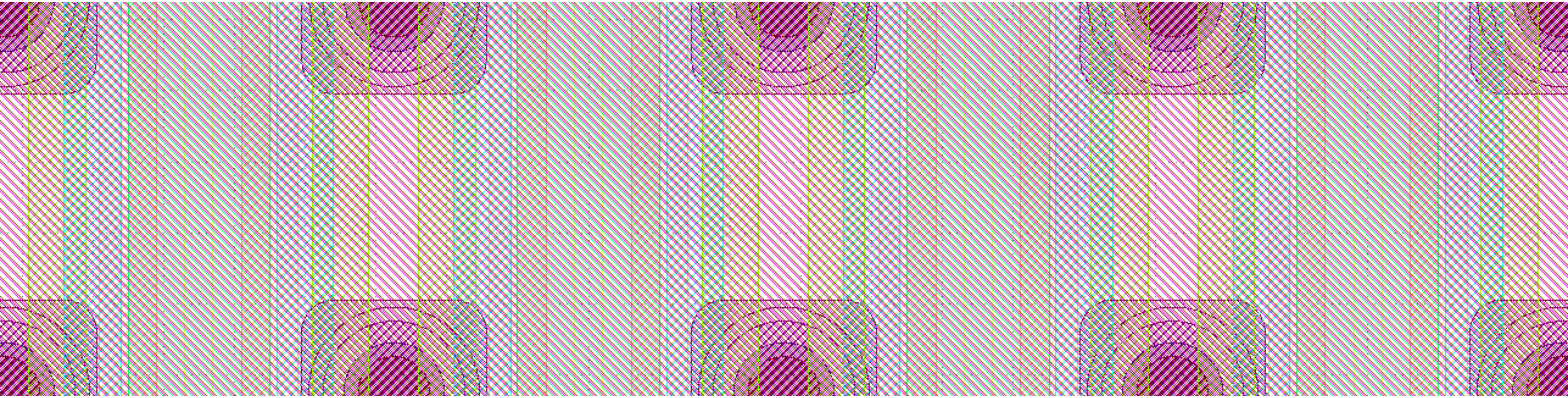
Enhanced Lateral Drift Sensors

Towards the production



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09.02.2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
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CiS Forschungsinstitut für Mikrosensorik GmbH
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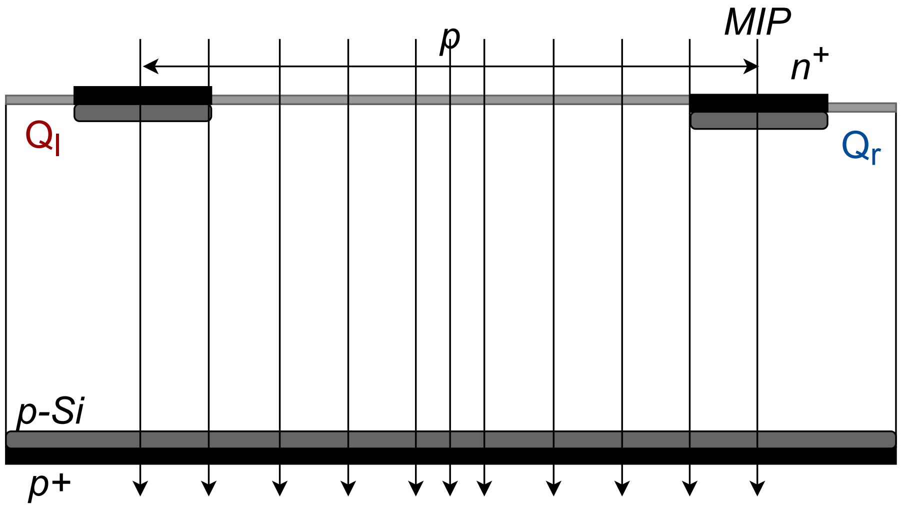
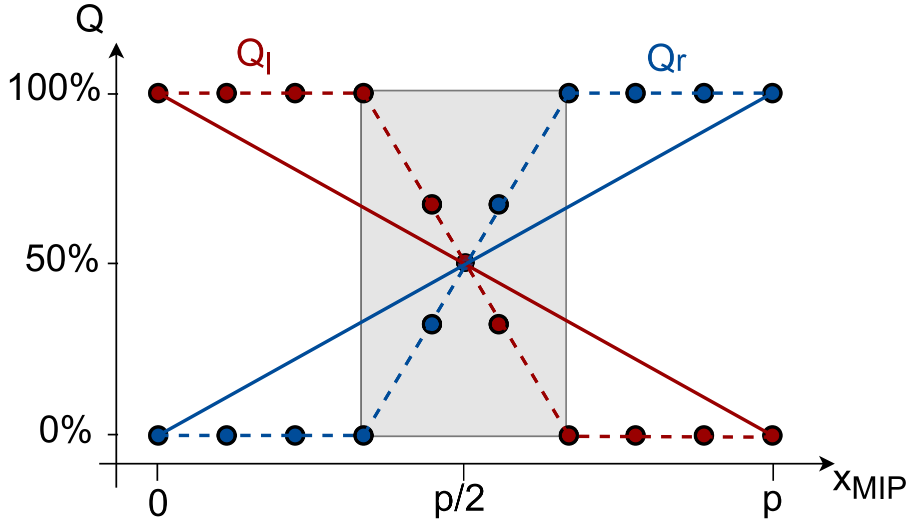
DESY.

Charge sharing

Towards the theoretical optimum of position resolution



$$\eta = Q_l/(Q_l+Q_r)$$



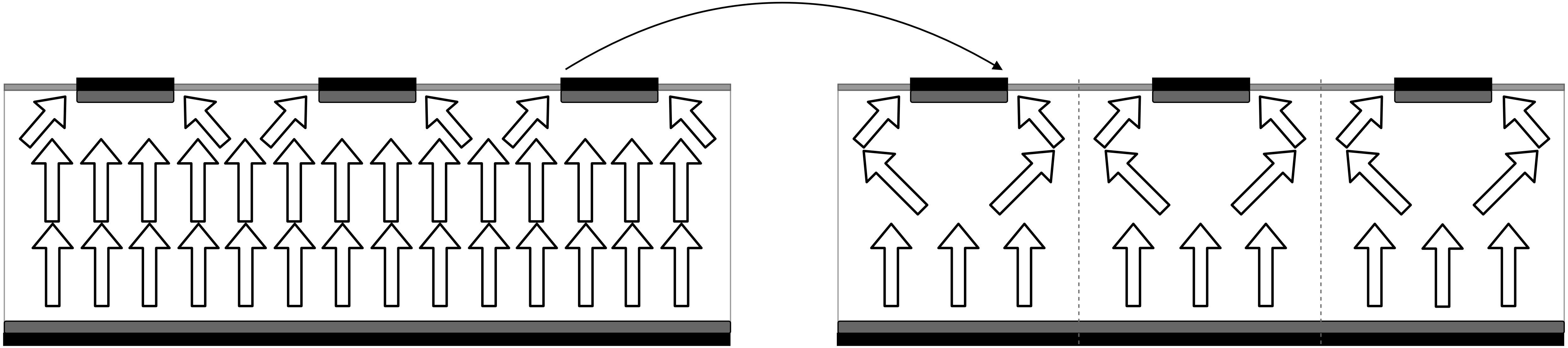
- Standard sensor design:
  - charge in the left part of pitch collected by 1st strip
  - charge in the right part of pitch collected by 2nd strip
- In an ideal case:
  - charge distribution between 1st and 2nd strip is **linear** → best charge sharing

Concept of an Enhanced Lateral Drift Sensor

Manipulating the electric field

- Charge carriers in sensor follow the electric field lines
- **How to achieve improved position resolution of charged particle sensors?**

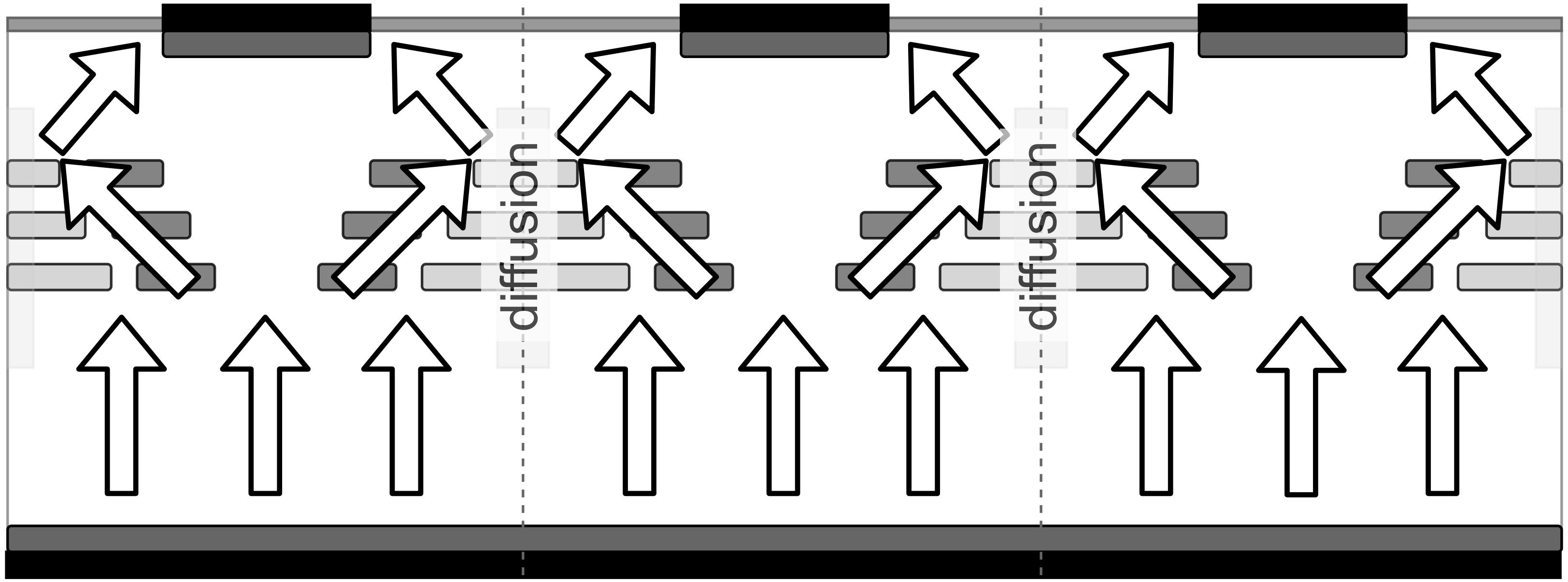
  → Induce lateral drift by locally engineering the electric field
- Introduce a lateral electric field inside the bulk



Concept of an Enhanced Lateral Drift Sensor

Manipulating the electric field

- **Buried implants → regions of additional doping**

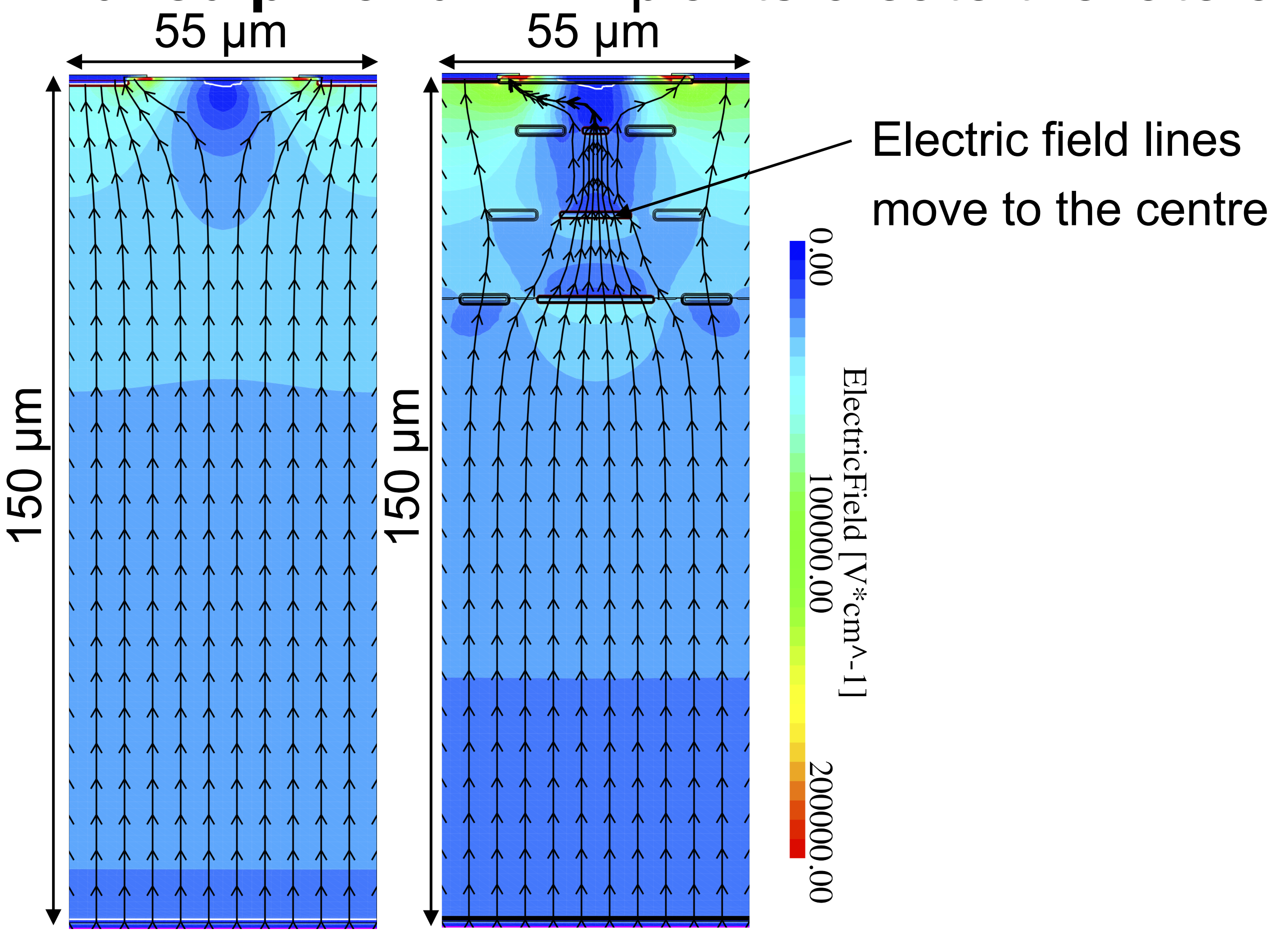


- Lateral electric field → repulsive/attractive areas inside the bulk
- **Modified drift path of the charge carriers**

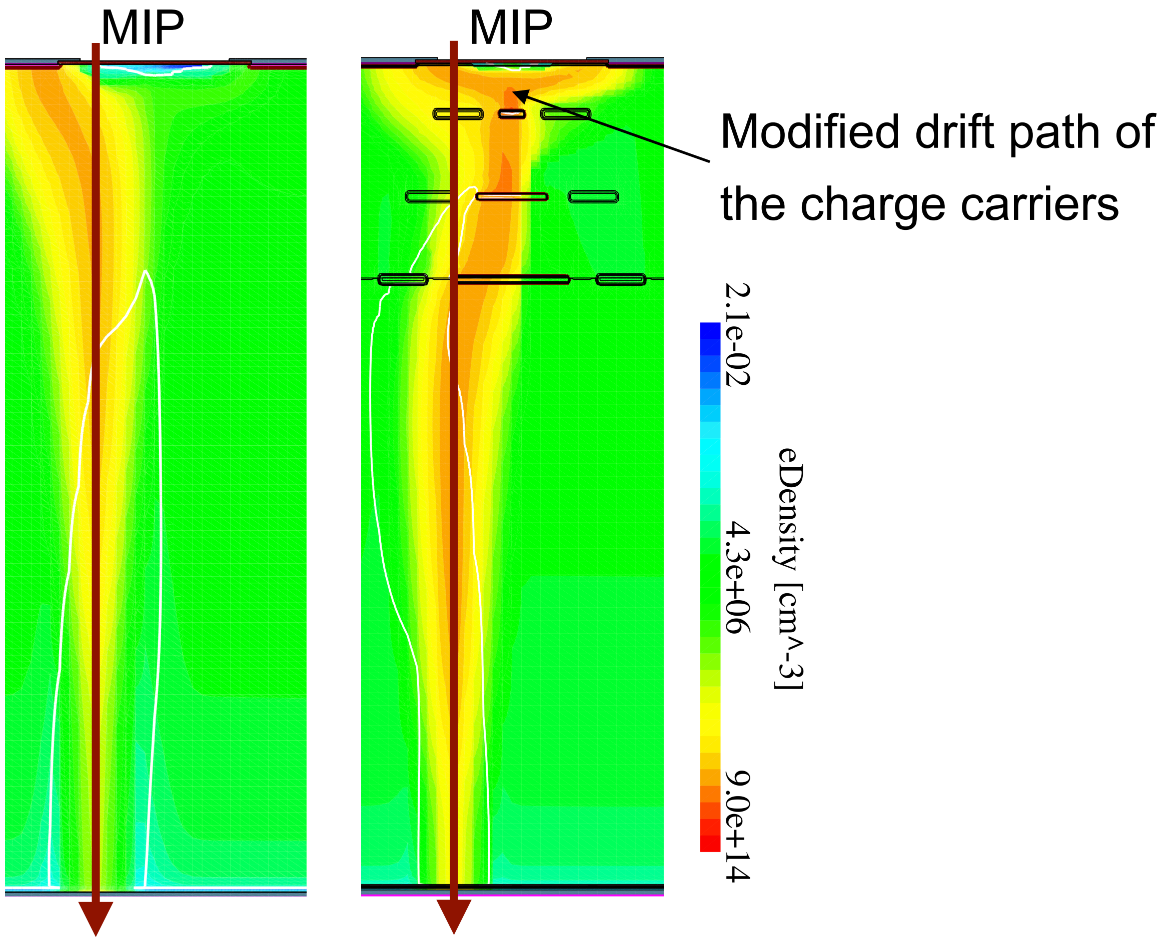
Simulations of the ELAD Sensors

TCAD Electric Field & Transient Simulations

- Buried **p⁺**- and **n⁺**-implants create the lateral electric field in the bulk.



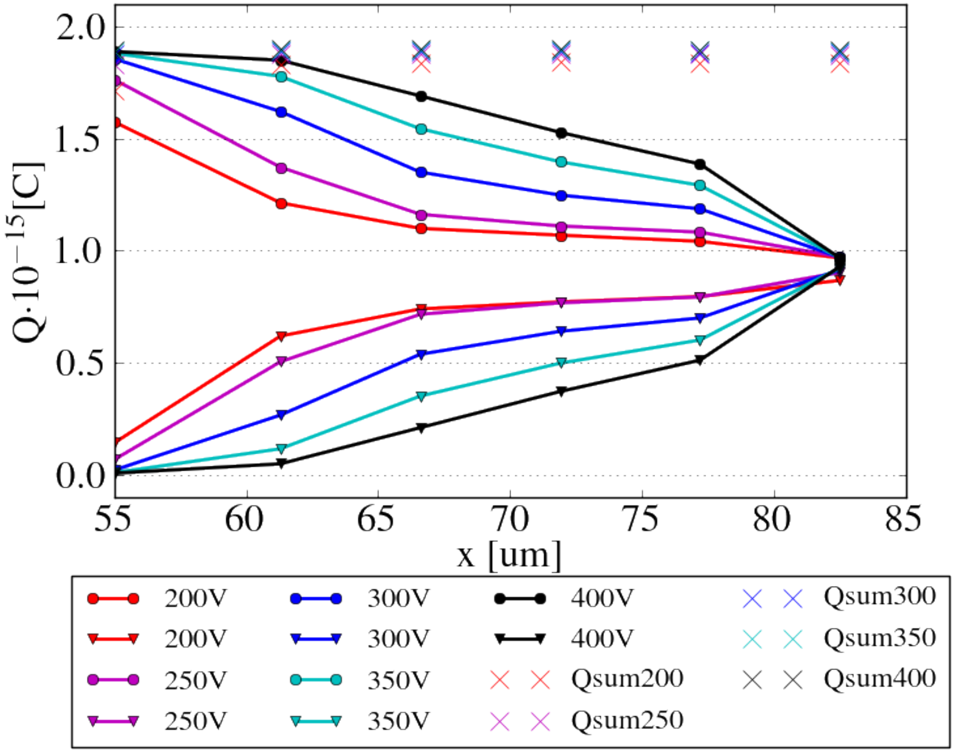
Planar sensor *p-ELAD*

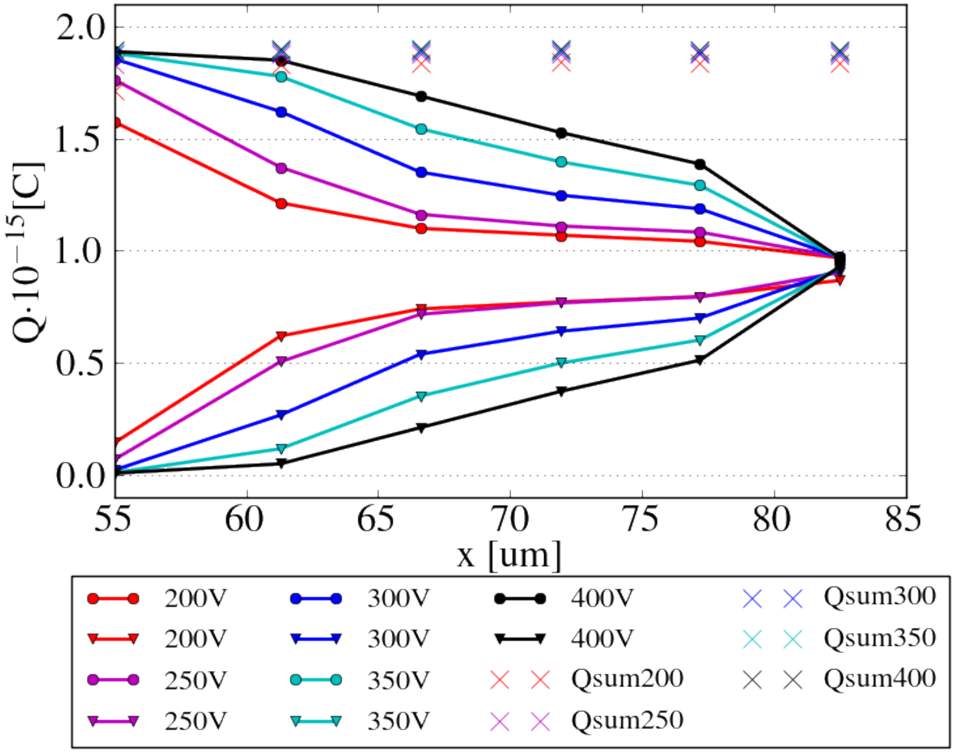


Planar sensor *p-ELAD*

Simulations of the ELAD Sensors

TCAD η - function 150 μm ELAD $n_{di}=3 \times 10^{15}$ cm^{-3}



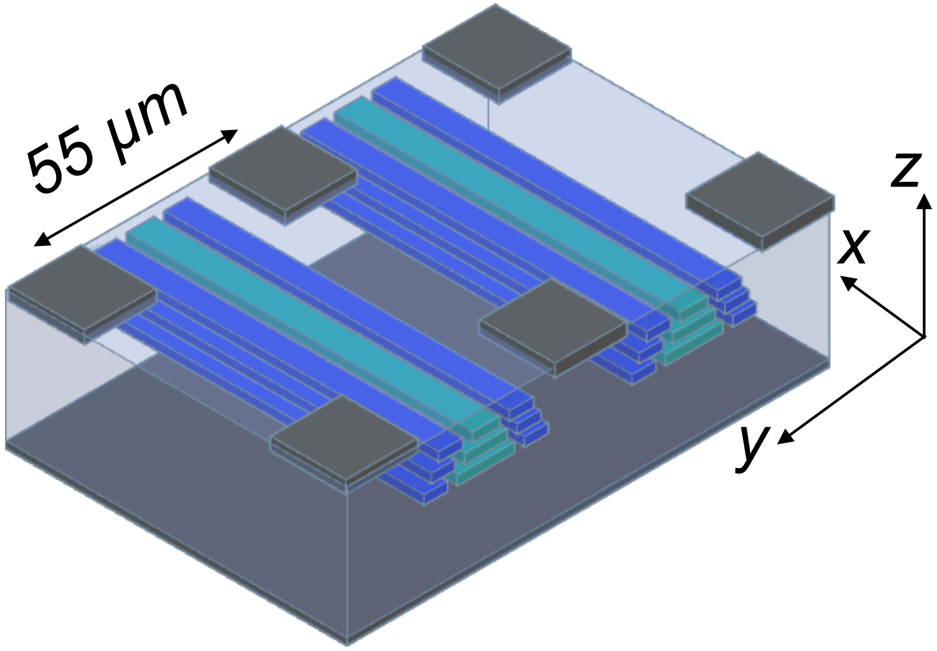


- p-ELAD: optimal voltage → 300V and 350V
- n-ELAD: optimal voltage → 250V and 300V
- **tuning** of the **lateral** and **longitudinal** components of the electric field

Simulations of the ELAD Sensors

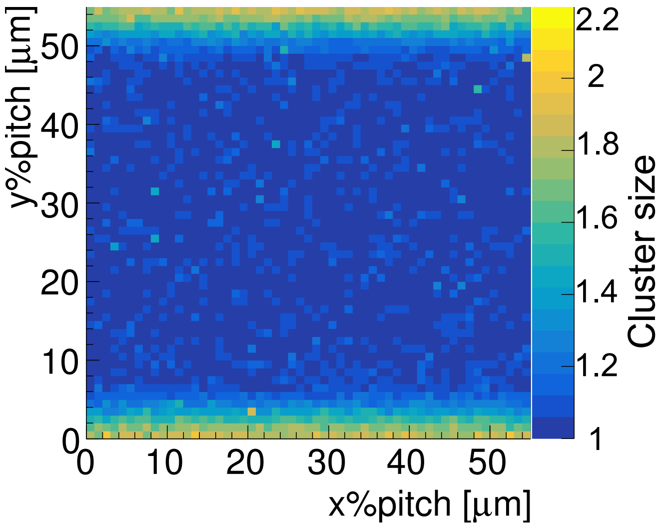
Allpix² resolution studies

- To estimate the position resolution → AllPix² simulations
- Allpix² - generic simulation framework for silicon tracker and vertex detectors
- Simulations with MC particles
- Based on Geant4 and ROOT
- Uses TCAD electric field

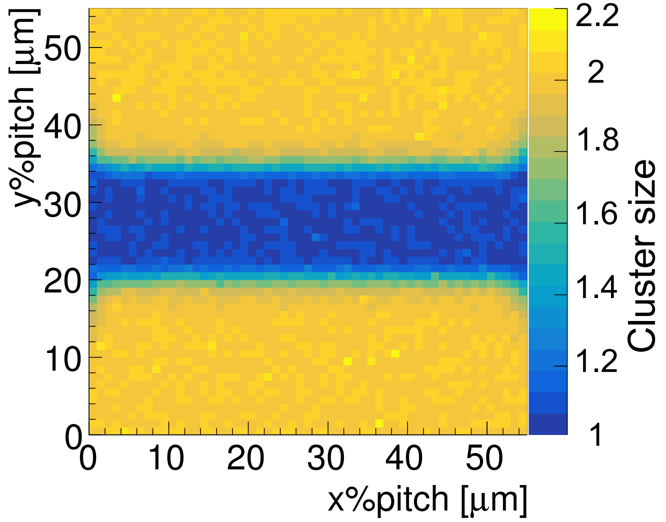


Simulations of the ELAD Sensors

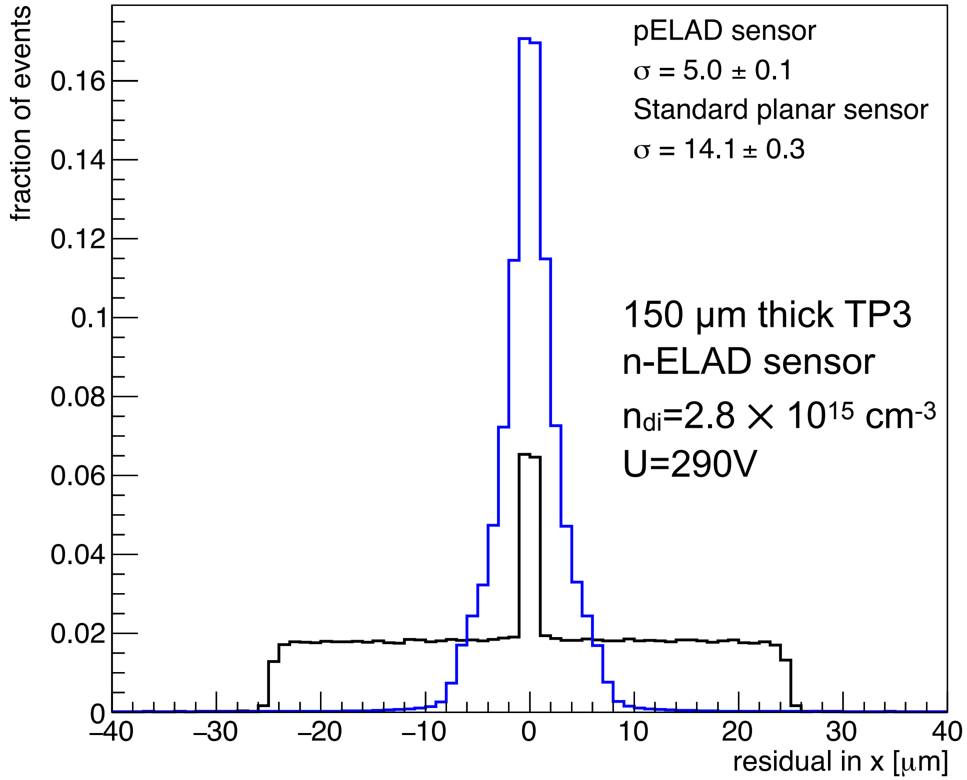
Allpix² resolution studies.



- Cluster size in *x* ~1
- Edges of the pixel ~2
- no ELAD effect



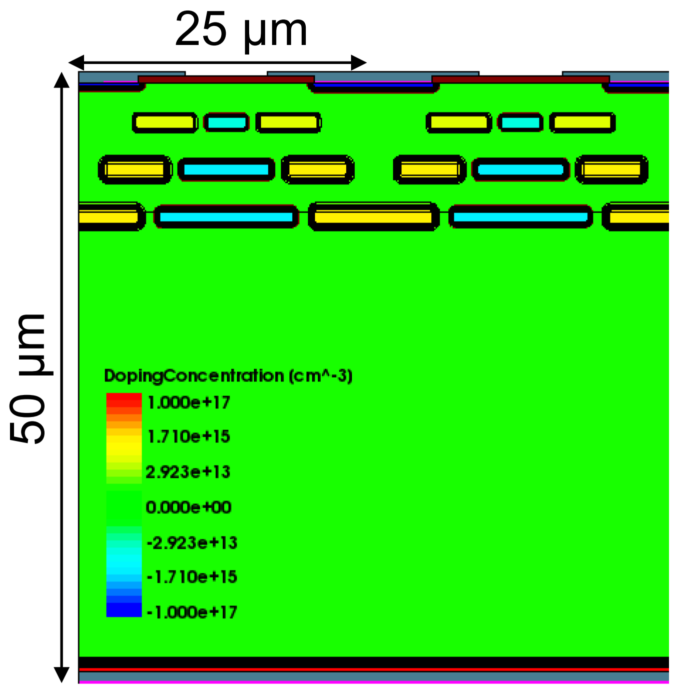
- Cluster size in *y* ~2
- Center of the pixel ~1
- ELAD charge sharing

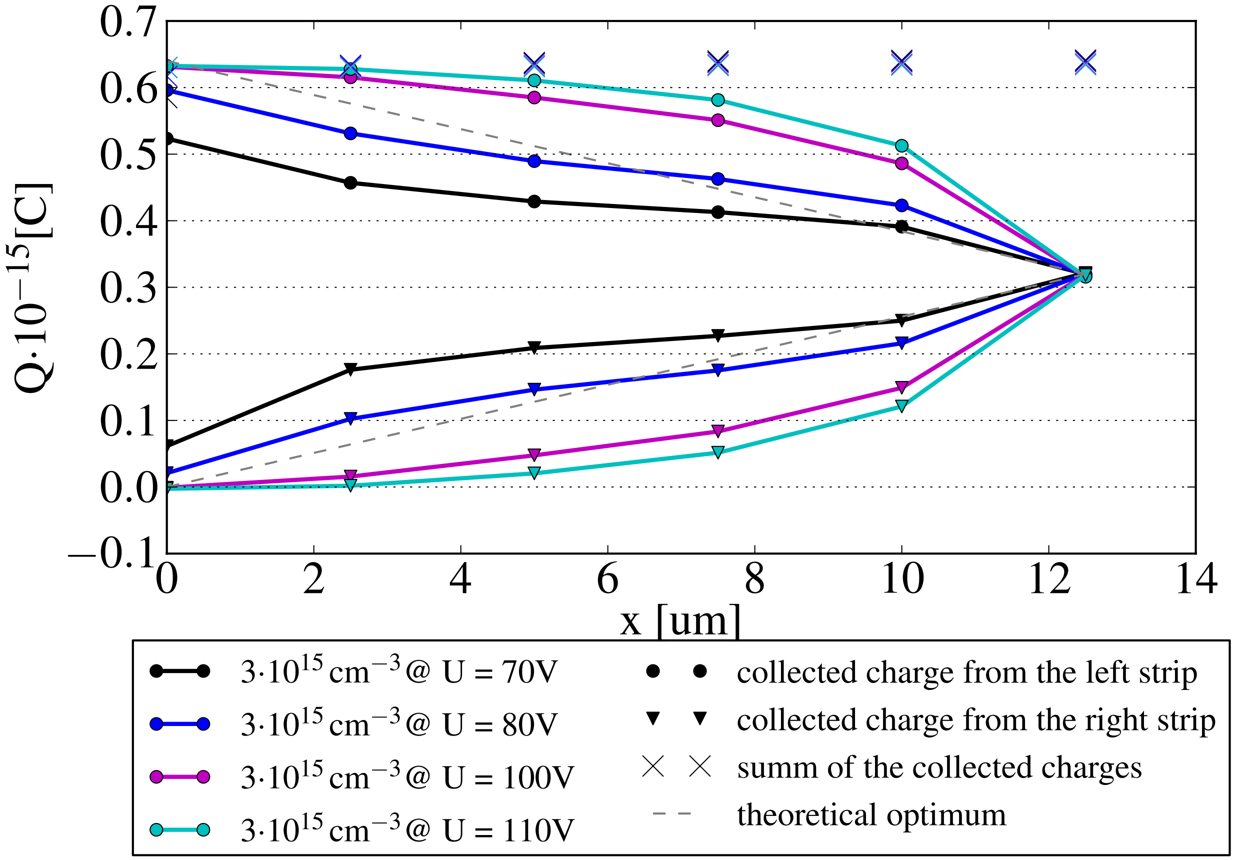


nELAD CP2

TCAD simulations | 50 µm thick CP2 n-ELAD sensor n_{di}=3 × 10^{15} cm^{-3}

- smaller distance between the buried implants layers
- wider buried implants



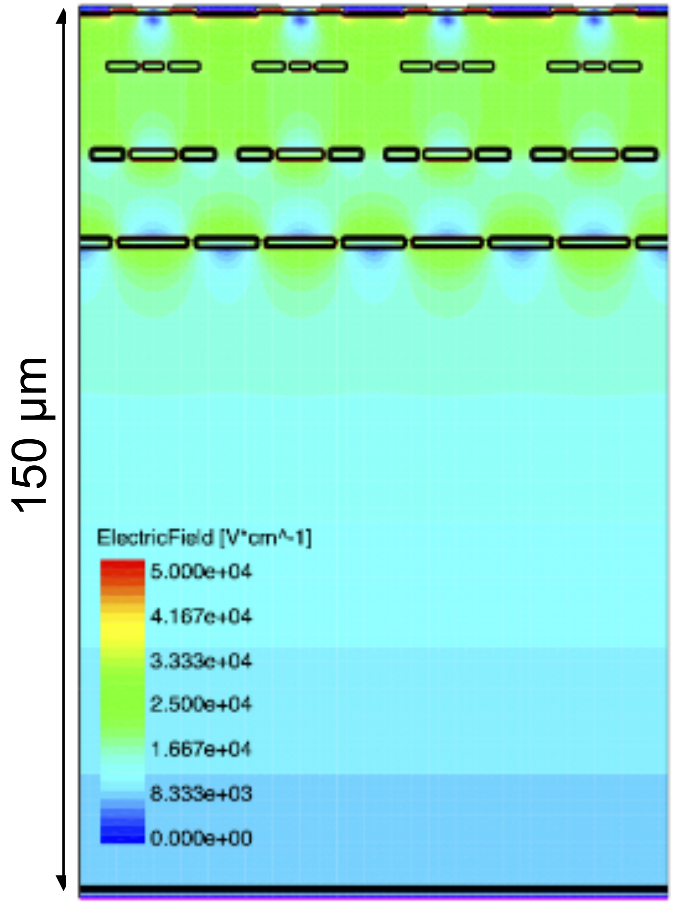


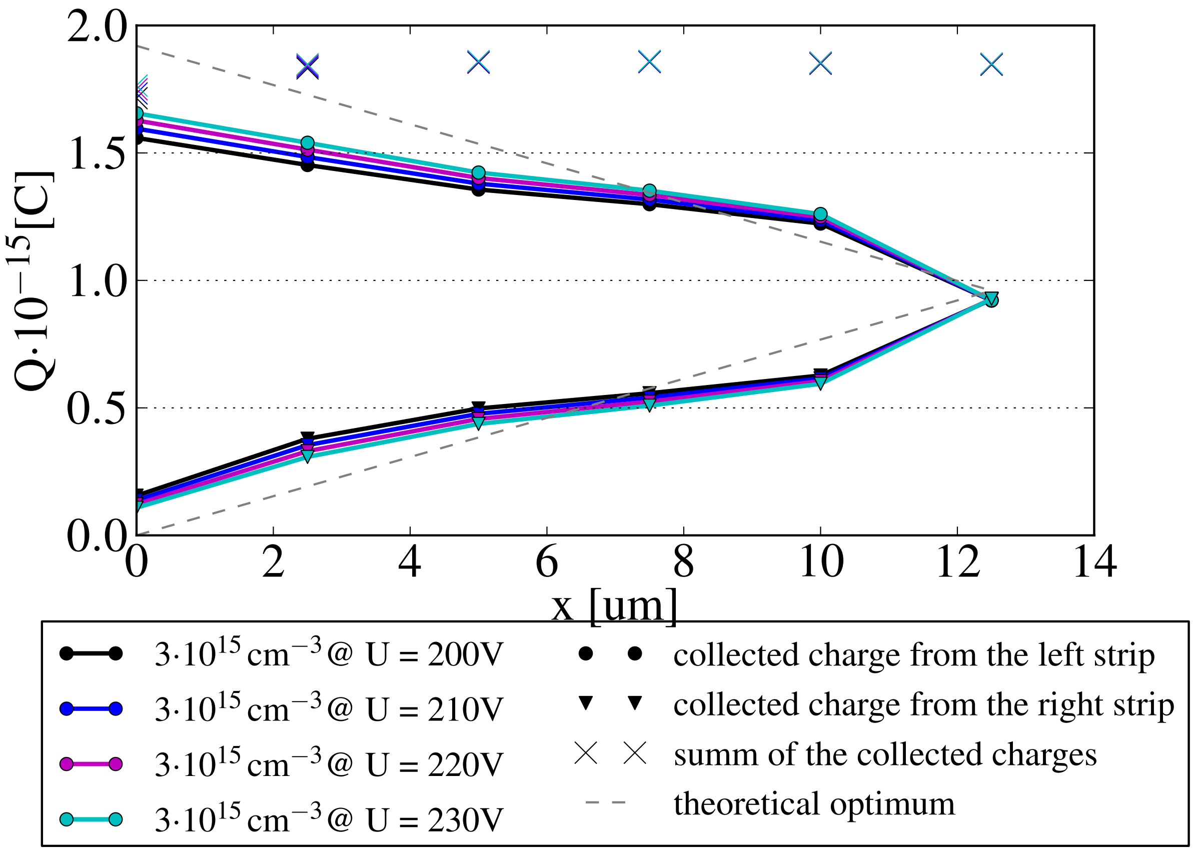
- ELAD design optimised to the read-out pitch and thickness

nELAD CP2

TCAD simulations | 150 µm thick CP2 p-ELAD sensor n_{di}=3 × 10^{15} cm^{-3}

- 150 µm CP2 design for the first production

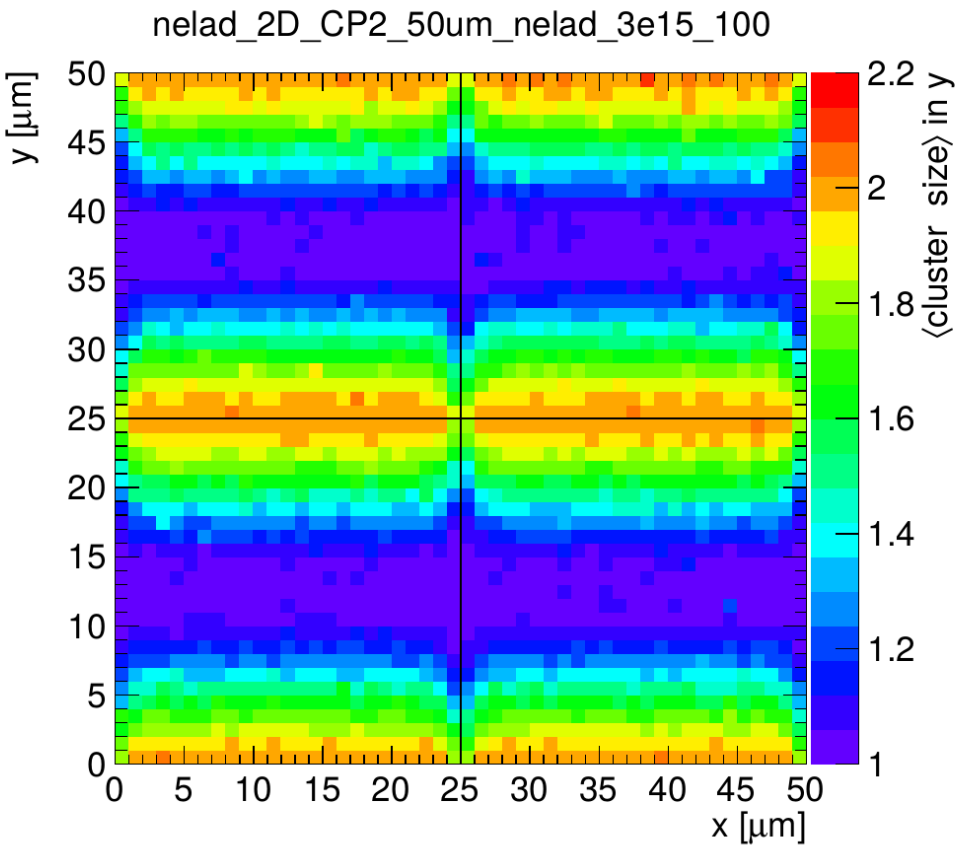


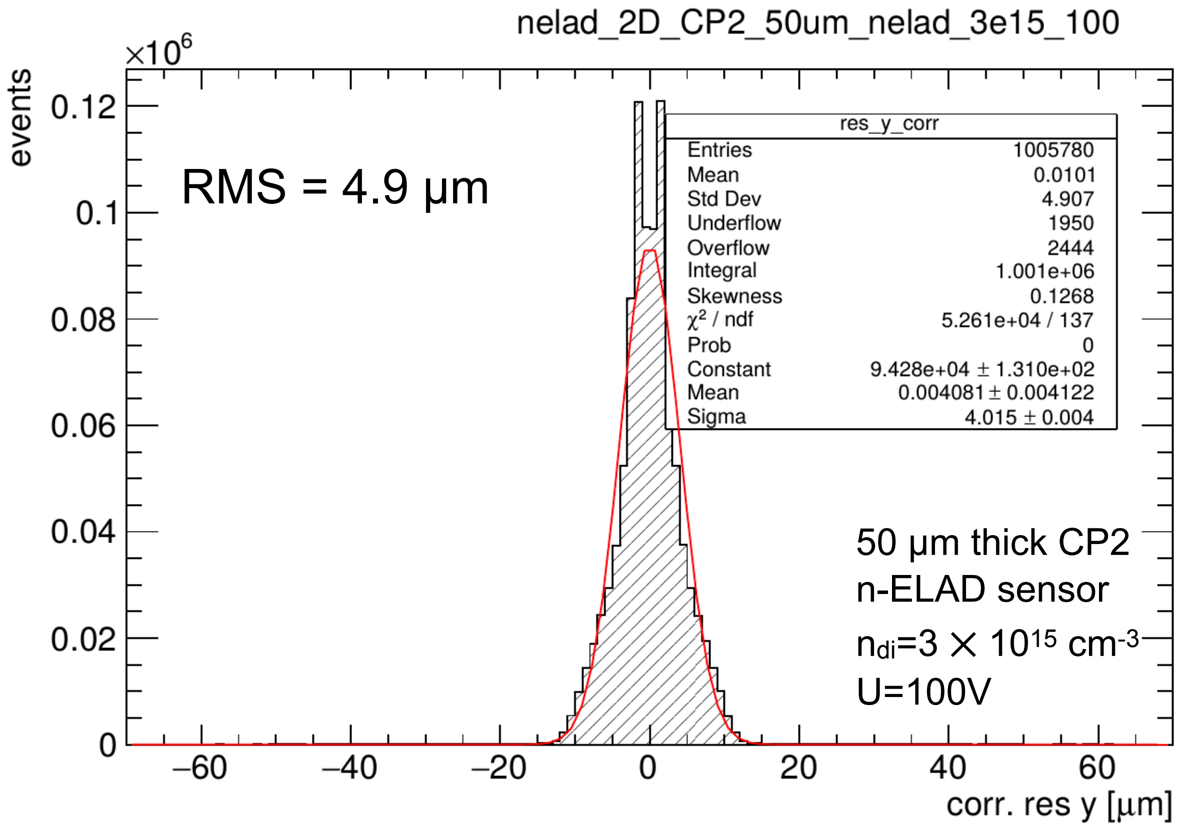


- no specific optimisation for this design

Simulations of the ELAD Sensors

Allpix² resolution studies.

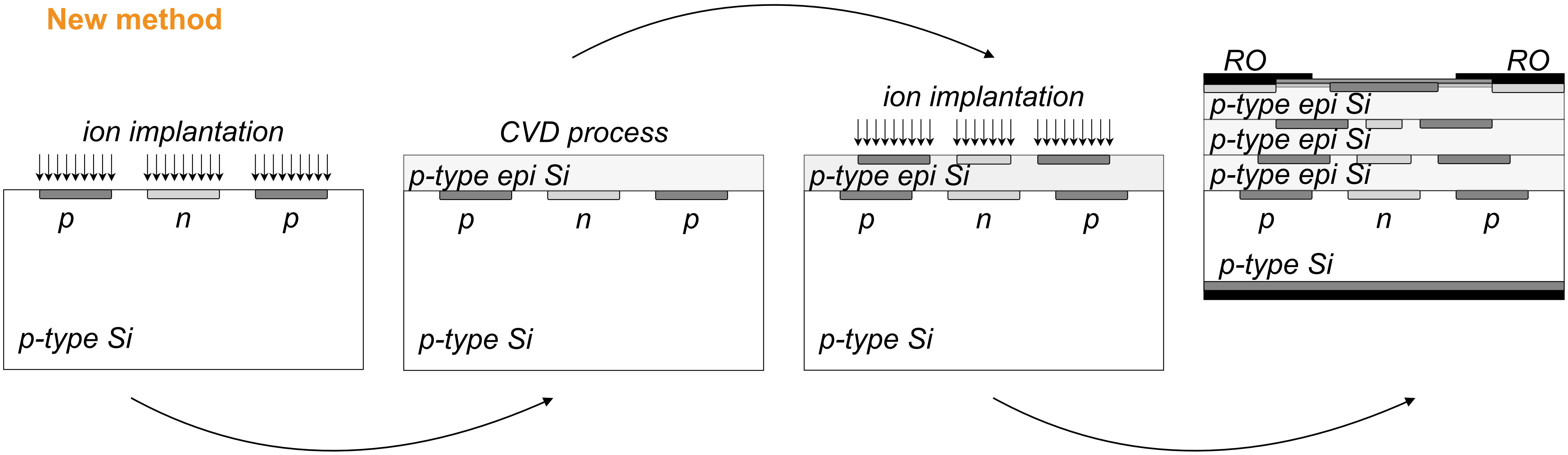




- Cluster size in *y* ~2 → ELAD charge sharing

Production

New method



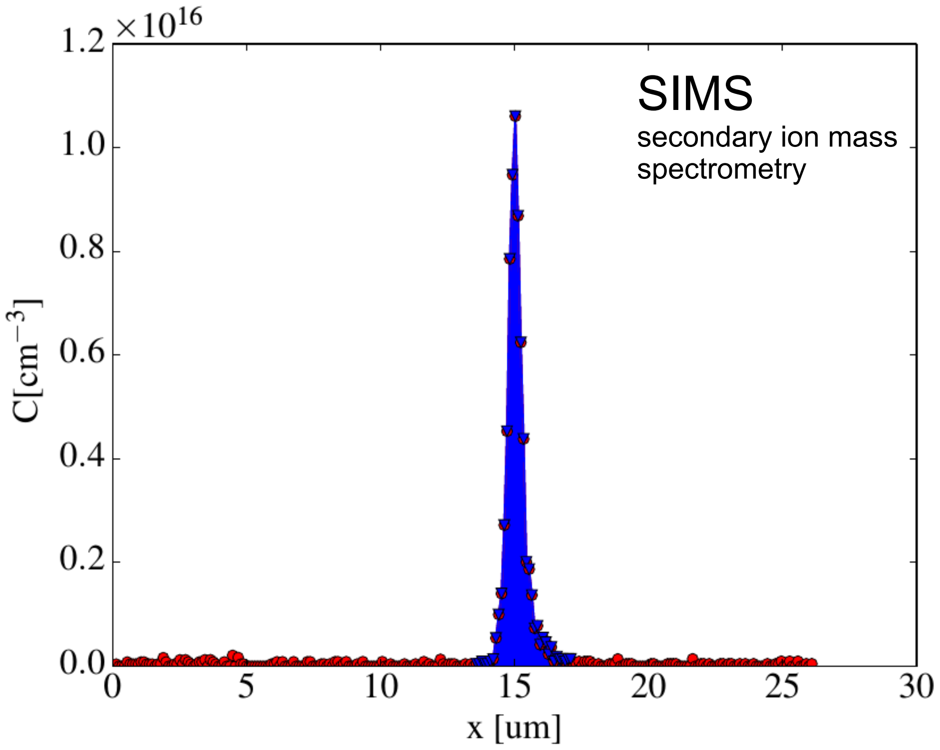
- Epitaxial growth process, a thin silicon layer is grown on the wafer surface. Process temperature ~ 1050°C.
- Combination of implantation and epitaxial growth is repeated three times. After the last epitaxial growth → implantation for the readout electrodes.

Process development

Pilot studies

- Processing steps:

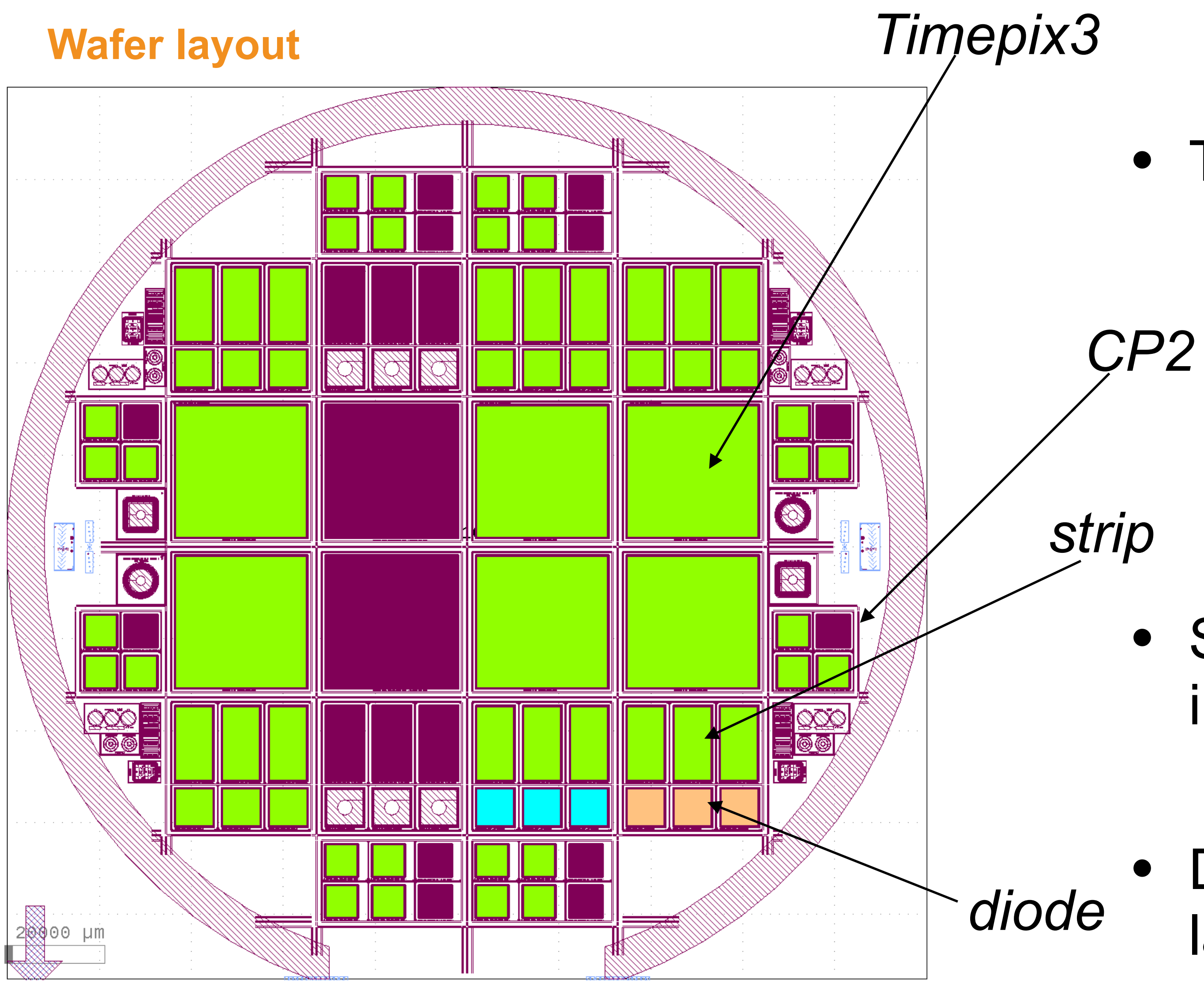
1. Five 200 mm wafers, p-type, 5kOhmcm
2. Implant 3x unstructured p,
   2x n on p-substrate through oxide
4. RTA or oven annealing
5. Grow intrinsic EPI (slightly p), 15 um
6. Heat in oven for temperature budget mimicking 2x more EPI
7. SRP and SIMS for depth analysis



→ Allows understanding of buried implants and qualification for possible ELAD run

Production

Wafer layout



- Three types of sensors:
  - Timepix3 pixel sensor (test beam)
  - strip sensor (test beam & TCT & lab)
  - diode (lab)
- Sensors with and without the buried implants
- Diodes with 1 and 2 buried implants layers

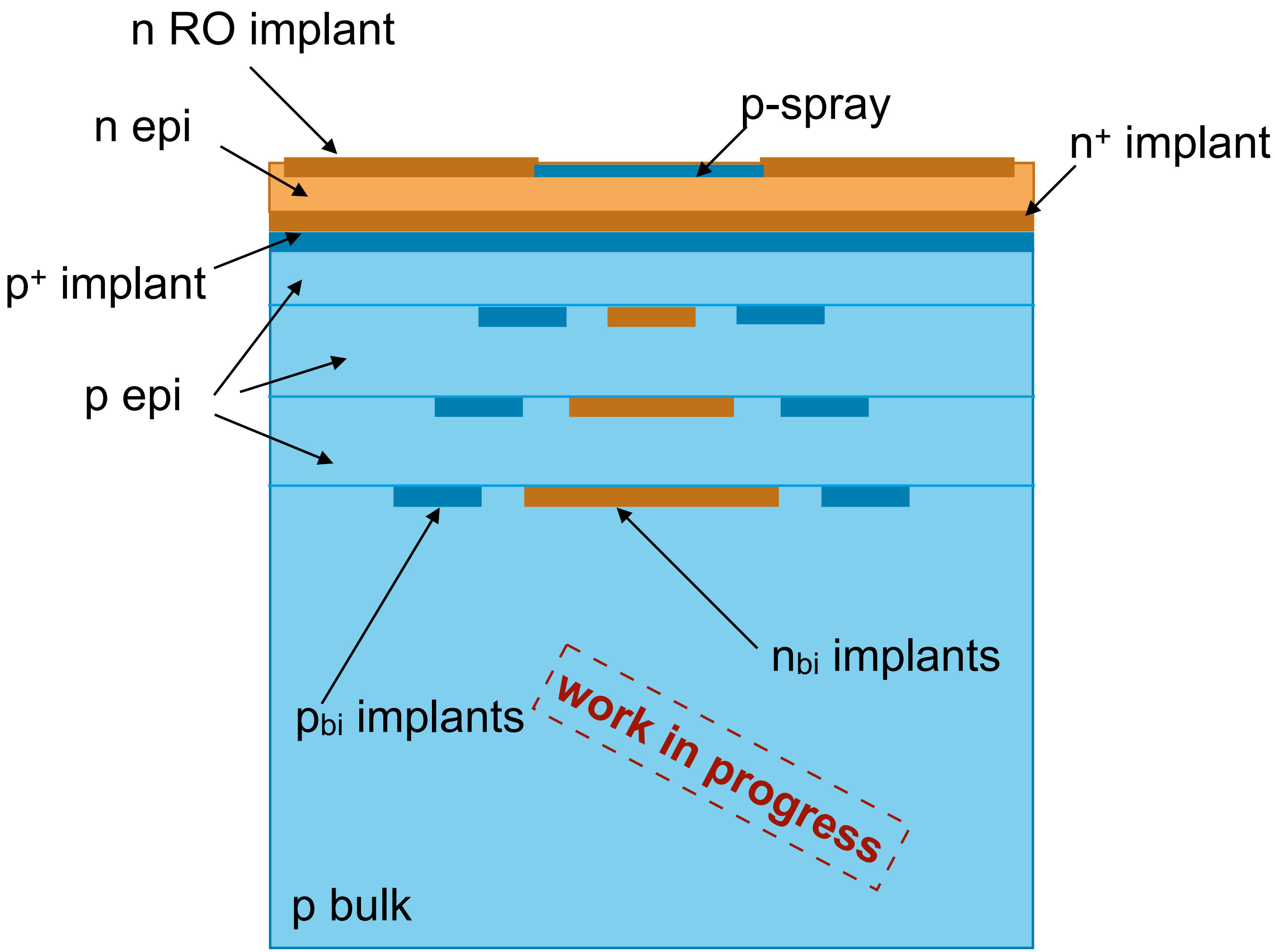
ELAD with multiplication layer

First attempt

- extra n⁺ p⁺ multiplication layer

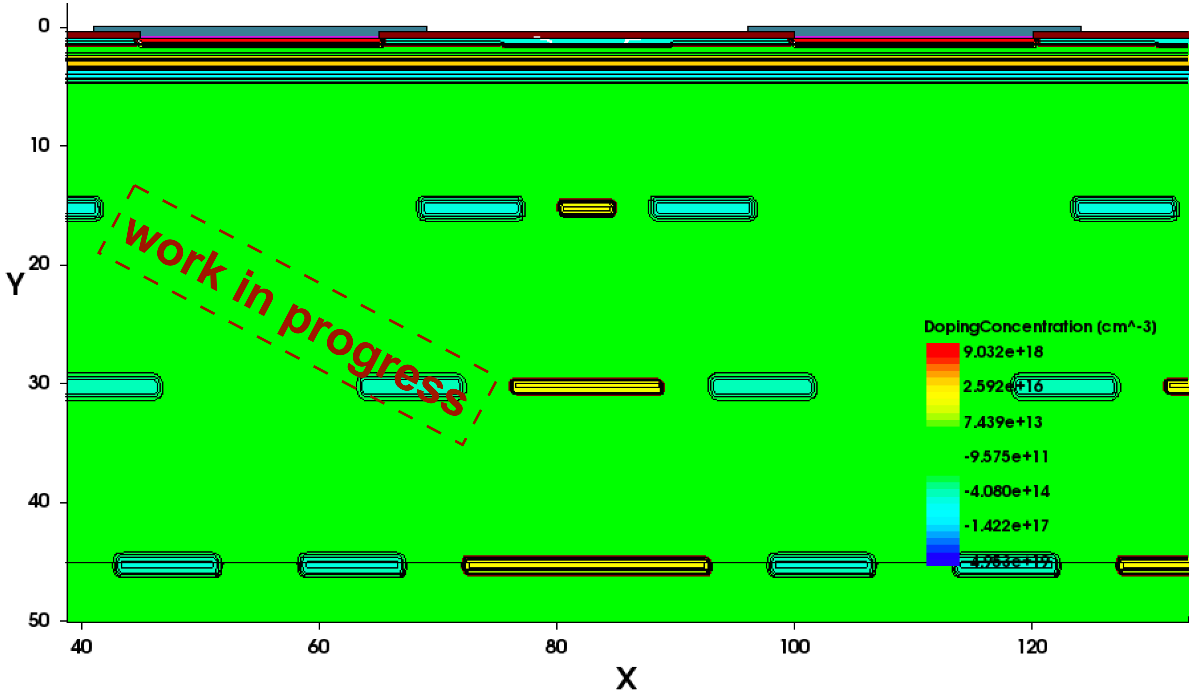
- n-epi on top of the multiplication layer

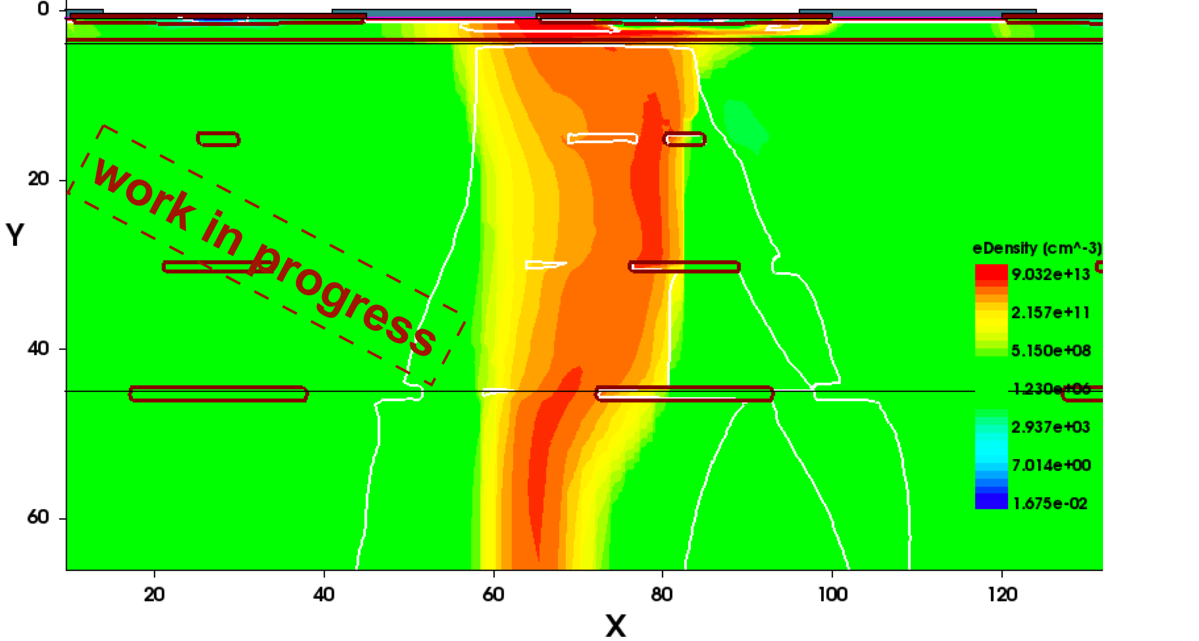
- ELAD structure with p-epi layers beneath the multiplication layer

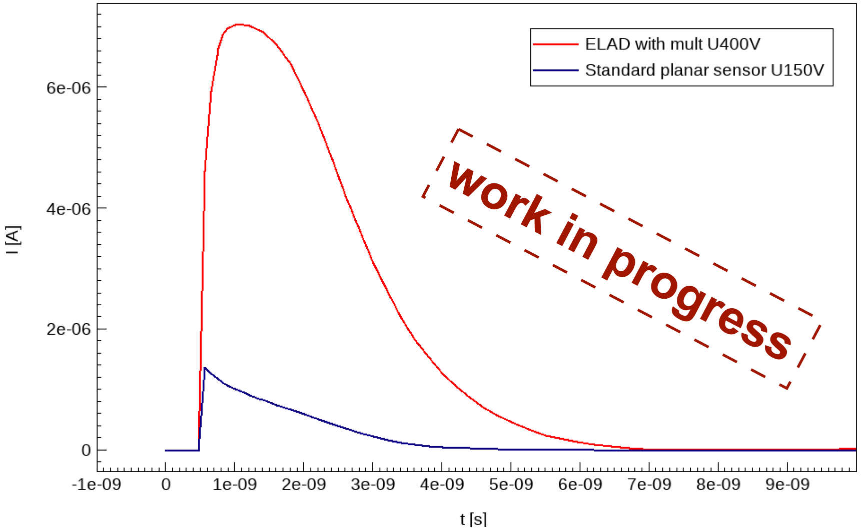


ELAD with multiplication layer

First attempt

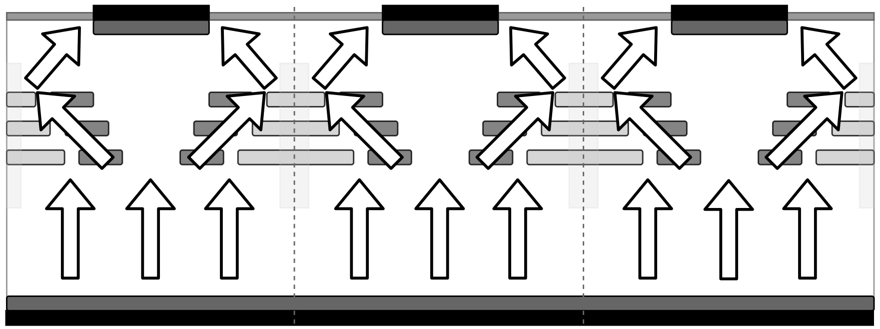


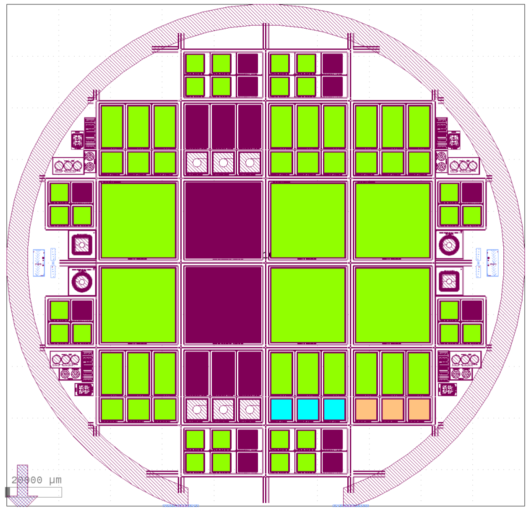




- multiplication of the charge is achieved (~9x)
- more tuning needed
- aiming for 3 um spatial resolution at 55 um pitch combined with sub 100 ps timing resolution (with appropriate ASIC).

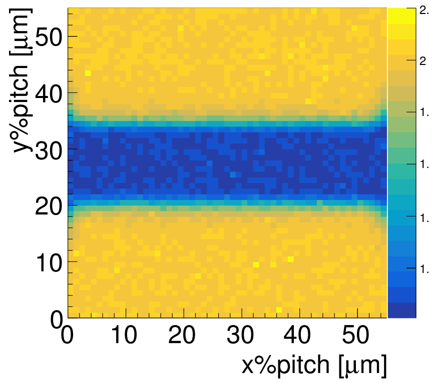
Summary & Outlook





Summary:

- Test-structures prove the production technique
- Production of the first sensors is started
- Recently started preliminary study on buried multiplication layer



Outlook:

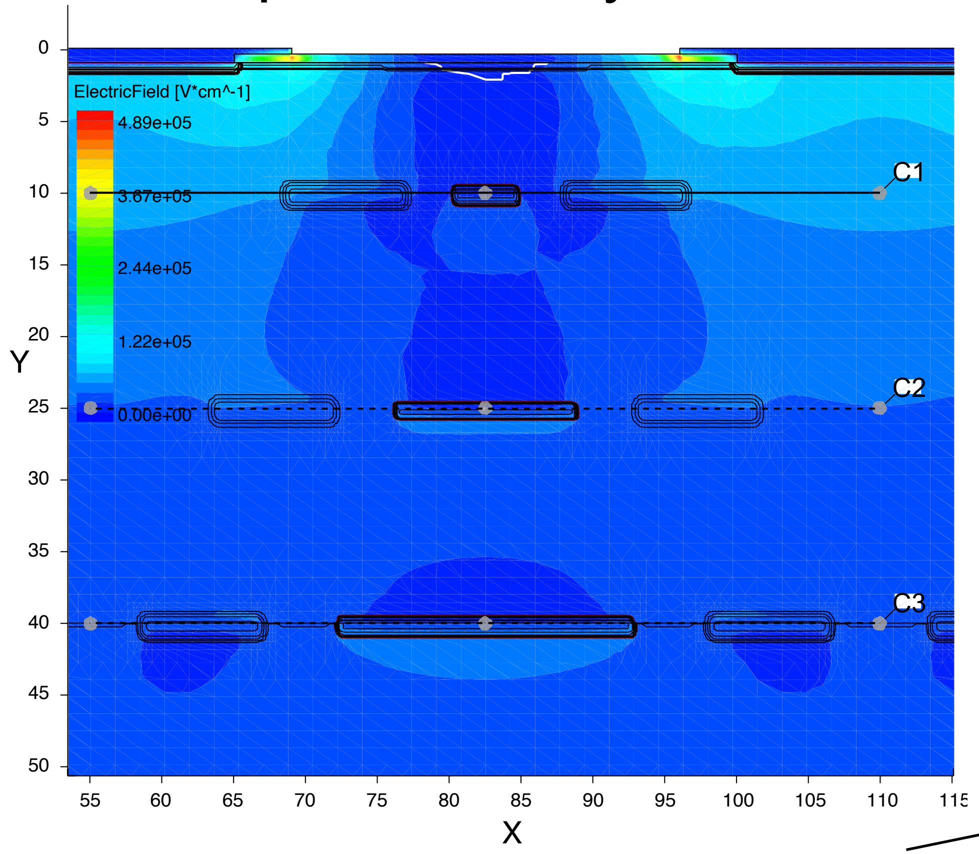
- Looking forward to the receiving of the samples
- Looking further into buried multiplication layer, especially concerning gain, depth and electric field close to read-out electrodes

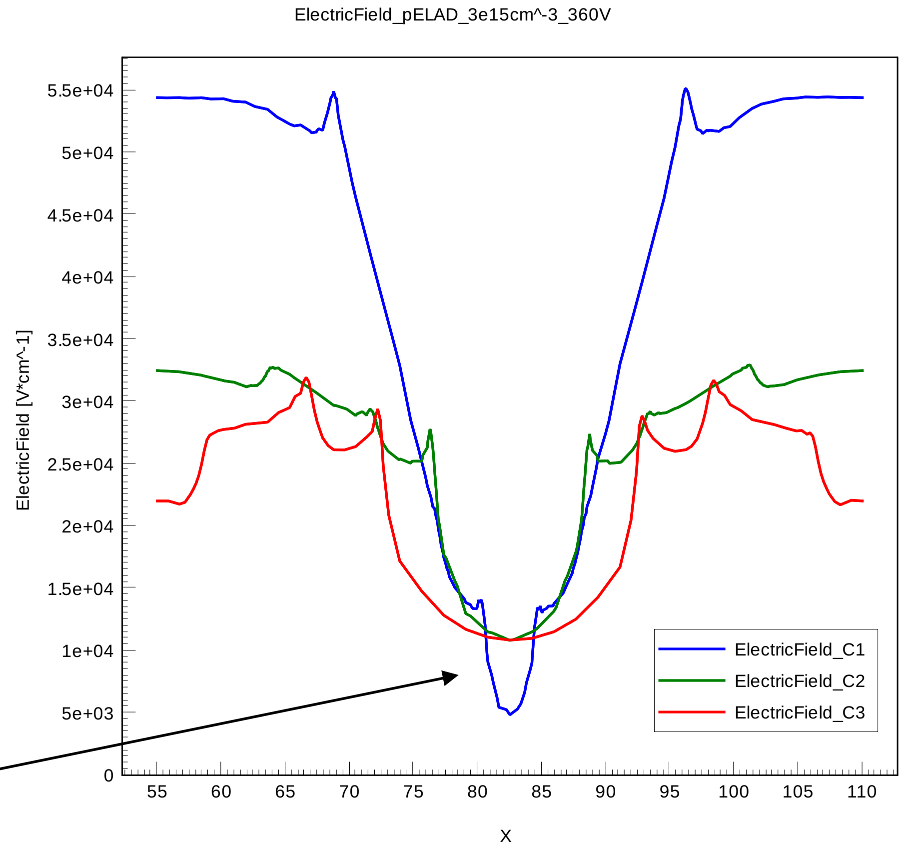
Backup

Simulations of the ELAD Sensors

TCAD Electric Field | Buried implants area | x-scan

- Buried implants modify the electric field in the sensor.



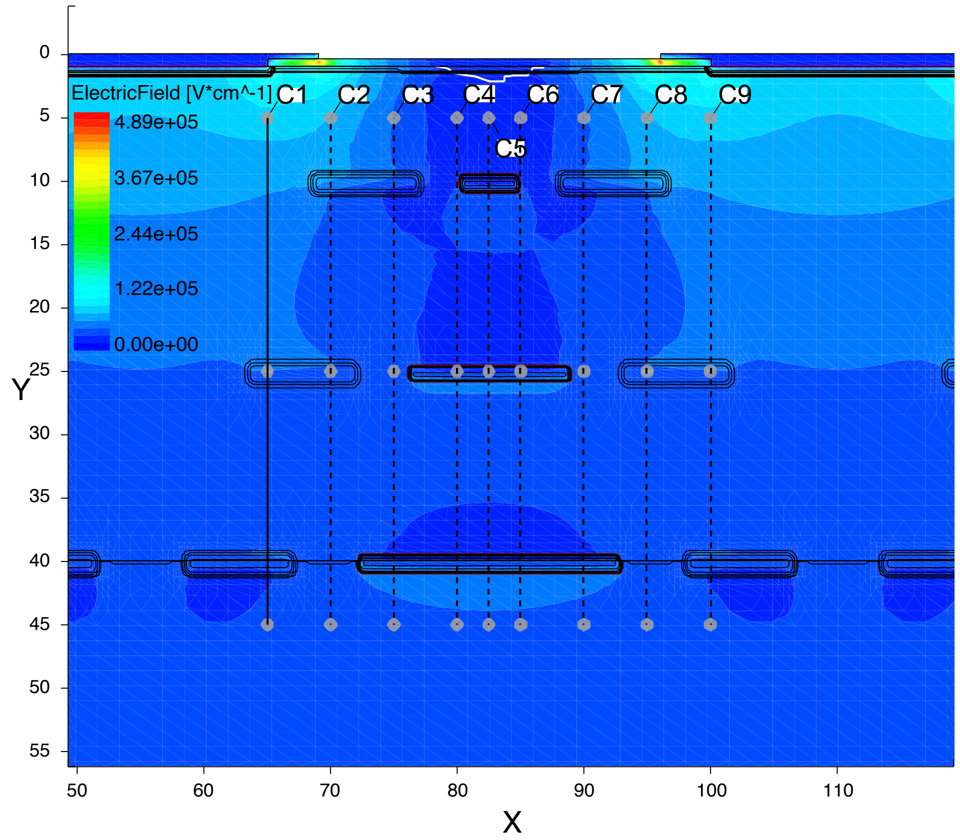


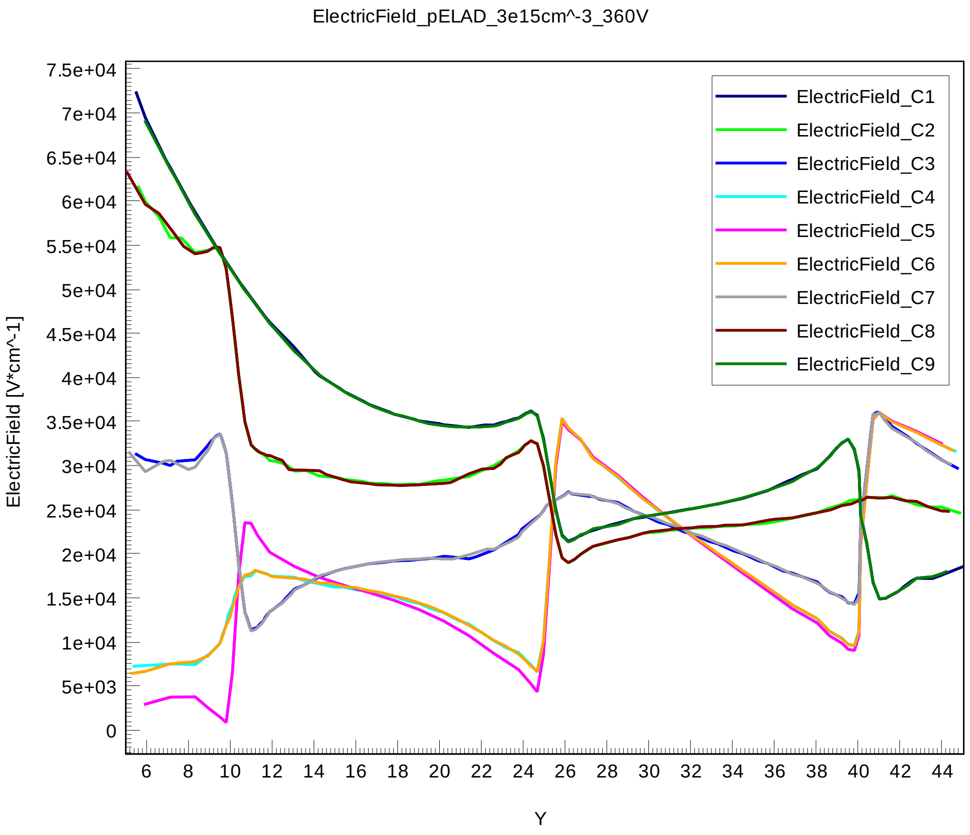
- low field area → drift + diffusion → charge sharing

Simulations of the ELAD Sensors

TCAD Electric Field | Buried implants area | y-scan

- Buried implants modify the electric field in the sensor.



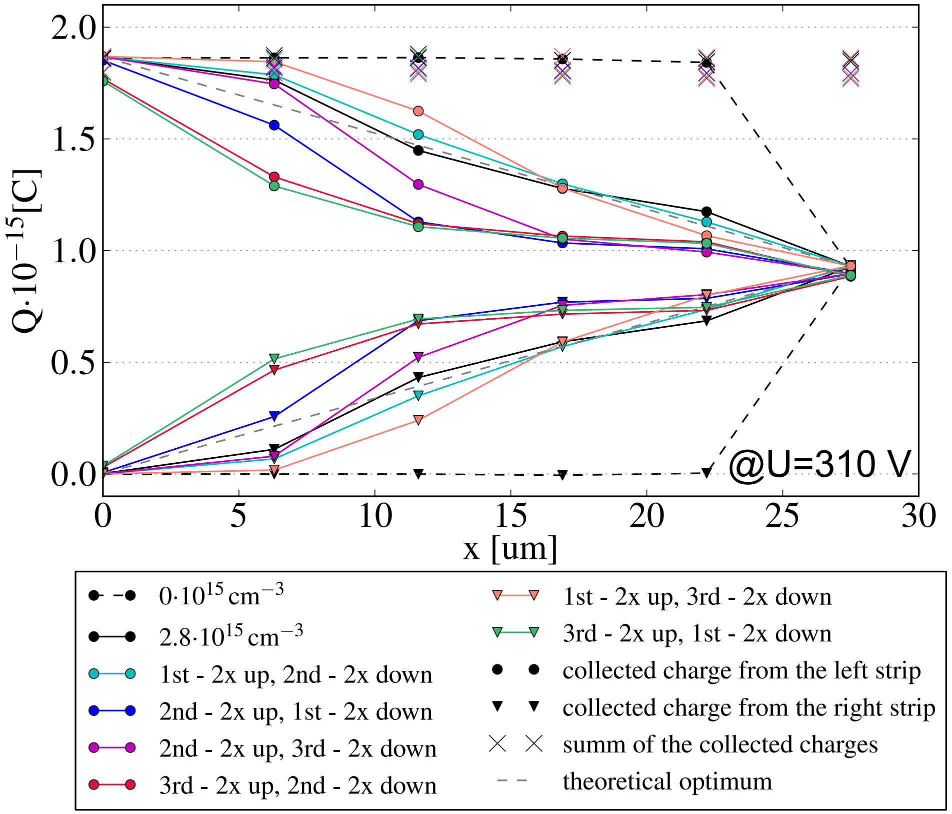


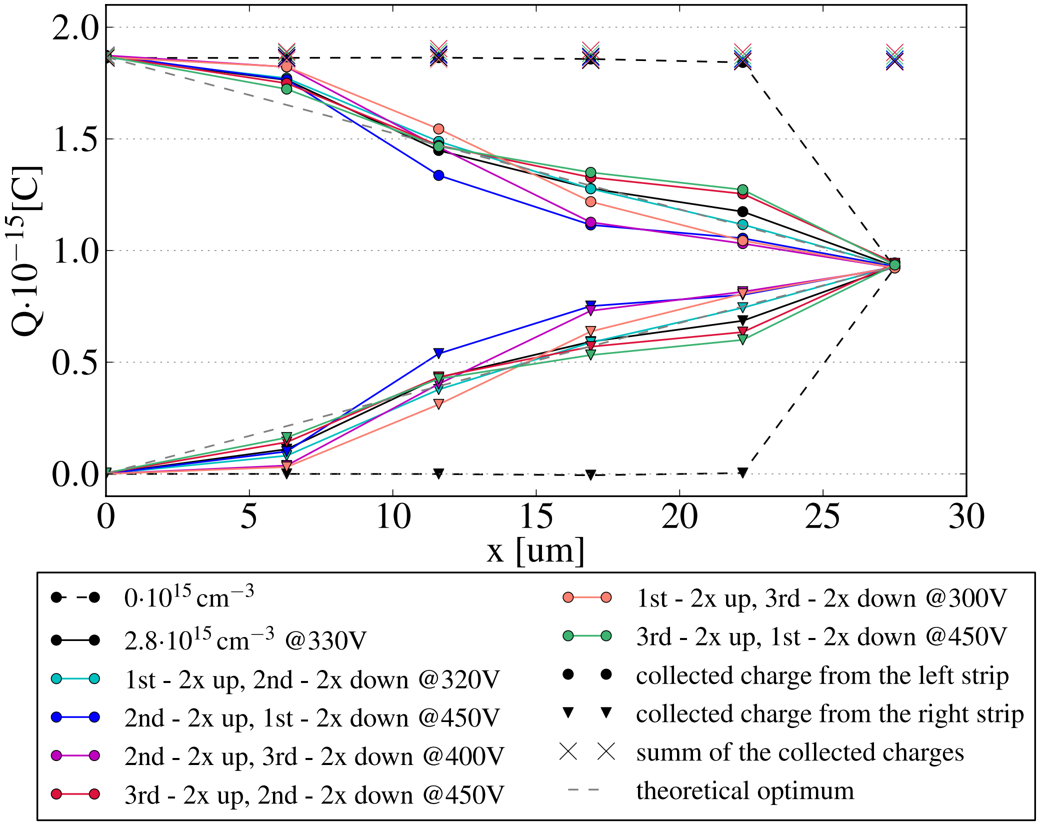
- < 2×10^5 V/cm → no charge multiplication in the ELAD sensor

Simulations of the ELAD Sensors

TCAD Transient | "MC" of the buried implants concentration

- Buried implants concentration 2x↑ and 2x↓ from layer to layer.



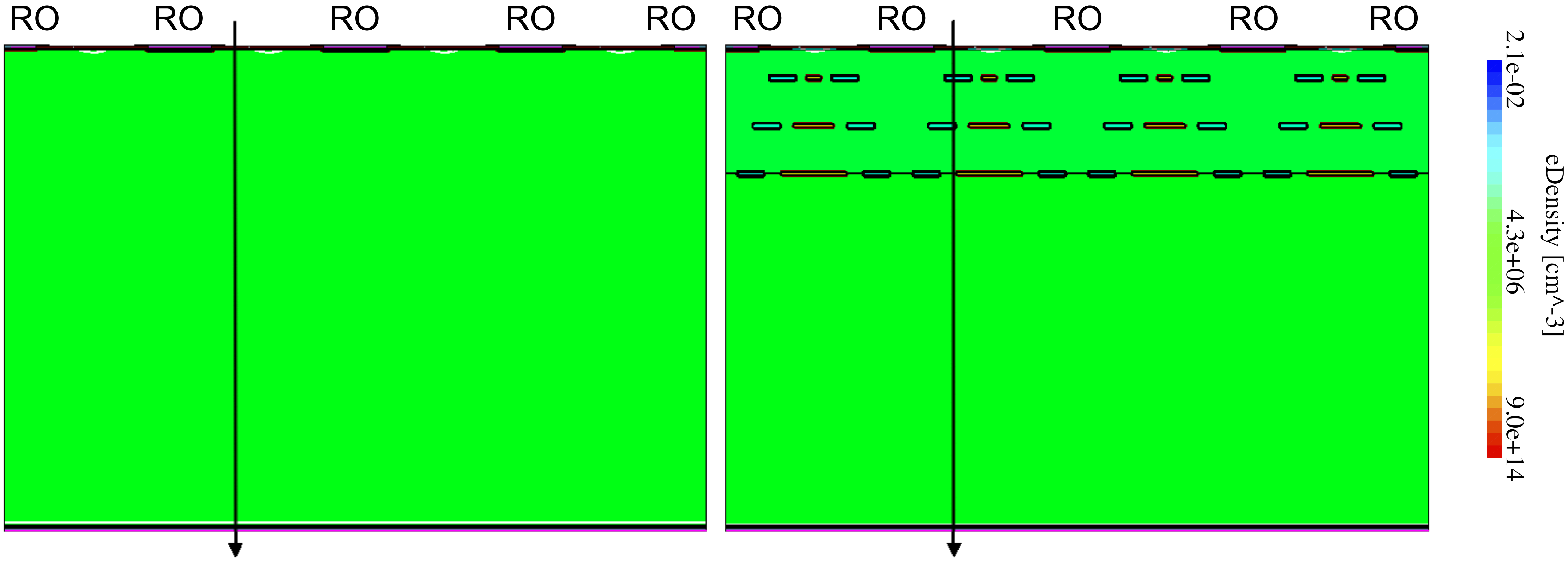


- inaccuracy in doping can be corrected by bias voltage

Simulations of the ELAD Sensors

TCAD Transient

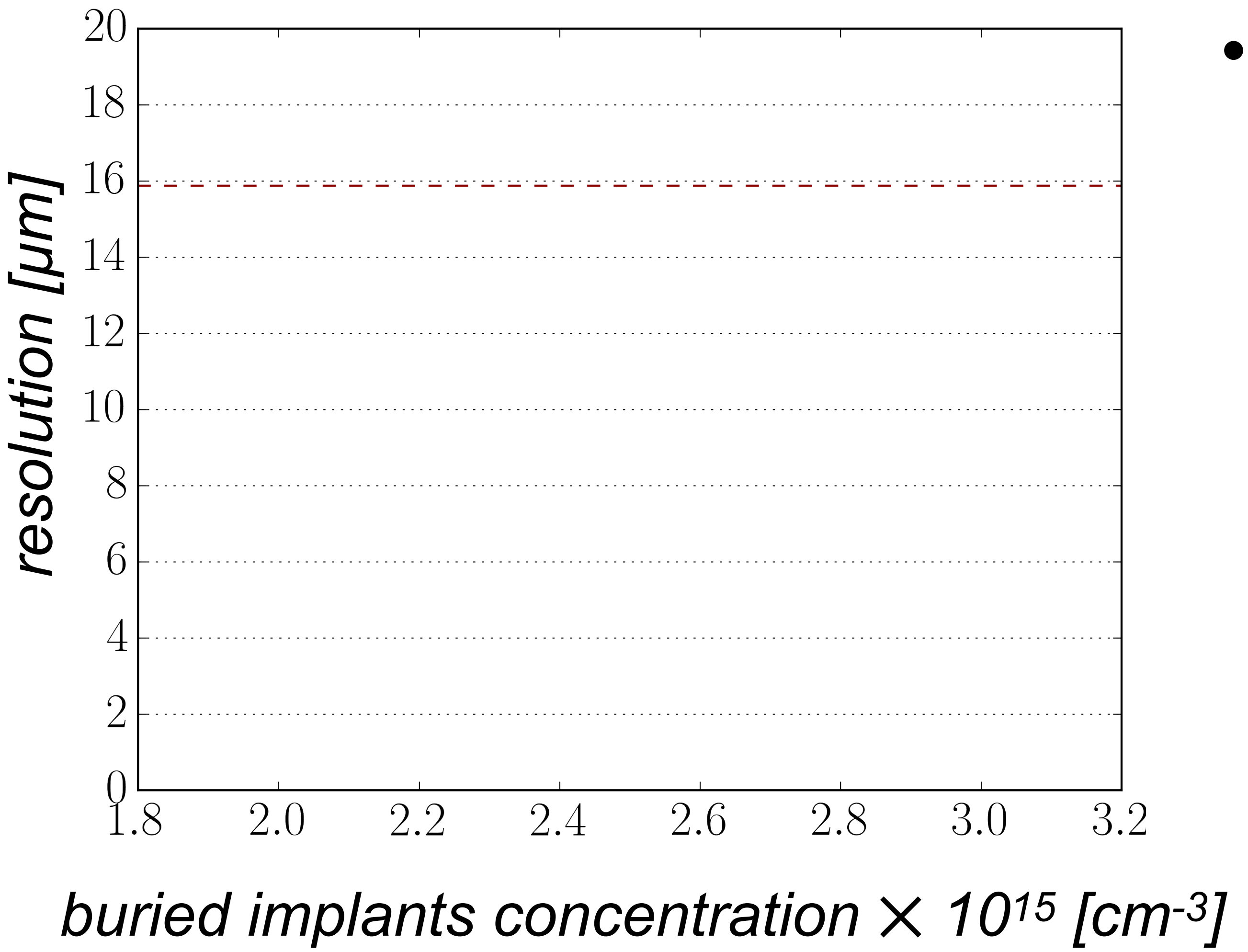
- In comparison to the usual design, with the same MIP position and applied voltage, in the ELAD sensor the charge is shared between **two strips**.



Standard planar sensor @ U=150 V *p-ELAD n_{di}=2.8·10^{15} cm^{-3} @ U=330 V*

Simulations of the ELAD Sensors

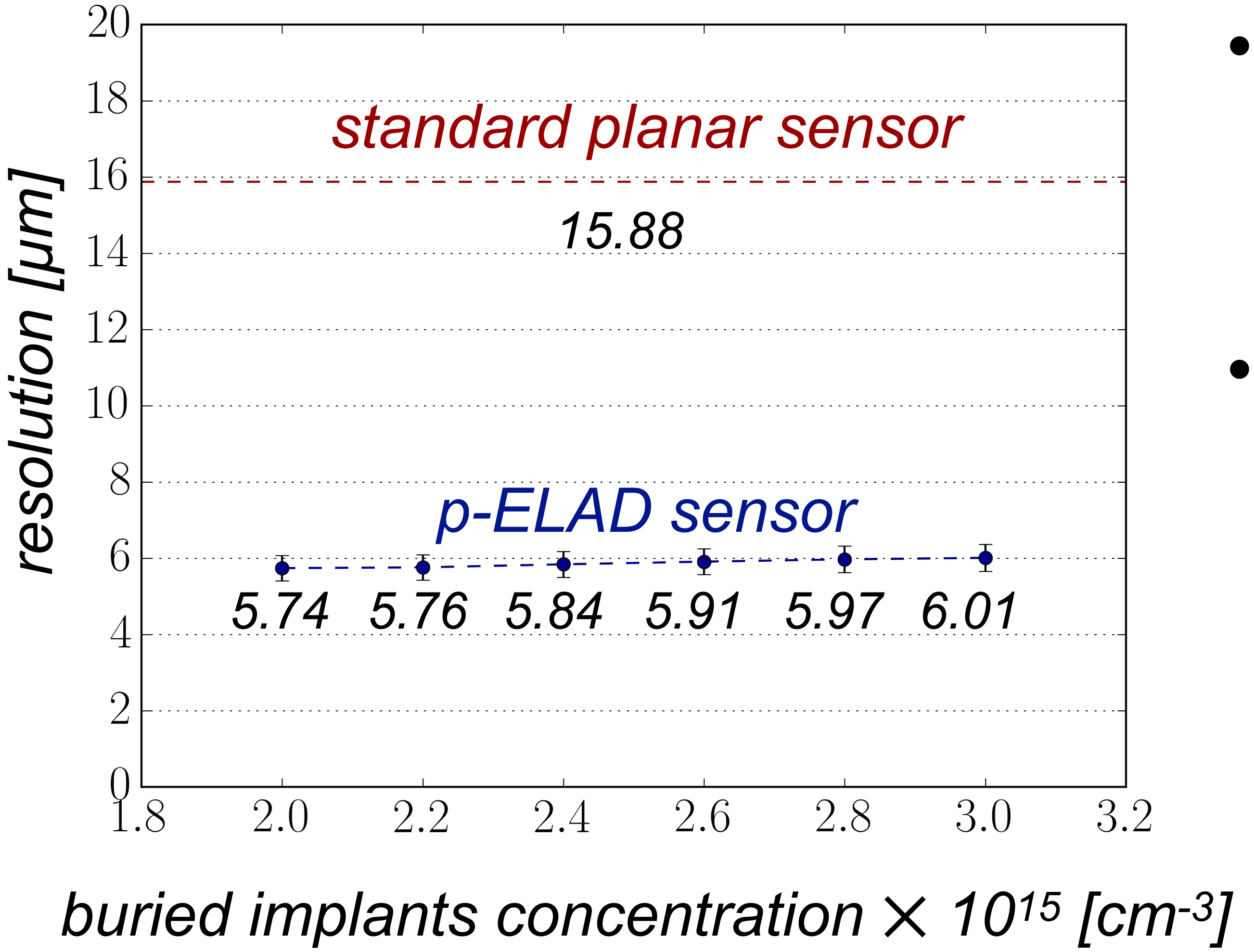
Allpix² resolution studies. Results 150 µm thick p-ELAD sensors.



- Standard planar sensor resolution for pitch 55 µm - **15.88** µm (binary read-out)

Simulations of the ELAD Sensors

Allpix² resolution studies. Results 150 µm thick p-ELAD sensors.

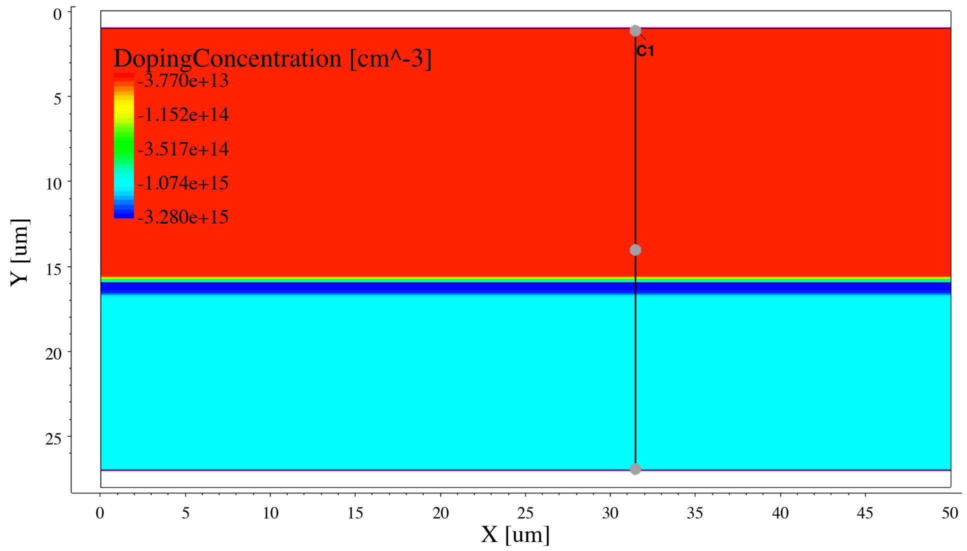


- Standard planar sensor resolution for pitch 55 µm - **15.88** µm (binary read-out)
- p-ELAD sensors→**3 times better** resolution at optimal voltage

Production

Test structures

- **Boron**
  - Wafer 1 annealing 900 °C 30 min
  - Wafer 2 annealing 1050 °C 30 min
  - Wafer 3 no annealing
- **Phosphorus**
  - Wafer 4 annealing 900 °C 30 min
  - Wafer 5 annealing 1050 °C 30 min

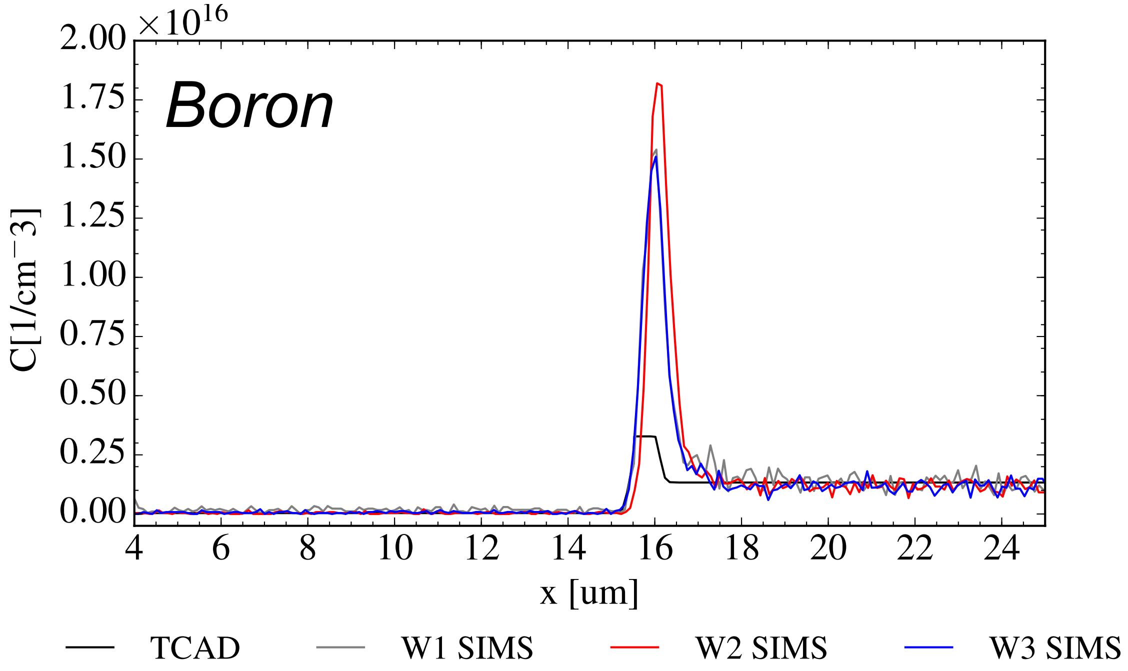


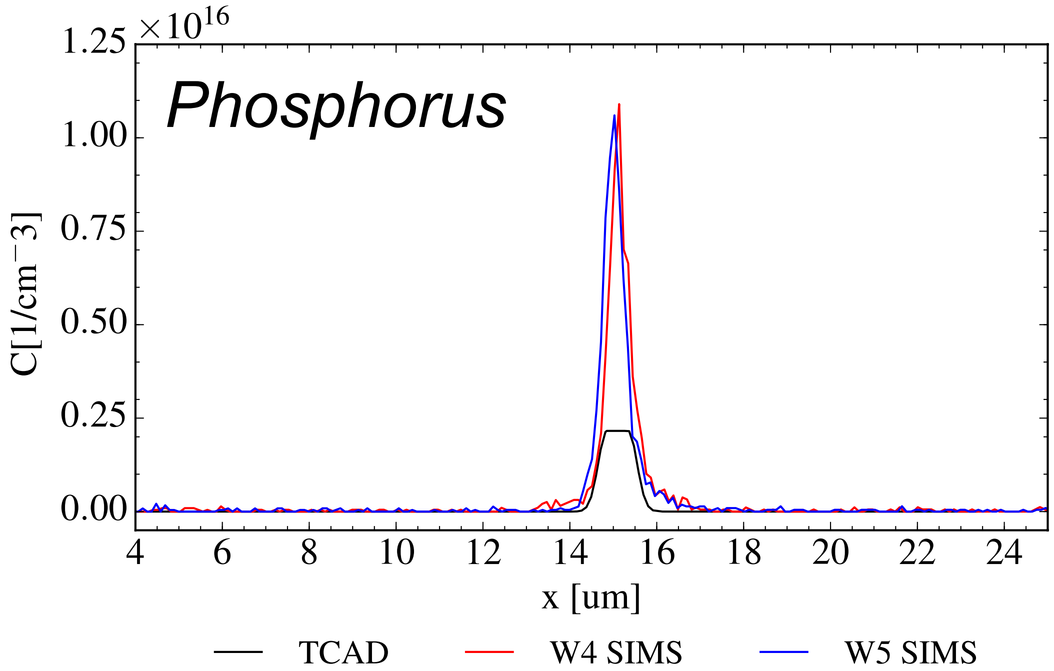
TCAD model Boron

Energy 70 keV, Dose 1 × 10^{12} 1/cm^2, Epi 15 µm 1050 °C, ~ 10 min

Production

Test structures SIMS





W1 = 2.42*10^12 cm^-2

W2 = 1.37*10^12 cm^-2

W3 = 1.6*10^12 cm^-2

TCAD = 3.04*10^11 cm^-2

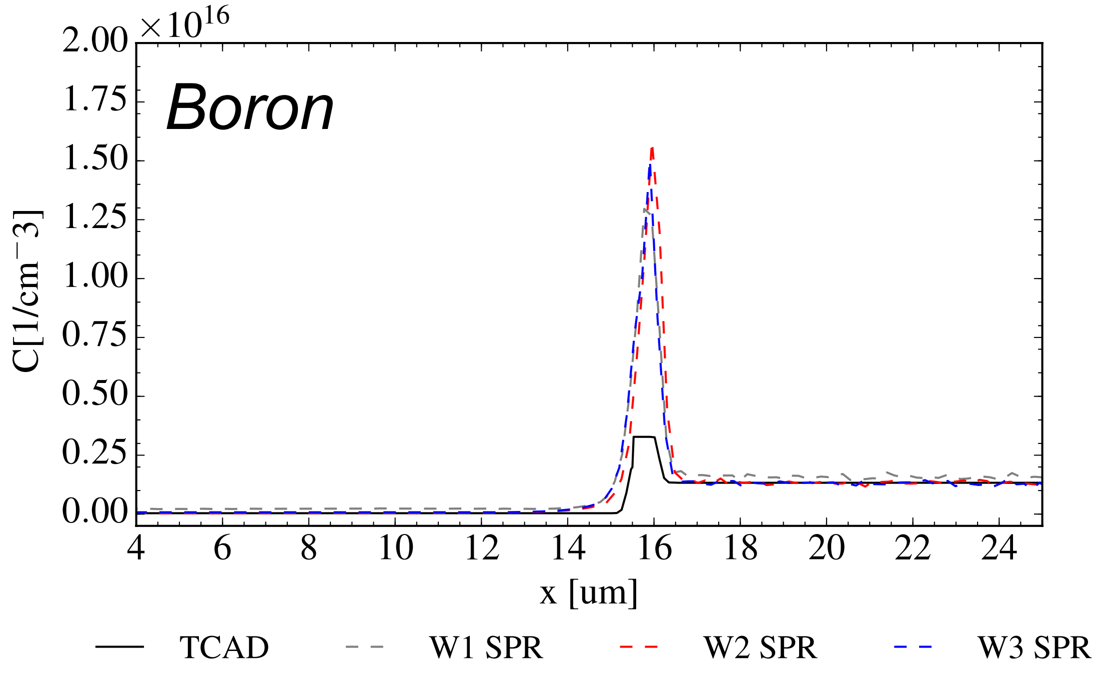
W5 = 6.53*10^11 cm^-2

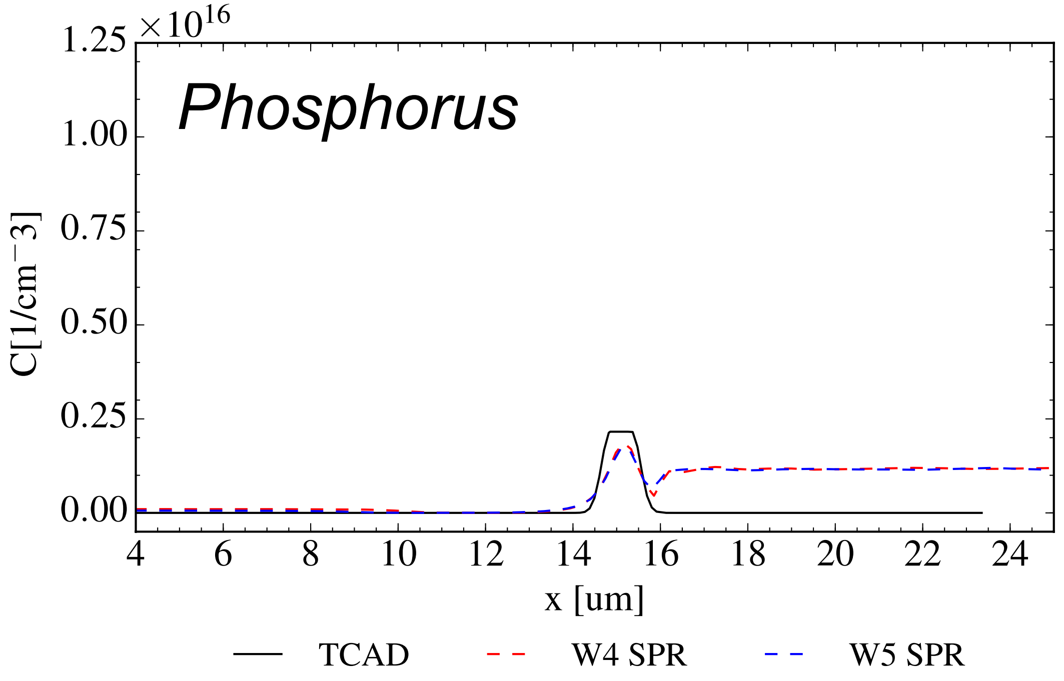
W6 = 6.89*10^11 cm^-2

TCAD = 2.14*10^11 cm^-2

Production

Test structures SRP





W1 = 2.32*10^12 cm^-2

W2 = 1.04*10^12 cm^-2

W3 = 1.24*10^12 cm^-2

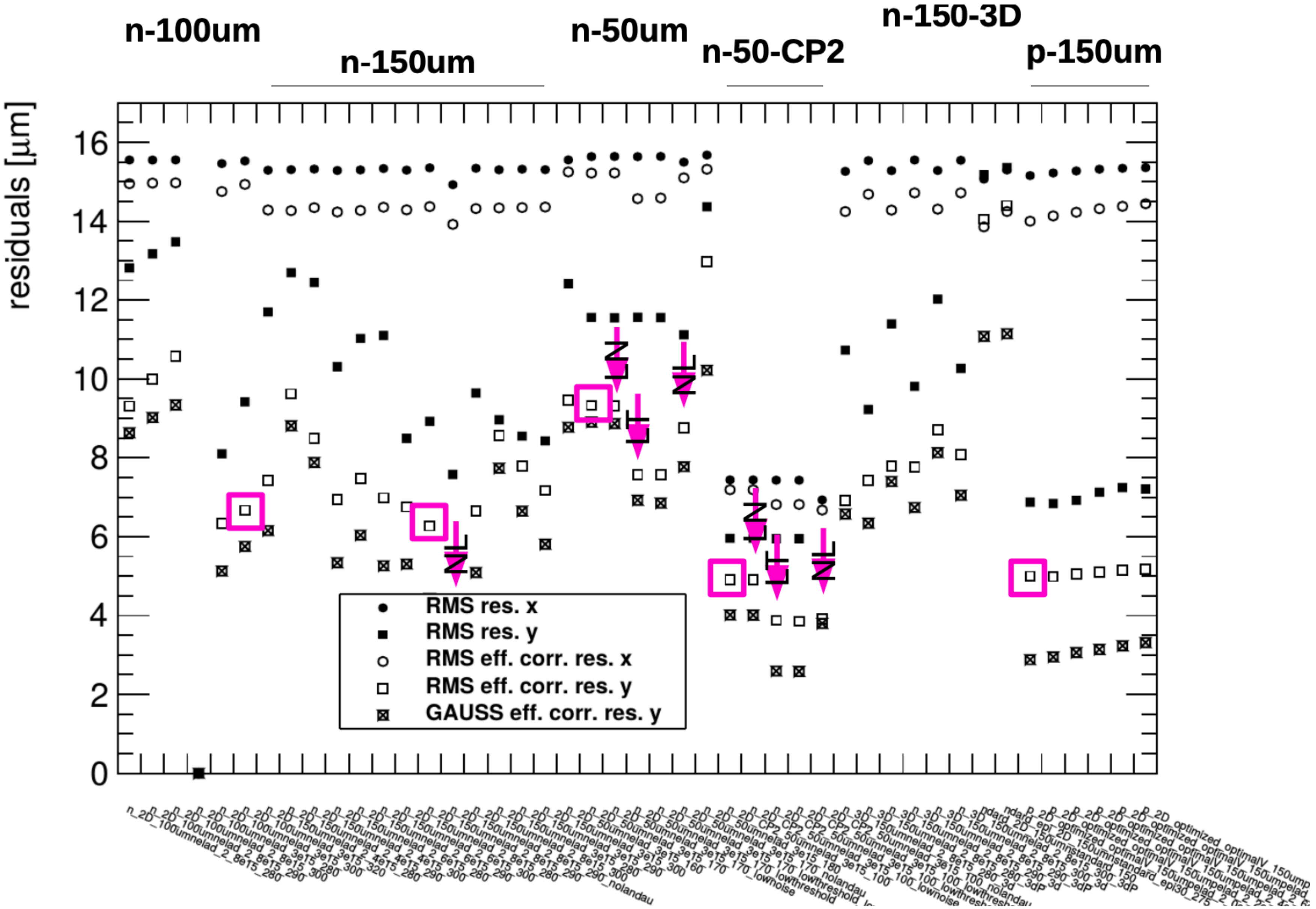
TCAD = 3.04*10^11 cm^-2

W5 = 1.86*10^11 cm^-2

W6 = 1.85*10^11 cm^-2

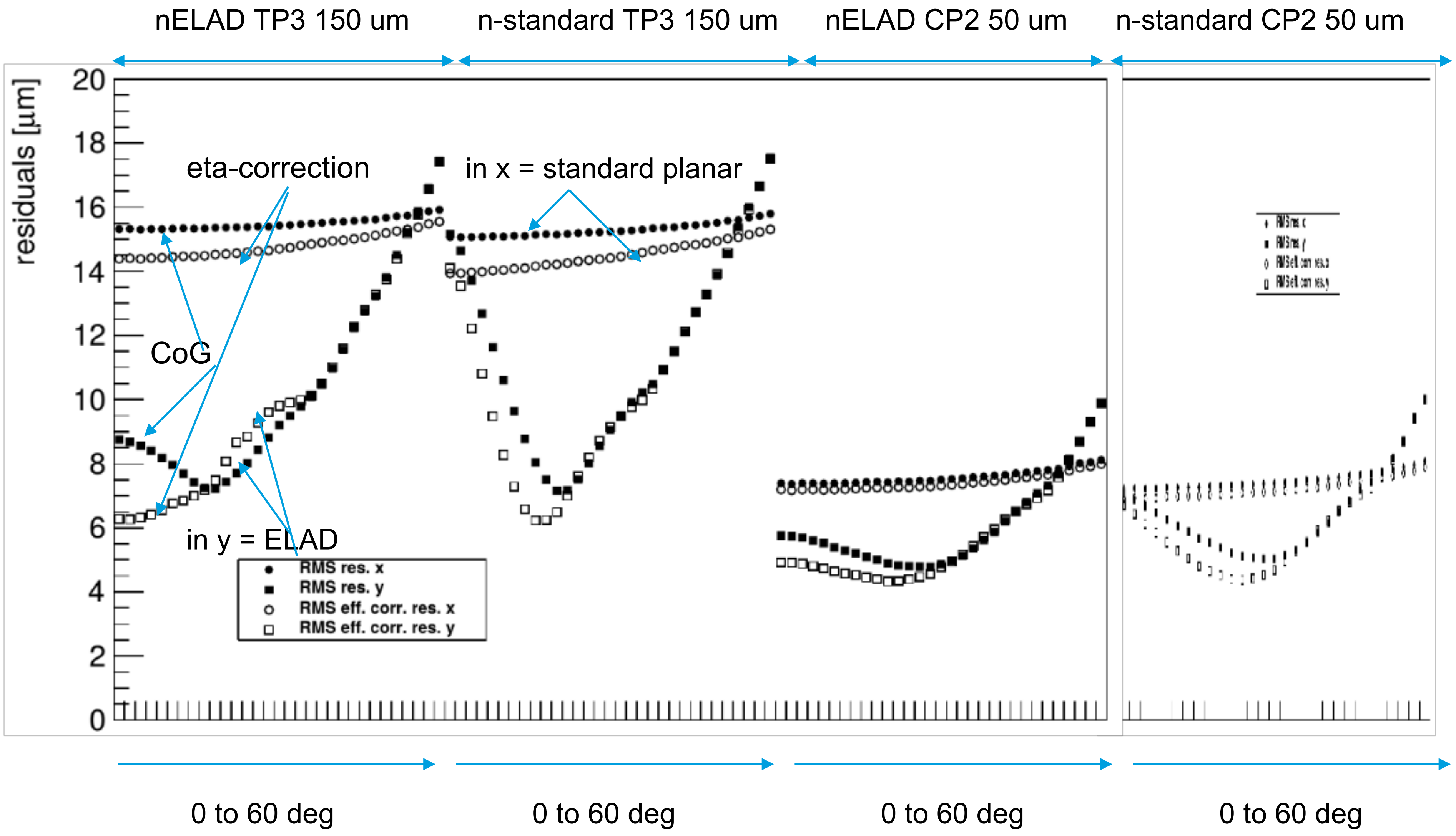
TCAD = 2.14*10^11 cm^-2

Residuals



n-100um
n-150um
n-50um
n-50-CP2
n-150-3D
p-150um
residuals [µm]
0
2
4
6
8
10
12
14
16
RMS res. x
RMS res. y
RMS eff. corr. res. x
RMS eff. corr. res. y
GAUSS eff. corr. res. y

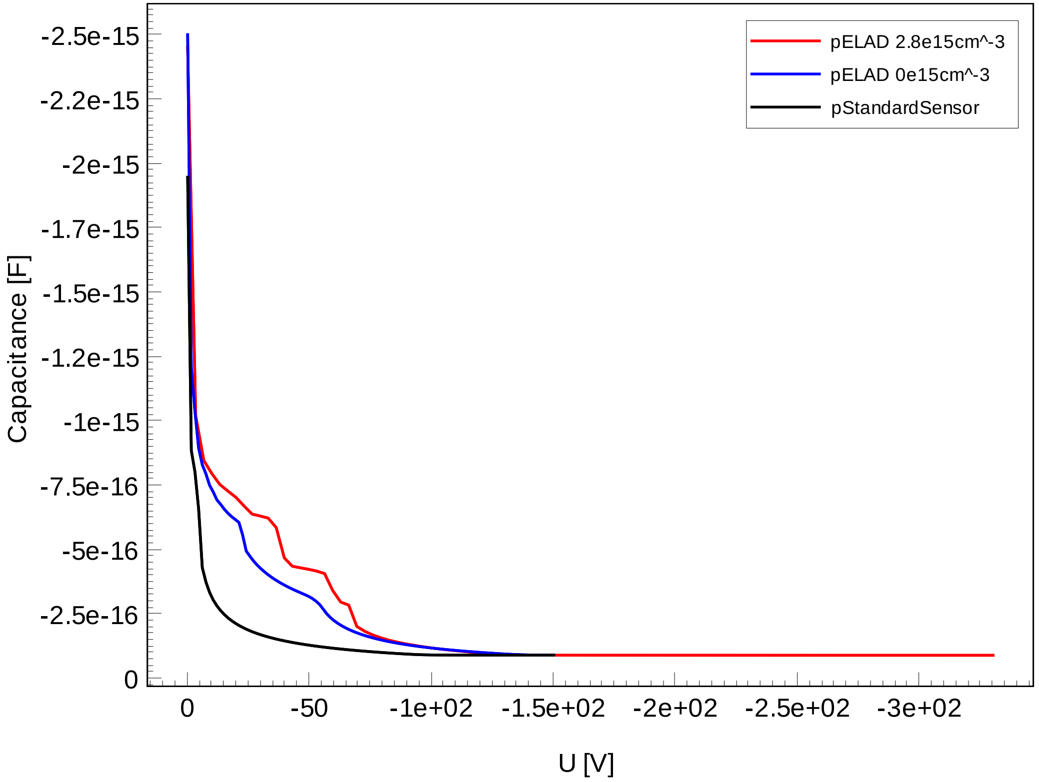
Residuals


nELAD TP3 150 um
n-standard TP3 150 um
nELAD CP2 50 um
n-standard CP2 50 um
residuals [µm]
20
18
16
14
12
10
8
6
4
2
0
eta-correction
in x = standard planar
CoG
in y = ELAD
RMS res. x
RMS res. y
RMS eff. corr. res. x
RMS eff. corr. res. y
0 to 60 deg
0 to 60 deg
0 to 60 deg
0 to 60 deg

Simulations of the ELAD Sensors

TCAD Electric Field | Capacitance

- Comparison between standard planar sensor, sensor with epi-layer and pELAD



- buried implants structure does not change the capacitance of the sensor