TRENTO Workshop, March 2022

Magdalena Munker on behalf of the MONOLITH team.

Picosecond time stamping in fully monolithic highly granular silicon pixel detectors

funded by the H2020 ERC Advanced grant 884447

MONOLITH

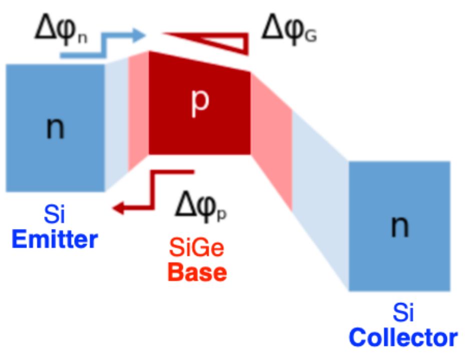
UNIVERSITÉ DE GENÈVE

FACULTY OF SCIENCE
Department of Nuclear and Particle Physics

European Research Council
Established by the European Commission

SiGe BiCMOS front end technology

NPN SiGe HBT
(depleted regions in light colors)
from wikimedia



SiGe HBT = BJT with Germanium as base material:
→ higher doping in base possible
→ thinner base
→ **reduced base resistance R_b**

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

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 with:

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

→ Implemented in silicon sensor
→ Used for pre-amplifier and drivers

The MONOLITH team at UniGe

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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

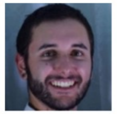
Magdalena Munker
- Sensor design
- Laboratory test

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

Main research partners:

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Mehmet Kaynak
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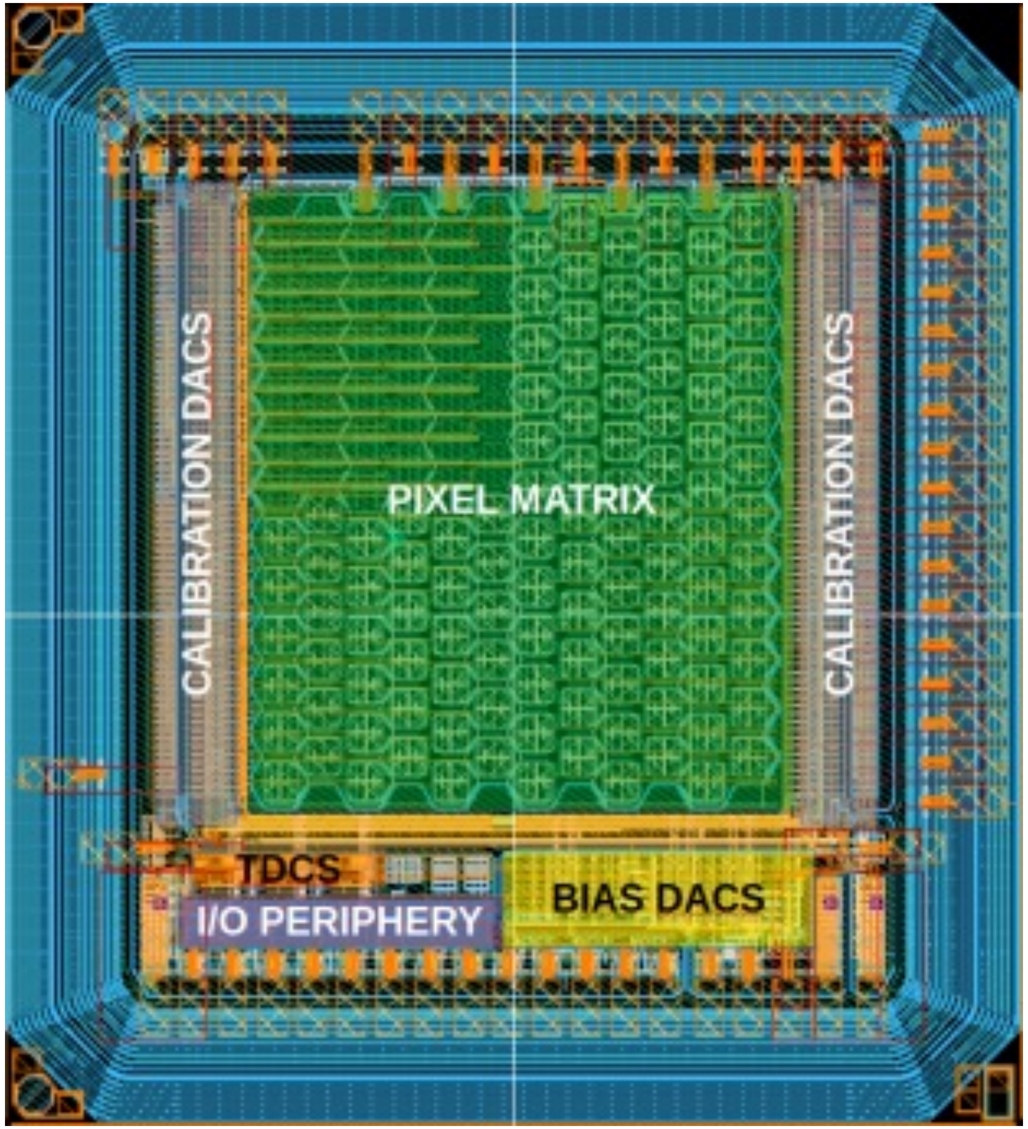
Bernd Heinemann
IHP Mikroelektronik

Wide range of activities:
Chip design and simulation, sensor design and simulation, sensor + chip testing in probe station, climate chamber, test-beam,…

https://www.unige.ch/dpnc/en/groups/giuseppe-iacobucci/research/monolith-erc-advanced-project/

The ATTRACT prototype

MPW submission in 2019 funded by H2020:



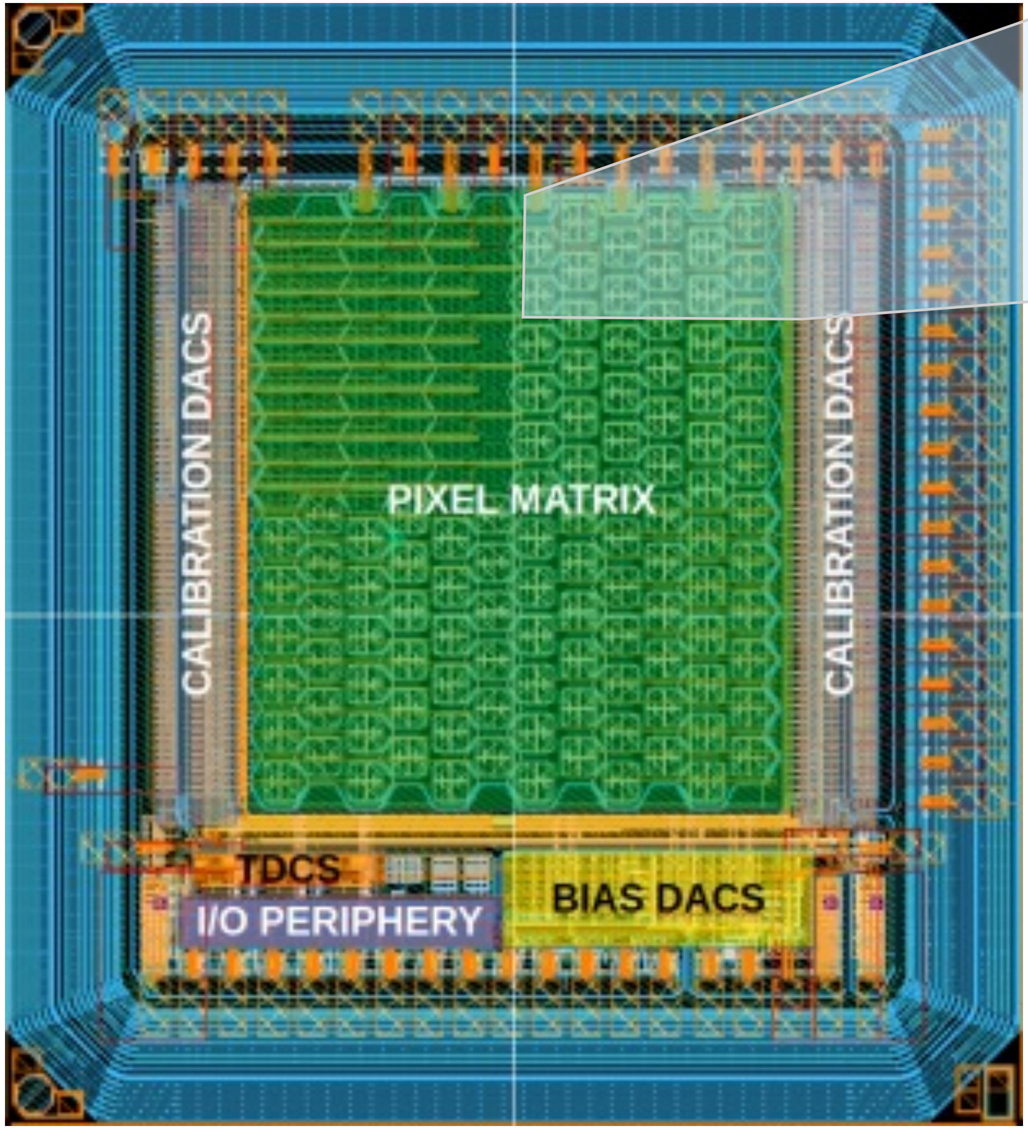
- **Hexagonal pixels with large collection electrode:**
  - Homogenous drift field
  - Reduced breakdown probability at pixel implant corners
- **100µm pitch**
- **25µm p-type epitaxial layer**

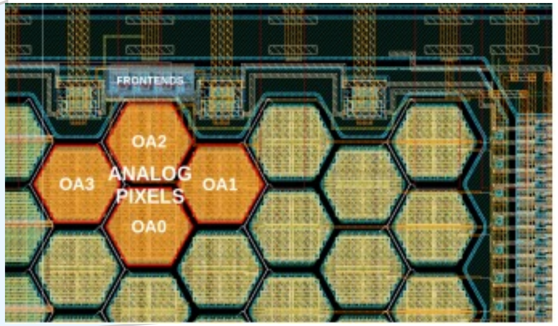
Four Matrices:

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

Analogue pixels of the ATTRACT chip

MPW submission in 2019 funded by H2020:





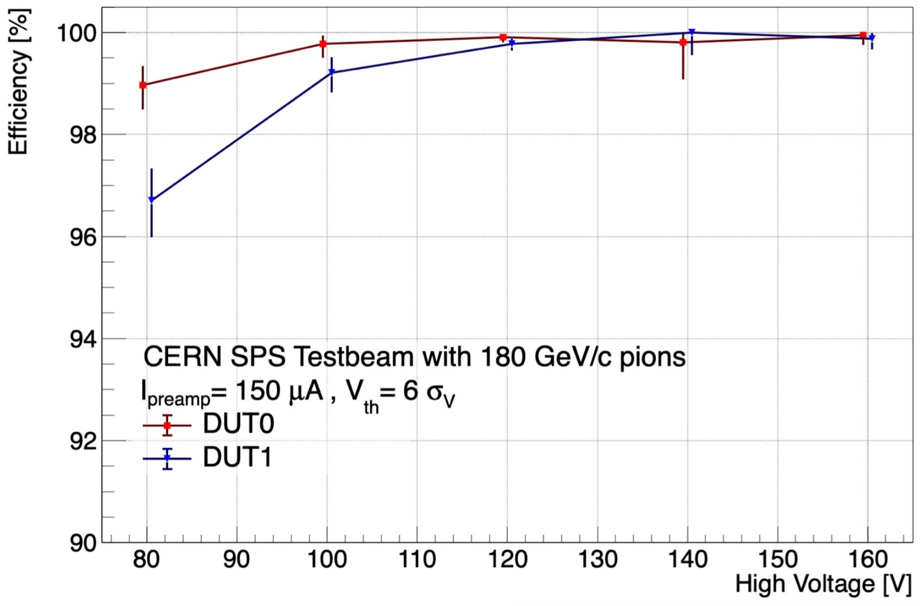
4 analog channels include:
HBT preamp + two HBT Emitter Followers to 500Ω Resistance on pad.

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

Test beam results – performance for different sensor bias

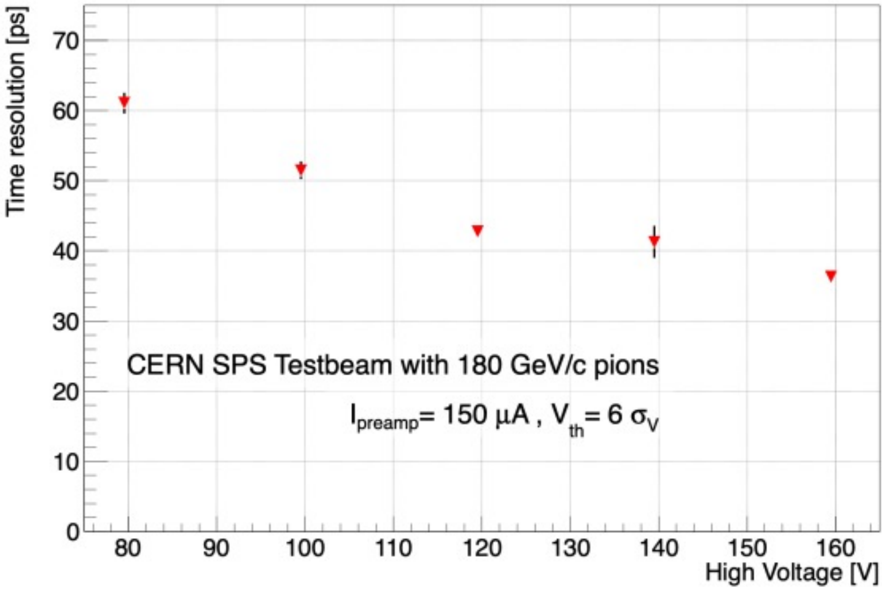
CERN SPS 180GeV pion beam, FEI4 Telescope ($\sigma_x \sim 10\mu m$ $\sigma_y \sim 15\mu m$), 2 DUTs for timing reference
https://doi.org/10.1088/1748-0221/17/02/P02019

Efficiency as a function of high voltage:



- Large efficient operation range
- Differences of DUTs due to different threshold values

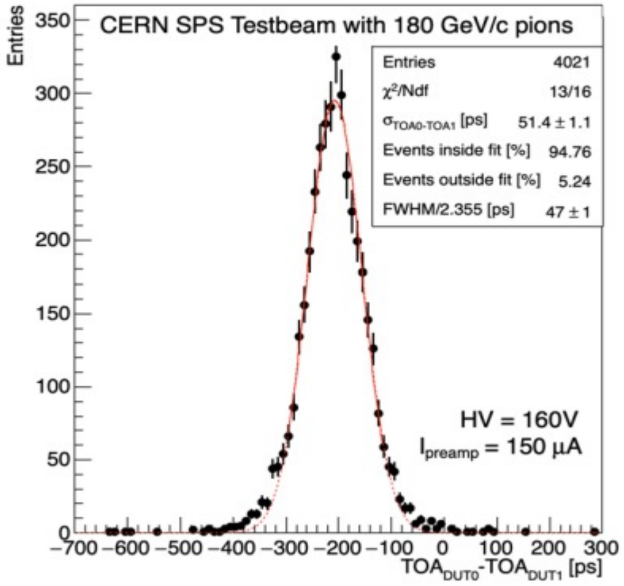
Time resolution as a function of high voltage:



$$\sigma_t = \frac{\sigma_{TOA0\text{-}TOA1}}{\sqrt{2}} = (36.4 \pm 0.8)\text{ps}$$

Without gain layer

Timing residual:

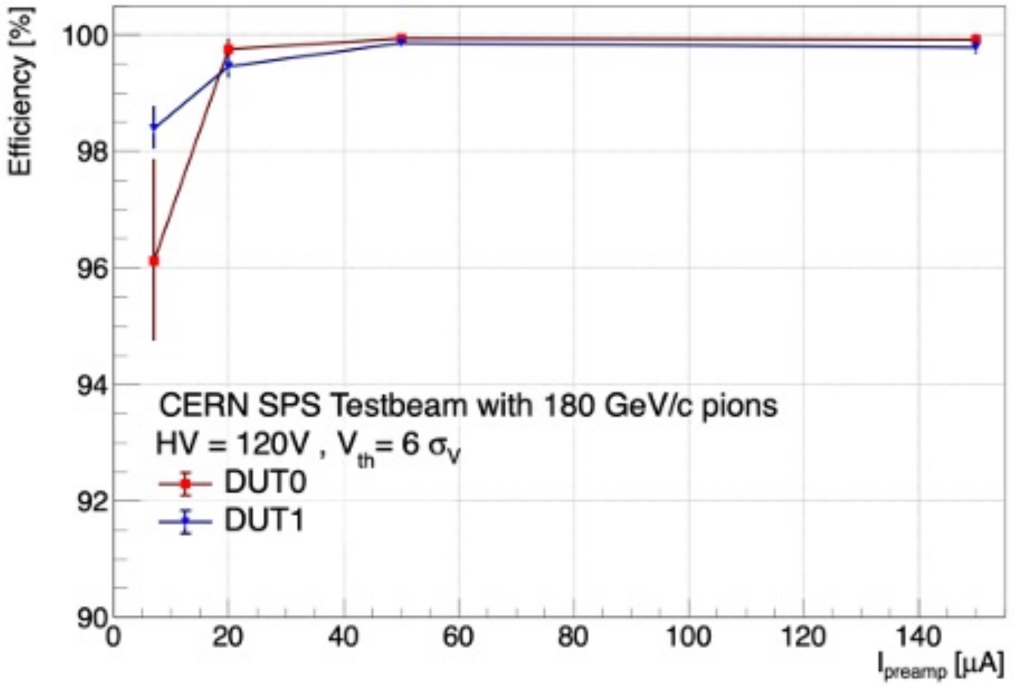


- Gaussian distribution of timing residual

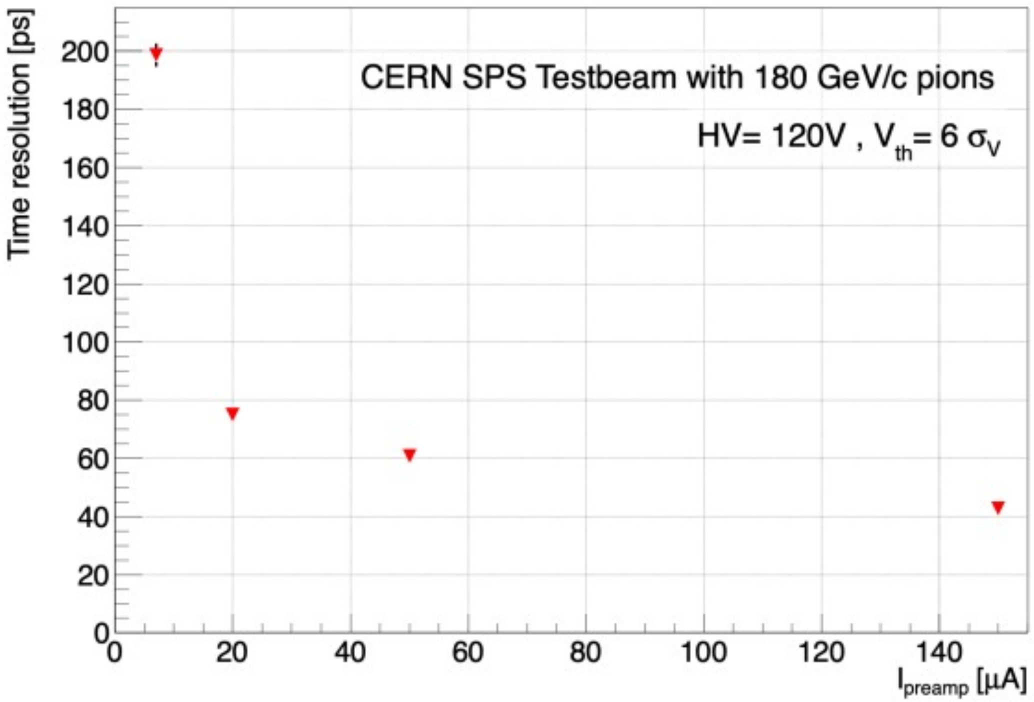
Test beam results – performance for different pre-amp current

CERN SPS 180GeV pion beam, FEI4 Telescope ($\sigma_x \sim 10\mu m$ $\sigma_y \sim 15\mu m$), 2 DUTs for timing reference
https://doi.org/10.1088/1748-0221/17/02/P02019

Efficiency as a function of preamplifier current:



Time resolution as a function of preamplifier current:



- Power consumption dominated by preamplifier current
- Efficiency > 99.5% and time resolution below 80ps even at low preamplifier current of 20μA

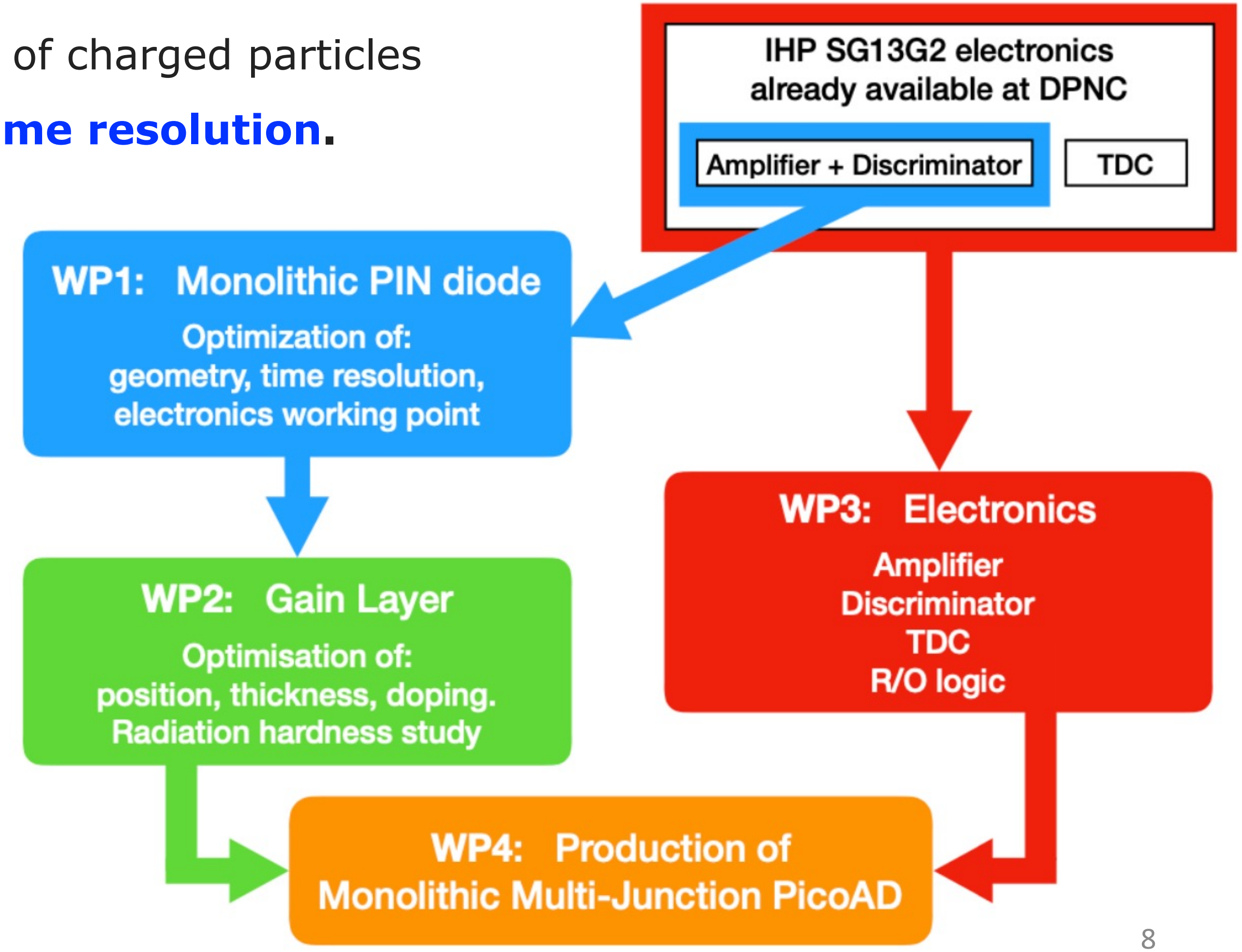
The MONOLITH ERC Advanced Project

5 year ERC project to develop:

Monolithic silicon sensor

able to measure precisely the 3D spatial position of charged particles

while providing at the same time **picosecond time resolution.**



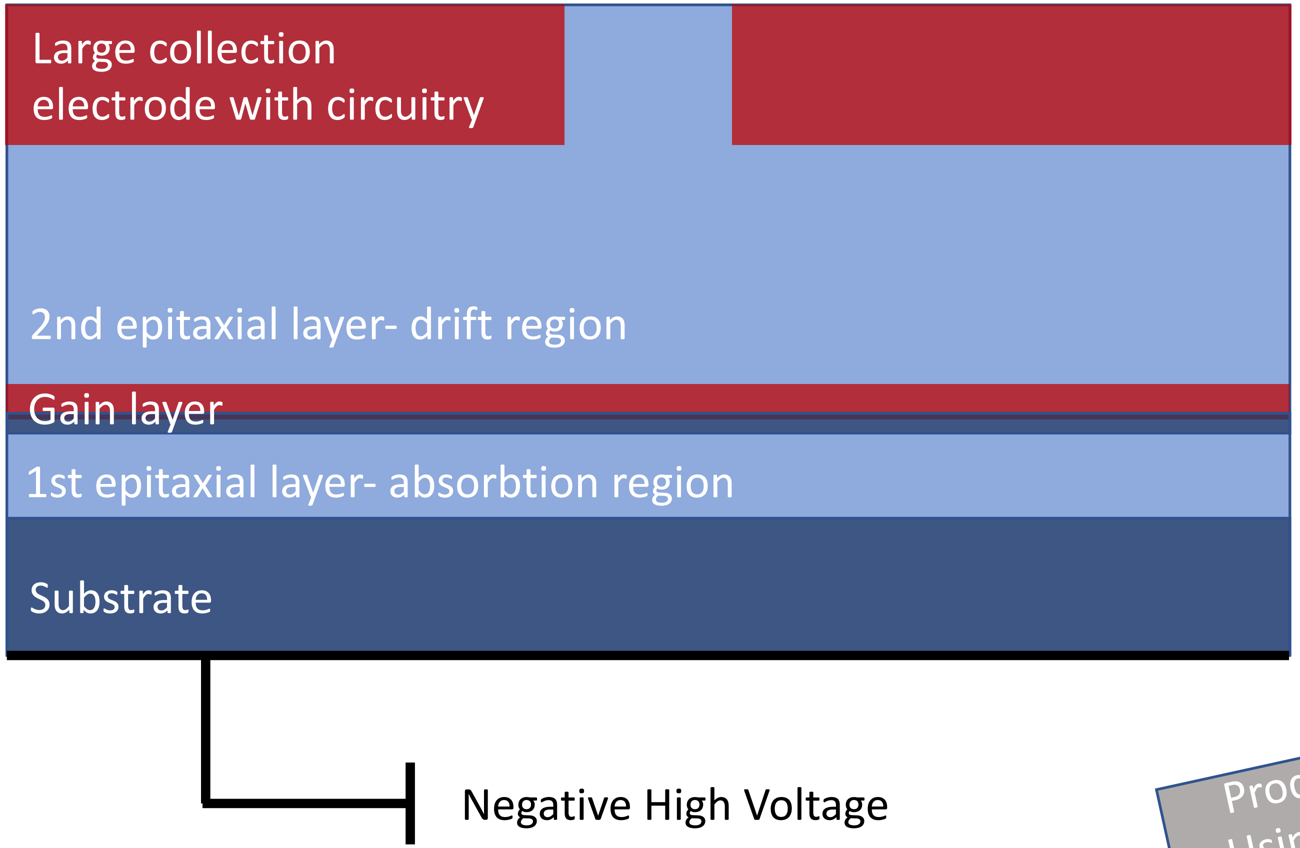
H2020 ERC Advanced grant 884447,
July 2020 - June 2025

https://www.unige.ch/dpnc/en/groups/giuseppe-iacobucci/research/monolith-erc-advanced-project/

PicoAD sensor concept

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

Schematic view of PicoAD sensor concept:

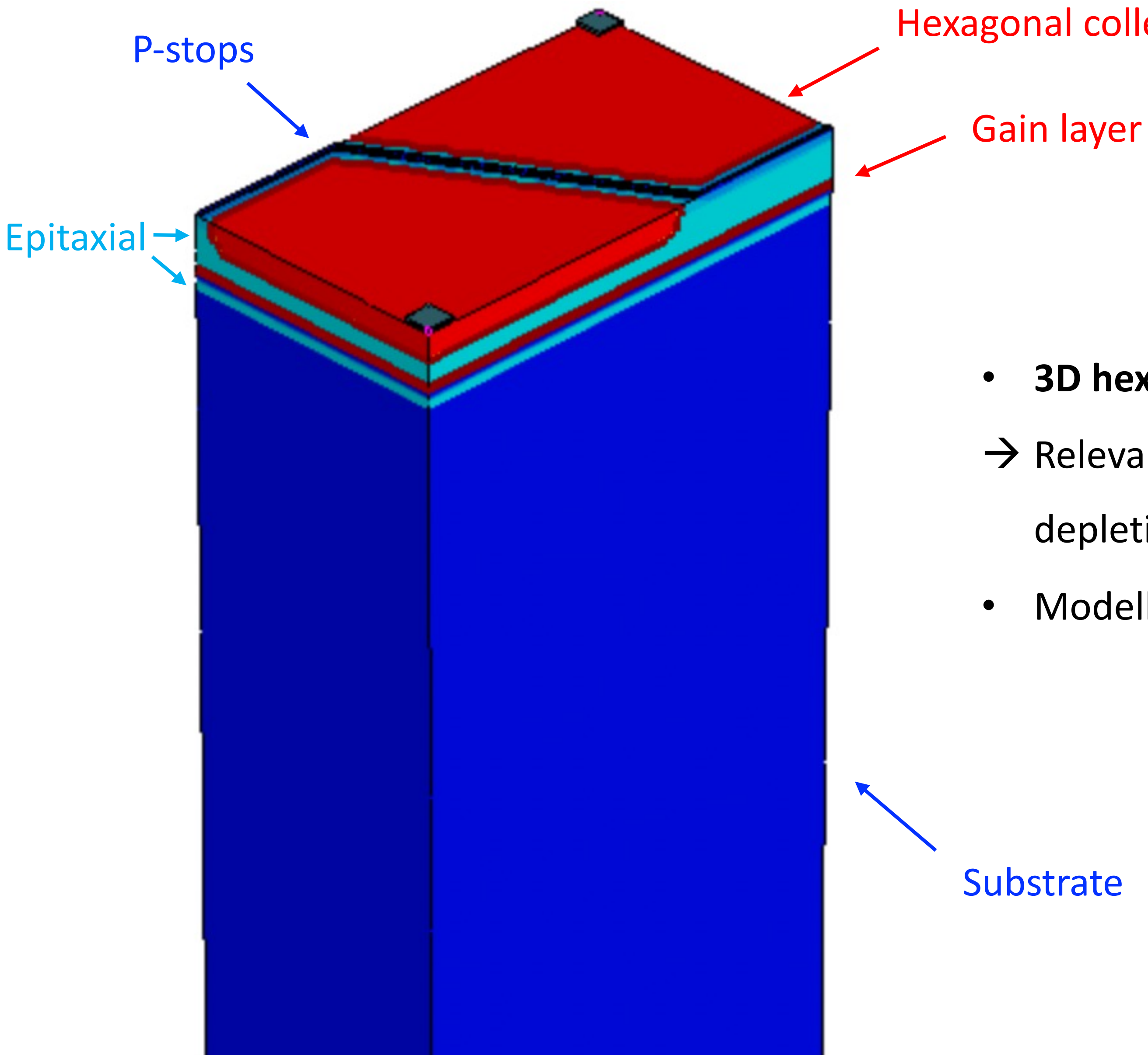


Placement of gain layer deep inside sensor:

- De-correlation from pixel implant size/geometry
  → High pixel granularity possible (*spatial precision*)
- Only small fraction of charge gets amplified
  → Reduced charge fluctuations (*timing precision*)

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

PicoAD – 3D TCAD structure



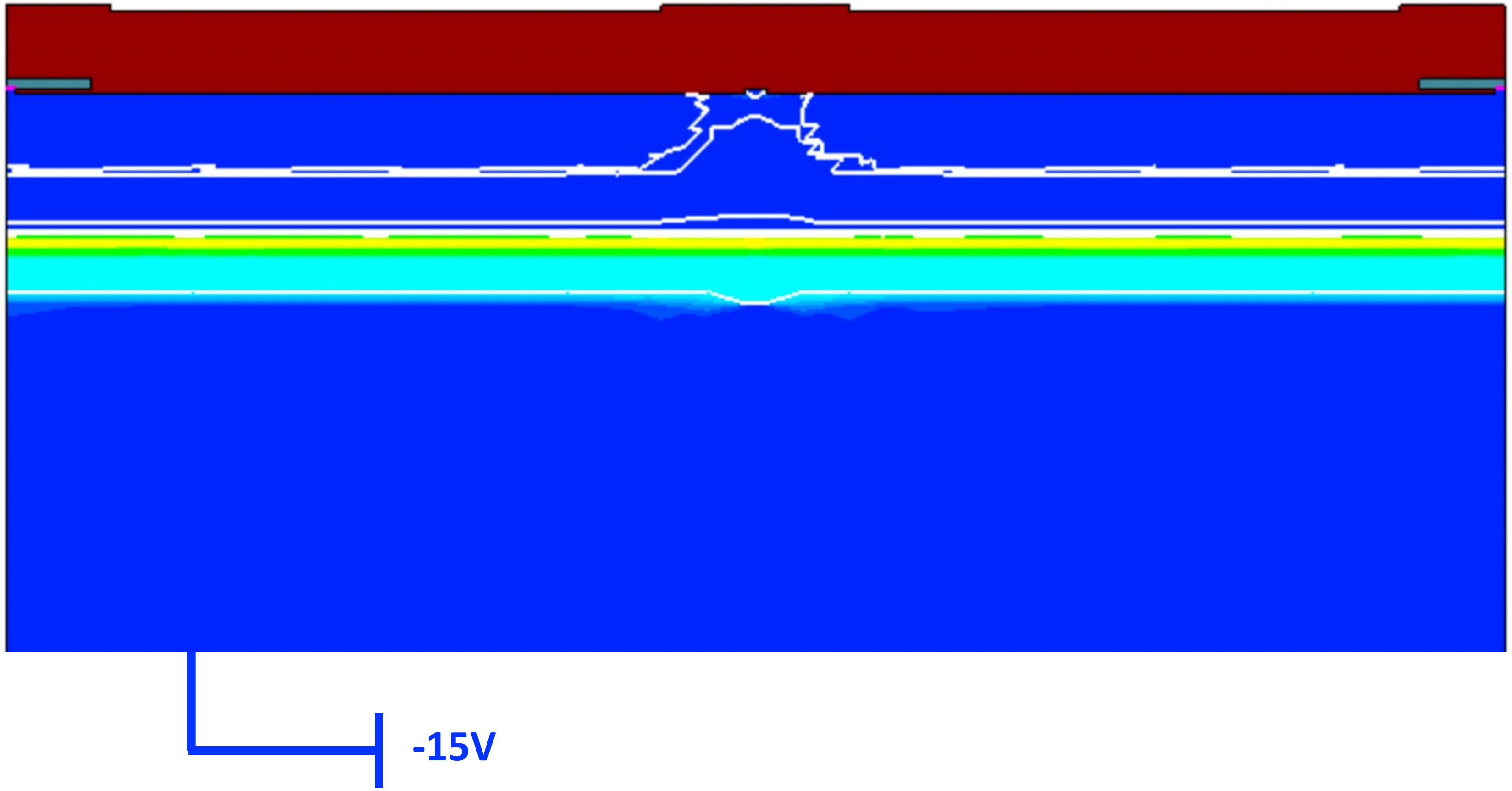
- **3D hexagonal pixel structure** of pixels in matrix

→ Relevant for pixel corners, breakdown around p-stops and depletion and field in drift region

- Modelling of Si/Oxide interface (not presented here)

PicoAD – 3D TCAD, electric field and depletion

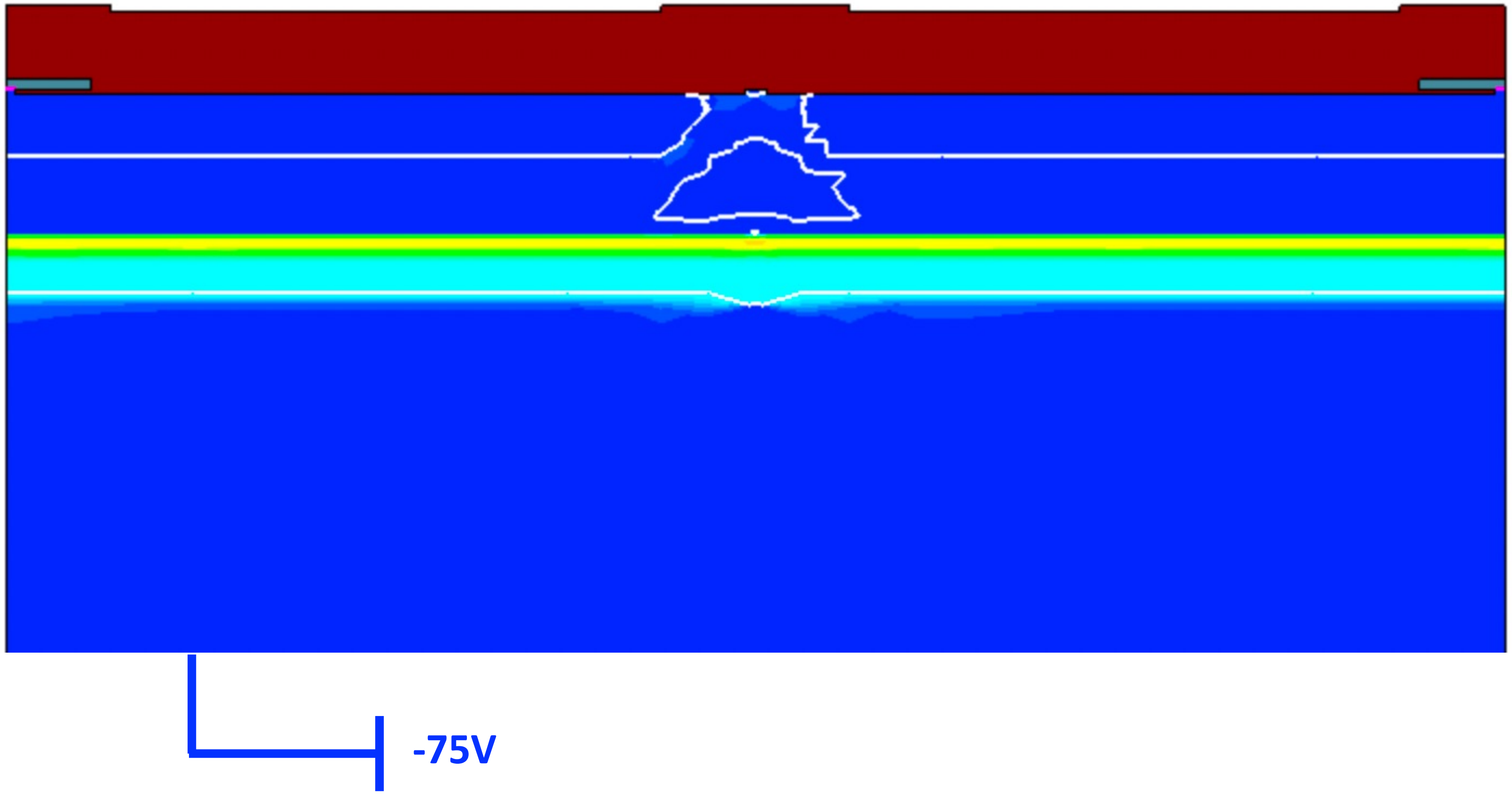
2D cross section of 3D TCAD, electic field (color scale) and depletion (white line):



Depletion and electric field first build up in absobtion layer, when applying voltage to the backside

PicoAD – 3D TCAD, electric field and depletion

2D cross section of 3D TCAD, electic field (color scale) and depletion (white line):



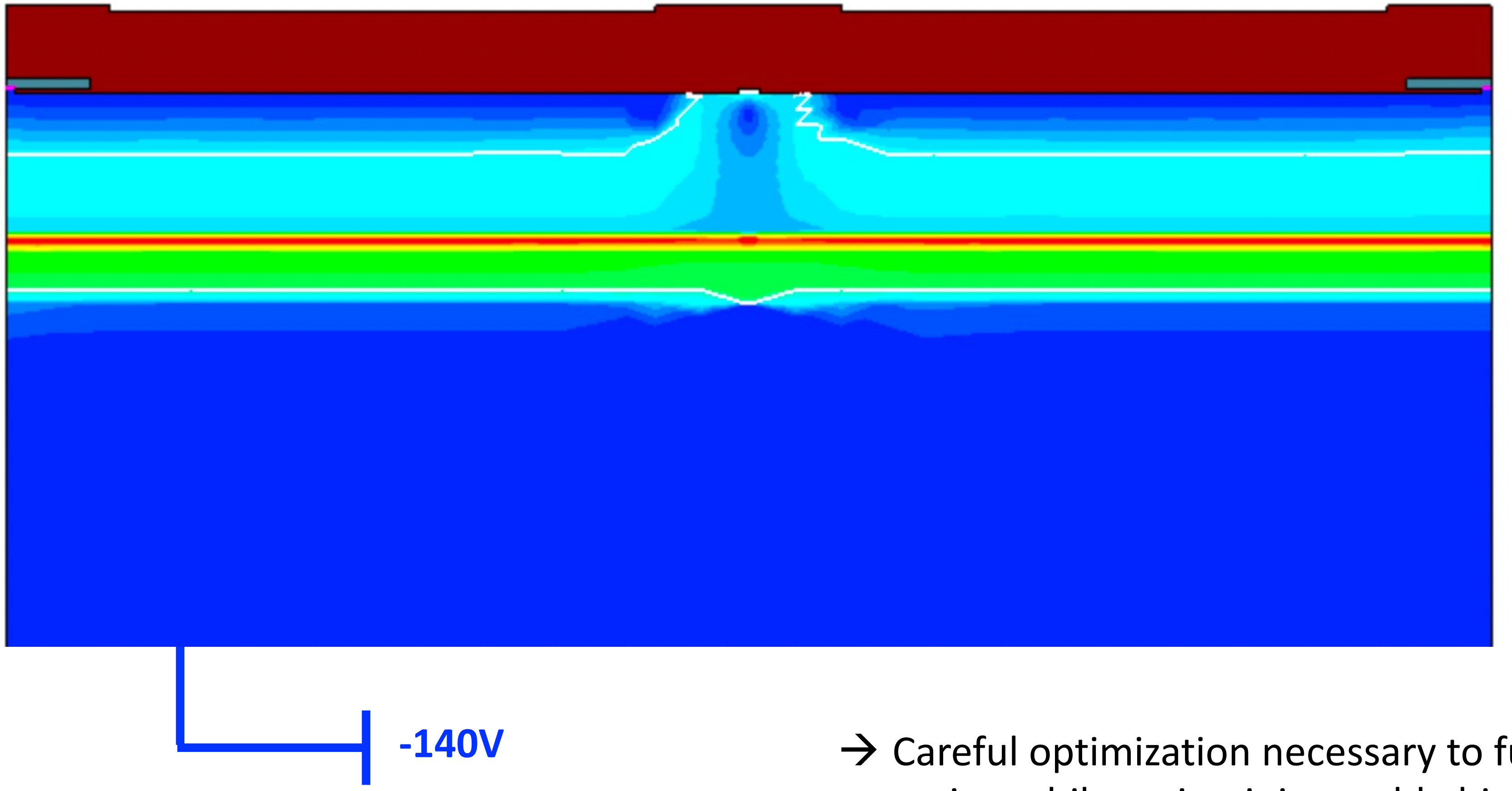
Electrtic field and depletion in drift layer start to build up after depletion of gain layer

'Pockets' under p-stops in 2nd epitaxial layer deplete last

→ Relevance of 3D modelling and optimisation of inter-pixel region

PicoAD – 3D TCAD, electric field and depletion

2D cross section of 3D TCAD, electic field (color scale) and depletion (white line):



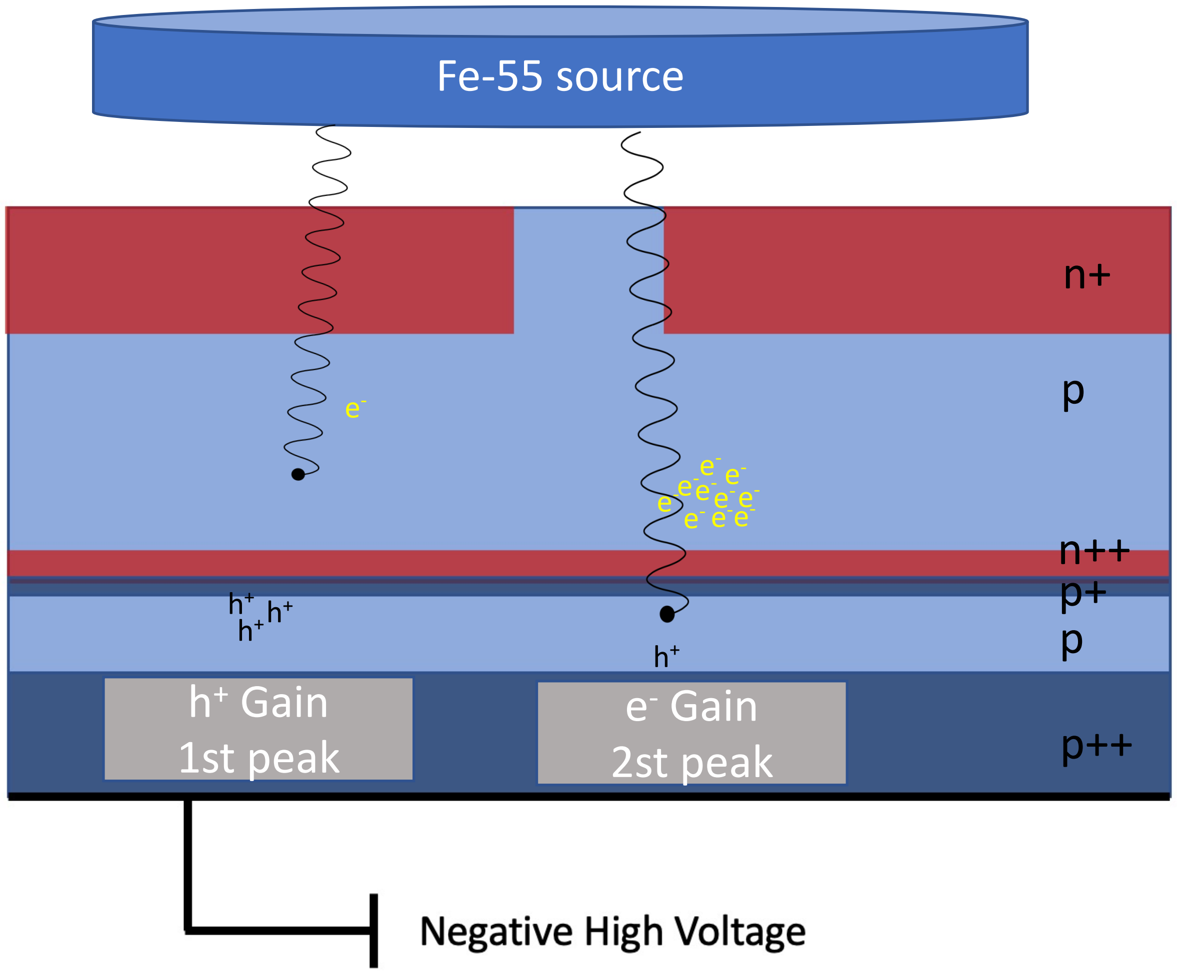
After full depletion the drift field in the 2nd epitaxial layer is build up

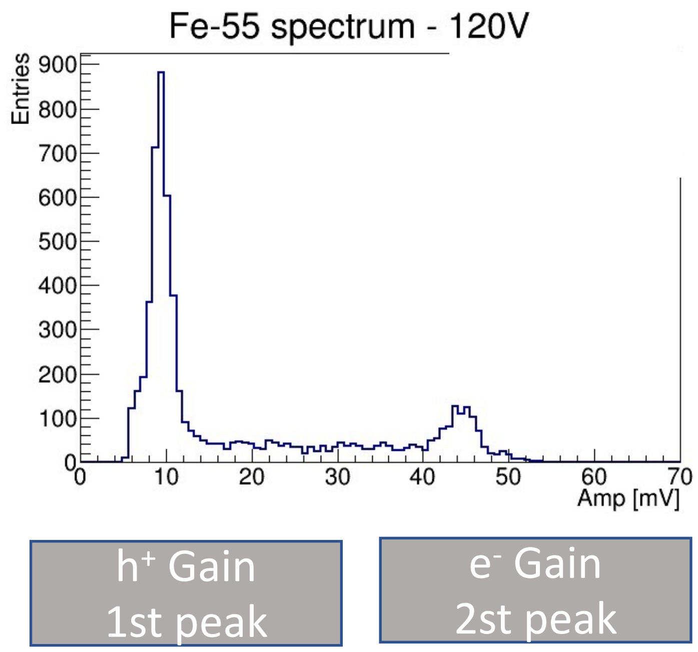
→ Important to saturate drift velocity

Planar field in drift and gain layer except for p-stop region

→ Careful optimization necessary to fully deplet and build up field in drift region while maintaining stable high field in gain layer.

55-Fe measurement concept

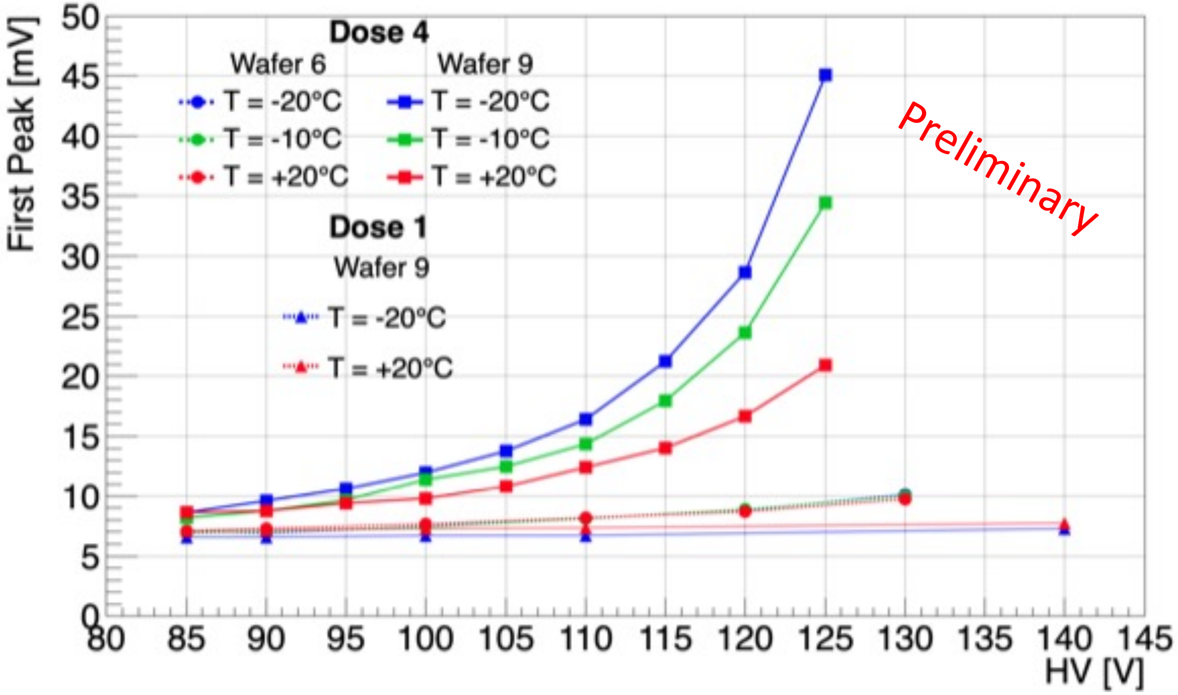




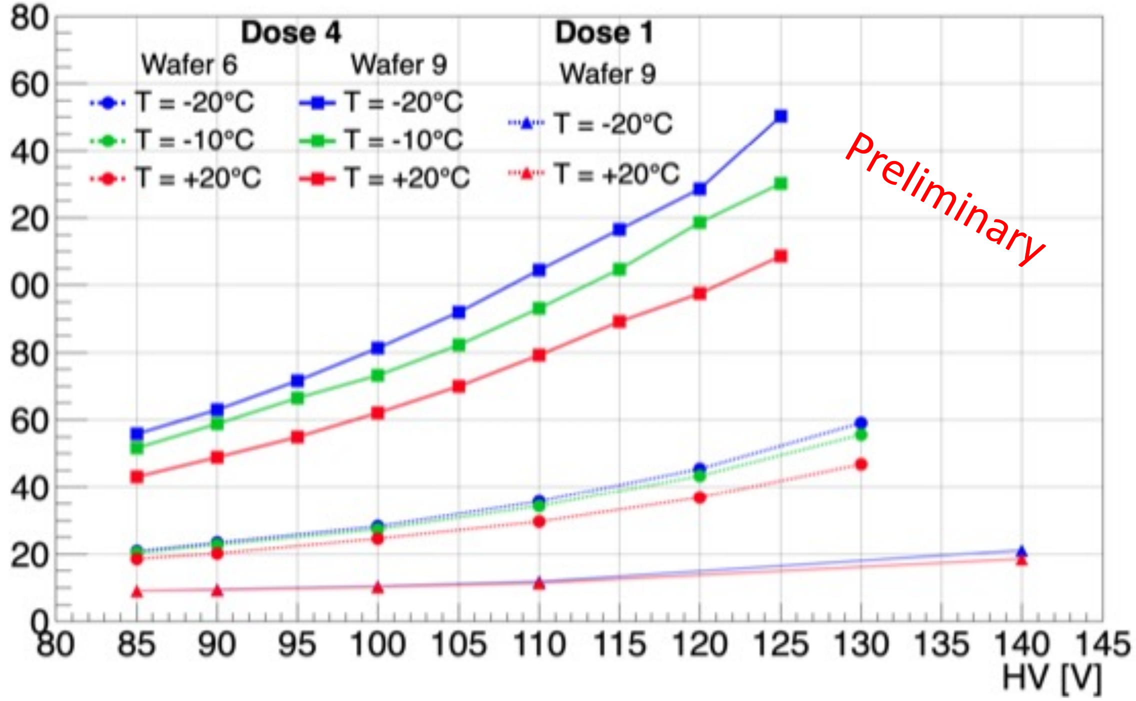
- Only carriers passing through the gain layer are multiplied
- Two different peaks for e^- and h^+
- Measurements performed in climate chamber to investigate gain as a function of temperature

55-Fe climate chamber measurement results

First peak of the 55-Fe spectrum as a function of the High Voltage (HV):

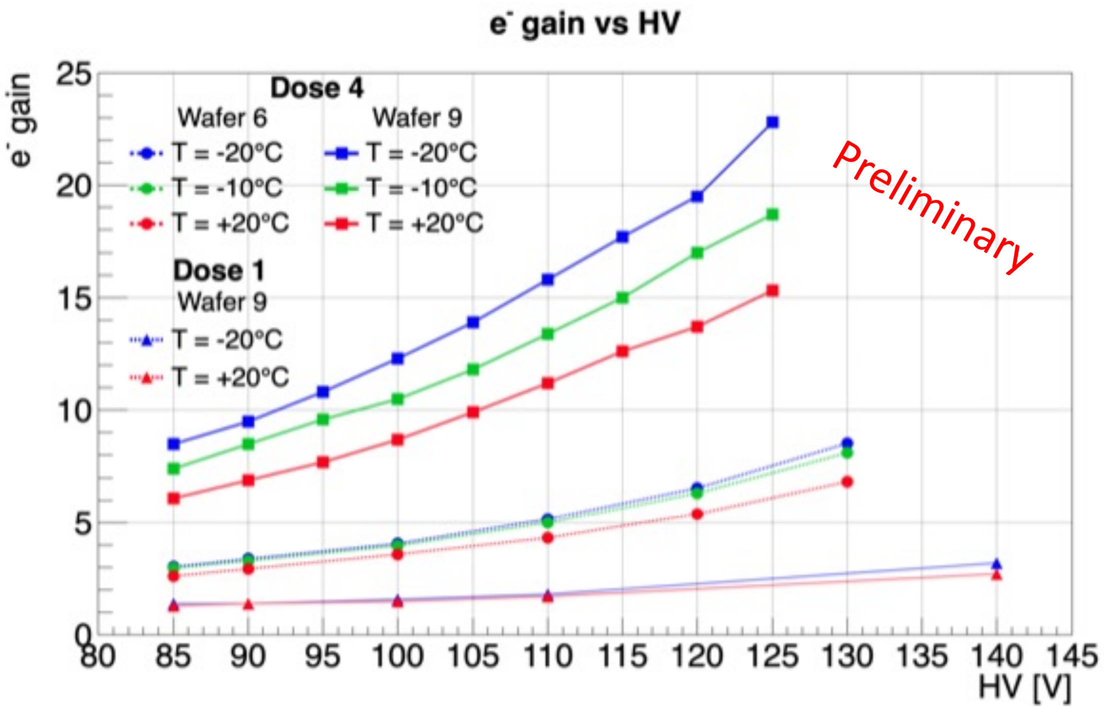


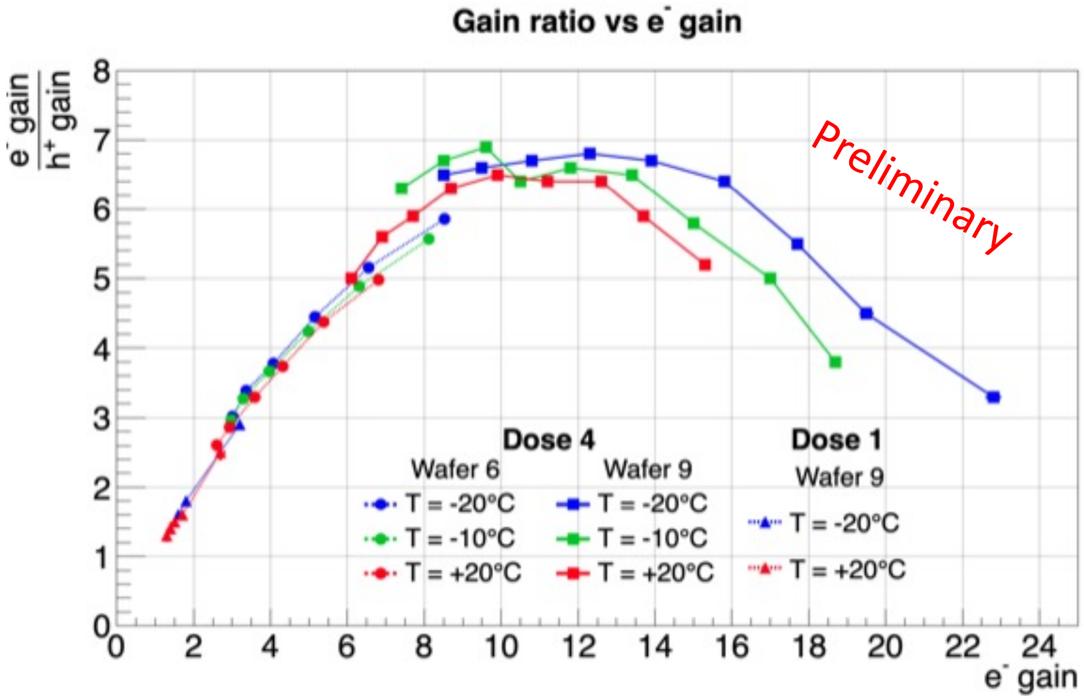
Second peak of the 55-Fe spectrum as a function of the High Voltage (HV):



- Electron and hole gain increase with HV and temperature
- Clear difference between wafer 6 and wafer 9 for the same dose (under investigation)
- Lowest dose 1 shows almost no hole gain, used for normalization to get electron gain (next slide)

55-Fe climate chamber measurement results





- Gain up to above 20 for wafer 9
- Gain most likely underestimated due to space charge effects from high local charge from 55-Fe

- Consistent behaviour of the 3 samples
- Ratio of e/h-gain decreaseds at higher e-gain values (expected to saturate)
- Possible explanation: space charge effects

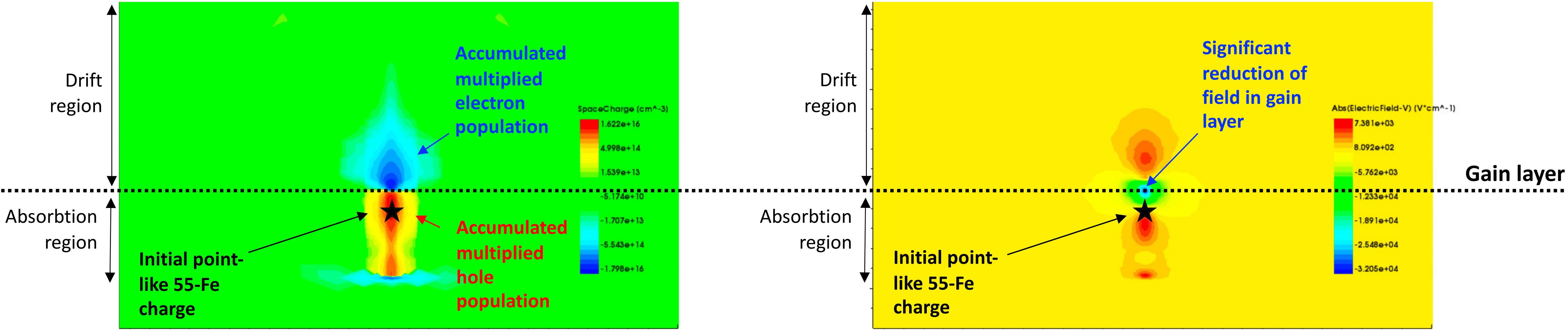
Space charge effects in picoAD double junction sensor

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

Preliminary

Space charge:
50ps after charge generation – before charge generation:

Electric field:
50ps after charge generation – before charge generation



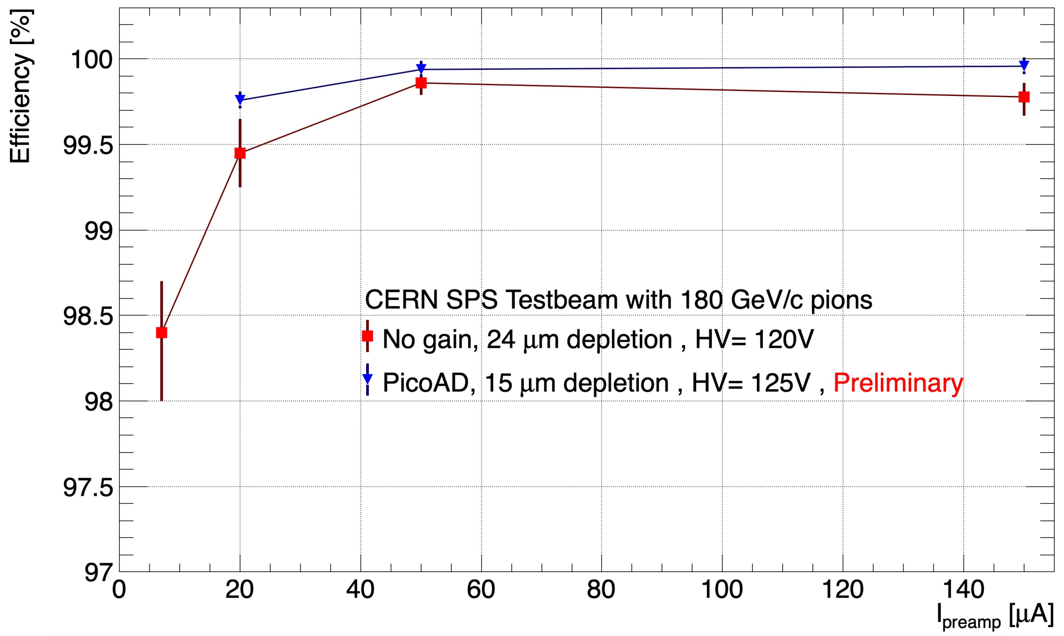
→ Reduced e-gain for higher local charge densities (higher initial charges or higher field values in gain layer, resulting in larger number of multiplied charges)

→ Transient field simulation necessary

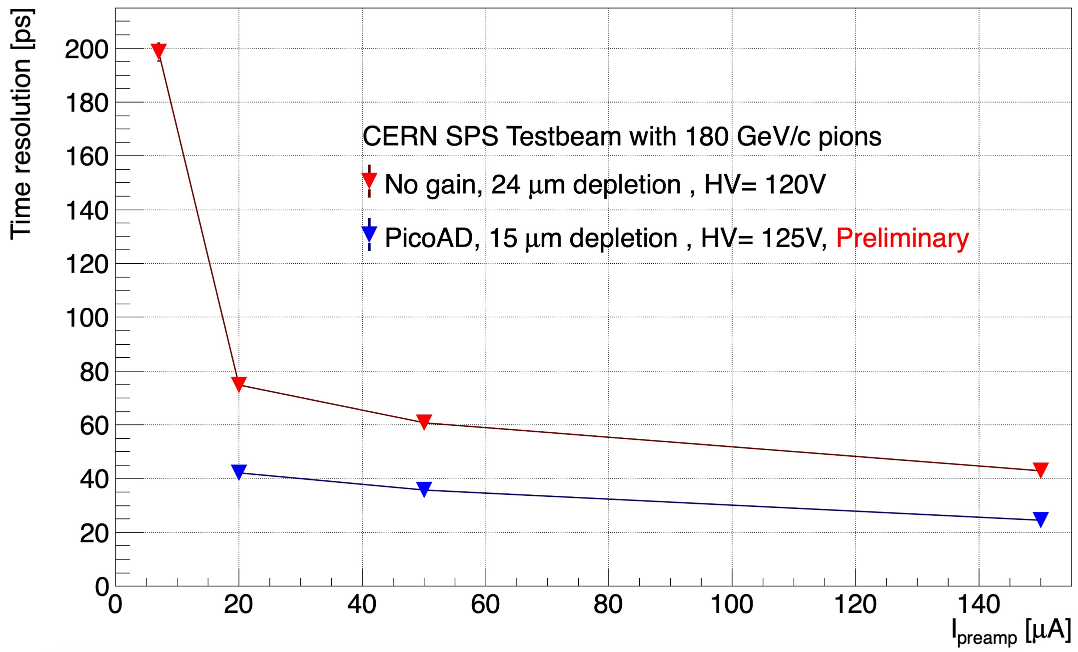
Test beam results for PicoAD

CERN SPS 180GeV pion beam, FEI4 Telescope ($\sigma_x \sim 10\mu m$ $\sigma_y \sim 15\mu m$),
2 DUTs for timing reference

Efficiency as a function of preamplifier current:



Time resolution as a function of preamplifier current:



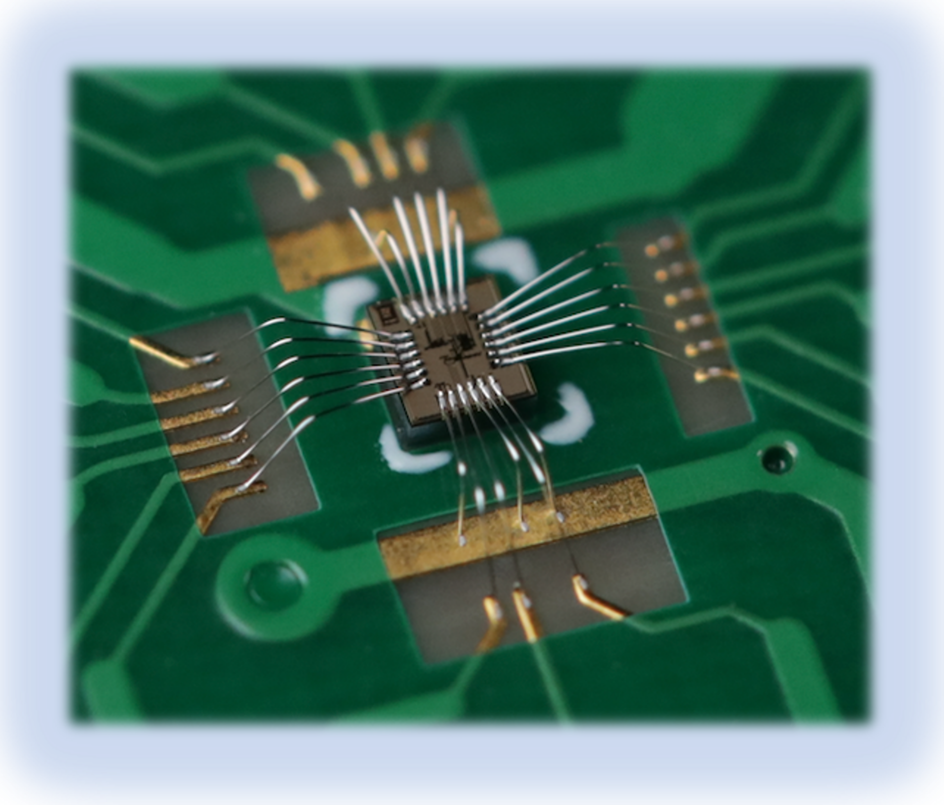
Improved efficiency for prototype with gain layer, despite reduction of epitaxial thickness w.r.t. prototype with gain.

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

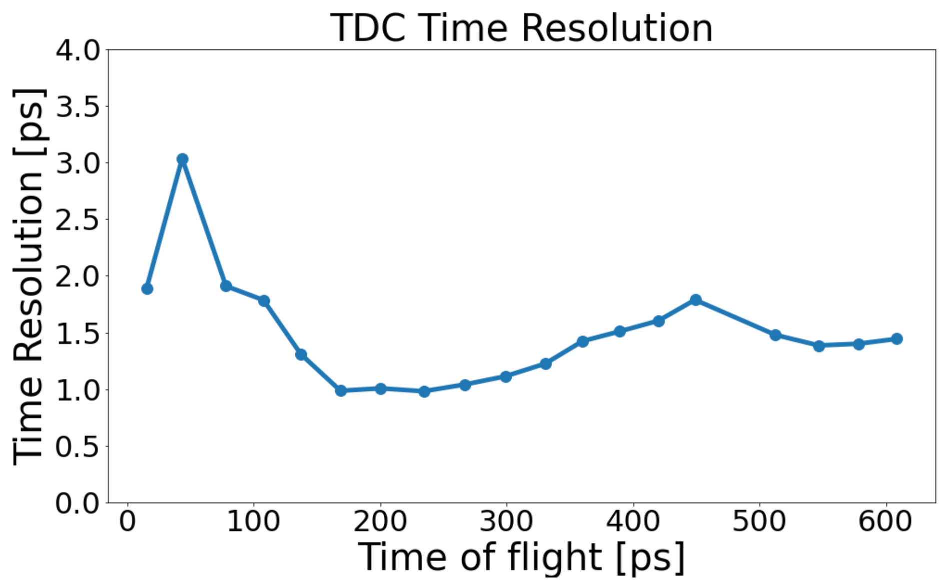
→ Proof of concept, not optimized for timing yet.

→ Efficiency > 99.5% and time resolution ~40ps even at low preamplifier current of 20μA.

Picosecond TDC



Picosecond TDC test chip



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

Conclusion and outlook

- **Proof of concept of PicoAD sensor + HBT frontend:**
- > 99.9% efficiency ~25ps time resolution

- **Study of fundamental electron-hole gain processes in multi junction sensor**

- **Development of picosecond TDC for fully monolithic MONOLITH chip**

- **Development of optimised sensor with TCAD**

BACKUP