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FACULTY OF SCIENCE
Department of Nuclear and Particle Physics

MONOLITH project simulations and test-beam results

Magdalena Muenker on behalf of **the MONOLITH team**

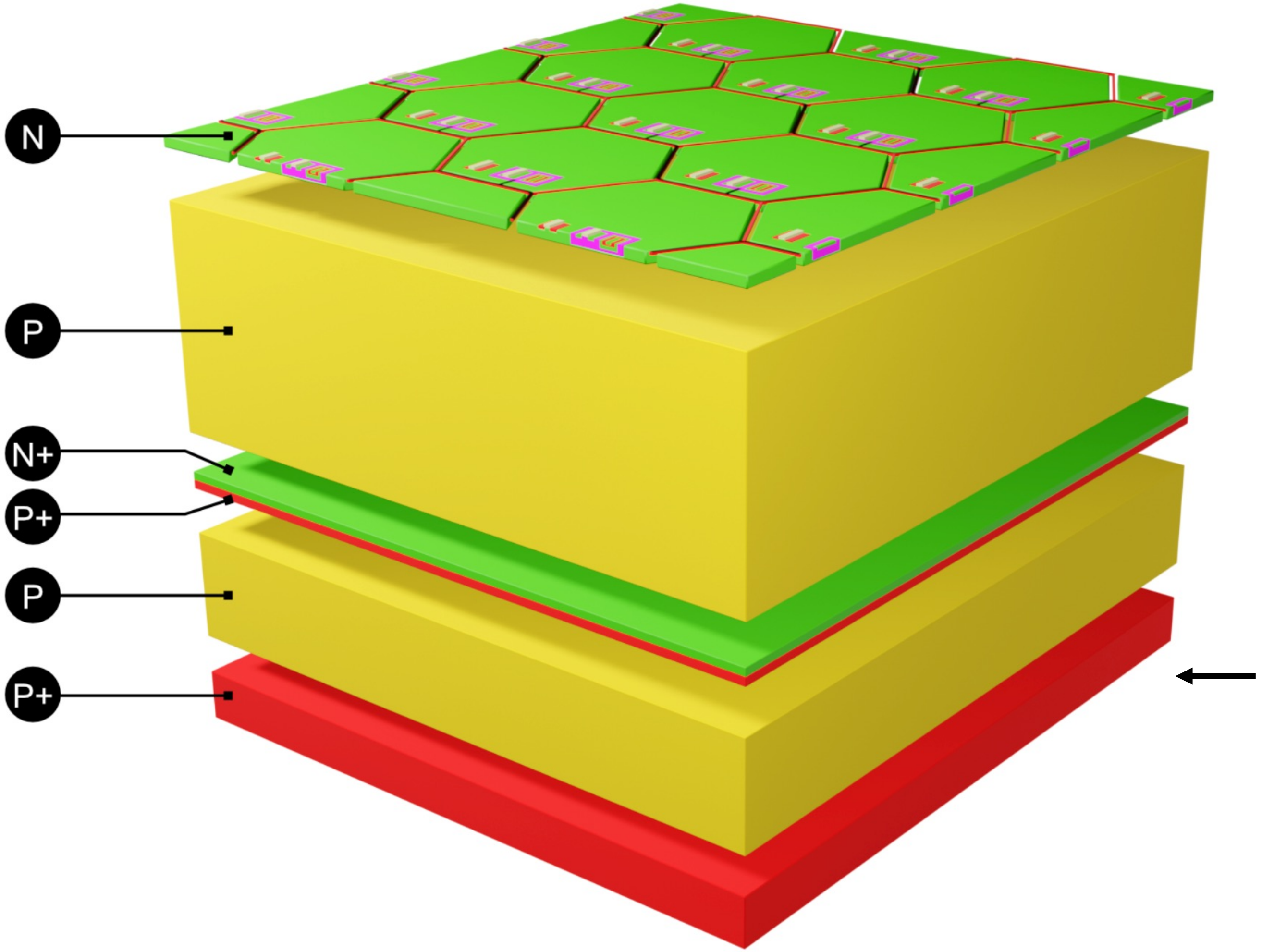
(University of Geneva)

ATTRACT

European Research Council
Established by the European Commission

PicoAD - sensor design concept

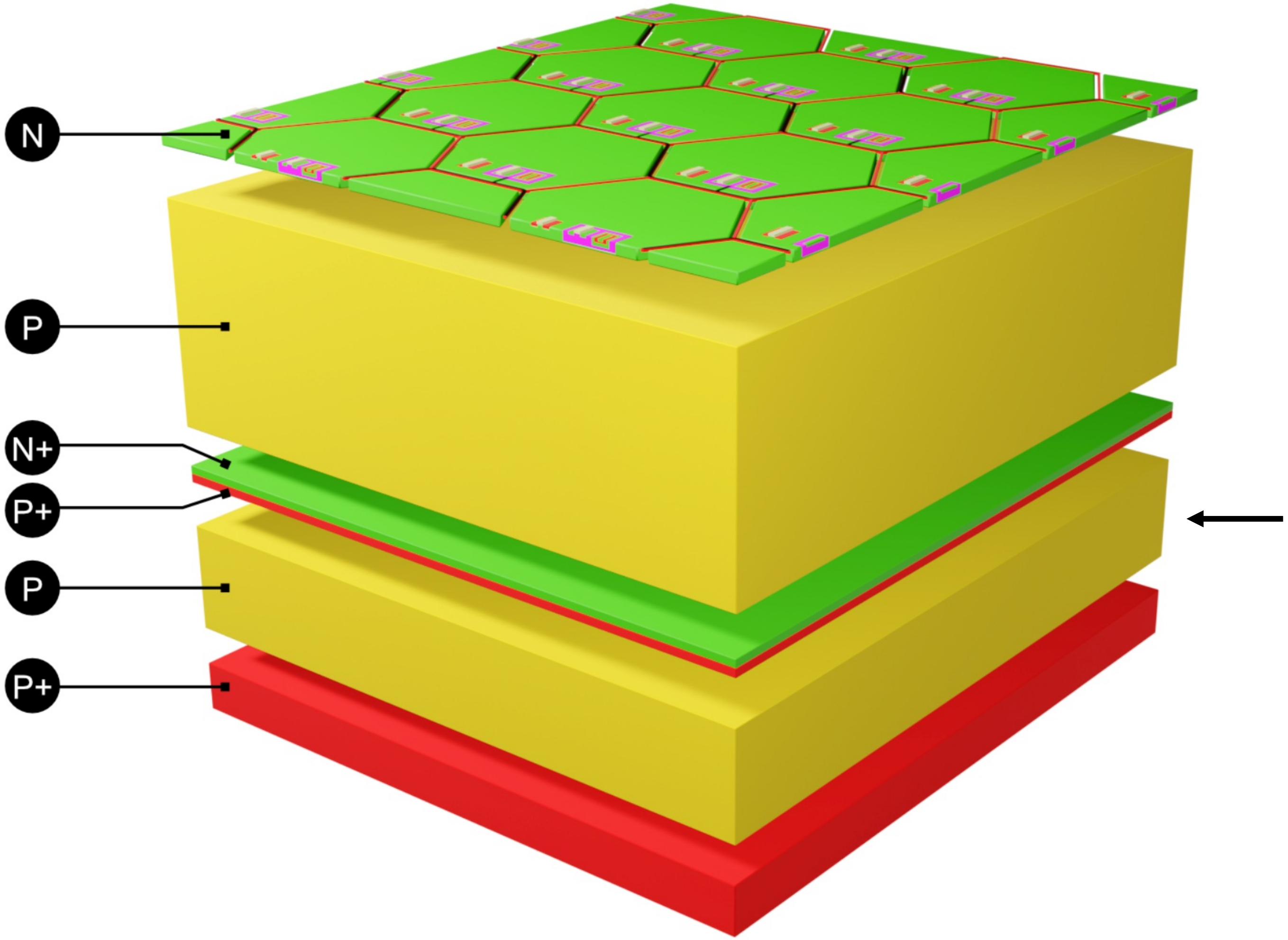
Picosecond Avalanche Detector (PicoAD): EU Patent EP18207008.6



Sensor growth on low resistivity wafers:

1. **No dedicated backside processing** needed
2. Low resistivity important to end depleted active region of sensor and minimise coupling to FE integrated in pixel

PicoAD - sensor design concept

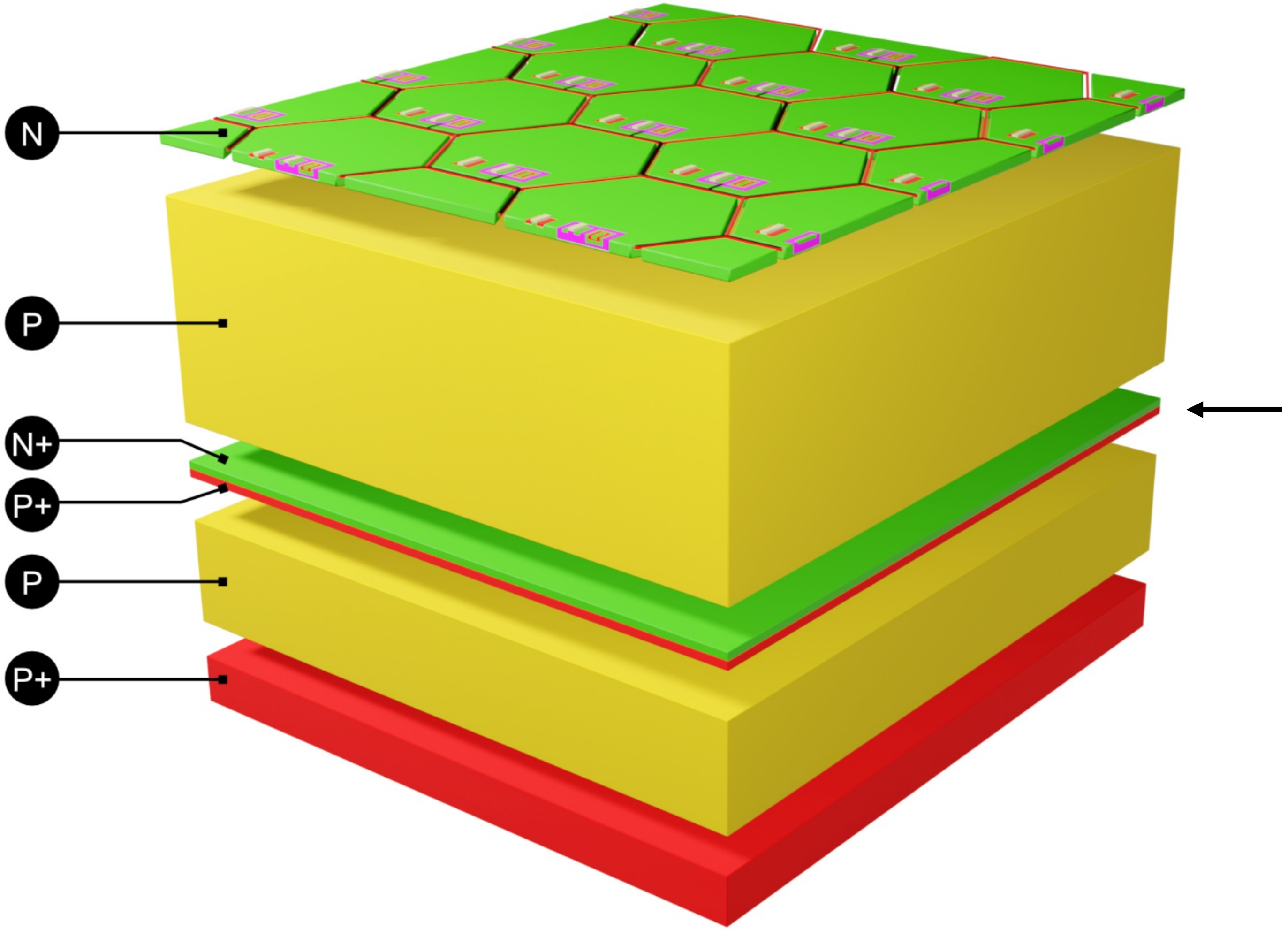


Thin ‘absorbtion region’, 1st epitaxial layer:

1. Region where primary charge charge drifting towards topside gets amplified is produced

2. Thin layer (~5µm) to **minimise charge collection noise** (see Werner Rieglers talk)

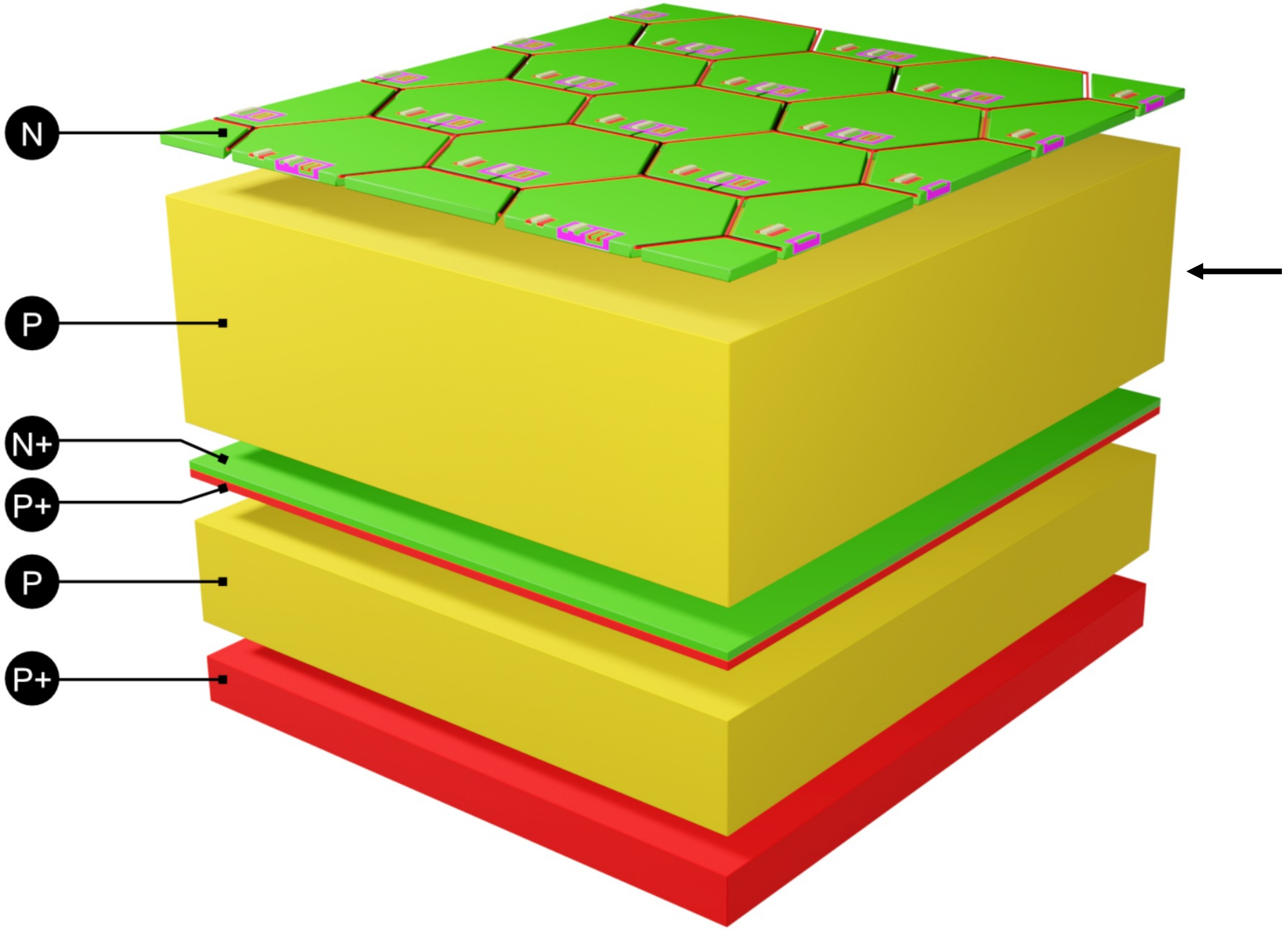
PicoAD - sensor design concept



Thin and uniform deep gain layer:

- Same doping of gain layer over full pixel cell (full ‘fill-factor’):
  - Uniform gain and minimisation of pixel edge effects
- Gain layer physically seperated from pixel implant:
  - Can decrease absorbtion region to minimise charge collection noise without increasing sensor capacitance (coupling to backside substarte p+)
  - Can integrate FE electronics inside pixel implant (**fully monolithic CMOS**)

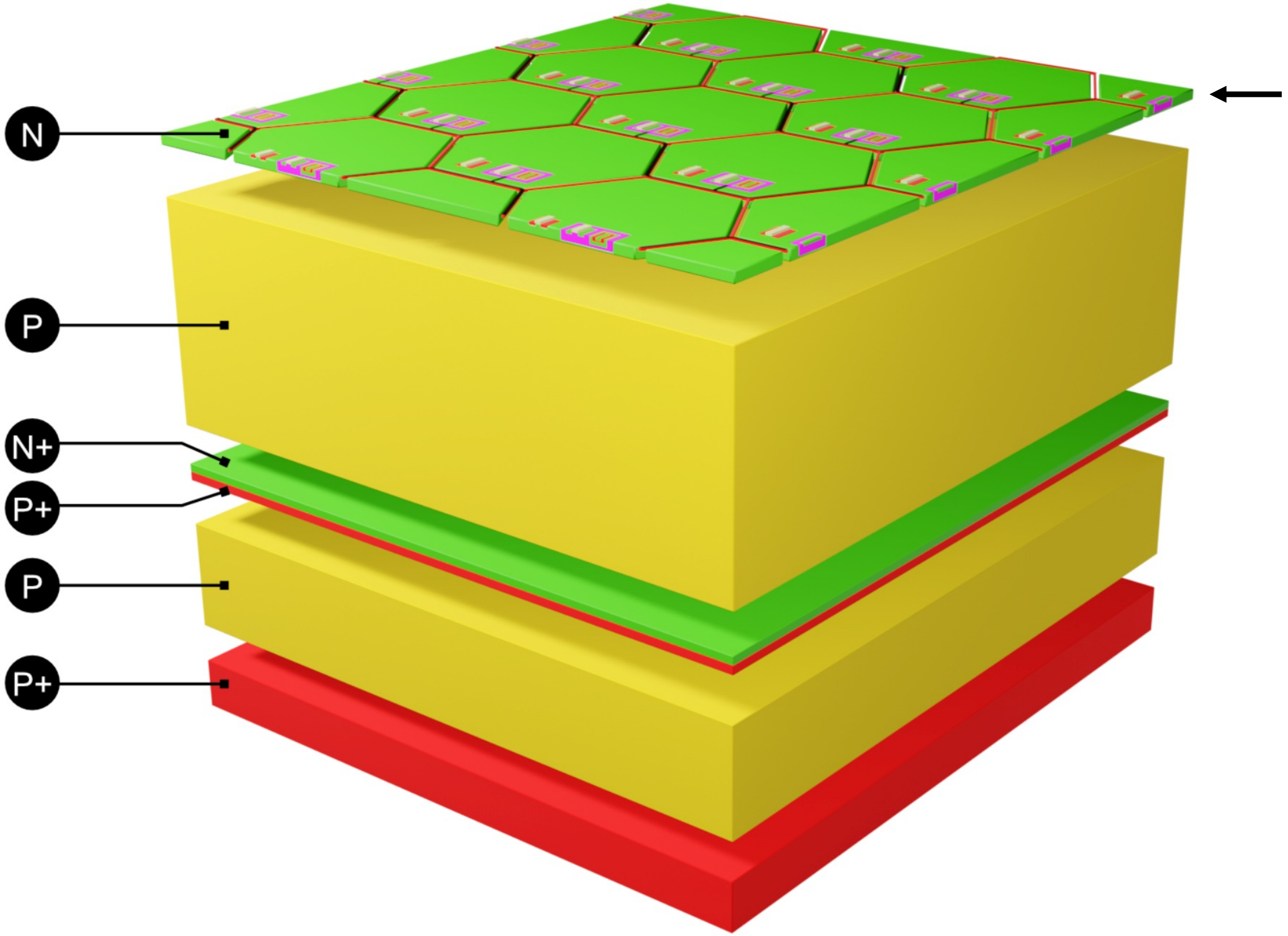
PicoAD - sensor design concept



Thicker 'drift region', 2nd epiaxial layer:

- Constrains:
  - ➢ Needs to be as thin as possible to:
    - ➢ Maximise weighting field (∝ 1/depletion)
    - ➢ Maximise drift field
  - ➢ Needs to be as thick as possible to:
    - ➢ Sufficantly minimise capacitance
    - ➢ Sufficiantly minimise impact of pixel implants on gain layer uniformity

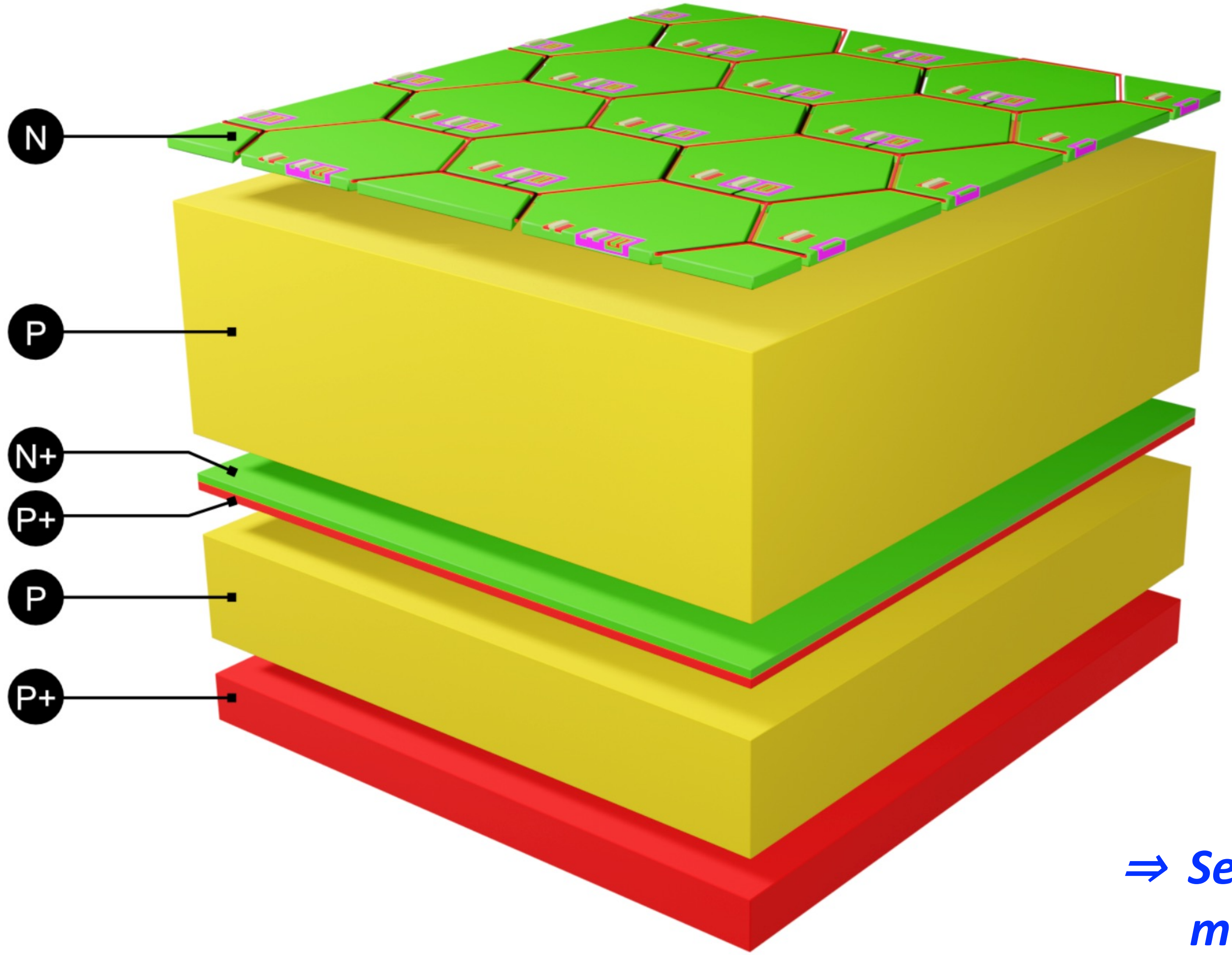
PicoAD - sensor design concept



Fully monolithic CMOS processing:

- Implemented in **large collection electrode design to maximise weighting** field over full pixel cell
- **Pixel implant size can be minimised** while maintaining gain layer uniformity!
- **Hexagonal design to minimise edge effects** (impact on gain layer + high field breakdown between pixels)

PicoAD - sensor design concept



⇒ PicoAD concept provides **simultaneusly**:

- Reduced charge collection noise
- Reduced sensor capacitance
- Improved weighting field

} Pico-second sensor timing

- Small pixel size
- Fully monolithic CMOS design

⇒ Sensor optimised for picosecond timing in fully monolithic small pixel design

Data used for sensor optimisation

TCAD – detailed sensor simulations:

Development of sensor concept

In-depth understanding of physics

AllpixSquared – simulation:

Simulation of interaction of radiation with sensor

Full statistics MC (high stats + charge collection/landau noise)

→ Performance evaluation

Experimental data:

Full picture of sensor performance

PicoAD simulation - **3D TCAD setup**

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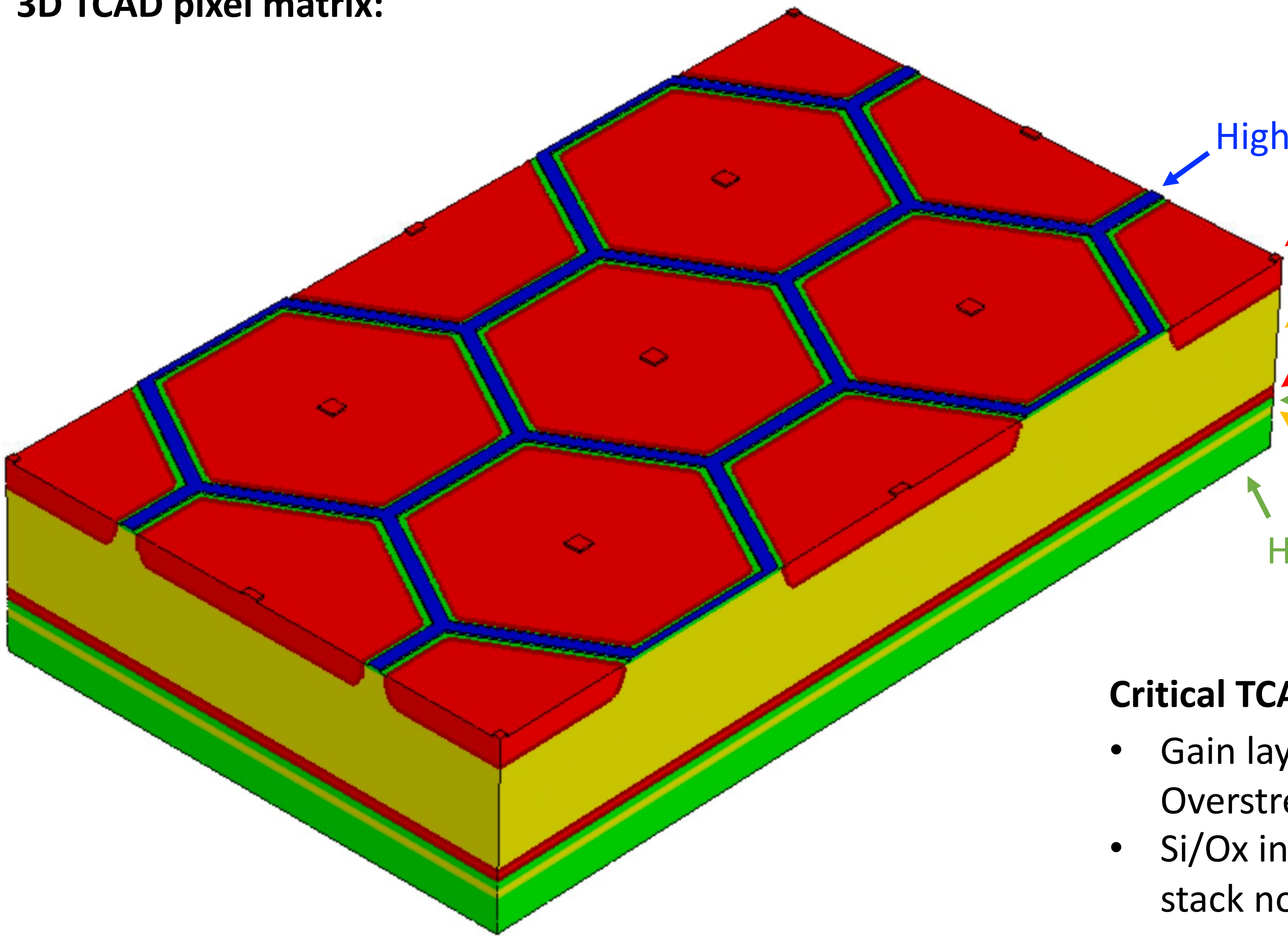
3D TCAD pixel matrix:



Critical TCAD aspects:

- Gain layer: meshing & modelling (Okuto, van Overstreaten etc…)
- Si/Ox interface in inter pixel region (top layer oxide stack not shown here)

PicoAD 3D TCAD - **electrostatic potential**

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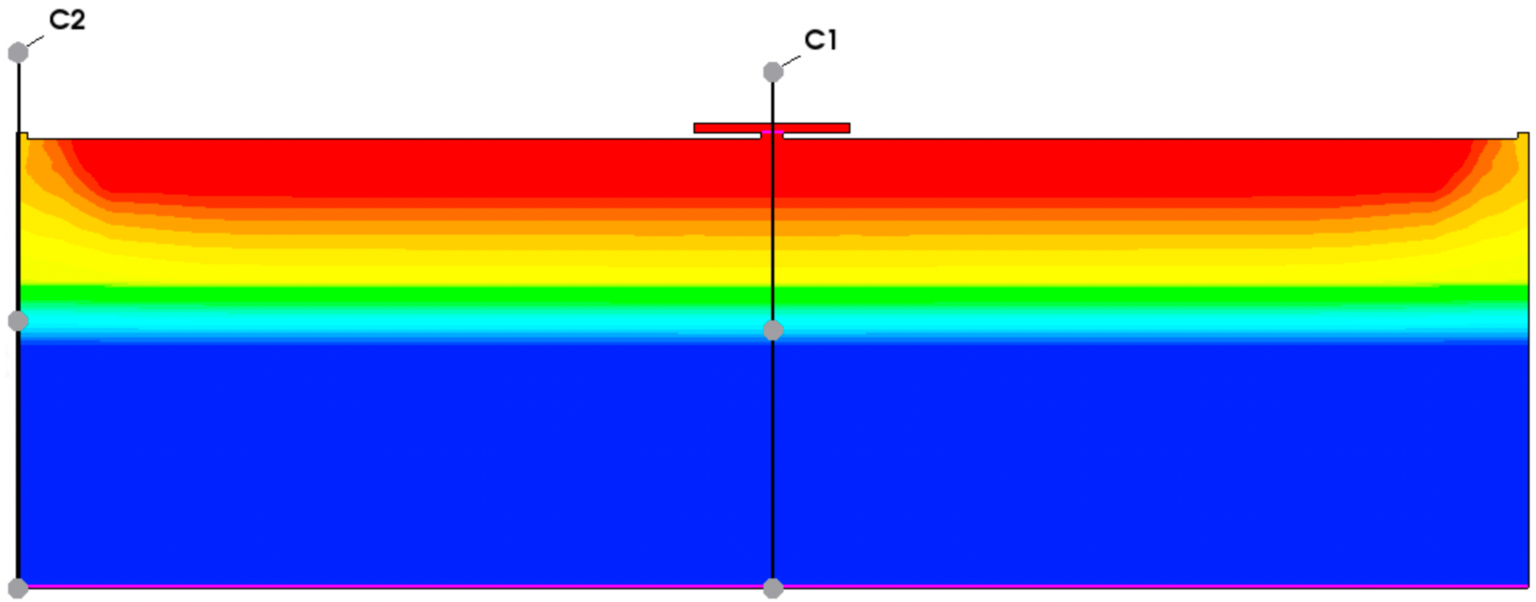
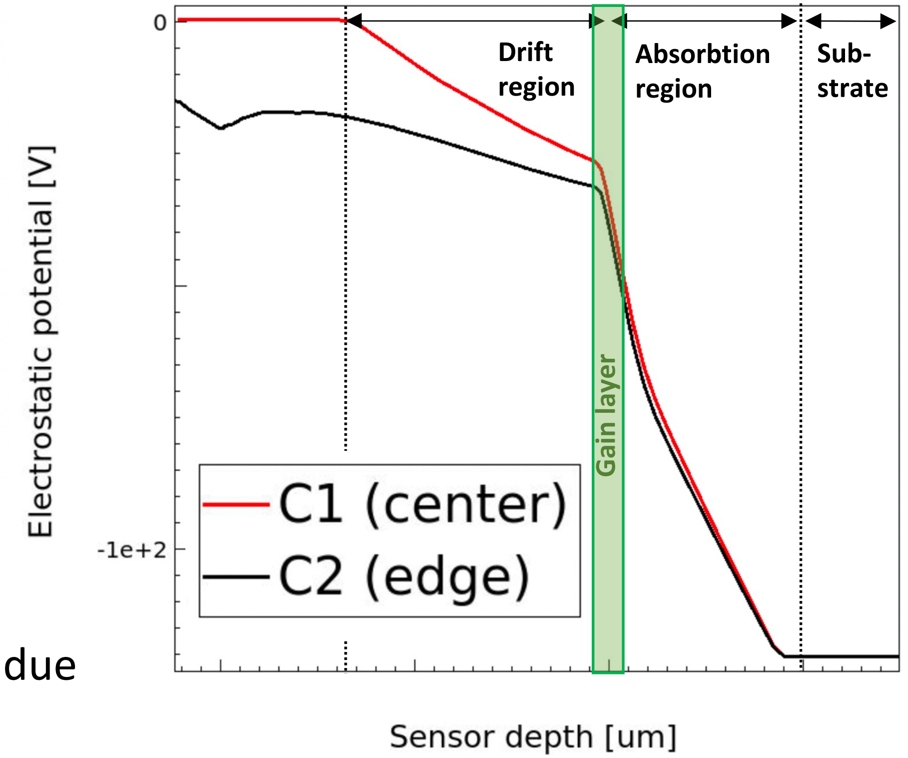
Electrostatic potential – 2D map:



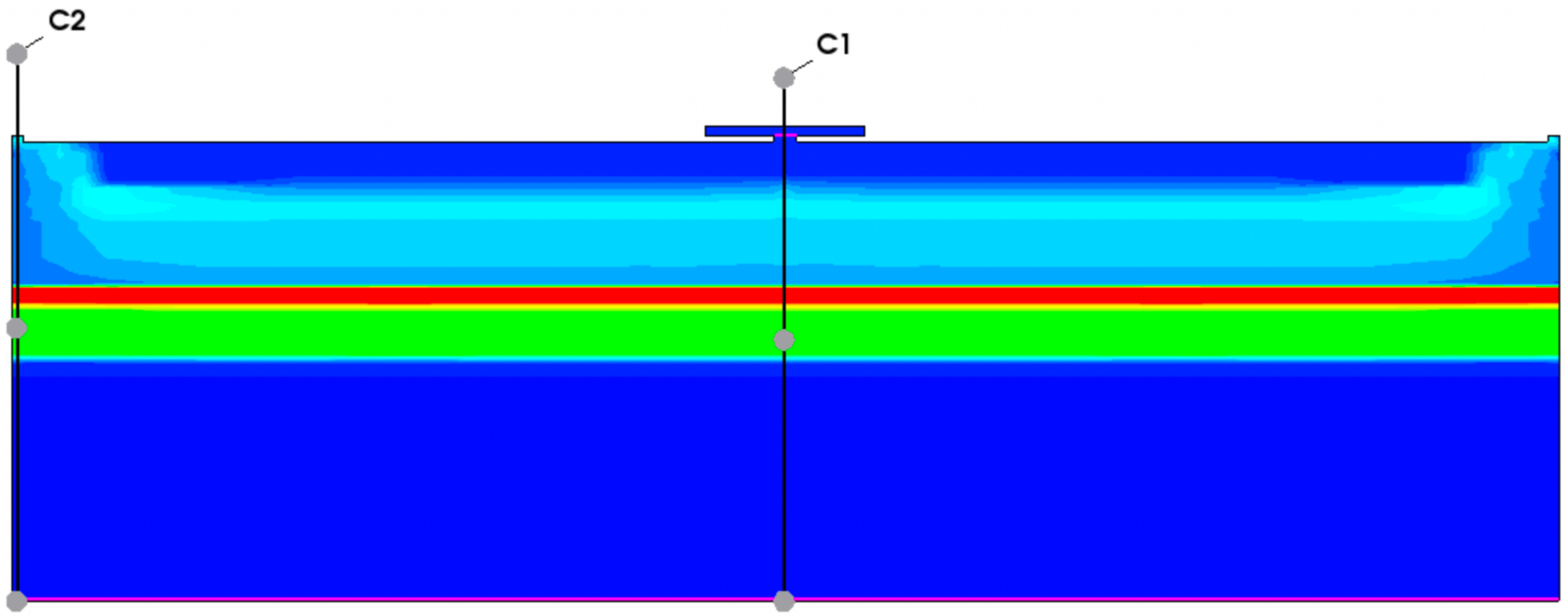
Electrostatic potential – cuts C1, C2:



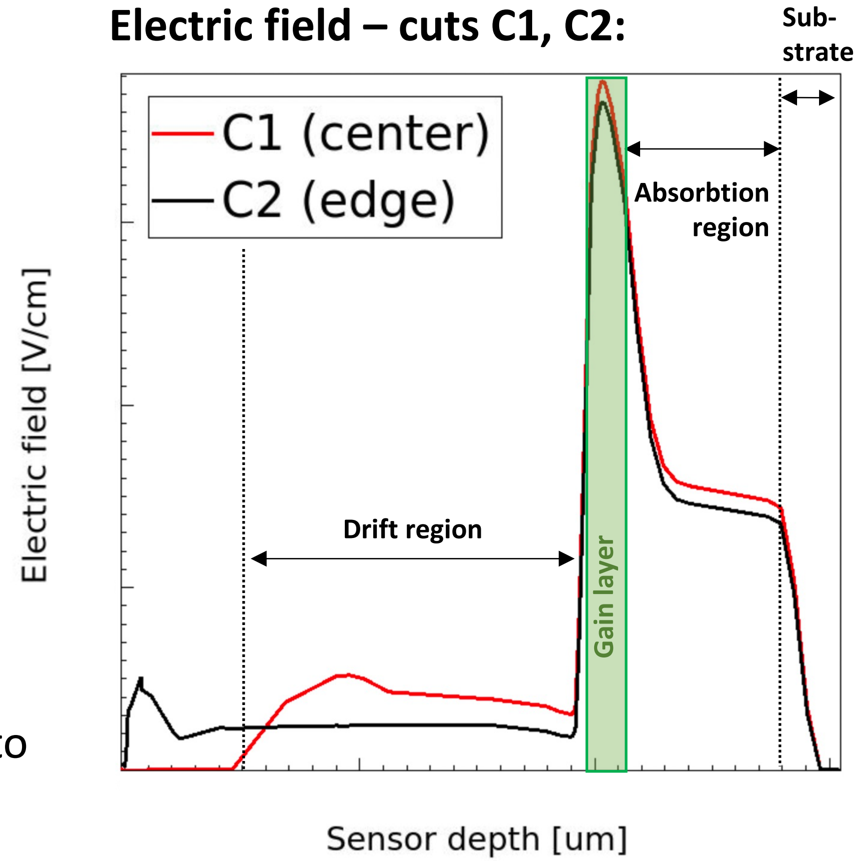
- Highest potential drop in gain layer (as expected)
- Significant potential drop in drift region, less compared to absorbtion region due to increased thickness
- In inter-pixel region:
  - Potential maximum close to surface
  - Reduced potential drop in drift & gain layer region

PicoAD 3D TCAD - **Electric field**

Electric field – 2D map:



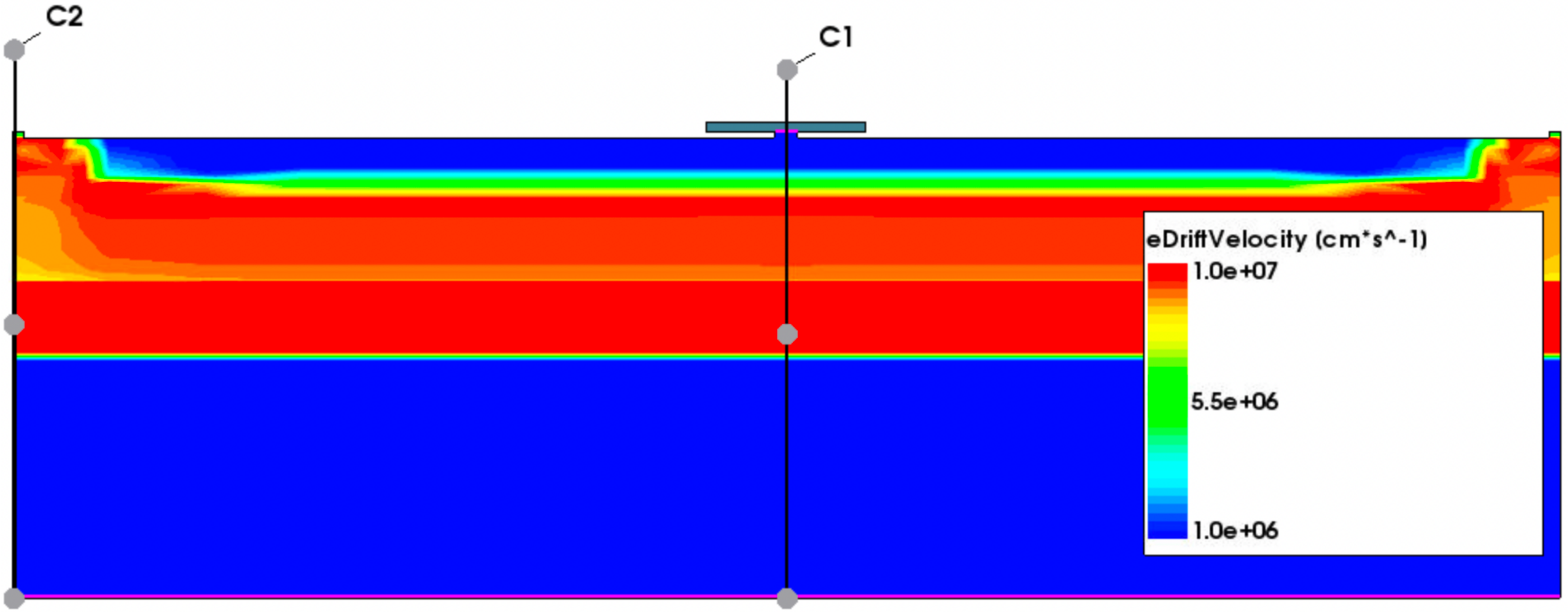
Electric field – cuts C1, C2:



- Highest elecric field in gain layer (as expected)
- Significant electric field in drift region, less compared to absorbtion region due to increased thickness
- In inter-pixel region:
    - Field minimum close to surface
    - Reduced field in drift & gain layer region → lower gain in inter pixel region

Electron drift velocity

Electron drift velocity – 2D map:



→ Electron drift velocity very close to saturation in full pixel volume (note the scale!)
→ Important for precise timing

Weighting potential & field

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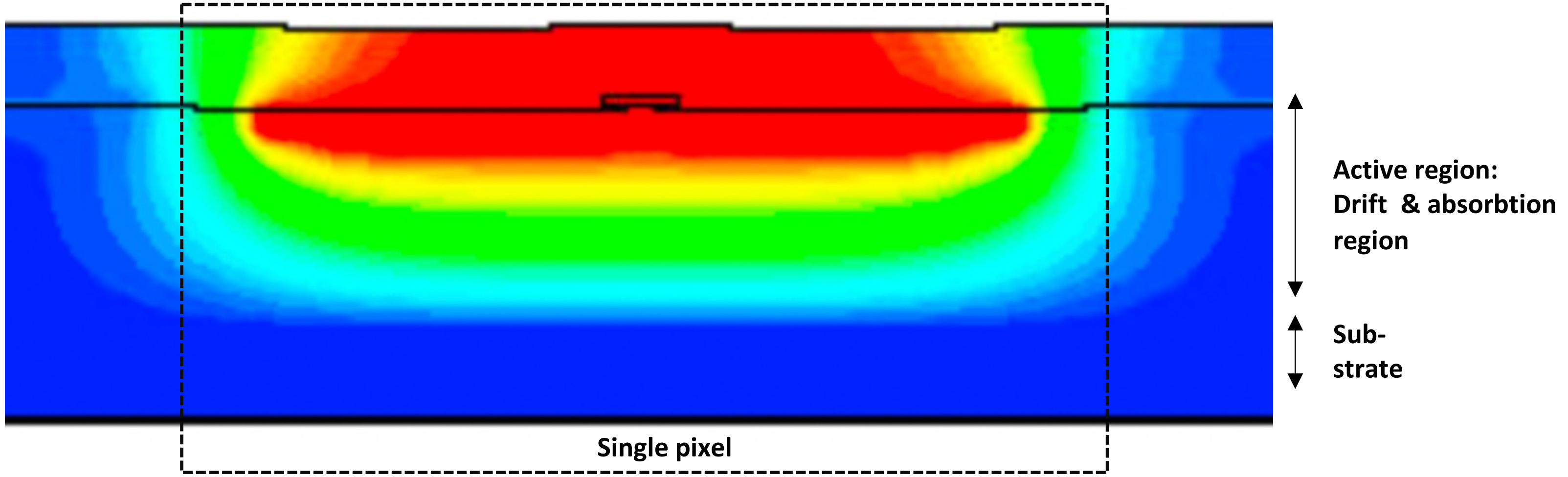
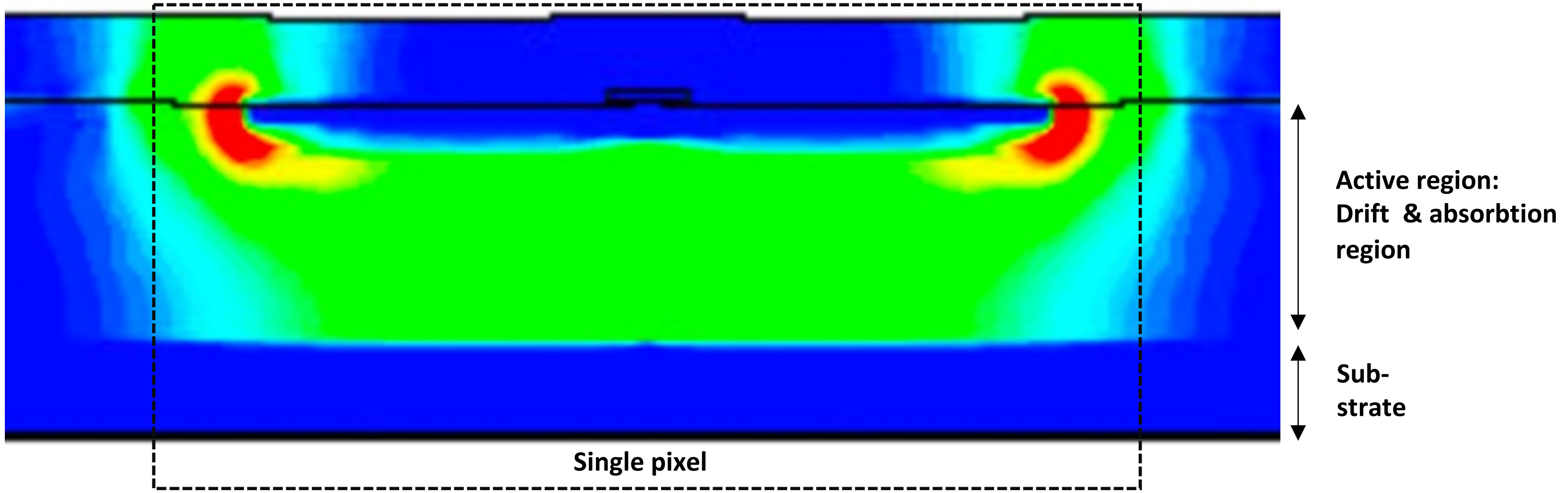
Weighting potential – 2D map:



Weighting field – 2D map:



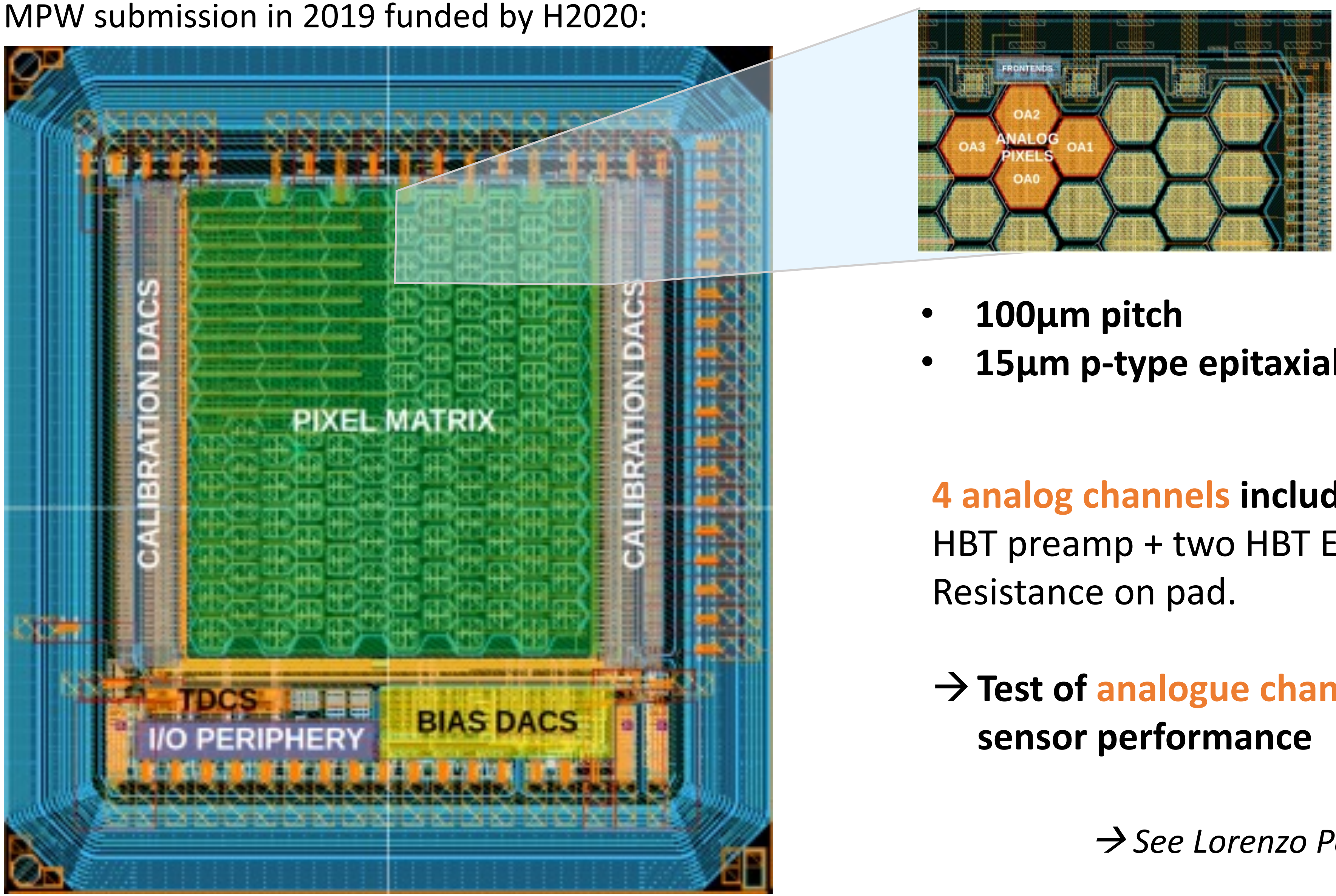
- No impact of gain layer on weighting potential & field
- High weighting field over full active thickeness

→ Important for precise timing

- Highest weighting field in pixel implant corners due to largest potential drop

Analogue pixels of the ATTRACT chip

MPW submission in 2019 funded by H2020:



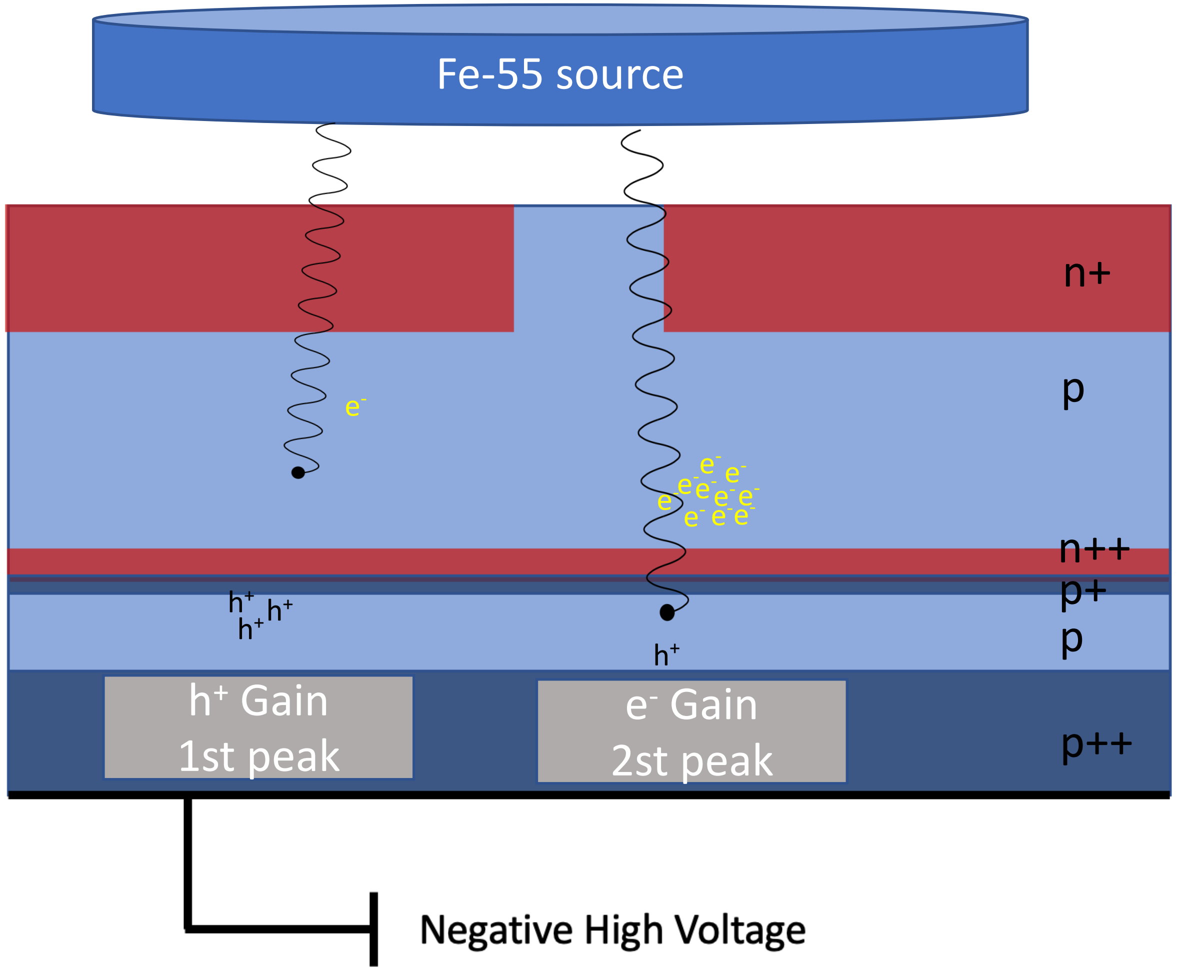
- **100µm pitch**
- **15µm p-type epitaxial layer**

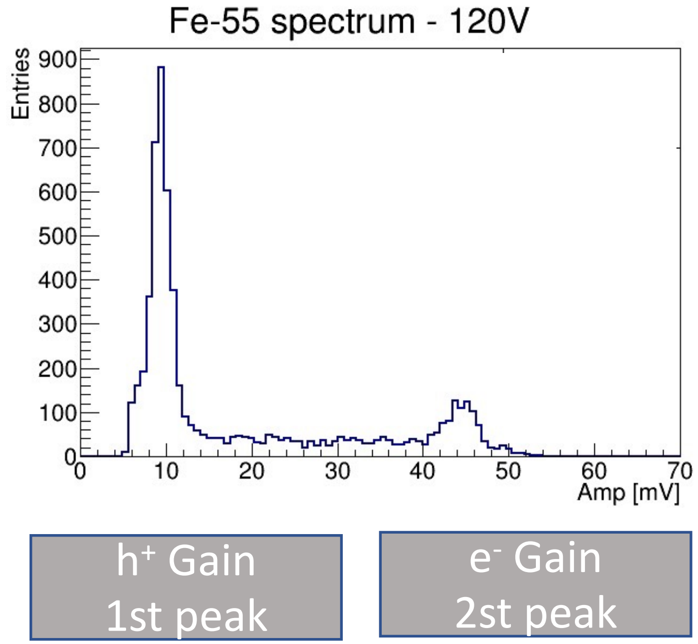
4 analog channels include:
HBT preamp + two HBT Emitter Followers to 500Ω Resistance on pad.

→ **Test of analogue channels to investigate HBT and sensor performance**

→ See Lorenzo Paolozzies talk

55-Fe measurement concept





- Only carriers passing through the gain layer are multiplied
- Two different peaks for e^- and h^+
- Measurements performed in climate chamber to investigate gain as a function of temperature

PicoAD – proof of concept

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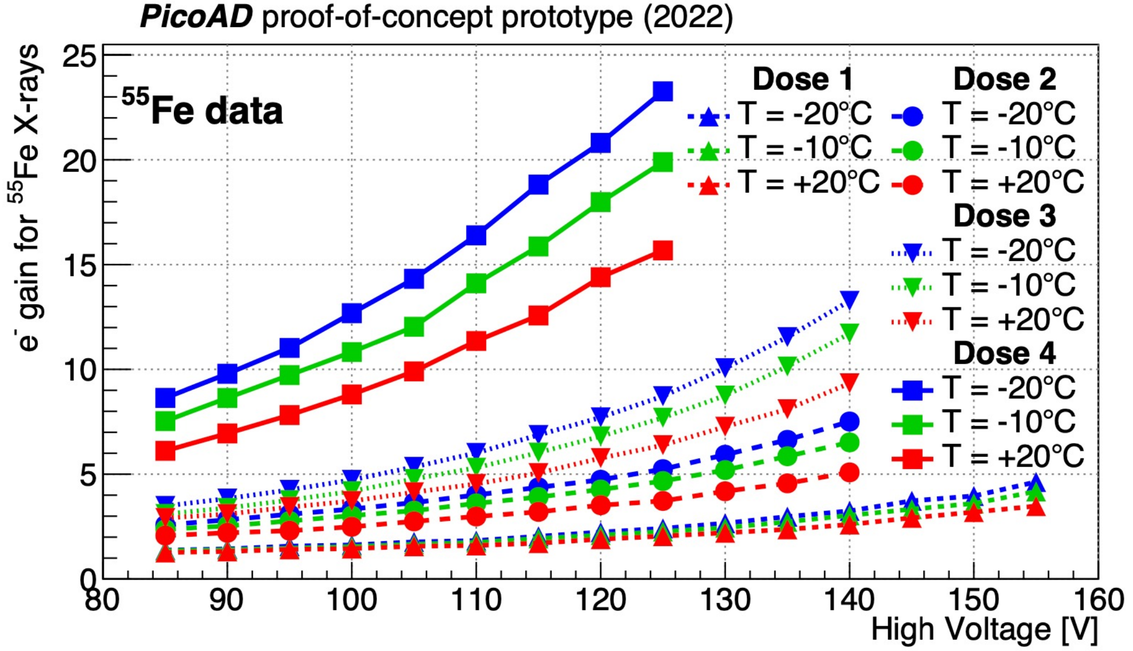
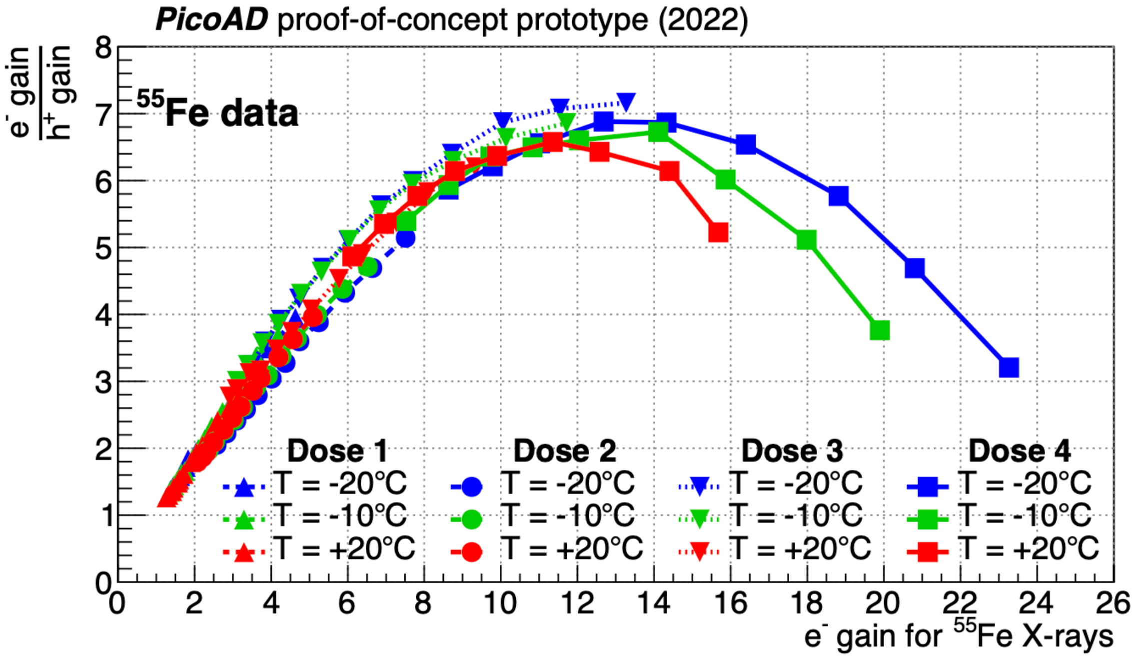
Electron gain, measured with 55Fe:



Ratio of e/h-gain, measured with 55Fe:



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

[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

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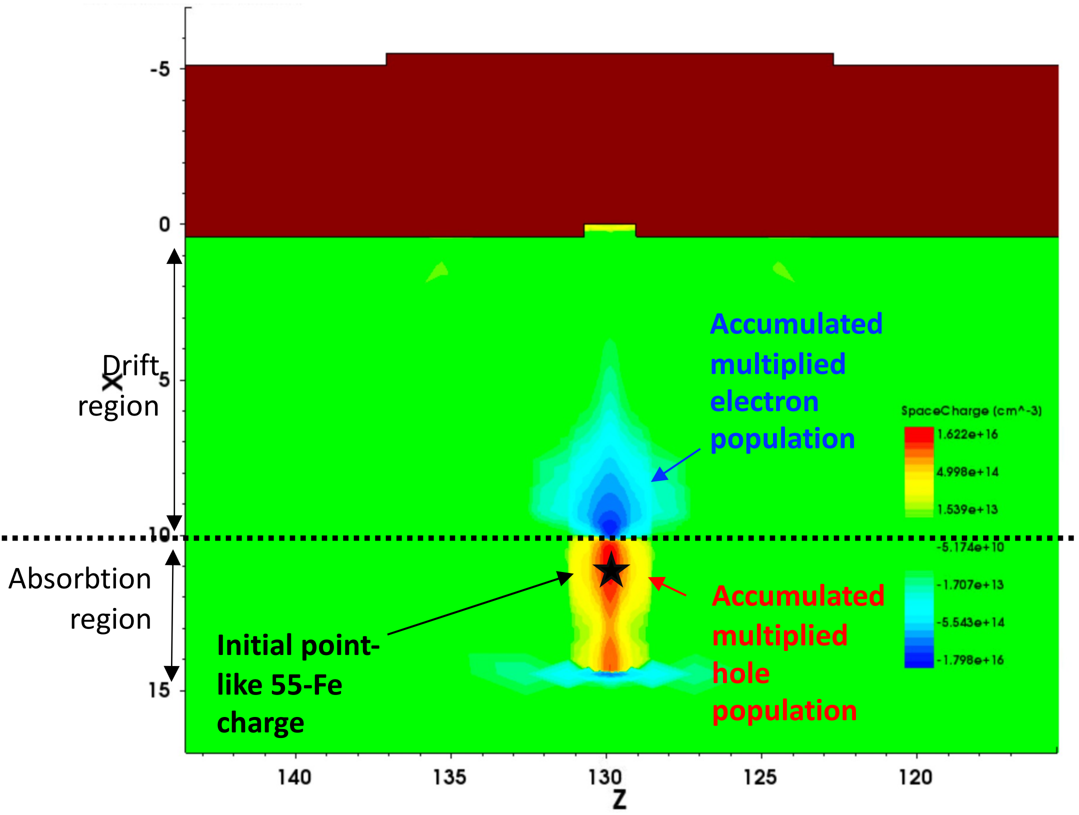
- A gain for 55Fe X-rays of ~20 is reached at HV = 120V and T=-20°C
- Evidence for gain suppression due to space charge effects

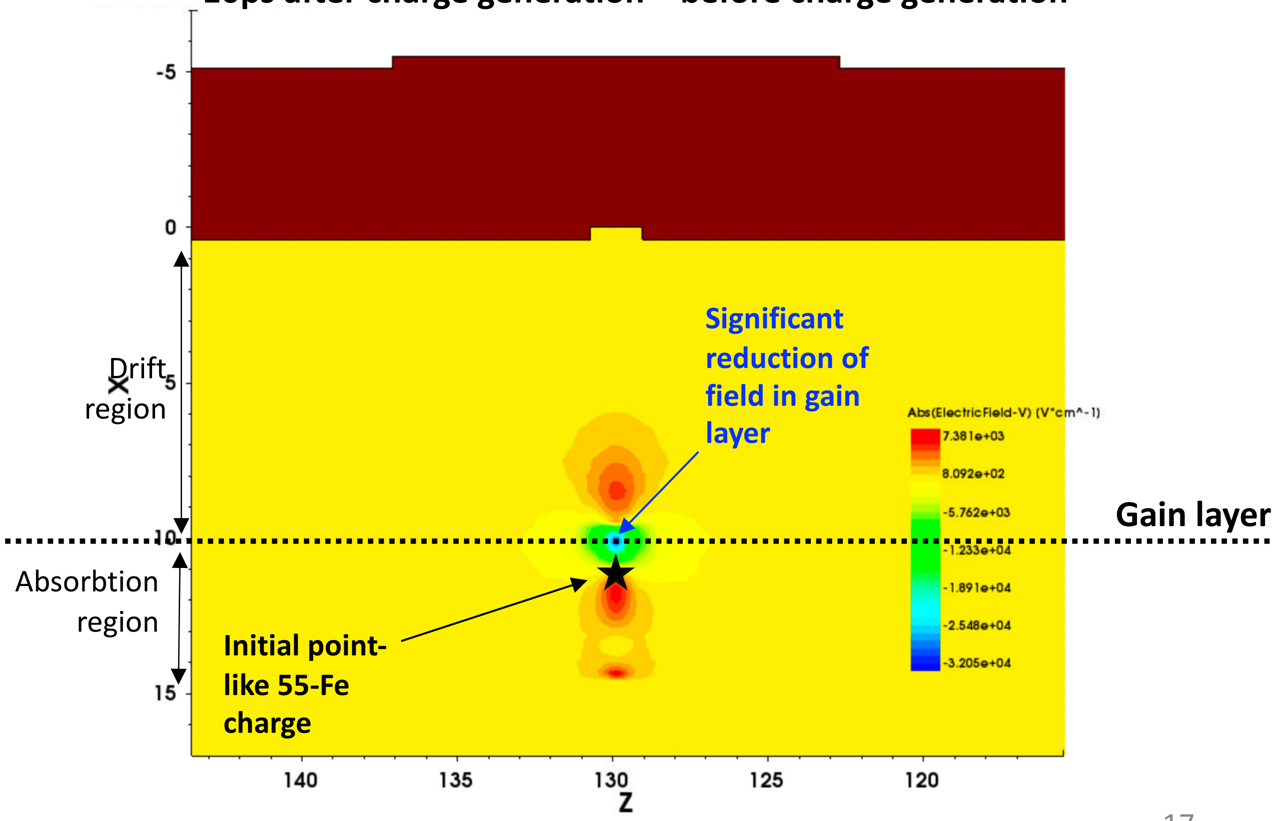
Transient space charge effect

Transient 3D TCAD simulation of point like 55-Fe charge deposition in absorption layer:

Space charge:
10ps after charge generation – before charge generation:

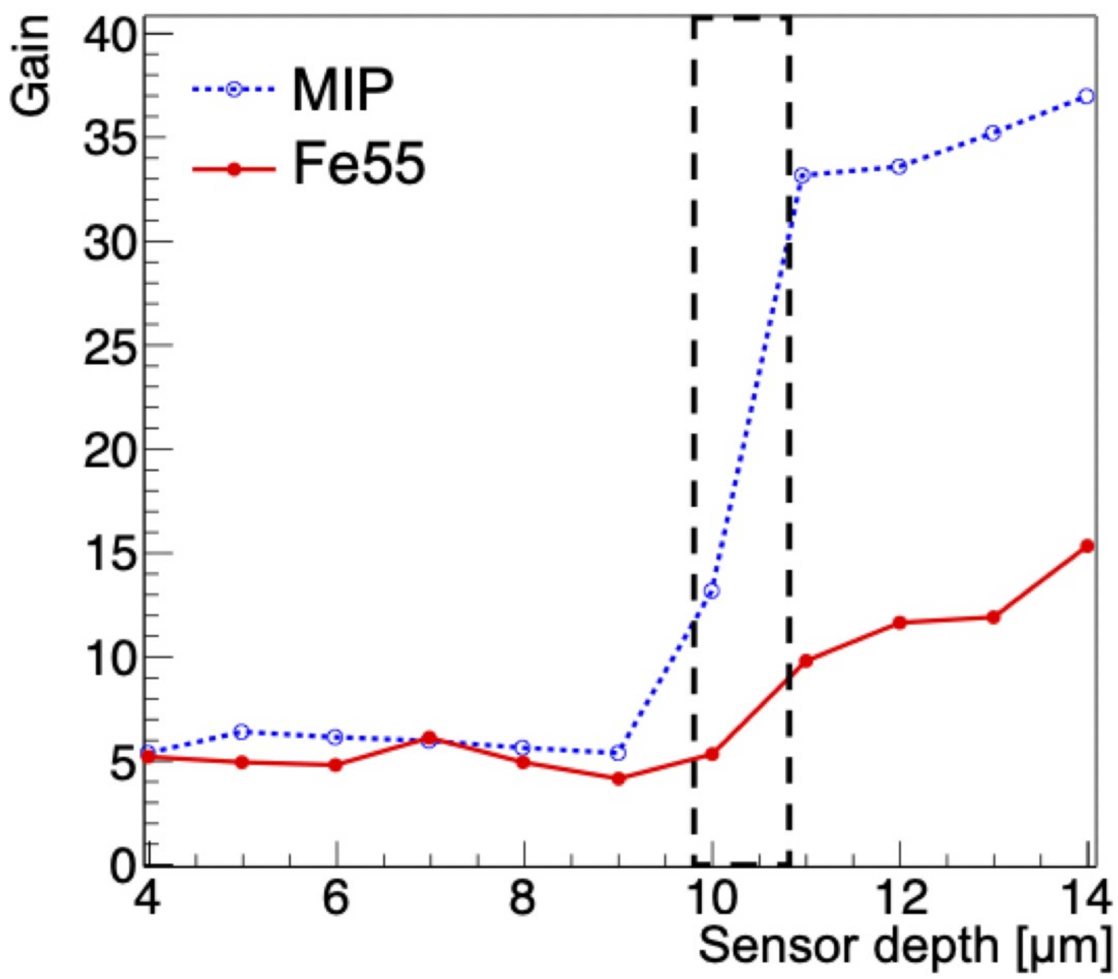


Electric field:
10ps after charge generation – before charge generation



Transient space charge effect

Gain as function of sensor depth for different primary charge carrier densities:



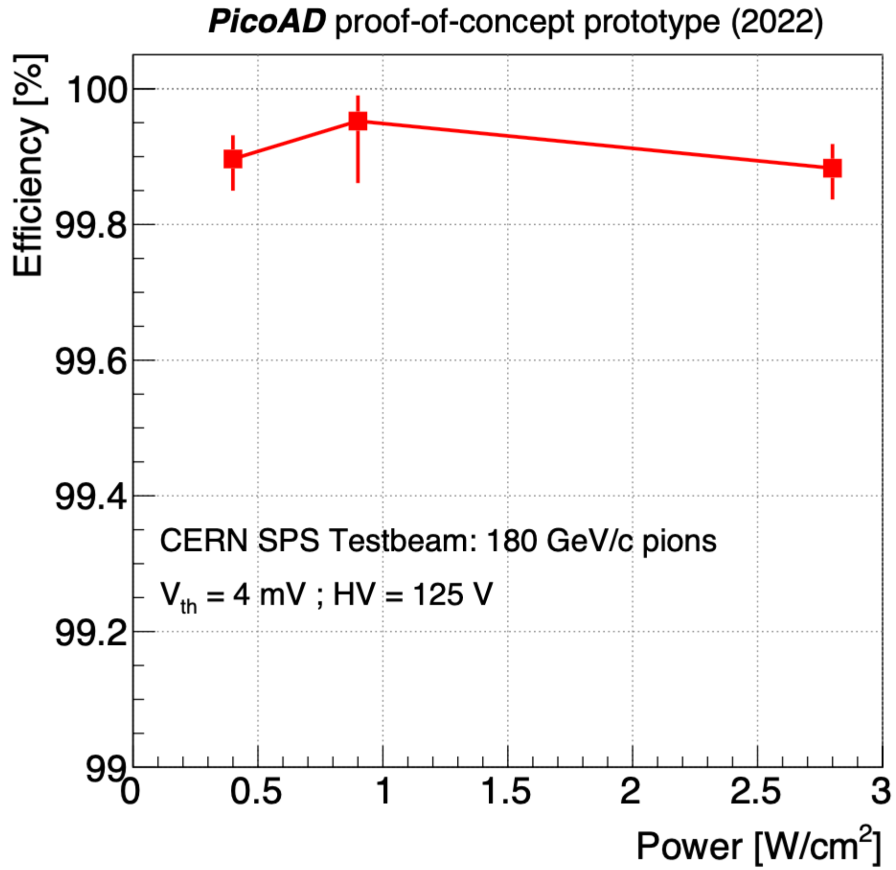
- For high charge carrier densities (Fe55) the gain is suppressed compared to lower charge carrier densities (MIPs).
- Simulated suppression factor of Fe55 w.r.t. MIP charge compatible to calculation of compression factor from test-beam and Fe55 measurements.

→ Measured gain for Fe55 significantly supressed by transient space charge effect.

→ Need of fully self consistent transient TCAD simulations.

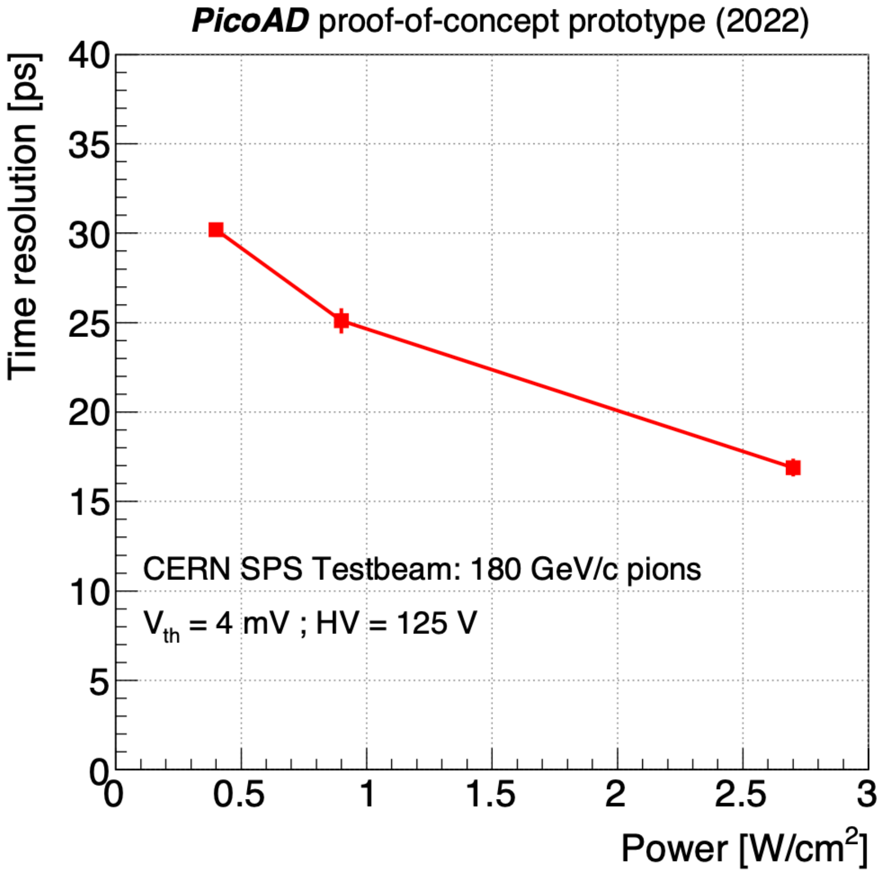
PicoAD – test-beam results

Efficiency vs. power:



→ **Efficiency > 99.8%** for all power consumptions.

Time resolution vs. power:



→ Timing resolution is ≲30 ps, even for the **lowest power consumption.**

→ **Best timing resolution of 17 ps.**

Testbeam Results of the Picosecond Avalanche Detector Proof-Of-Concept Prototype, G. Iacobucci et.al, arXiv:2208.11019v1, submitted to JINST

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PicoAD – test-beam results

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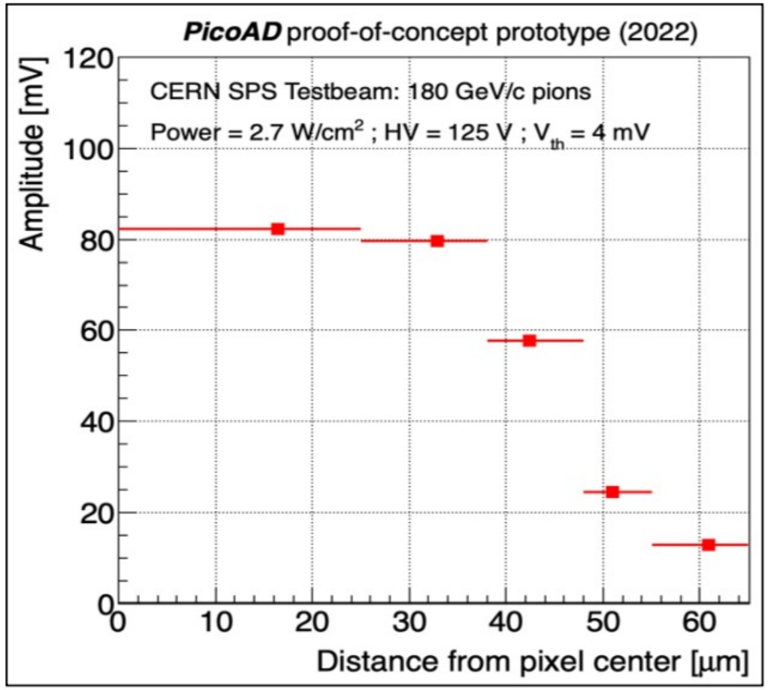
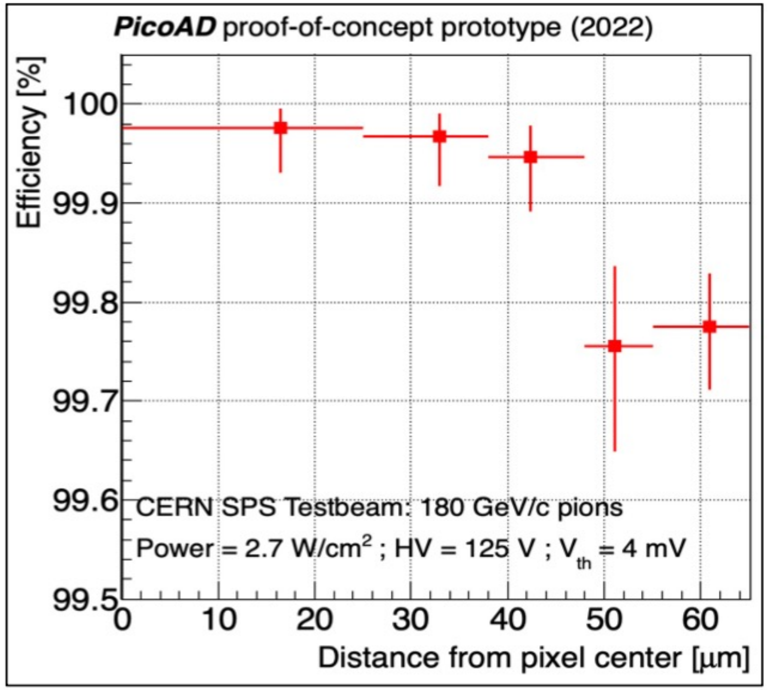
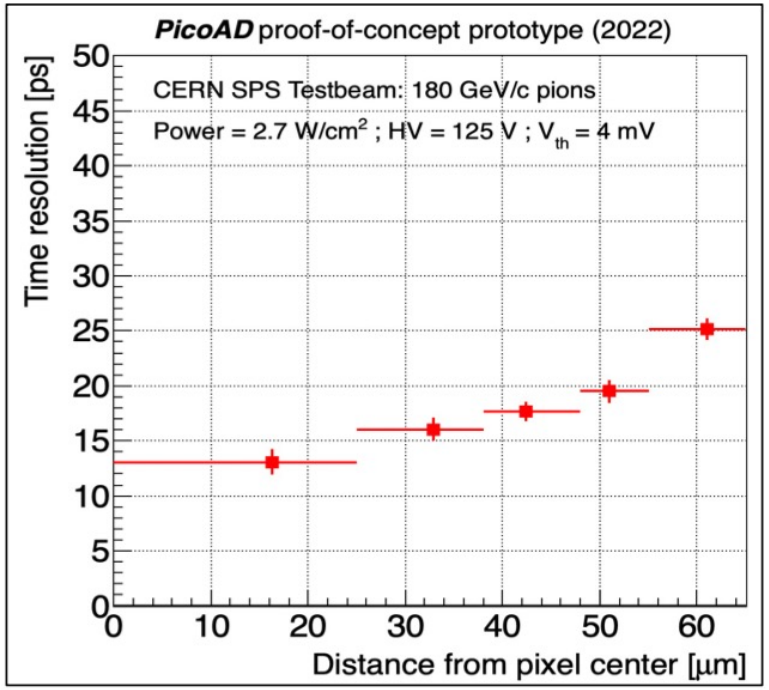
Amplitude vs. distance pixel center:



Efficiency vs. distance pixel center:



Time resolution vs. distance pixel center:



- 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 **13.2 ± 0.8** ps within 25 µm from the pixel center

Next submission – optimisation of drift region

First proof of concept prototype with non-optimal drift region thickness:

- Thickness of epi limited by production process

→ Significant gain variations in inter-pixel regions:

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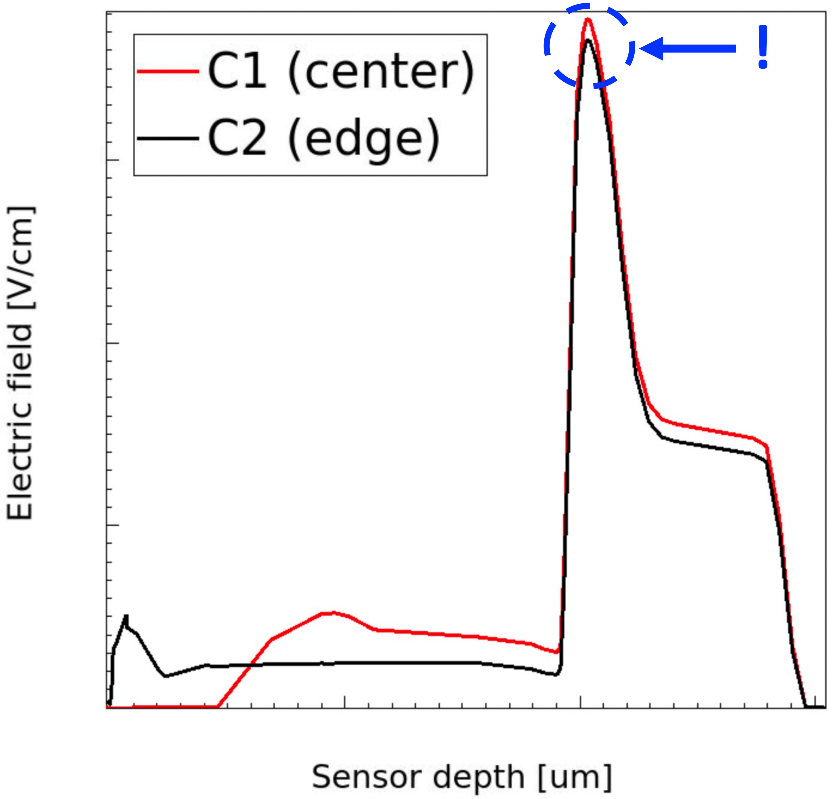
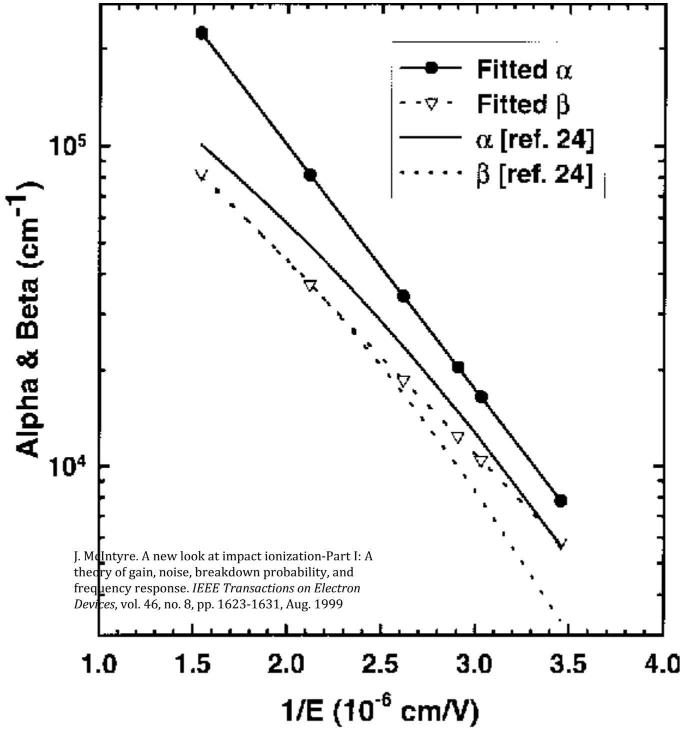
E-field, 1st prototype, 10µm drift region:



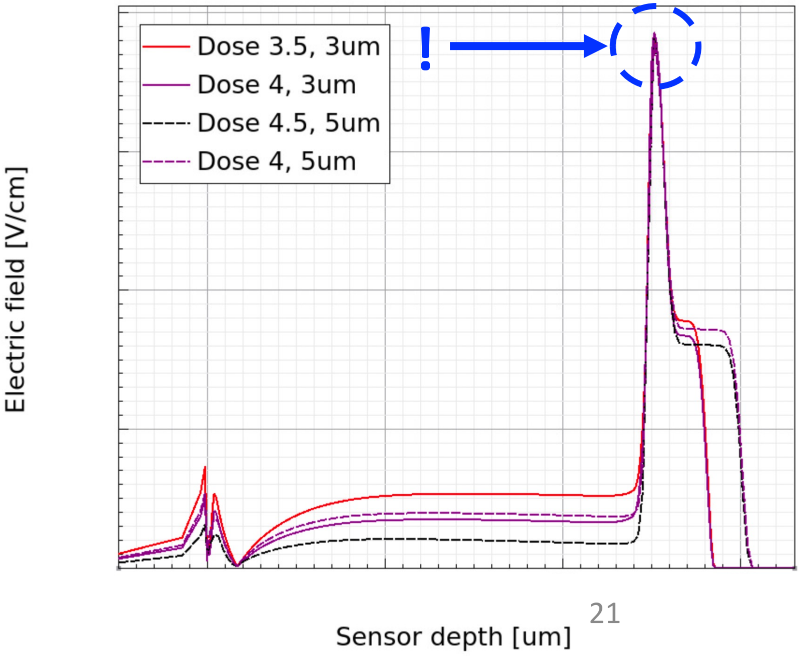
At high voltage, small variations of the electric field in the gain layer result in large gain variations:



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

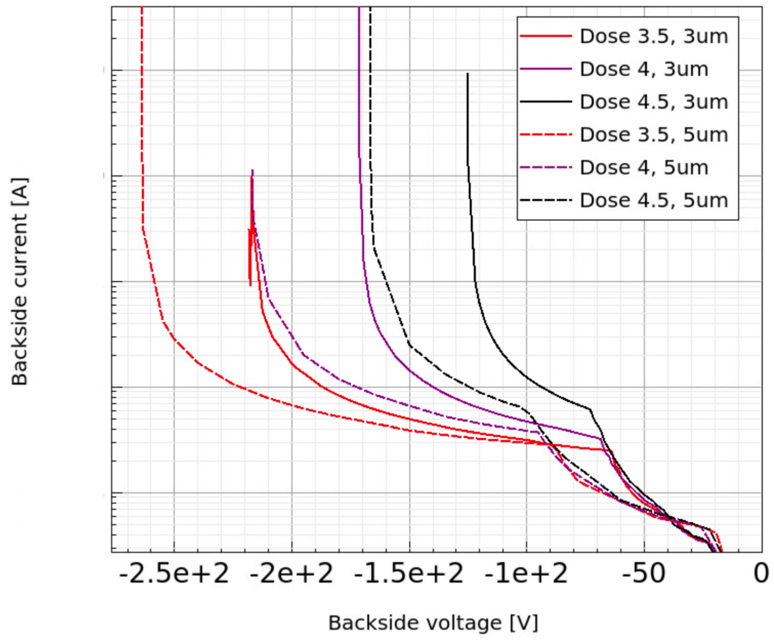
→ Next production of thicker epitaxial for drift region with external foundry

E-field, 2nd prototype, 25µm drift region:

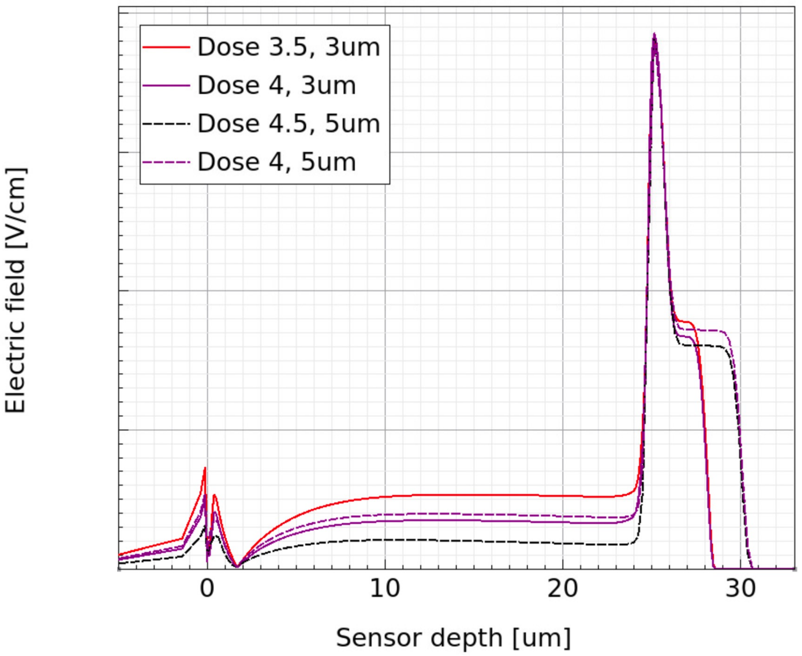


Next submission – optimisation gain layer doses

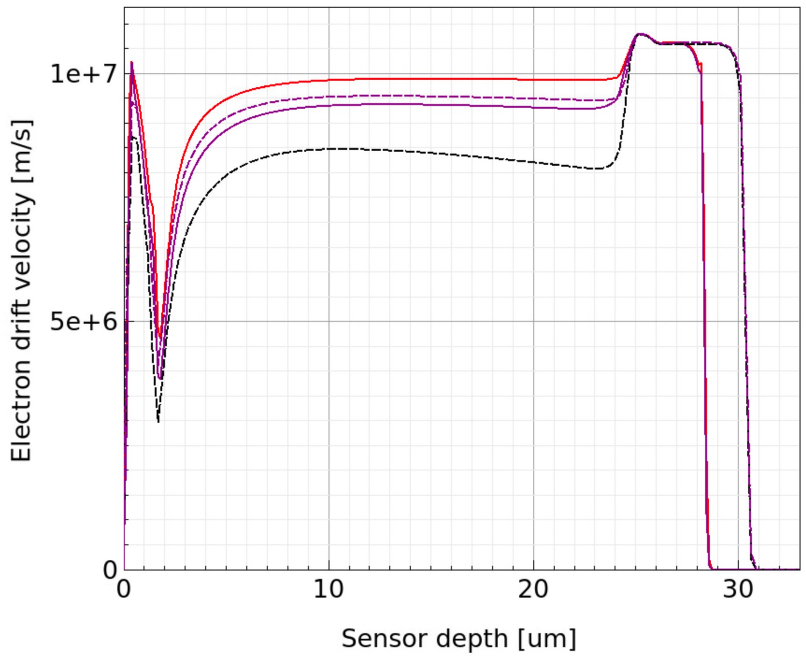
IV curve:



Electric field:



Electron drift velocity:



Higher electron drift velocity for lower dose ← BUT → higher voltage needed for lower dose (general trade-off)

Thinner 1st absorption region considered to investigate charge collection noise:

- Allows for same dose, same field and drift velocity, to operate at lower voltage → margin

PicoAD AllpixSquared + TCAD - setup

Sensor simulaion in 3D TCAD:

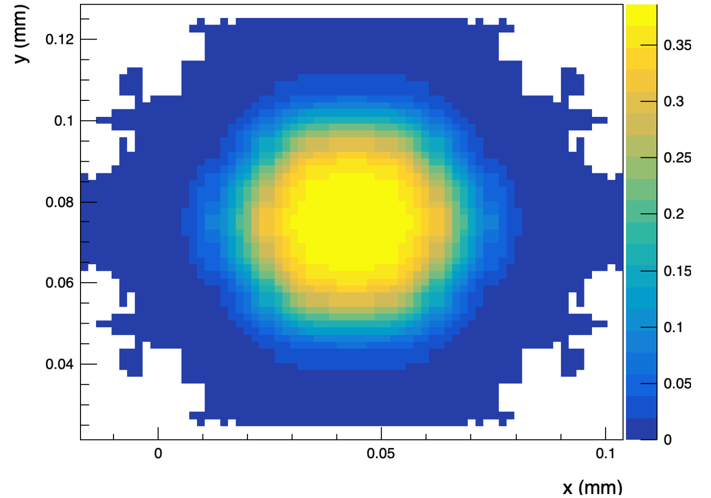
- Electric field map.
- Weighting potential map.
- Doping map.

import →

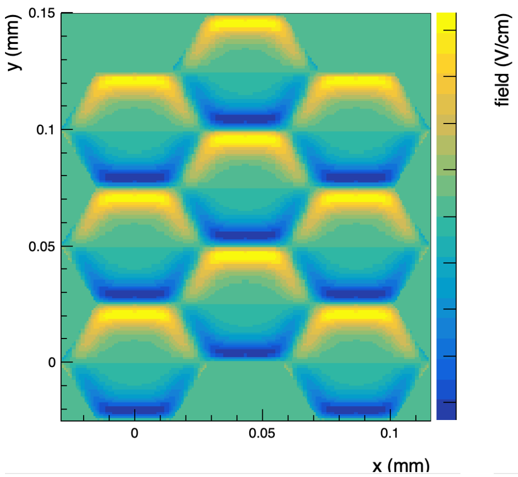
AllpixSquared simulation:

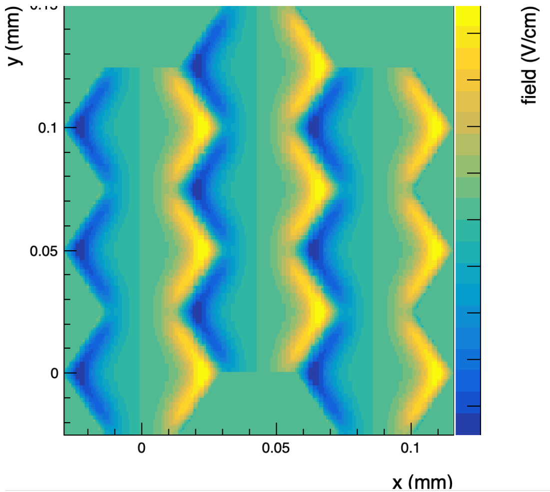
- Simulation of particle interaction with sensor, using Geant4 and sensor simulation from TCAD.
- Calculation of transient sensor response for high statisics.

Hexagonal weighting field map importet from TCAD to AllpixSquared:



Hexagonal lateral electric field maps importet from TCAD to AllpixSquared:

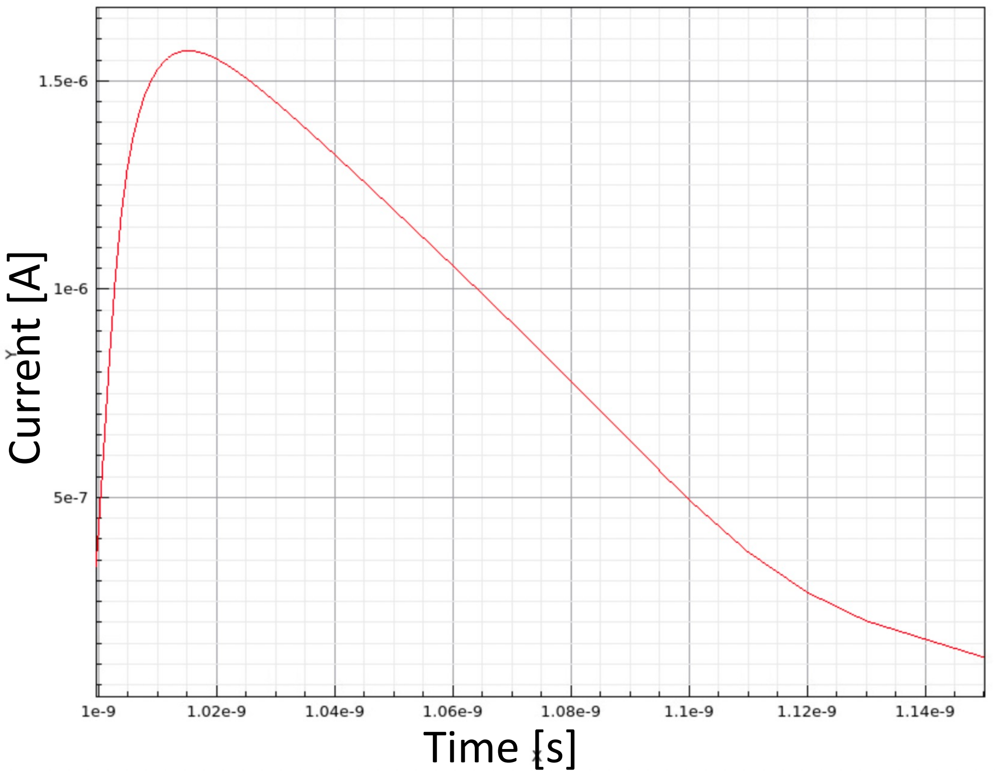




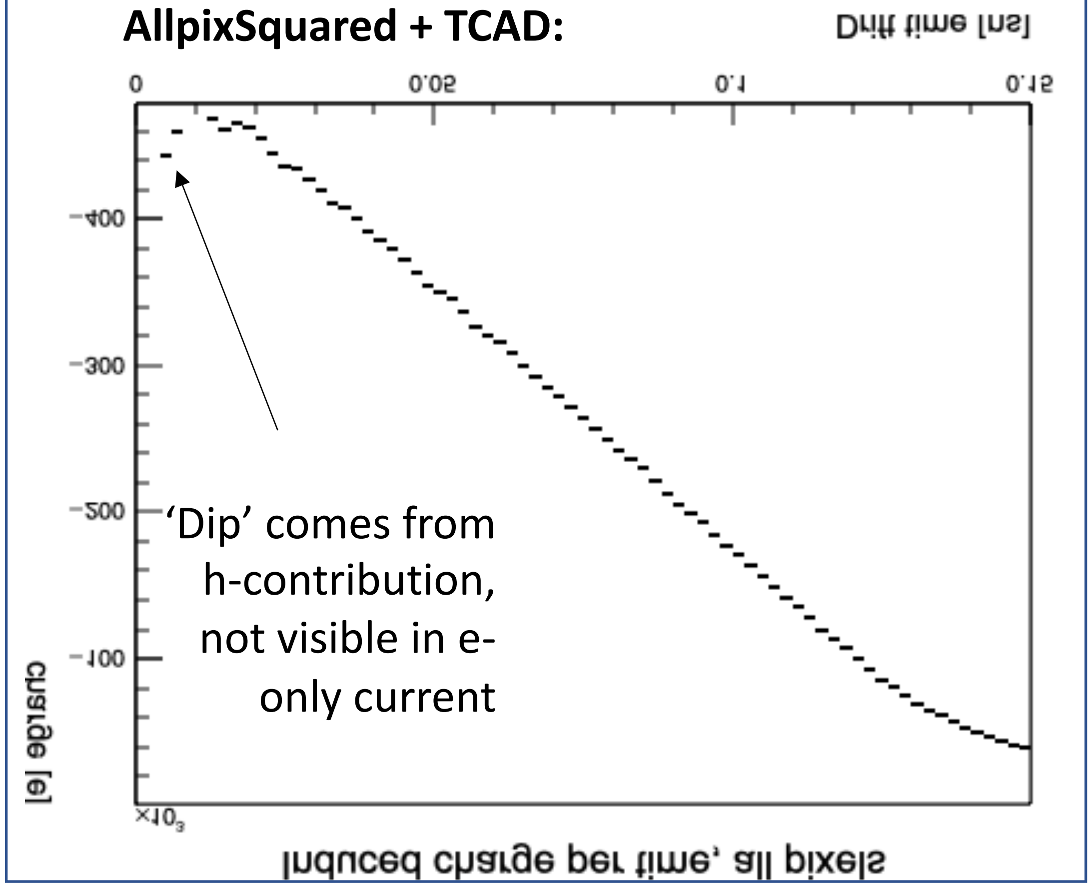
PicoAD AllpixSquared + TCAD - validation

Results for design without gain layer at high sensor bias voltage of -200V:

Transient TCAD:



AllpixSquared + TCAD:



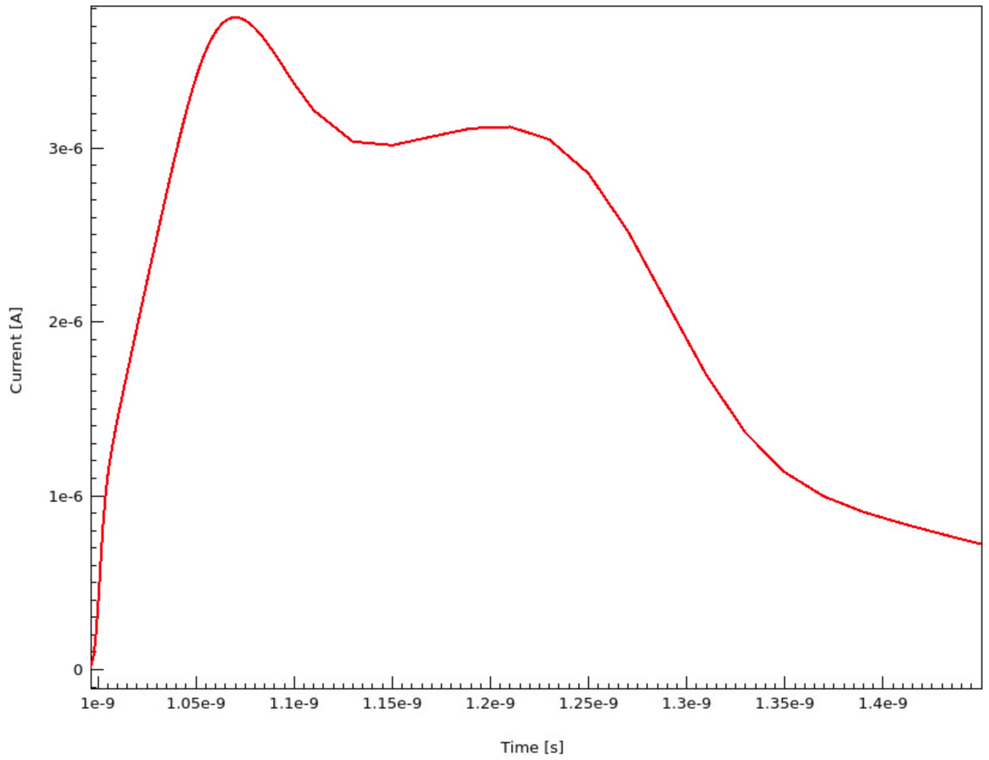
→ Validation of transient simulation for hexagonal large collection electrode design.

PicoAD AllpixSquared + TCAD - validation

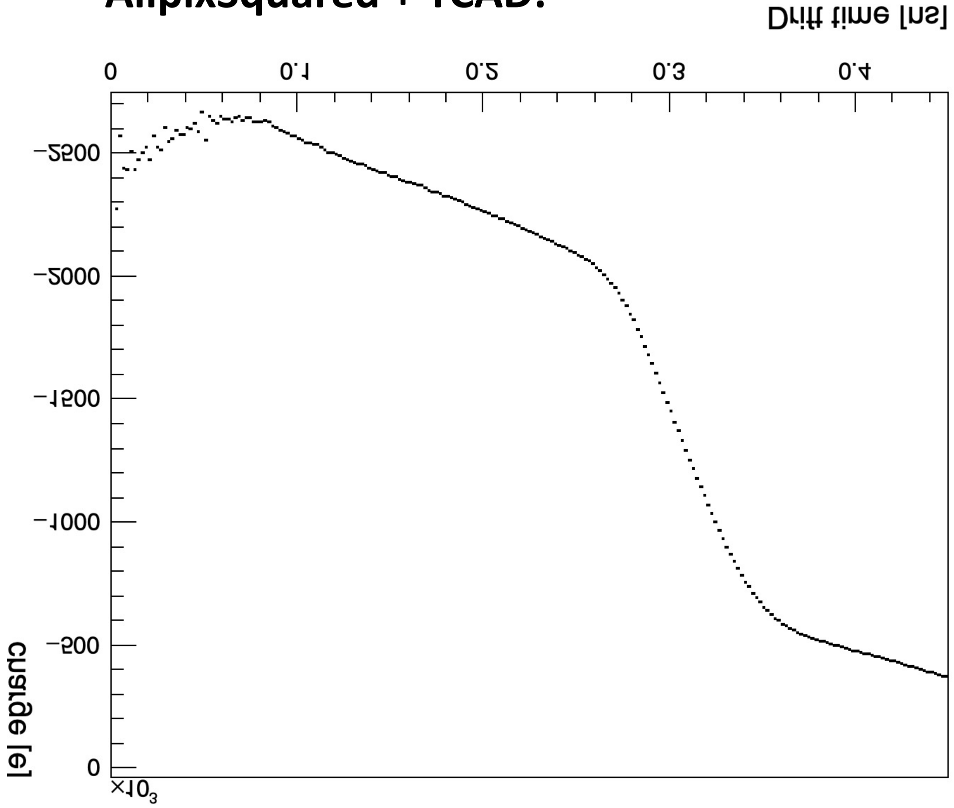
Results for design with gain layer at high sensor bias voltage of -200V:

Select low voltage, just above depletion → most 'challenging' to model

Transient TCAD:



AllpixSquared + TCAD:



→ Main features of current pulse reproduced by AllpixSquared + TCAD setup, finer features missing due to meshing → ongoing work.

Summary

- PicoAD sensor concept developed for **picosecond timing in fully monolithic small pitch designs**.

- 3D TCAD simulations to optimise design and understand physics:
  - Understanding of **transient space charge effect** in multi-junction PicoAD design.
  - Optimisation of geometry.

- AllpixSquared + TCAD simulations to evaluate high statistic transient response:
  - Setup close to being **validated for complex PicoAD sensor** design (hexagonal, large c-electrode, internal deep gain layer).

- **Time resolution of 17ps measured, efficiency > 99.8%.**

Backup

PicoAD – test-beam results

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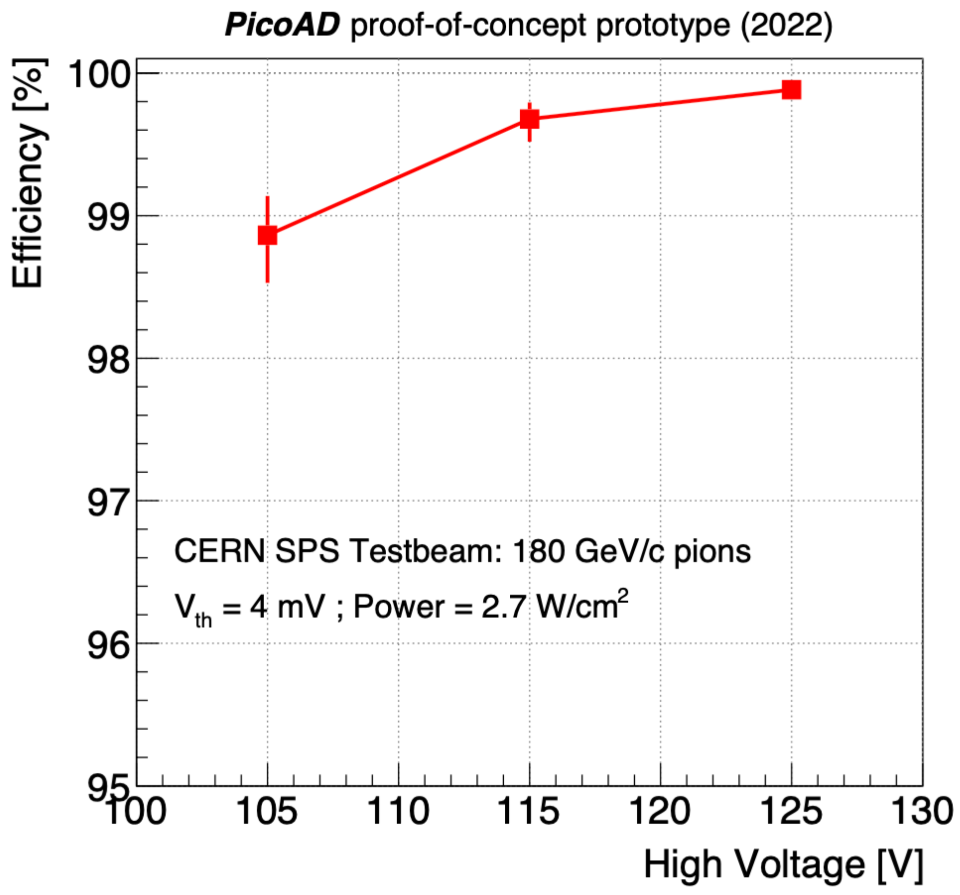
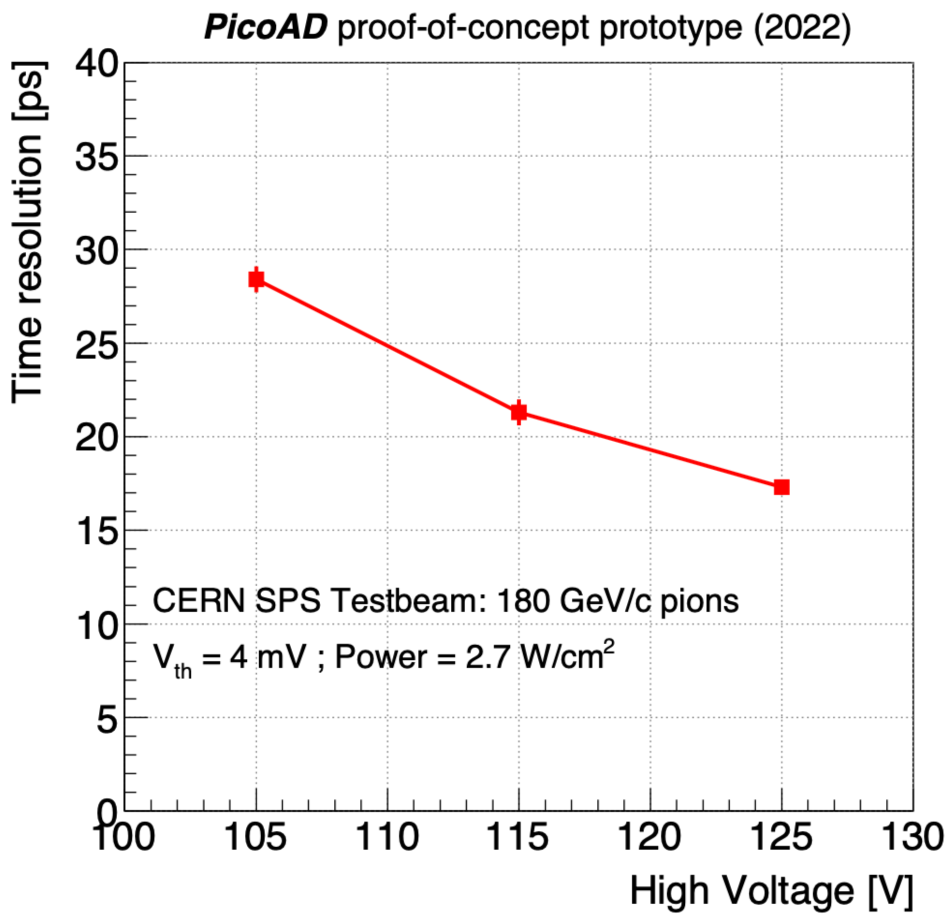
Efficiency vs. sensor bias voltage:



→ **Efficiency drops to ~ 99%** at sensor bias voltage of -105V

Time resolution vs. sensor bias:



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→ **Best timing resolution of 17 ps**