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MONOLITH - Picosecond Time Stamping in Fully Monolithic Highly-granular Pixel Sensor

Matteo Milanesio on behalf of the MONOLITH team

10th Beam Telescopes and Test Beams Workshop, Lecce

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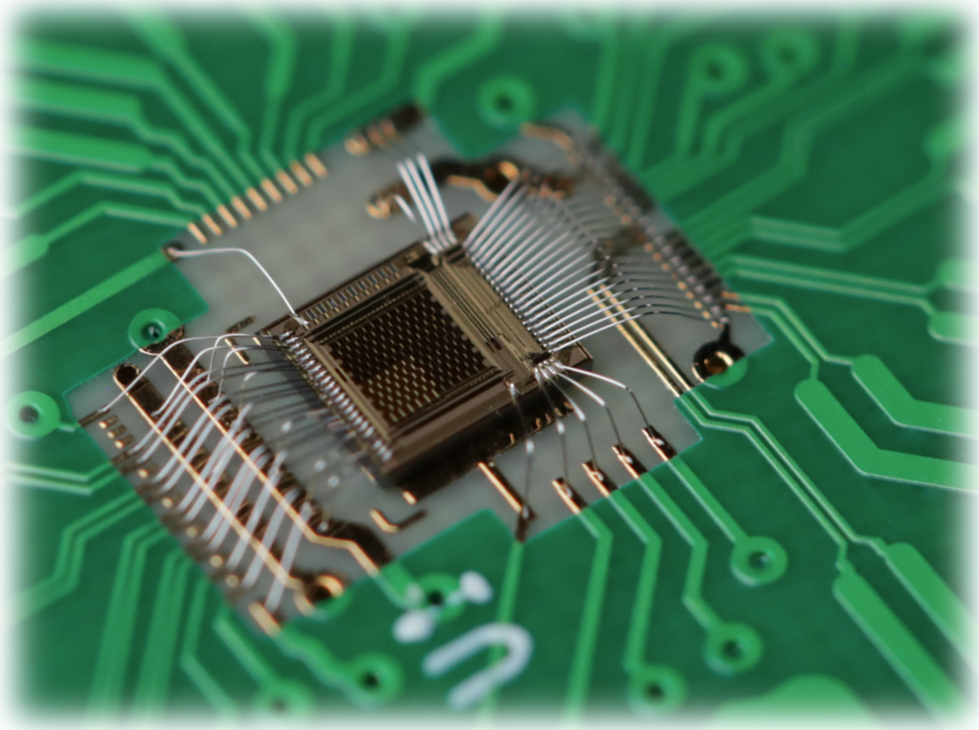
Outline

- The MONOLITH ERC Project
- Gain Measurements
- Test Beam Measurements
  - Experimental setup
  - Efficiency
  - Time Resolution



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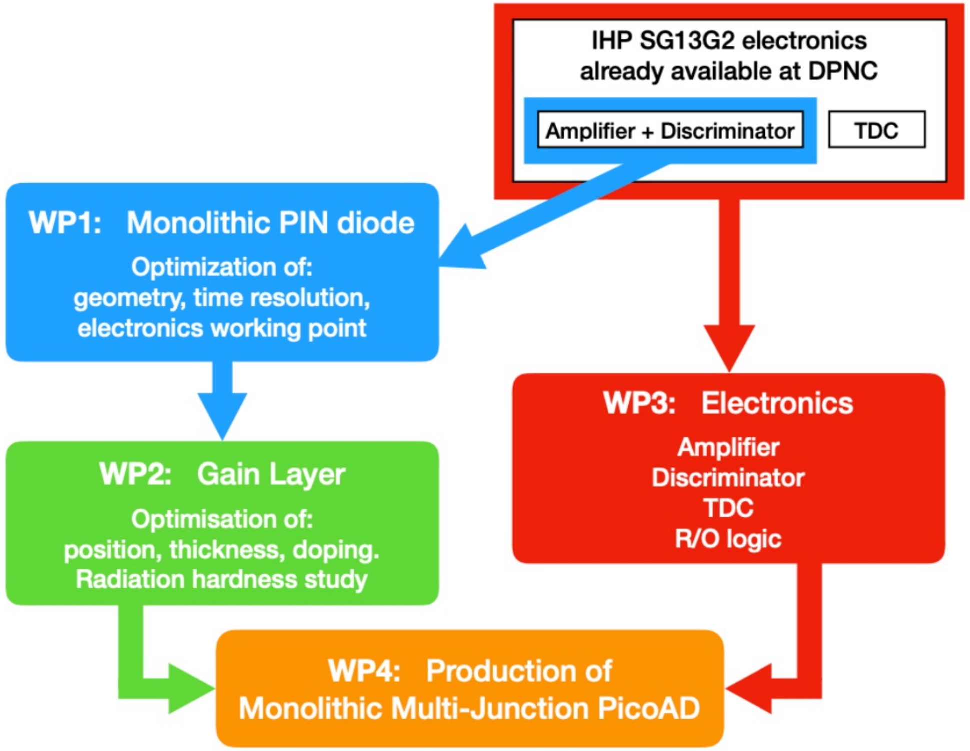
The MONOLITH ERC Project

- Funded by the H2020 ERC Advanced grant 884447[1], July 2020 - June 2025
- **Monolithic silicon sensor** able to:
  - measure precisely the 3D spatial position of charged particles
  - provide picosecond time resolution
- Fast and low-noise **SiGe BiCMOS** electronics
- Novel sensor concept, the **Picosecond Avalanche Detector**



[1]MONOLITH H2020 ERC Advanced Project Web Page - https://www.unige.ch/dpnc/en/groups/giuseppe-iacobucci/research/monolith-erc-advanced-project/

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PicoAD Sensor Concept

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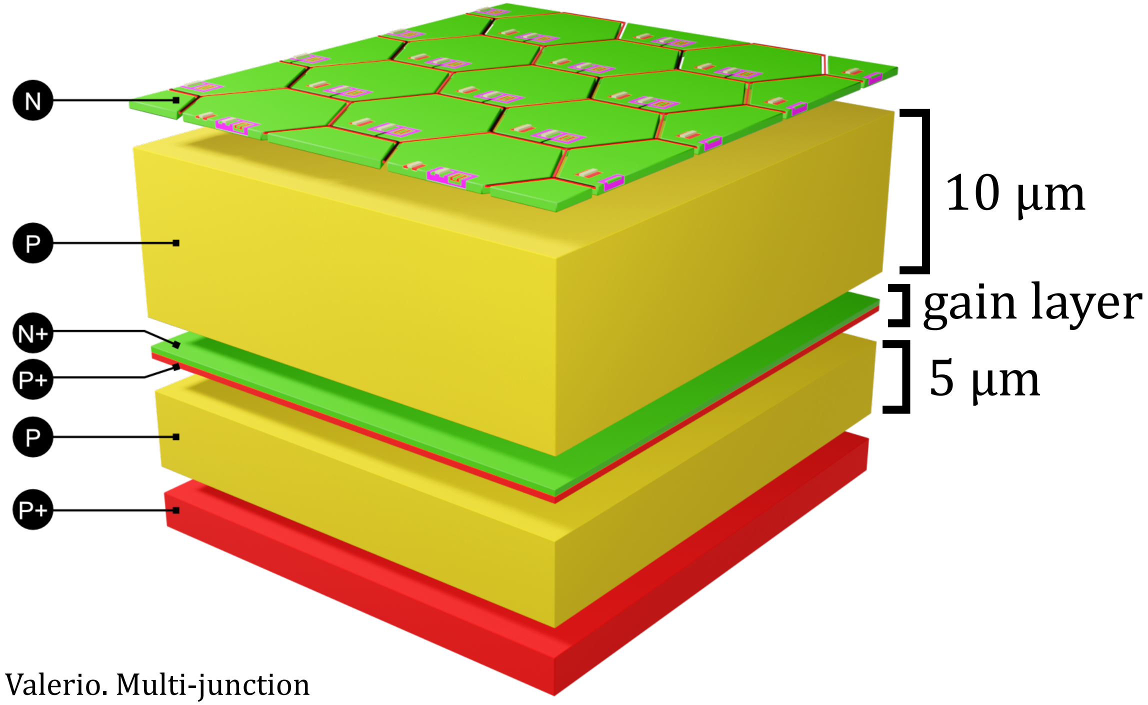
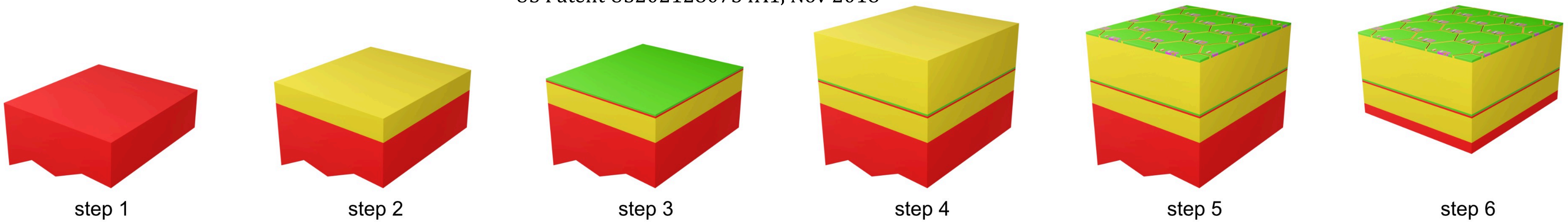
- Multi-Junction Pico-Avalanche Detector[2]
- Continuous and deep gain layer
  - de-correlation from implant size/geometry -> high **pixel granularity** possible (enhance spatial resolution)
  - only small fraction of charge gets amplified -> **reduced charge collection noise** (enhance timing resolution)



[2]G. Iacobucci, L. Paolozzi and P. Valerio. Multi-junction pico-avalanche detector. European Patent EP3654376A1, US Patent US2021280734A1, Nov 2018



PicoAD First Prototype

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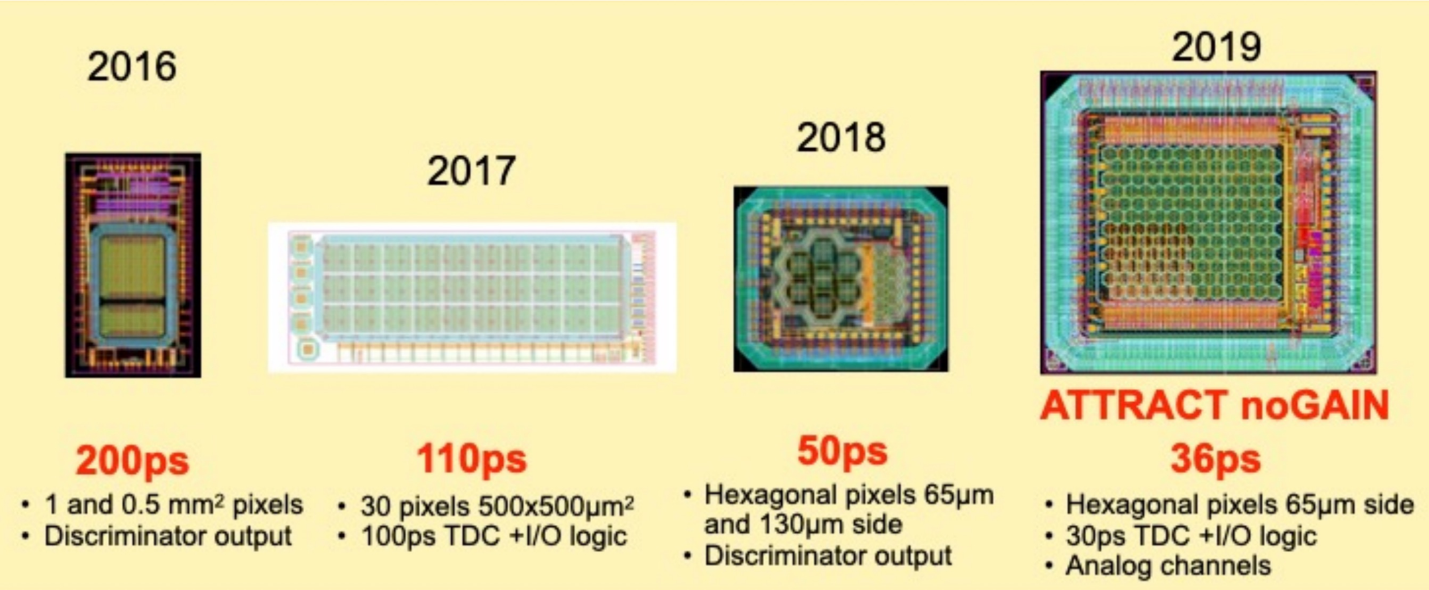

- See the previous talk from Théo on ATTRACT

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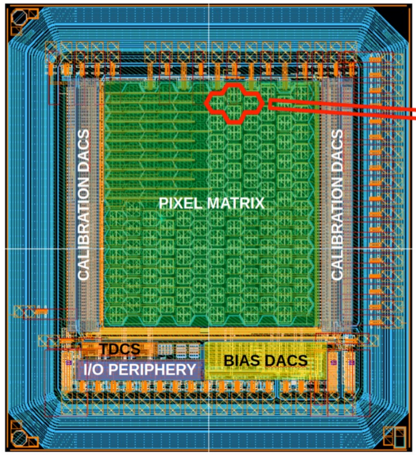
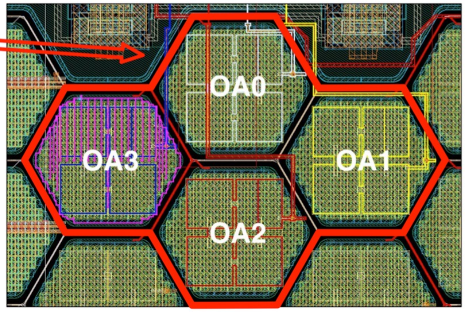
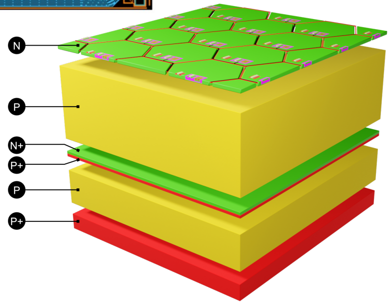
2021





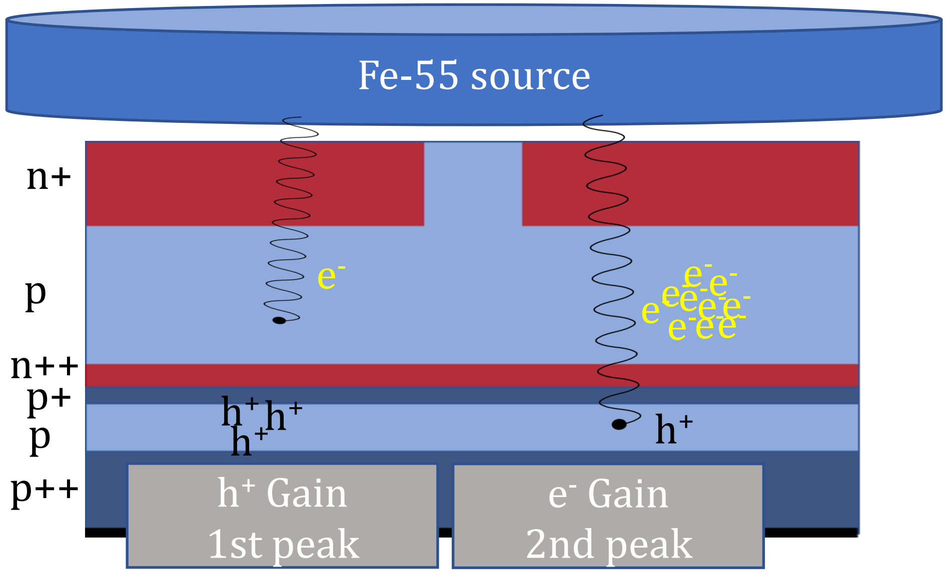


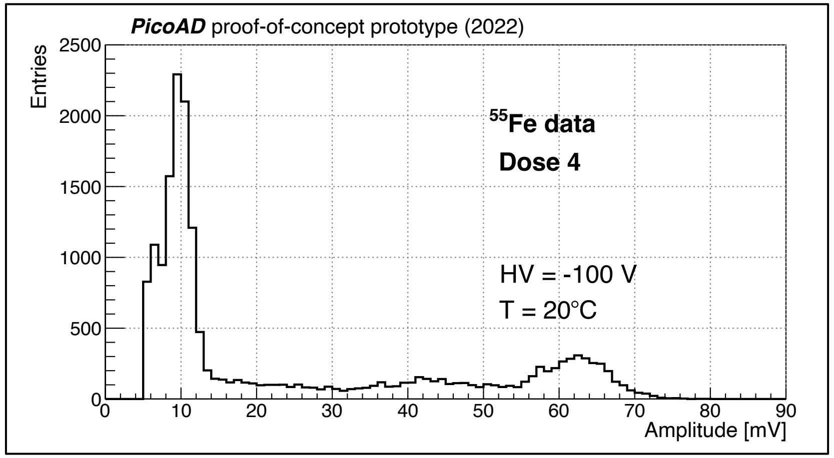
PicoAD
17 ps

- **Same electronics as ATTRACT**
- **PicoAD Sensor Concept**
- **4 different gain layer doses**

Gain Measurements

- ^{55}Fe radioactive source:
  - mainly ~5.9 keV photons
  - point-like charge deposition
- Characteristic double-peak spectrum
  - photon absorbed in the drift region
    - -> holes multiplication
    - -> **first peak** in the spectrum
  - photon absorbed in the absorption region
    - **->** electrons multiplication
    - -> **second peak** in the spectrum





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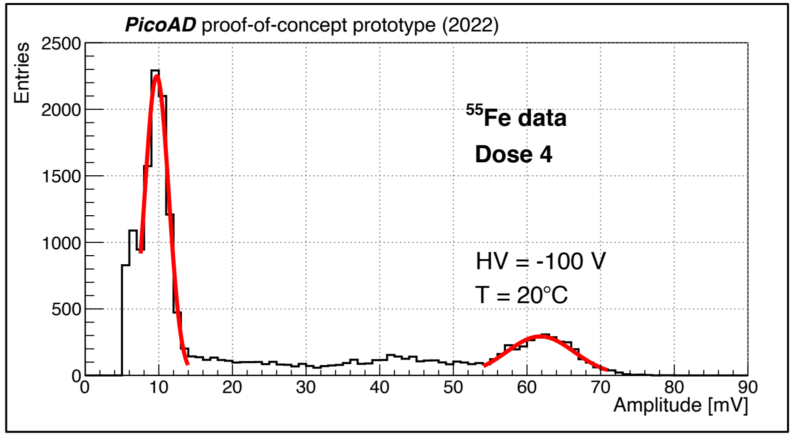
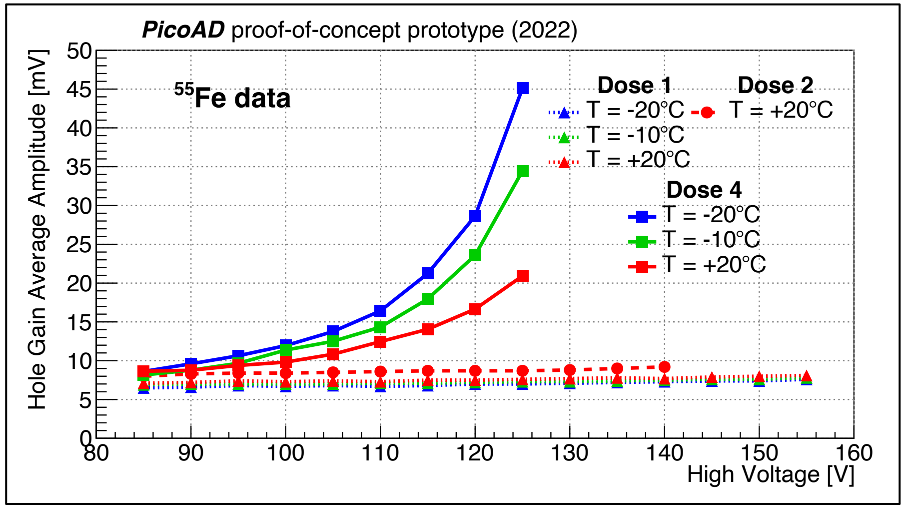
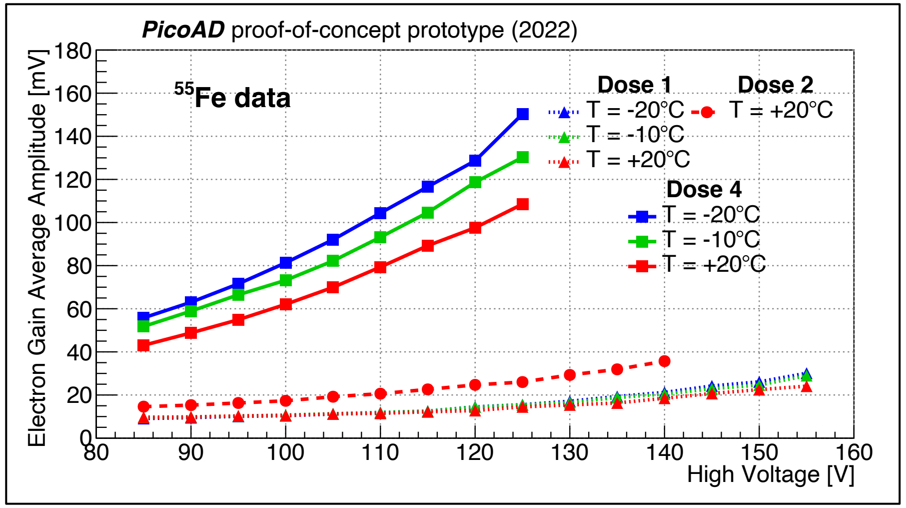
First and Second Peak

- The average amplitudes of hole and electron gains are extracted with a gaussian fit around the local maximum







- Assumption of no gain multiplication when:
  - the photon is absorbed in the drift region
  - the voltage is the lowest (85 V)
  - the dose is the lowest (dose 1)

    -> **normalization value**

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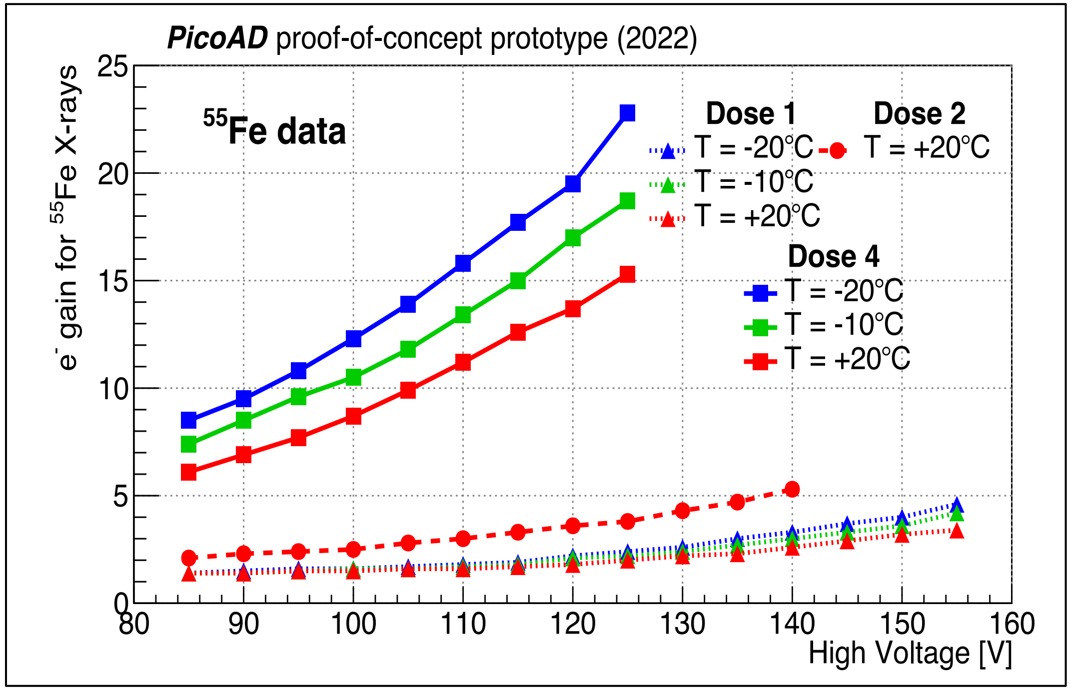
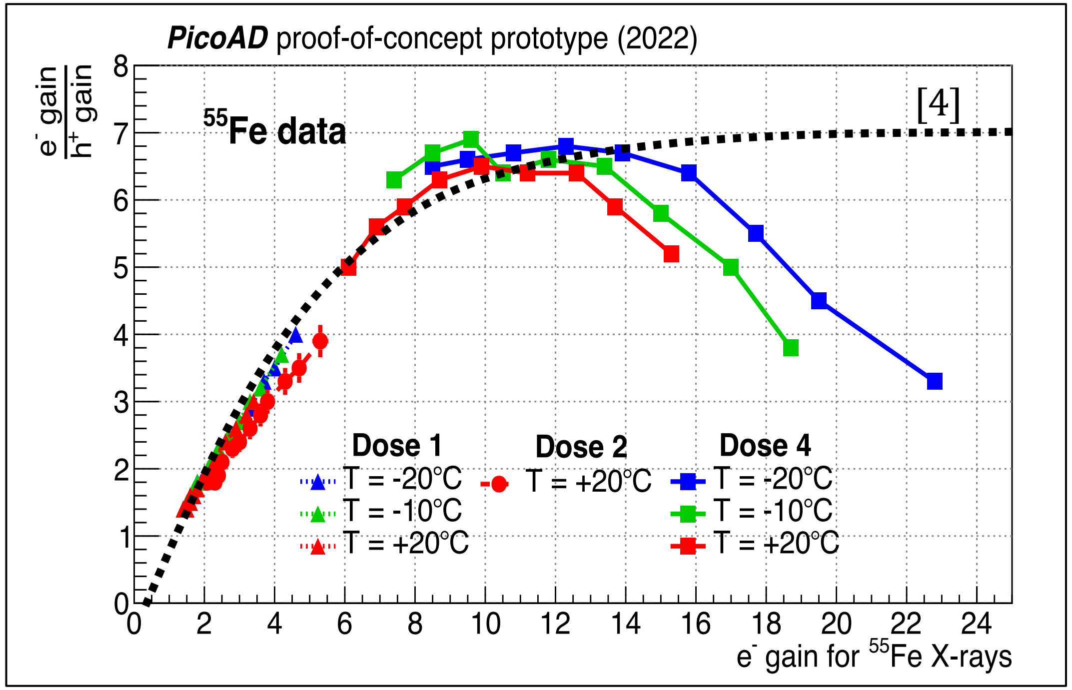
Gain Results

- A gain for ^{55}Fe X-rays of **~20** is reached at HV = 120 V and T = -20 °C[3]
- Evidence for **gain suppression** due to space charge effects





[3]L. Paolozzi et al. Picosecond Avalanche Detector - working principle and gain measurement with a proof-of-concept prototype. arXiv:2206.07952v1, June 2022

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[4]R. J. McIntyre. A new look at impact ionization-Part I: A theory of gain, noise, breakdown probability, and frequency response. *IEEE Transactions on Electron Devices*, vol. 46, no. 8, pp. 1623-1631, Aug. 1999

Test Beam Experimental Setup

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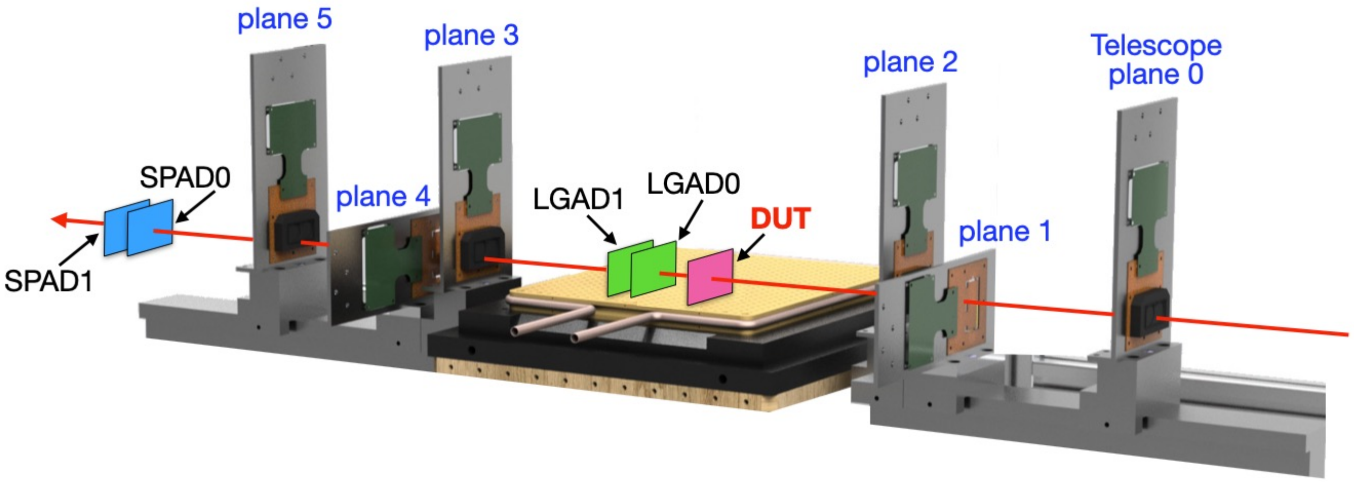
- CERN SPS Testbeam with 180 GeV/c pions
- **UNIGE FE-I4 telescope**[5] to provide the spatial information
- **Two LGADs** (σ_t ~35 ps) to provide the timing reference (and two SPADs with σ_t ~20 ps)
- **Efficiency** and **timing resolution** measured as a function of:
  - High Voltage
  - Power consumption (related to preamplifier current)



[5]Benoit et al. The FE-I4 telescope for particle tracking in testbeam experiments. JINST, 11 P07003, july 2016

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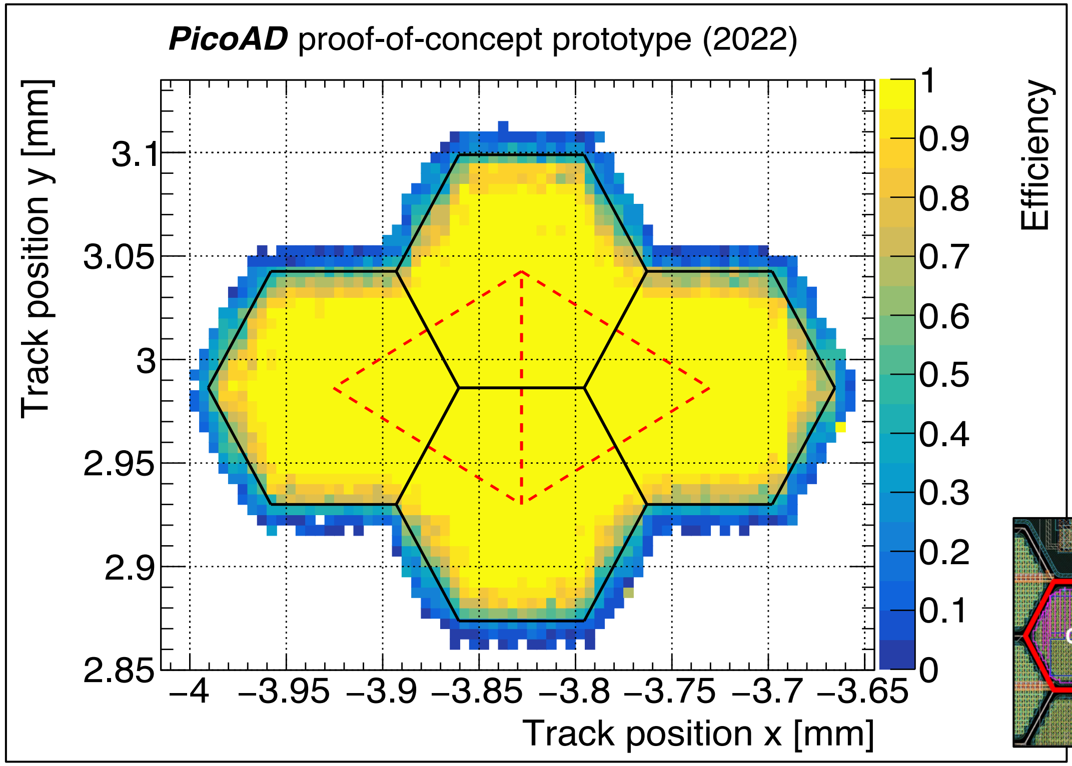
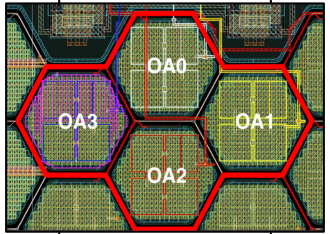
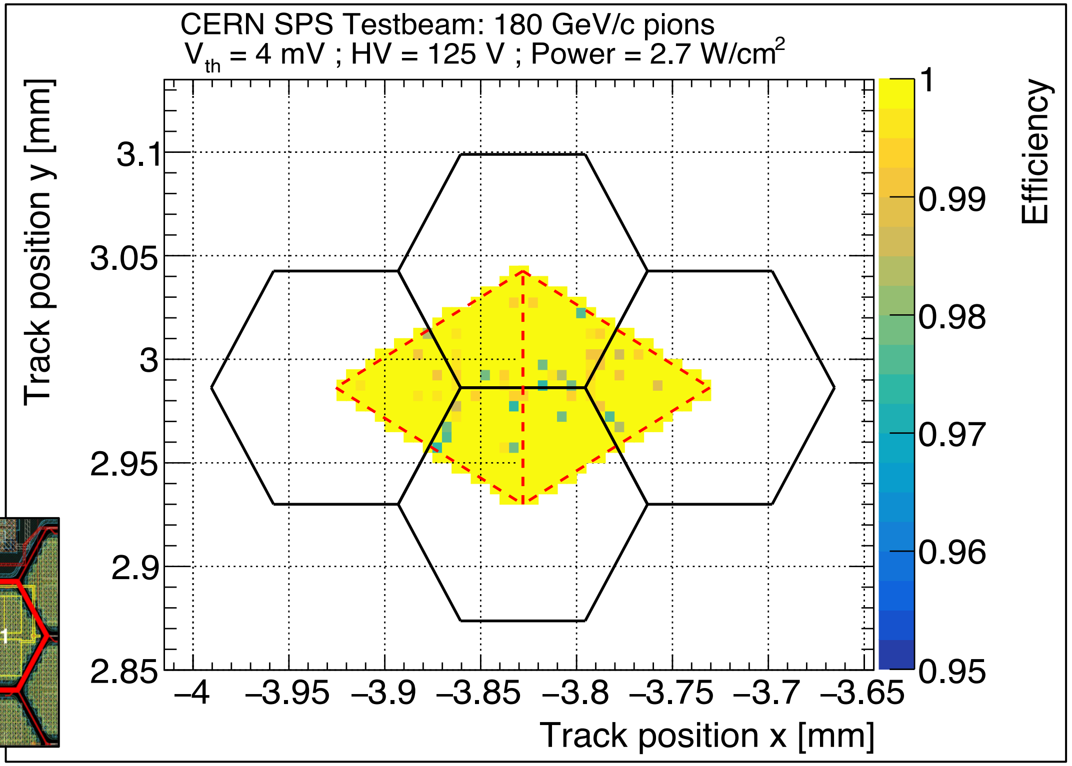
Efficiency Maps





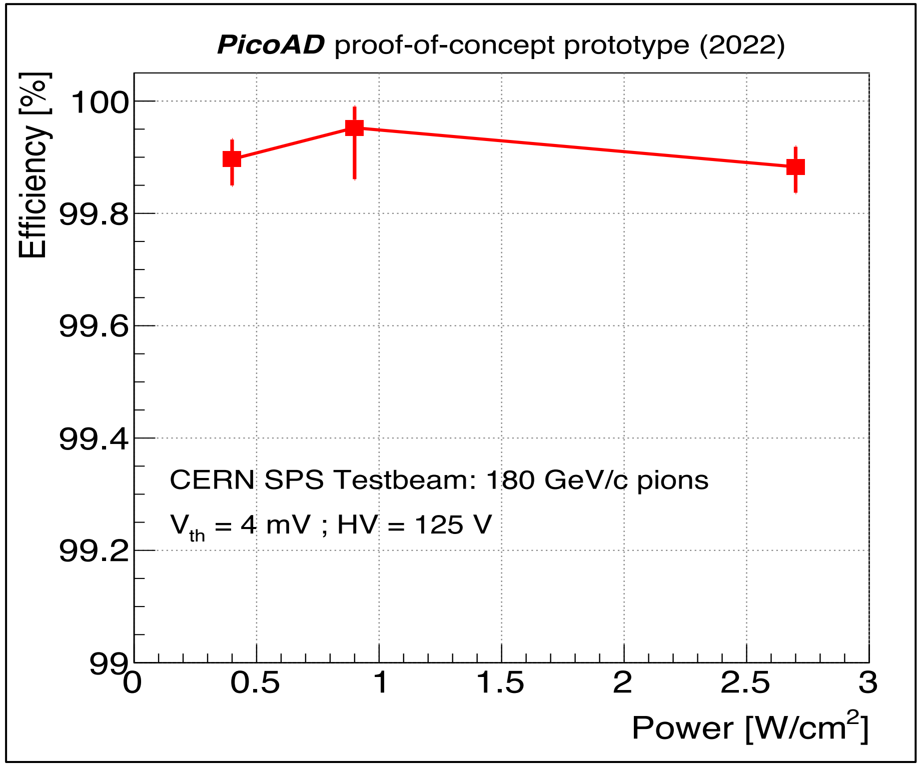


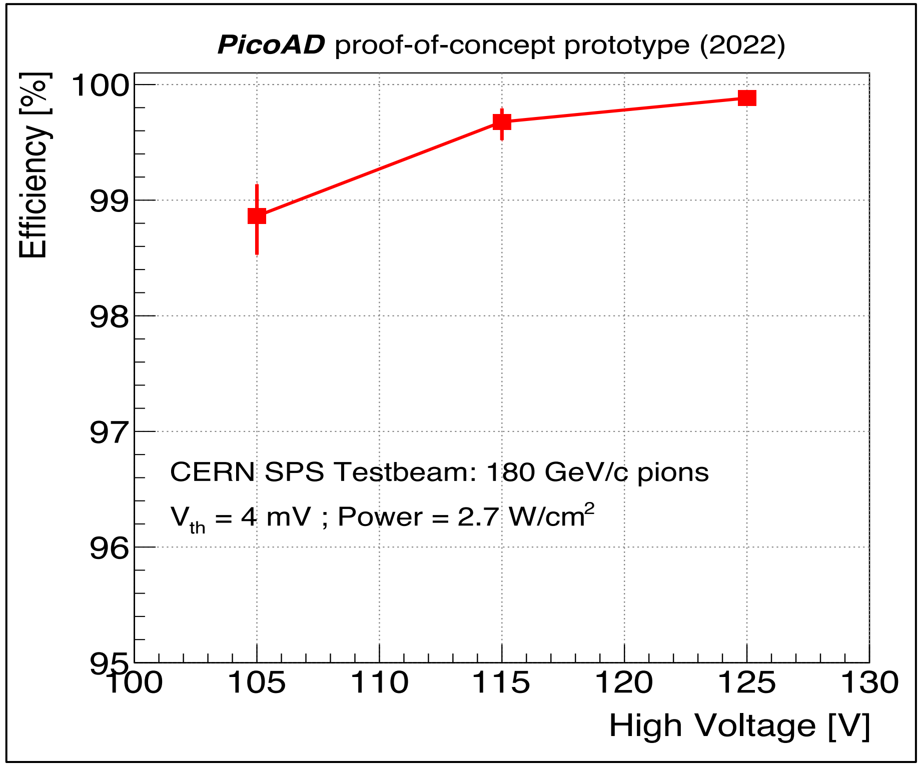
- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~10 µm)

- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

Efficiency Scans

- Efficiency inside the two unbiased triangles

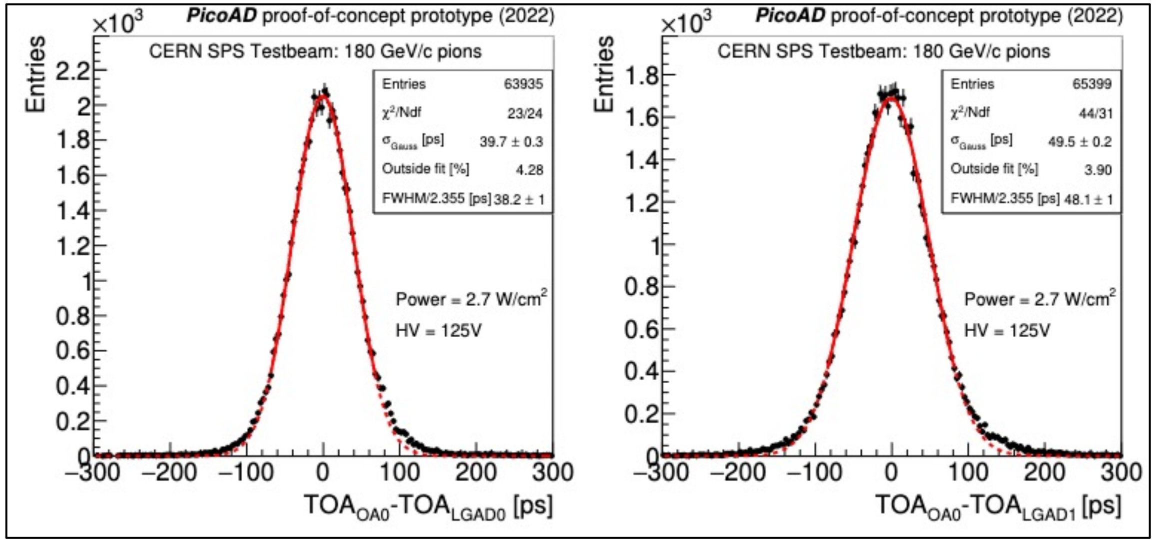


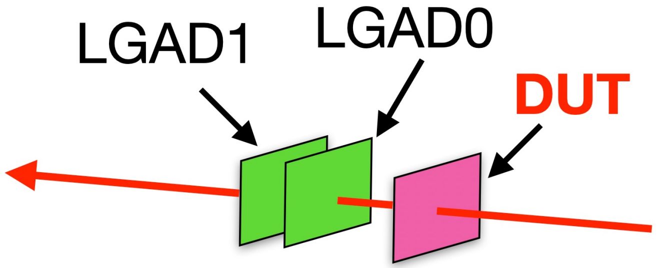


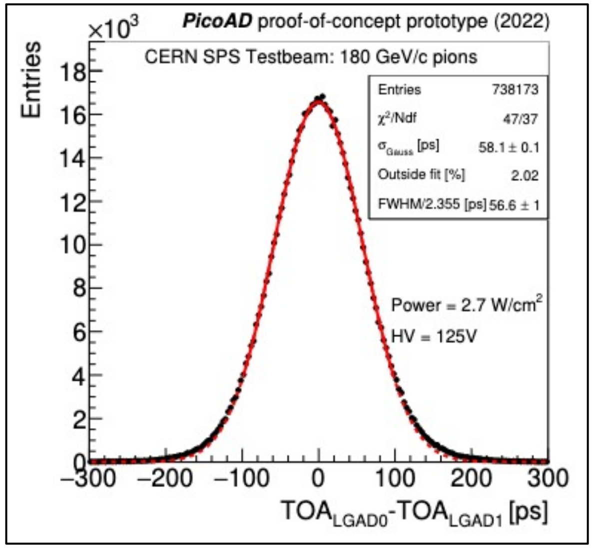
- The efficiency is compatible with 99.9% for all the power consumptions
- The efficiency drops to ~99% for HV=105V

Timing Resolution Distributions

- Time Of Arrival as a time at a Constant Fraction
- Distributions after time-walk correction
- The distributions are **gaussian**
  - ~2-4 % of the entries are in non-gaussian tails
- The three σ_{Gauss} from the fits give the timing resolution of:
  - the DUT
  - the two LGADs







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Timing Resolution Scans

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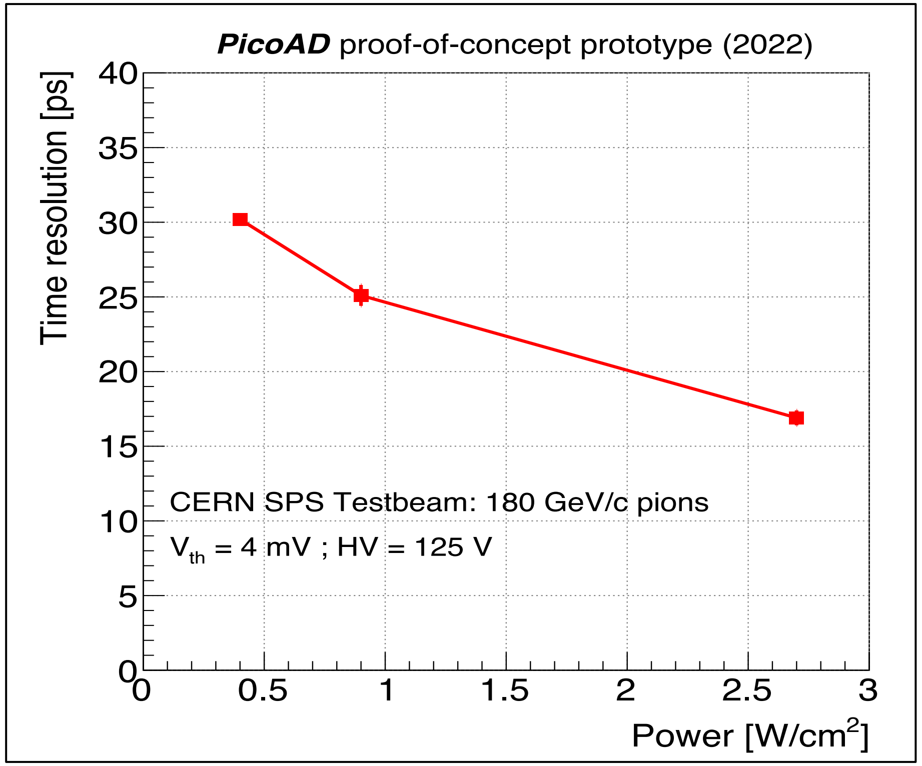
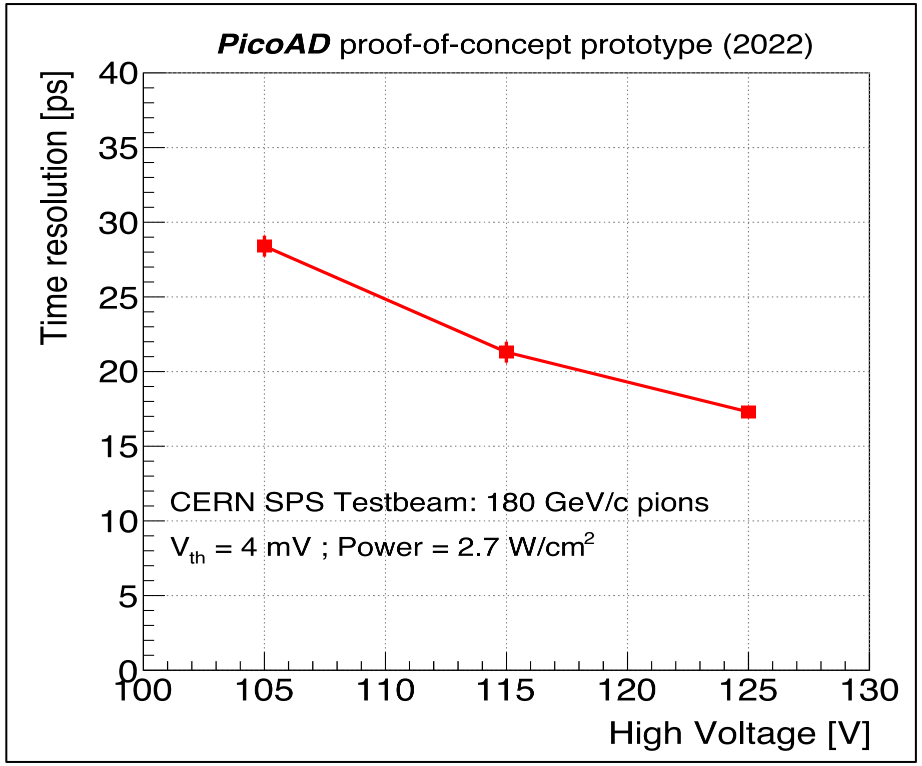
- Timing resolution for pixel 0





- The timing resolution is ≲30 ps, even for the **lowest power consumption**
- The best value is $\mathbf{(17.3 \pm 0.4)}$ **ps**

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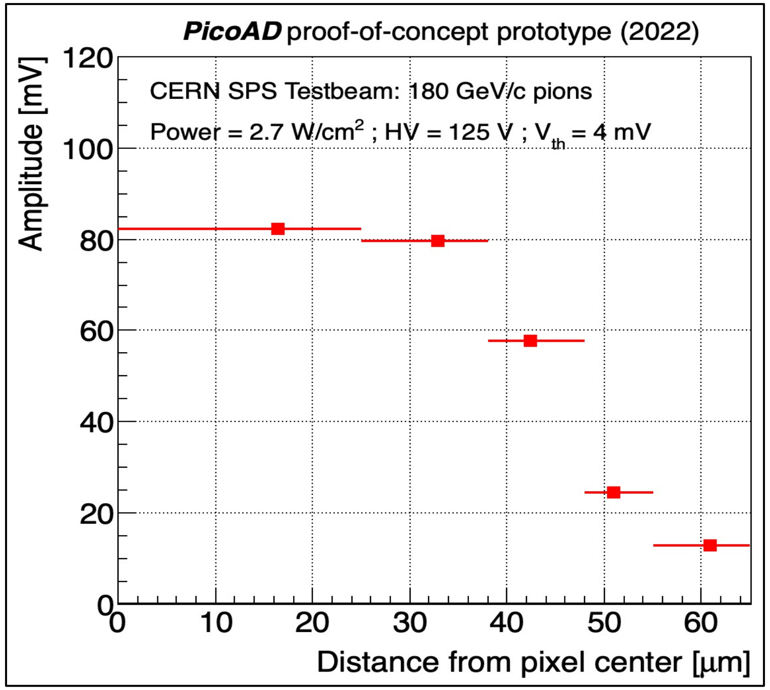
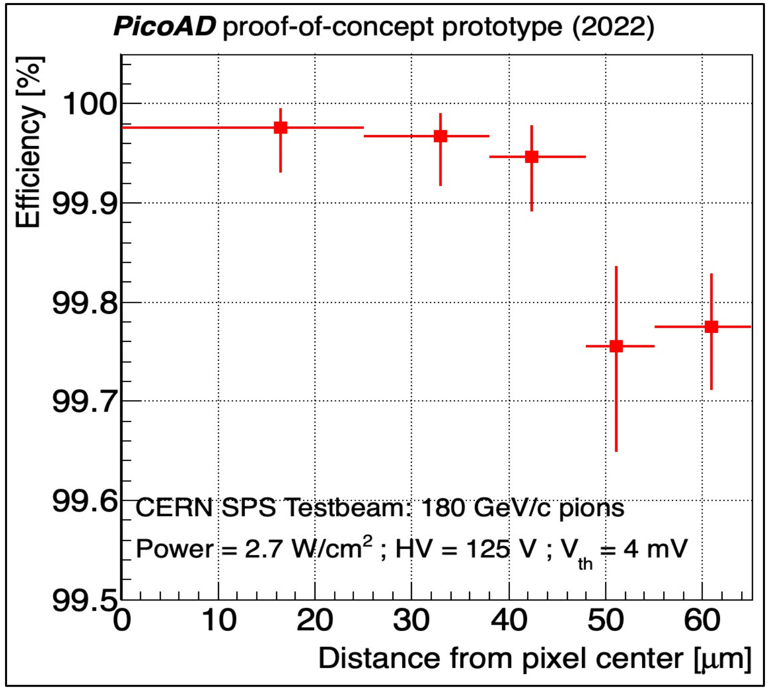
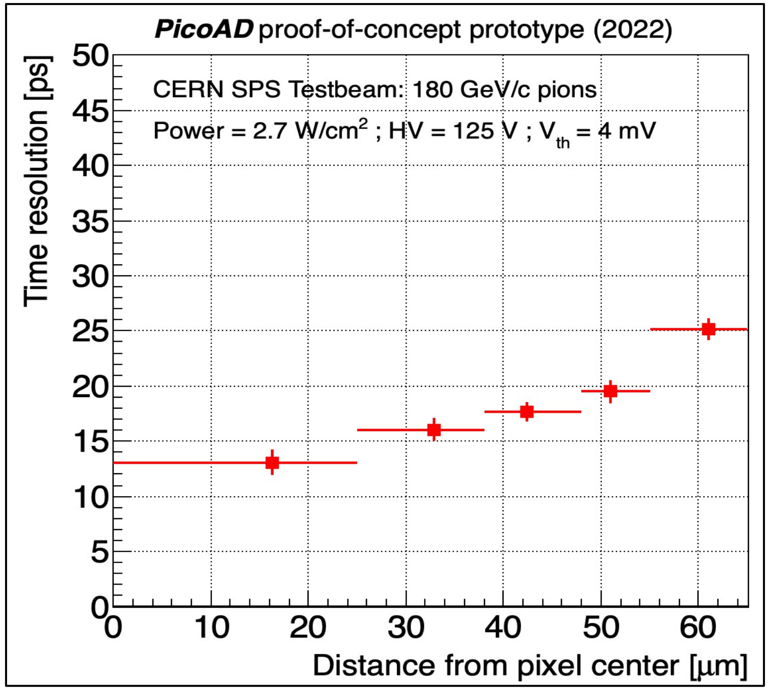
Results vs. Position Within the Pixel







- Small degradation of the performance towards the edge of the pixel
- Effect of the finite resolution of the telescope convoluted with the real degradation
- The best timing resolution is $(\mathbf{13.2 \pm 0.8})$ **ps** within 25 μm from the pixel center

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Summary and Outlook

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- Proof-of-concept of PicoAD sensor (not yet optimized for timing) and HBT frontend:
  - **gain for ^{55}Fe X-rays of up to 23**
  - efficiency **~ 99.9 %**
  - time resolution $\boldsymbol{\sigma_t = (17.3 \pm 0.4)}$ **ps**
    - $\boldsymbol{\sigma_t = (13.2 \pm 0.8)}$ **ps** within 25 μm from the pixel center

- Ongoing activities include:
  - optimization for timing of the sensor design with TCAD
  - design of smaller pixels pitch and thicker active layer to achieve $\lesssim$ 10 ps
  - development of picosecond TDC[6] for fully monolithic chip

[6] R. Cardarelli, L. Paolozzi, P. Valerio and G. Iacobucci, European Patent Application / Filing - UGKP-P-001-EP, Europe Patent EP 18181123.3. 2 July 2018.

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Thanks for your attention

Many thanks to the CERN SPS Test Beam Personnel

The MONOLITH team

Giuseppe Iacobucci
- project P.I.
- System design

Didier Ferrere
- System integration
- Laboratory test

Pierpaolo Valerio
- Lead chip design
- Digital electronics

Mateus Vicente
- System integration
- Laboratory test

Yana Gurimskaya
- Radiation tolerance
- Laboratory test

Stefano Zambito
- Laboratory test

Lorenzo Paolozzi
- Sensor design
- Analog electronics

Sergio Gonzalez-Sevill
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- Laboratory test

Magdalena Munker
- Sensor design
- Laboratory test

Roberto Cardella
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- Analog electronics

Fulvio Martinelli
- Chip design

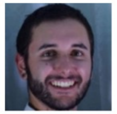
Yannick Favre
- Board design
- RO system

Stéphane Débieux
- Board design
- RO system

Théo Moretti
- Laboratory test

Antonio Picardi
- Chip design
- Laboratory Test

Chiara Magliocca
- Laboratory test



Matteo Milanesio
- Laboratory test

Jihad Said
- Laboratory test

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Mehmet Kaynak
IHP Mikroelektronik

Backup

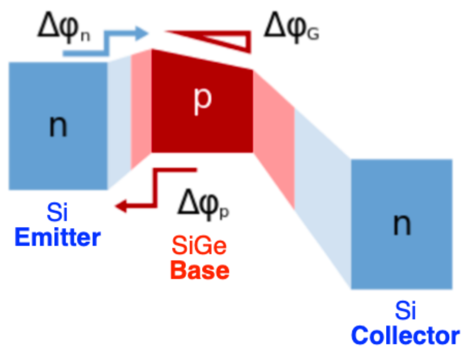
SiGe BiCMOS Technology

- SiGe HBT = BJT with Germanium as base material:
  - higher doping in base possible
  - thinner base
  - **reduced base resistance R_b**
- Grading of Ge doping in base:
  - charge transport in base via drift
  - reduced charge transit time in base
  - **high current gain β**
- Leading-edge technology IHP SG13G2, 130 nm process featuring SiGe HBT

$$ENC_{series\ noise} \propto \sqrt{k_1 \frac{C_{tot}^2}{\beta} + k_2 R_b C_{tot}^2}$$

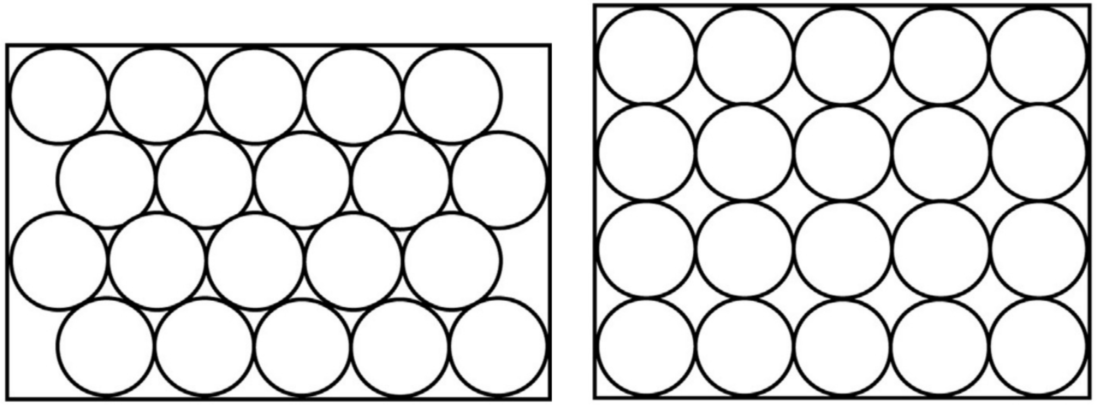
NPN SiGe HBT

(depleted regions in light colors)
from wikimedia

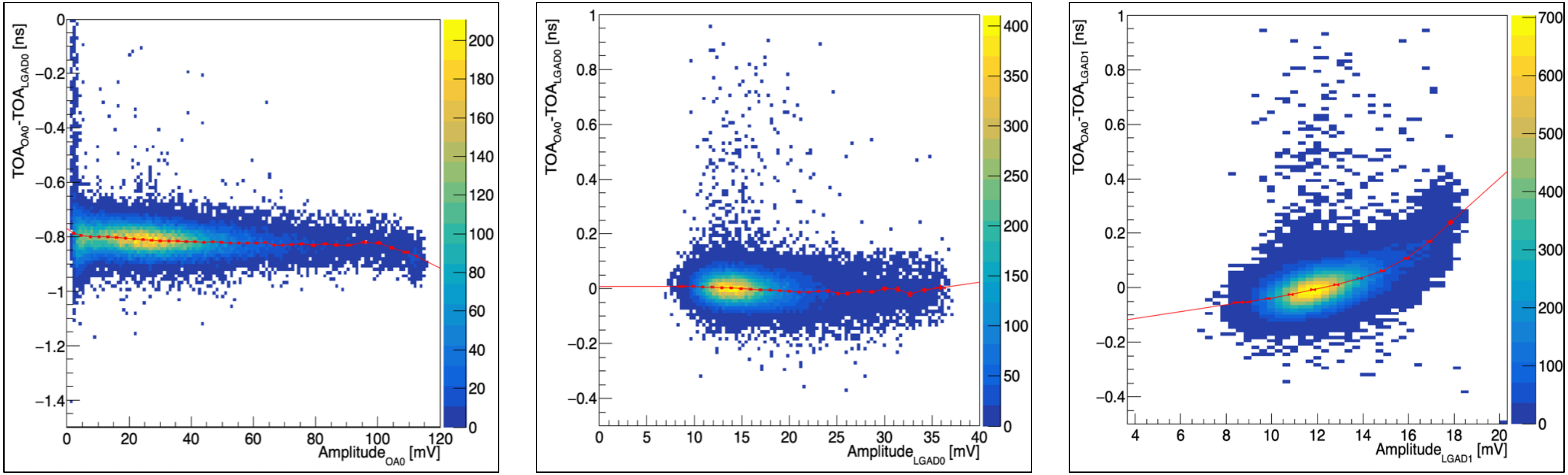


Benefits of Using Hexagonal Pixels

- Three possible regular shapes to use:
  - equilateral triangles
  - squares
  - regular hexagons
- Hexagons have the highest angles (120°) -> **electric fields** in the corners are better **under control**
- Moreover, the same amount of pixels can fits in less space than squares



Time Walk Correction



- Shift at 200 ps of the waveform to subtract low-frequency noise
- Time at 25% constant fraction
- Amplitude based time walk correction method