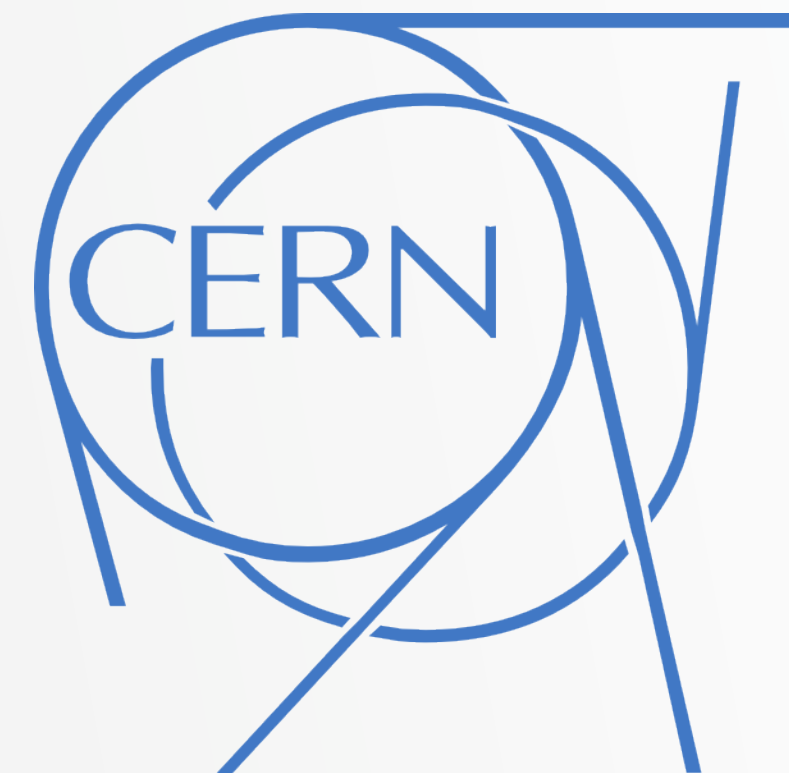


Improving timing and spatial resolution for CMOS sensors with a small collection electrode

M. Munker, T. Kugathasan, W. Snoeys

CLICdp Collaboration meeting

28.08.2019



Outline

- Introduction of technology & challenges
- Optimisation to overcome challenges
- Summary & outlook

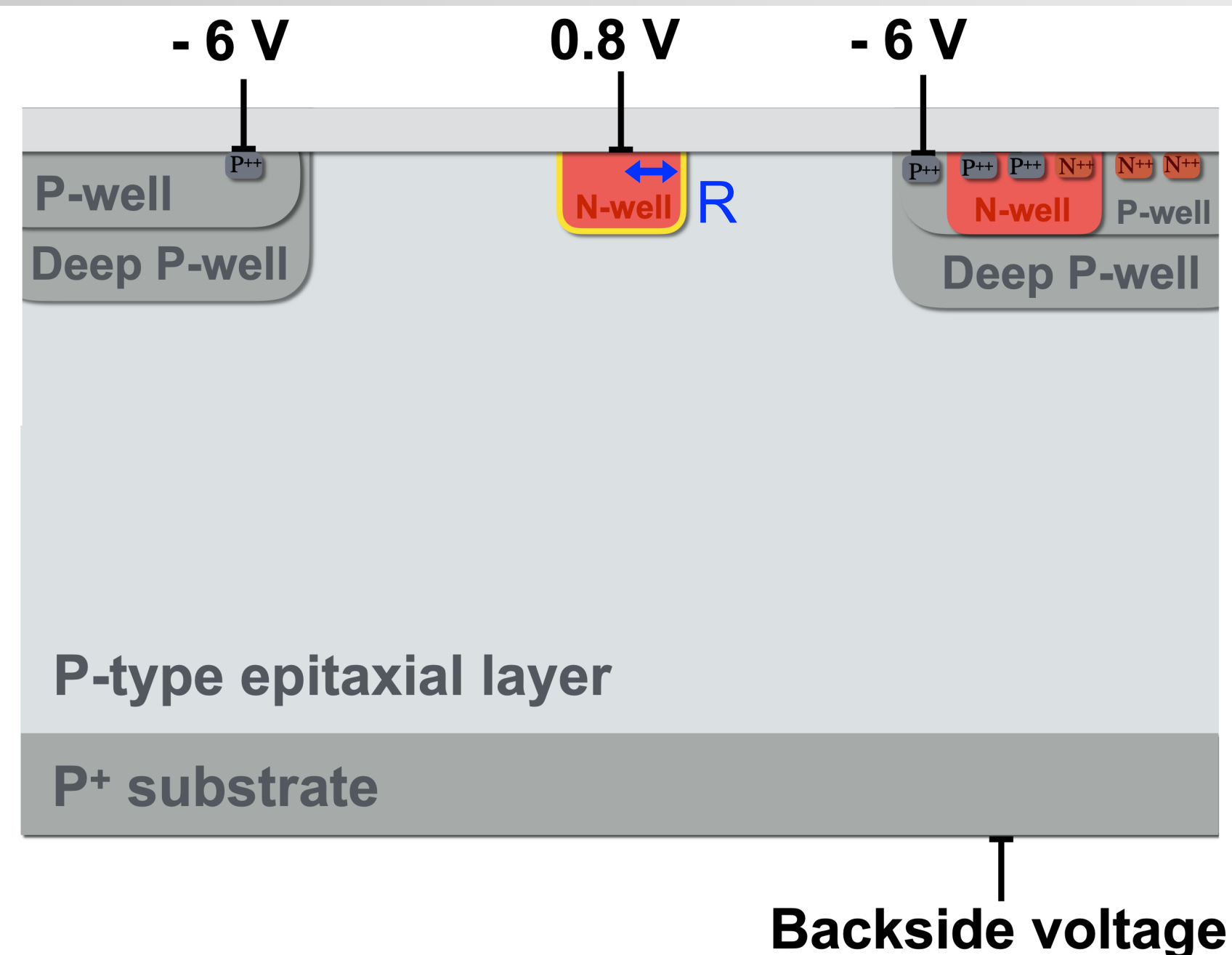
Introduction of technology & challenges

Small collection electrode CMOS - advantages

Monolithic CMOS:

- Standard CMOS technology —> low costs
- No interconnects between readout chip & sensor —> facilitate large scale production effort

Monolithic CMOS sensors with a [small collection electrode](#):



Circuitry placed in shielding p-wells separated from collection electrode:

- > Minimise **radius R** of collection electrode
- > Minimise sensor **capacitance** $C \propto R$
- > Maximise readout **charge** $Q = I/C$, I = induced current
- > Maximise **signal/noise**
- > Minimise **threshold** (below 100 electrons)
- > Minimise **analogue power** $P \propto (C/S)^4$

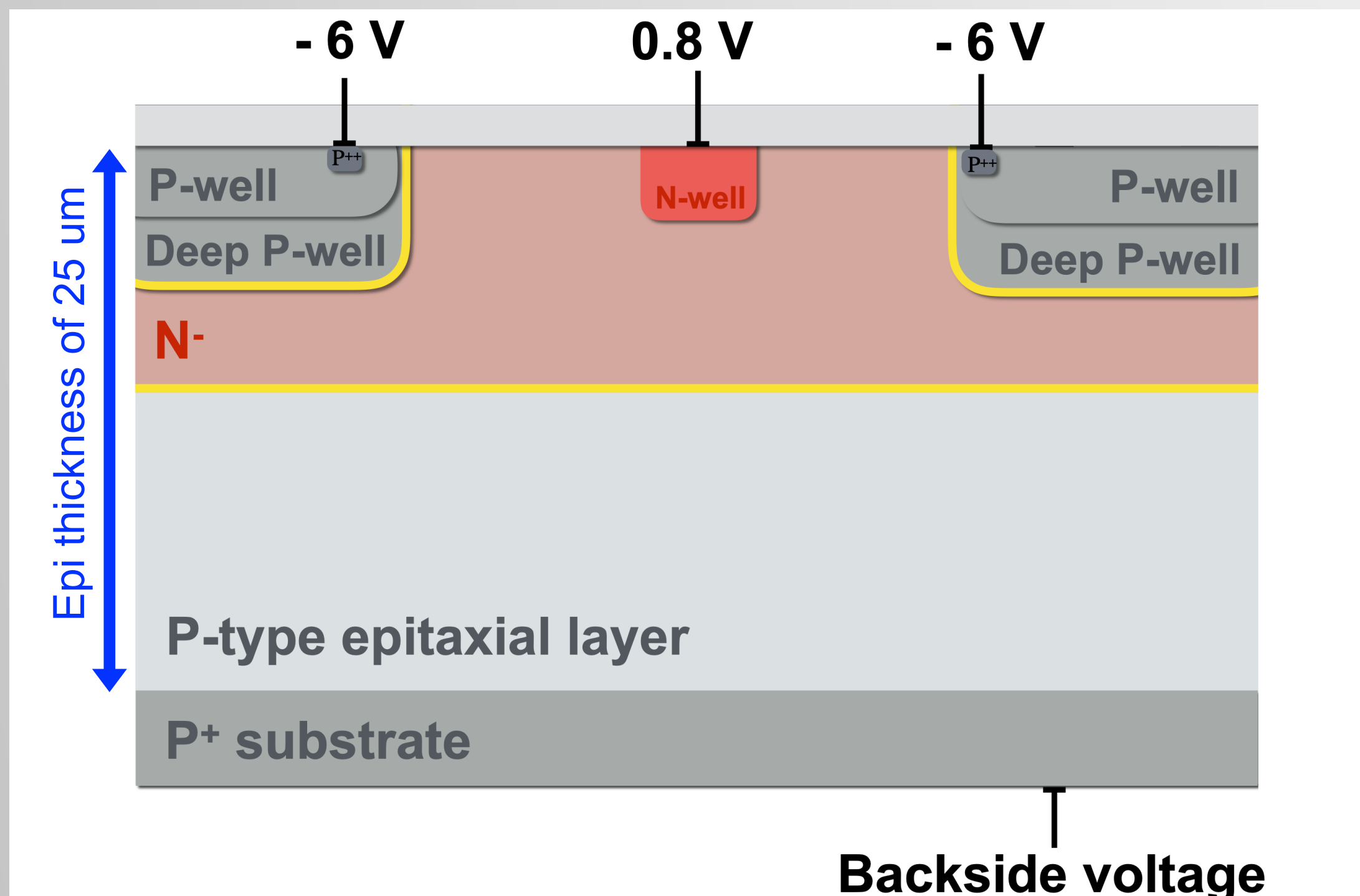
↪ Combine advantages of monolithic CMOS with advantages of small collection electrode.

Small collection electrode CMOS sensors - challenges

Challenge = electric field:

- Placement of circuitry in sensor (p-wells) alters the electric field
- Difficult to reach high field over full pixel area with very small collection electrode
- Especially relevant since bias on p-wells is connected to backside and limited by what circuitry can tolerate ($< 6\text{ V}$)

Modified process / [baseline design for optimisation](#):



To reach higher field:

- **High resistivity** epitaxial layer
- **Process modifications** —> **deep planar n-implant**
W. Snoeys et al.: <https://doi.org/10.1016/j.nima.2017.07.046>
 - > Deep planar junction results in **full depletion**
 - > Isolation of circuitry in p-wells from backside substrate
 - > **Higher bias on substrate** possible

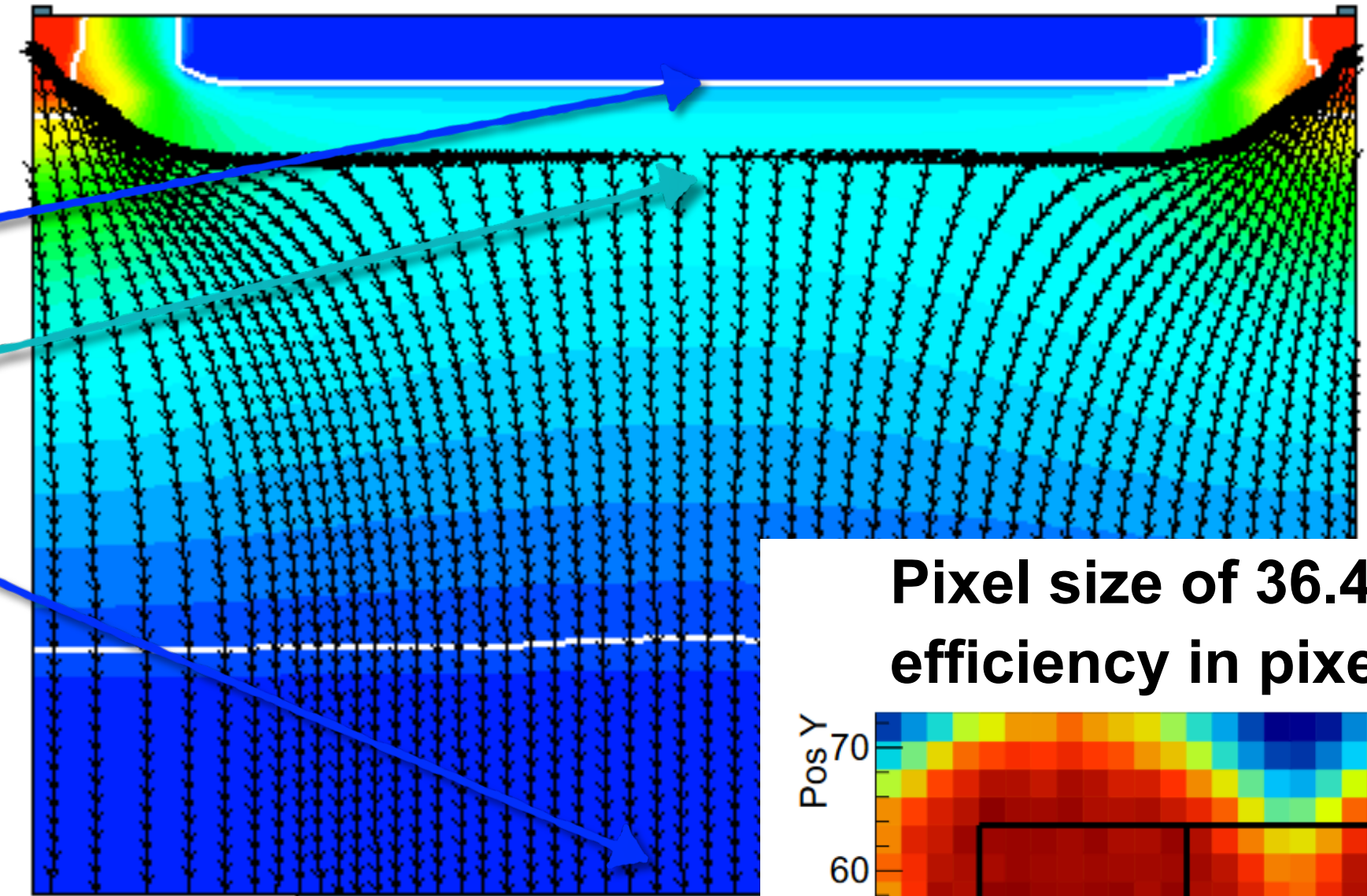
* Epi thickness fixed to 25 um for following talk

How do the p-wells alter the field? - the electric field minimum

Origin of electric field minimum:

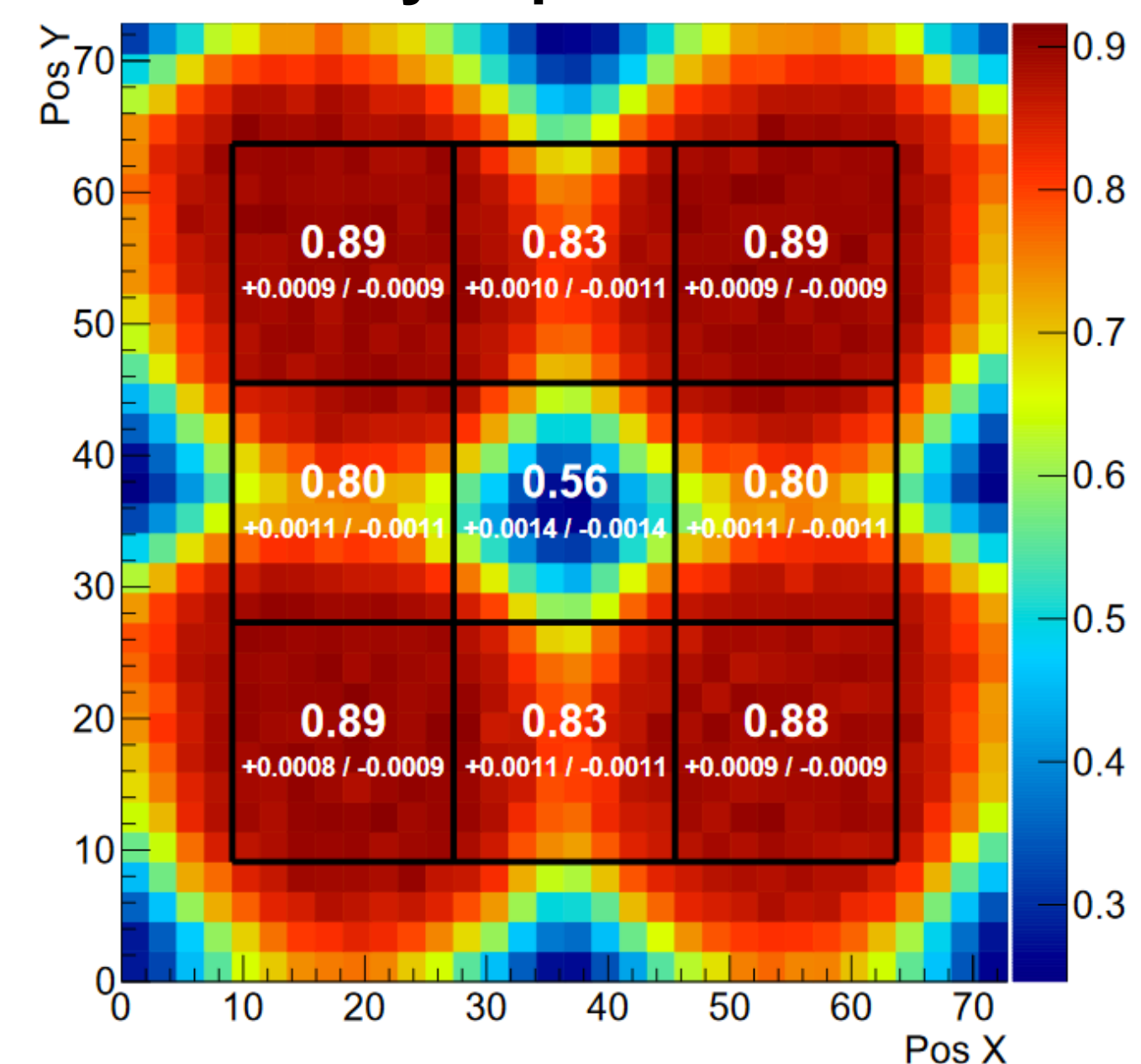
- Placement of p-wells with circuitry at pixel border
- > **Two bias terminals** on front & backside of sensor
- > Between both, **maximum potential** crossed
- > Local point of **zero electric field**
- > Electric field streamlines (and as such collected charge) go first through minimum before they are bend towards collection electrode
- > **Significantly longer drift path**
- > **Less precise timing & charge loss after irradiation**

Pixel size of 36.4 um, potential & streamlines:



Modified process, bias of -6 V

Pixel size of 36.4 um, efficiency in pixel cell:

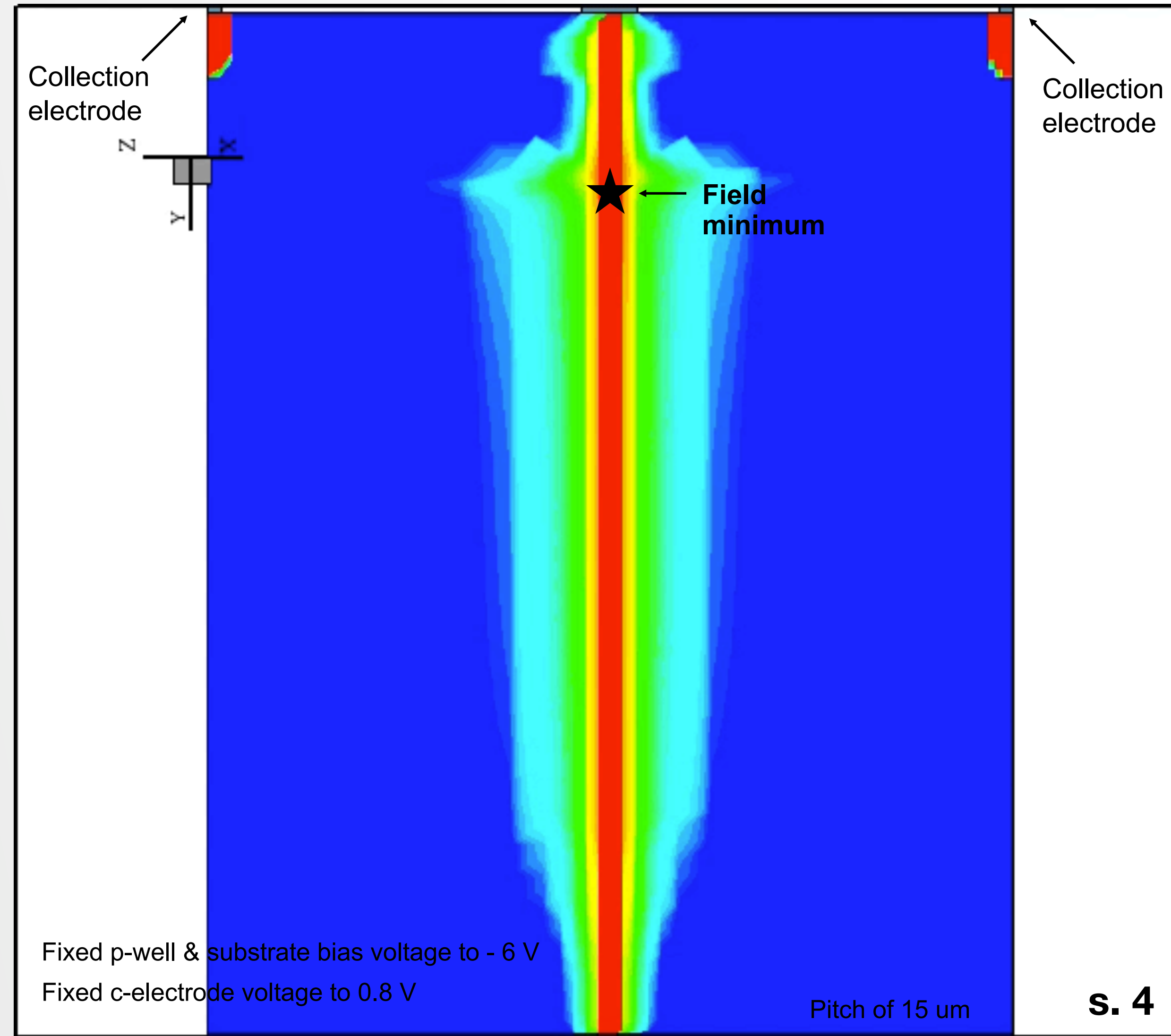


Measured charge loss in pixel corners of Mini-Malta after irradiation with dose of $1e^{15}$ neq/cm²:

Main challenges & differences with standard planar sensors

- Electric field minimum:
—> Crucial for **charge collection**.

Signal charge density after particle incidence at pixel border (100 ps steps):



Main challenges & differences with standard planar sensors

Electrostatic potential for different bias voltage on p-wells & backside:

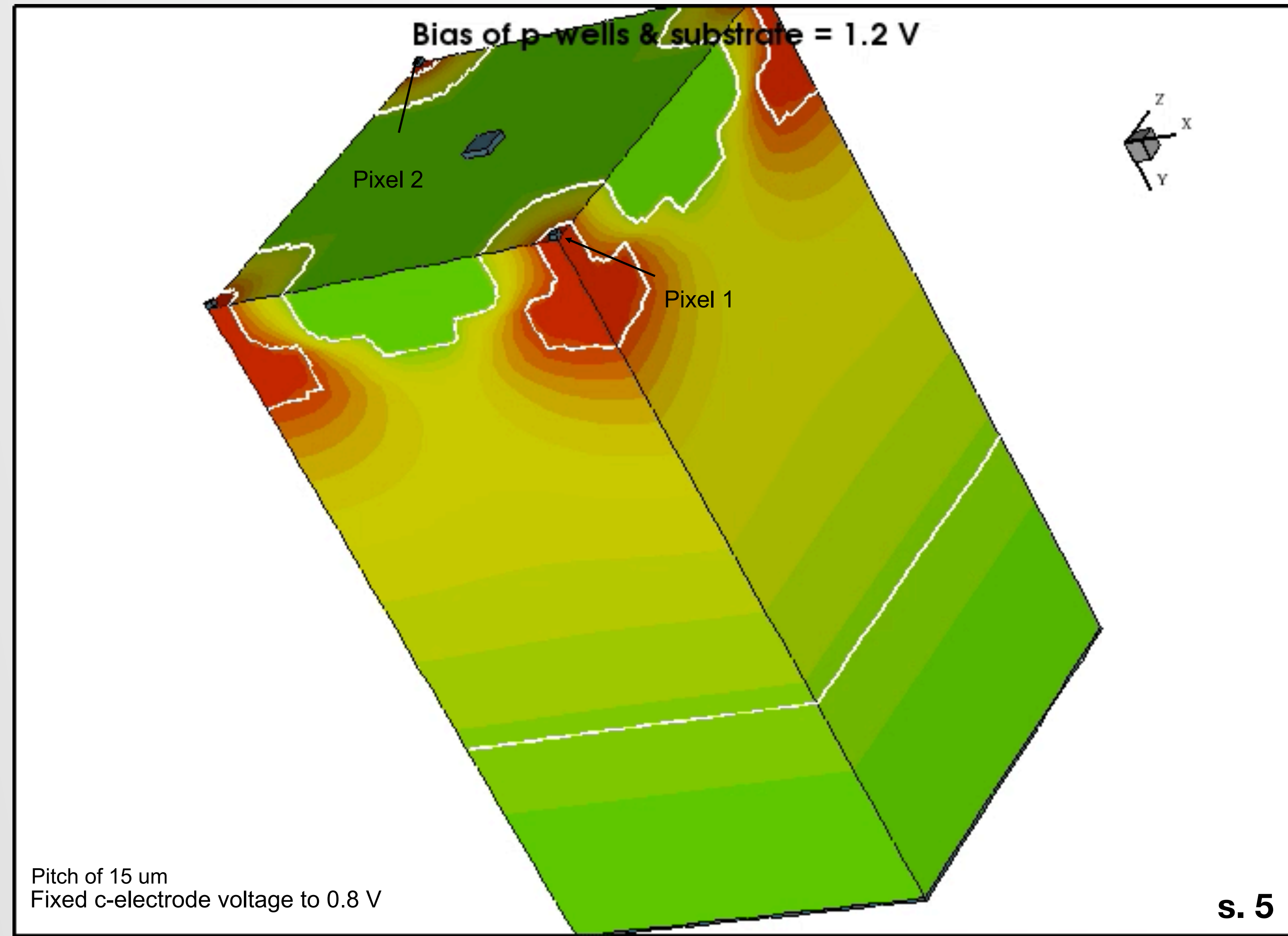
- Electric field minimum:
—> Crucial for **charge collection**.

- Evolution of depletion:
—> Crucial for **capacitance**.



↪ **Need to understand & optimise electrostatic solution**
(electric field, depletion & capacitance)

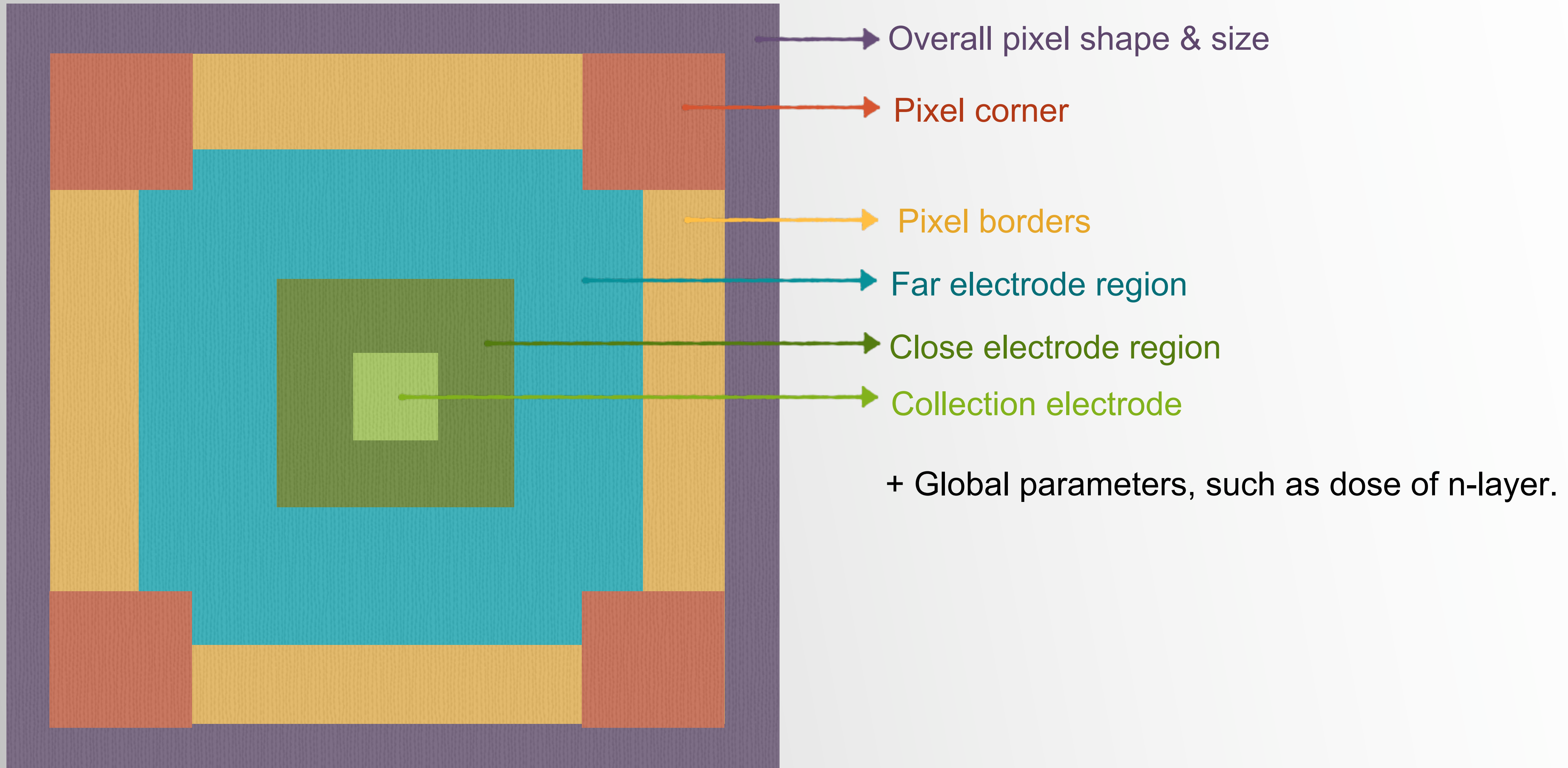
↪ **Finite element 3d TCAD simulations necessary.**

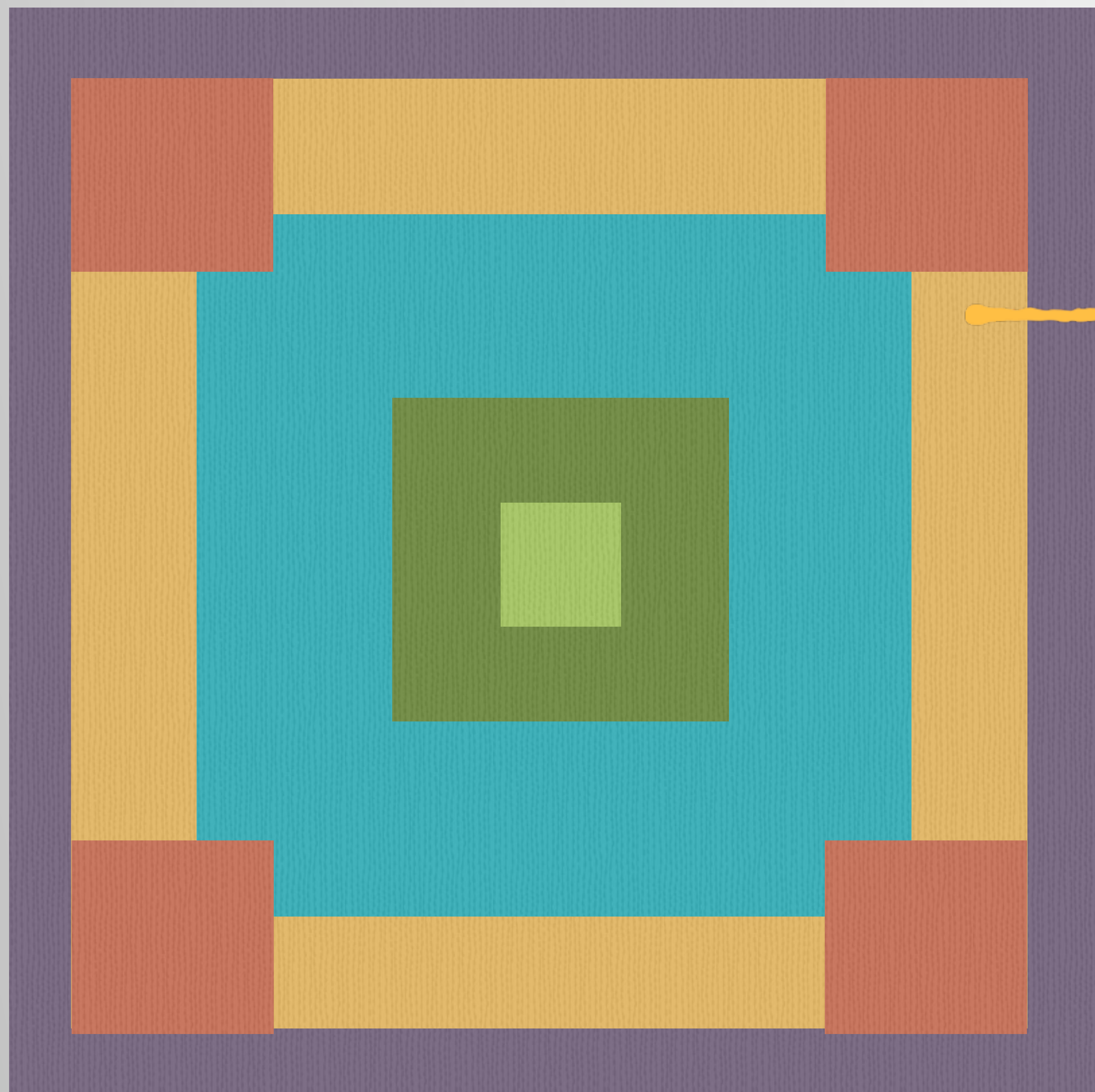


Optimisation to overcome challenges

Optimisations to overcome challenges

Schematic of top-view on pixel:

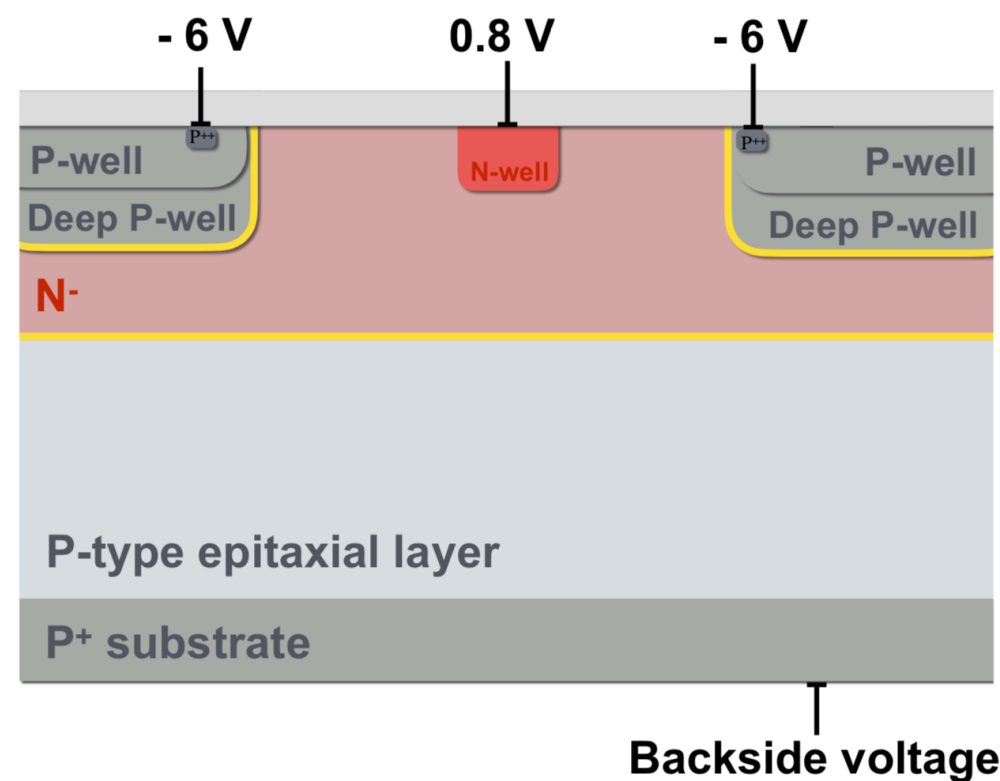




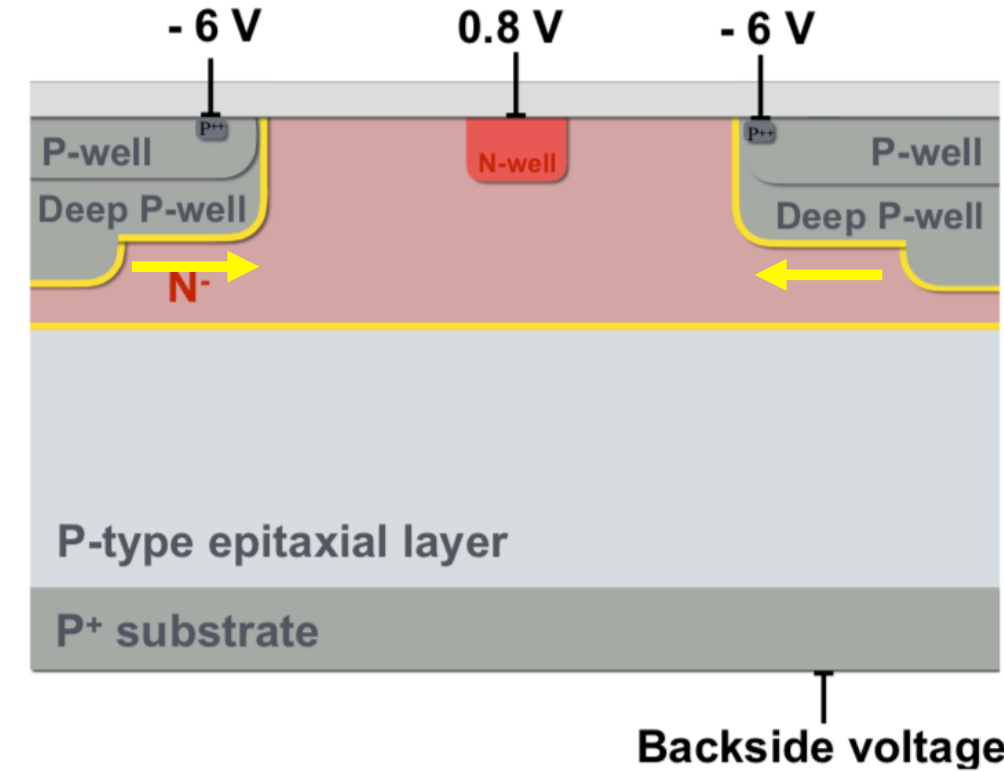
Pixel borders

Optimising the pixel borders - push charge out of minimum

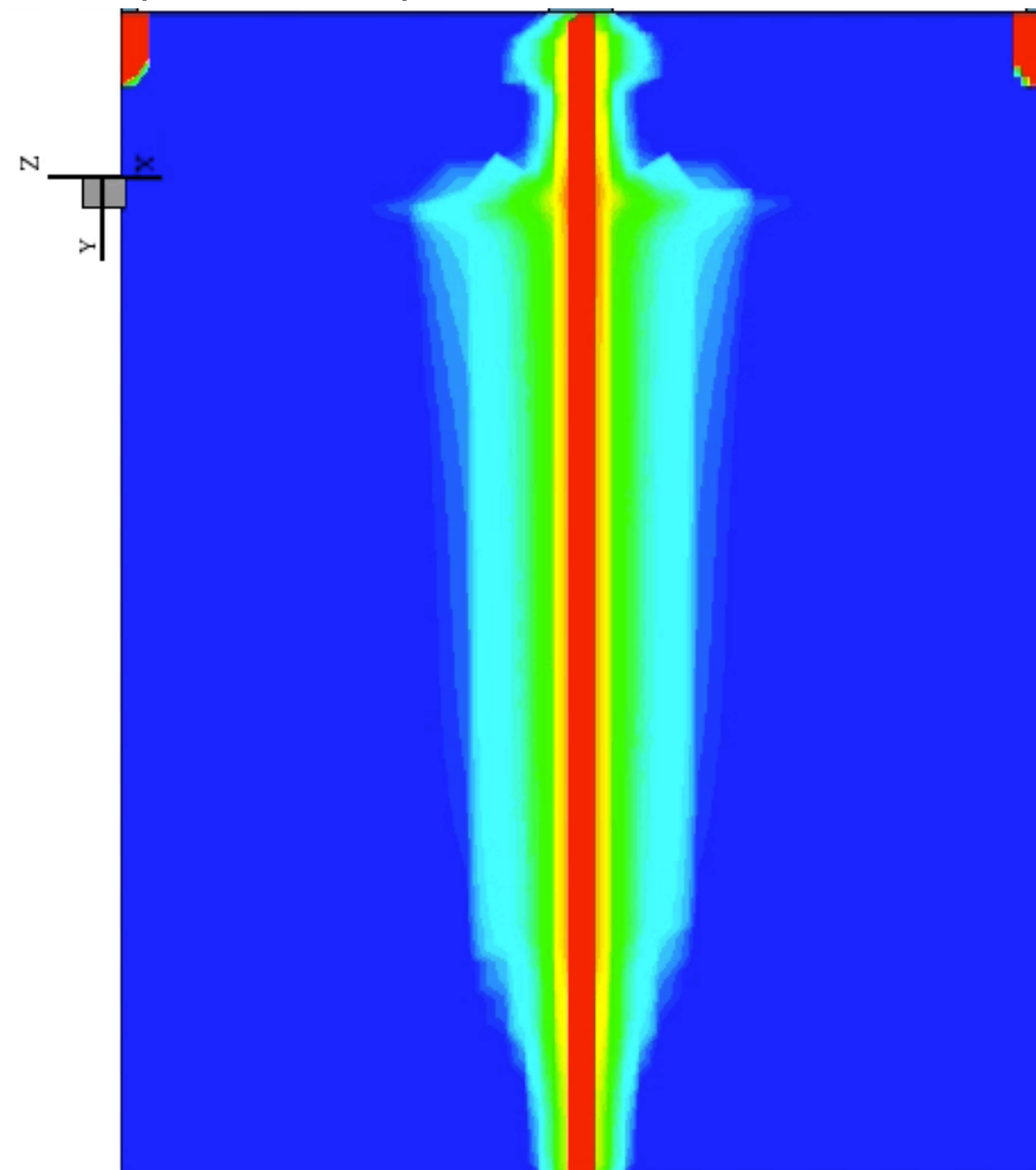
Blanked n-layer, modified process:



Additional p-implant:



Signal charge density after particle incidence (100 ns steps):

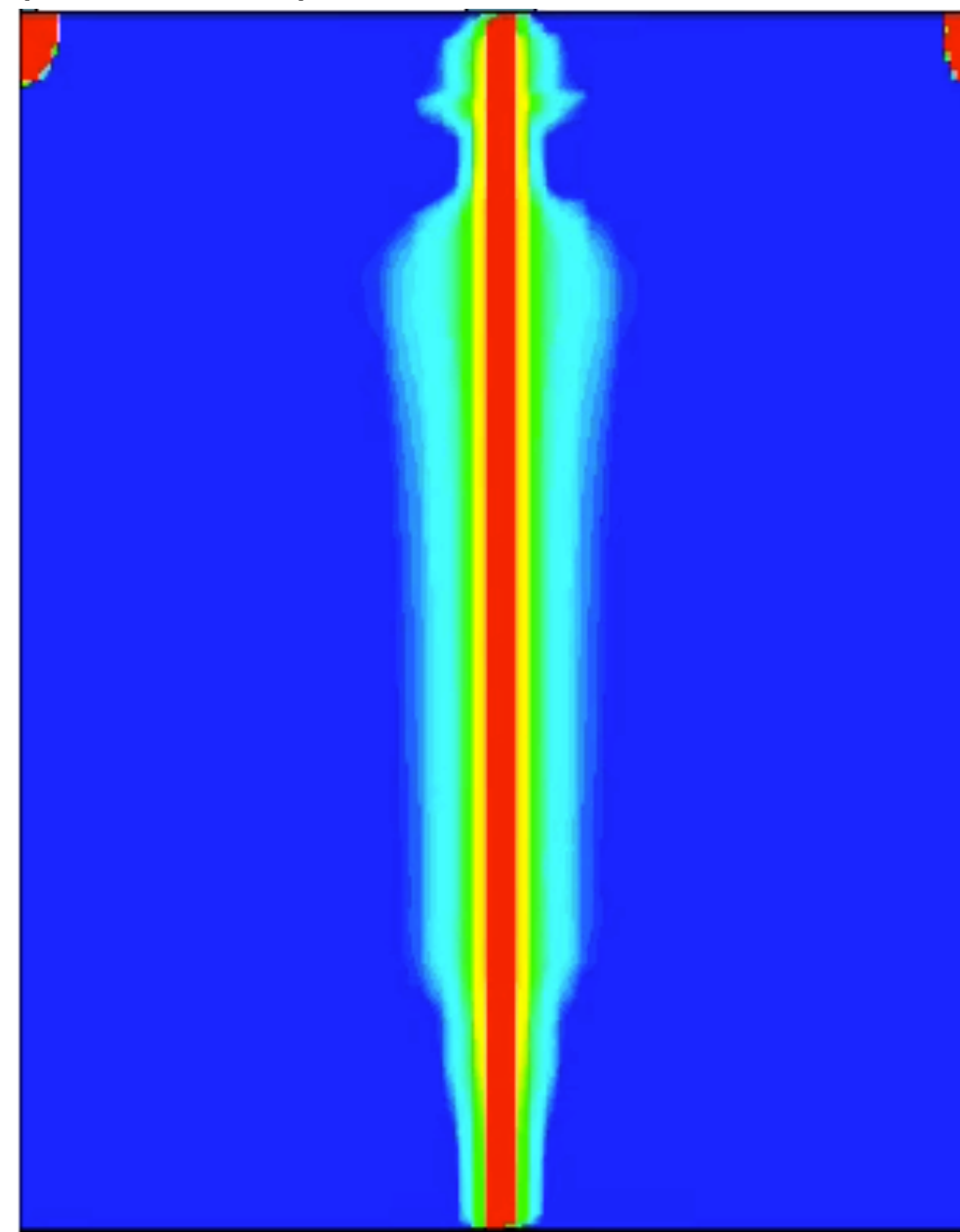


Fixed p-well & substrate bias voltage to -6 V

Fixed c-electrode voltage to 0.8 V

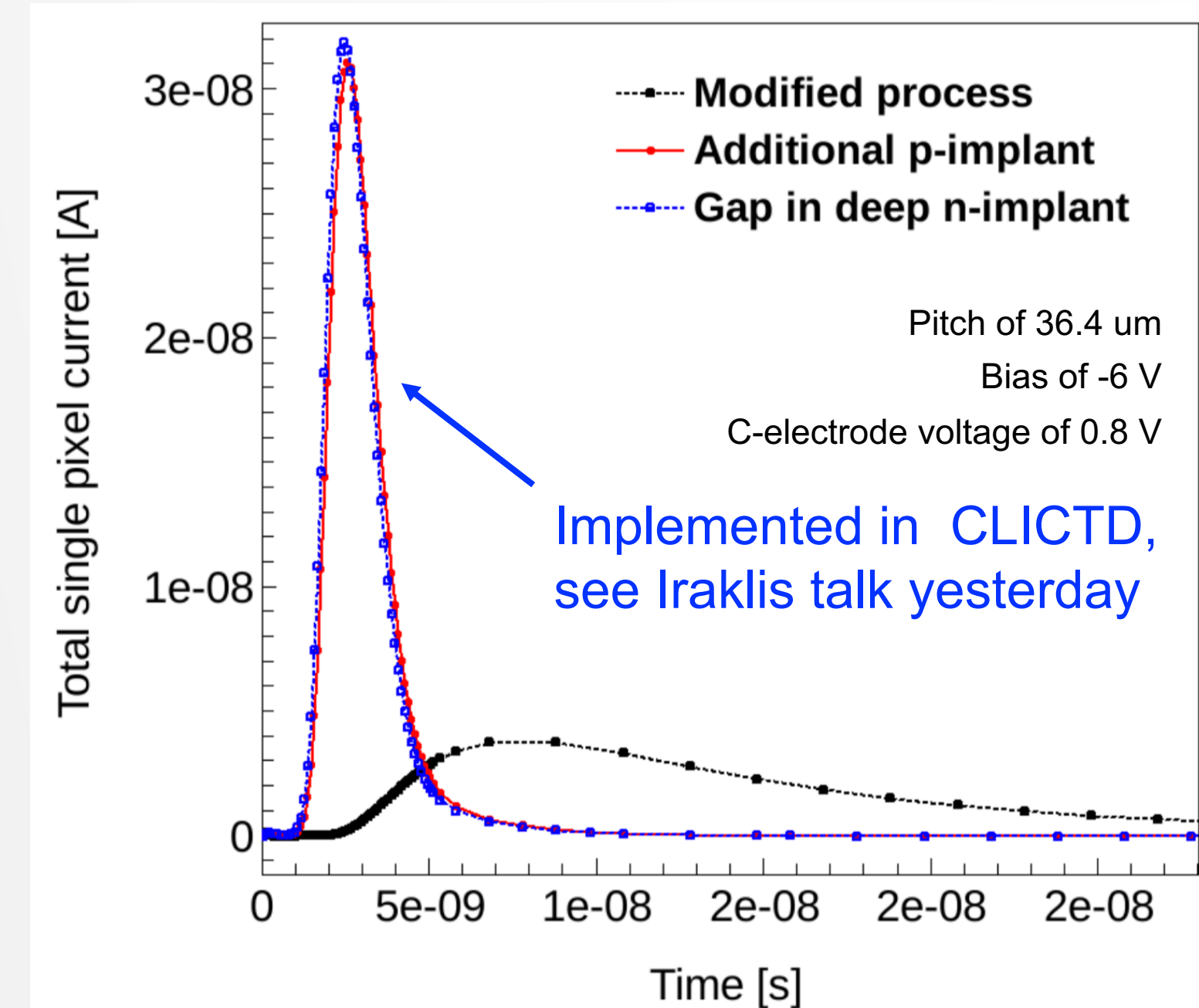
Pitch of 15 um

Signal charge density after particle incidence (100 ns steps):

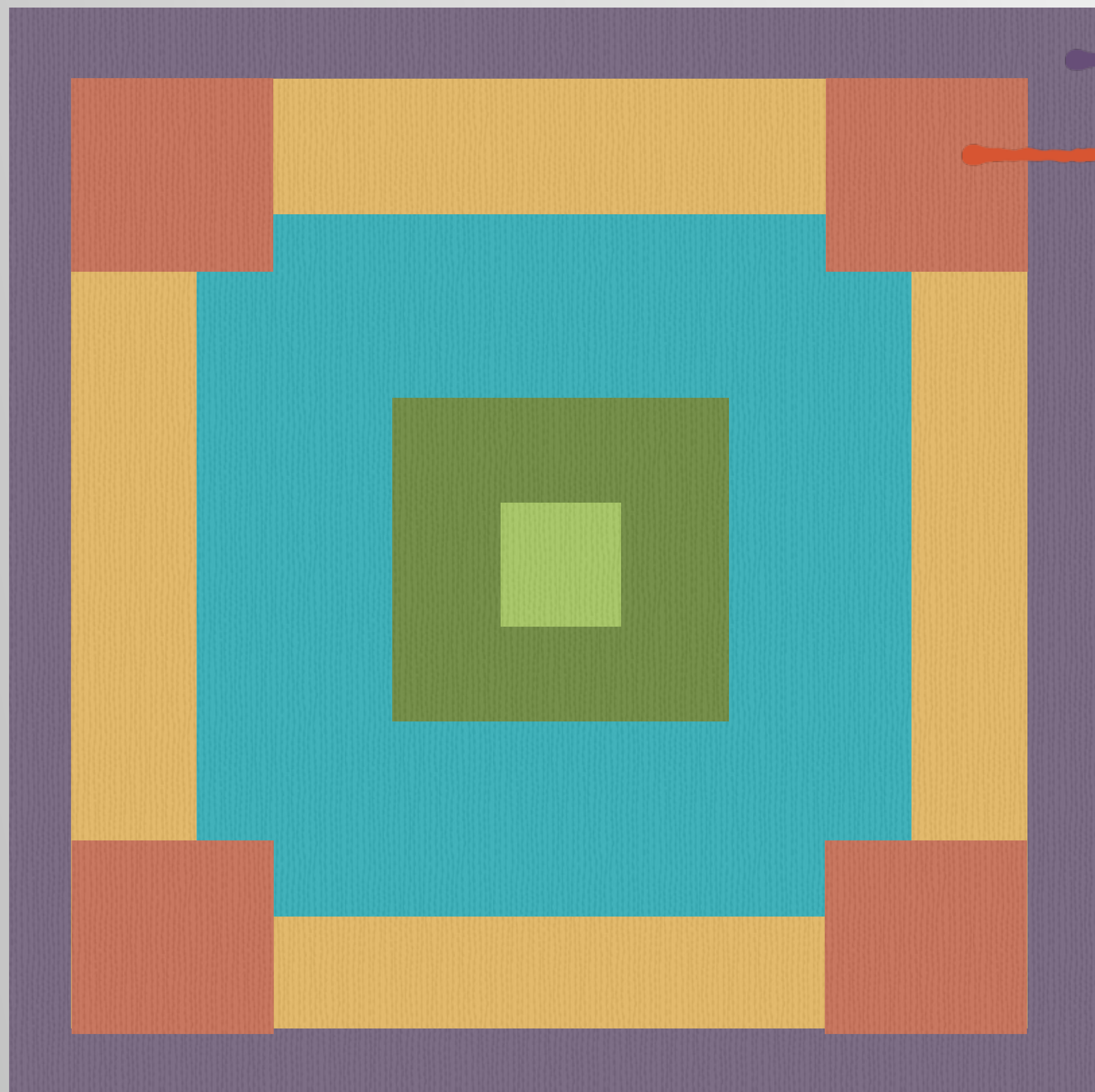


Sensor designs to push charge out of electric field minimum: [M. Munker et al 2019 JINST 14 C05013](#)

- **Additional p-implant** at pixel borders
 - **Gap in n-layer** at pixel borders
- > **Lateral junction/electric field (yellow arrows)** pushes charge at pixel border towards collection electrodes



Fully efficient for pixel pitch of 36.4 um after irradiation of $1e^{15}$ neq/cm² —> proof of principle.



Overall pixel shape & size

Pixel corner

Optimising the overall pixel shape - hexagonal pixels

Why hexagonal pixels, especially for this technology?:

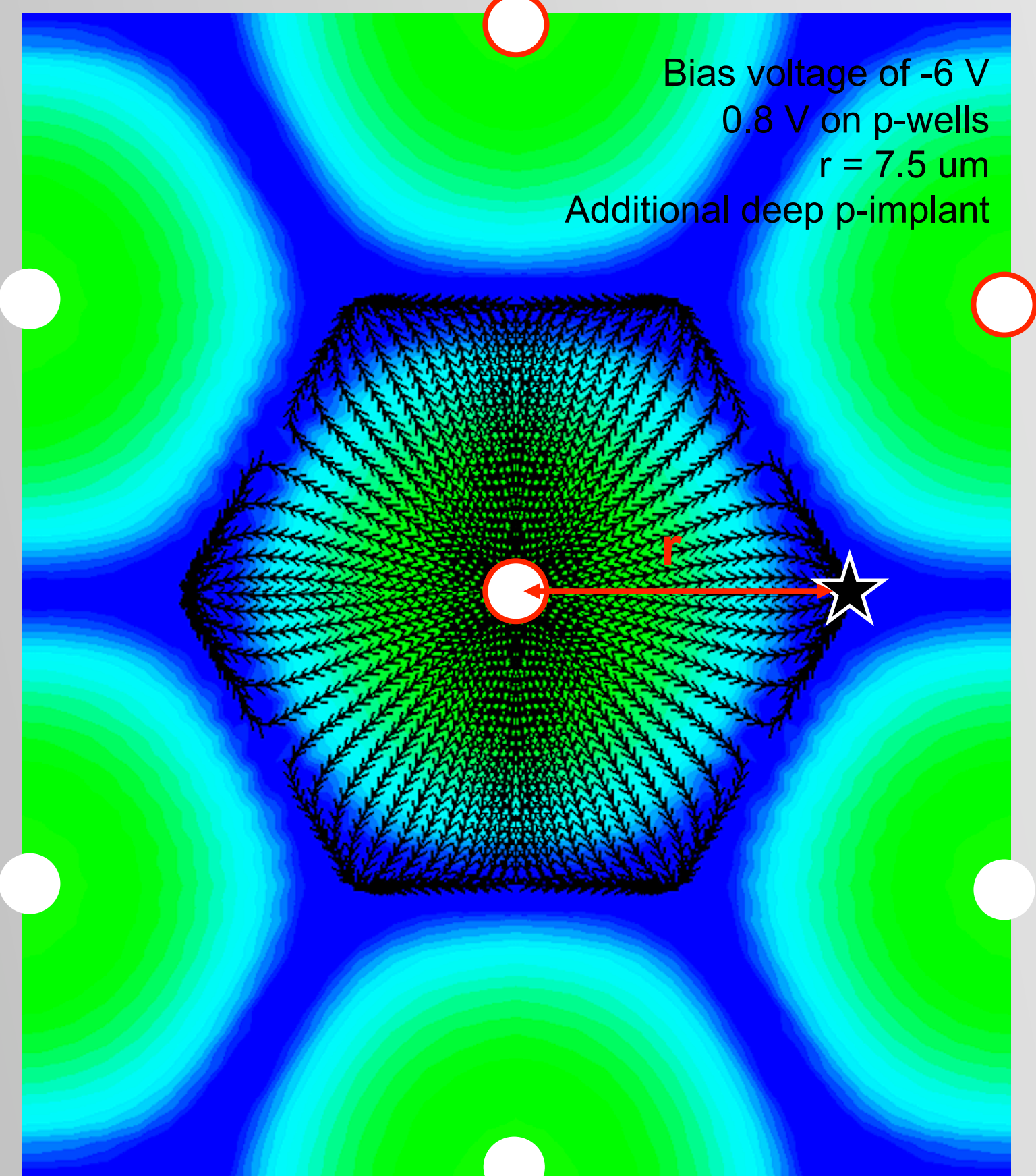
Keep pixel & circuitry area constant while further reducing the distance between the collection electrodes

1. Reduce low field edge regions
2. Reduce number of closest neighbours —> reduce charge sharing —> improved signal/noise in seed pixel

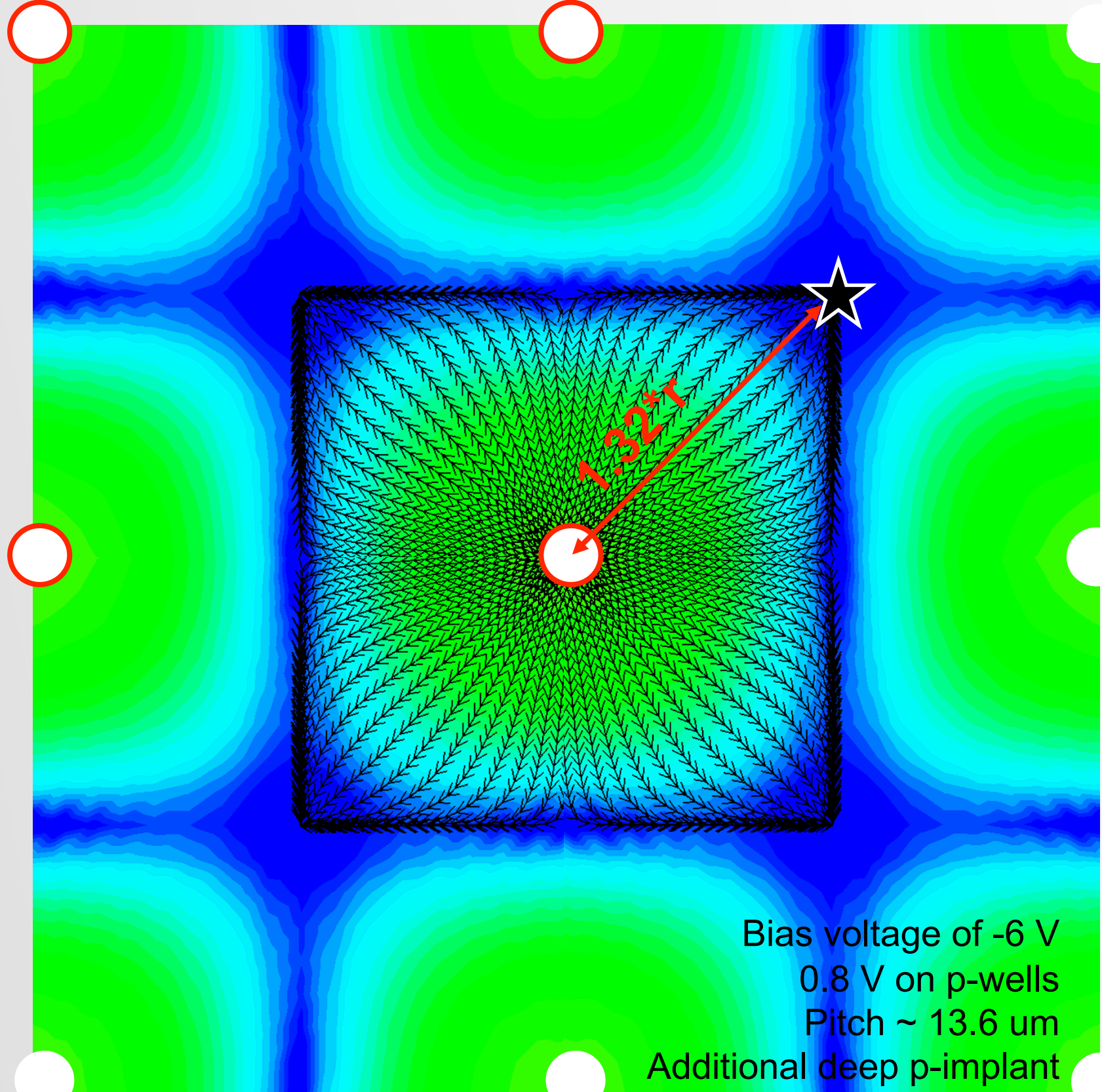
→ Improve timing

Absolute value & streamlines of electric field:

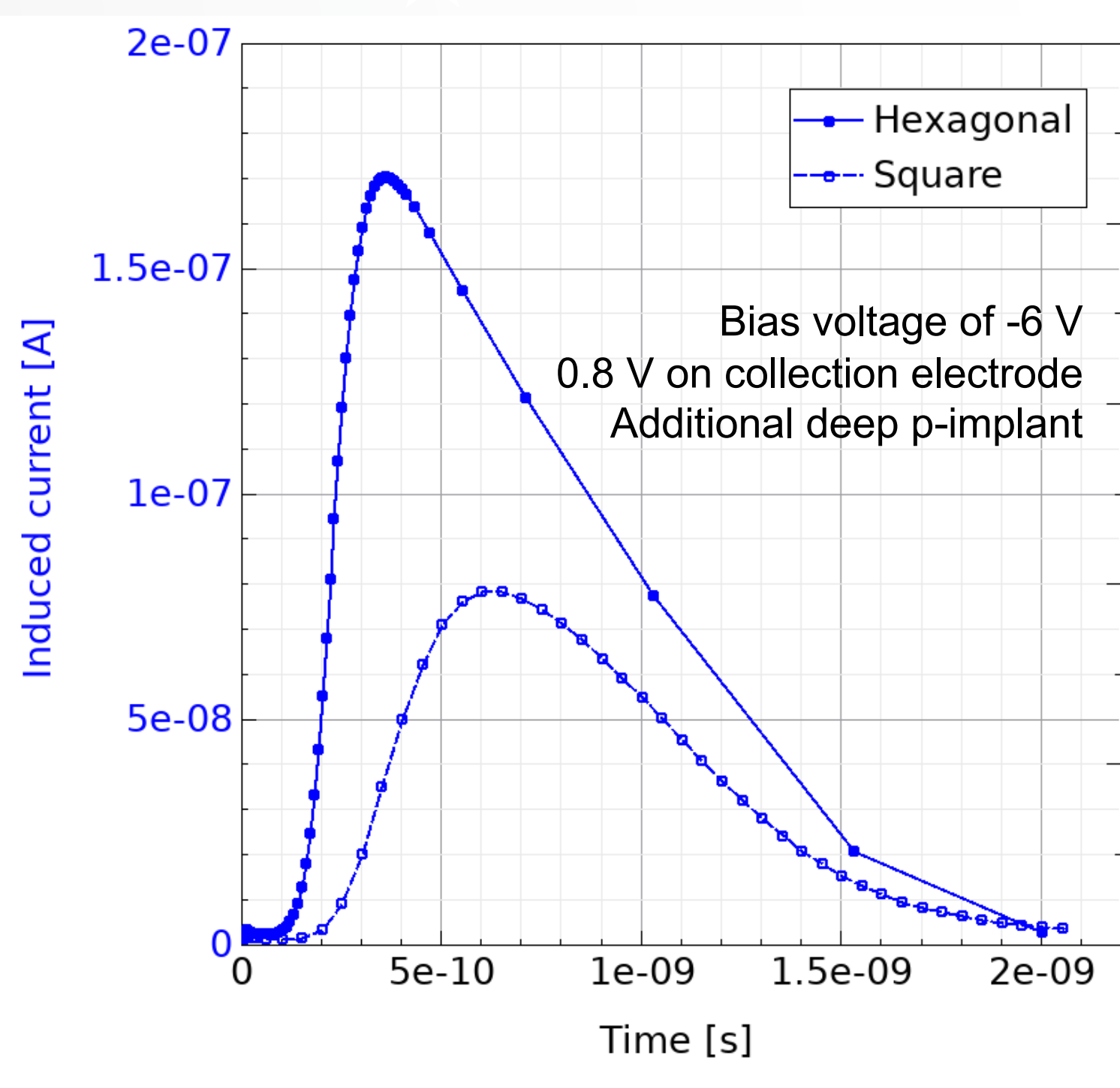
Hexagonal pixel:

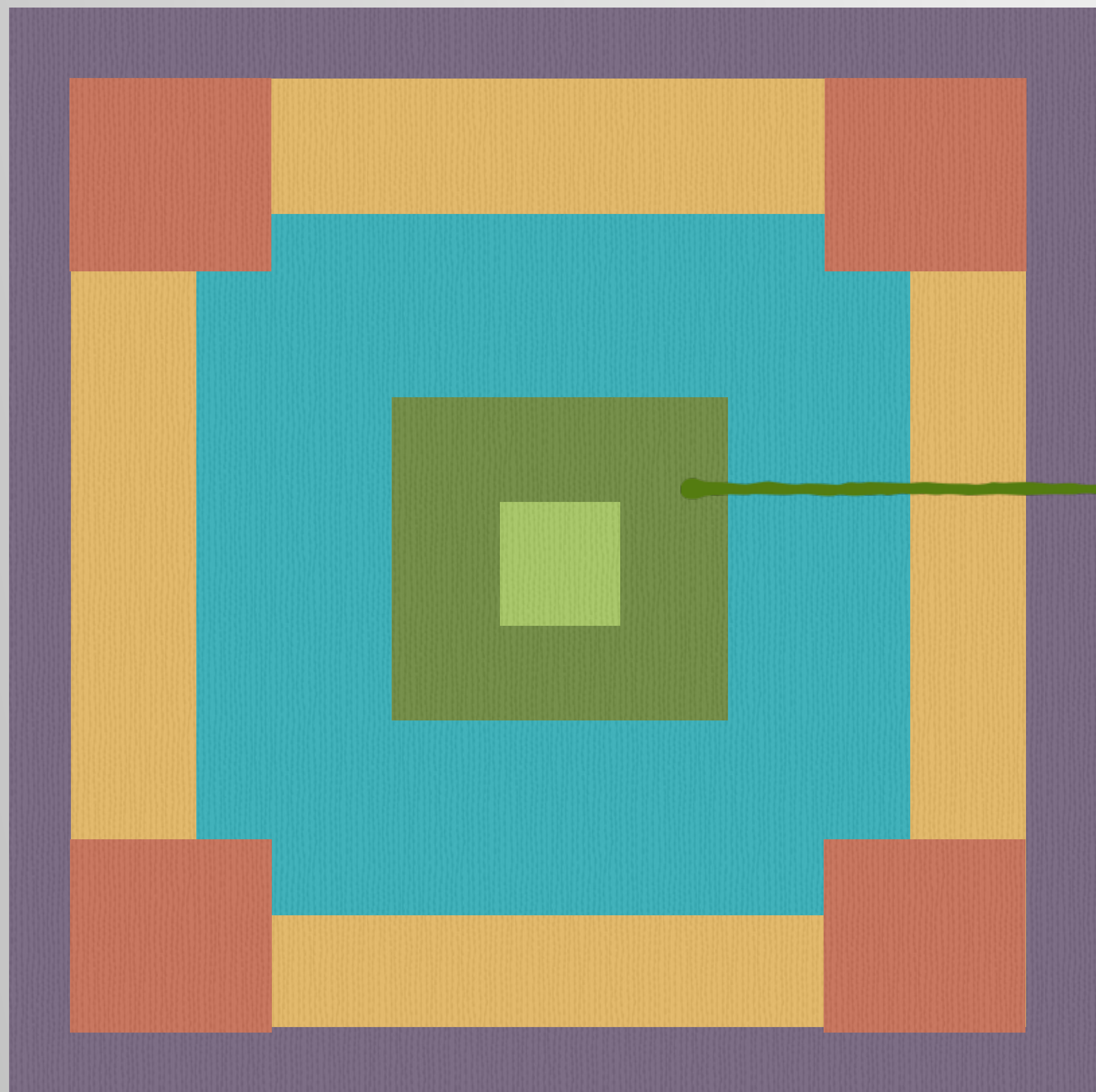


Square pixel:



Induced current for particle incidence @ worst case ★ :



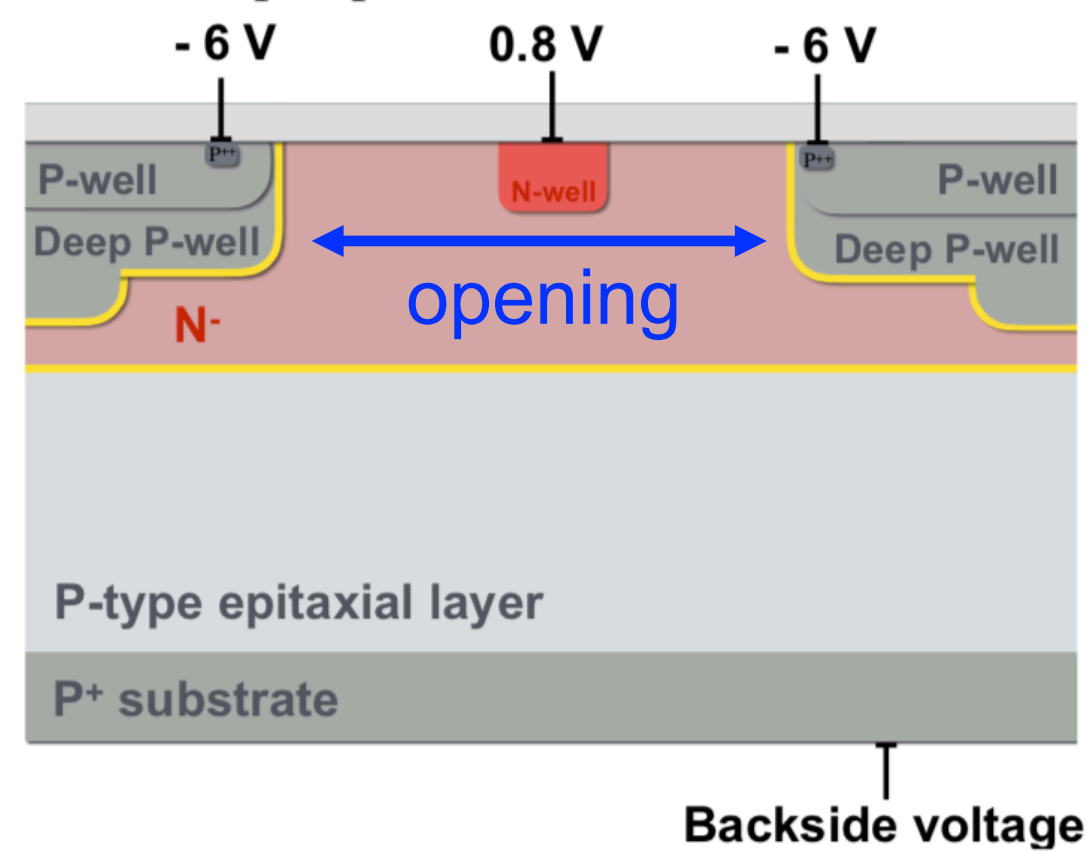


Close electrode region

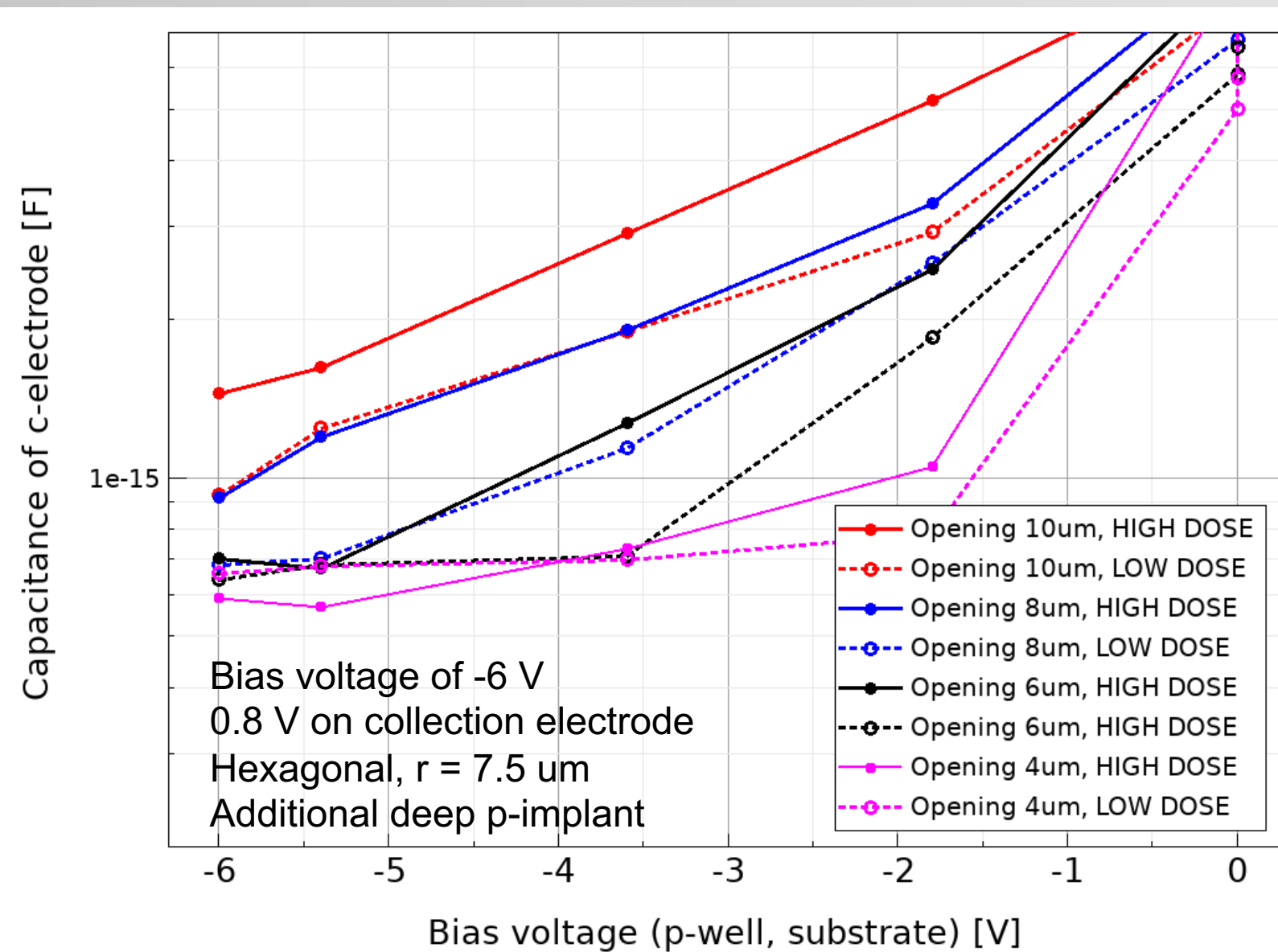
Optimising the opening

Definition of opening:

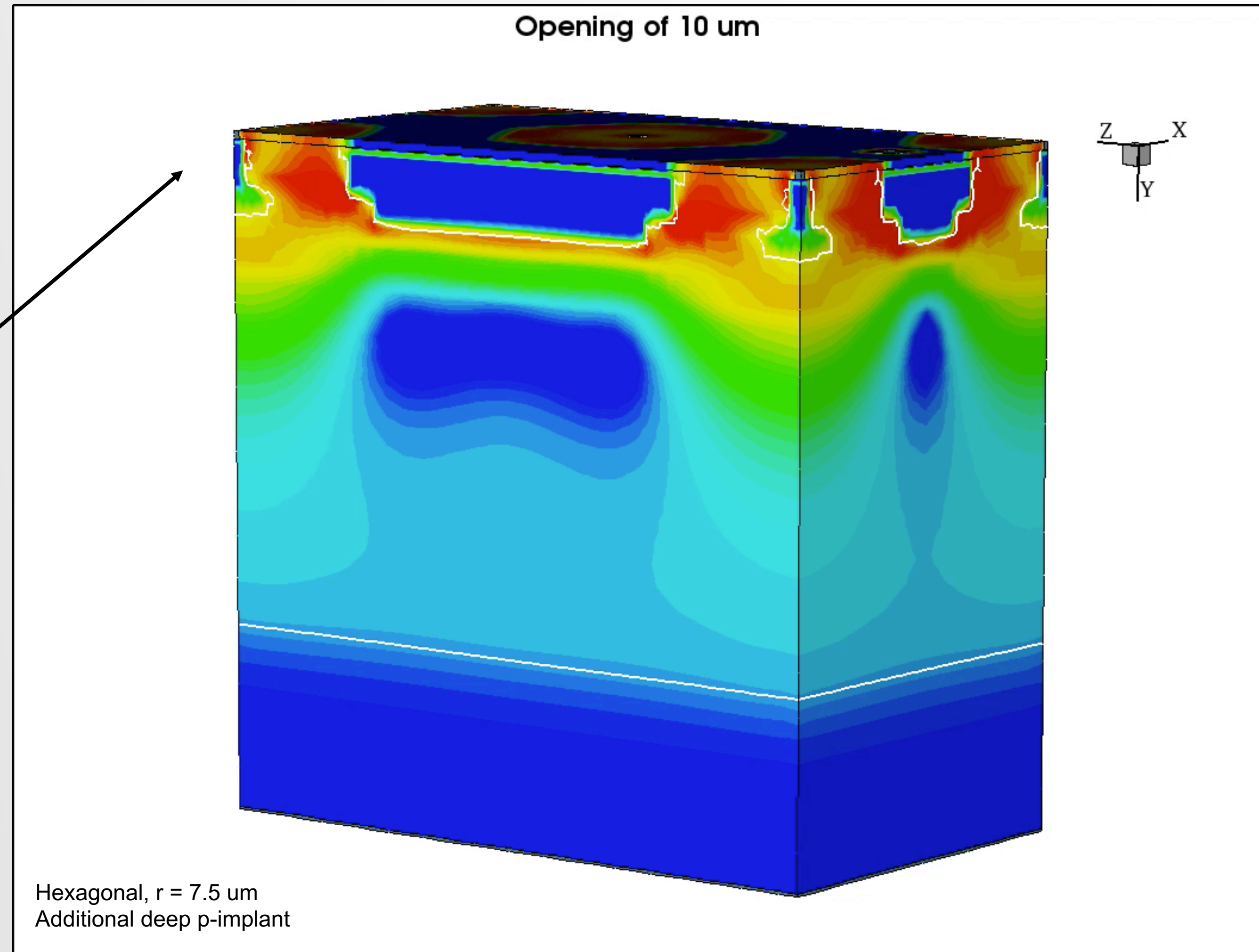
Additional p-implant:



Capacitance for different n-layer doses:

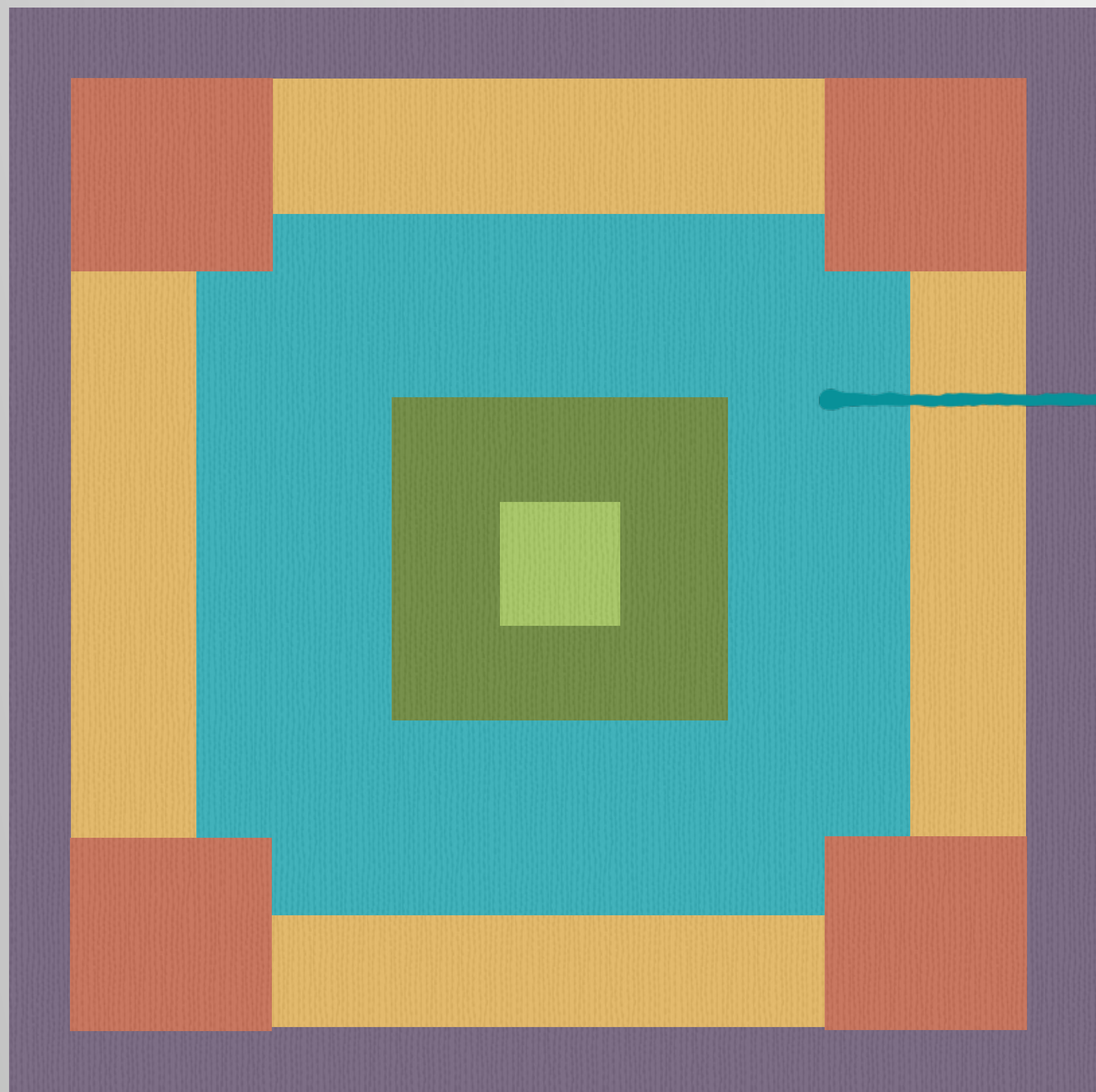


Electric field & depletion around collection electrode for different openings:



Trade off between small capacitance & high field

Select largest opening that still fully depletes around collection electrode

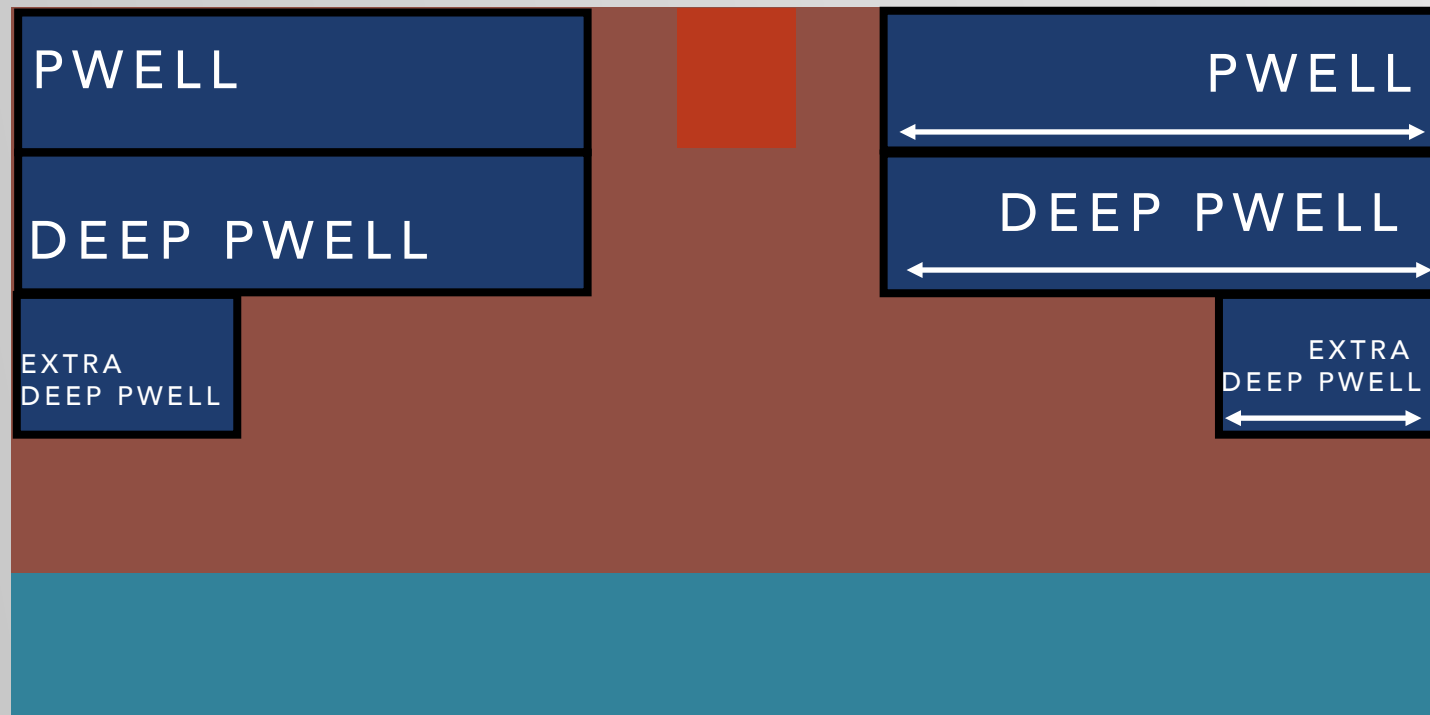


Far electrode region

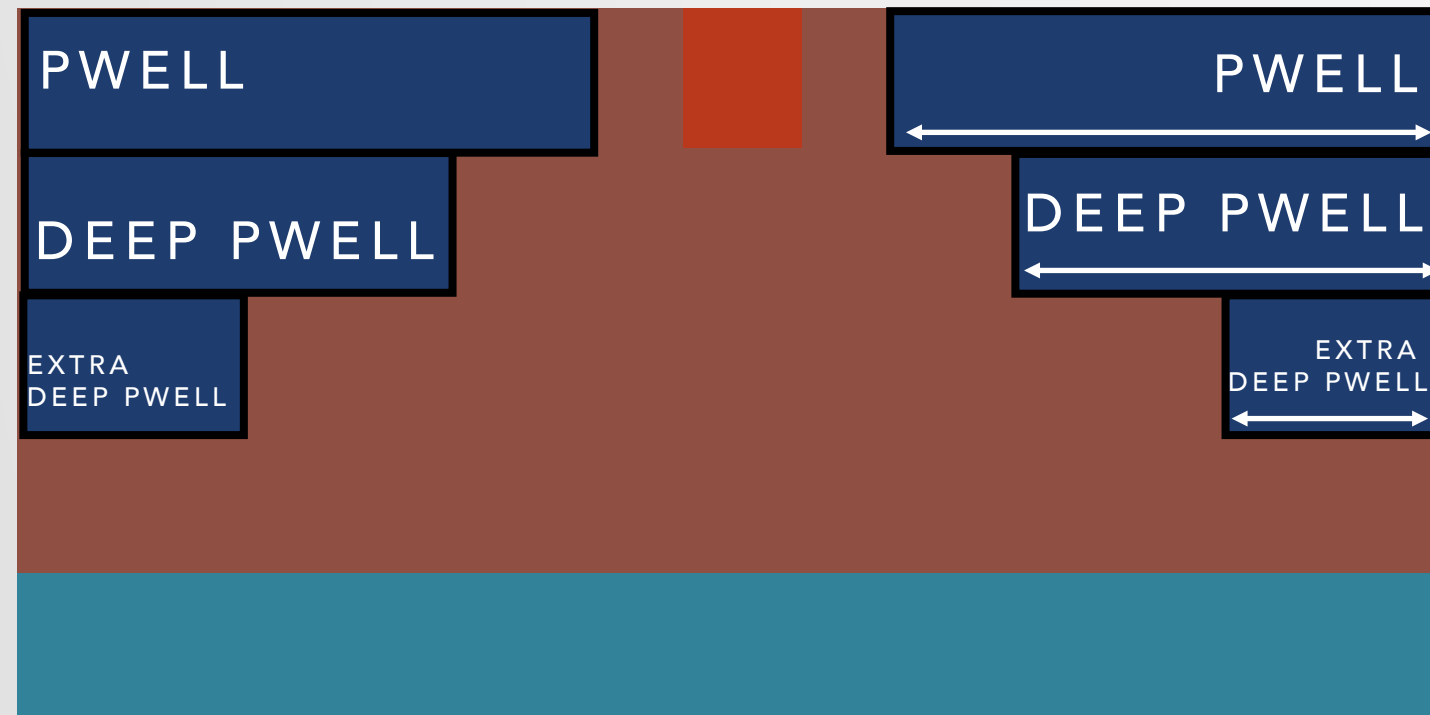
Retracing the deep p-well

Idea: can we at the same time optimise the field & capacitance by retracting the deep p-well?:

P-well & deep p-well with same distance to collection electrode:



Deep p-well with larger distance to collection electrode:



Deep p-well further away from c-electrode

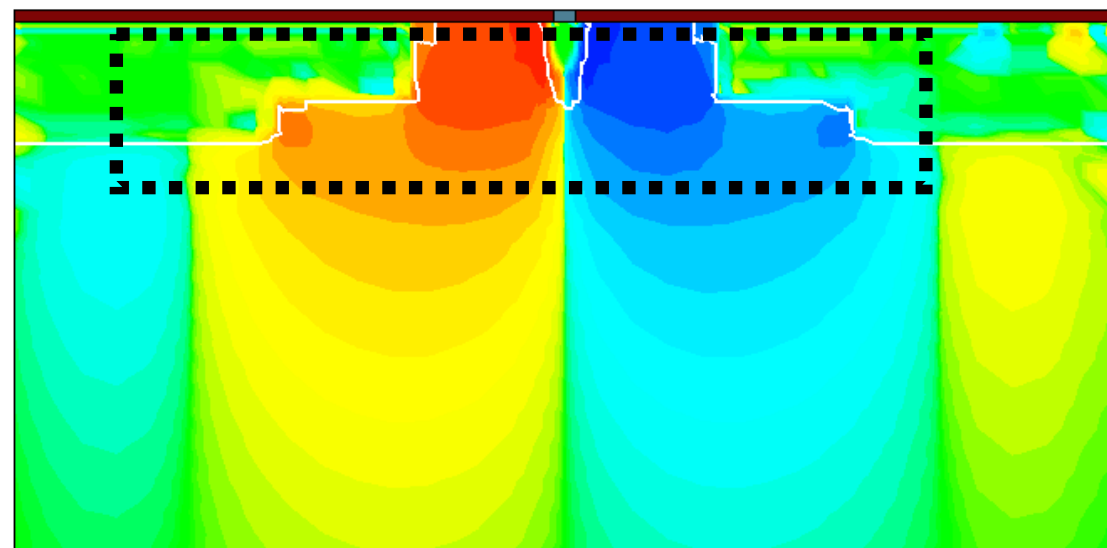
—> Faster charge collection

BUT:

- P-well stays close to deplete around collection electrode
- Deep p-well needs to shield circuitry (PMOS)

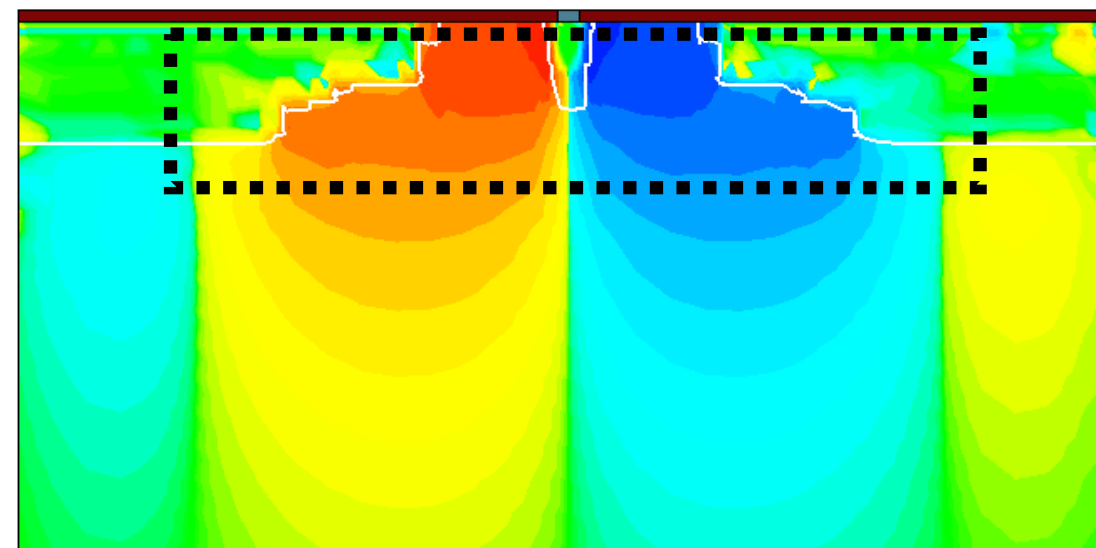
Lateral field:

P-well & deep p-well with same distance to collection electrode:



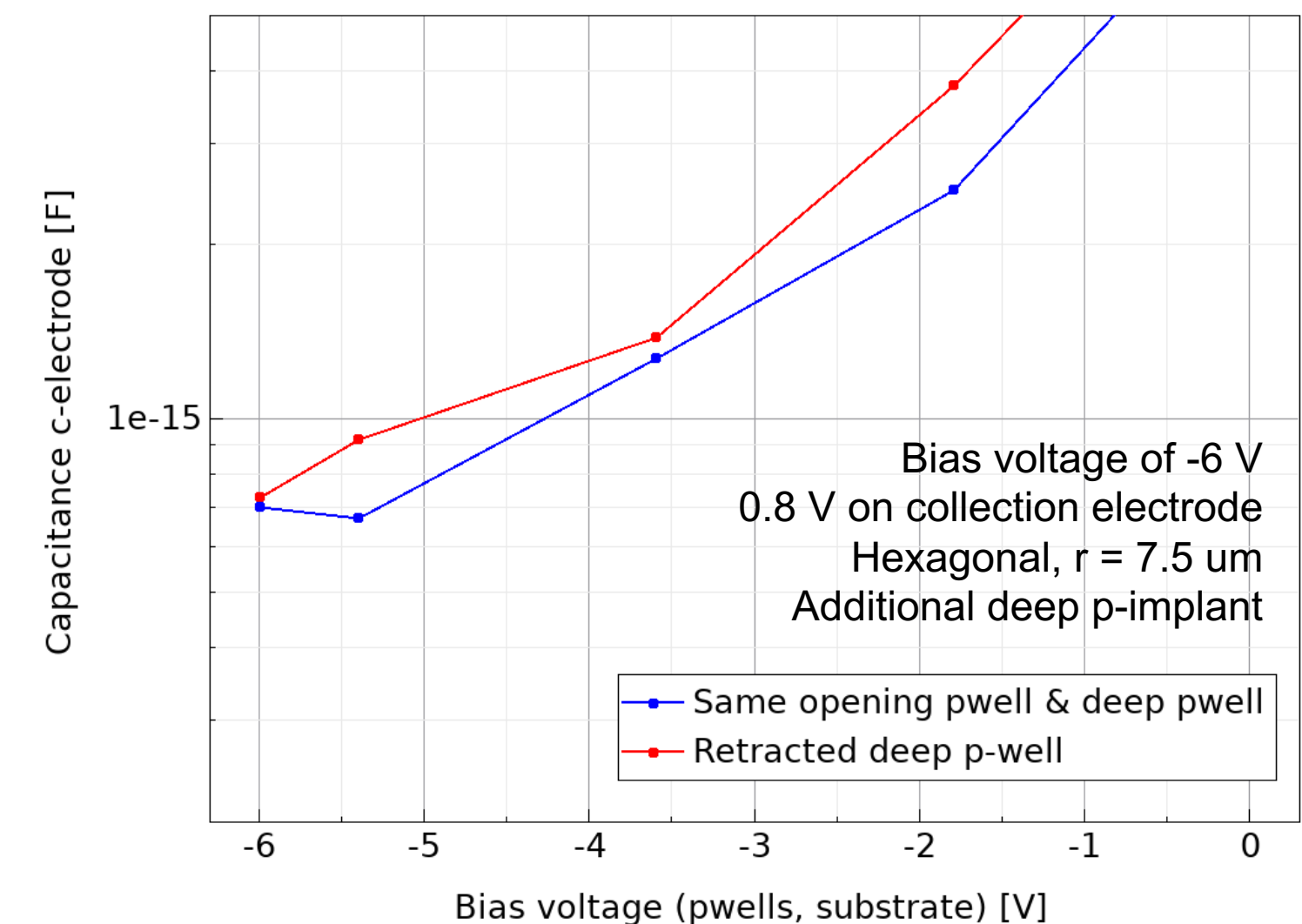
—> Enhancement of lateral field by retracting deep p-well.

Deep p-well with larger distance to collection electrode:



Bias voltage of -6 V
0.8 V on collection electrode
Hexagonal, $r = 7.5 \mu\text{m}$
Additional deep p-implant

Capacitance:

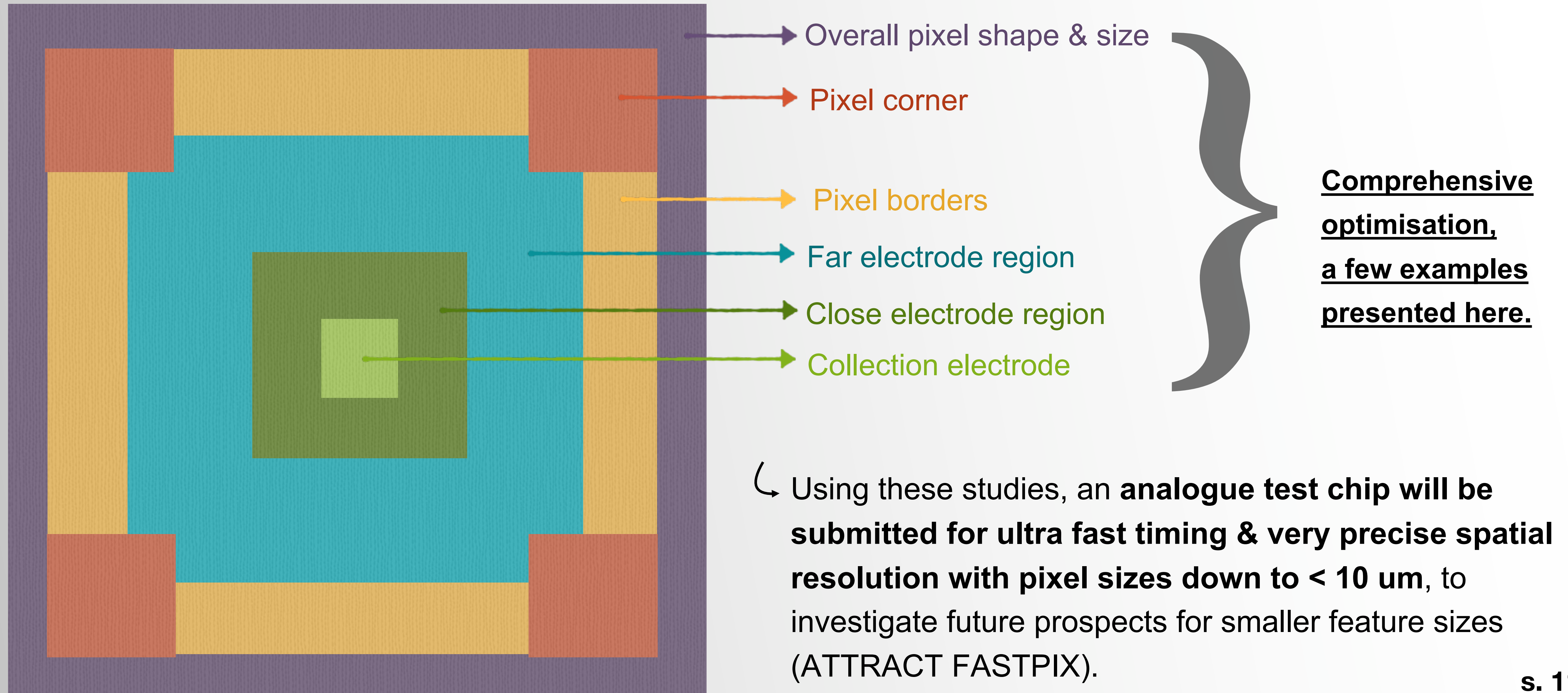


—> Retracted deep p-well does not harm capacitance.

Retracting the deep p-well maximises the field while still guarantying full depletion around collection electrode & small capacitance. s. 10

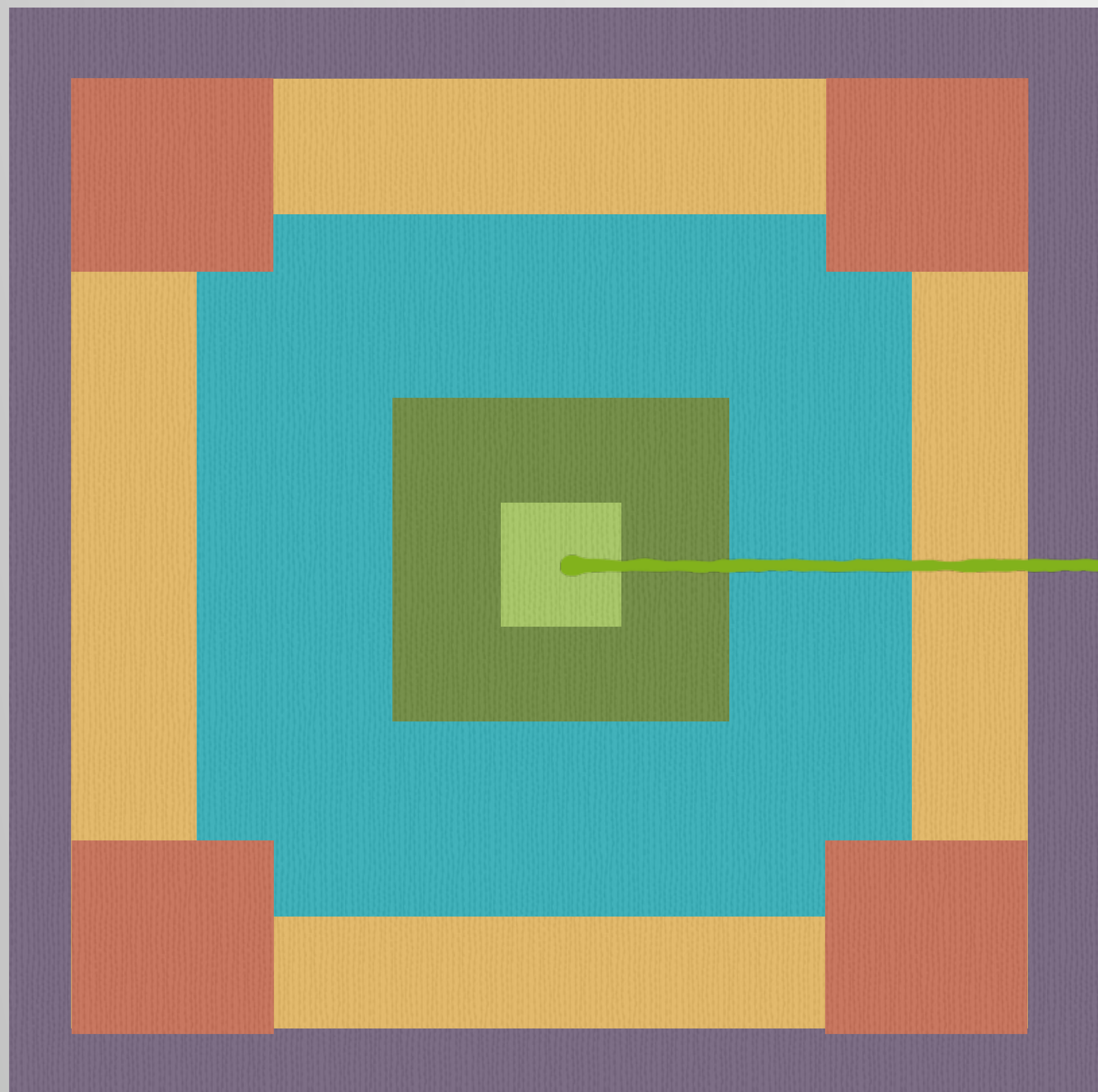
Summary & outlook

Optimised CMOS sensors with a small collection electrode w.r.t. fast charge collection, small sensor capacitance and precise spatial resolution:



Thank you.

BACKUP



Collection electrode

Optimising the collection electrode

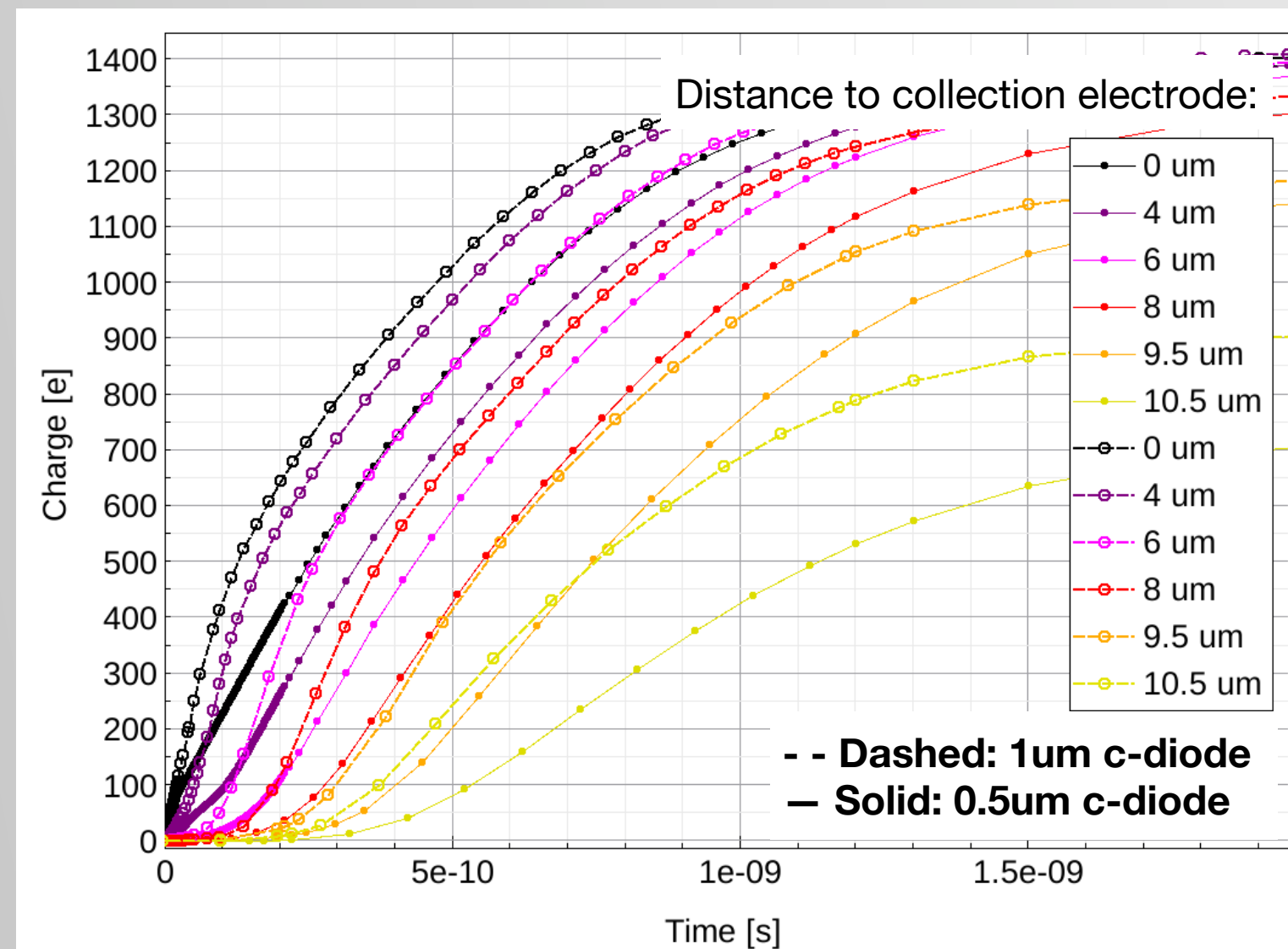
Minimisation of capacitance:

- Sensor **capacitance** $C \propto$ **radius of collection electrode**

—> Want collection electrode as **small** as possible to **minimise capacitance** (maximise readout **charge** $Q = I/C$)

Maximisation of electric field:

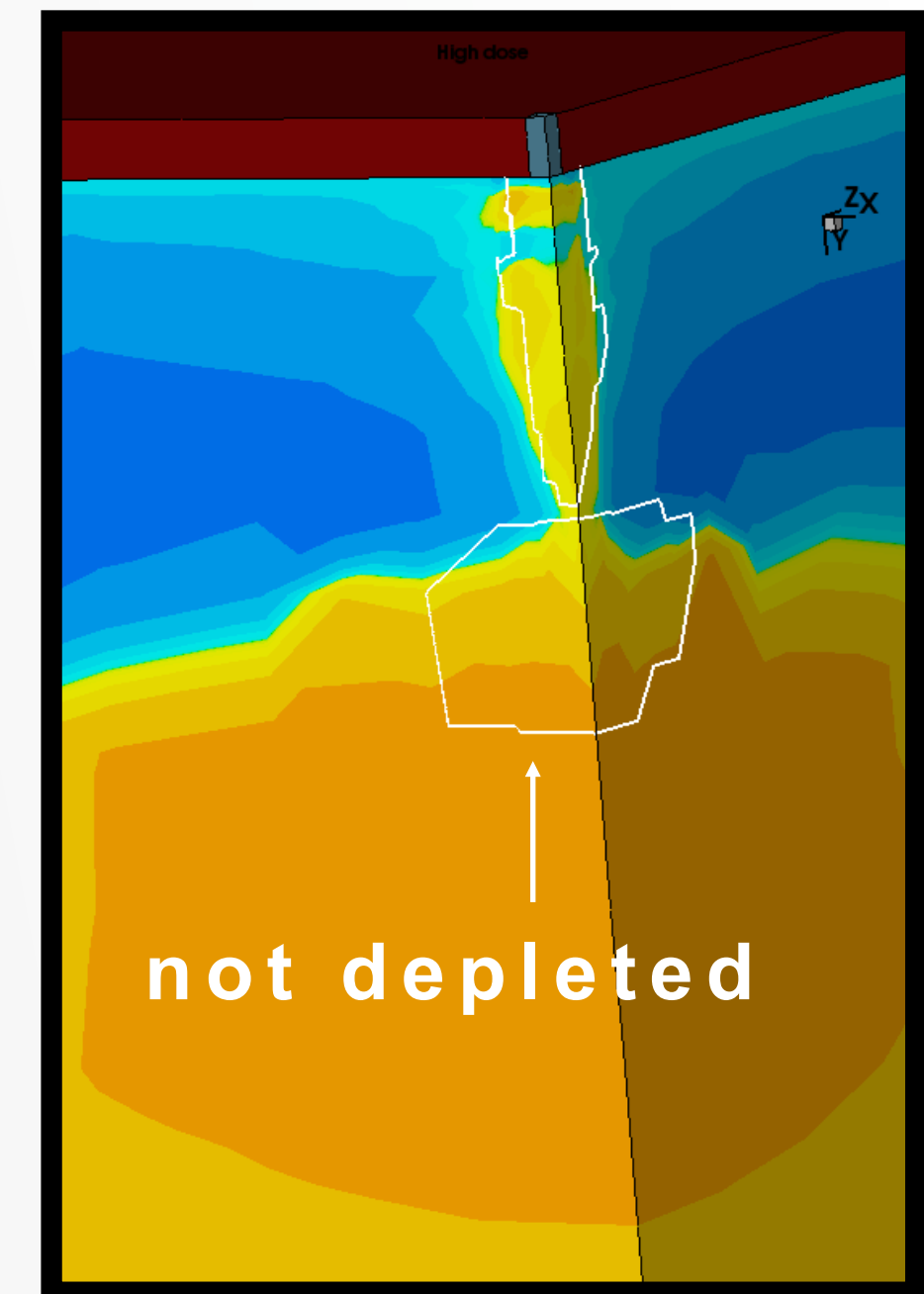
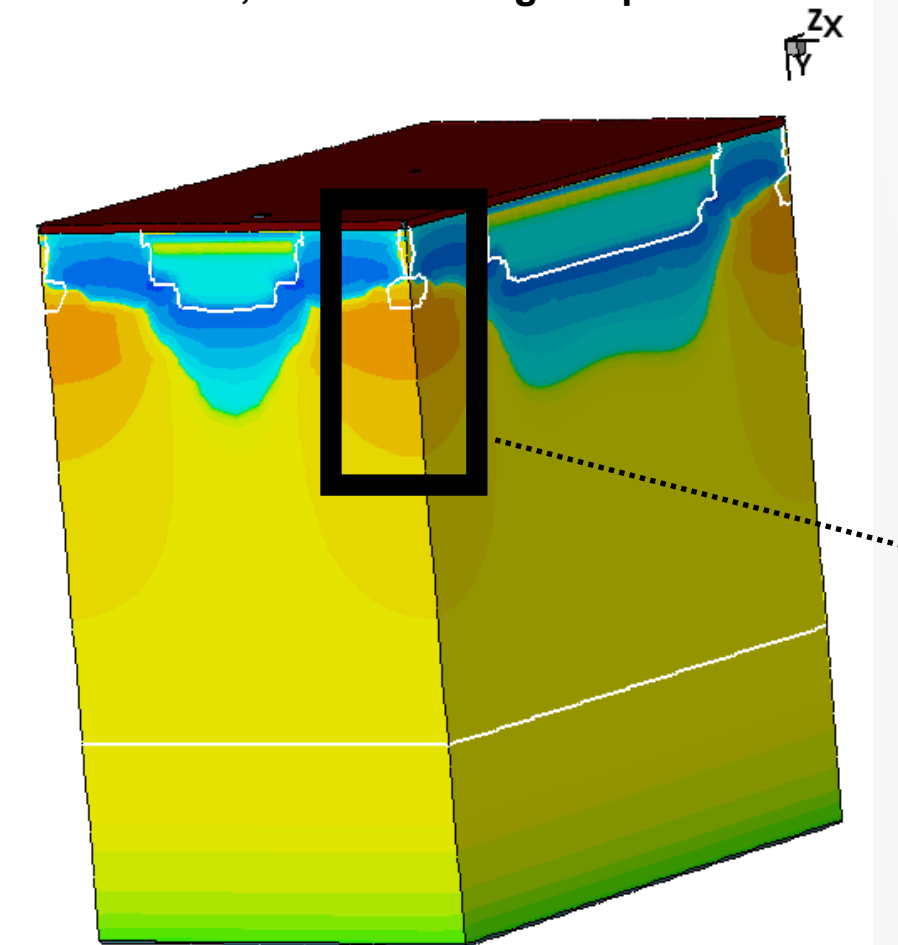
—> Want collection electrode as **large** as possible to
maximise electric field & charge collection speed



Guarantee full depletion:

—> Challenging to fully deplete for collection
electrode sizes $< 1 \text{ um}$

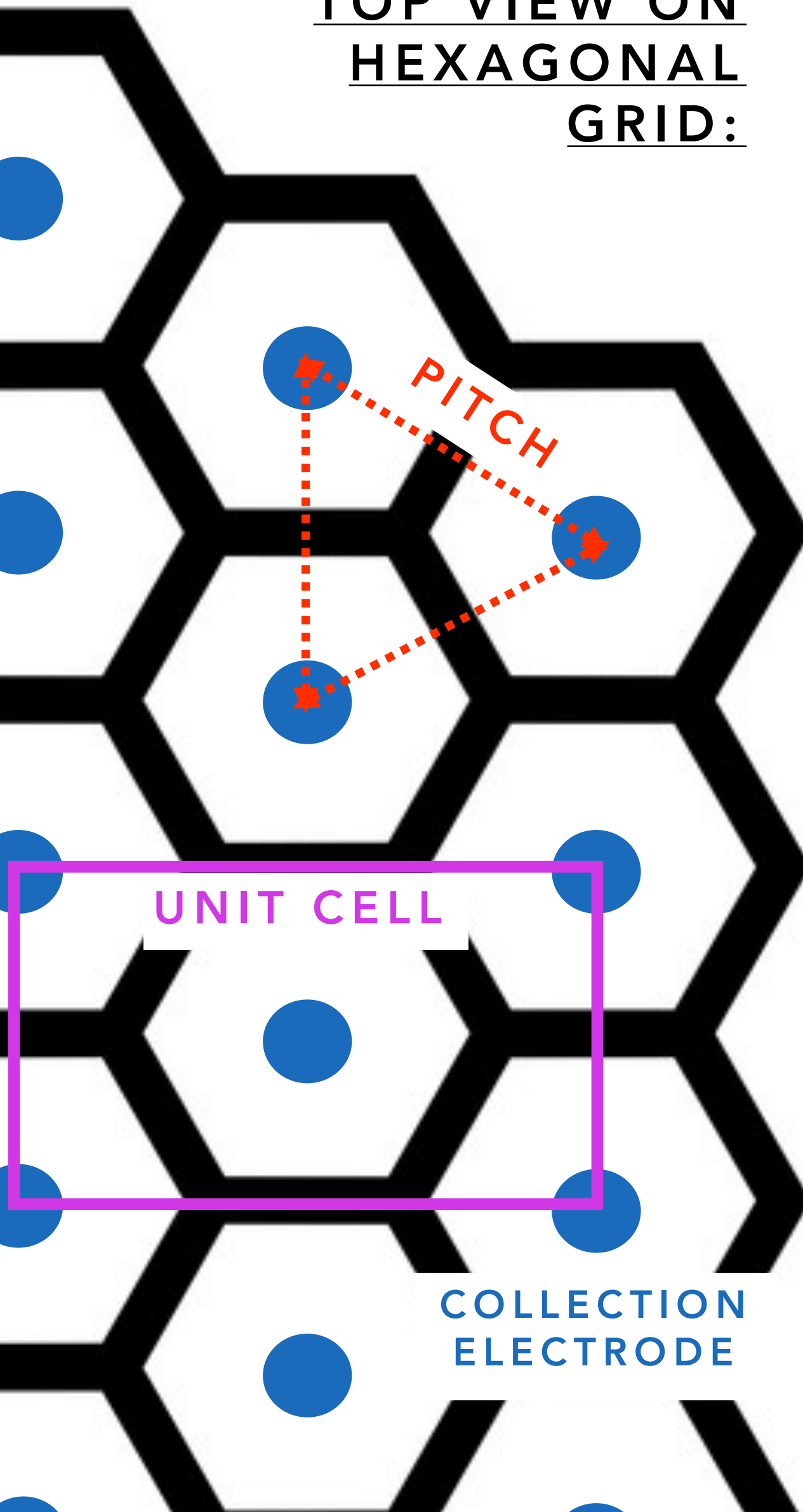
Example of design with non
depleted regions for c-electrode
of 0.5um, field along depth:



↪ Select collection electrode size of 1um.

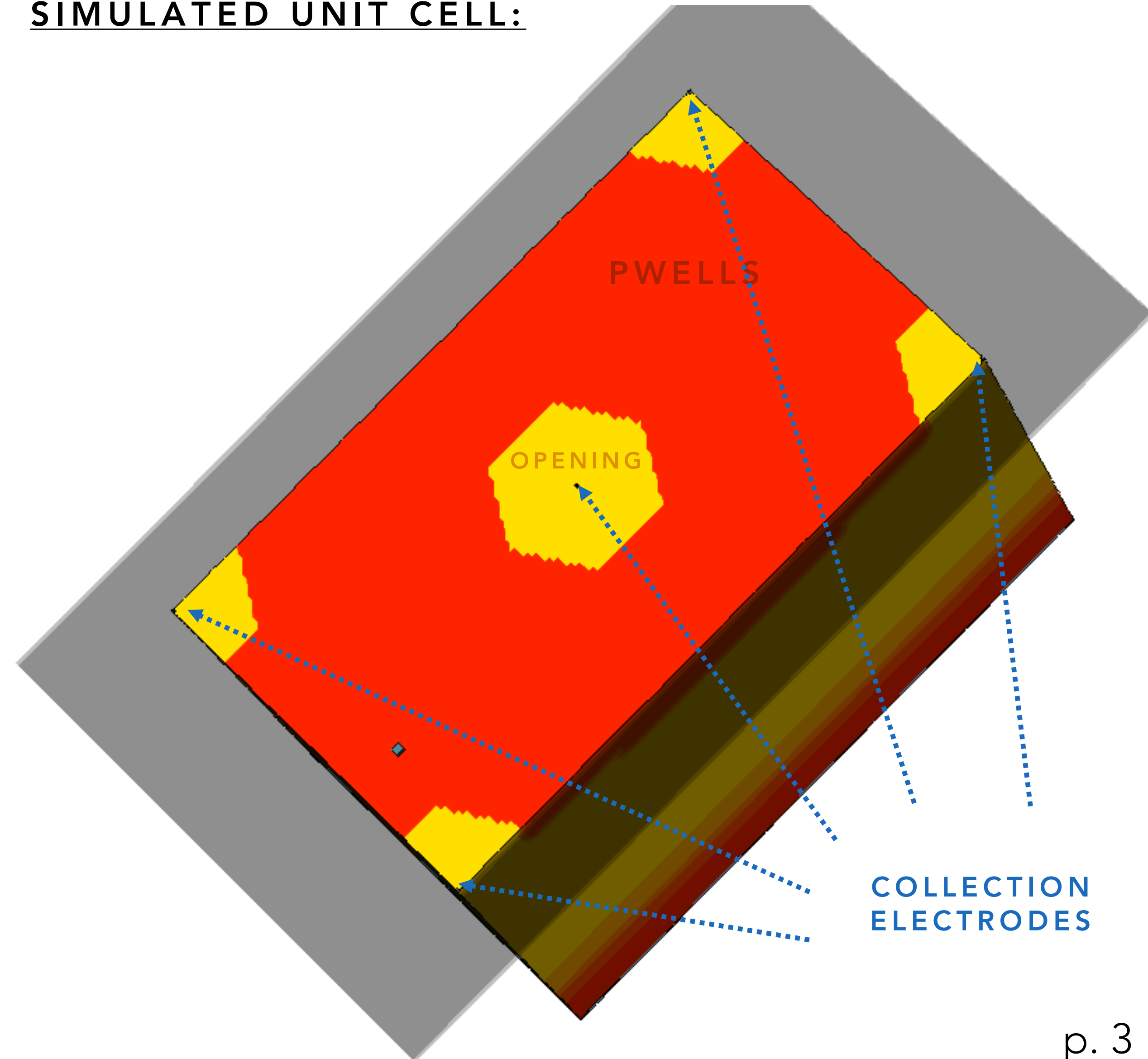
HEXAGONAL PIXELS - STUDIED DESIGN

TOP VIEW ON
HEXAGONAL
GRID:



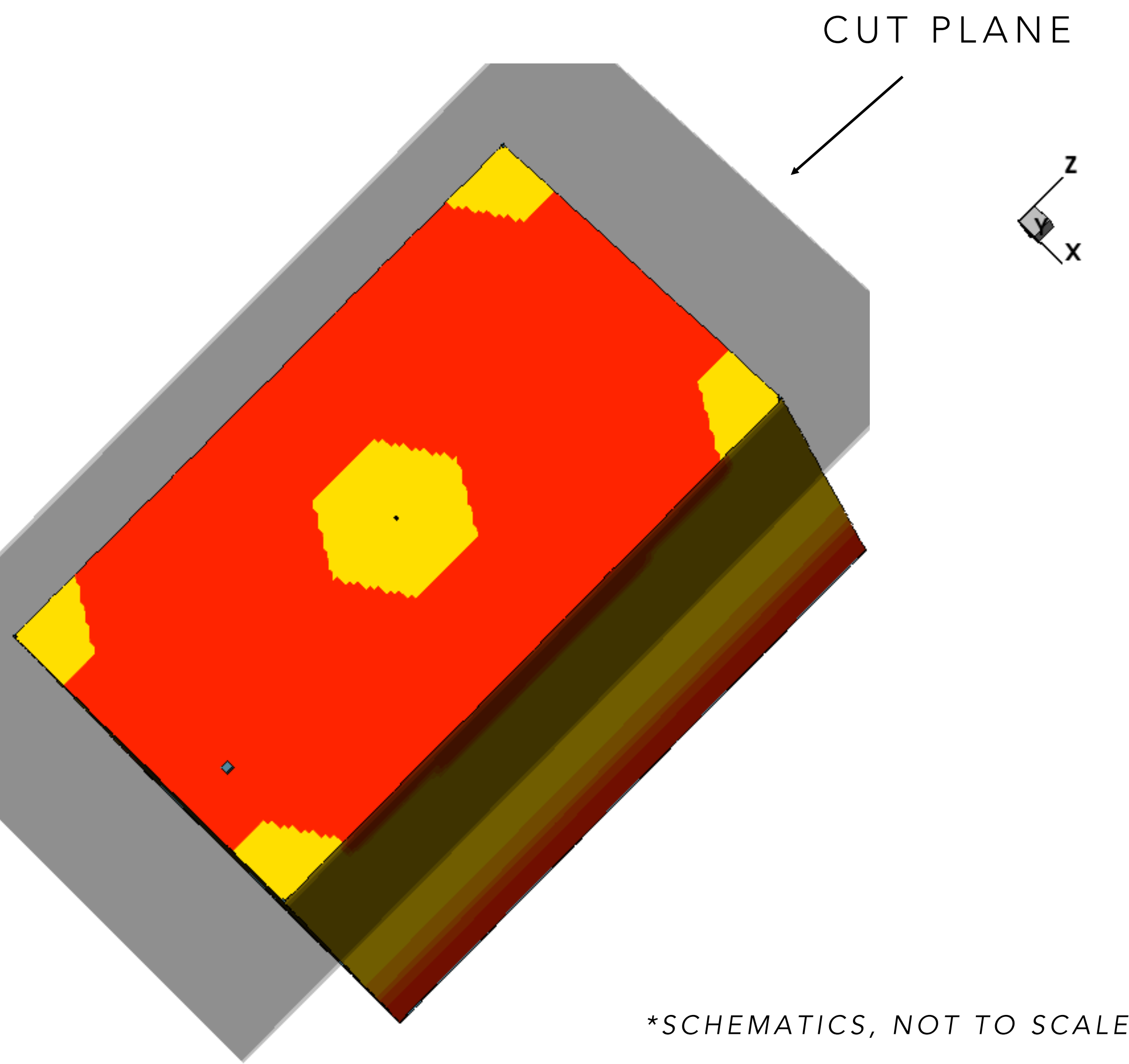
UNIT CELL:
Smallest cell that
can periodically
reproduce
hexagonal grid
and holds
symmetry for
transient study

SIMULATED UNIT CELL:

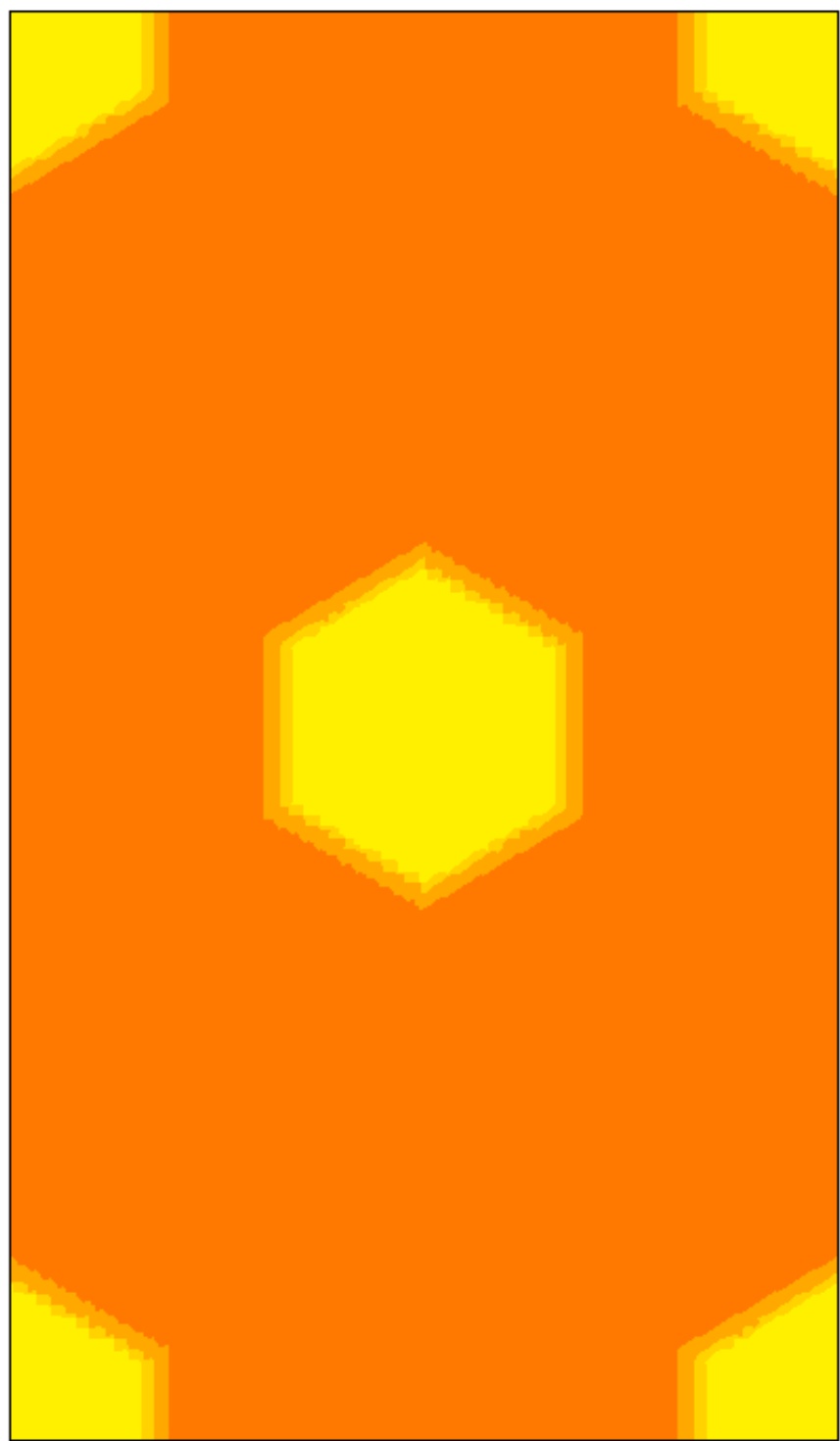


HEXAGONAL PIXELS - STUDIED DESIGN

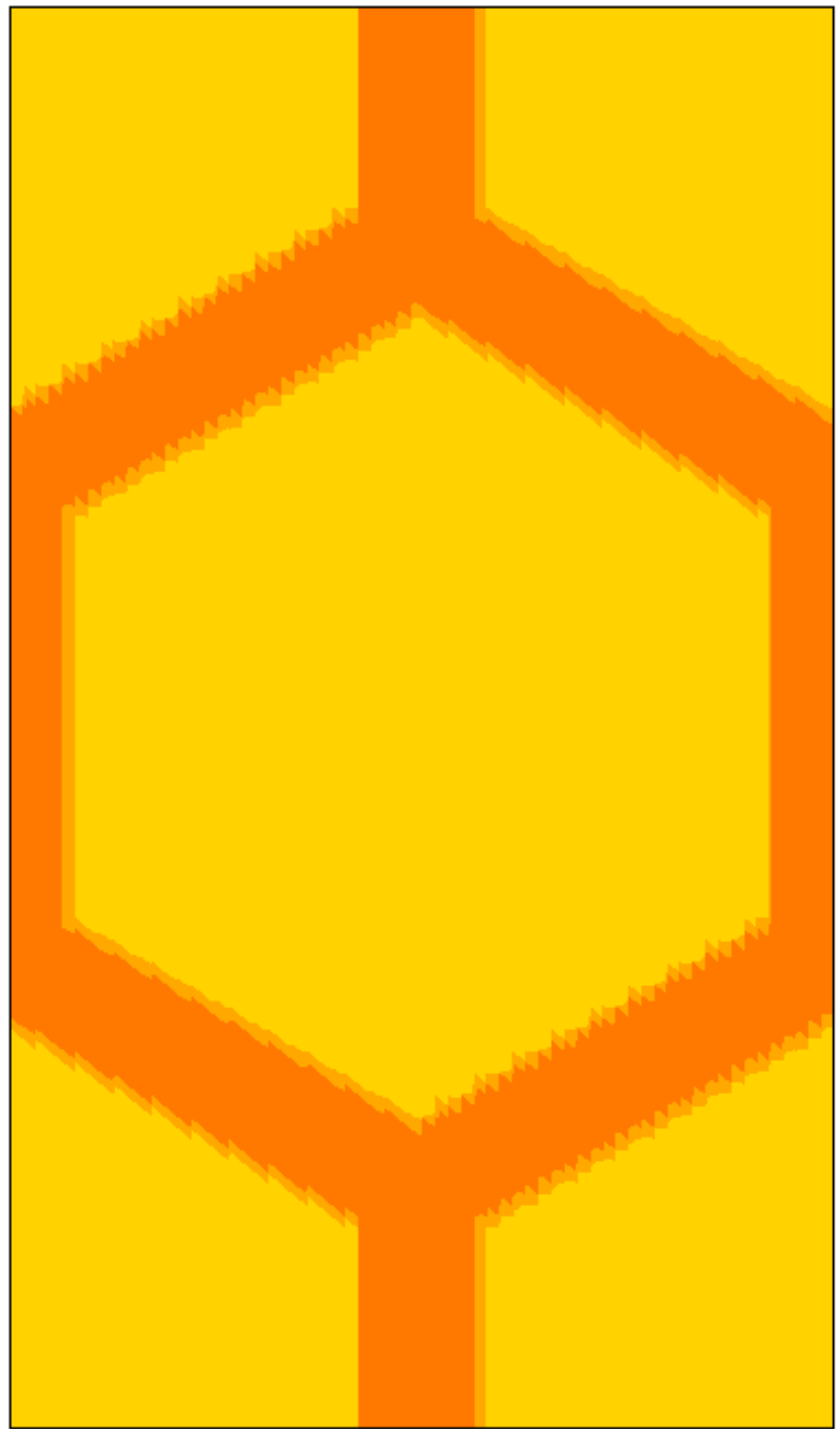
Simulated unit cell:



CUT @ DEPTH OF
PWELLS:



CUT @ DEPTH OF
ADDITIONAL P-IMPLANT:



Lesson learned

- Electric field fundamentally different w.r.t. standard planar sensors
- The lateral field is most important, especially in the pixel corners
- Implants at pixel edge help to increase lateral field & charge collection
- Trade off between high field & low capacitance:
 - A smaller opening is favourable to reduce the capacitance, while a larger opening is favourable for a fast charge collection
 - A smaller collection electrode is favourable for a minimised capacitance, while a large collection electrode is favourable for a higher field
- Retracting the deep p-well helps to simultaneously optimise capacitance & field

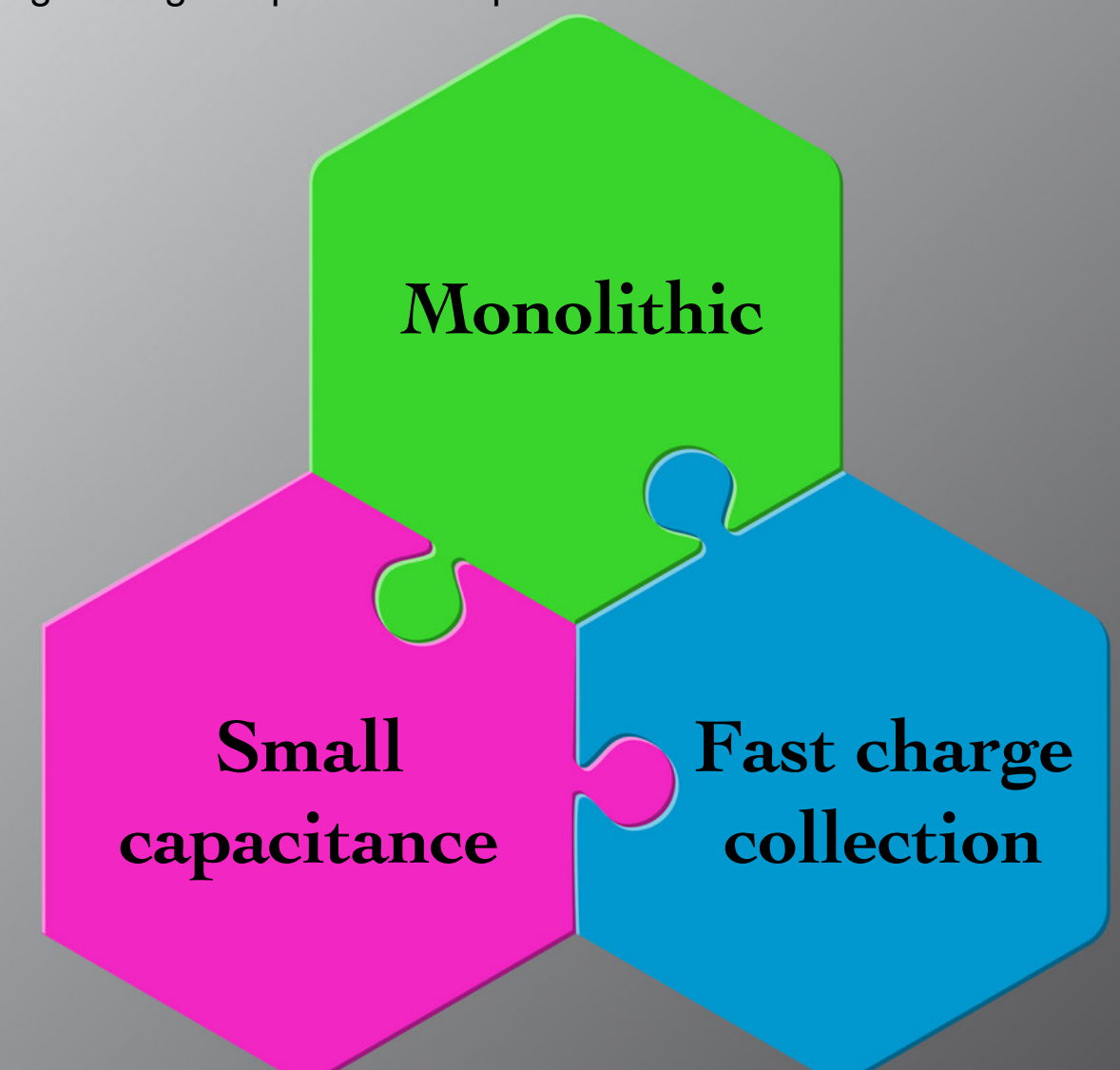
Motivation - why to further optimise?

In the framework of attract FASTPIX:

Combine advantages of CMOS sensors with a small collection electrode (**low cost & material, reduced production effort, small sensor capacitance**) with a fast charge collection (**ultra fast timing & radiation tolerance**) and precise spatial resolution

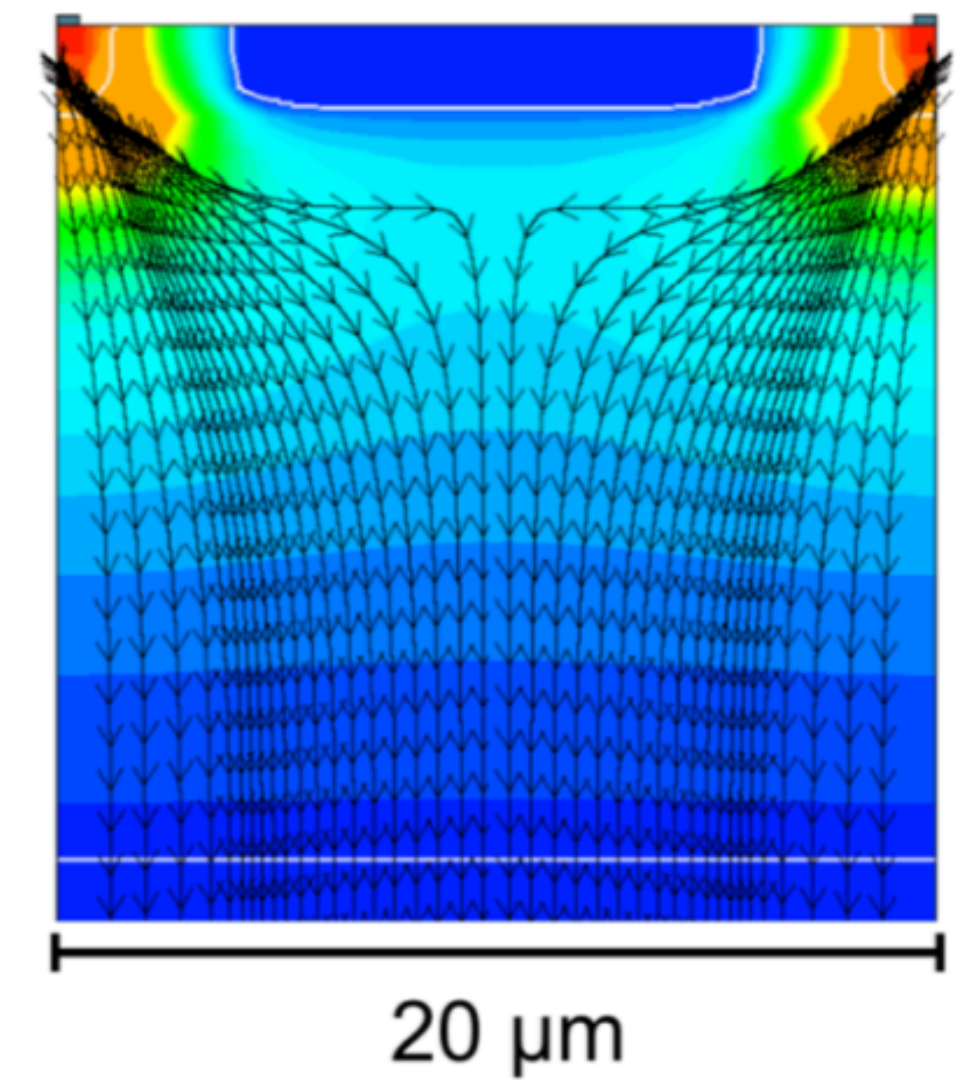
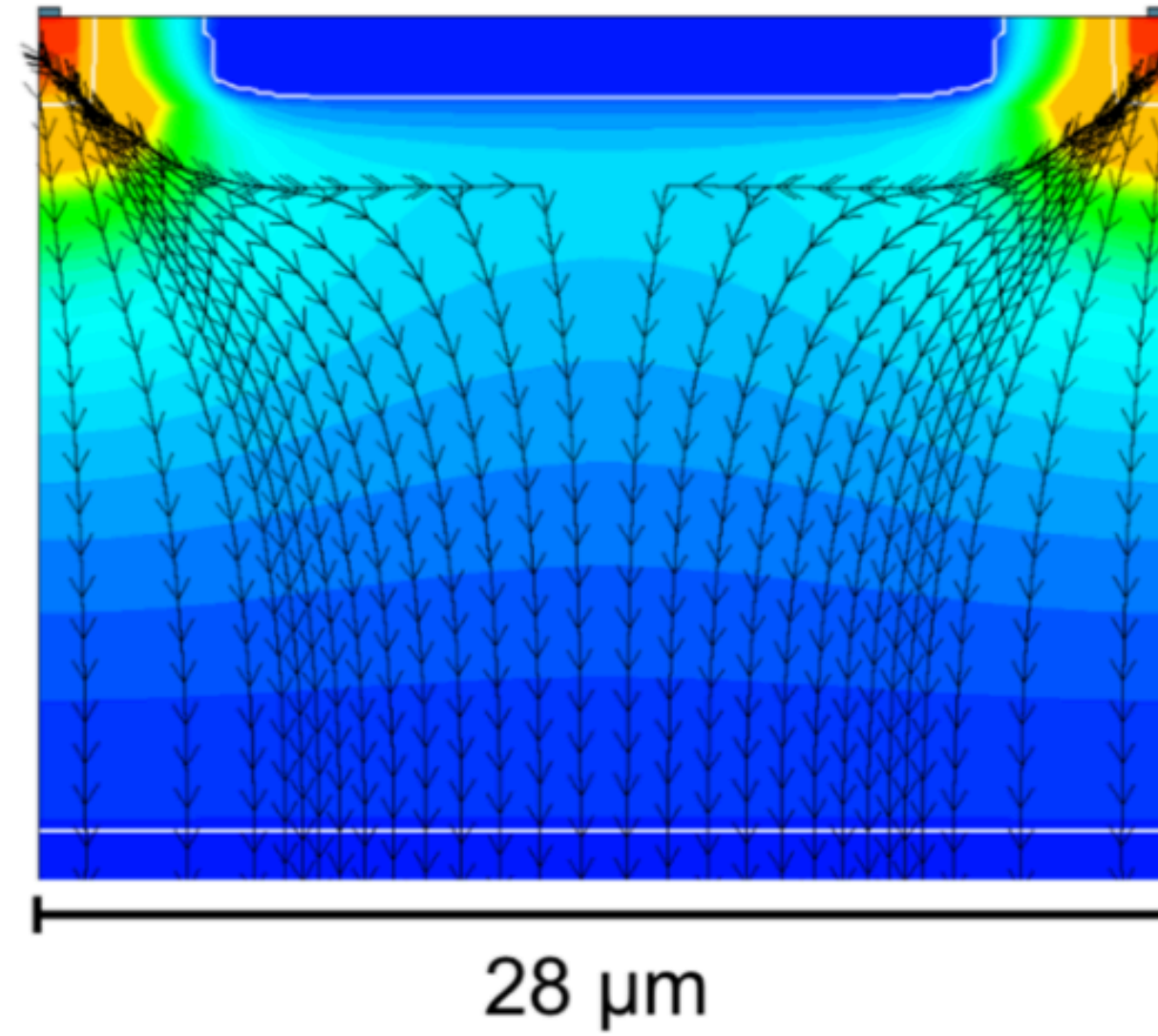
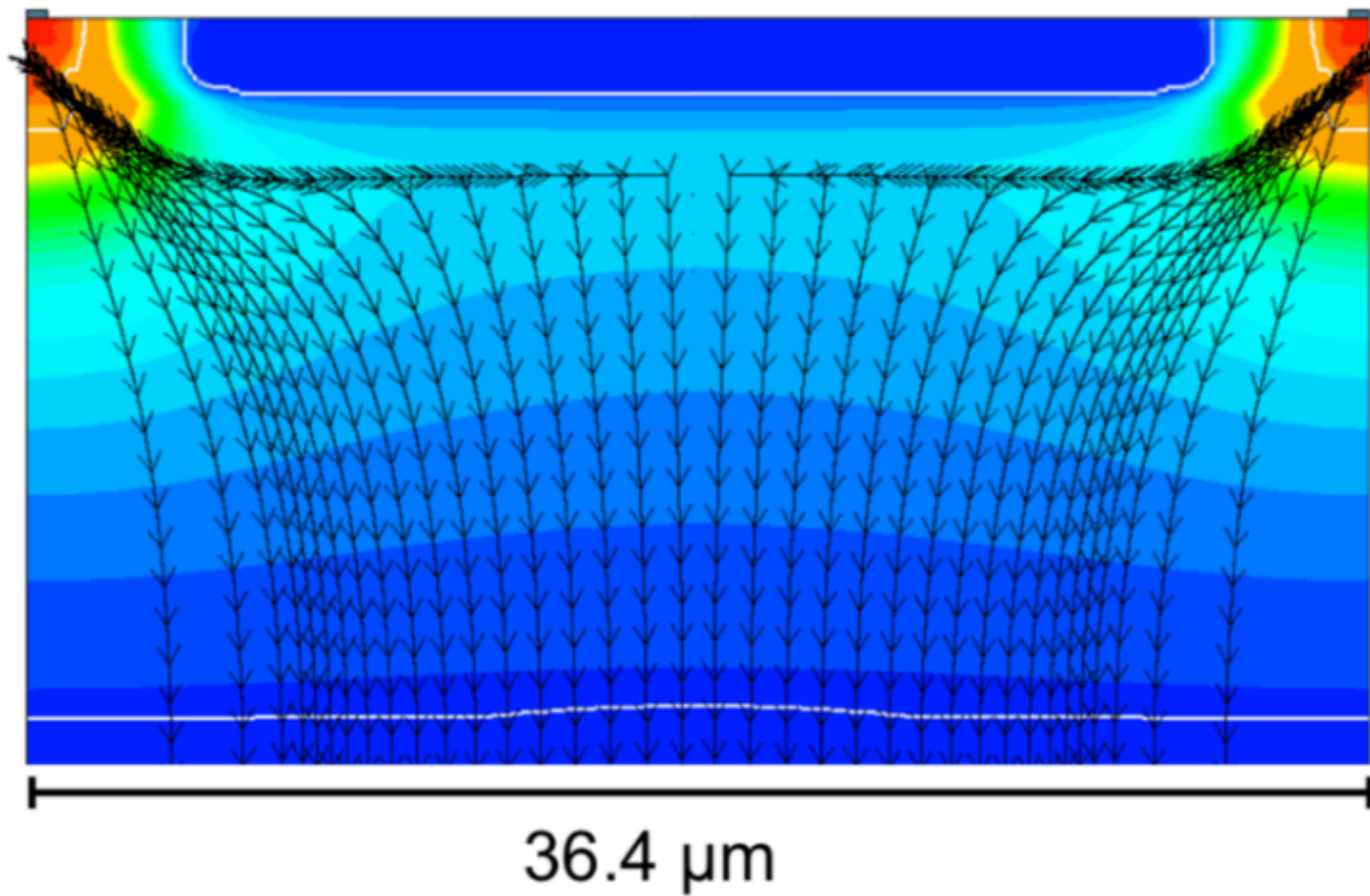
- Aim for first year: benchmark sensor designs (“analogue” performance)
- Relevance for CLIC vertex detector: precise resolution with small pixels, low material monolithic detector

<https://www.vectorstock.com/royalty-free-vector/three-piece-puzzle-hexagon-diagram-puzzle-3-step-vector-21053559>



Optimising the overall pixel shape - pixel pitch

Electrostatic potential & streamlines for different pixel pitch:

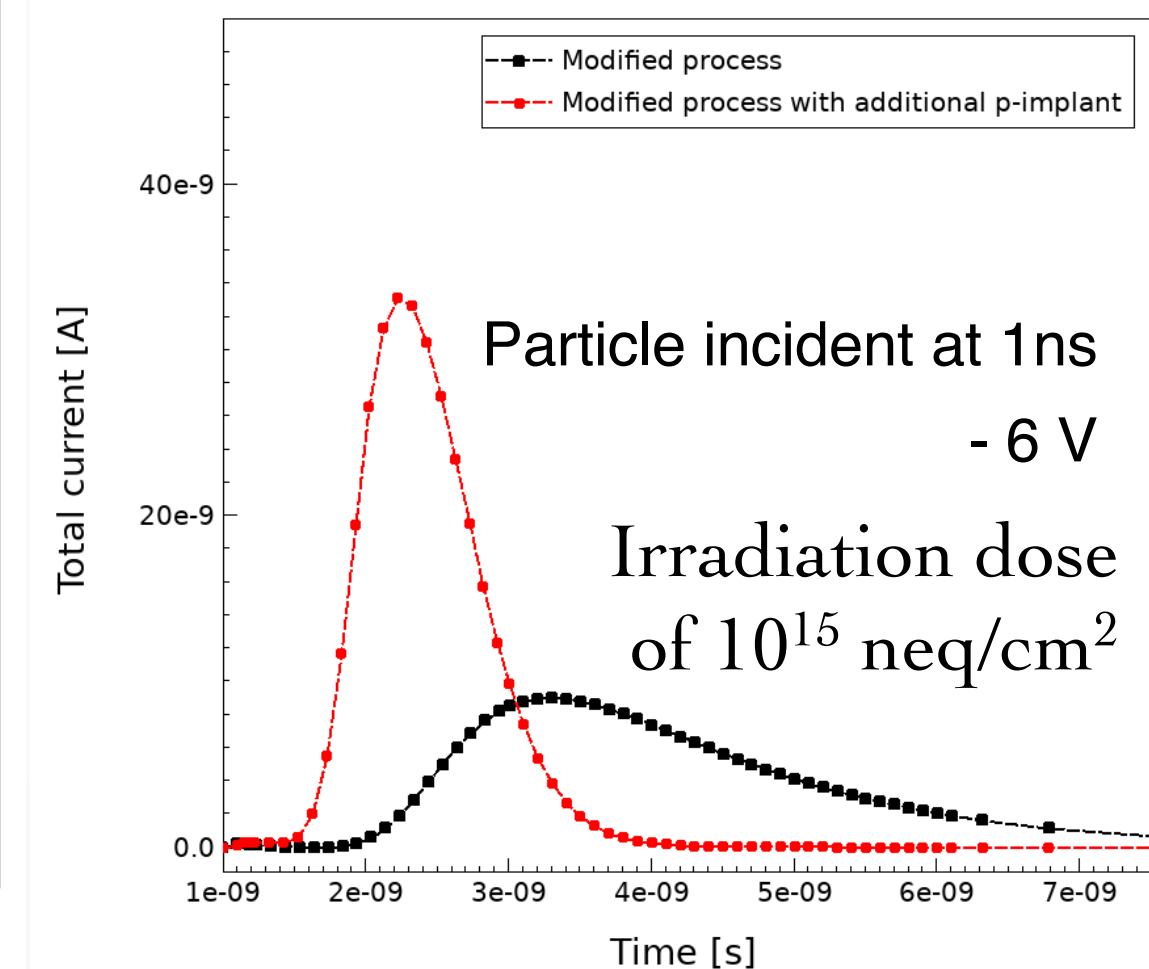
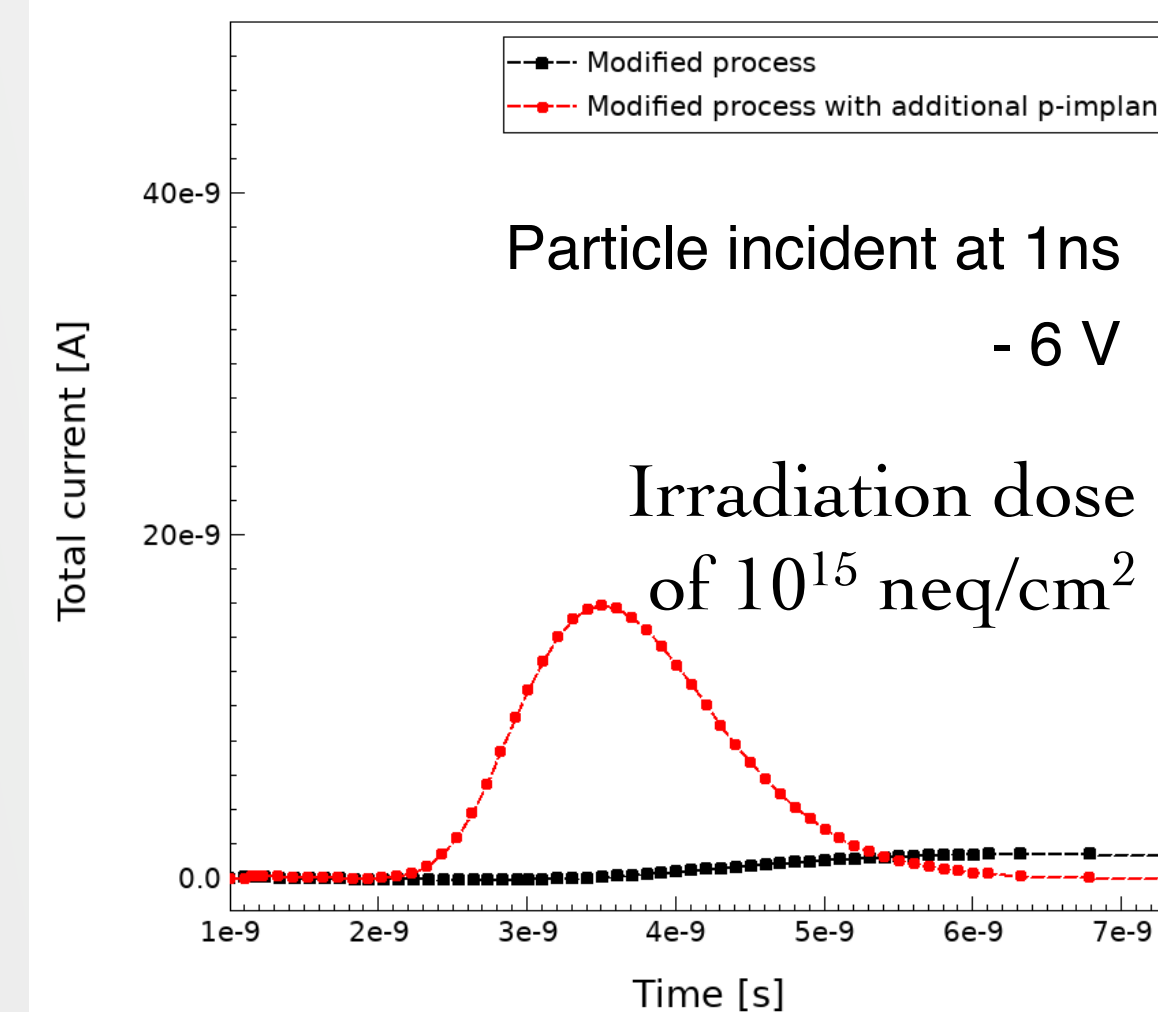


Better opening of streamlines towards collection electrode
for smaller pixels

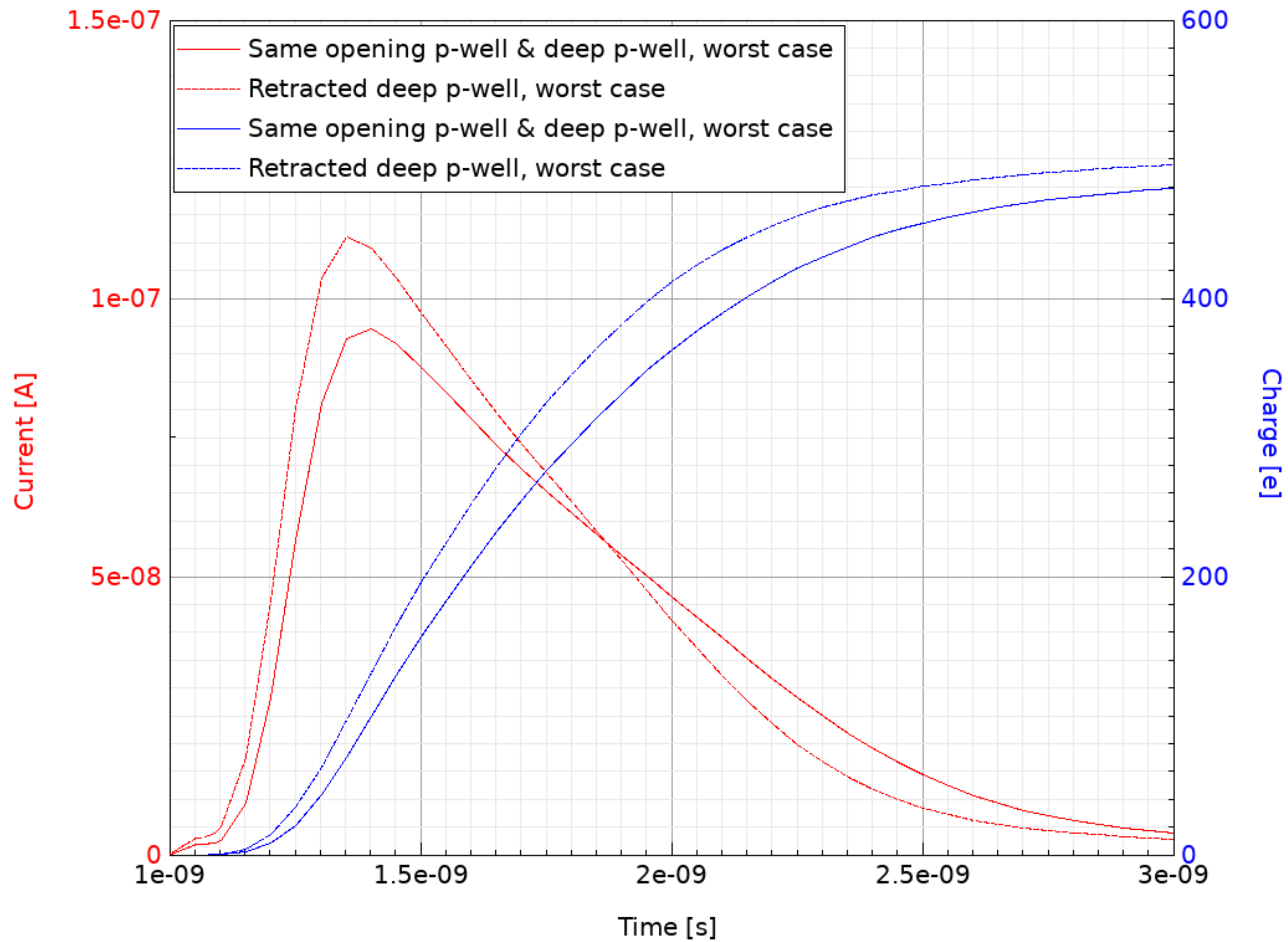
Strong dependancy of performance on pixel pitch:

<https://doi.org/10.1088/1748-0221/13/01/C01023>

Pixel size **36.4 x 36.4 μm^2** : Pixel size **28 x 28 μm^2** :

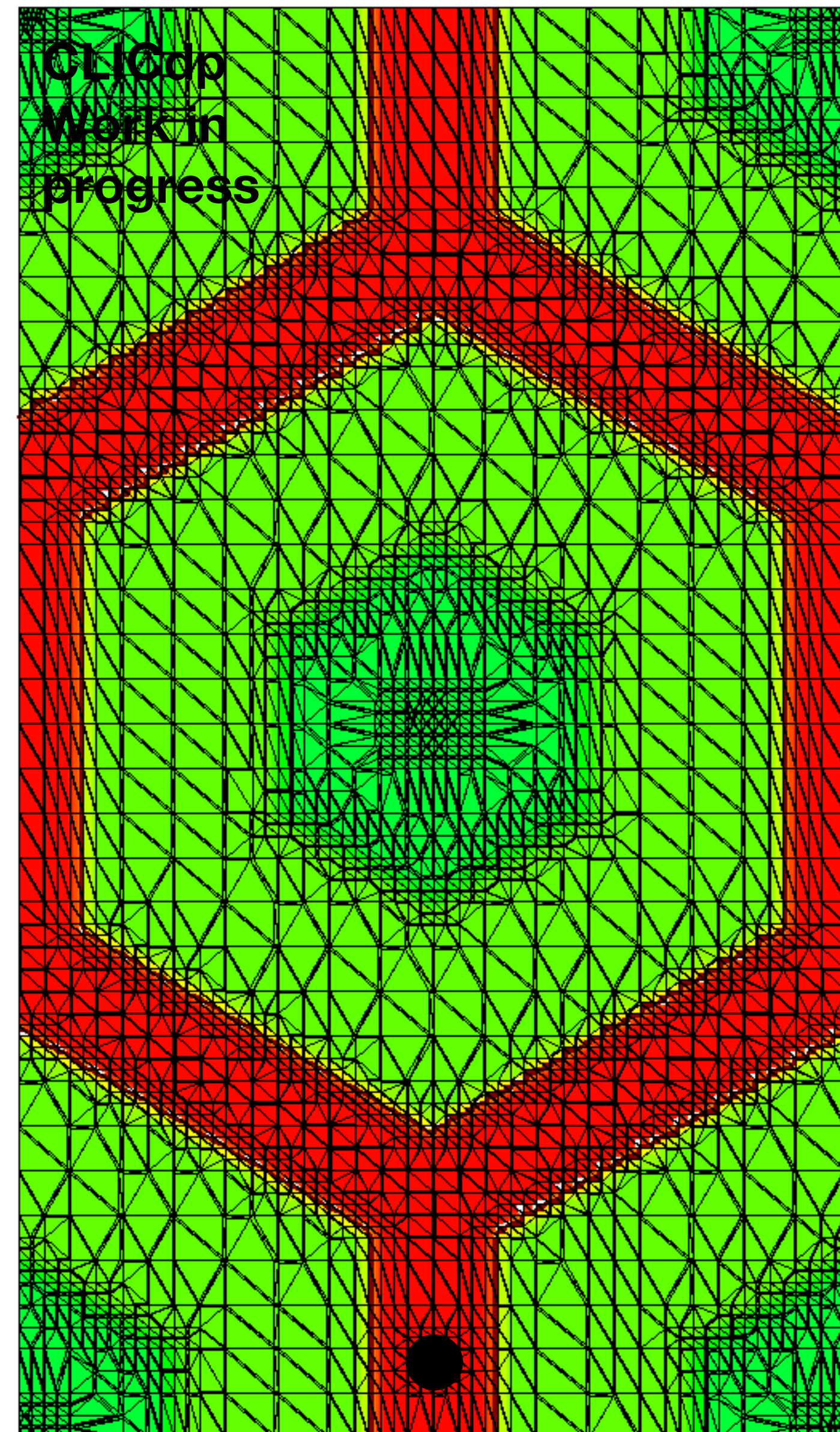


RETRACTED DEEP P-WELL

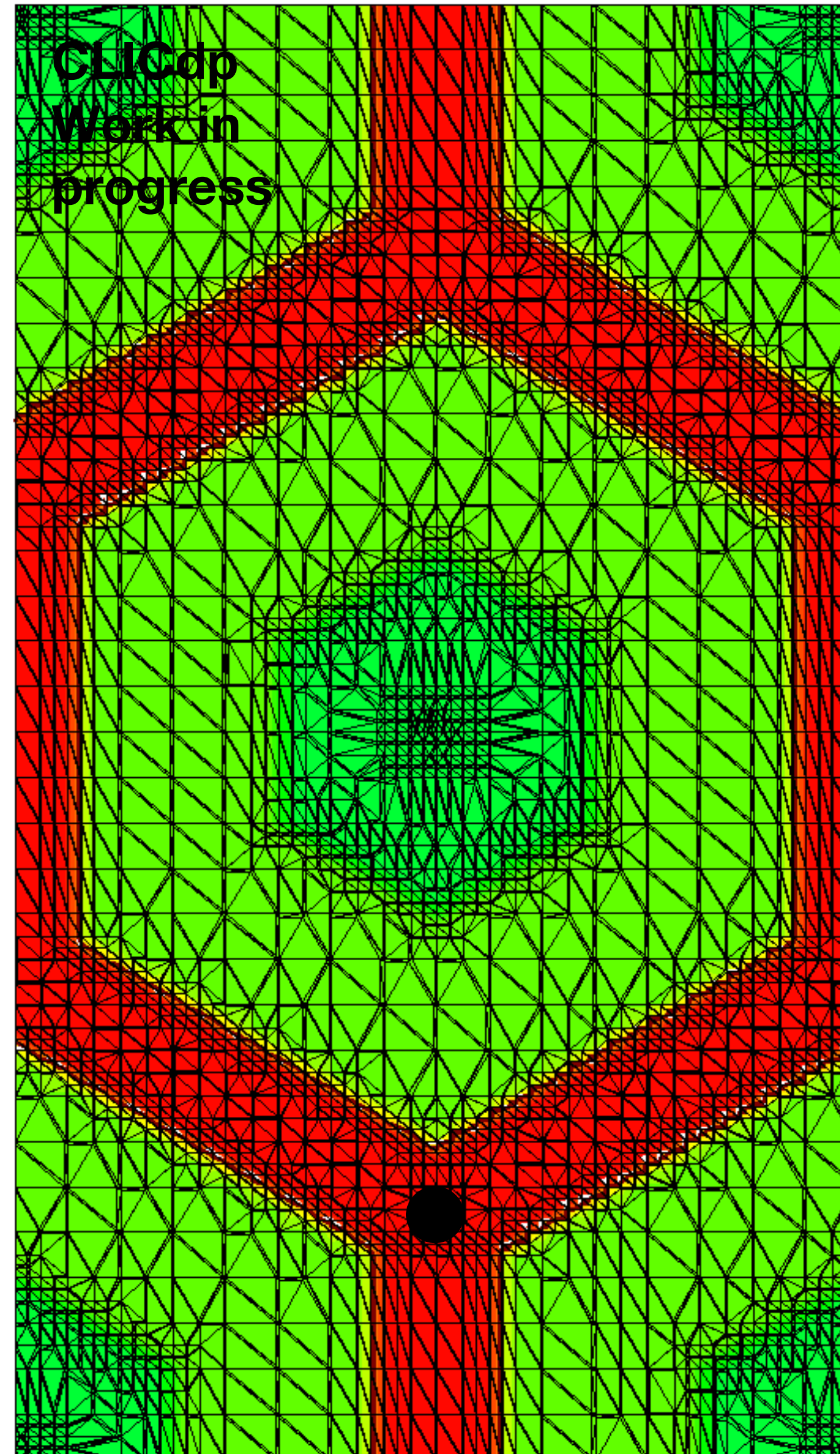


Some considerations on the ‘worst case’ in the hexagonal pixel design

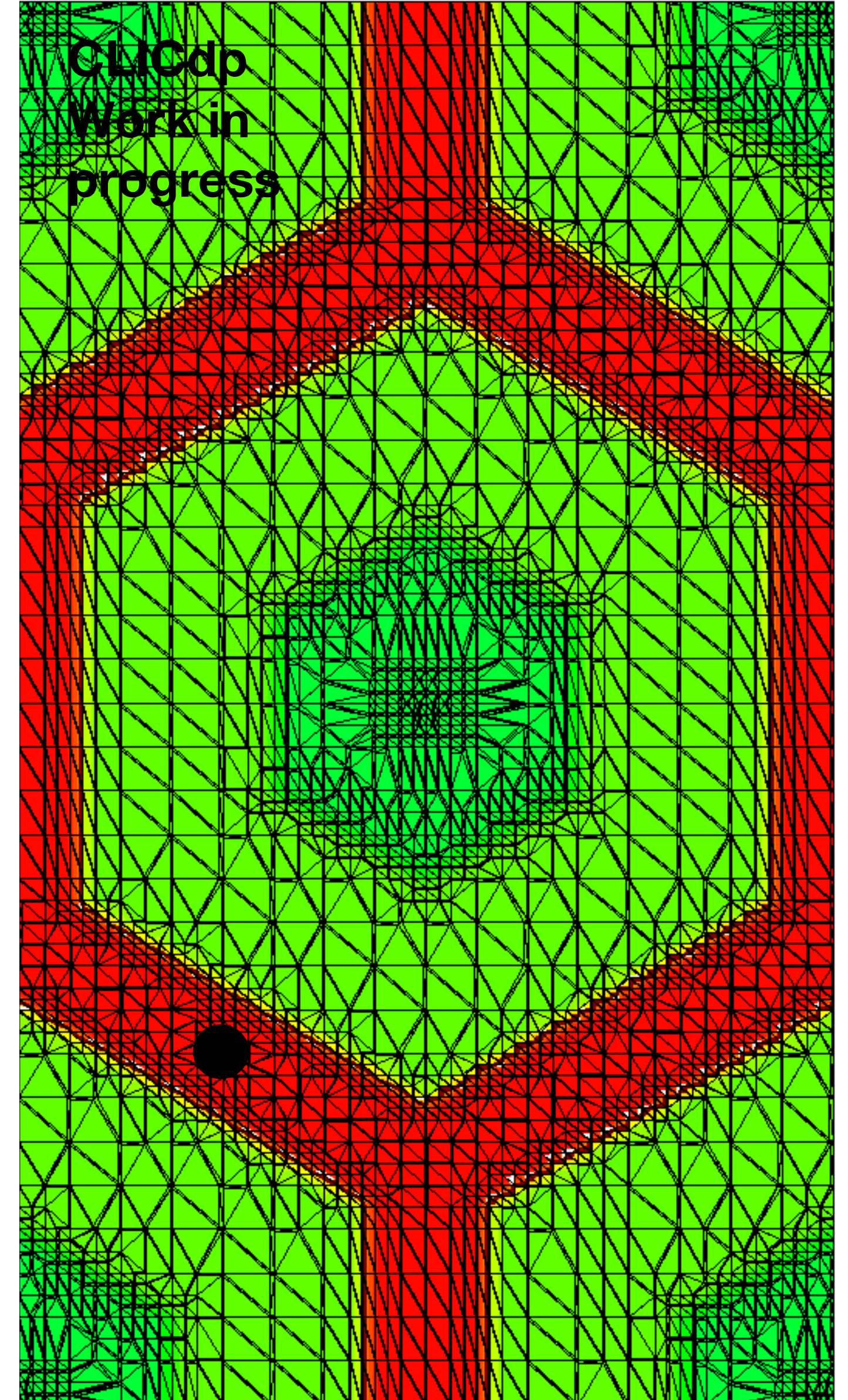
Position 0:



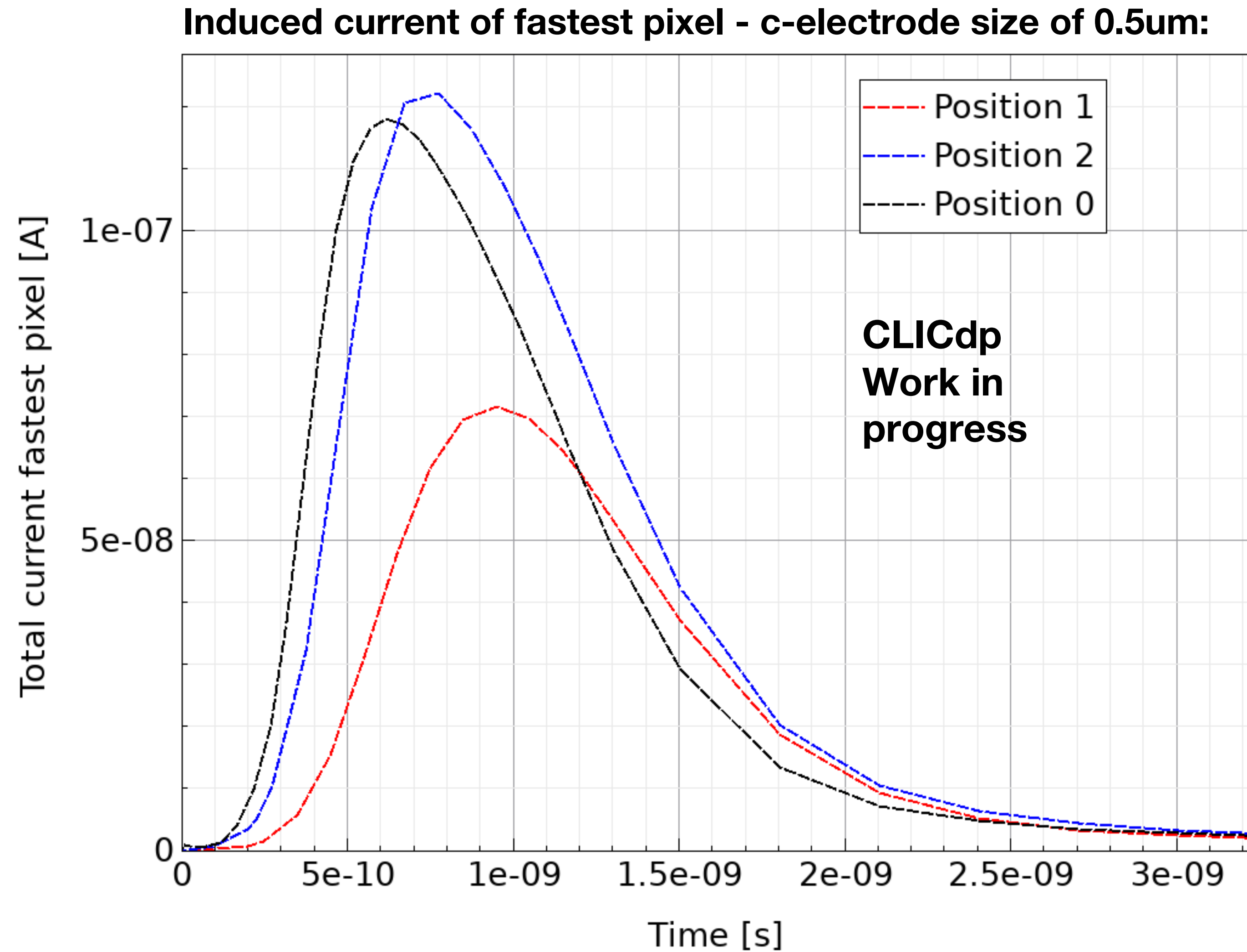
Position 1:



Position 2:



Some considerations on the 'worst case' in the hexagonal pixel design



—> Position 1 with equal distance to collection electrodes is worst case in view of timing.