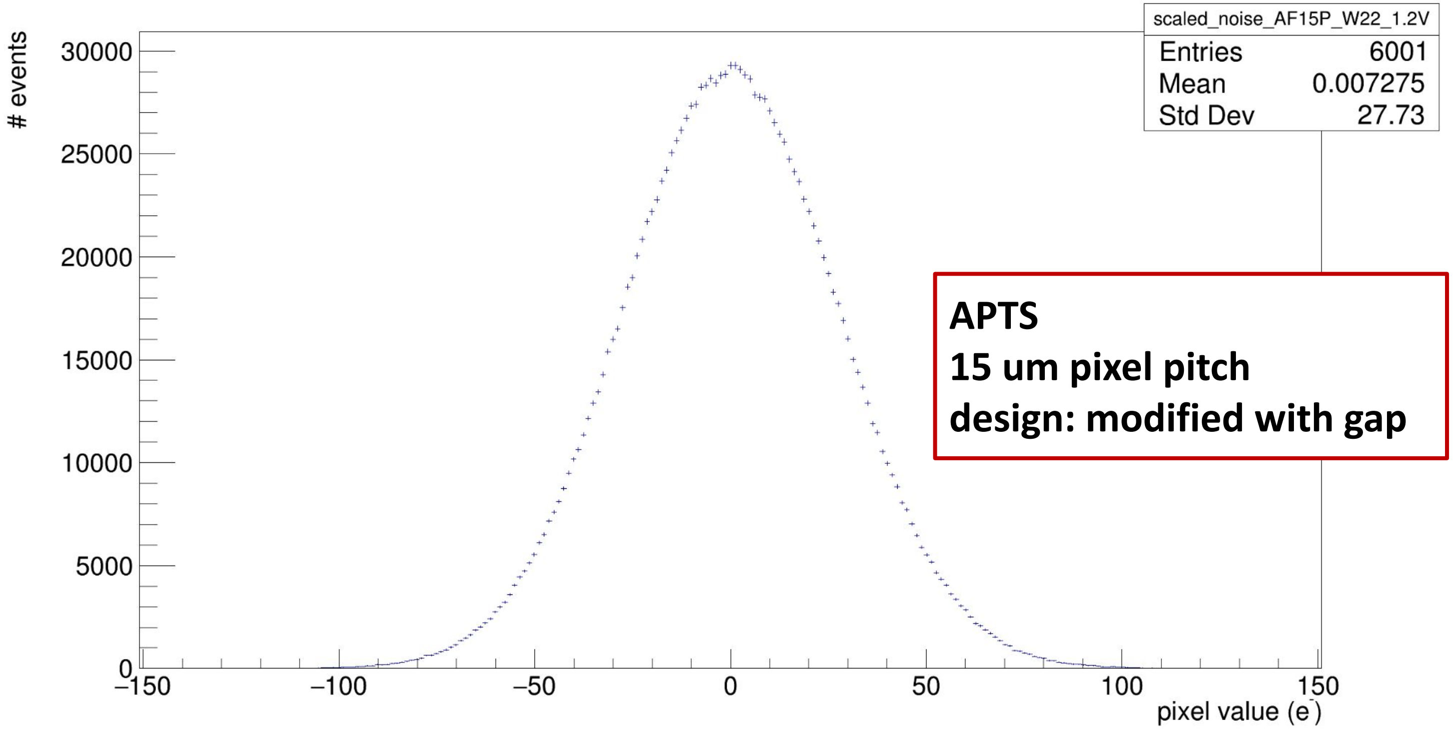
Telescope alignment:
- Performed excluding the DUT from the track reconstruction
- NO region-of-interest inside the sensor

DUT alignment:
- 4 steps with decreasing spatial cut
  - spatial cut decreases starting from 4*pitch to the APTS pitch
- baseline selection: frame 96
- signal selection: frames 98-101

Analysis with Corryvreckan - Noise estimation

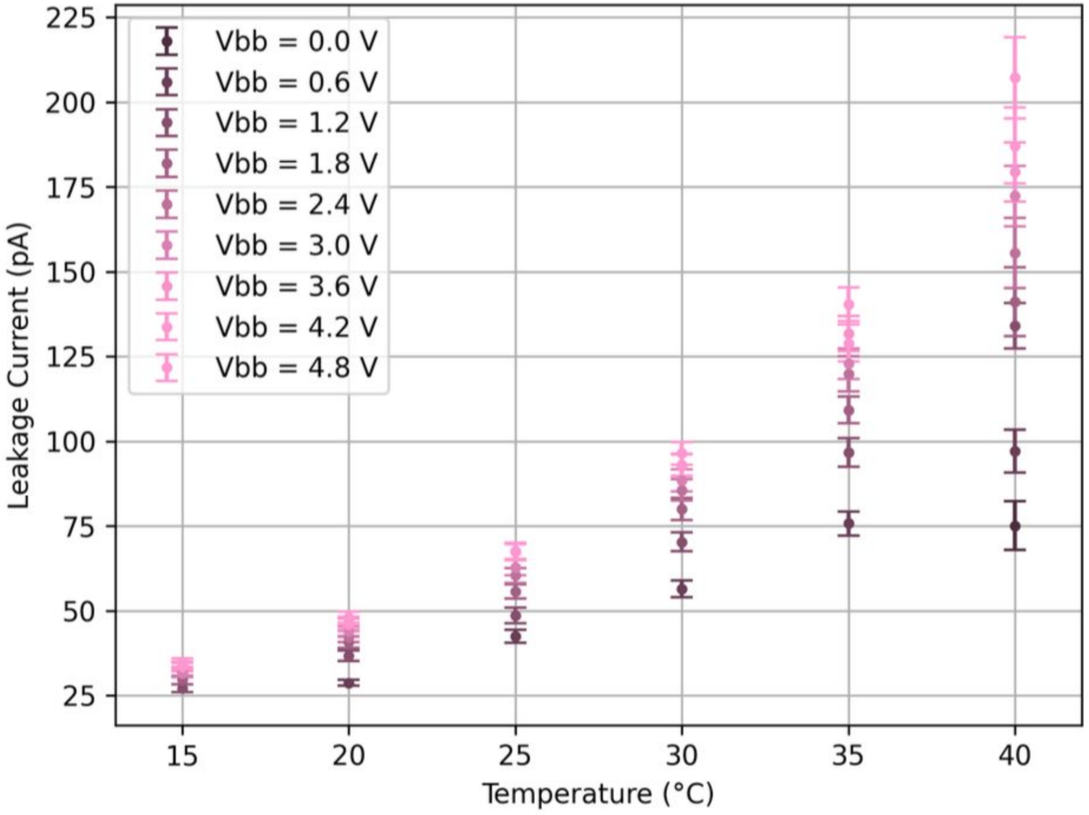
For each pixel obtained a gaussian distribution:

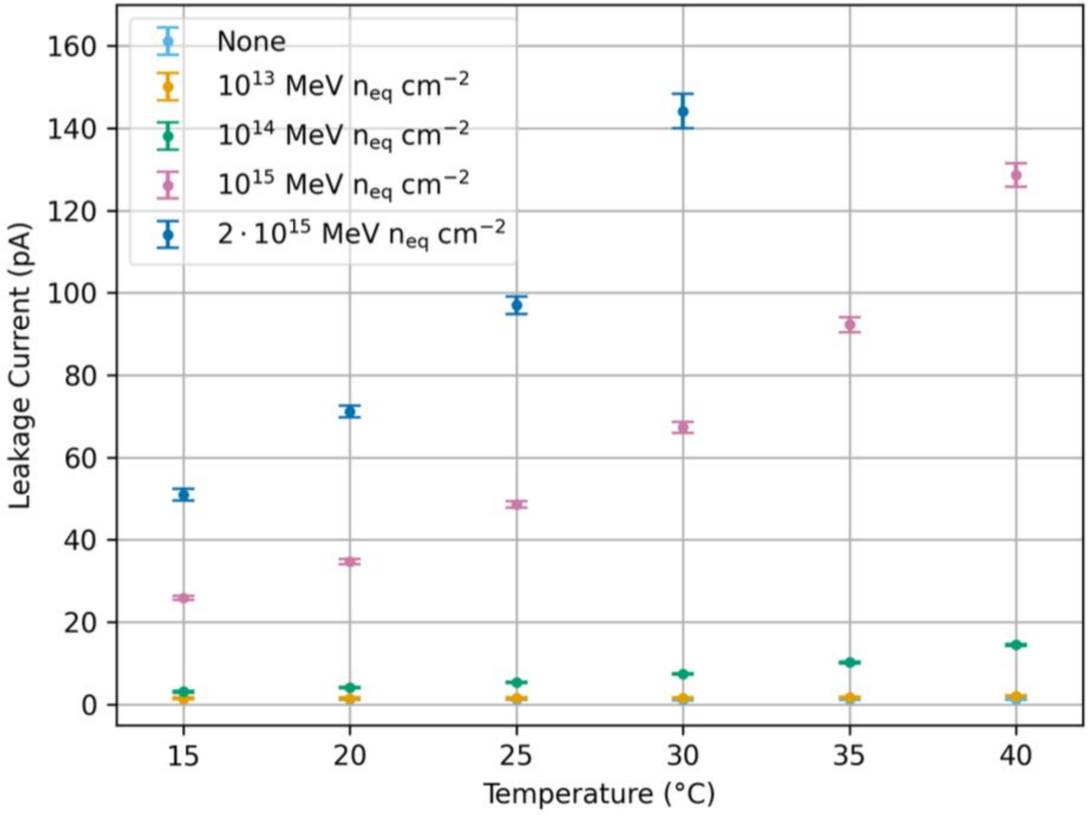
- the RMS of the pixel value distributions is the noise
- noise estimation done for all the analysed runs
- resolutions and efficiencies plotted only for:
  threshold > 3*RMS



- **Baseline** selection: frame 96 (Nb)
- **Signal** selection: minimum searched between frame 98 and 101 (Ns)
- **Noise** selection: frame 2Nb - Ns→ same done for APTS in laboratory

APTS Leakage Current





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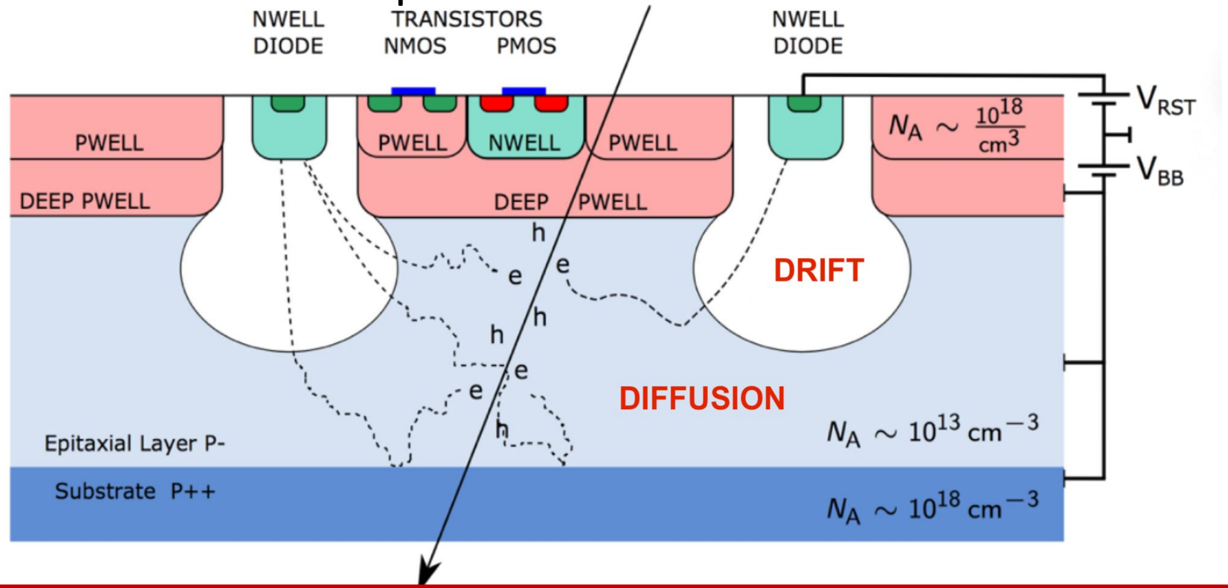
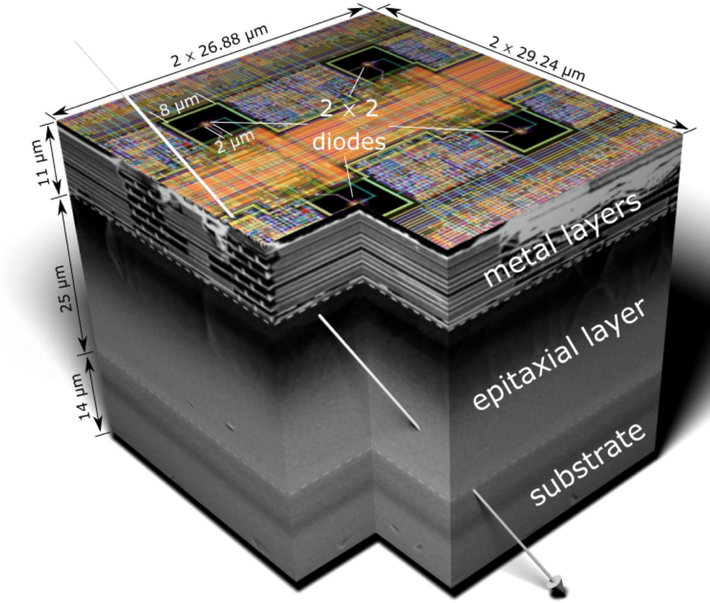
Monolithic Active Pixel Sensors (MAPS)

- The single Si chip includes both detection volume and readout electronics (instead of connecting two different units - hybrid pixel sensors)
- Many advantages:
  - small pixel pitch O(10-30 µm)
  - lower power consumption O(10-100 mW/cm^2) thanks to lower capacitance
  - thin: <50 µm (0.05% X_0)
  - commercial process





Pointing resolution and vertex detectors layers

The pointing resolution σ_p can be written as:

$$\sigma_p \sim \sigma_p^{sp} \oplus \sigma_p^{ms}$$

where σ_p^{ms} is the contribution due to the multiple scattering and σ_p^{sp} the one given by the structure of the detector (number of layers ad proximity to the Interaction Point.)

This indicates that is possible to achieve a better σp by having a better spatial resolution of the detector, going closer to the IP, and having a lower material budget (in this particular case, of the beampipe and the innermost layer).

$$\sigma_p^{ms} \sim r_1 \theta_{RMS}$$

$$\sigma_p^{sp} = \sqrt{\left(\frac{r_2}{r_2 - r_1}\sigma_1\right)^2 + \left(\frac{r_1}{r_2 - r_1}\sigma_2\right)^2}$$