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

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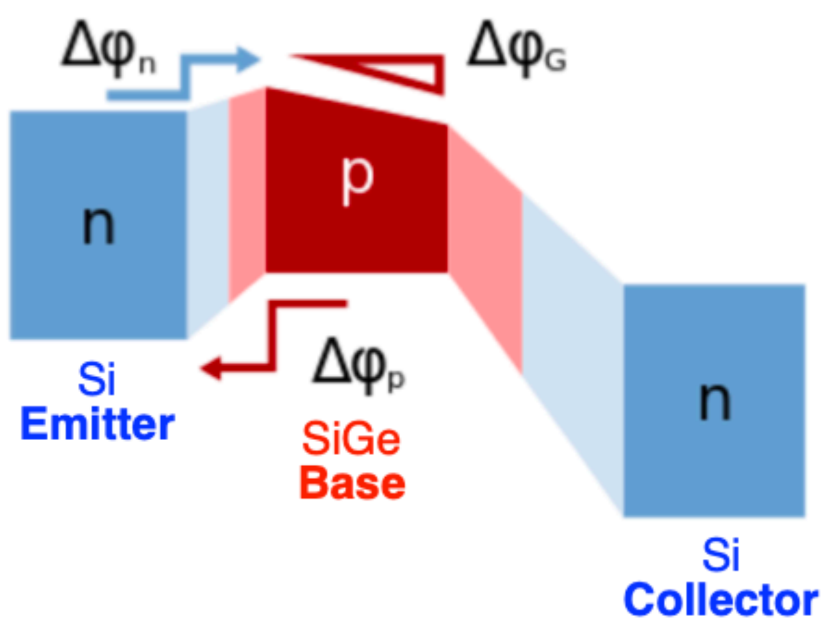
SiGe Bi-CMOS process

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

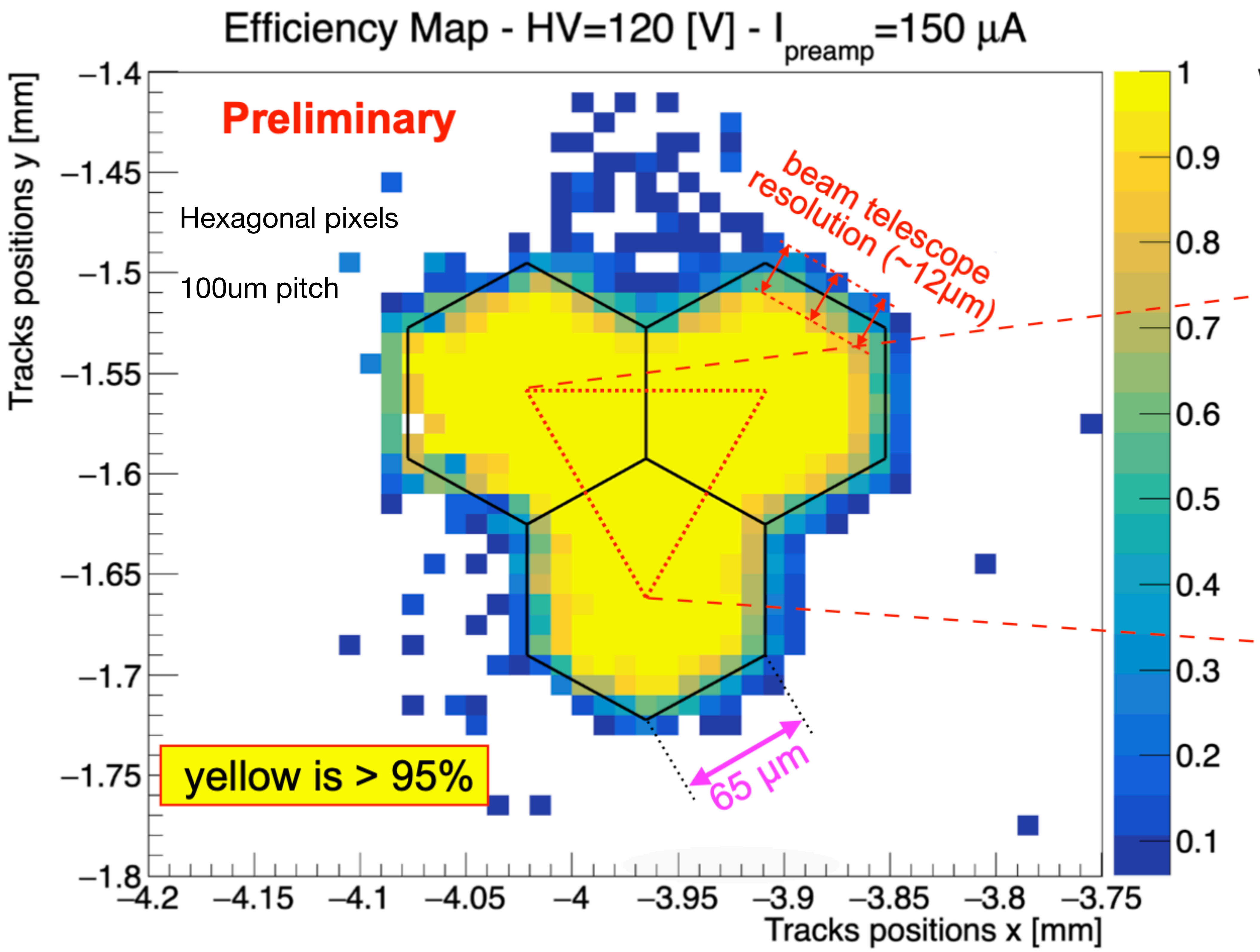
—> HBTs used for fast, high gain, low noise, low power amplifiers

See also talk from Fulvio Martinelli, 15th of September, 18:25:
A monolithic silicon pixel sensor in SiGe BiCMOS for the FASER high granularity pre-shower detector

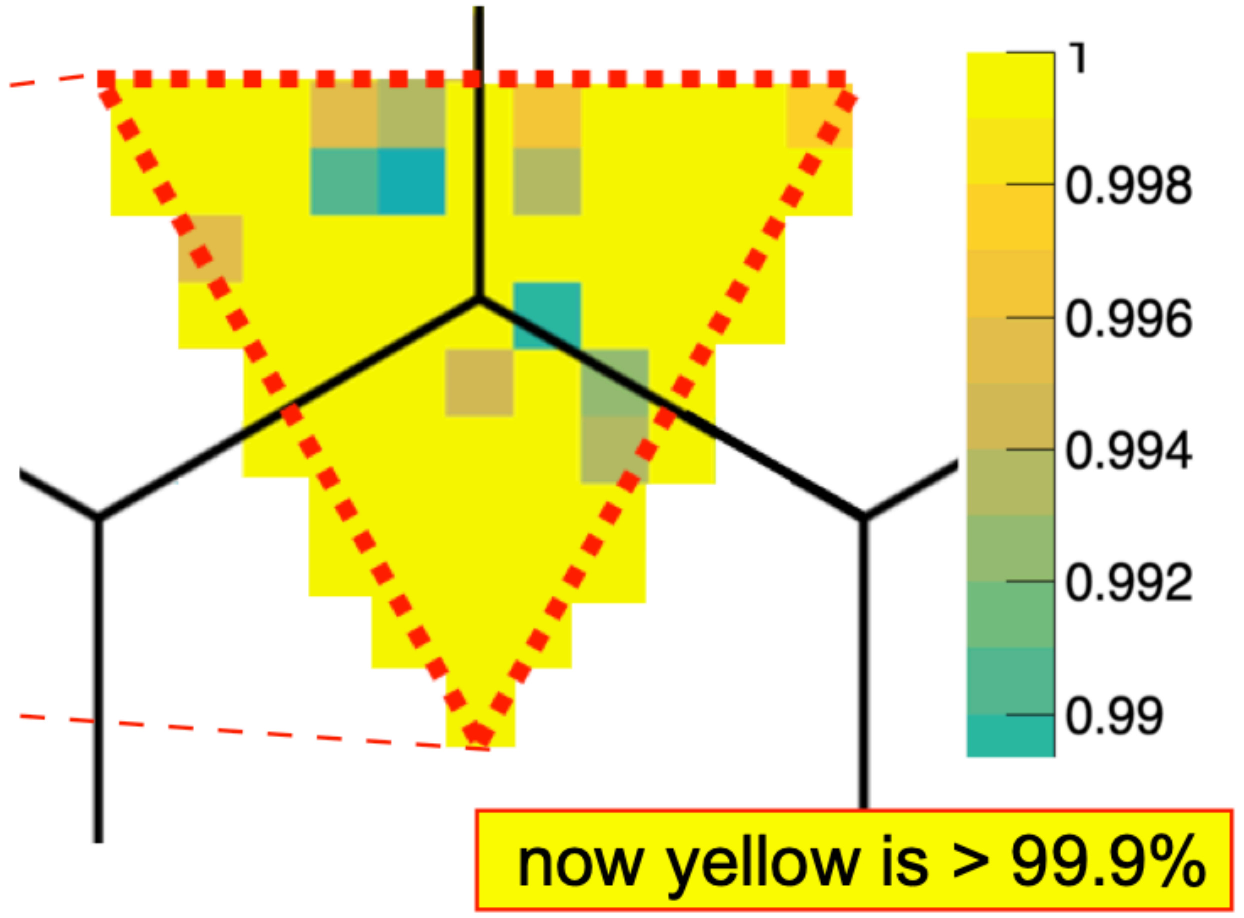
Small-area pixels power consumption: JINST 15 (2020) P11025, https://doi.org/10.1088/1748-0221/15/11/P11025
Hexagonal small-area pixels: JINST 14 (2019) P11008, https://doi.org/10.1088/1748-0221/14/11/P11008
TT-PET demonstrator chip testbeam: JINST 14 (2019) P02009, https://doi.org/10.1088/1748-0221/14/02/P02009
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:



To get rid of the effect of the telescope precision, we can use the bins of **the area inside the red triangle**, that represents the entire pixel area **in the right proportions** :



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

Fully efficient operation, even in pixel edges.

Test-beam measurements - time-stamping

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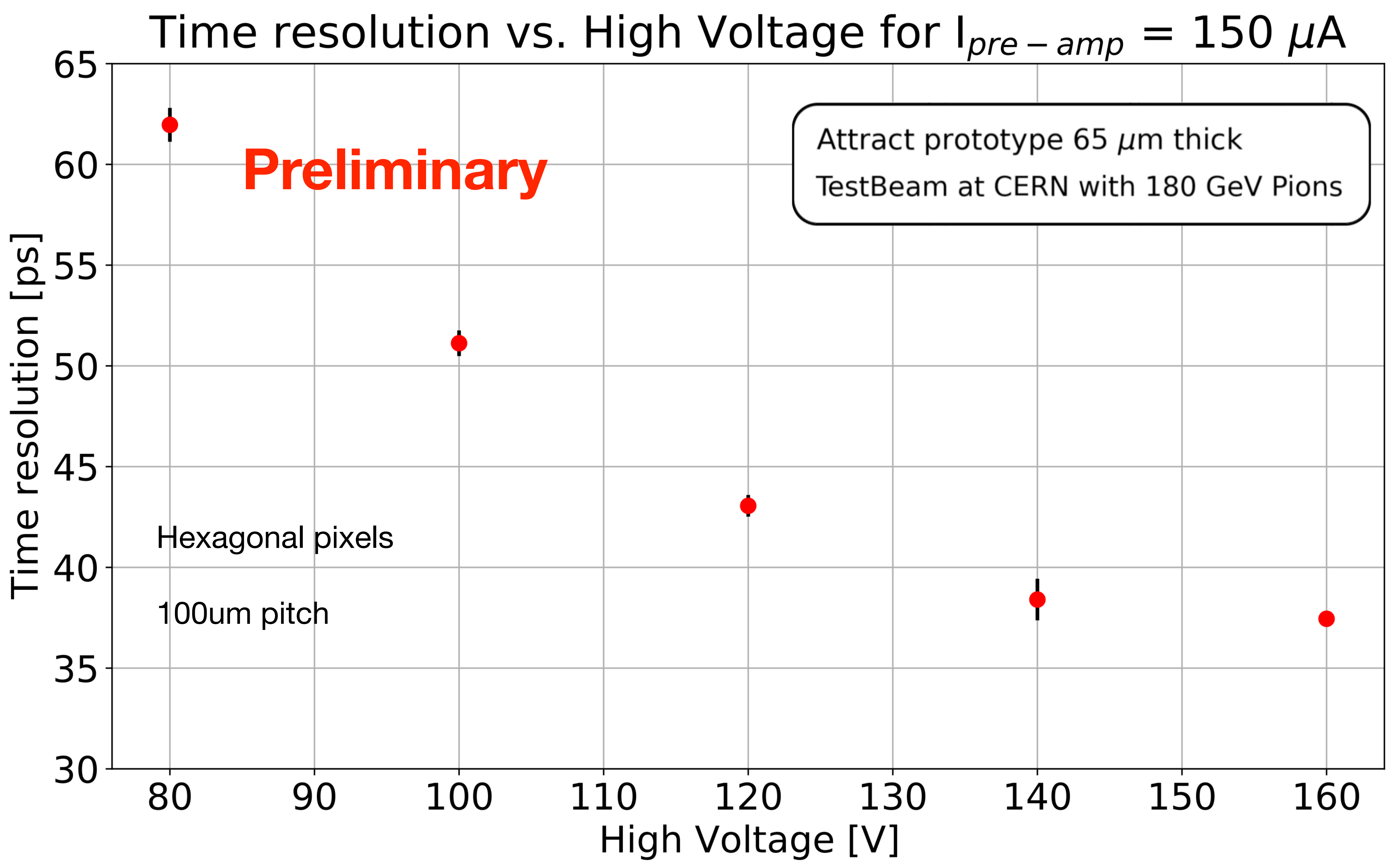
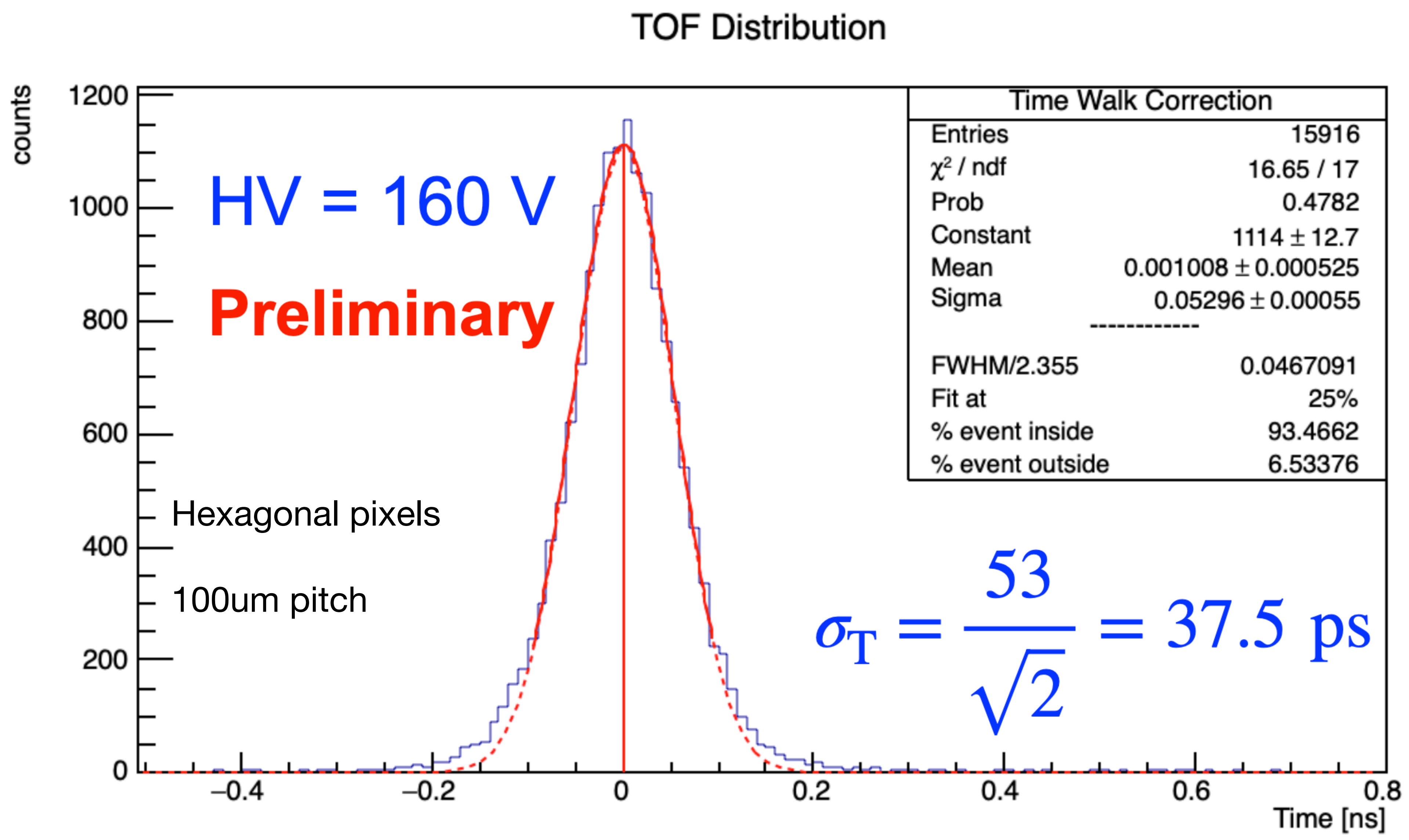




Time stamping precision of ~38 ps without gain layer.

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

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

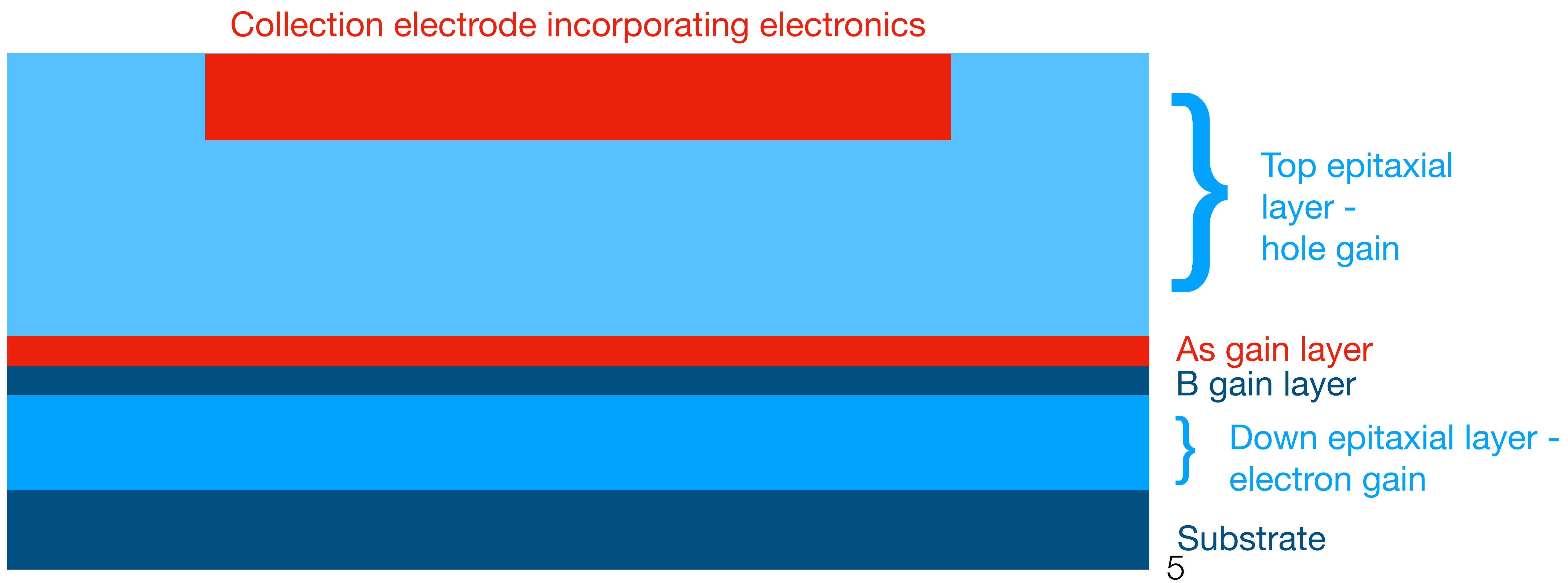
The MONOLITH ERC Advanced Project

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:



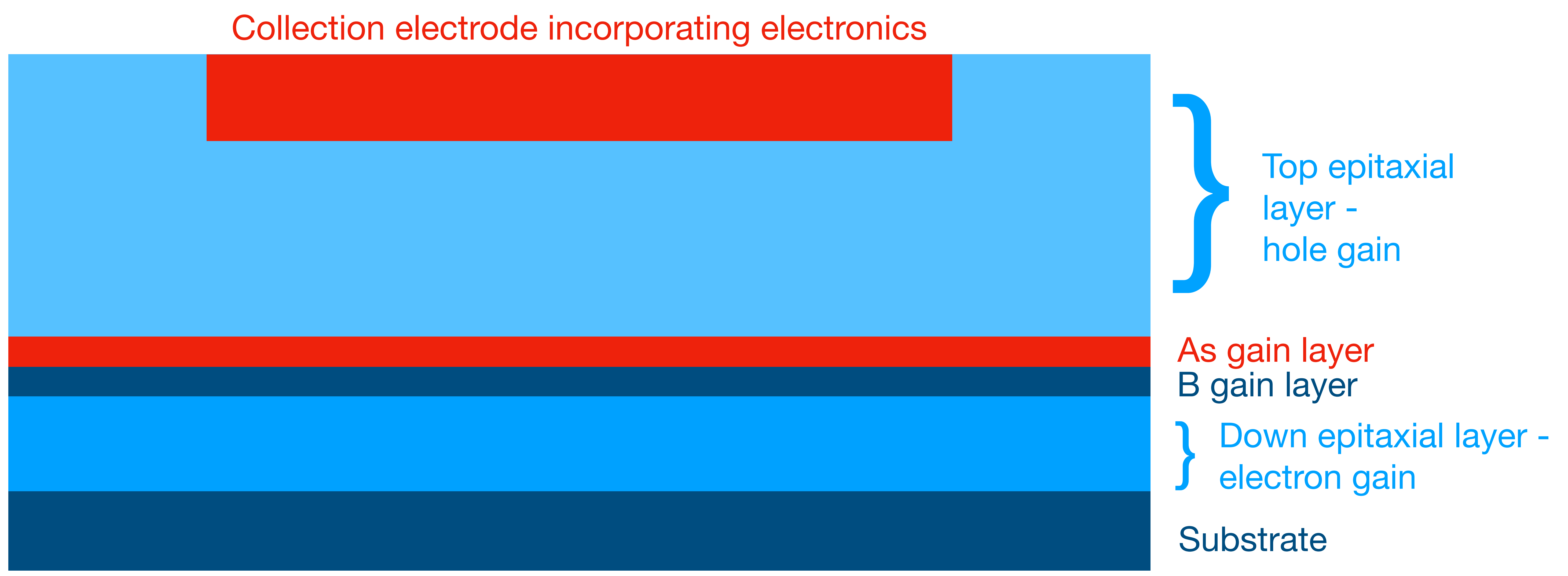
Larger Signal/Noise from sensor and frontend gain:

- 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:



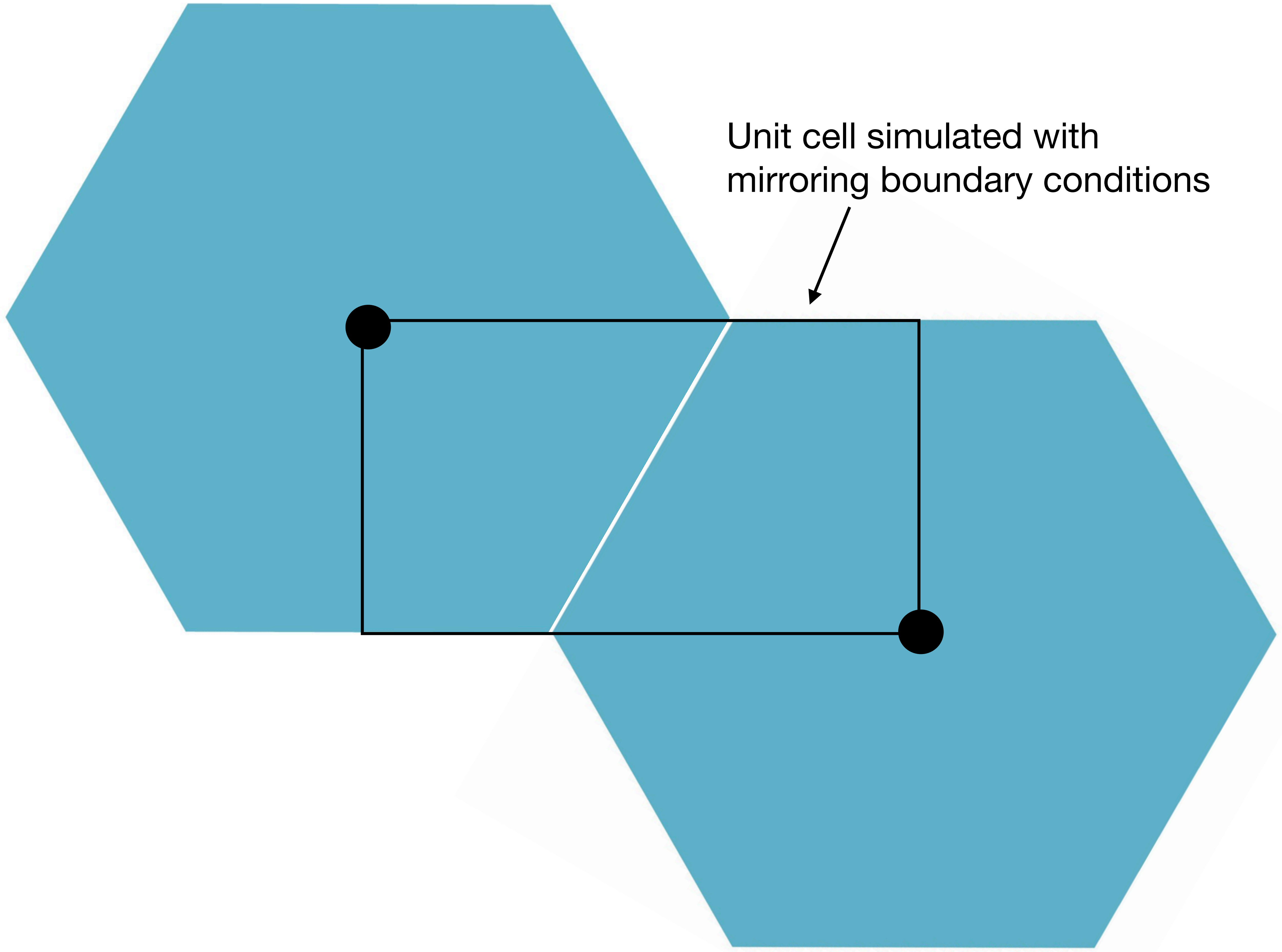
Placement of gain layer deep inside sensor:

—> 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*)

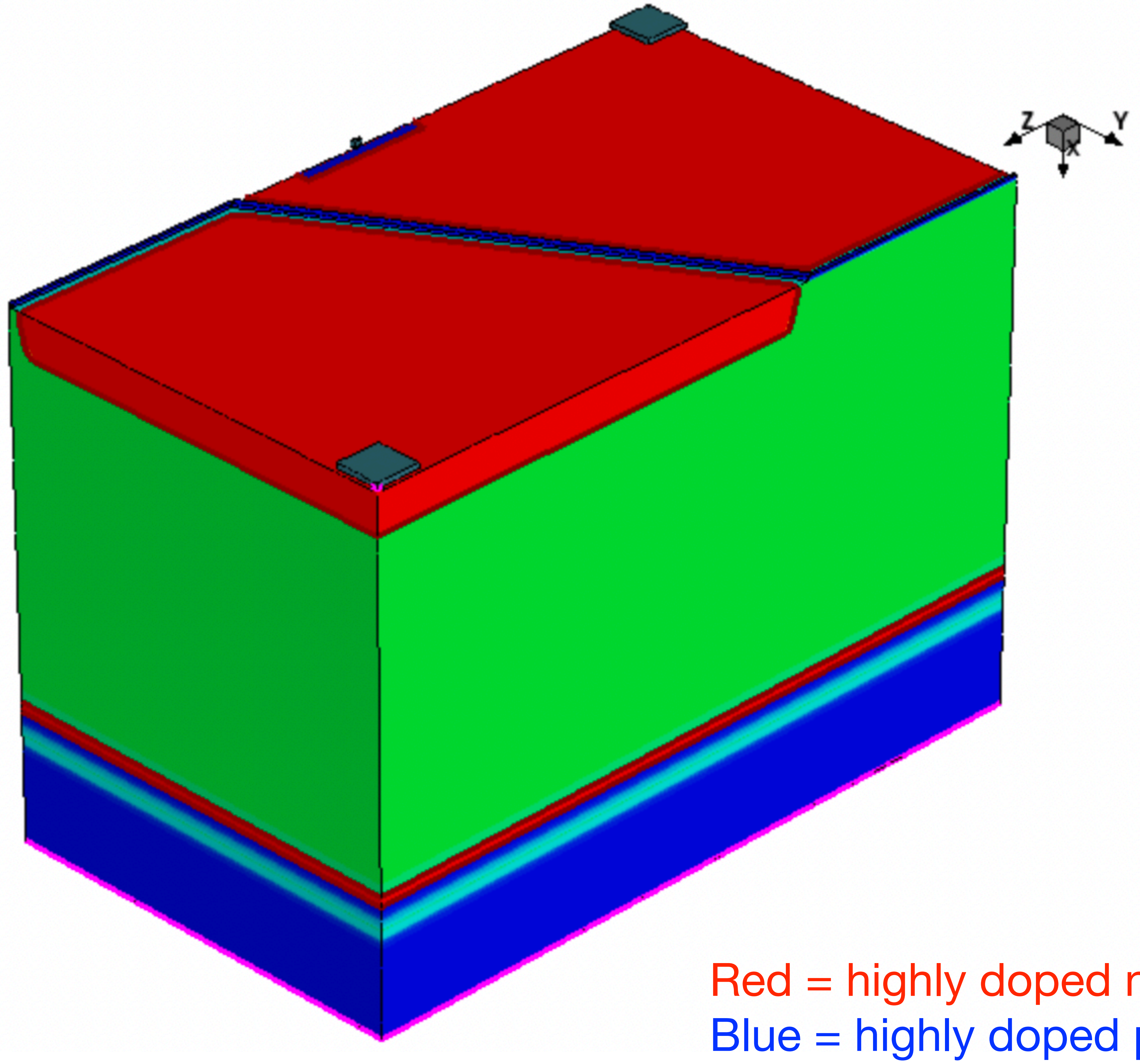
Understanding of sensor concept - 3D TCAD

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:

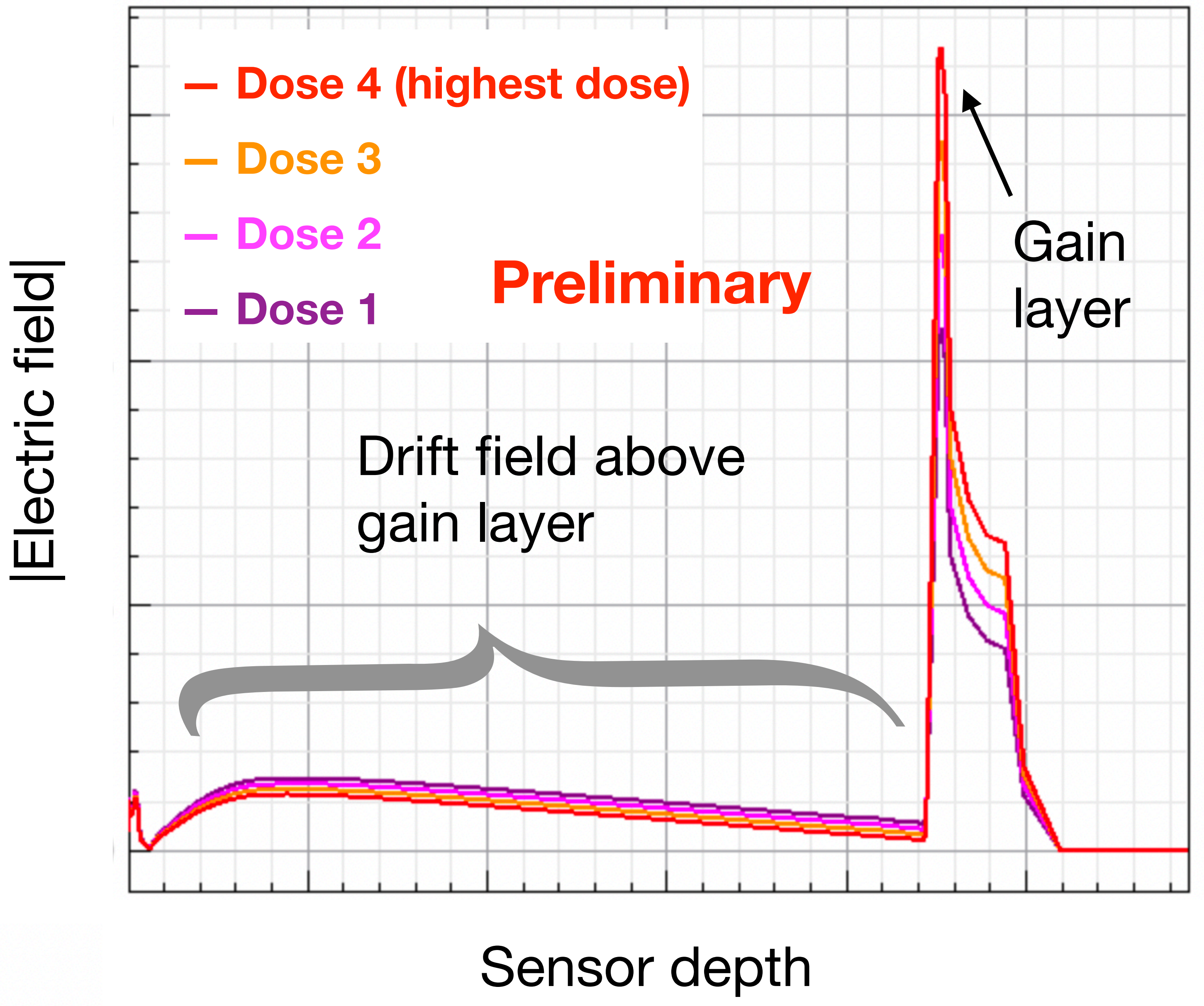


Red = highly doped n-type
Blue = highly doped p-type
Green = lowly doped p-type

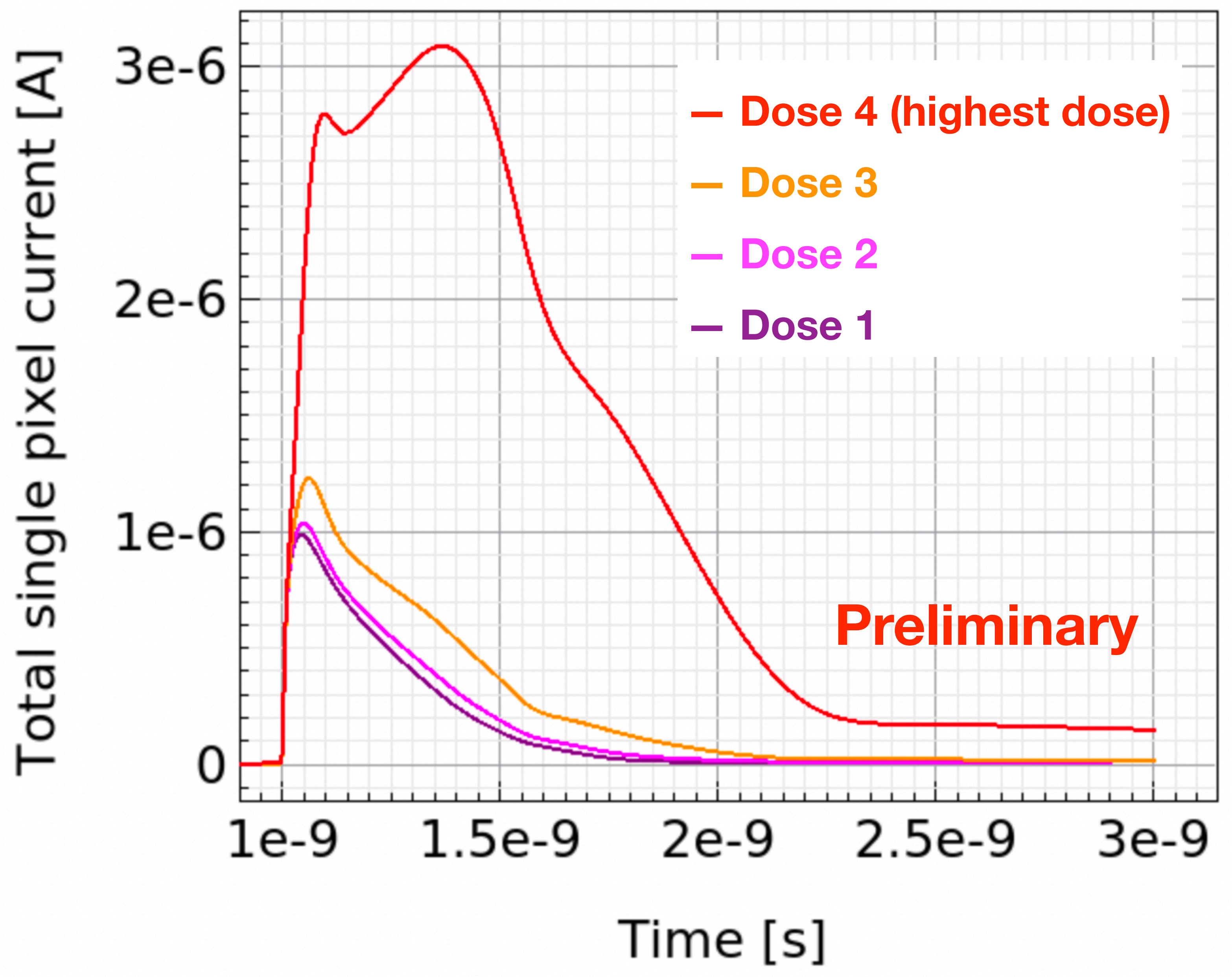
Gain layer optimisation with 3D TCAD

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 and sufficient 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)

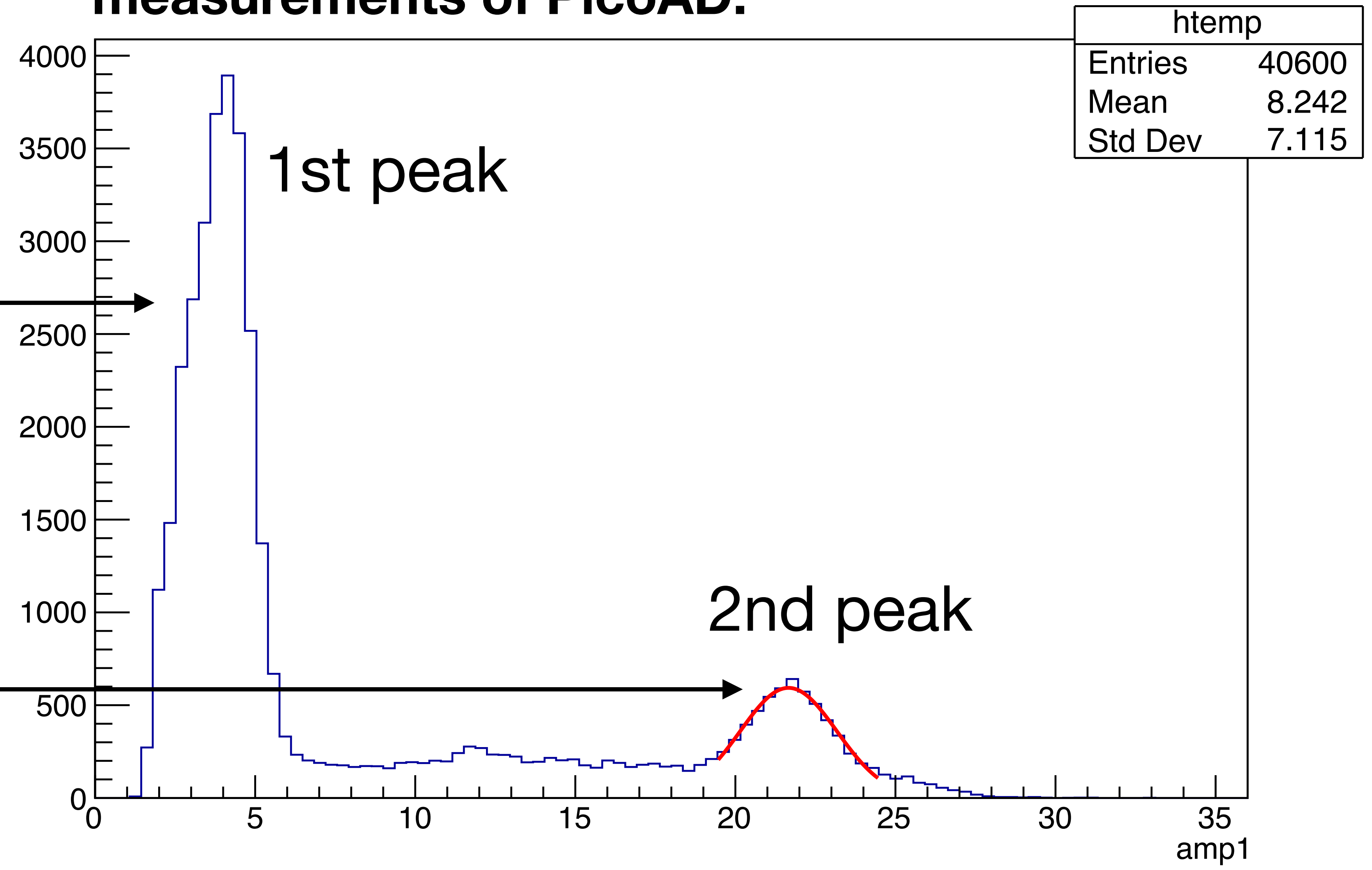
- Higher drift field above gain layer for lower gain layer dose

- 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:

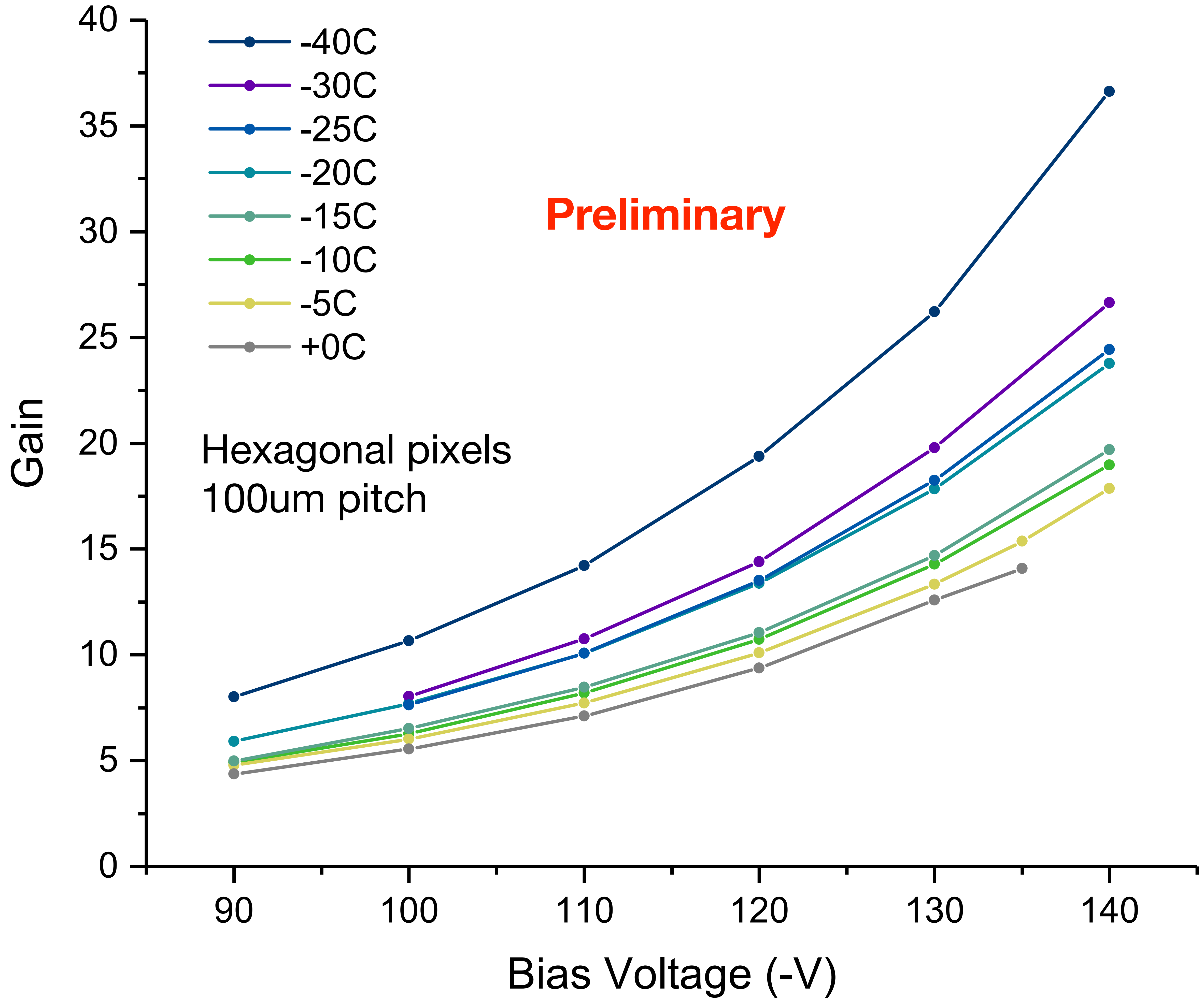
Typical spectrum from 55-iron measurements of PicoAD:



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



—> Proof of novel picoAD concept

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

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)

Summary and outlook

- 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 (gain up to ~40)

- 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

Image of first MONOLITH prototype: