MONOLITH – pico-second time-stamping in fully monolithic highly-granular pixel sensors

The 30th International Workshop on Vertex Detectors

September 2021

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ATTRACT

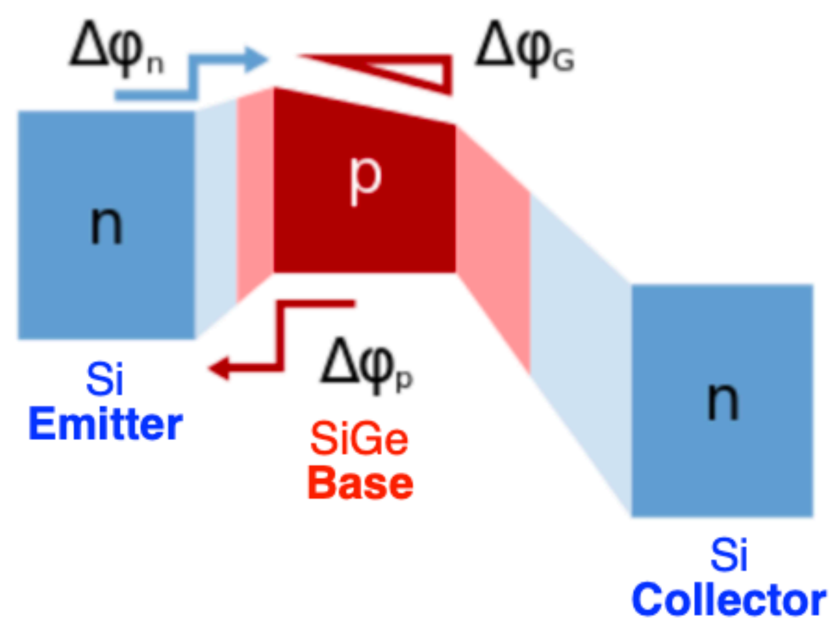
European Research Council
Established by the European Commission

funded by the H2020 ERC Advanced grant 884447

SiGe Bi-CMOS process

SiGe Hetrojunction Bipolar Transistors (HBT):

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



- BJT: small current applied to base allows for large current between emitter and collector —> amplification, switching

- SiGe HBT = BJT with Germanium as base material:
  —> higher doping in base possible
  —> thinner base
  —> reduced base resistance

- Grading of Ge doping in base:
  —> charge transport in base via drift
  —> reduced charge transit time in base —> high current gain (beta)

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IHP 130nm SiGe Bi-CMOS large collection electrode process, with state-of the art SiGe HBTs:

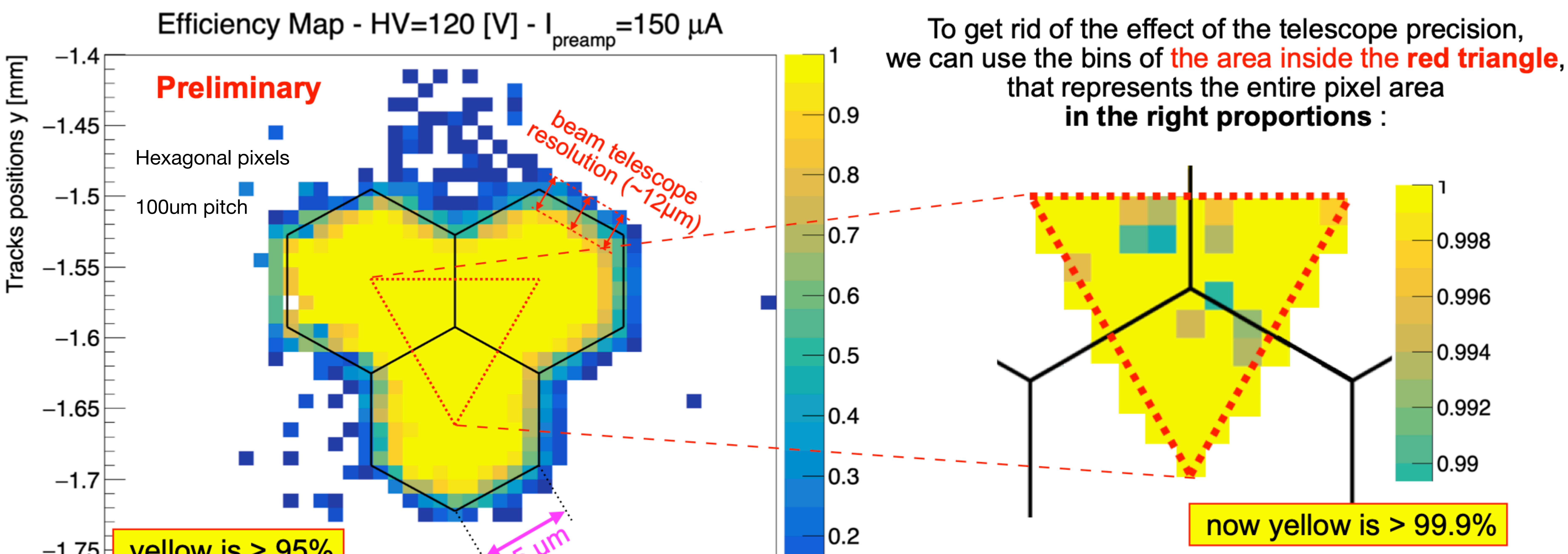
- Transistor frequency with ft = 0.3 THz
- Current gain with beta = 900
- Delay gate with 1.8 ps

—> HBTs used for fast, high gain, low noise, low power amplifiers

Small-area pixels power consumption: JINST 15 (2020) P11025, https://doi.org/10.1088/1748-0221/15/11/P11025
Hexagonal small-area pixels: JINST 14 (2019) P11008, https://doi.org/10.1088/1748-0221/14/11/P11008
TT-PET demonstrator chip testbeam: JINST 14 (2019) P02009, https://doi.org/10.1088/1748-0221/14/02/P02009
TT-PET demonstrator chip design: JINST 14 (2019) P07013, https://doi.org/10.1088/1748-0221/14/07/P07013
First TT-PET prototype: JINST 13 (2017) P02015, https://doi.org/10.1088/1748-0221/13/04/P04015
Proof-of-concept amplifier: JINST 11 (2016) P03011, https://doi.org/10.1088/1748-0221/11/03/P03011

Test-beam measurements - efficiency

- Test-beam measurements performed at CERN SPS H8 beam line using 180GeV high intensity pion beam
- FEI4 telescope used as reference system for particle tracking (σx ~10um, σy ~15um, 25ns time bins)
- Installation of two DUTs for precise reference timing
- Measurement of analogue pixels of ATTRACT prototype without gain layer:



Inside red triangle:
efficiency = (99.87 ± 0.13)%

Fully efficient operation, even in pixel edges.

Test-beam measurements - time-stamping

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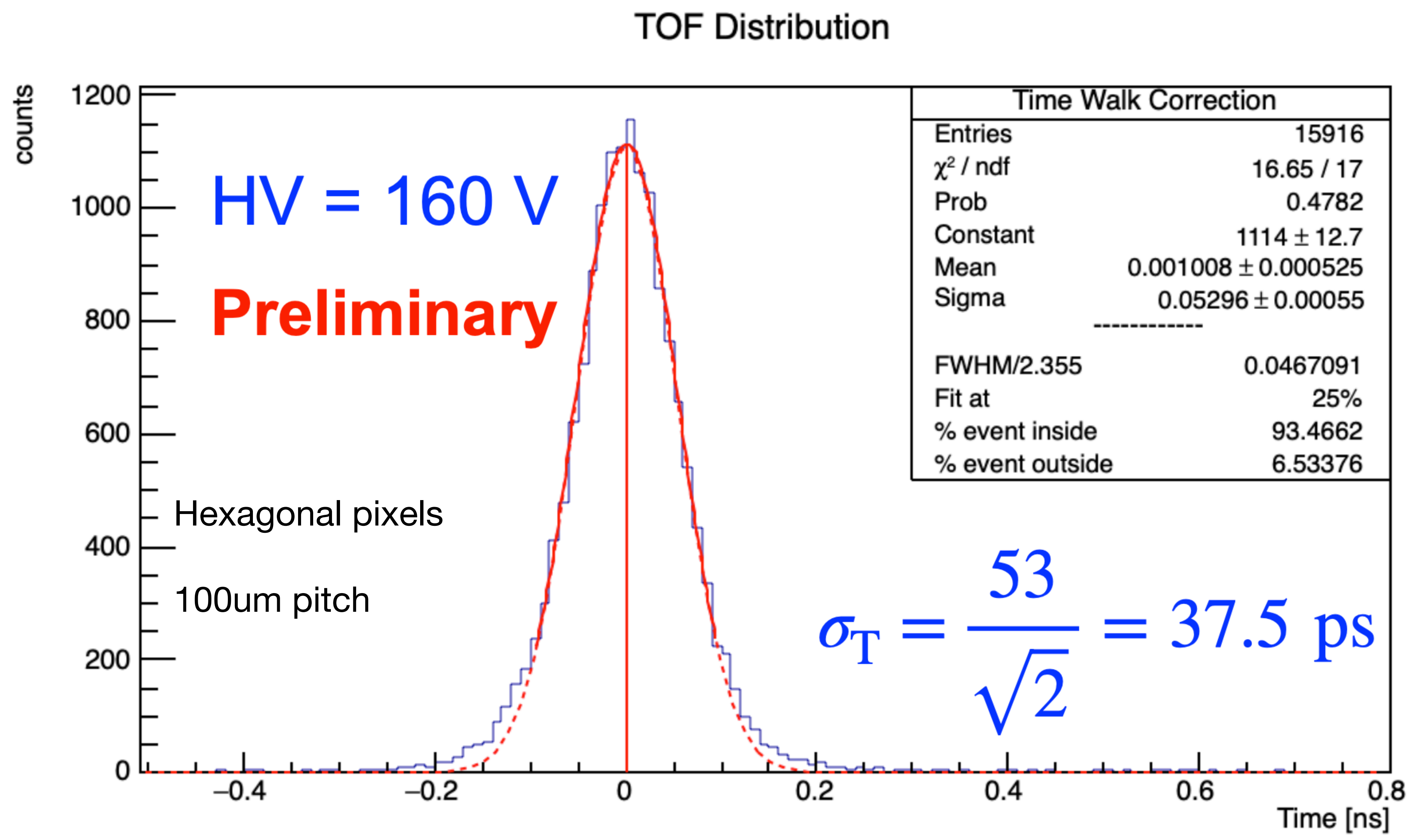
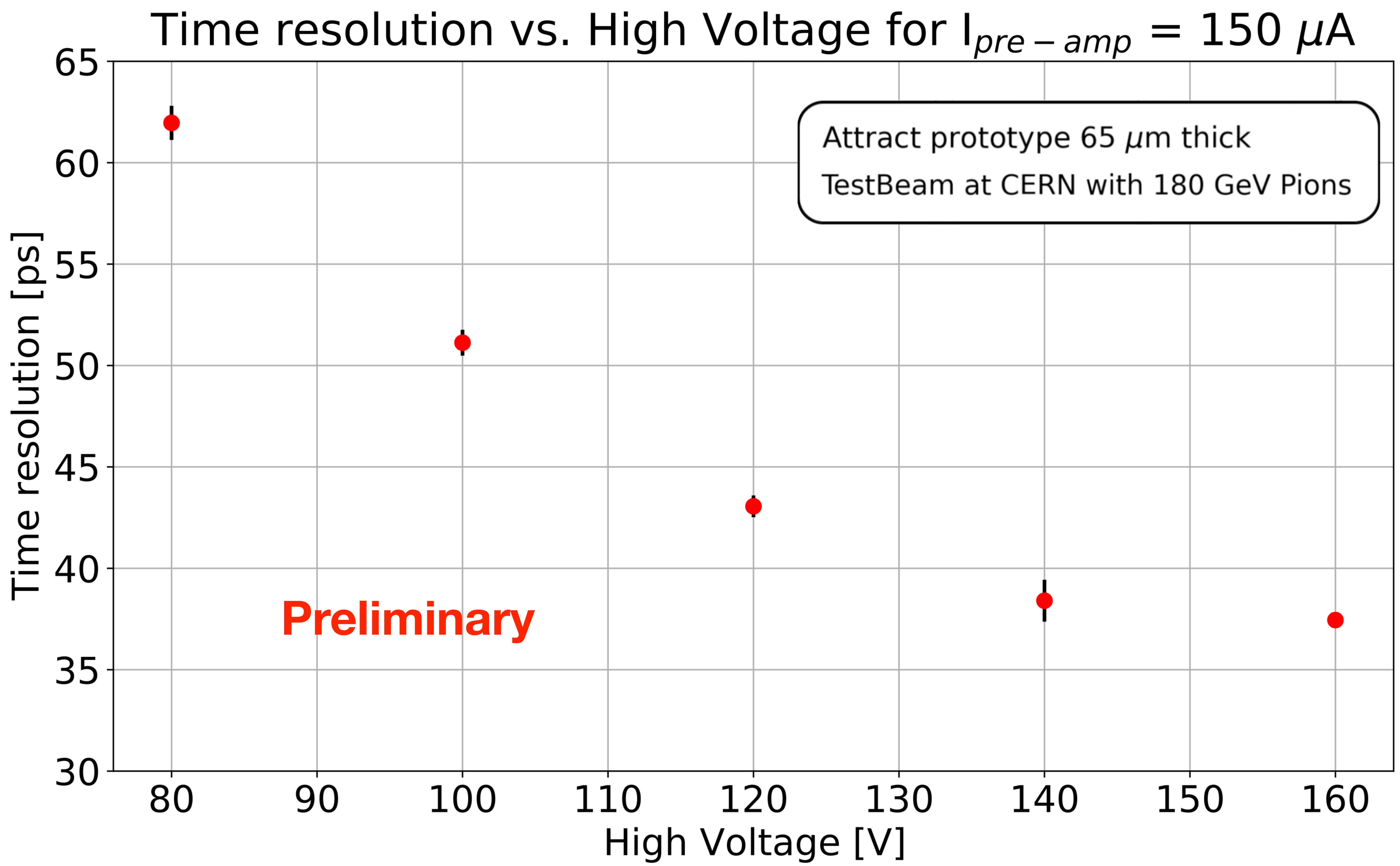


Time stamping precision of ~38 ps without gain layer.



$\sigma_{time} \propto t_{rise}$ / (Signal/Noise)

—> Maximise ratio of Signal/Noise with sensor gain layer to further improve time stamping capabilities to the picosecond level

The MONOLITH ERC Advanced Project

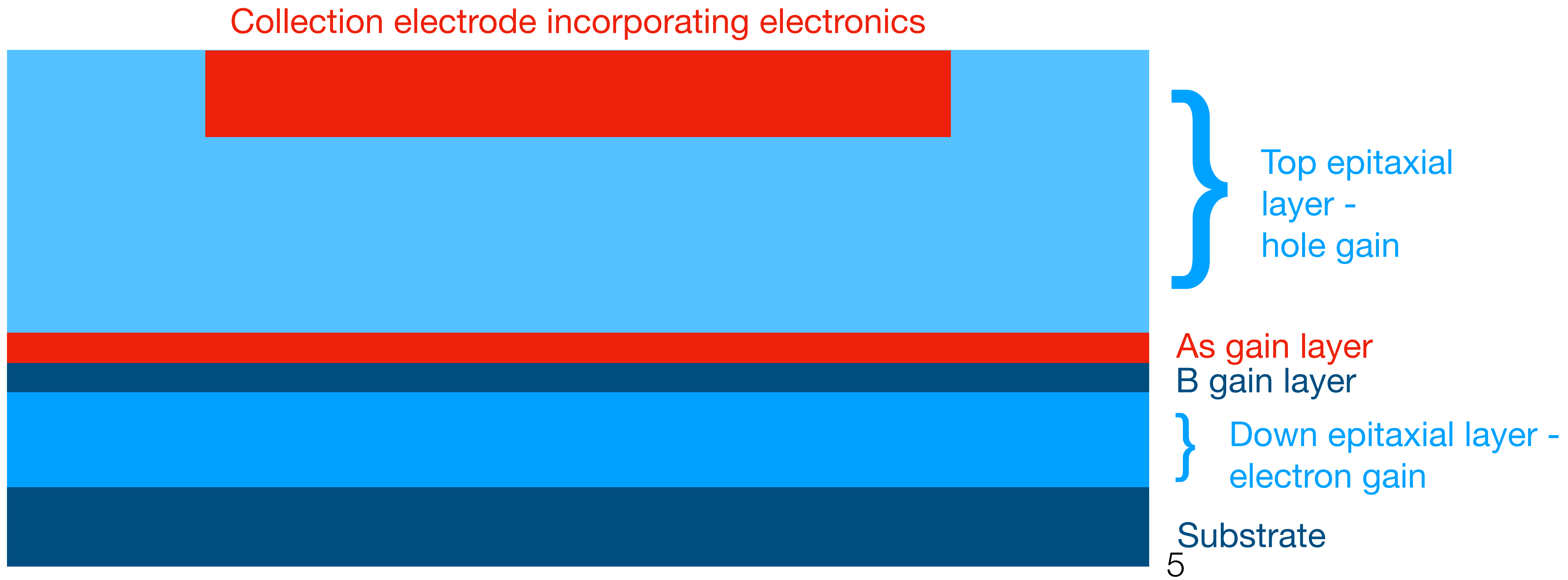
https://www.unige.ch/dpnc/en/groups/giuseppe-iacobucci/research/monolith-erc-advanced-project/

Picosecond time stamping resolution combined with high spatial precision in a fully monolithic design for the detection of ionising radiation:

- Improvement of time resolution by order of magnitude w.r.t. present best values while maintaining high spatial precision and monolithic design

- Realised by HBT transistors and deep multi-junction sensor concept:

Schematic sketch of deep multi-junction PicoAD sensor process:



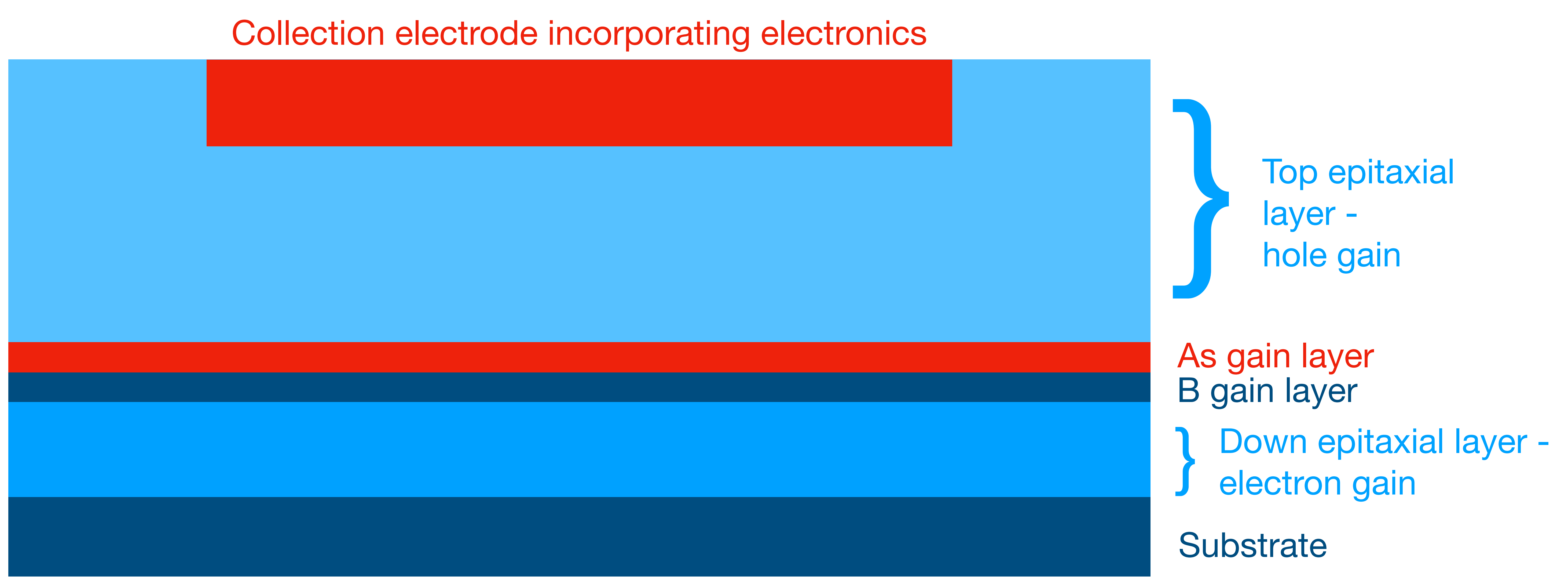
Larger Signal/Noise from sensor and frontend gain:

- Precise time stamping
- Reduced material budget
- Reduced power consumption

Deep multi-junction PicoAD sensor concept

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

Schematic sketch of deep multi-junction PicoAD sensor process:



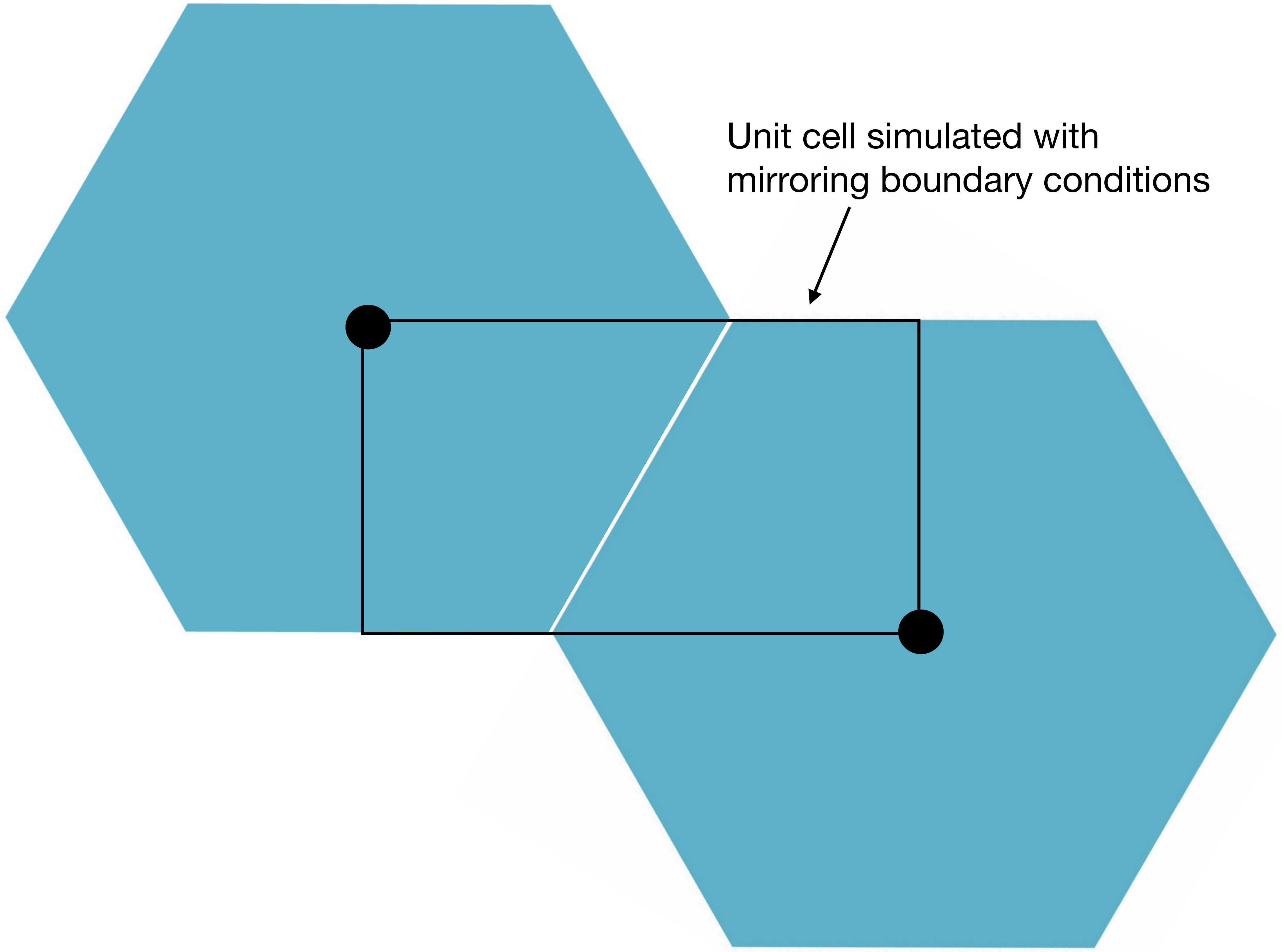
Placement of gain layer deep inside sensor:

—> 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*)

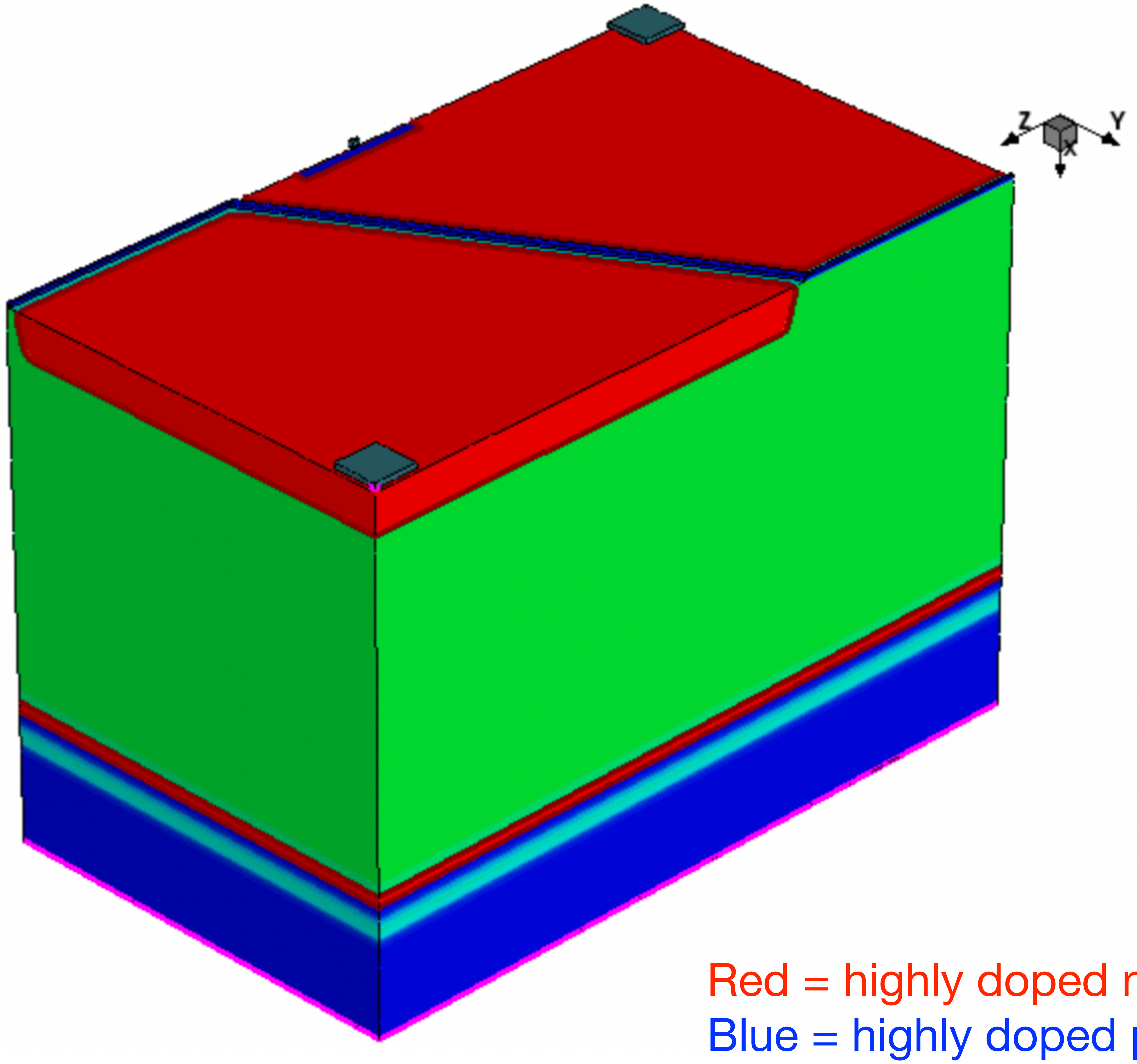
Understanding of sensor concept - 3D TCAD

Selected unit cell of hexagon:



Hexagonal pixels to minimize edge effects (field breakdown in pixel corners, impact of edge effects on gain layer)

3D TCAD simulation of unit cell - oxide not shown:

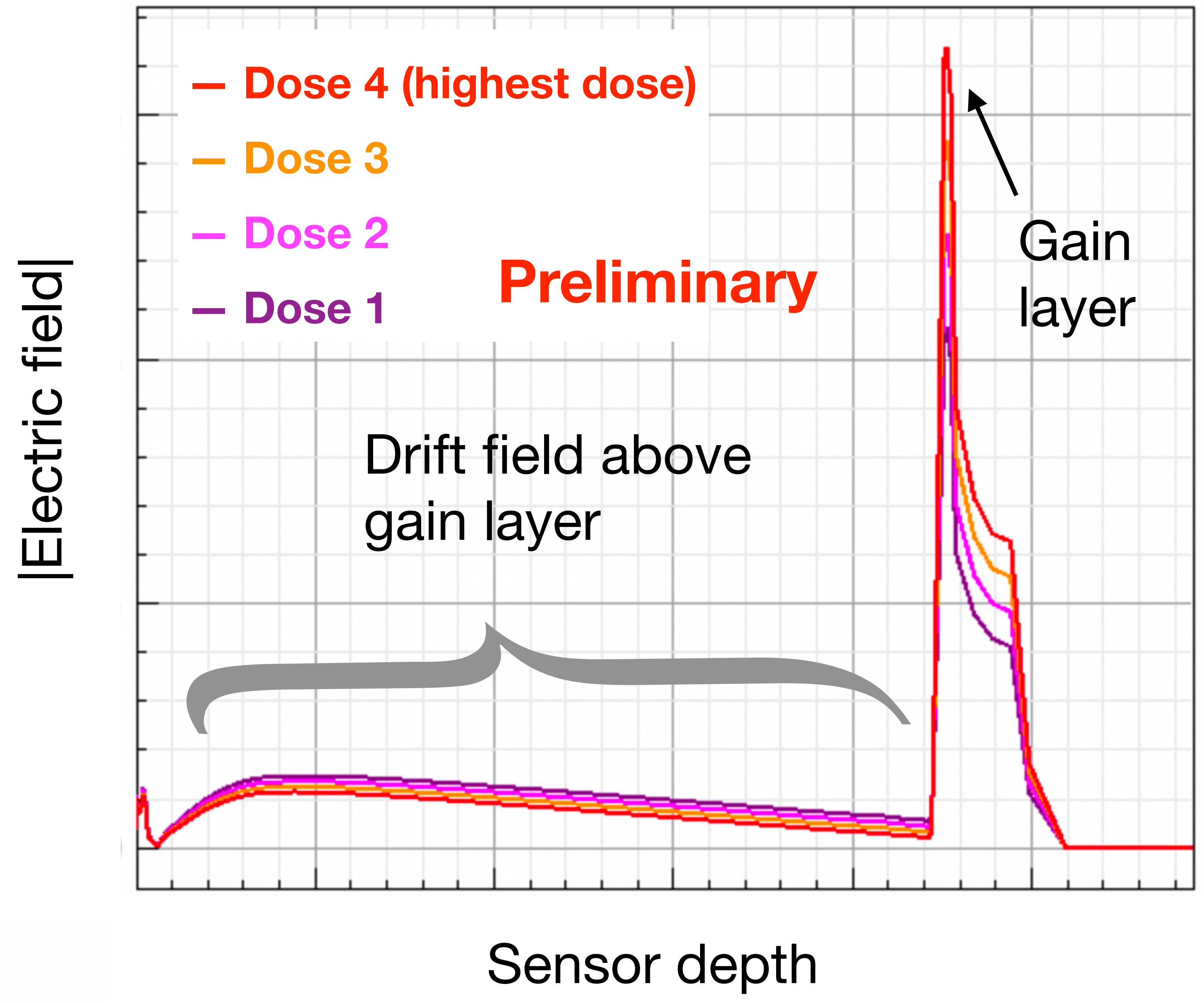


Red = highly doped n-type
Blue = highly doped p-type
Green = lowly doped p-type

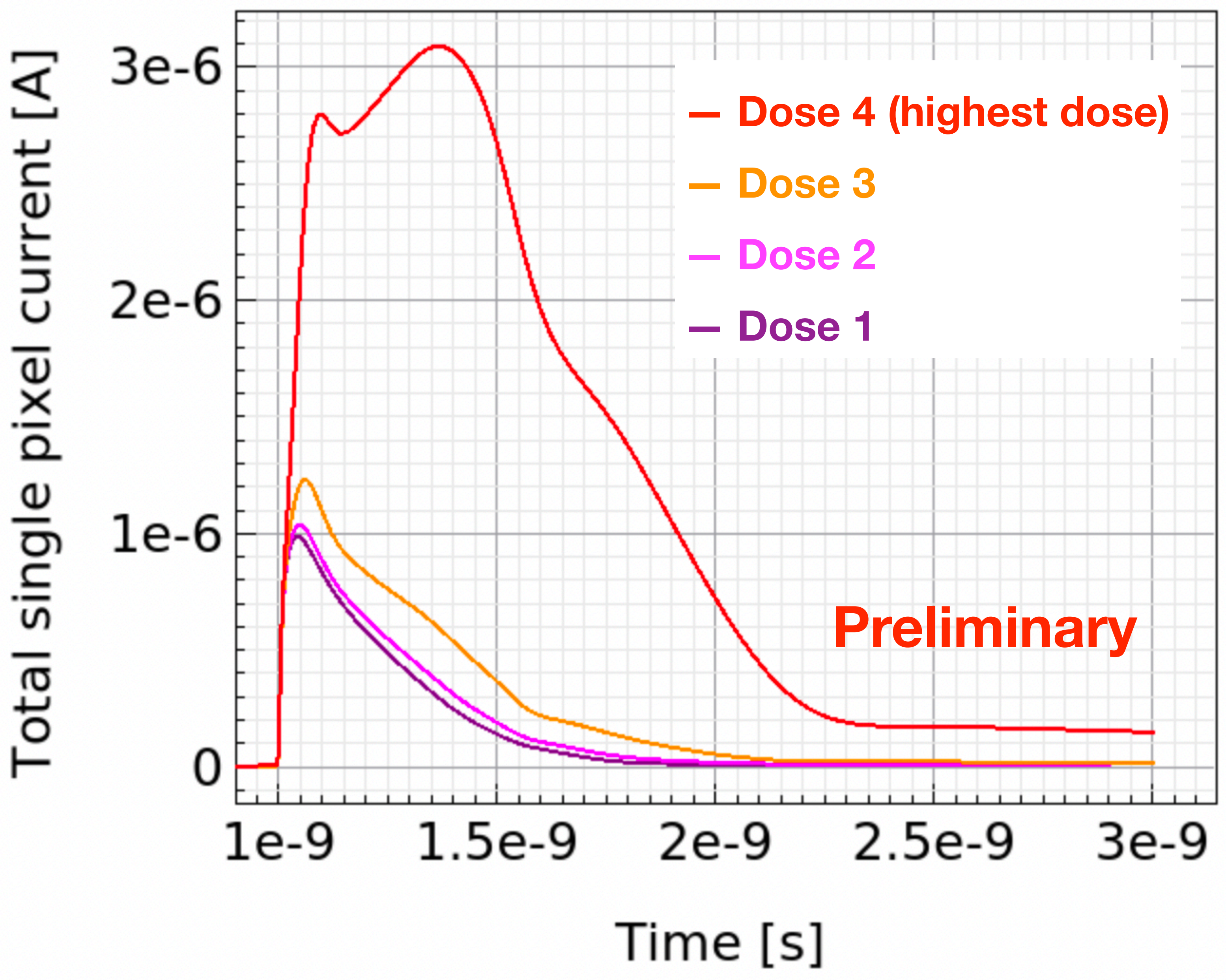
Gain layer optimisation with 3D TCAD

Trade-off between drift field and field in gain layer:

Electric field for different gain layer doses:



Transient response for MIP incident at pixel corner for different gain layer doses at -240V:



High gain layer dose 4 gives significantly **larger gain,** sufficiently **high drift field** and sufficiently **large operation range** before field breakdown in gain layer.

- Higher field in gain layer for higher gain layer dose

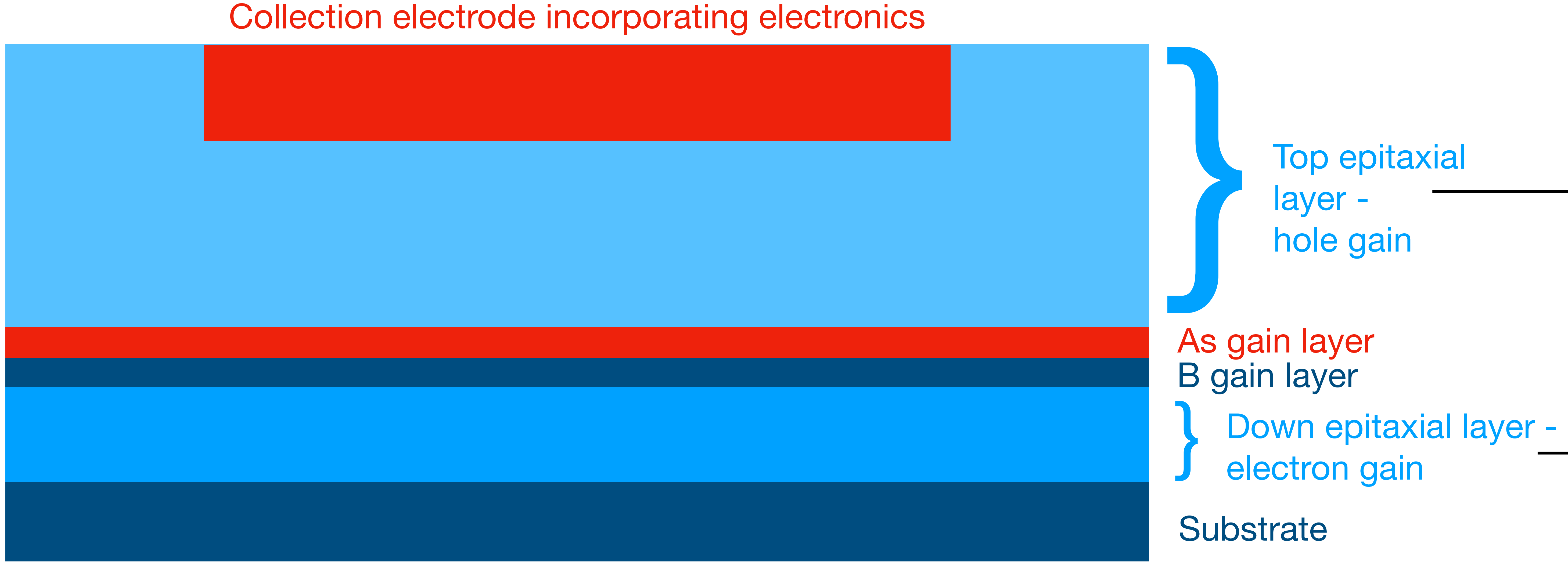
—> Electric field breakdown in gain layer at lower voltages for higher gain layer doses (<250V for highest dose 4)

- Higher drift field above gain layer for lower gain layer dose

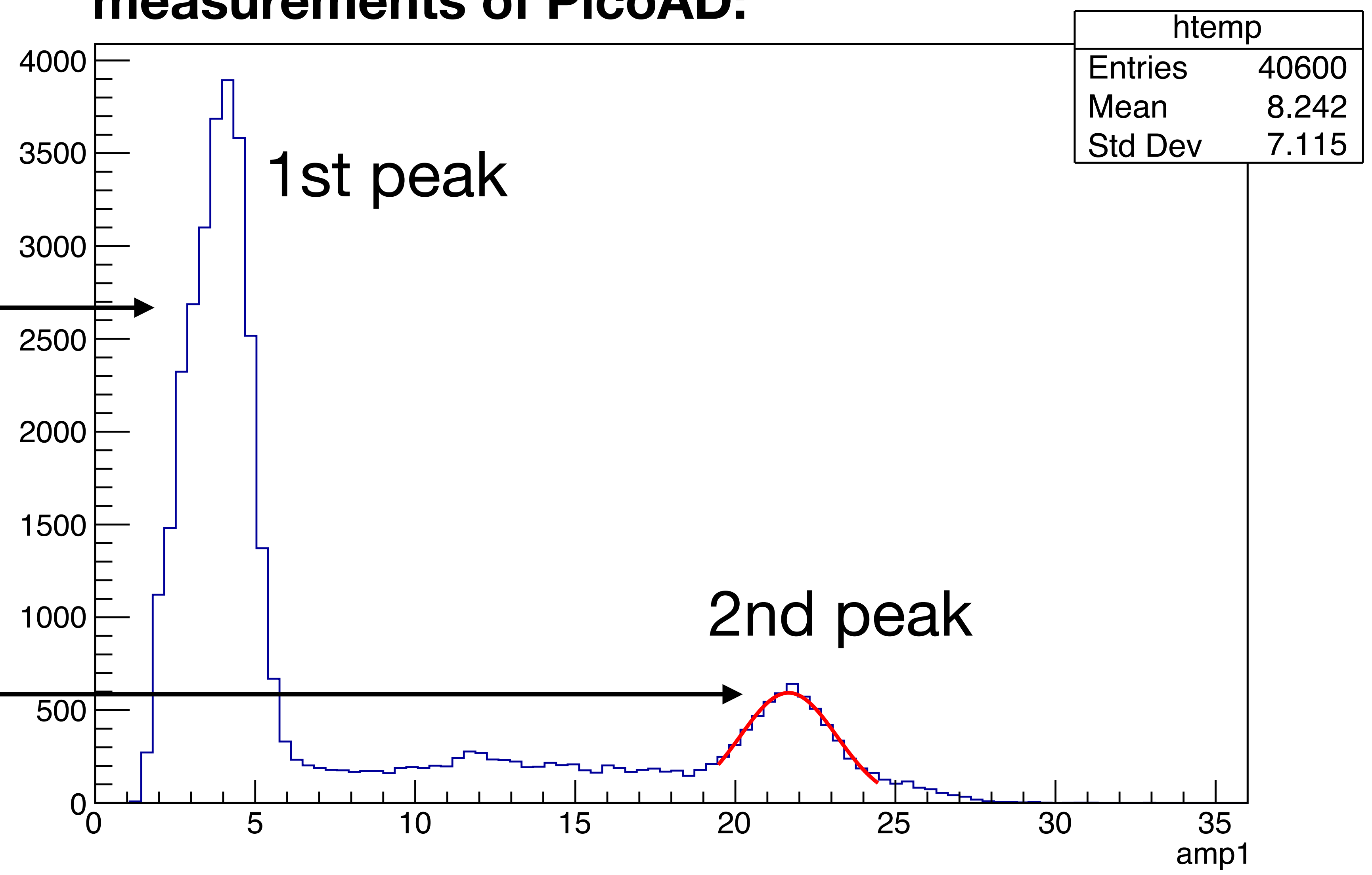
- Higher gain for higher gain layer doses due to higher field in gain layer

Proof of PicoAD sensor concept - Climate chamber measurements

- First prototype from PicoAD ATTRACT project
- Measurements of analogue signal from 55-iron source (point-like charge deposition) as a function of sensor bias and temperature climate chamber:



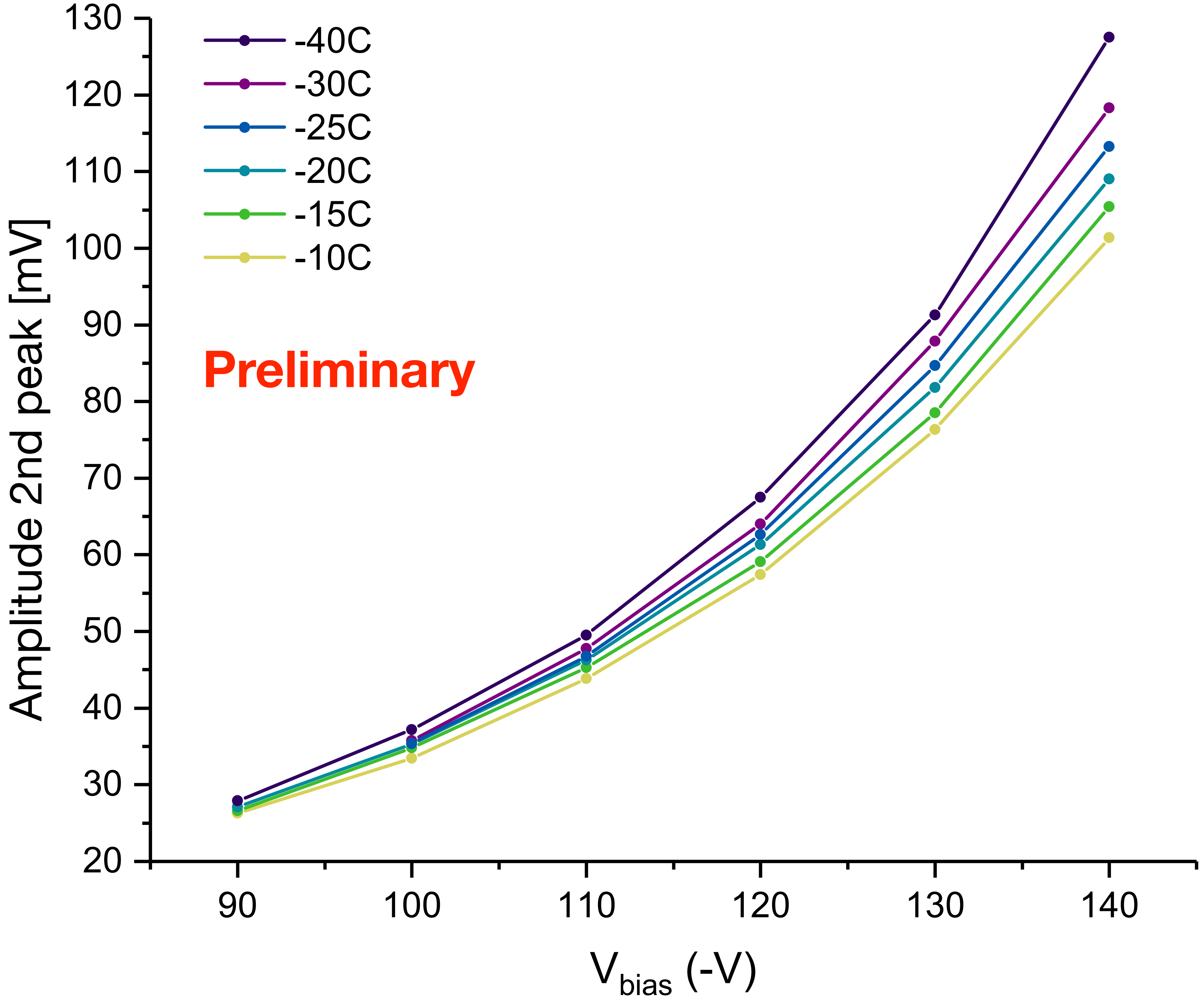
Typical spectrum from 55-iron measurements of PicoAD:



Gain = 2nd peak / 1st peak before hole gain

Proof of PicoAD sensor concept - Climate chamber measurements

Measurements of sensor gain using 55-iron source in climate chamber:



Measured sensor gain depends on temperature:

Higher gain for lower temperatures due to change in impact ionisation coefficient α:

$$G \propto e^{\alpha(E,T)\cdot d} \quad with \quad \alpha(E,T) \propto e^{-(a+b\cdot T)/E}$$

G = Gain, d=distance, E=electric field

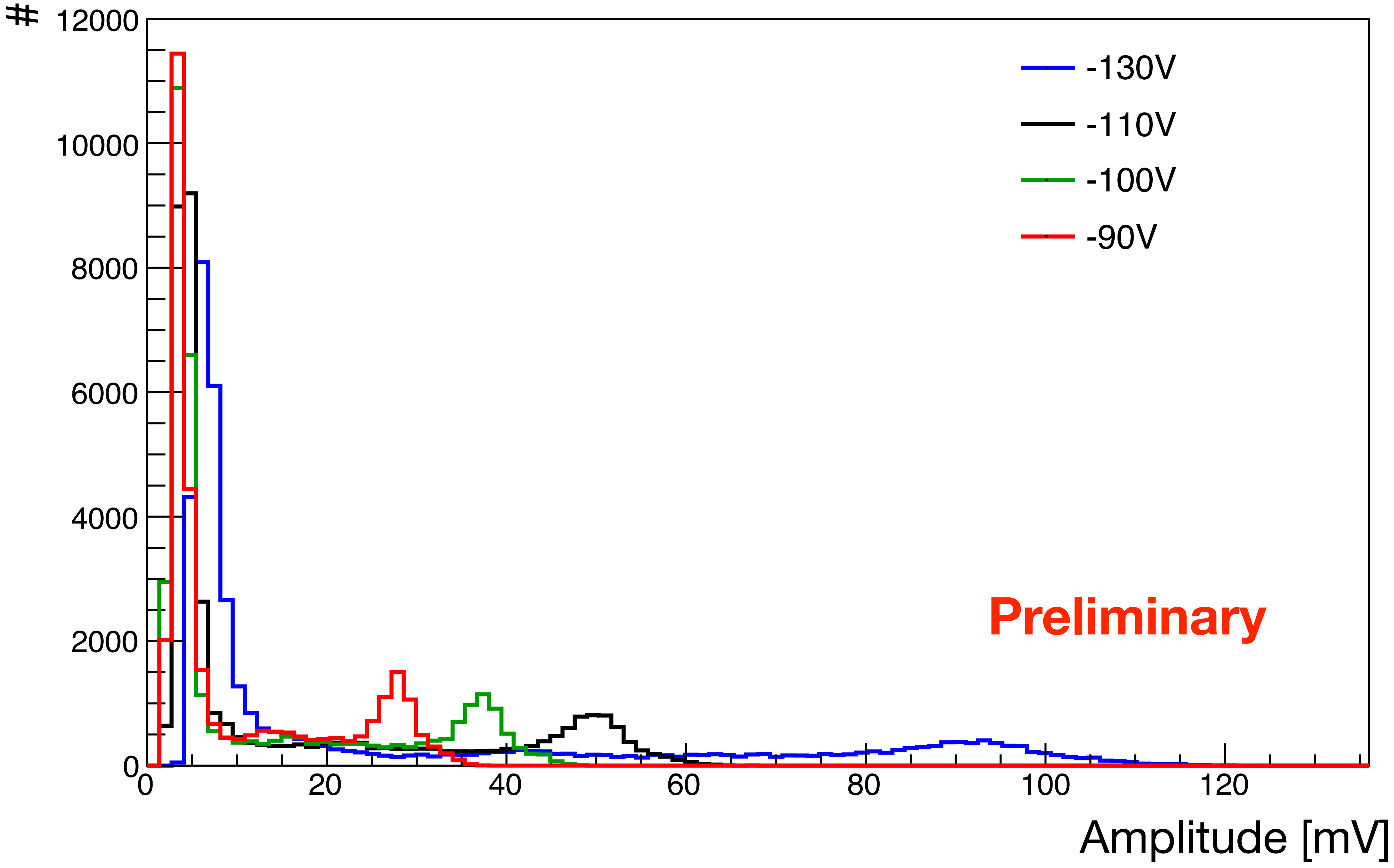
Significant gain of > 20

Note: challenging to determine due to convolution of sensor and frontend effects at lower temperatures

—> Proof of novel picoAD concept

Proof of PicoAD sensor concept - Climate chamber measurements

Measurements of sensor gain using 55-iron source in climate chamber @-40degree



Measured sensor gain depends on voltage:

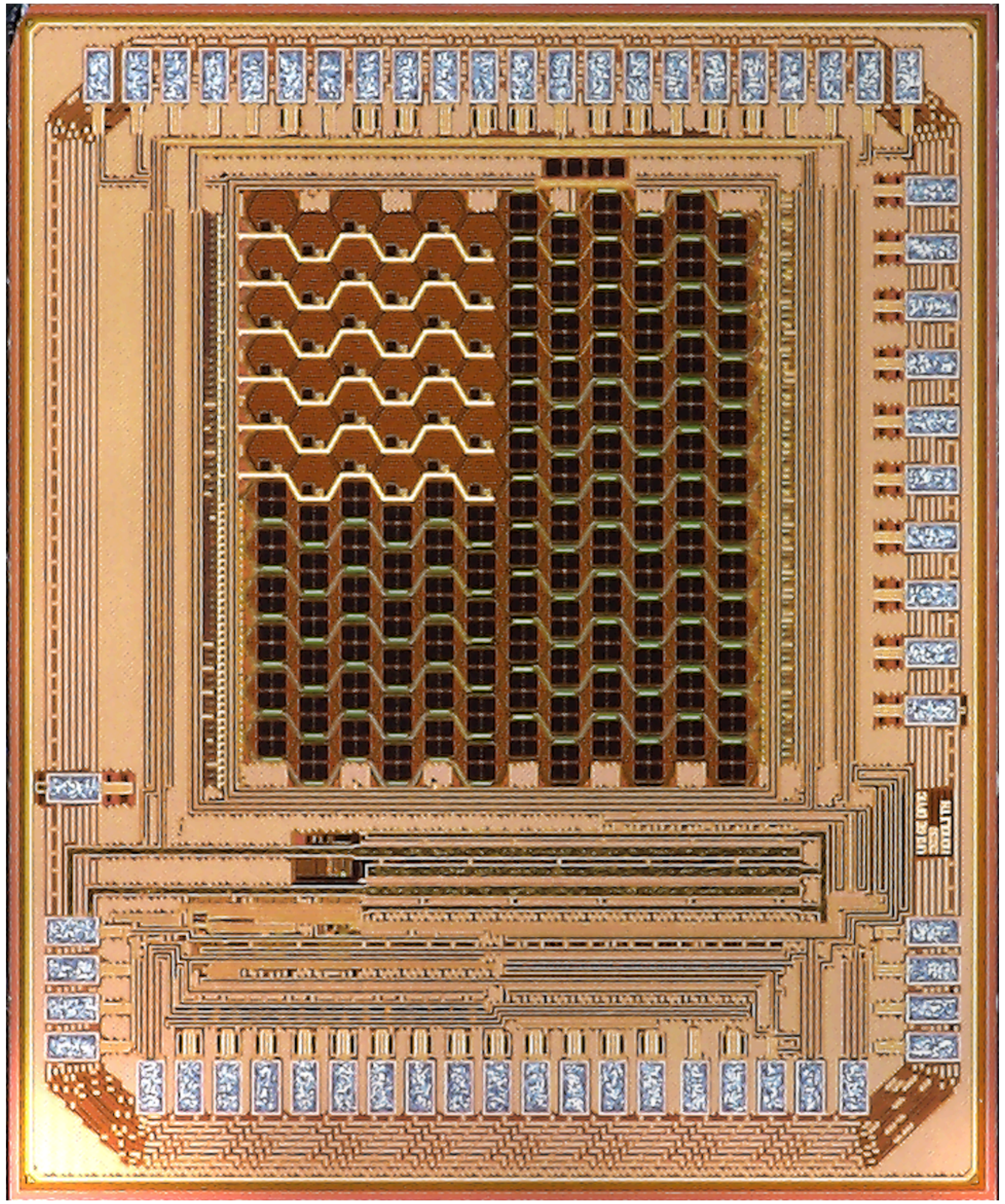
Higher gain for higher sensor bias due to higher field in gain layer (trivial, but important to maximise range with high gain below field breakdown)

Intermediate region between first and second peak:

Lower field in inter pixel regions results in lower filed in gain layer.

Summary and outlook

Image of first MONOLITH prototype:



- Application of SiGe BiCMOS process for low noise, high gain and fast timing
- Test-beam measurements of ATTRACT prototypes without gain layer show time-stamping capabilities of ~38ps and efficiency >99.8%
- Proof of novel deep multi-junction PicoAD sensor concept for low-gain avalanche in monolithic highly granular pixel detectors
- Test beam measurements of ATTRACT prototypes with gain layer currently ongoing
- First MONOLITH prototypes without gain layer currently under test
- Next submission of MONOLITH prototype with optimised gain layer end of this year