MONOLITH

picosecond time stamping capability in fully monolithic highly granular silicon pixel detectors

European Research Council
Established by the European Commission

funded by the H2020 ERC Advanced grant 884447

ROBERTO CARDELLA ON BEHALF OF THE MONOLITH TEAM.

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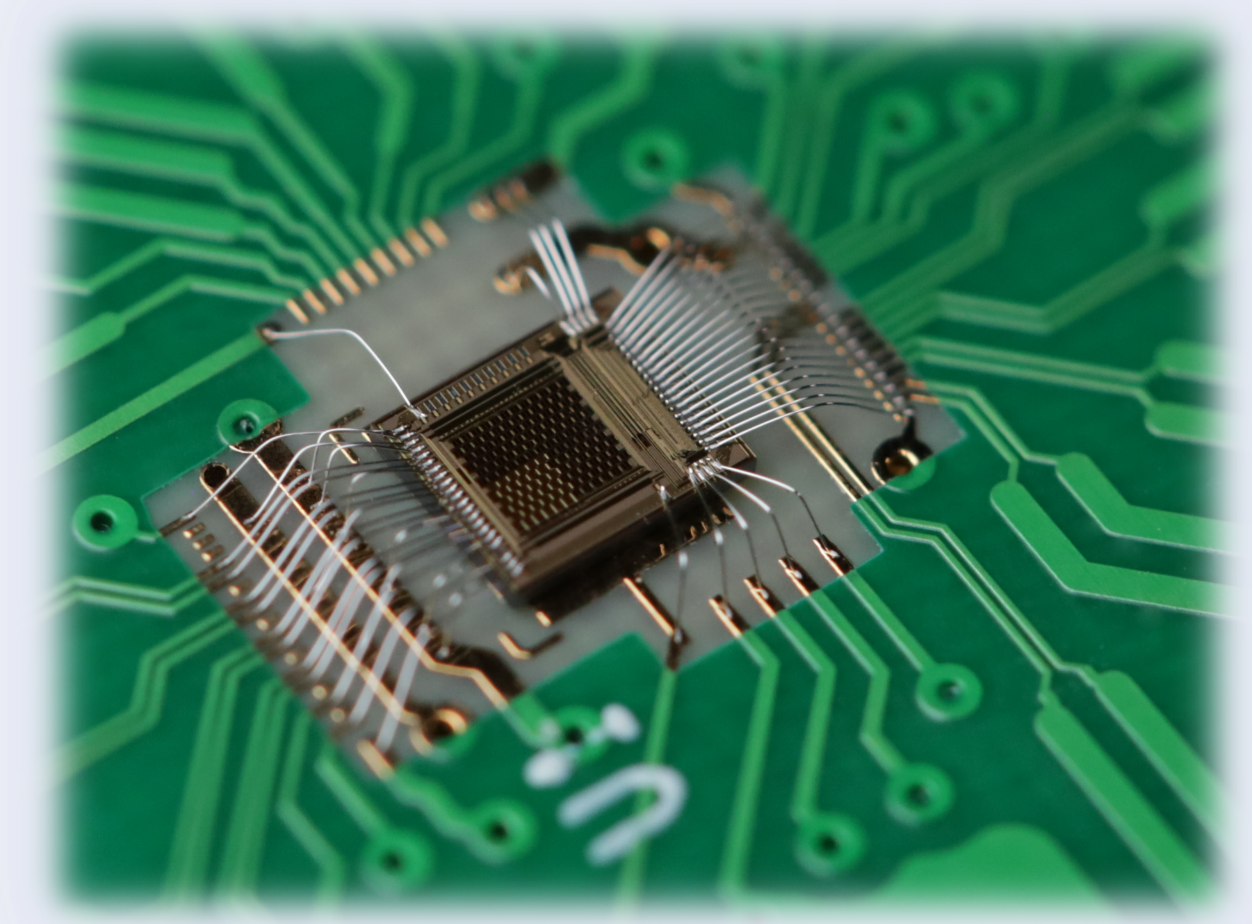
Department of Nuclear and Particle Physics

Outline

1. Introduction to SiGe BiCMOS Technology
2. ATTRACT prototype without Gain Layer
    1. Efficiency and Time Resolution
3. MONOLITH ERC
    1. PicoAD concept
    2. PicoAD p0: Efficiency and Time Resolution
    3. Electronics development: TDC
4. Summary and outlook



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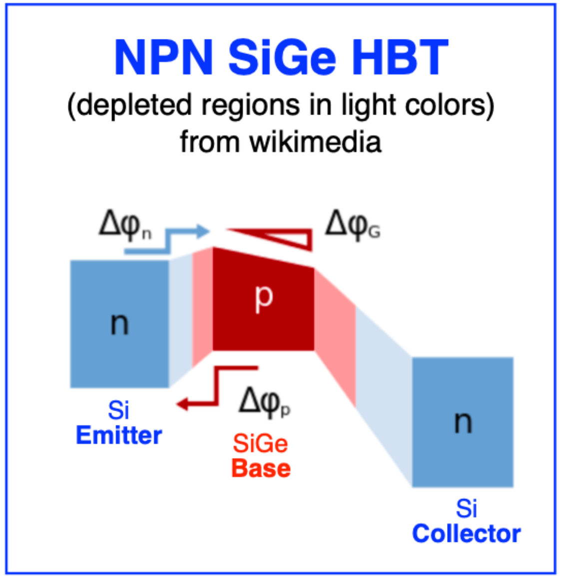
SiGe BiCMOS Process



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**

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

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SG13G2 technology from IHP Microelectronics

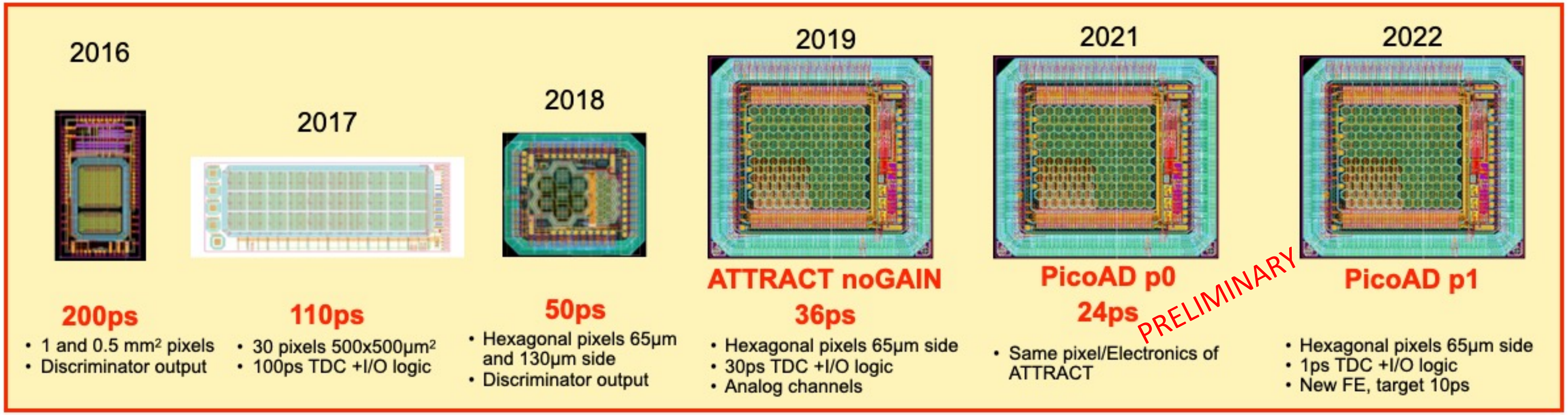
Leading-edge technology: **IHP SG13G2**

130 nm process featuring **SiGe HBT** with

- Transistor transition frequency: $f_t = 0.3\ THz$
- DC Current gain: $\beta = 900$
- Delay gate: **1.8 ps**

innovations for high performance microelectronics

Leibniz-Institut für innovative Mikroelektronik



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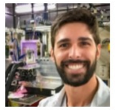
Silicon Group at UniGe


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


Stéphane Débieux
- Board design
- RO system


Théo Moretti
- Laboratory test


Antonio Picardi
- Chip design
- Laboratory Test


Lorenzo Paolozzi
- Sensor design
- Analog electronics


Sergio Gonzalez-Sevilla
- System integration
- Laboratory test

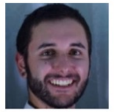

Magdalena Munker
- Sensor design
- Laboratory test


Roberto Cardella
- Sensor design
- Analog electronics


Fulvio Martinelli
- Chip design


Yannick Favre
- Board design
- RO system


Chiara Magliocca
- Laboratory test


Matteo Milanesio
- Laboratory test


Jihad Said
- Laboratory test

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Roberto Cardarelli
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CERN & UNIGE


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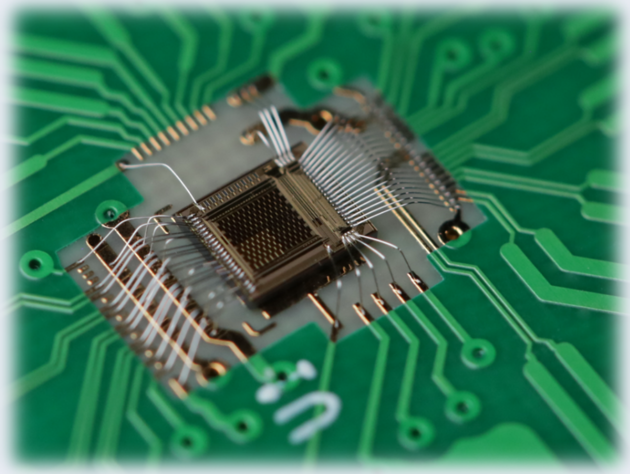
IHP Mikroelektronik


Mehmet Kaynak
IHP Mikroelektronik


Bernd Heinemann
IHP Mikroelektronik



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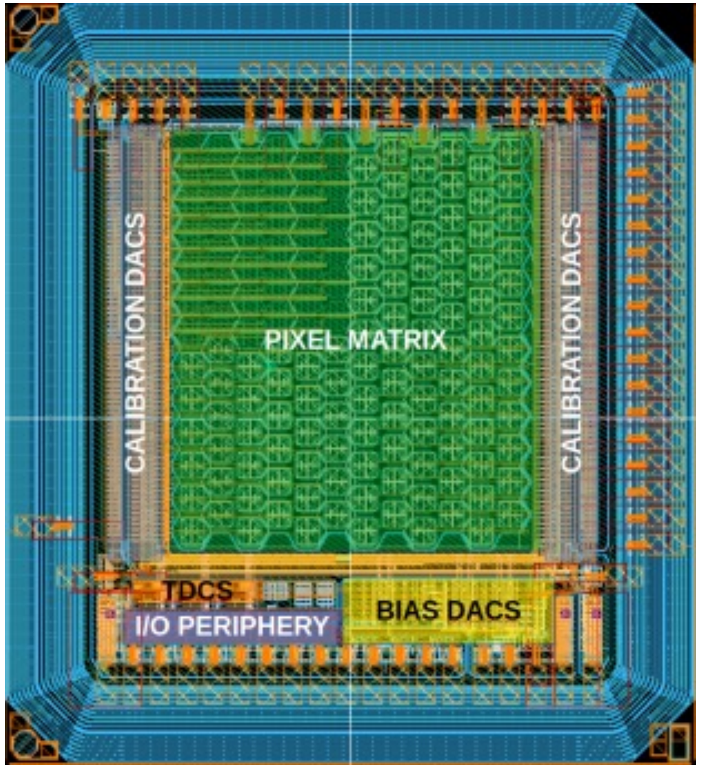
ATTRACT prototype

100µm pitch hexagonal pixels - 25µm depletion



MPW submission in 2019 funded by H2020 ATTRACT

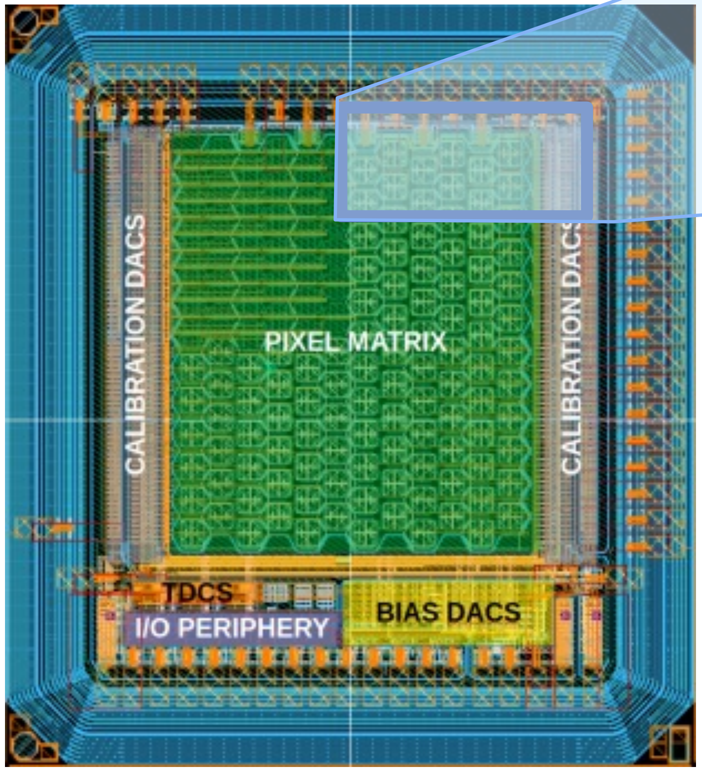
Four Matrices

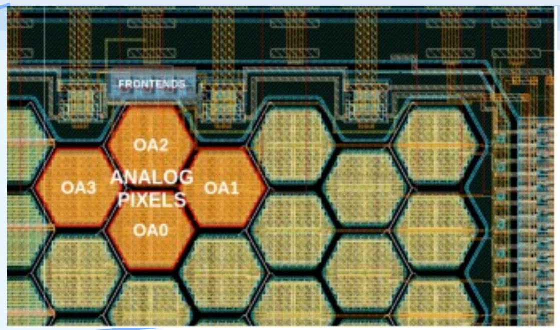
1. **Active pixel**
   - Front end in pixel
   - HBT preamp + driver (in pixel) + CMOS discriminator (outside pixel)
2. **Active pixel v2**
   - HBT preamp + CMOS discriminator
3. **Limiting amplifier:**
   - HBT preamp + HBT limiting amplifier
4. **Double threshold:**
   - HBT preamp + two CMOS discriminators

[G. Iacobucci et al 2022 JINST 17 P02019]

ATTRACT prototype

100µm pitch hexagonal pixels - 25 µm depletion

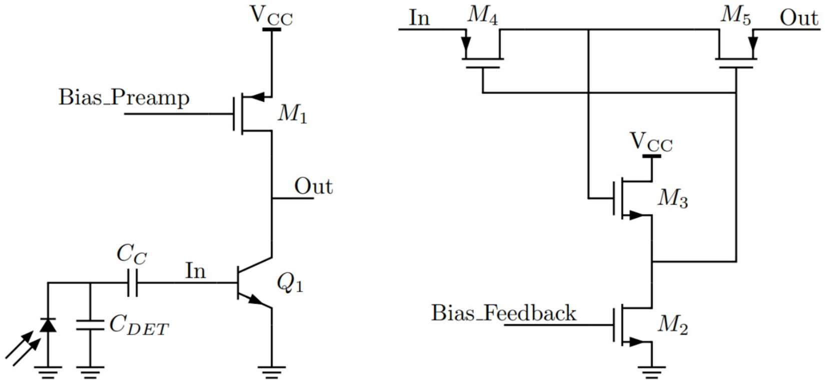




UNDER TEST HERE

Analog Channels:

HBT preamp + two HBT Emitter Followers to 500Ω Resistance on pad.



MPW submission in 2019 funded by H2020 ATTRACT

G. Iacobucci et al 2022 JINST 17 P02019

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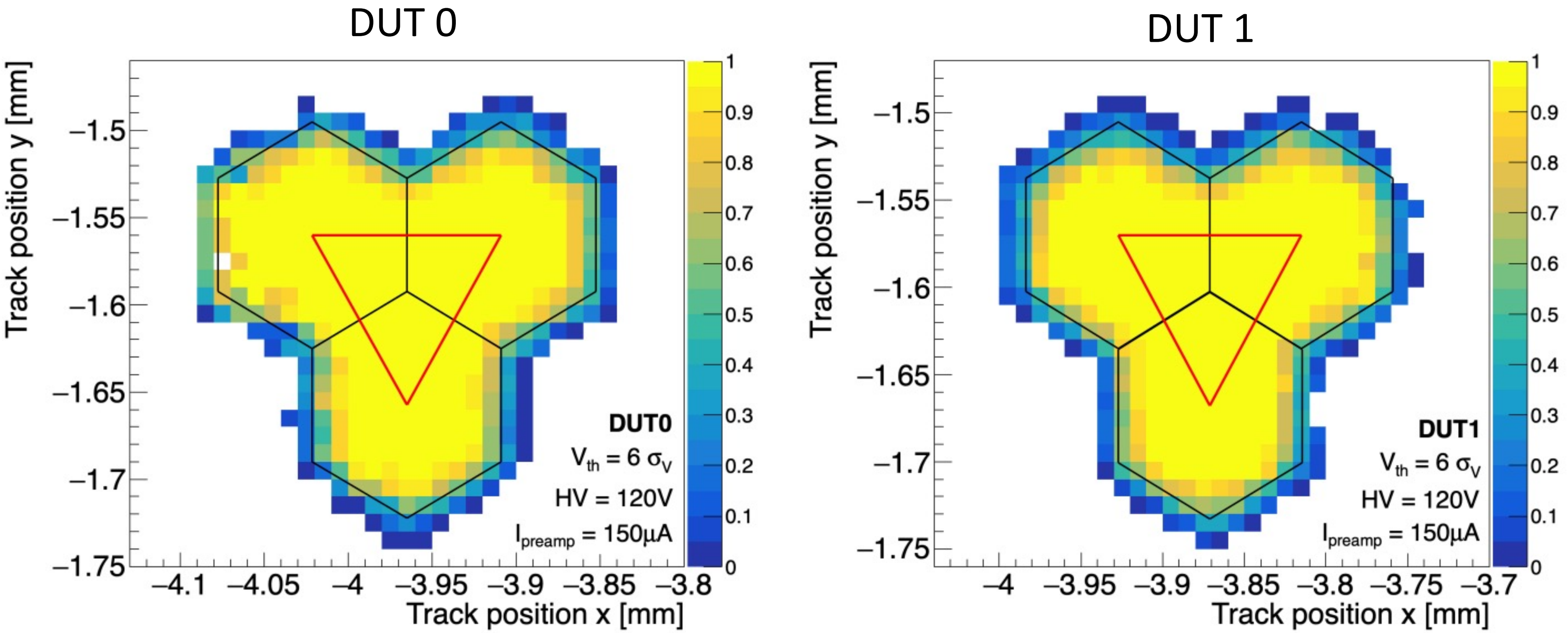
ATTRACT prototype - Efficiency

CERN SPS 180GeV pion beam
FEI4 Telescope ($\sigma_x \sim 10\mu m$ $\sigma_y \sim 15\mu m$)



To get rid of the effect of the telescope precision, we used the bins of the area inside the red triangle, that represents the entire pixel area in the right proportions.

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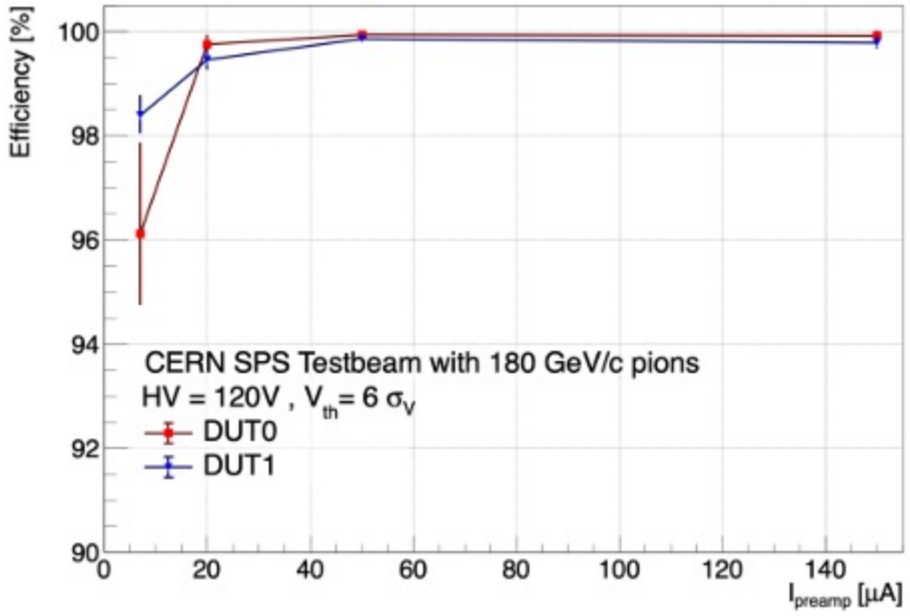
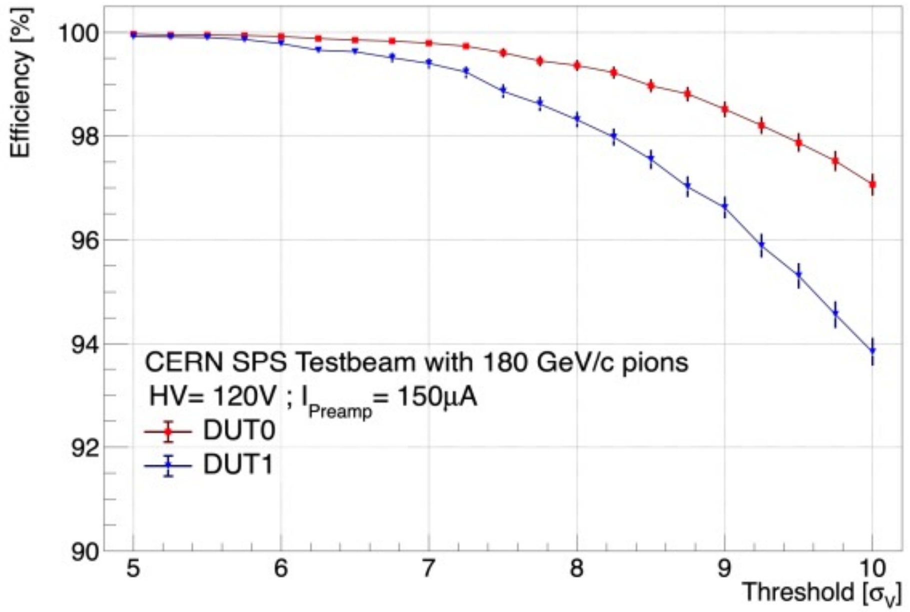
ATTRACT prototype – Detection Efficiency

Wide range of operation points above 99.5% detection efficiency





Efficiency measured at HV = 120 V				
I_{preamp} [μA]	7	20	50	150
Efficiency DUT0 [%]	$96.1^{+1.4}_{-1.7}$	$99.75^{+0.12}_{-0.17}$	$99.94^{+0.03}_{-0.05}$	$99.91^{+0.05}_{-0.08}$
Efficiency DUT1 [%]	$98.4^{+0.3}_{-0.4}$	$99.45^{+0.2}_{-0.2}$	$99.86^{+0.05}_{-0.07}$	$99.78^{+0.08}_{-0.11}$

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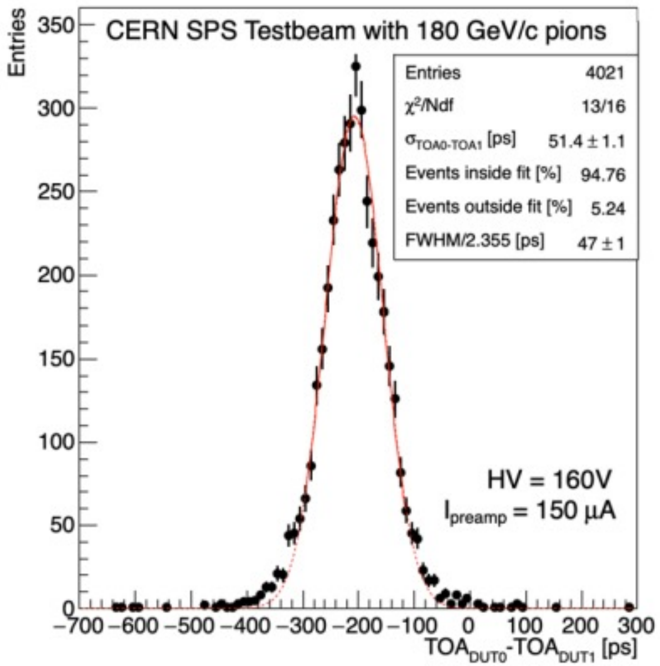
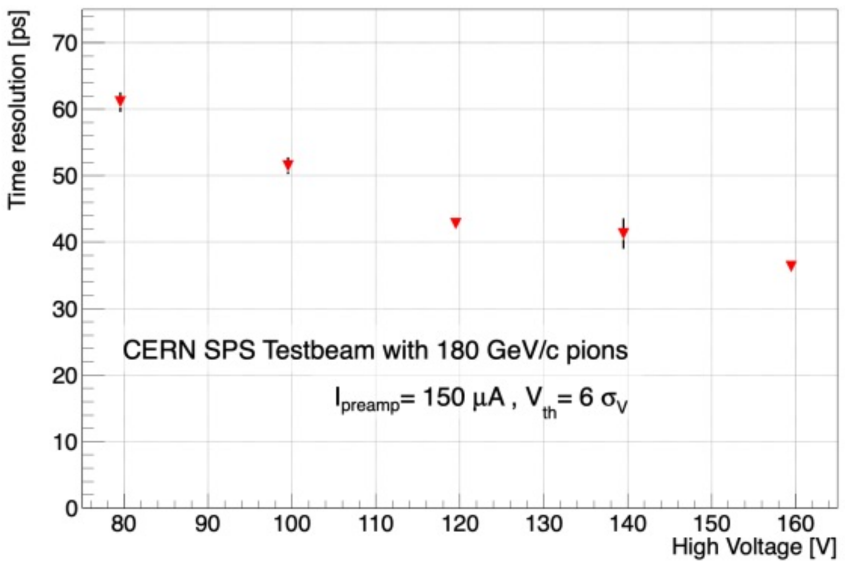
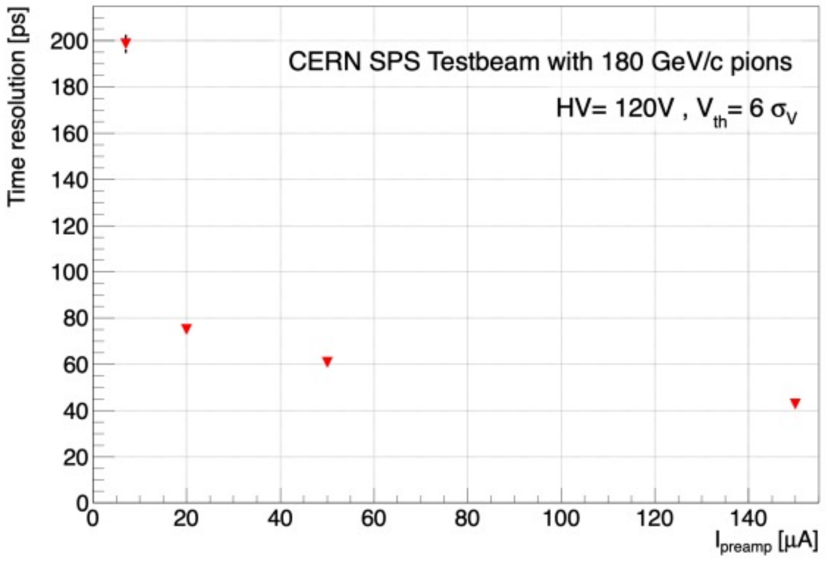
Time of flight between DUT0 and DUT1







$$\sigma_t = \frac{\sigma_{TOA0\text{-}TOA1}}{\sqrt{2}} = (36.4 \pm 0.8)\text{ps}$$ without gain structure

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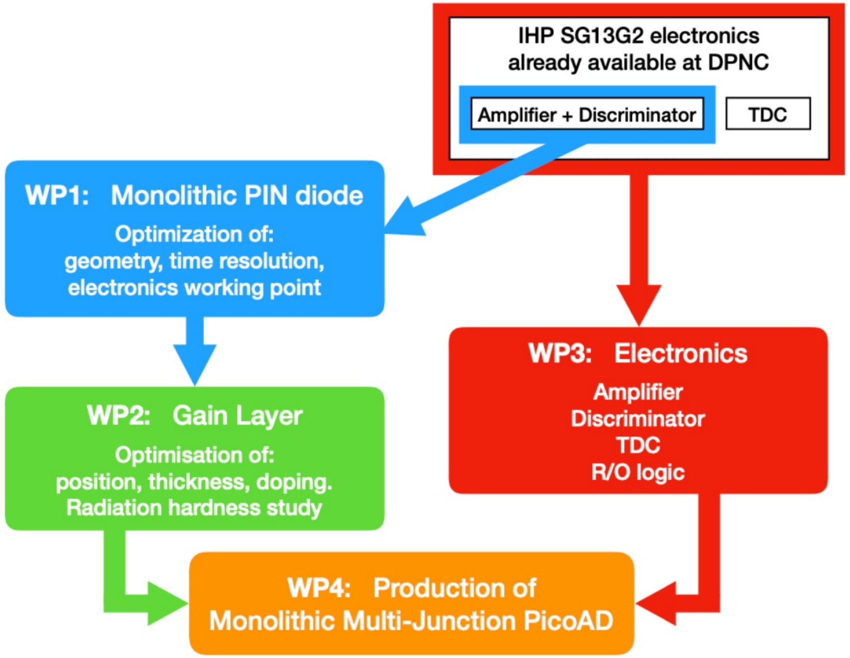
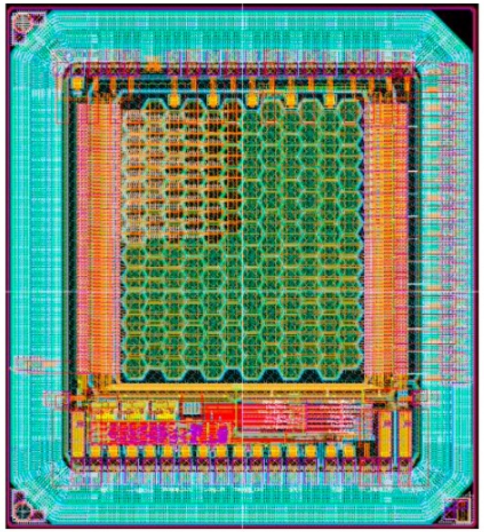
MONOLITH ERC project

5 year ERC project to develop a monolithic silicon sensor able to measure precisely the 3D spatial position of charged particles while providing at the same time **picosecond time resolution.**





H2020 ERC Advanced grant 884447,
July 2020 - June 2025

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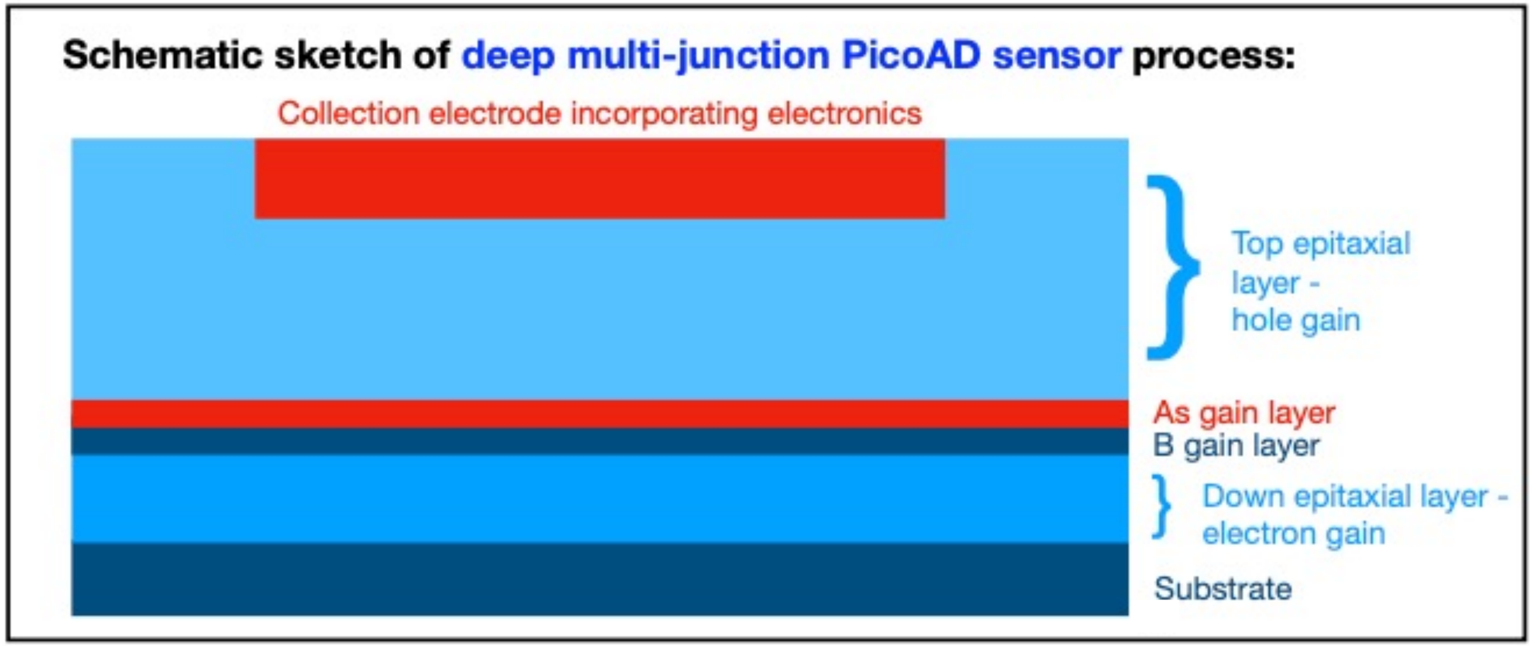
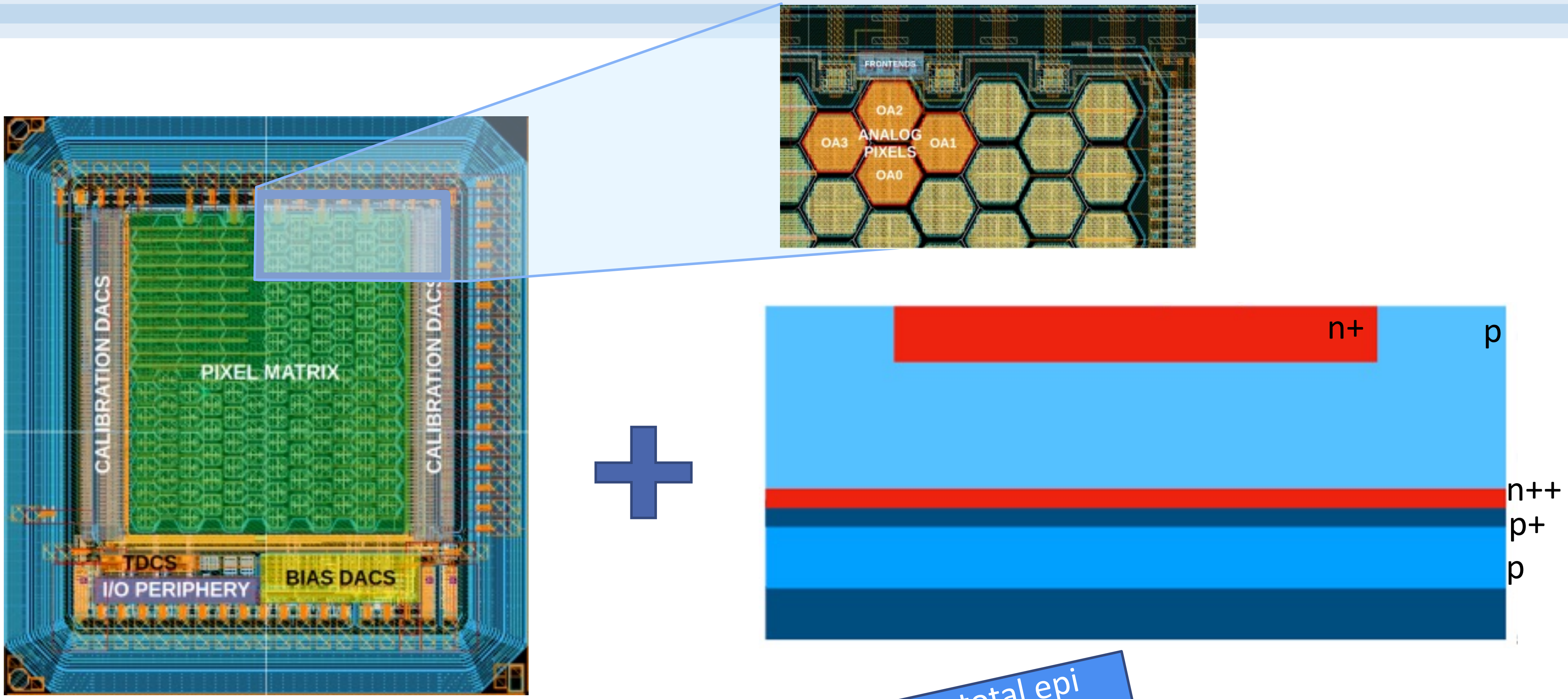
PicoAD sensor



Placement of gain layer deep inside sensor:
De-correlation from pixel implant size/geometry —> high pixel granularity possible (*spatial precision*)
Only small fraction of charge gets amplified —> reduced Landau charge fluctuations (*timing precision*)

Picosecond Avalanche Detector (PicoAD): EU Patent EP18207008.6

PicoAD prototype p0



Produced with different doses and 15µm total epi
Using the ATTRACT prototype electronics and pixel

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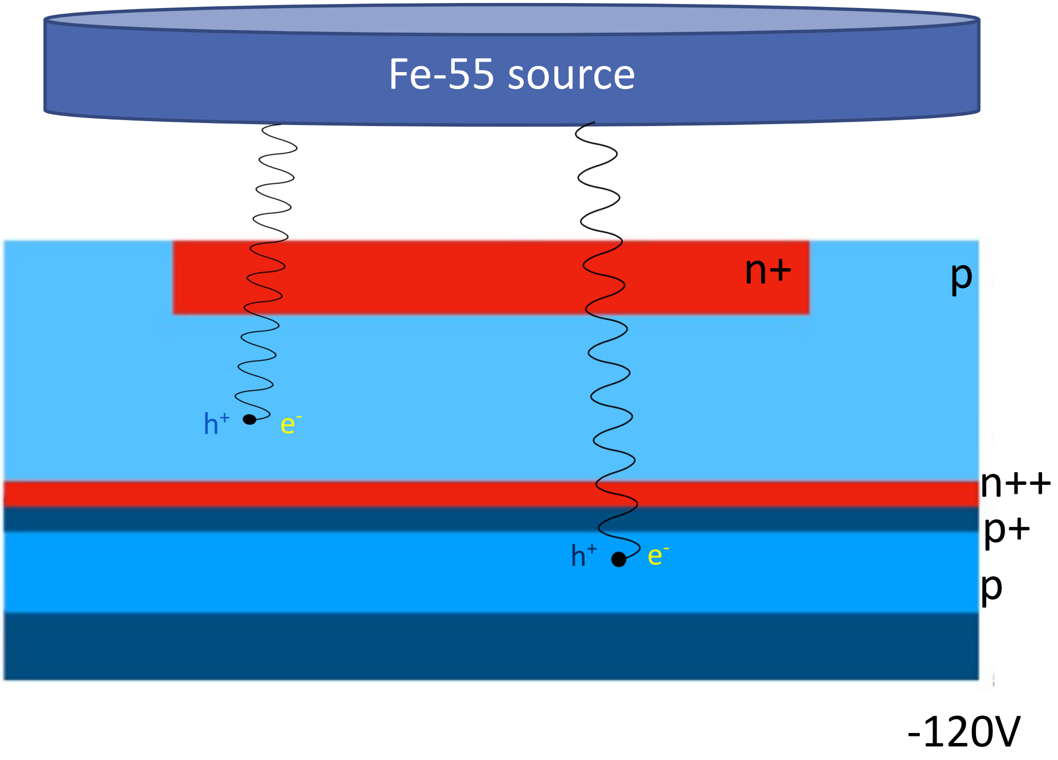
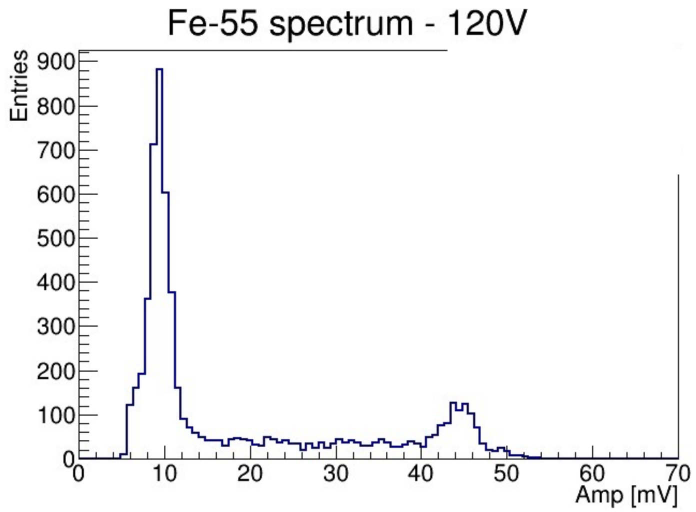
PicoAD sensor



e⁻ /h⁺ Generation



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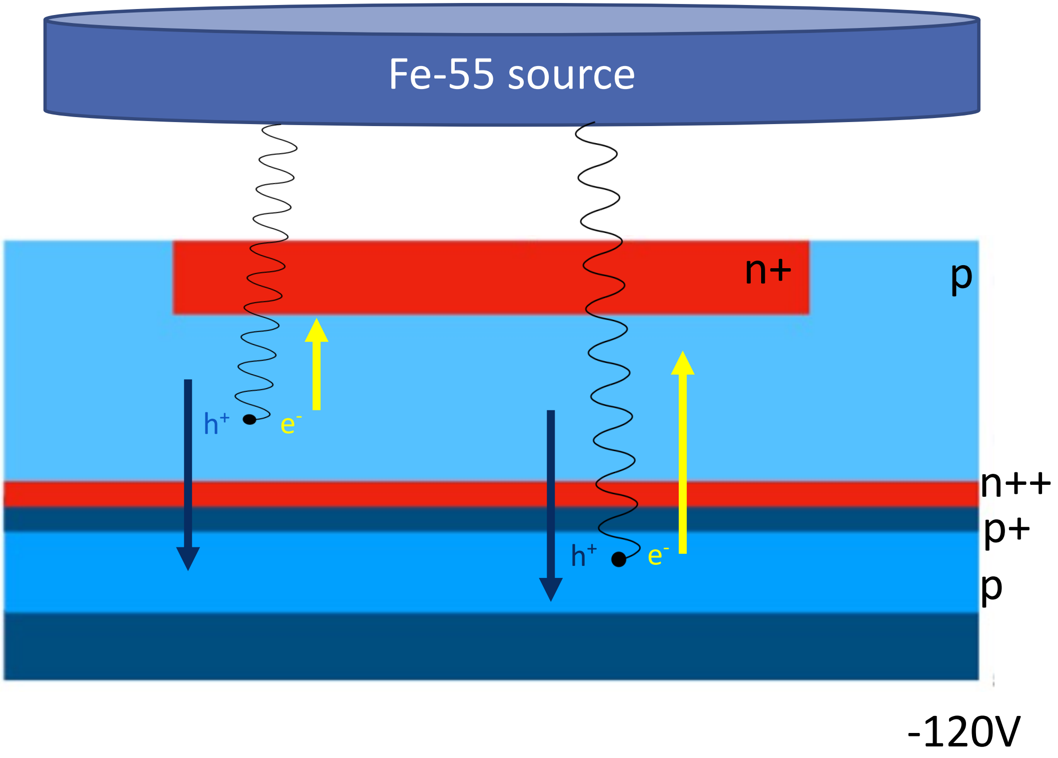
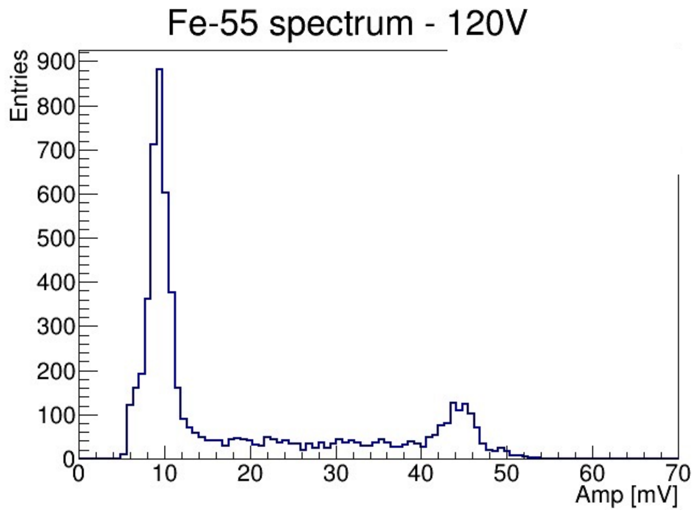
PicoAD sensor

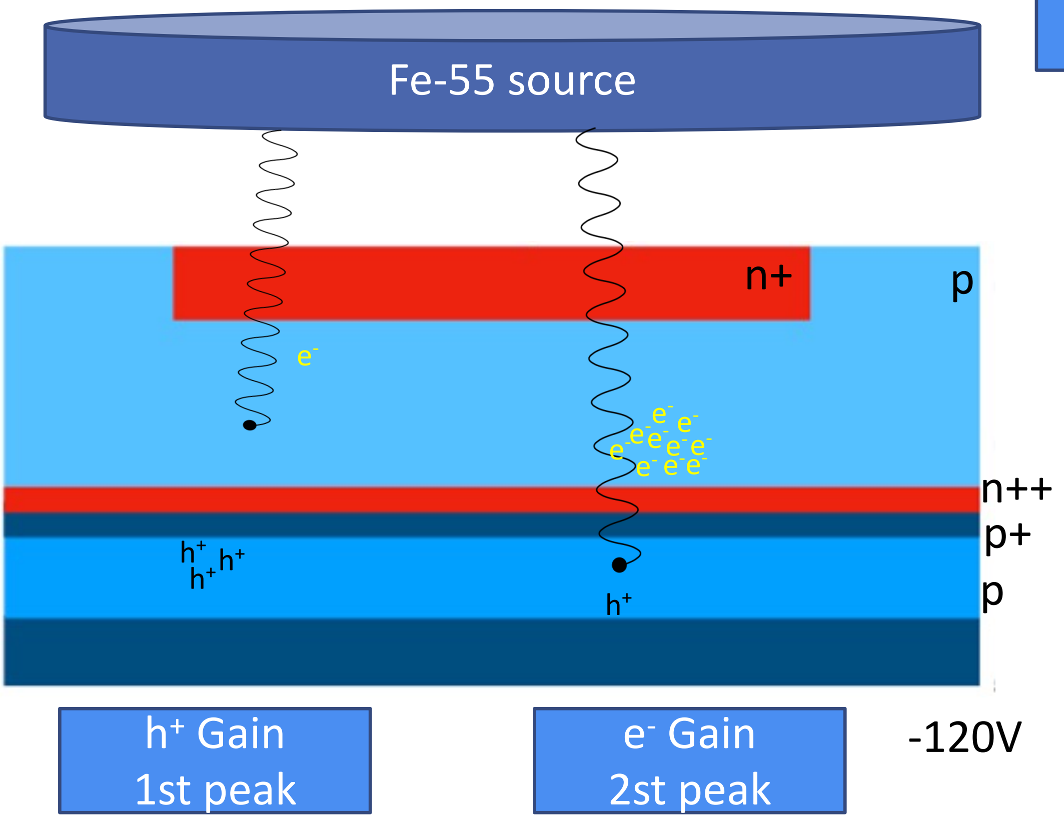


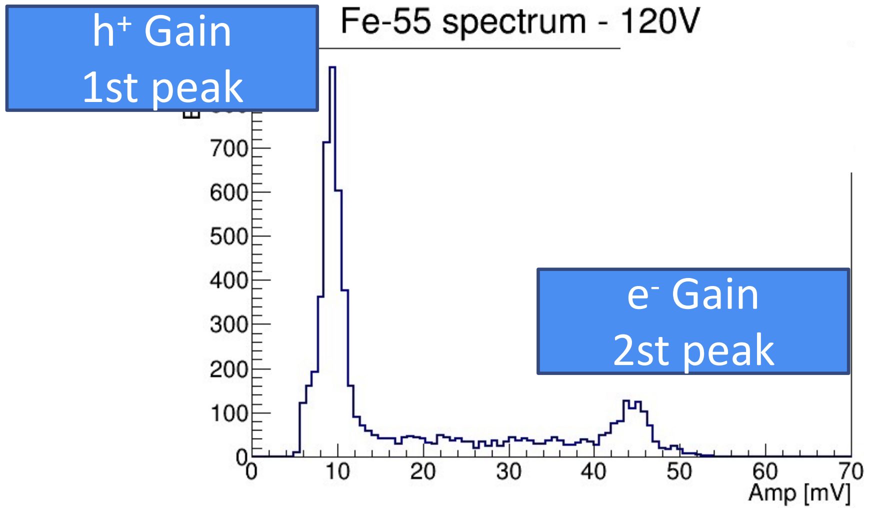
e- /h+ Generation

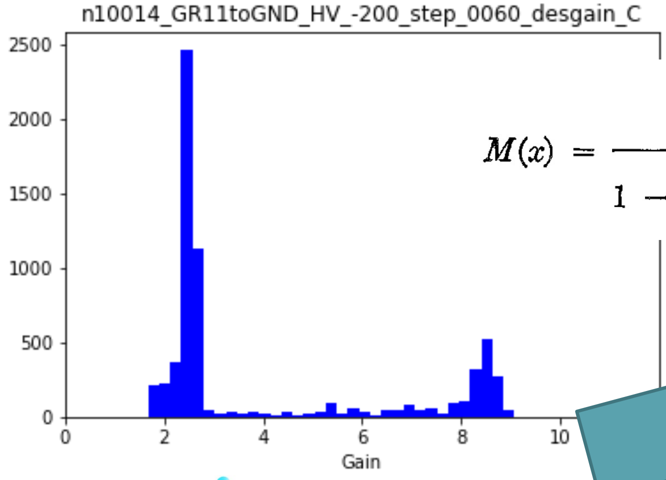
Electrict Field -> Drift transport



PicoAD sensor







$$M(x) = \frac{\exp\left[-\int_x^w (\alpha - \beta)\, dx'\right]}{1 - \int_0^w \alpha \exp\left[-\int_{x'}^w (\alpha - \beta)\, dx''\right] dx'}.$$

R. J. McIntyre Gain Model

Qualitative Simulation

Only carriers passing through the gain layer are multiplied
Two different peaks for e^- and h^+

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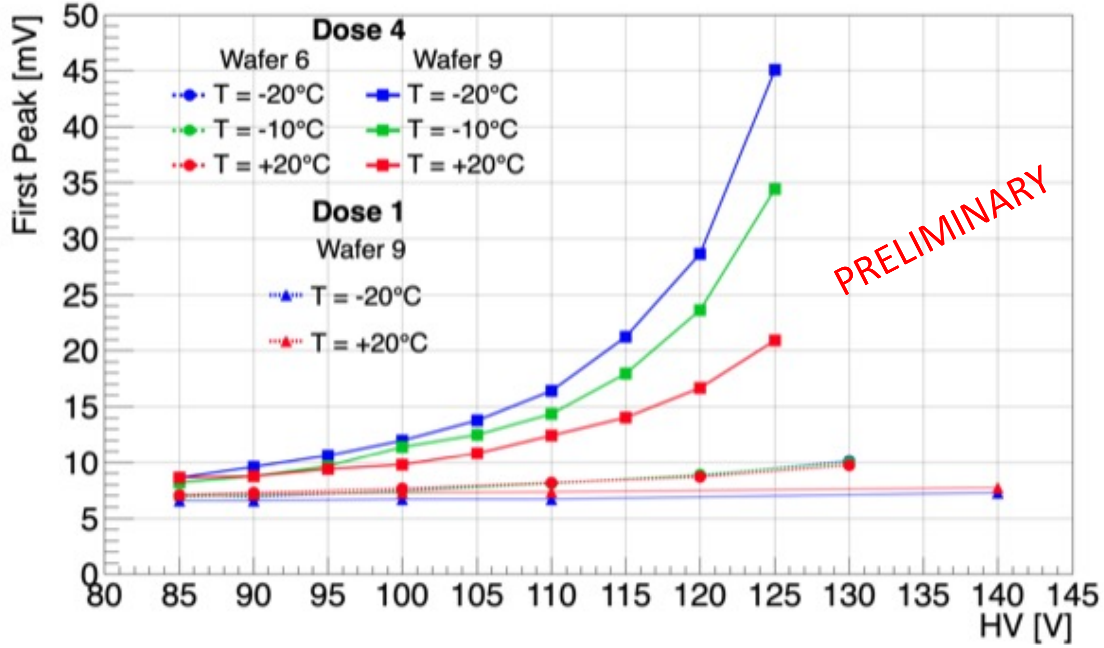
PicoAD – Gain Characterization

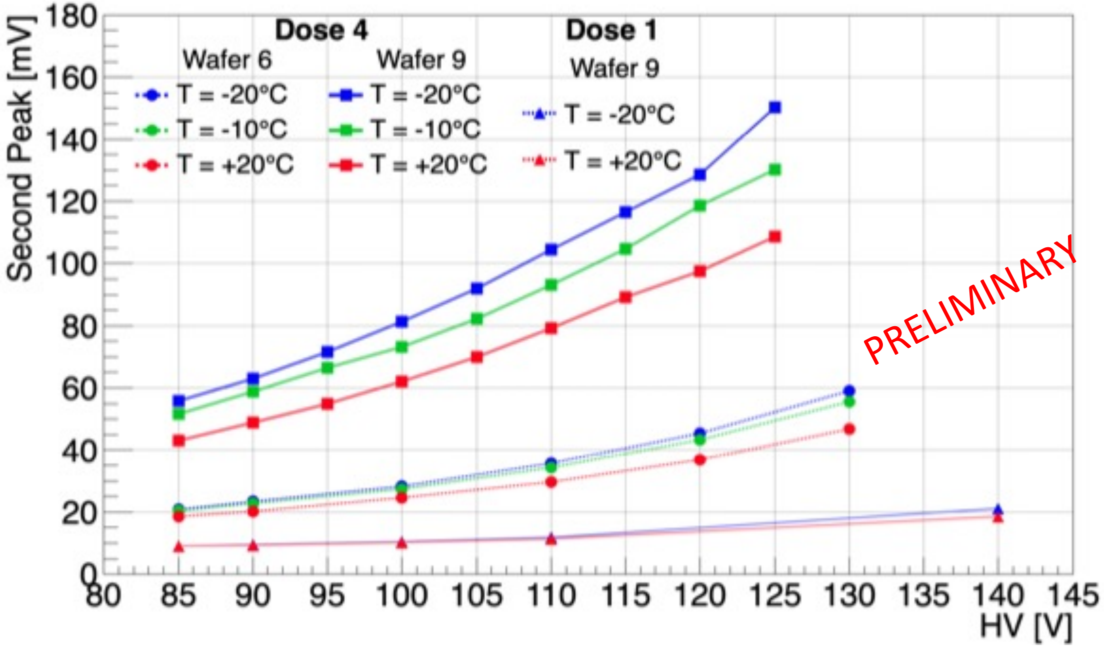
Peak amplitude of 3 Different Samples

Dose4>Dose1

Amplitude of first peak (holes) vs. HV



Amplitude of second peak (electrons) vs. HV



- Both peaks increase with HV
- Temperature dependence
- Clear difference between wafer 6 and wafer 9 for the same dose (under investigation)
- Dose 1 almost no holes gain, use for normalization to get electron gain

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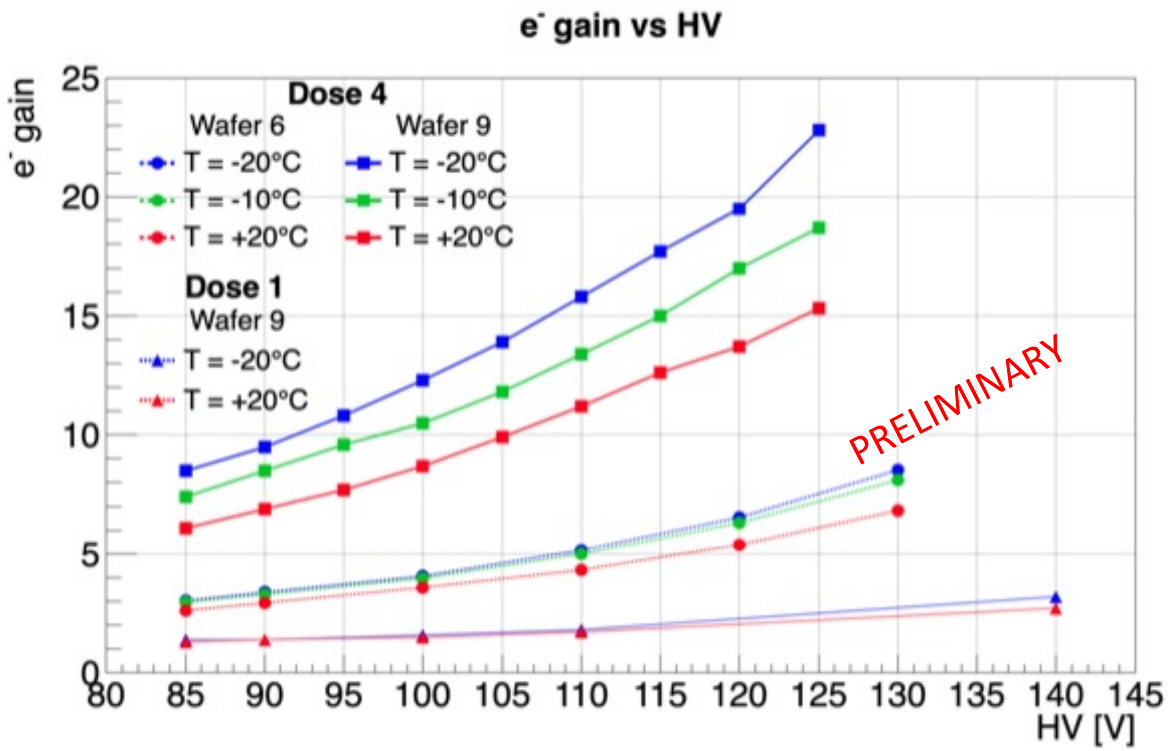
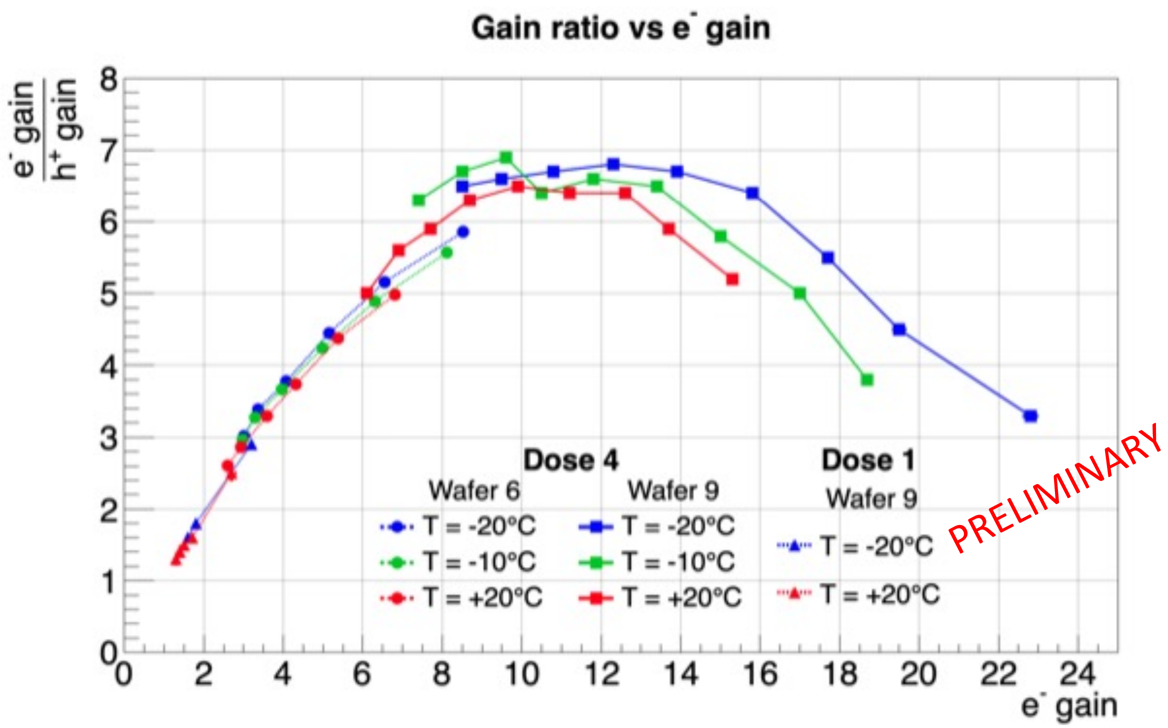
PicoAD – Gain Characterization





Wafer9 shows gain between 15 and 20 for temperatures between +20 and -20 degrees

Consistent behaviour of the 3 samples

The curve is expected to saturate:
Hypothesis -> Space Charges reduce electron gain

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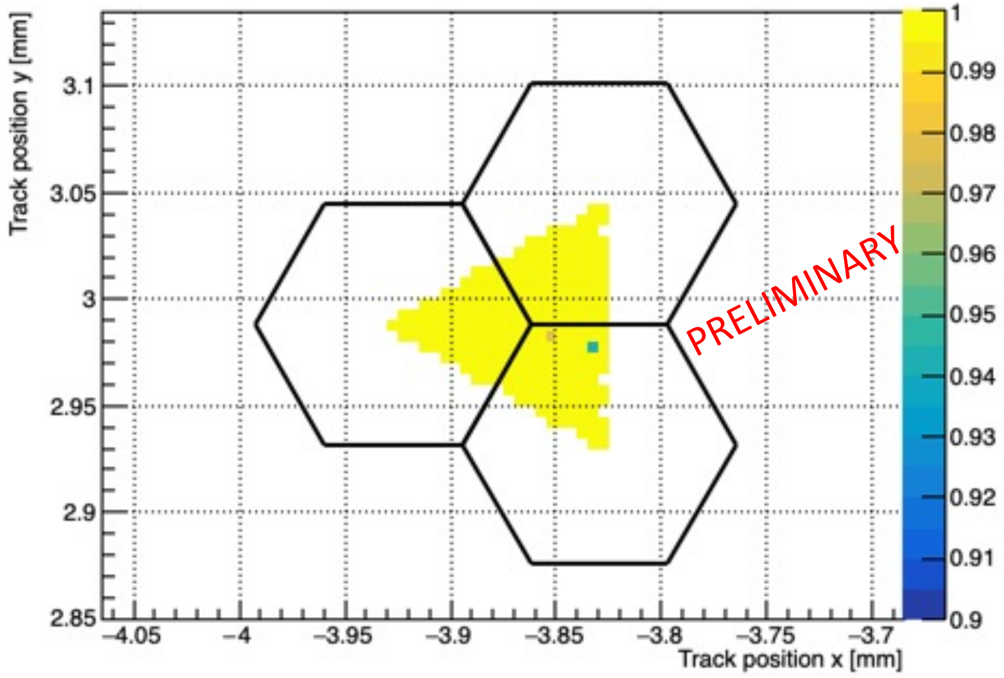
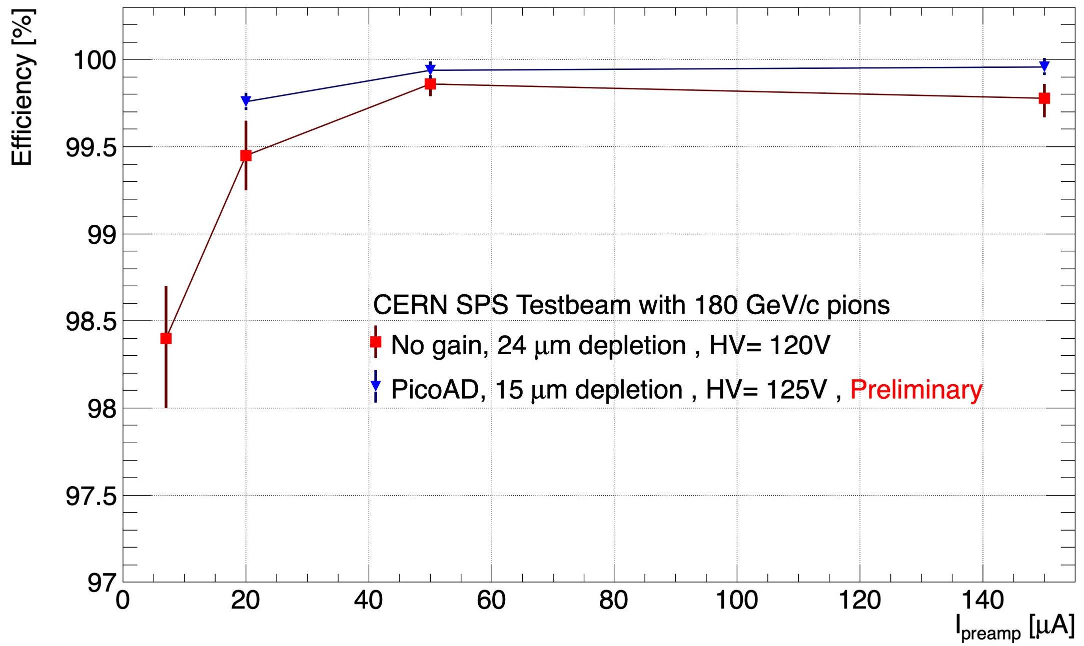
PicoAD p0 vs p0 NO GAIN

Testbeam at CERN SPS 180GeV pion beam. FEI4 Telescope ($\sigma_x \sim 10\mu m$ $\sigma_y \sim 15\mu m$)





Reduced depletion thickness and still better results

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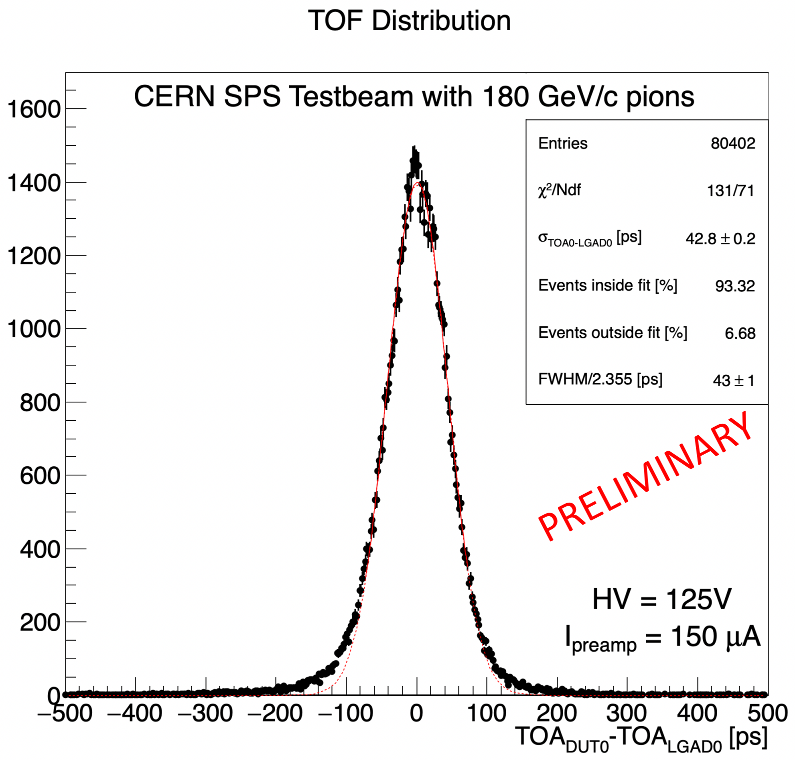
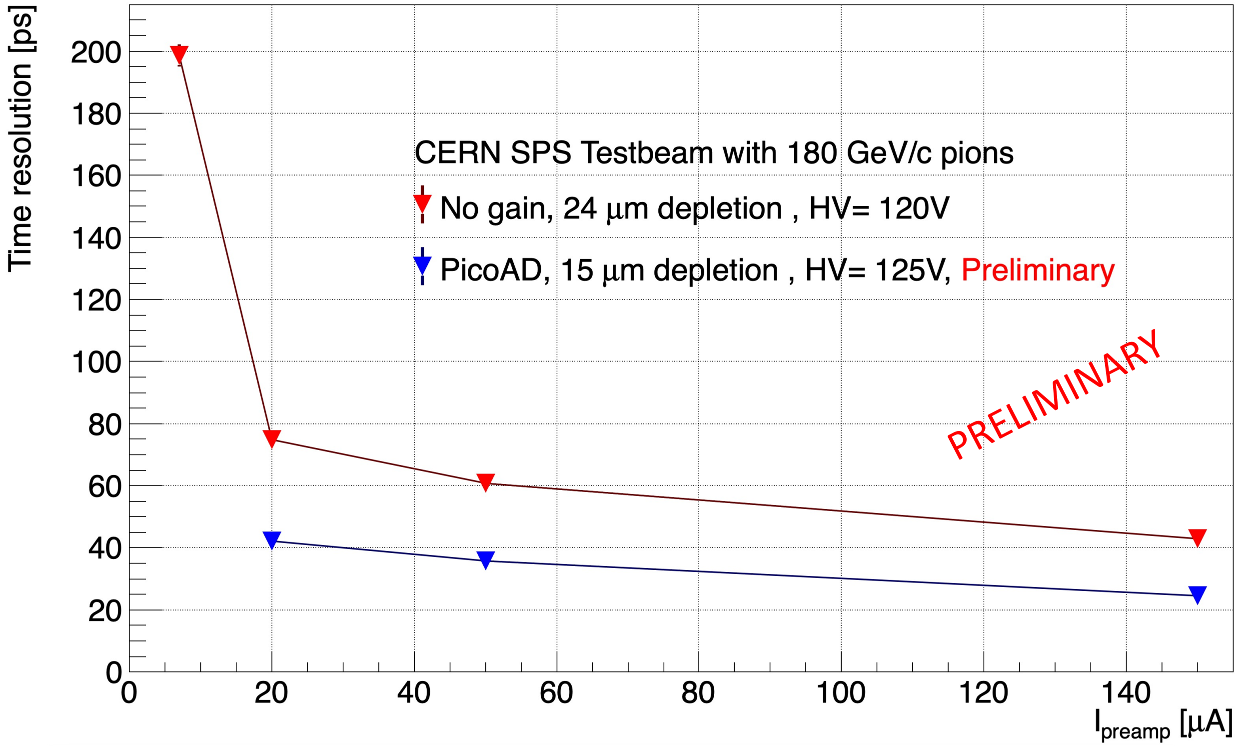
PicoAD - Time Stamping





Reference sensor

$\sigma_{LGAD} = (35.6 \pm 0.5)ps$

First **PicoAD** prototype, not yet optimized for timing:

$$\sigma_{PicoADp_0} = (24.2 \pm 0.7)ps$$

PRELIMINARY

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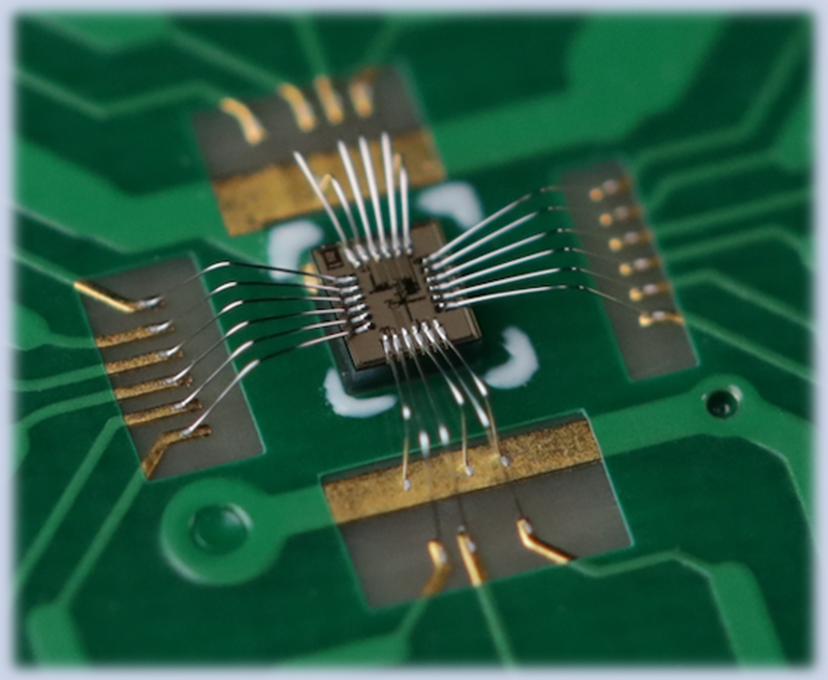
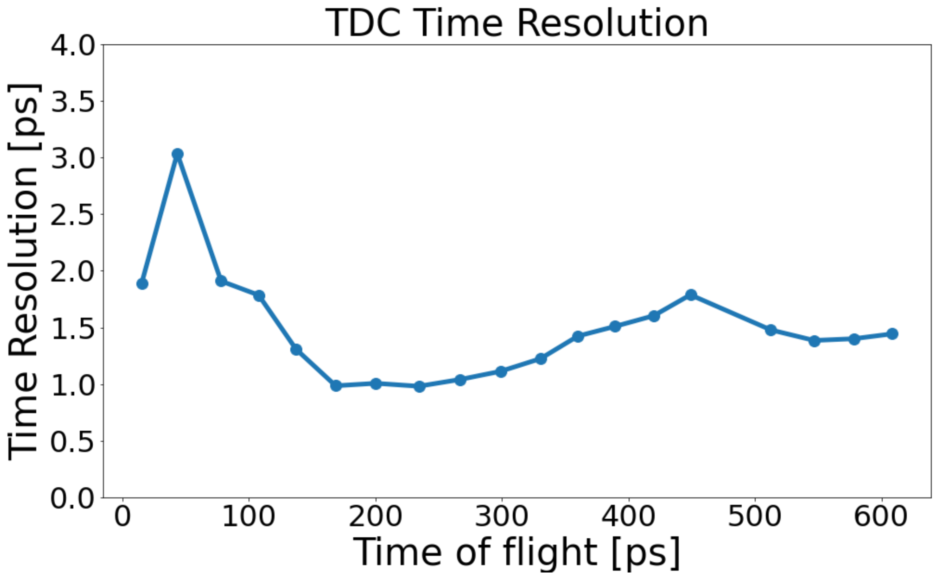
TDC Monolith



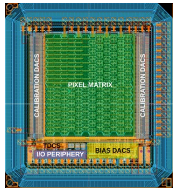
Picosecond TDC test chip



Integrated in MONOLITH p1 Prototype: under test
Improved TDC version back from foundry in April 2022.

Outlook and Summary

JINST 17 P02019



Kick off

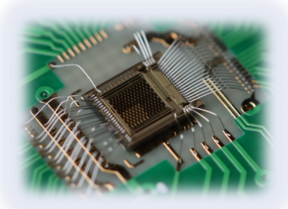
July2020

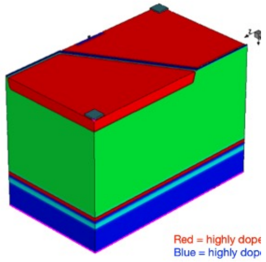
NoGain prototype

>99.5% efficiency

$\sigma_{NoGAIN} \approx 36ps$

Q4 2021





PicoAD p1

Optimized sensor design

Optimized FE + ps TDC

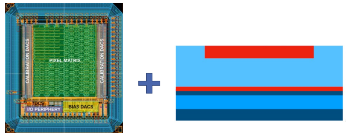
Q2 2022

Full reticle

Based on PicoAD p2

Q3 2024

TODAY



Proof of PicoAD Concept

$\sigma_{PicoADp_0} = (24.2 \pm 0.7)ps$

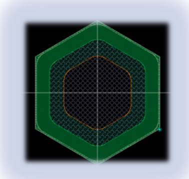
>99.5% Efficiency

PRELIMINARY

Q3 2023

PicoAD p2

Target: <10ps



50µm pitch hexagonal pixel

New FE for ps resolution

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