Summer program presentation Detector charge calibration of the DESY CHIP V2

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DESY Summer program 2025

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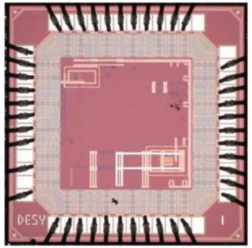

OVERVIEW

1. Motivation
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4. LAB measurements
5. Data analysis
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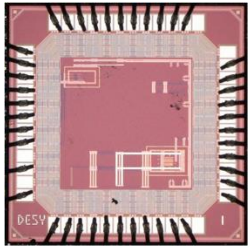


MOTIVATION – Tangerine R&D

The demand for performance and precision in HEP has driven **R&D**.

Requirements of next-generation lepton collider experiments:

- ✓ **Material budget**: < 0.05% X/X_0
- ✓ **Single-point resolution**: ~ 3μm
- ✓ **Time resolution**: ~ 1-10 ns
- ✓ **Rate capabilities**: 1 MHz particle rate
- ✓ **Granularity**: < 25 μm x 25 μm

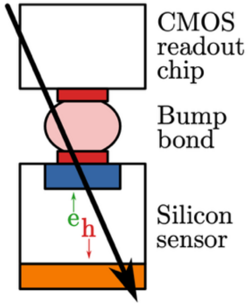
The **Tangerine project** (**TowArds Next GEneRation SIlicoN DEtectors**) began in 2020 to develop detectors for next generation lepton colliders.

- ➢ Development of **MAPS** (monolithic active pixel detectors) in a **65 nm CMOS** (Complementary Metal-Oxide-Semiconductor) Imagin technology.

MOTIVATION – MAPS vs. Hybrid detectors

Hybrid detectors

Sensor and readout electronics produced separately and connected using **bump bonding**.

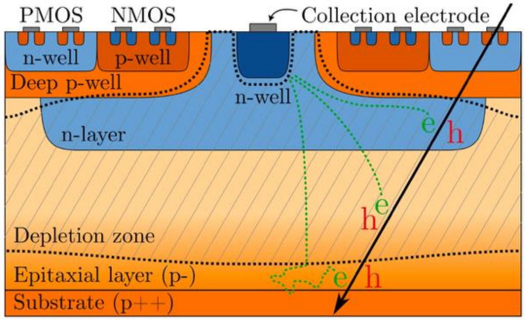


- Pixel sizes are constrained by the bump bonding pitch.

MAPS

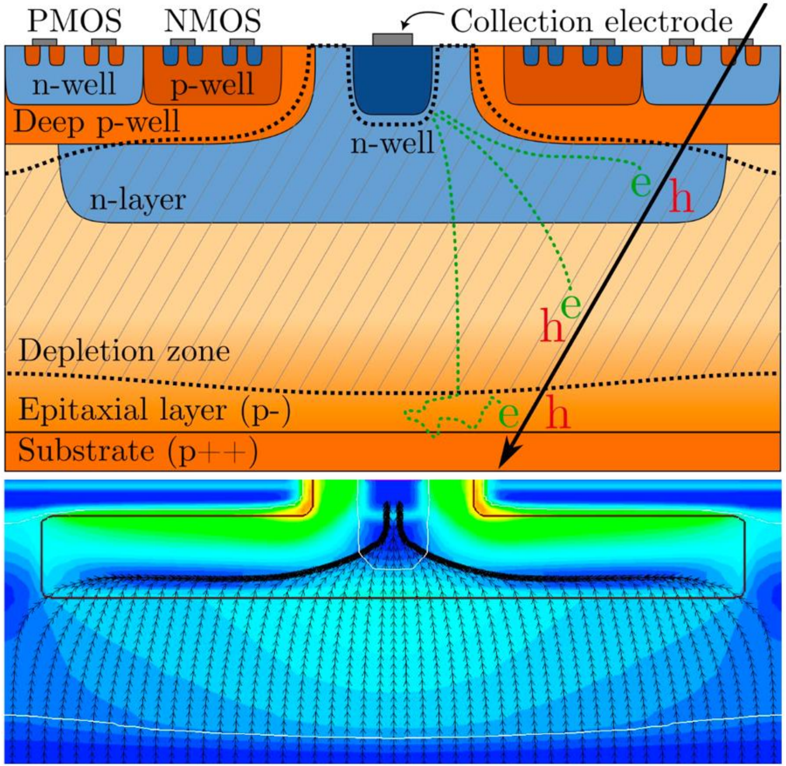
Sensing element and the readout circuitry **integrated in a single silicon layer**.

- ✔ Lighter, thinner, and capable of higher granularity.



Monolithic pixel sensor profile, DESY Chip V2, J. Dilg Master's Thesis

MAPS R&D



Monolithic pixel sensor profile, DESY Chip V2 and Electric field simulation (generic doping profile, electronics not included), J. Dilg Master's thesis

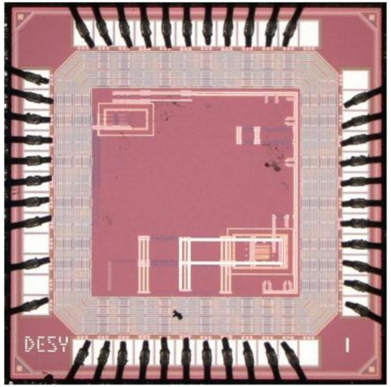
- Adding an **n-layer** extends the depletion zone to the pixel edges.
- Introducing a **gap** in the n-layer increases the lateral electric field near the edges, leading to a **faster response**.

When a particle passes through the detector, it causes **ionization**, generating **free electron-hole pairs**.

Drift under the influence of an electric field established by an external voltage.

Detection as **electrical signal** in the **collection electrodes**.

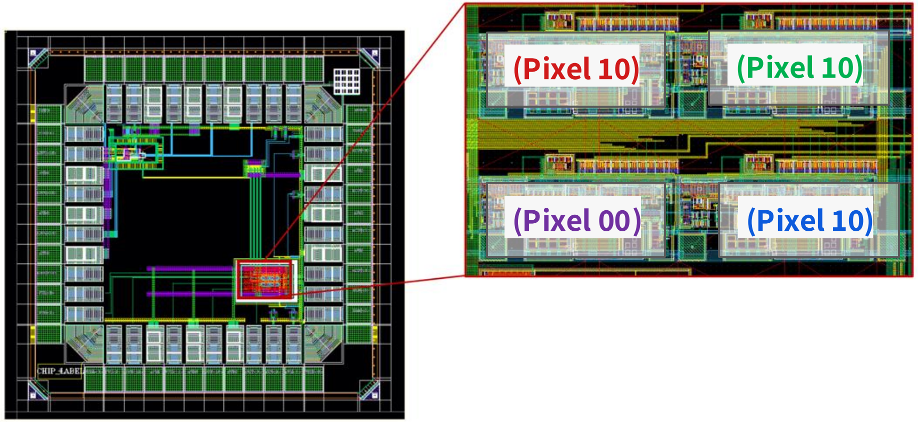
DESY CHIP V2



DESY CHIP V2
OR DESY ER1

- Designed at DESY
- 2 × 2 pixel matrix
- 35 × 25 μm^2 pitch
- In-pixel amplifier and analog output

Pixel Arrangement

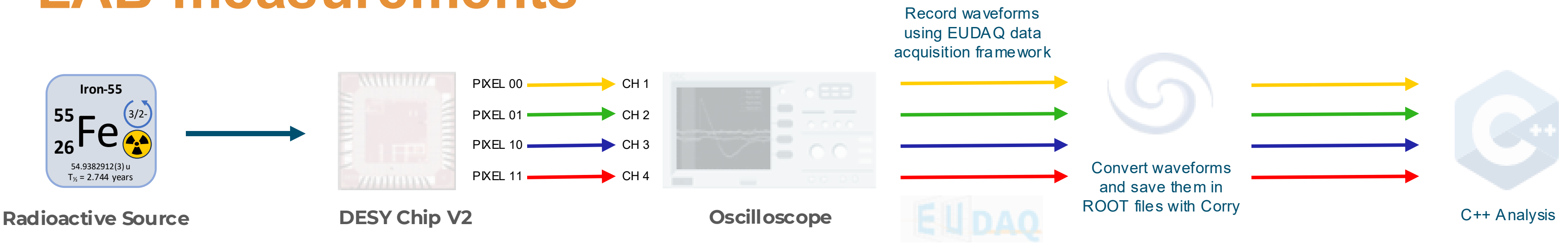


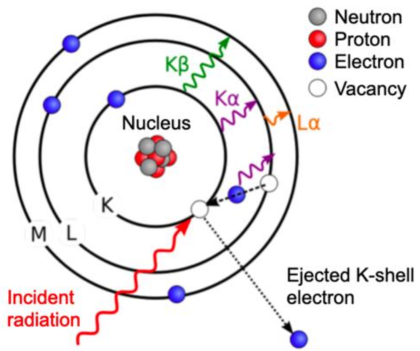
Study the performance of two n-gap layouts with different n-gap sizes:

- **4 µm**
- **2.5 µm**

A **larger n-gap** enhances the **lateral electric field near the pixel edges,** which leads to a **faster response .**

LAB measurements





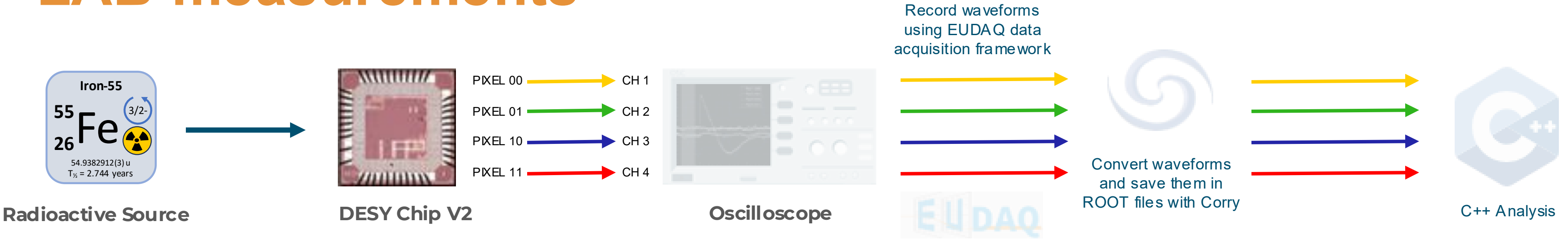
^{55}Fe decays by electron capture of an inner-Shell electron (usually K shell):

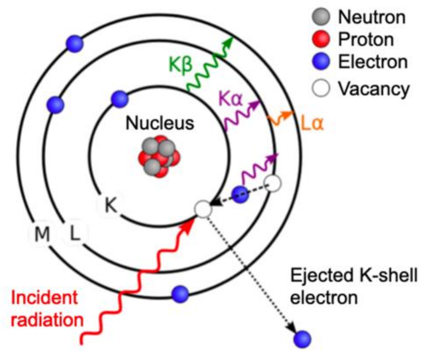
$^{55}Fe + e^- \rightarrow {}^{55}Mn + \nu_e$

Vacancy in the K shell filled by other e⁻ releasing energy:

- **X-ray emission**: a photon is emitted.
- **Auger electron emission**: the energy is transferred to another electron, which gets ejected from the atom.

LAB measurements





The emission lines of **X-rays are used for calibration**, knowing that the energy required to **create an electron–hole pair in silicon is 3.66 eV**, via the **photoelectric effect**.

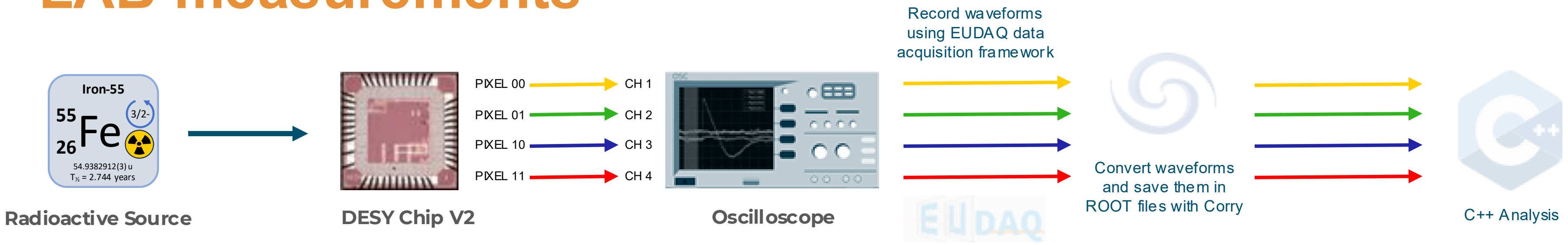
- **K_α lines**: transitions from L → K shell
  - $K_{\alpha 1}$ = 5.89875 keV (16.2%)
  - $K_{\alpha 2}$ = 5.88765 keV (8.2%)

  → As a single **K_α 5.895 keV X-ray** ~ **1617 eh-pairs** (25 %).

- **K_β line**: transition from M → K shell
  - **6.491 keV ~1778 eh-pairs** (2.85%)

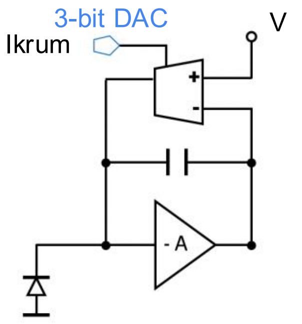
Auger electrons: ~5.19 keV (60.1%) – not detected

LAB measurements

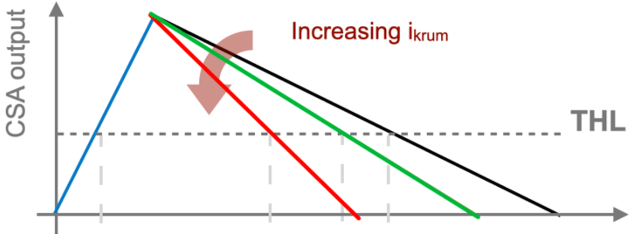


CSA (charge sensitive amplifier) converts induced current into a **voltage signal** → Signal is procesed and recorded with the **oscilloscope**.

In-pixel frontend:

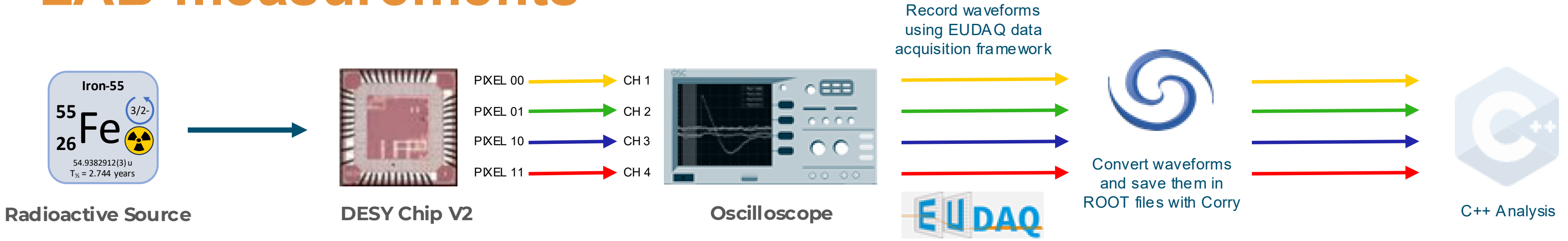


The **Krummenacher current (Ikrum)** returns the CSA output to baseline after each hit.



The strength of the Ikrum can be tuned individually for each pixel through a **3 bit DAC**.

LAB measurements



The signal is procesed and recorded with the **oscilloscope**. → Digitalized with **Corryvreckan**.

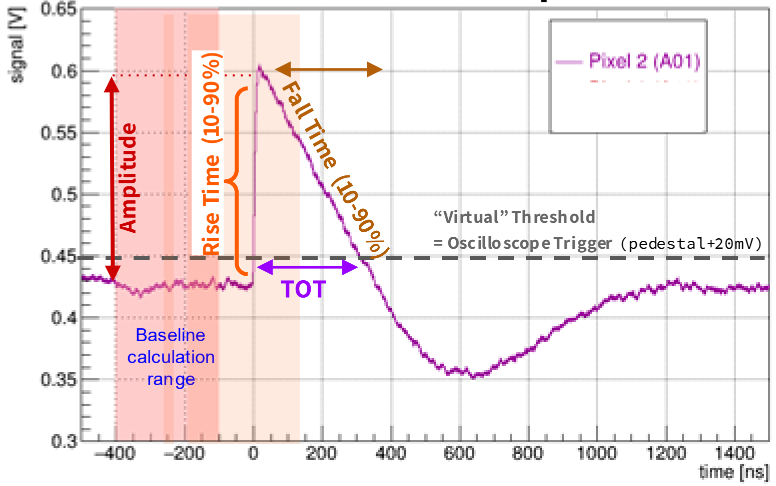
Measurable quantities:

- Pedestal (Baseline)
- Amplitude
- Time over Threshold (scope thr.)
- Rise Time (10-90%)
- Fall Time (10-90%)
- RMS of the noise

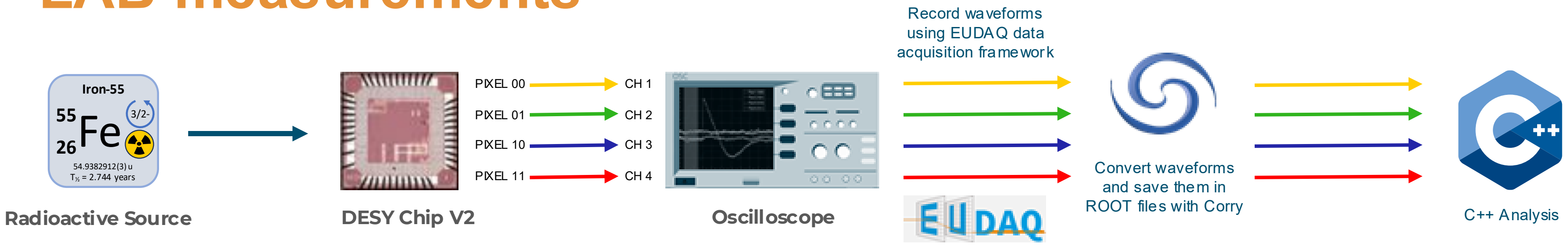
The amplitude is calculated as the maximum of the waveform minus the baseline.

The **amplitude** of the pulse is directly **proportional to the collected charge**.

Waveform example



LAB measurements



→ Data analysis in C++

- Calculate the **4 µm n-gap layout** detector **gain factor G** using a ^{55}Fe source fitting K_α and K_β peaks with the calibration constrained such that 0 V corresponds to 0 electron–hole pairs.

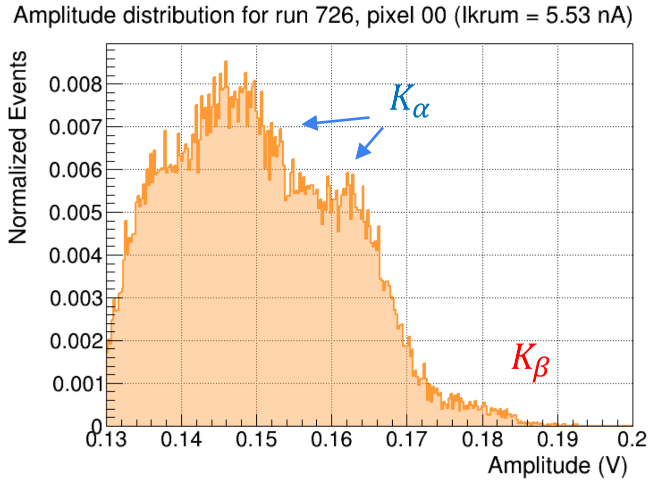
$$G = \frac{\text{waveform amplitude (V)}}{\text{number of deposited charges (e)}}$$

- **Compare the performance** of the two **n-gap layouts** (**2.5 µm and 4 µm**) to evaluate the impact of gap size on detector response.

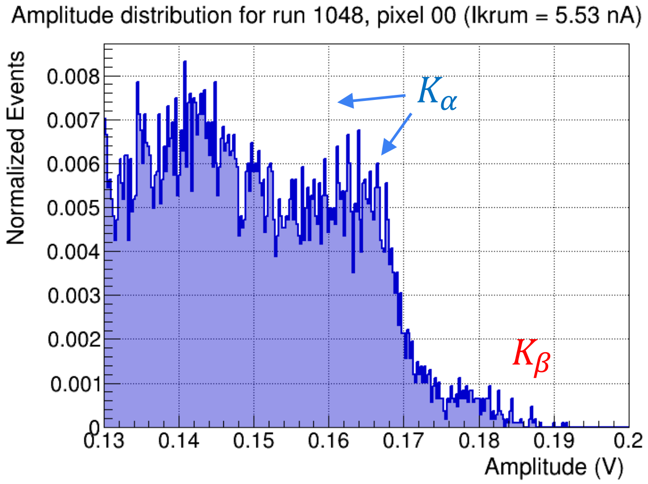
ANALYSIS – Layout comparison

Peaks of the spectrum of ^{55}Fe for 4 μm and 2.5 μm.

4 μm

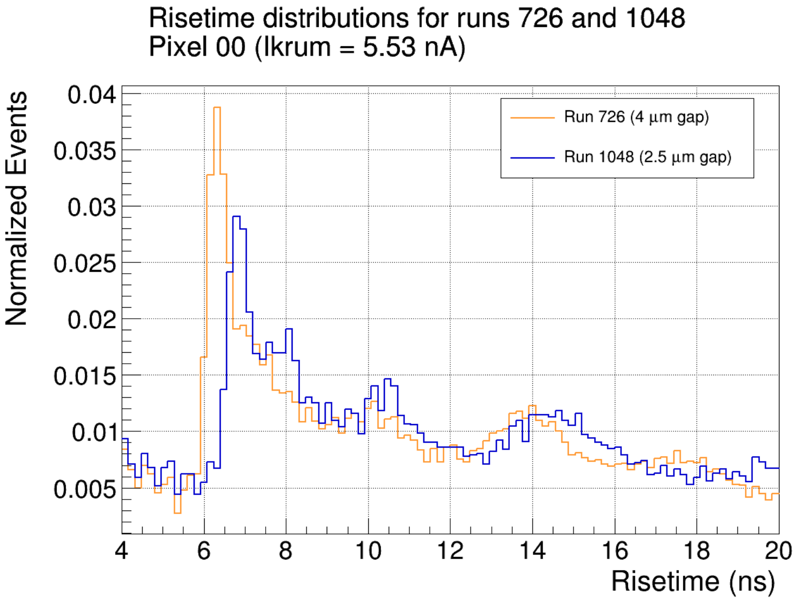


2.5 μm



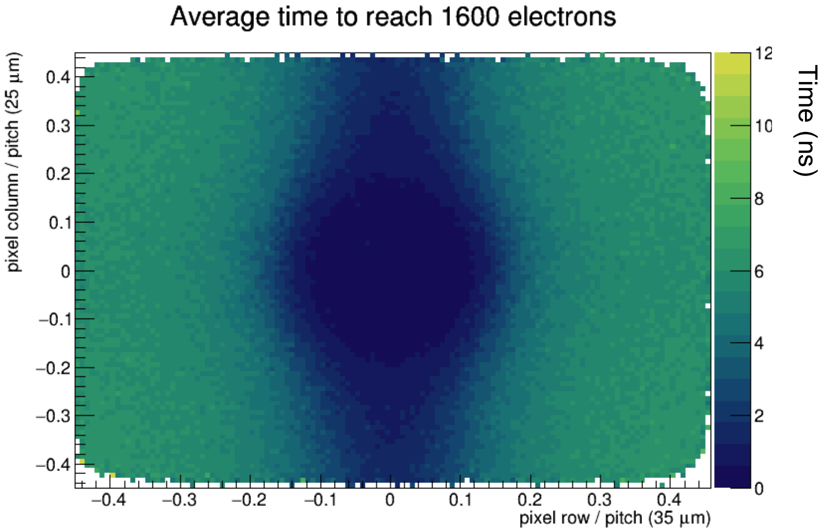
- The K_α **peak appears doubled** due to the rectangular geometry of the detector, which causes a non-uniform detector response.
- The K_β peak is comparatively very small (2.85%)

ANALYSIS – Layout comparison



- Faster response for the **4 µm** n-gap

- Rectangular geometry of the pixels causes a non-uniform charge collection

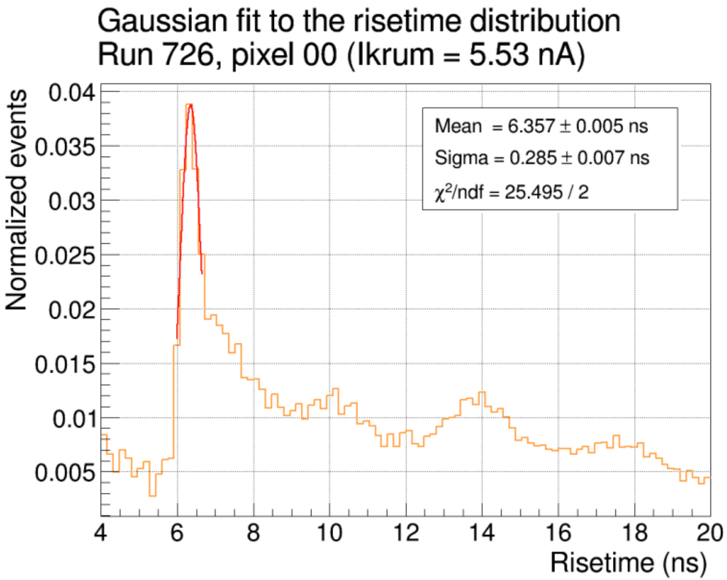


Simulation by Håkan Wennlöf, 2024

Solution: **Cut based on the signal rise time** to do the calibration of the **4 µm** n-gap layout.

ANALYSIS - Charge calibration

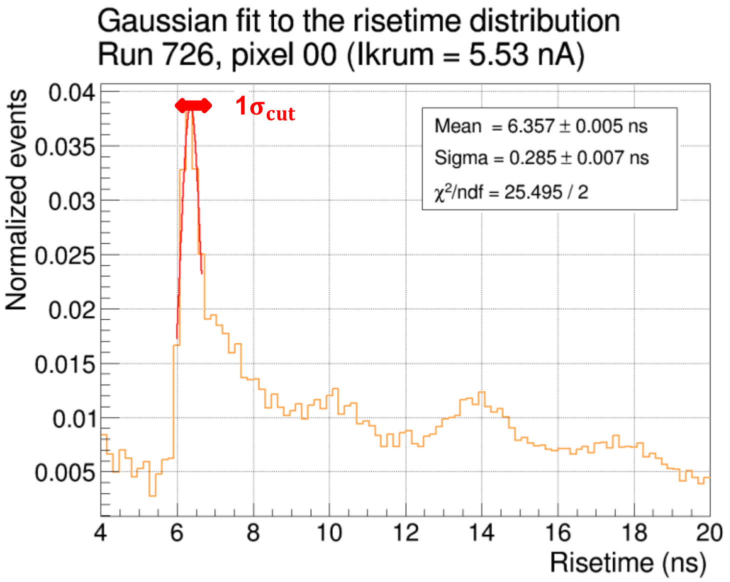
Apply a cut by selecting only the **fastest-response events**, followed by a Gaussian fit to the first peak.



Cut on the amplitude using the mean of the rise time fit ± $n\sigma_{cut}$

ANALYSIS - Charge calibration

Apply a cut by selecting only the **fastest-response events**, followed by a Gaussian fit to the first peak.



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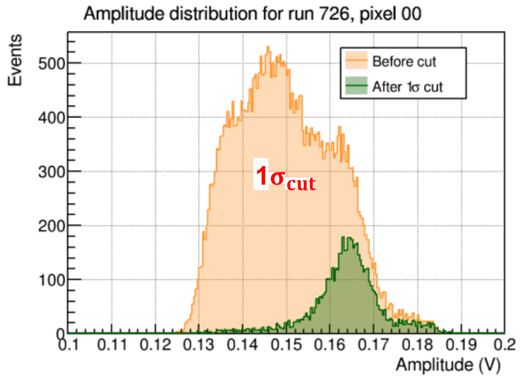
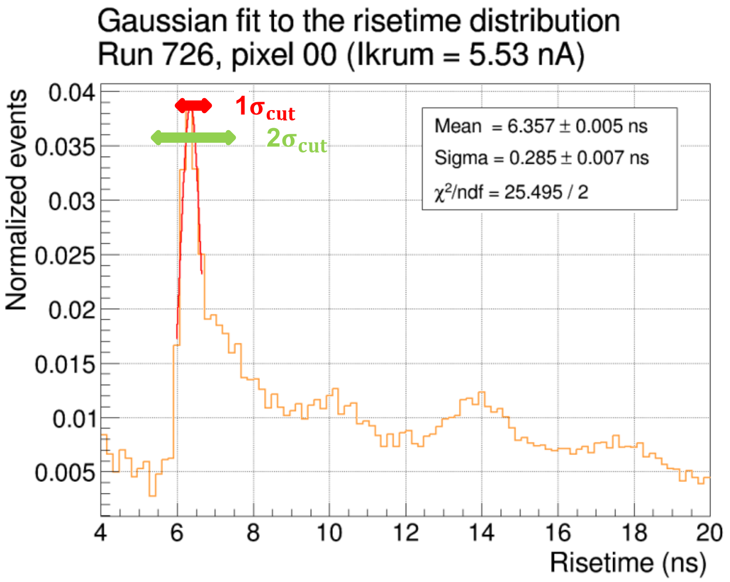
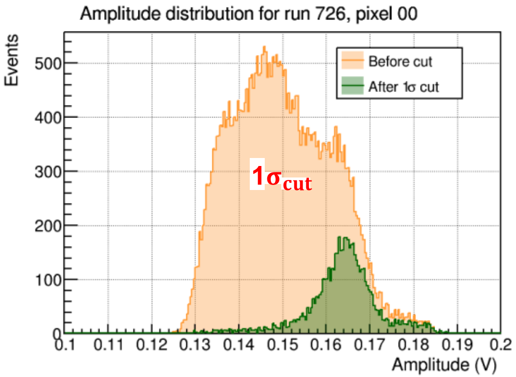


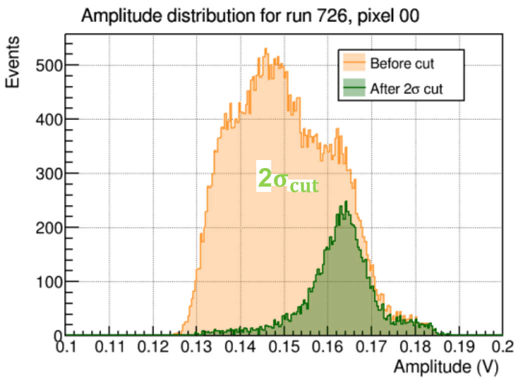
ANALYSIS - Charge calibration

Apply a cut by selecting only the **fastest-response events**, followed by a Gaussian fit to the first peak.



Cut on the amplitude using the mean of the rise time fit $\pm n\sigma_{cut}$





ANALYSIS - Charge calibration

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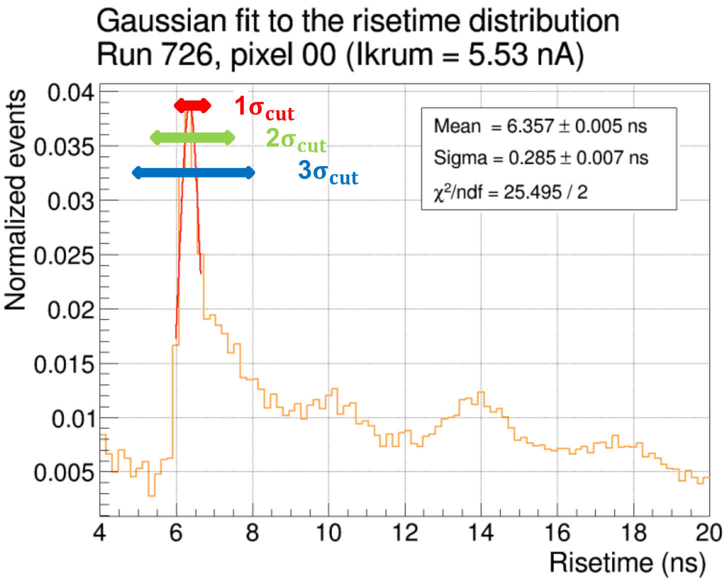

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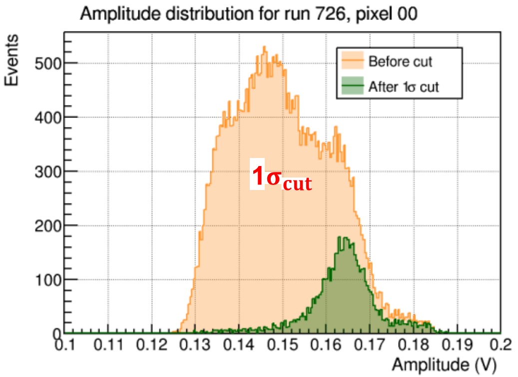

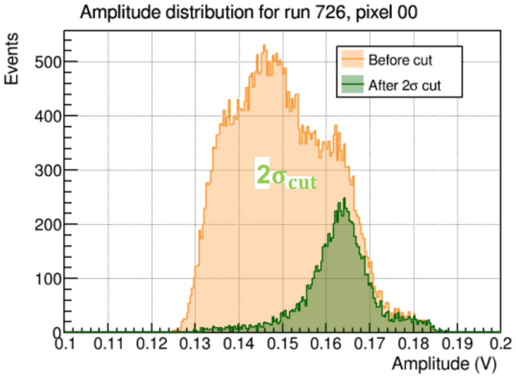

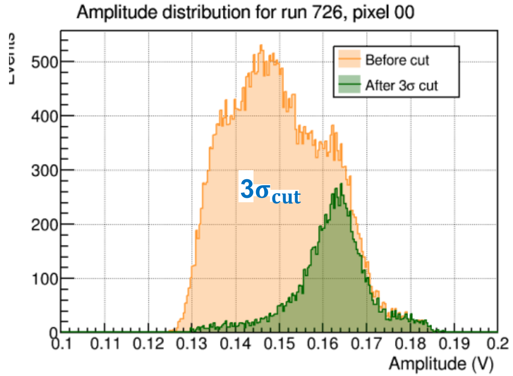

ANALYSIS - Charge calibration

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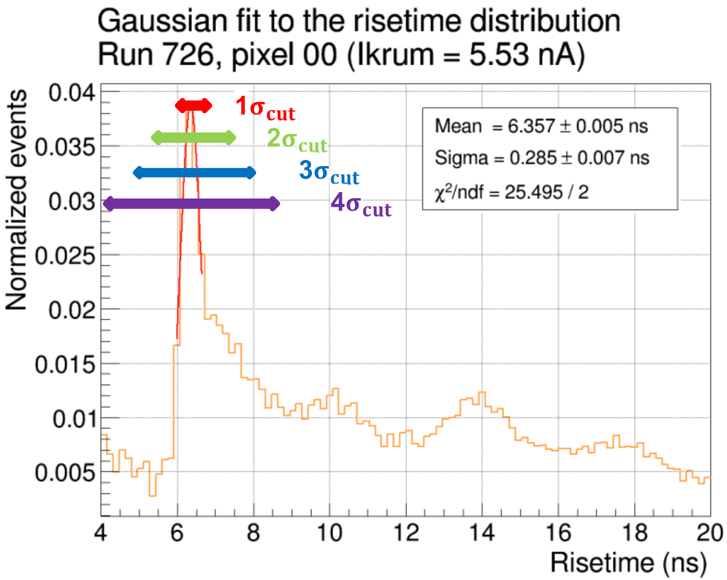
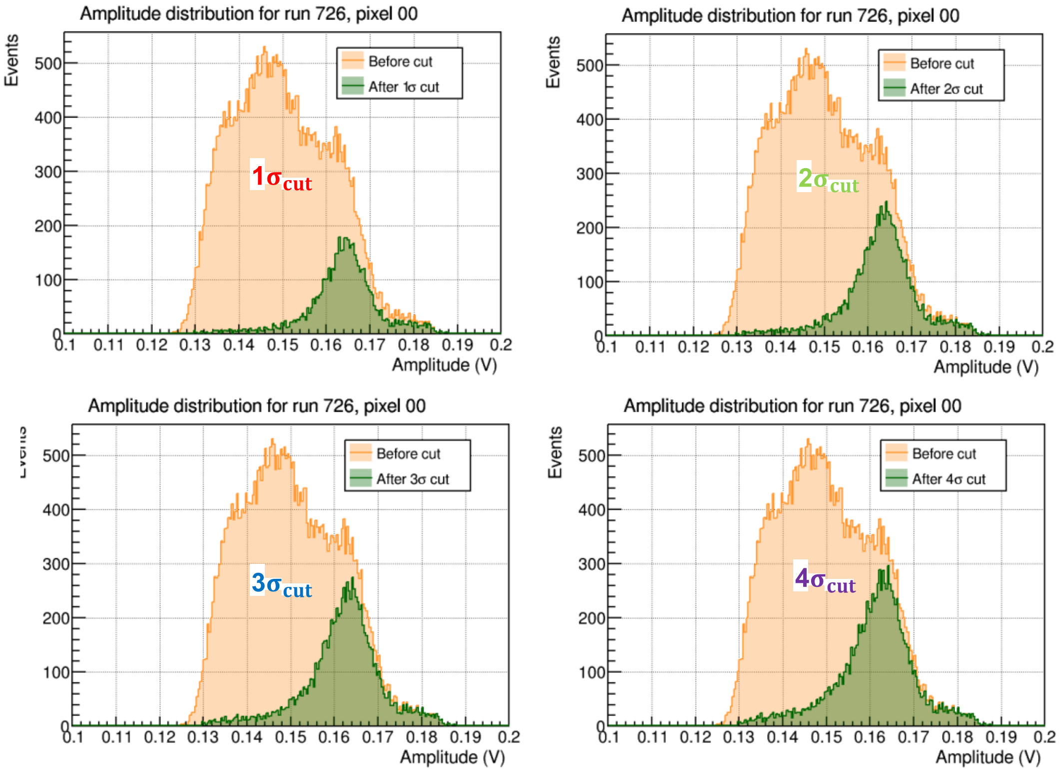
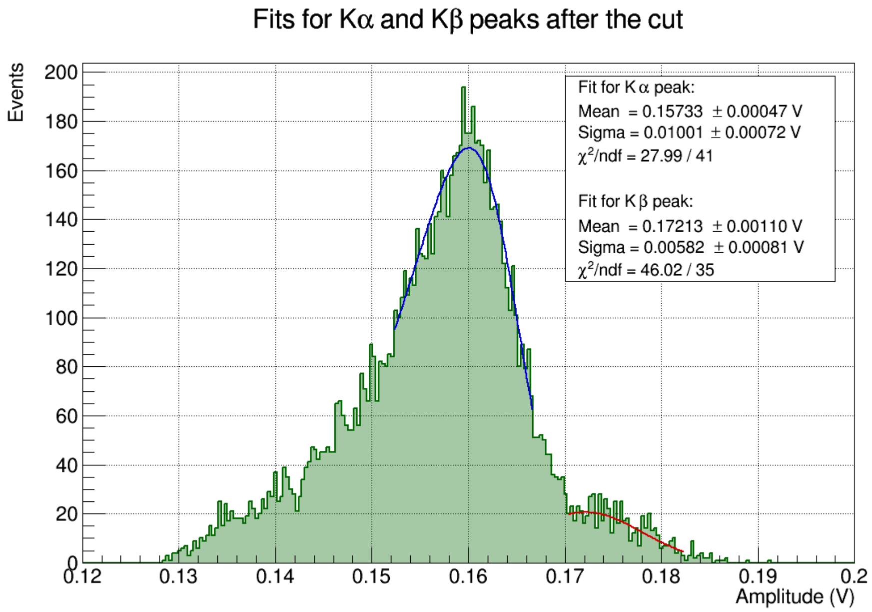


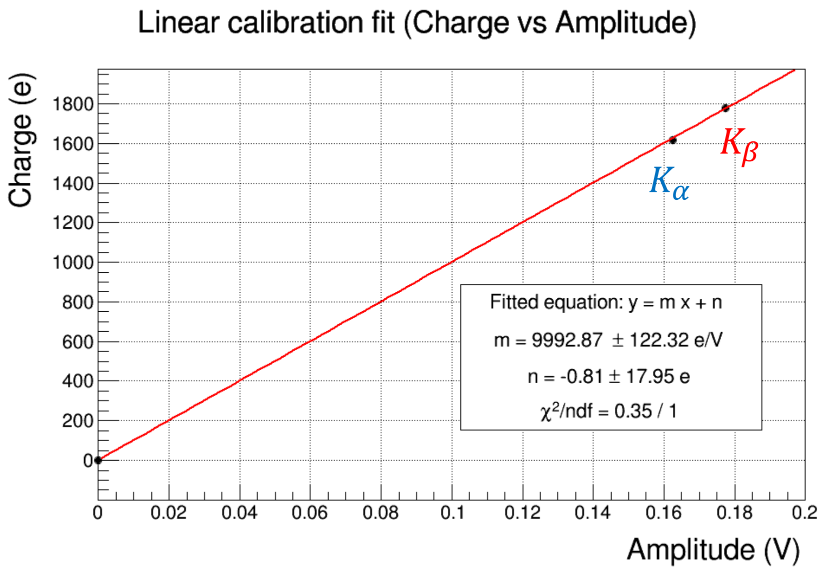
Cut on the amplitude using the mean of the rise time fit ± $n\sigma_{cut}$



ANALYSIS - Charge calibration

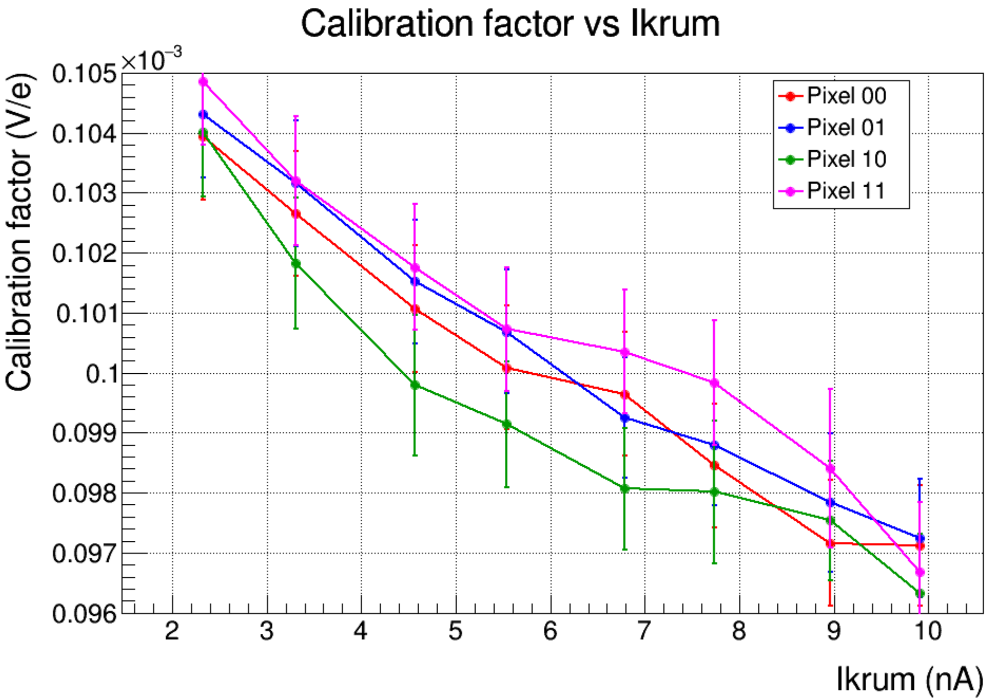
Skewed gaussian fit for K_α and gaussian fit for K_β for the case of $3\sigma_{cut}$.





ANALYSIS - Charge calibration

Repeating the procedure for every pixel and each run, applying a size cut of 3σ for the **4 µm** n-gap layout:



The **calibration factor** in V/e decreases with the **Ikrum**.

Large uncertainties observed for this method.

SUMMARY

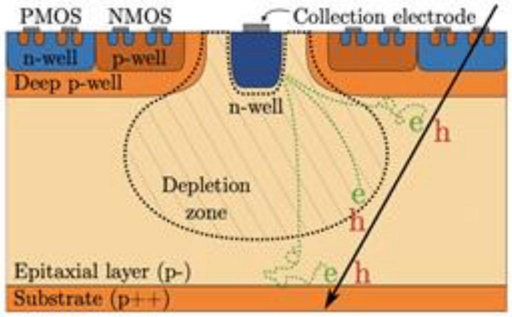
Comparison between the **4 µm and 2.5 µm** n-gap layouts. ⟹ The **4 µm** layout shows a **faster response**.

The **charge calibration factors** were obtained for different values of the Ikrum and their dependence was studied for the **4 µm** n-gap layout. ⟹ Calibration factor **decreases with Ikrum.**

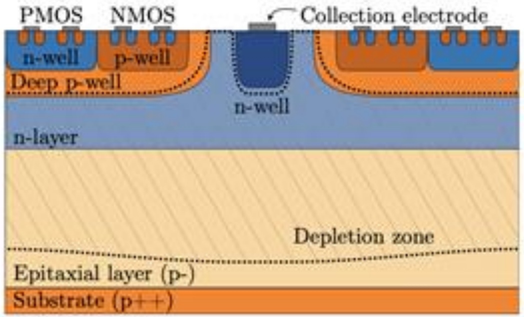
NEXT STEPS

- Calibration can be improved using the **slope** obtained for **each cut size** and adding more points to the fit.
- Perform the **calibration for the 2.5 µm layout** to complete the comparison between both layouts.
- Apply this calibration to the **test beam data** and allow comparison with other chips.

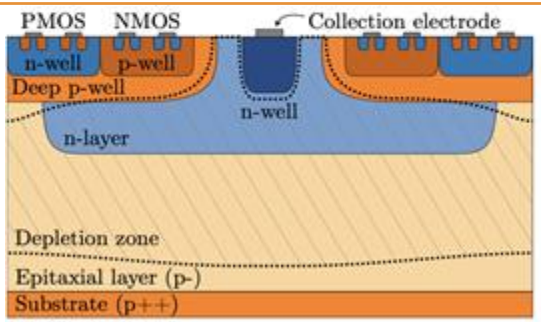
Backup– MAPS different layouts



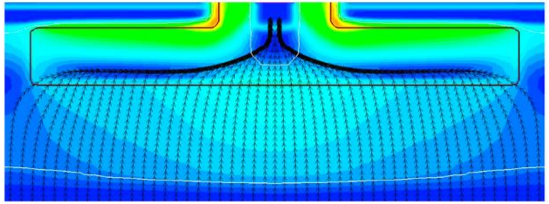
Standard layout



n-blanket layout



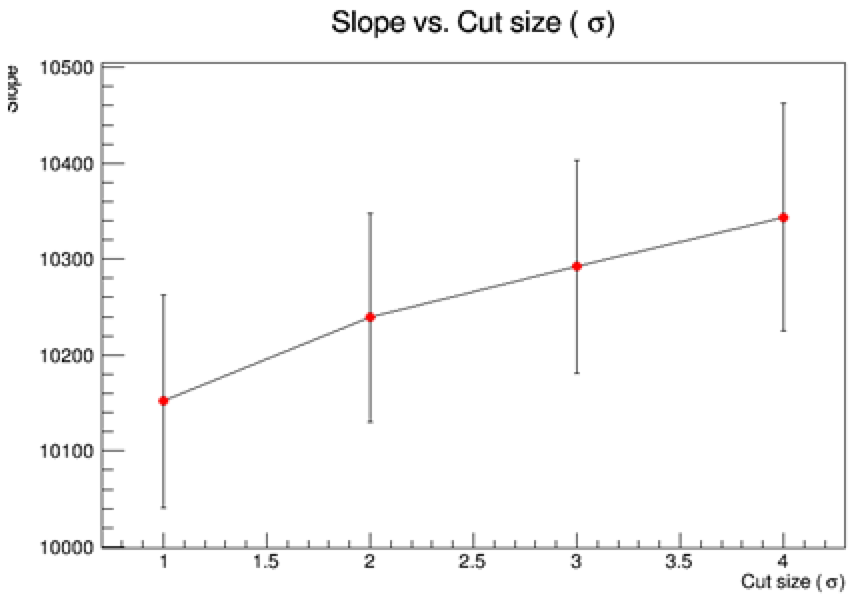
n-gap layout



- Adding an n-layer extends the depletion zone to the pixel edges.
- Introducing a gap in the n-layer increases the lateral electric field near the edges.

Backup – Slope vs. Cut size

Repeat for each cut size to study the **slope as a function of the cut size.**



The slope increases with the cut size.

We propose using the mean of the slopes for each cut size, and combining the standard deviation with the mean of the slope errors.