Home-made TCAD Sensor Simulations

Adriana Simancas

Hamburg, April 27th 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- Introduction to TCAD Simulations
- Applications & Motivation
- TCAD Tools
- Simulation Workflow Example
- TCAD Simulations in DESY and UHH
  - Simulations for Tangerine
  - Simulations in other groups (non exhaustive list)
- Conclusion

Introduction to TCAD Simulations

Technology Computer Aided Design

- Model semiconductor devices
- Use physical models to represent the wafer fabrication steps and device operation
- Works by modeling electrostatic potential (Poisson's equation) and carrier continuity equations (from J. Schwandt):

Poisson: $\nabla \cdot \epsilon \nabla \phi = -\rho$ with $\rho = q[p - n + N_D - N_A] - \rho_{traps}$

Electron continuity: $\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_n + R_{net}$ where $\mathbf{J}_n = q n \mu_n \mathbf{E} + q D_n \nabla n$

Hole continuity: $\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot \mathbf{J}_p + R_{net}$ where $\mathbf{J}_p = q p \mu_p \mathbf{E} - q D_n \nabla p$

Input

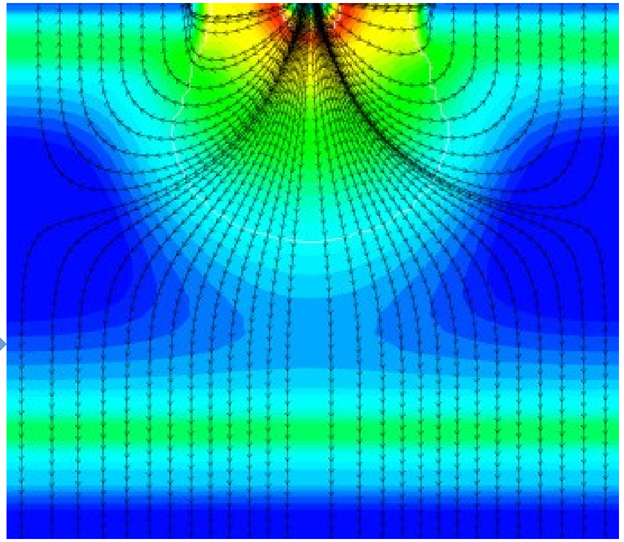
Structural properties:
- Physical: geometry, materials, …
- Electrical: doping profiles…

SYNOPSYS®
Silicon to Software™
Sentaurus TCAD

Output

Electrical Characteristics:
- I-V, C-V curves
- Electric fields
- Weighting potentials
- Pulse shape

Electric field of MAPS near collection implant

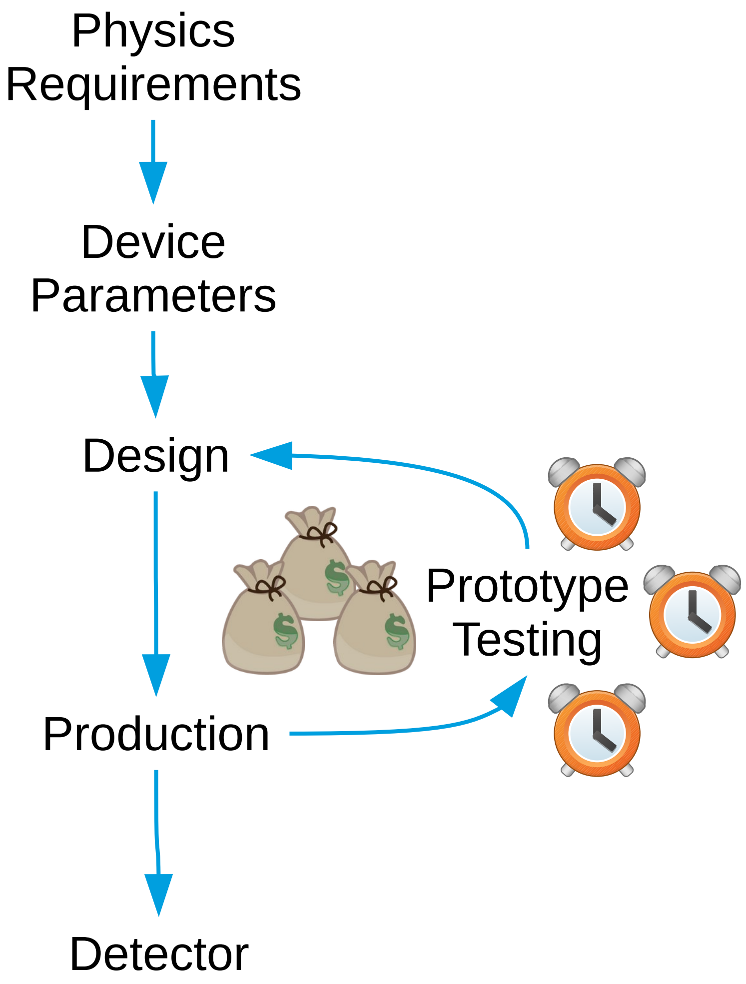


S. Spannagel et al. https://doi.org/10.1016/j.nima.2020.163784

Applications & Motivation

- Semiconductor Devices:
  - CMOS, FinFET
  - Memory (DRAM, NVM)
  - Power Devices (Si, SiC, GaN)
  - RF Devices (GaAs, InP, GaN)
  - Optoelectronics (CIS, Solar Cells, Photodetectors)
  - **Particle Detectors (since 2000's)**
    - Tangerine
    - CLICTD
    - ATTRACT FASTpix
    - MALTA/Monopix
    - ELAD
    - AGIPD
    - MSSD
    - MIMOSA
    - ...

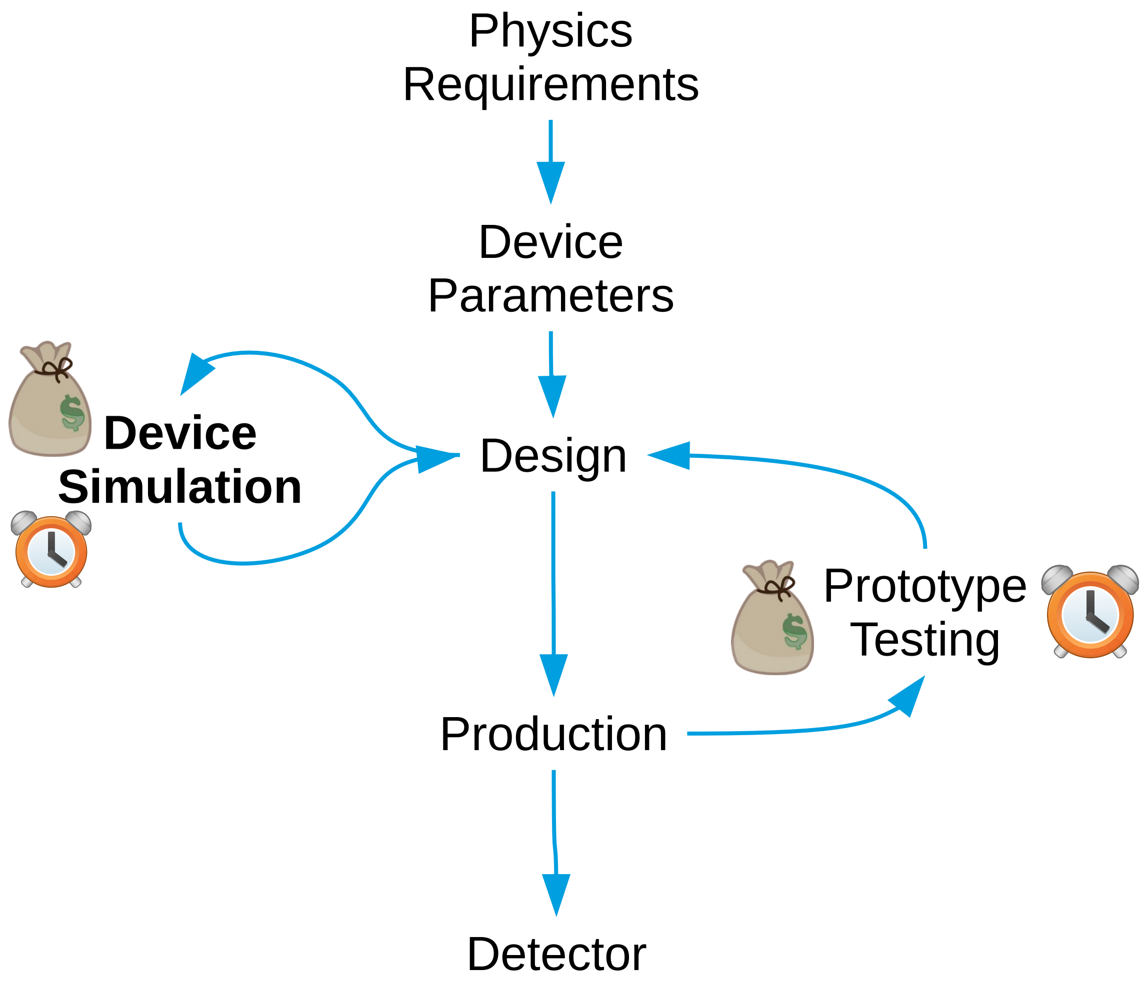
- Development of Semiconductor Particle Detectors:



Applications & Motivation

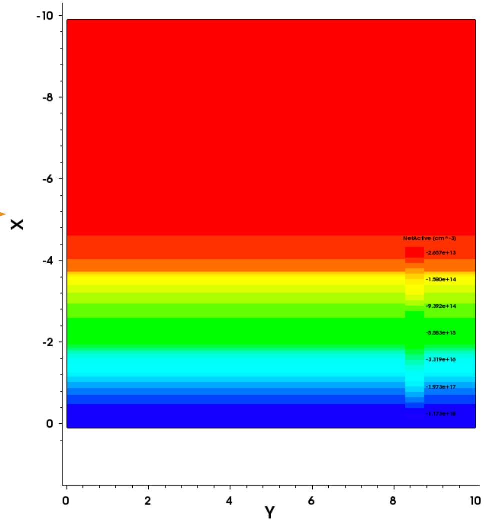
- Semiconductor Devices:
  - CMOS, FinFET
  - Memory (DRAM, NVM)
  - Power Devices (Si, SiC, GaN)
  - RF Devices (GaAs, InP, GaN)
  - Optoelectronics (CIS, Solar Cells, Photodetectors)
  - **Particle Detectors (since 2000's)**
    - Tangerine
    - CLICTD
    - ATTRACT FASTpix
    - MALTA/Monopix
    - ELAD
    - AGIPD
    - MSSD
    - MIMOSA
    - ...

- Development of Semiconductor Particle Detectors:

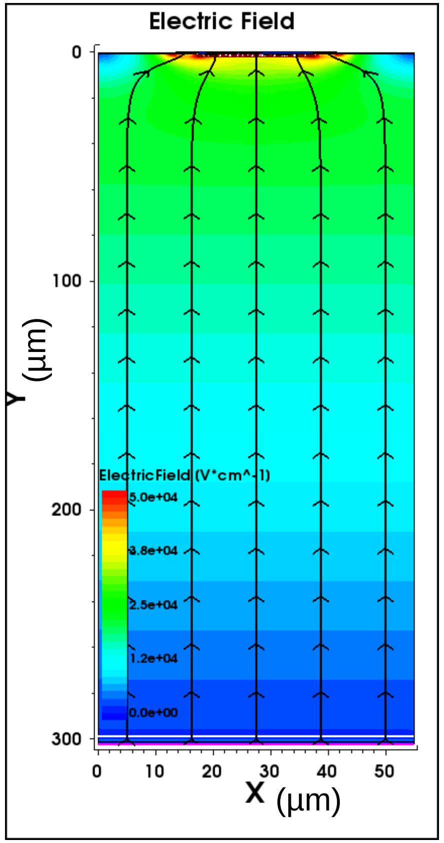


TCAD Tools

- **Process Simulations:** fabrication steps in silicon process technologies in 2D and 3D.



- **Structure Editing:** build and edit device structures in 2D and 3D using geometric operations.
- **Device Simulations:** electrical, thermal, and optical characteristics of silicon and compound semiconductor devices in 2D and 3D.



- **Interconnect Simulations:** physical phenomena concerned with back-end-of-line reliability.
- **Frameworks:**
  - Workbench: graphical environment for creating, managing, executing, and analyzing TCAD simulations.
  - Visual: interactive 1D, 2D, and 3D visualization and data exploration environment.
  - Process Compact Model Studio: encapsulate relationships between process variations and device performance to identify manufacturing problems.

Simulation Workflow Example

Device Simulations

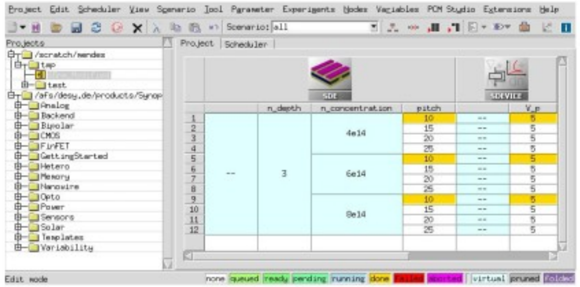
Manage simulations

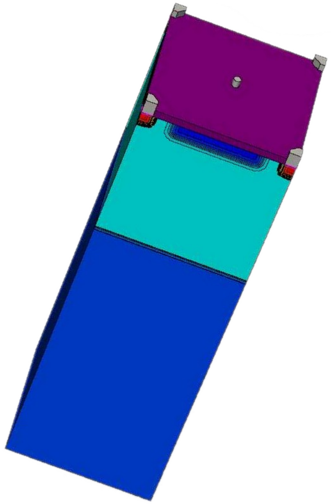
Create detector geometry

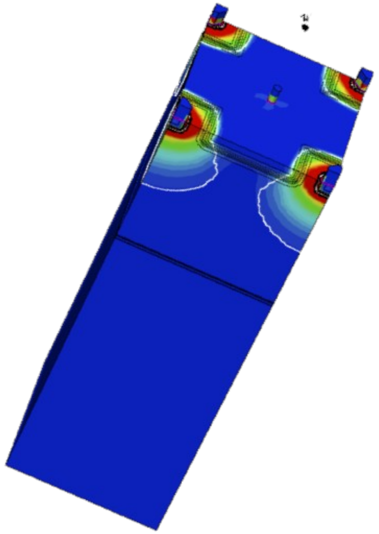
Obtain electrical characteristics

Visualize results

Sentaurus Workbench (SWB) → **Sentaurus Structure Editor (SDE)** → **Sentaurus Device (SDEVICE)** → **Sentaurus Visual (SVISUAL)**







TCAD Simulations in DESY and UHH

Development of MAPS in 65 nm CMOS Imaging Technology

The Tangerine Project - Towards Next Generation Silicon Detectors

Performance targets:

- Position resolution ≤ 3 µm
- Time resolution ~ 1 – 10 ns
- Material budget ~ 50 µm Si

Challenges of small collection electrode MAPS:

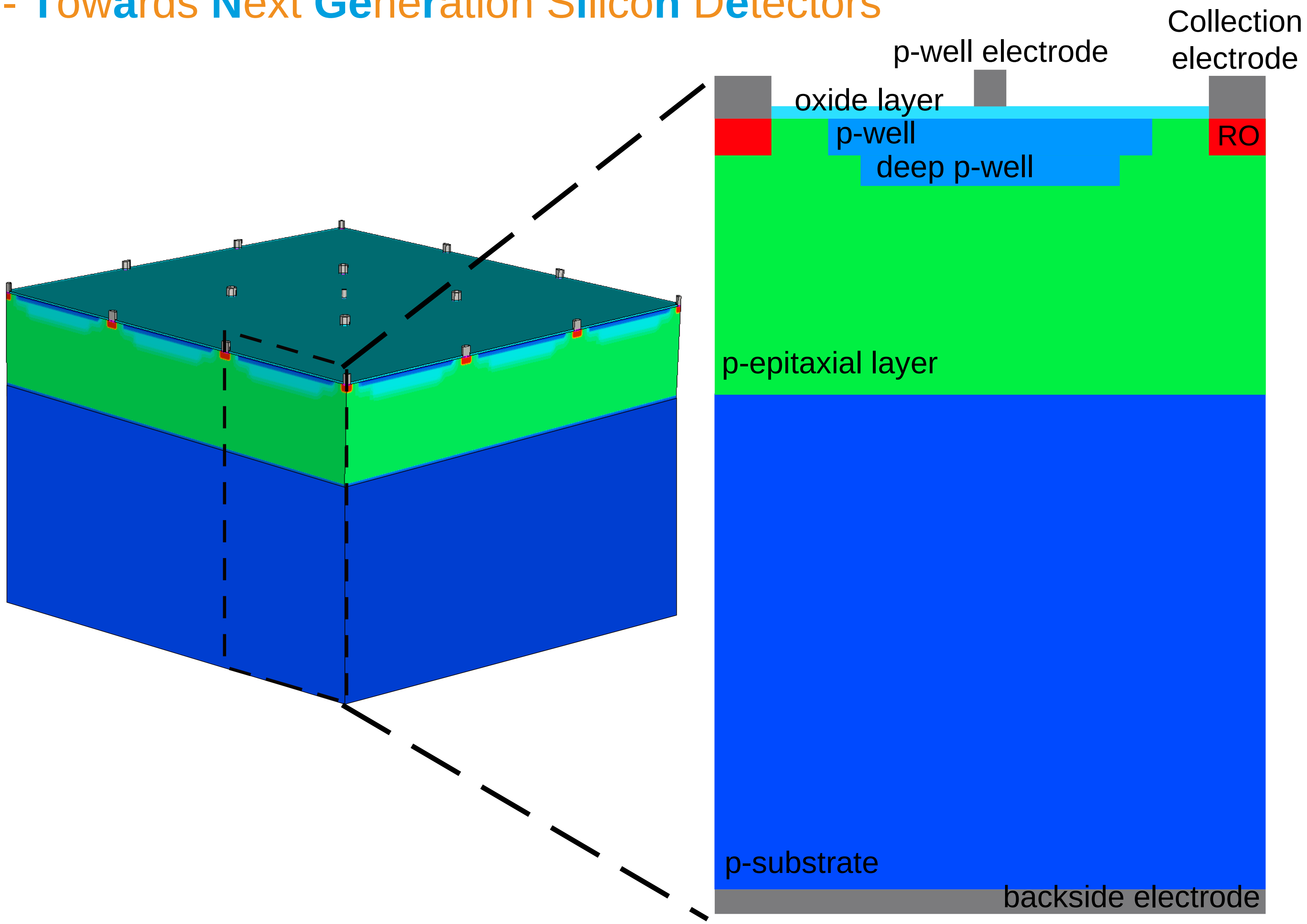
- Small signal → ASIC design
- Slow charge collection (diffusion)

⇩

Electric Field Optimization

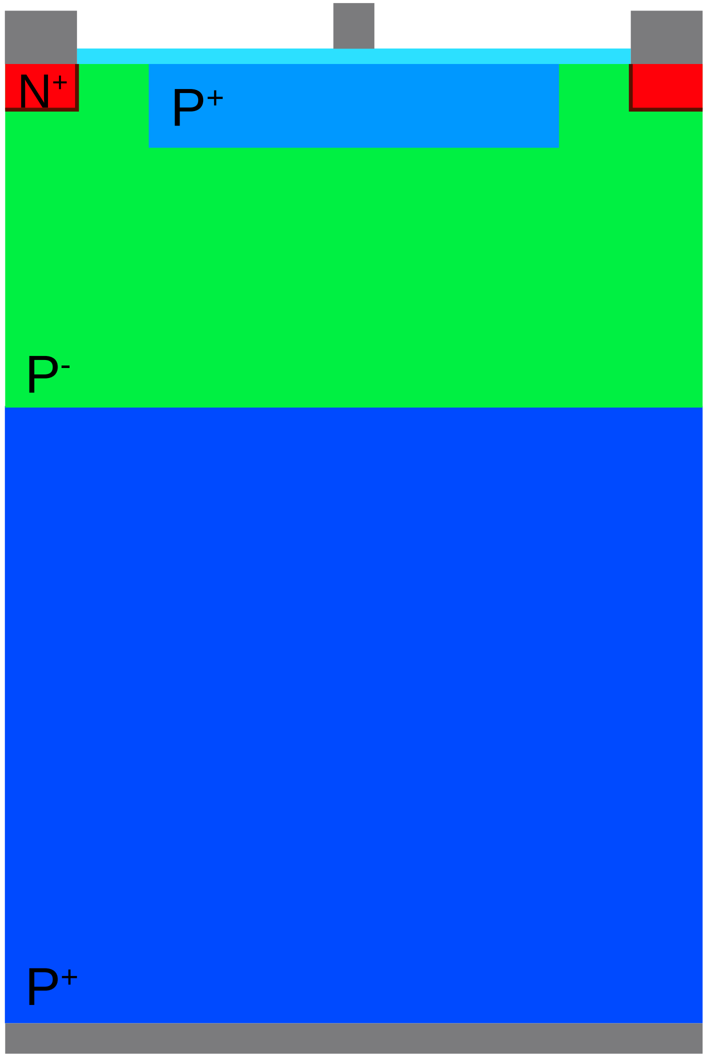
⇩

Sensor Design

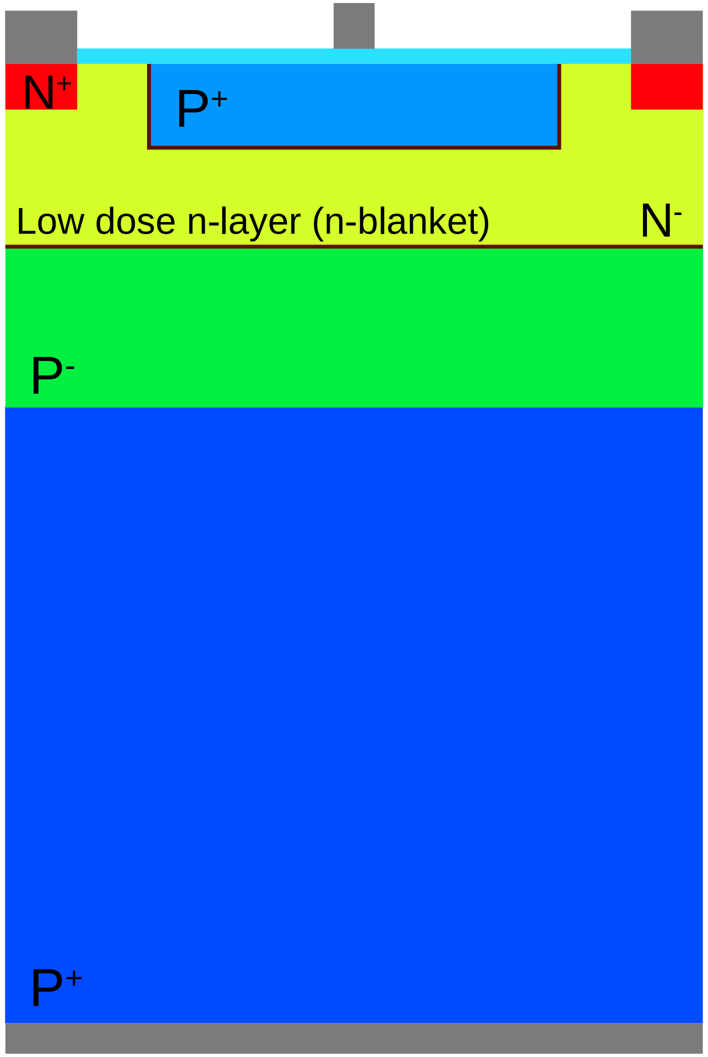


Sensor Modifications

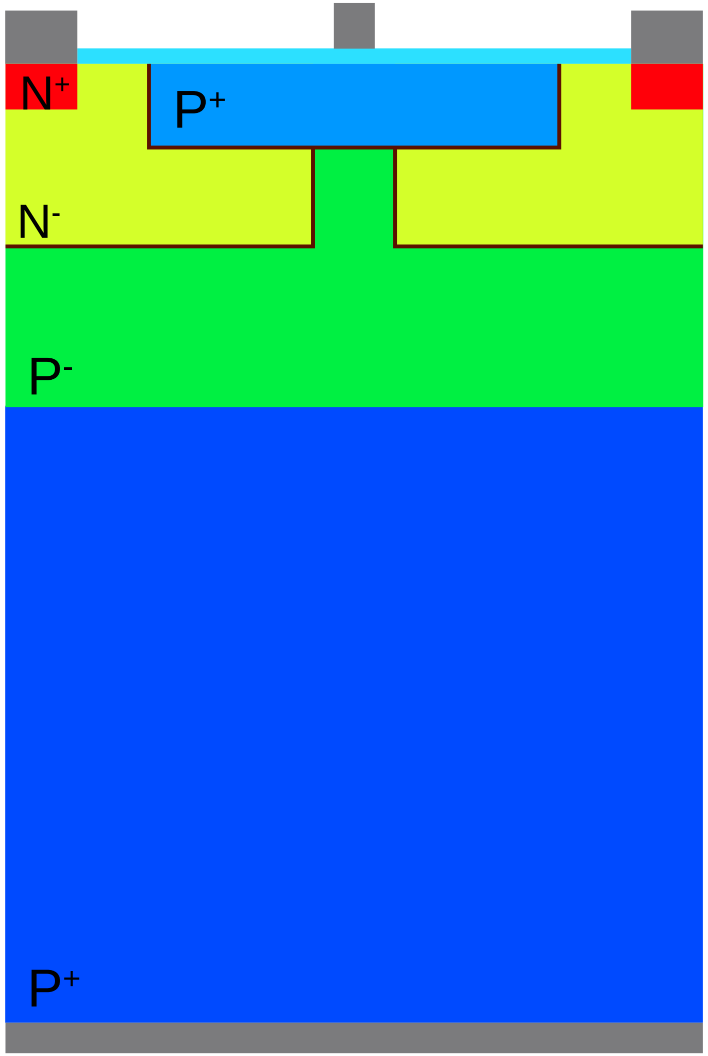
Standard Layout



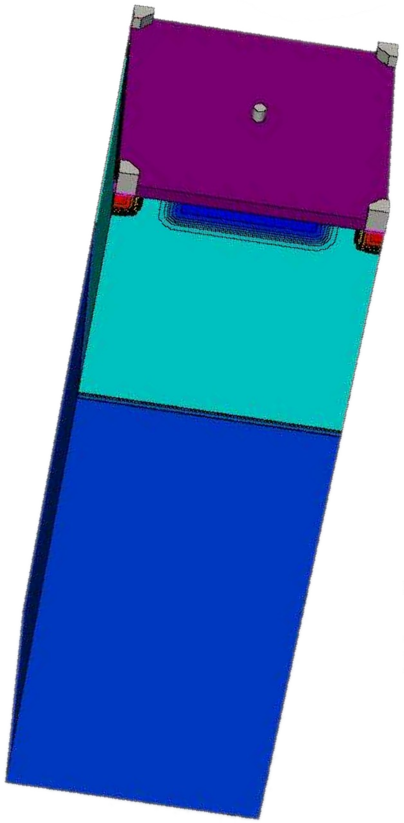
N-blanket Layout



N-blanket with gap Layout



TCAD Simulations: Needs and Strategy



What we need:

- Geometrical parameters
- Doping profiles

No access to real doping profiles

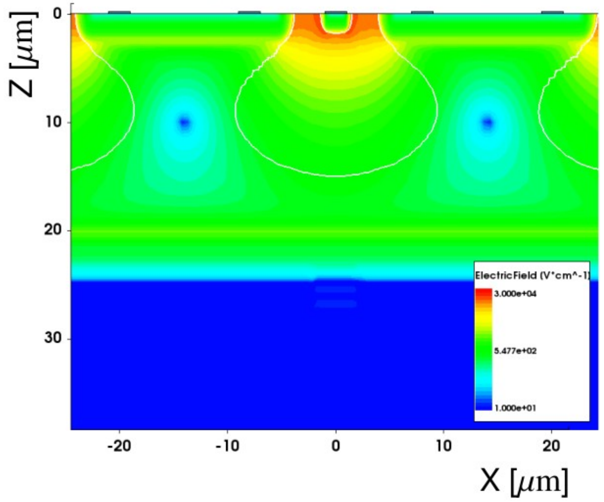
Strategy:

Use generic doping profiles and scan over different parameters.

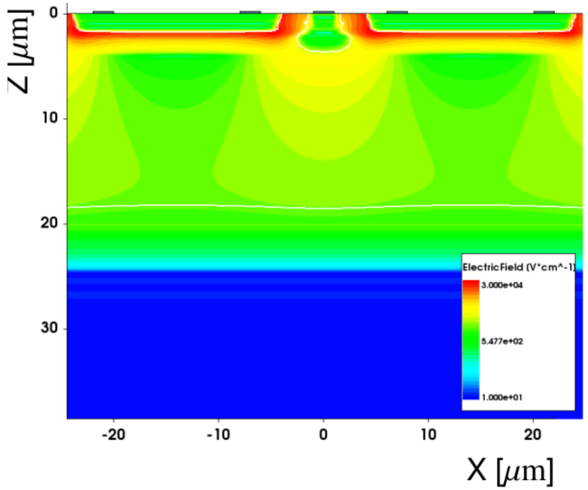
Scans:

Select parameter to study, vary it within range of values while fixing all the other parameters and observe behavior of electric, lateral field and depleted volume.

Standard, electric field, -3 V, norm:

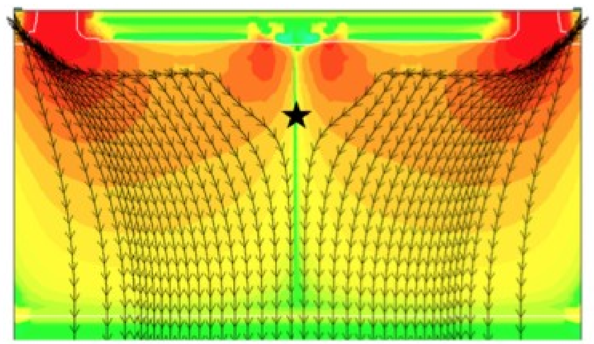


N-blanket , electric field, -3 V, norm:



N-blanket with gap

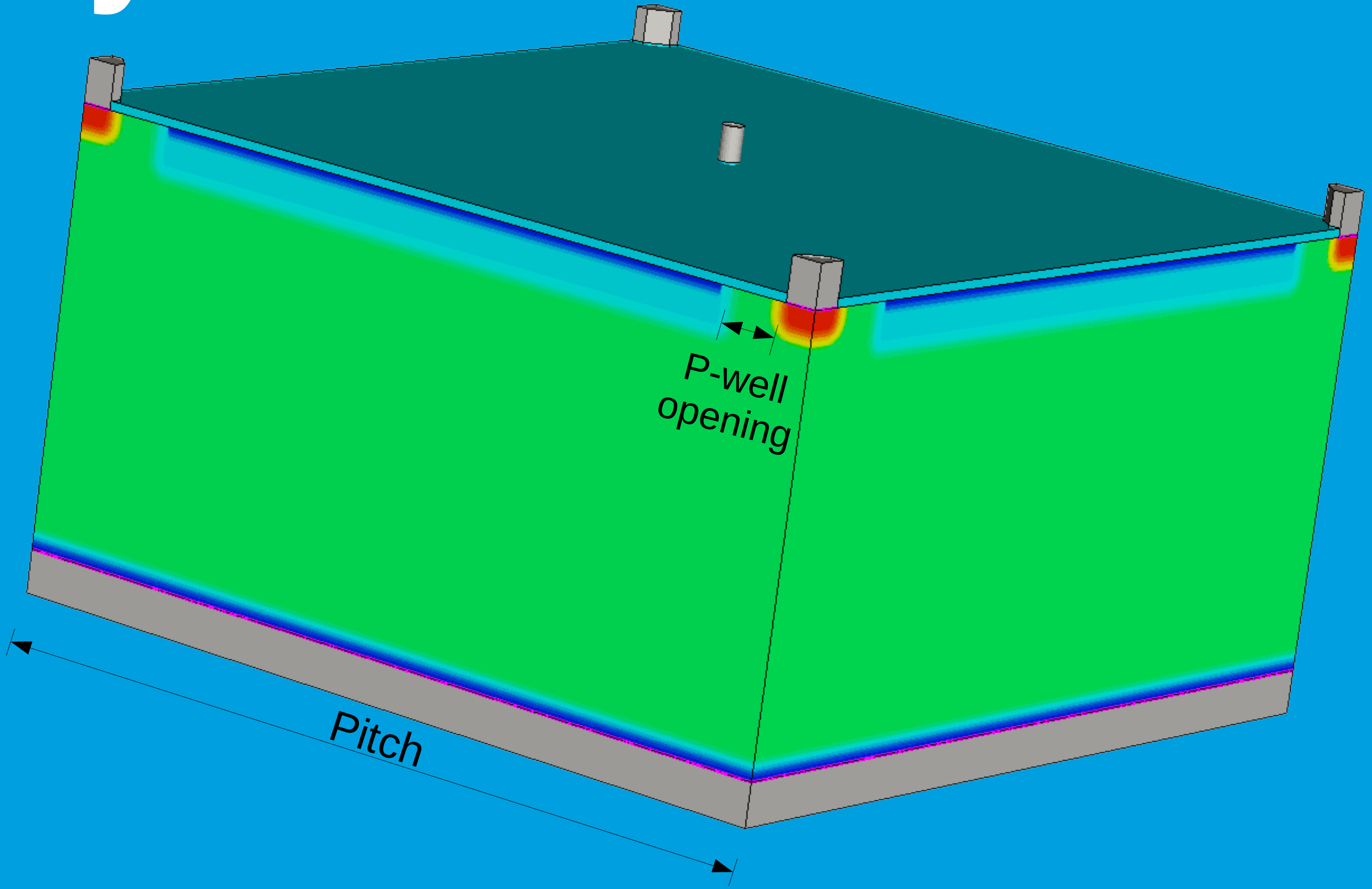
Lateral electric field:



Münker, M. 2018, "Test beam and simulation studies on High Resistivity CMOS pixel sensors", PhD Thesis, Universität Bonn, Bonn.

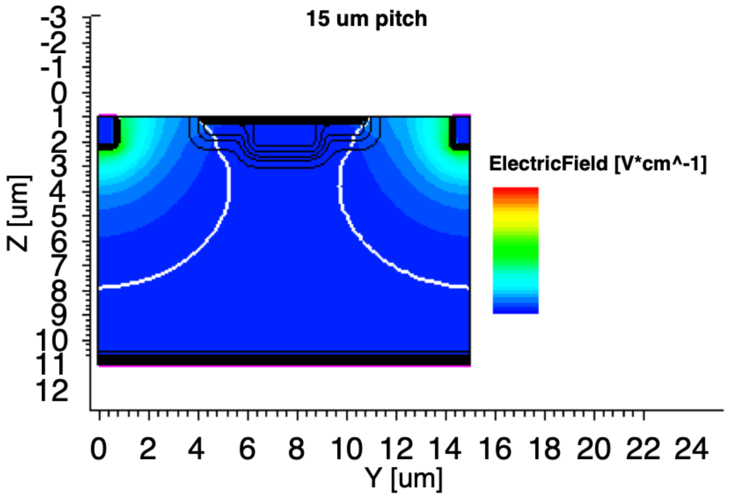
Results for Standard Layout

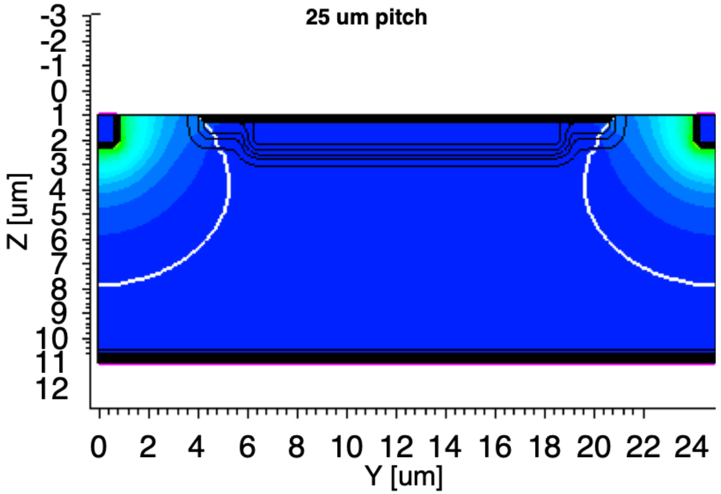
- Pitch
- P-well opening
- Transient simulation



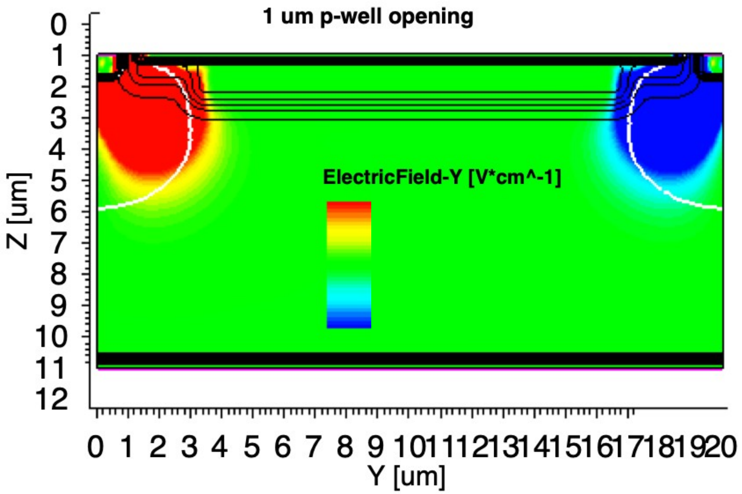
Results for Standard Layout

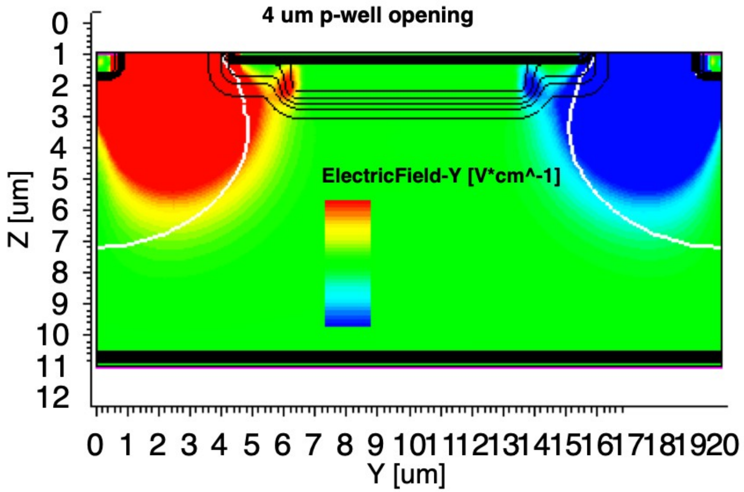
- **Pitch:** Decreasing improves depleted volume fraction within the sensor.





- **p-well opening:** Increasing improves lateral field.

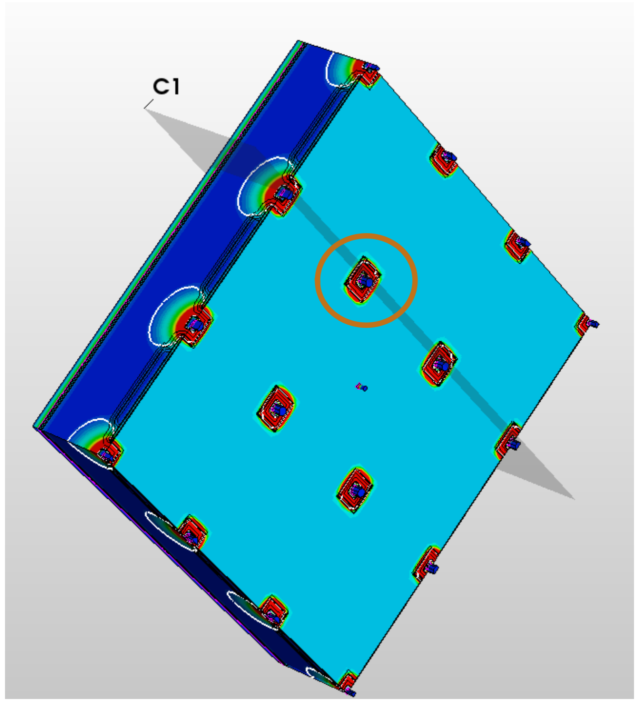


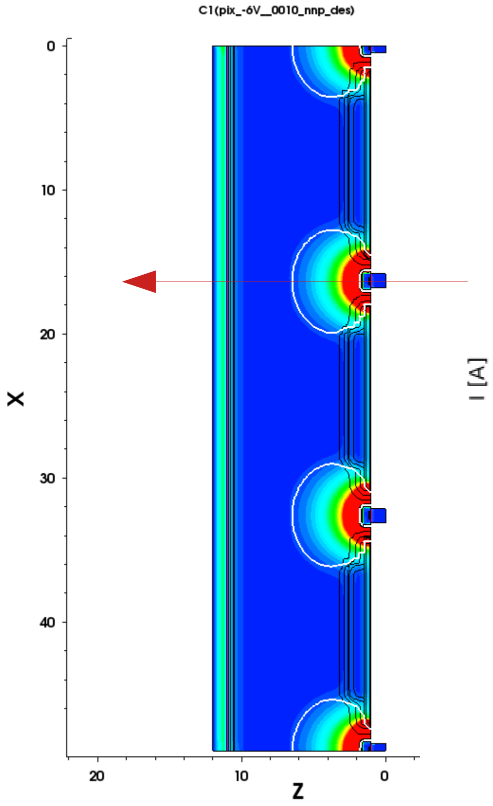


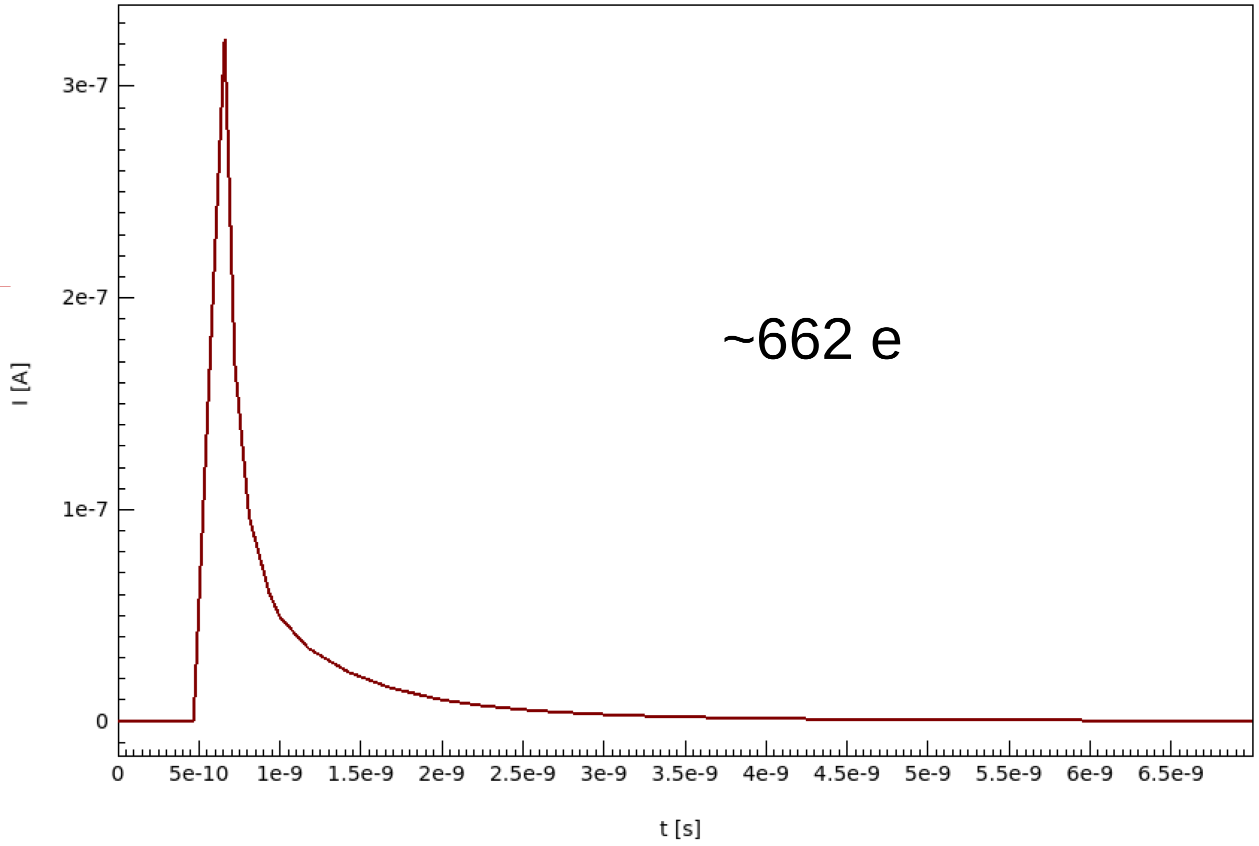
By A. Velyka

Results for Standard Layout

- **Transient Simulation:** Best case scenario (particle traversing center of pixel)



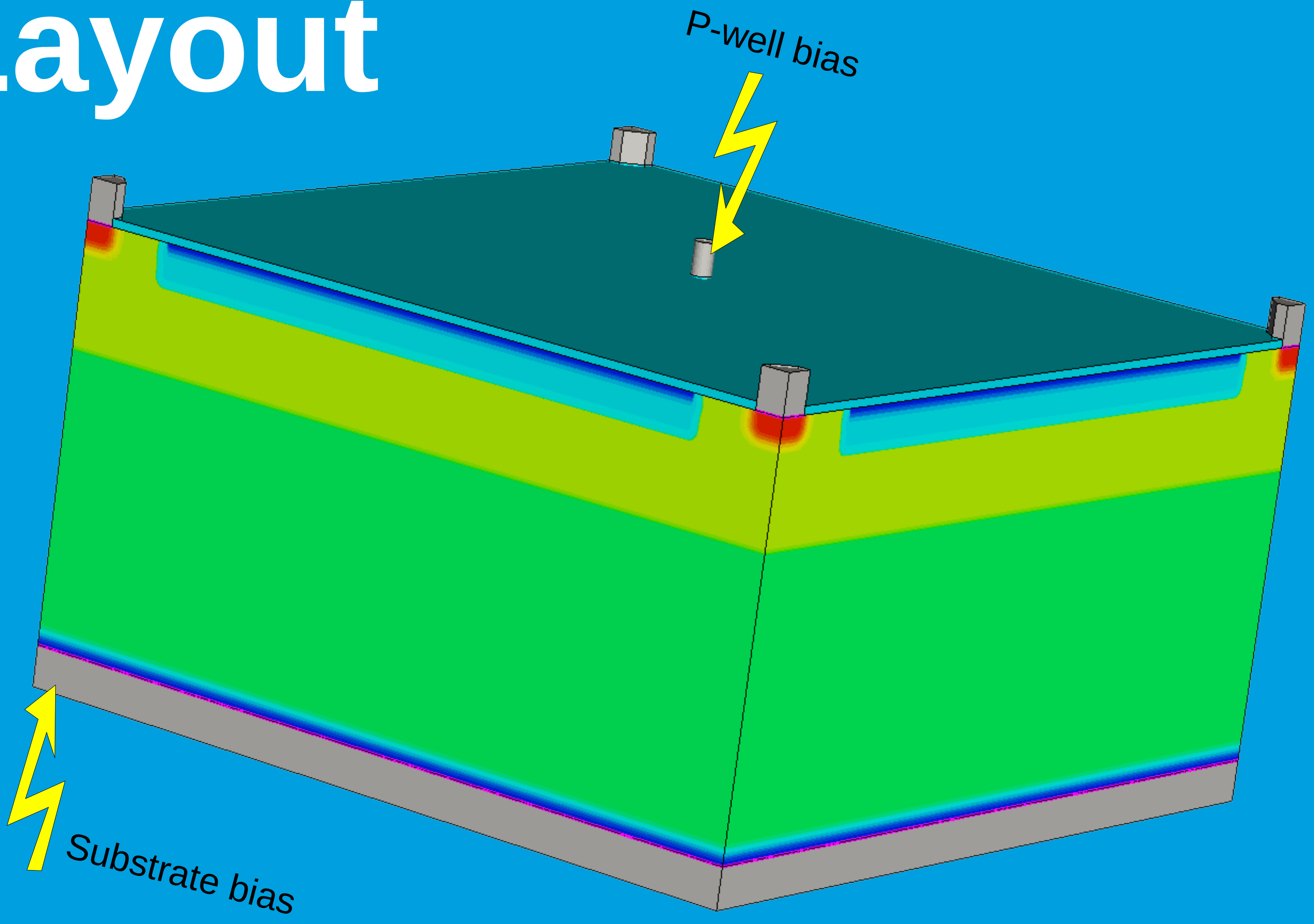




By A. Velyka

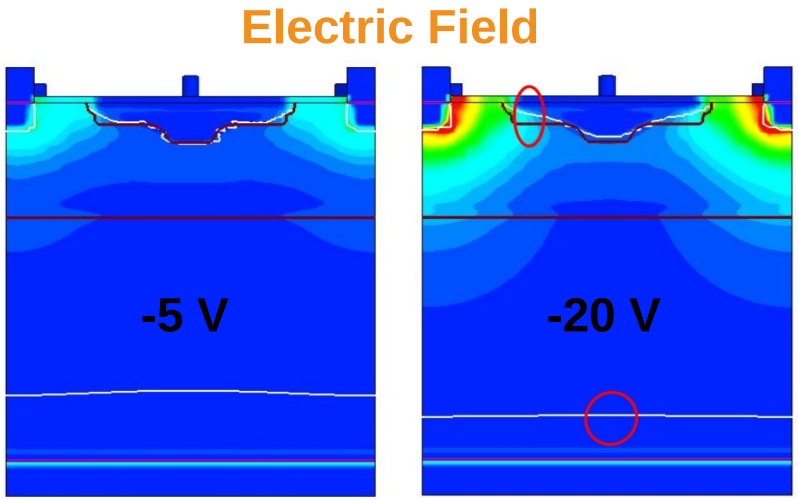
Results for N-blanket Layout

- Substrate and p-well bias

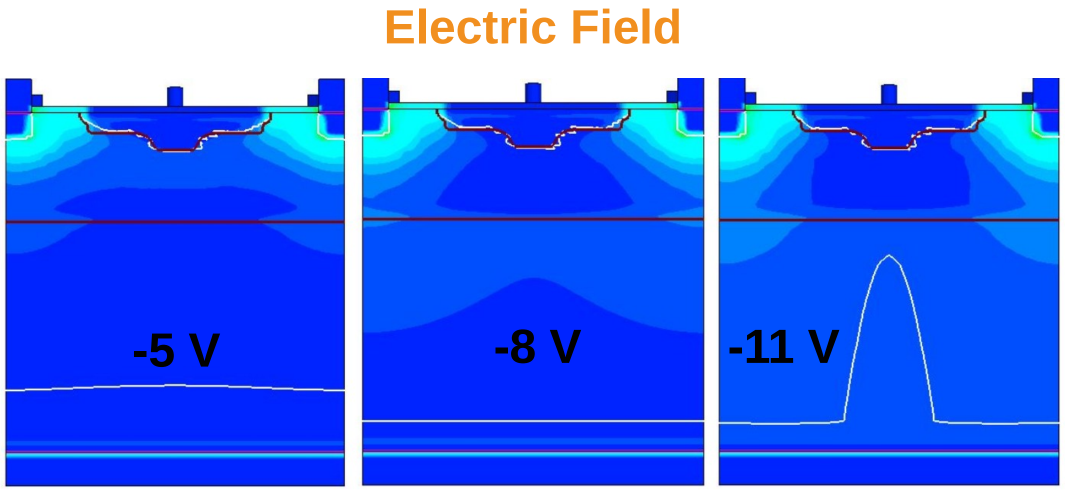


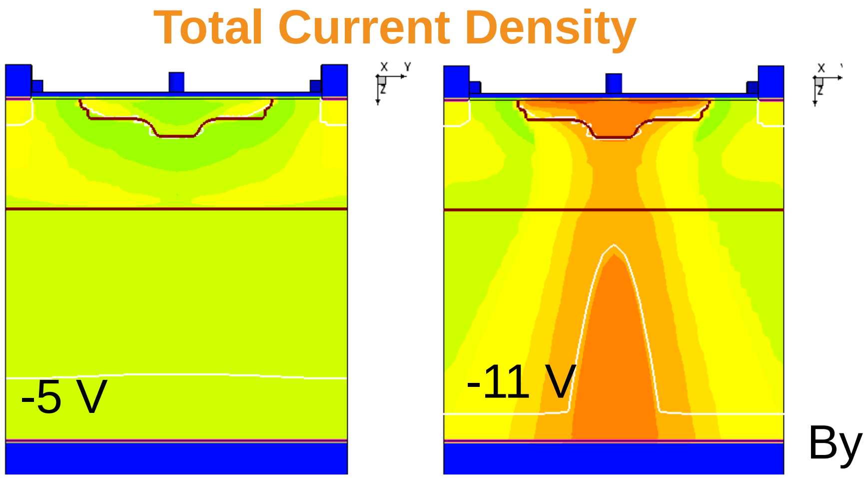
Results for N-blanket Layout

- Bias scan over p-well and substrate simultaneously



- Bias scan over substrate only, p-well fixed at -5 V

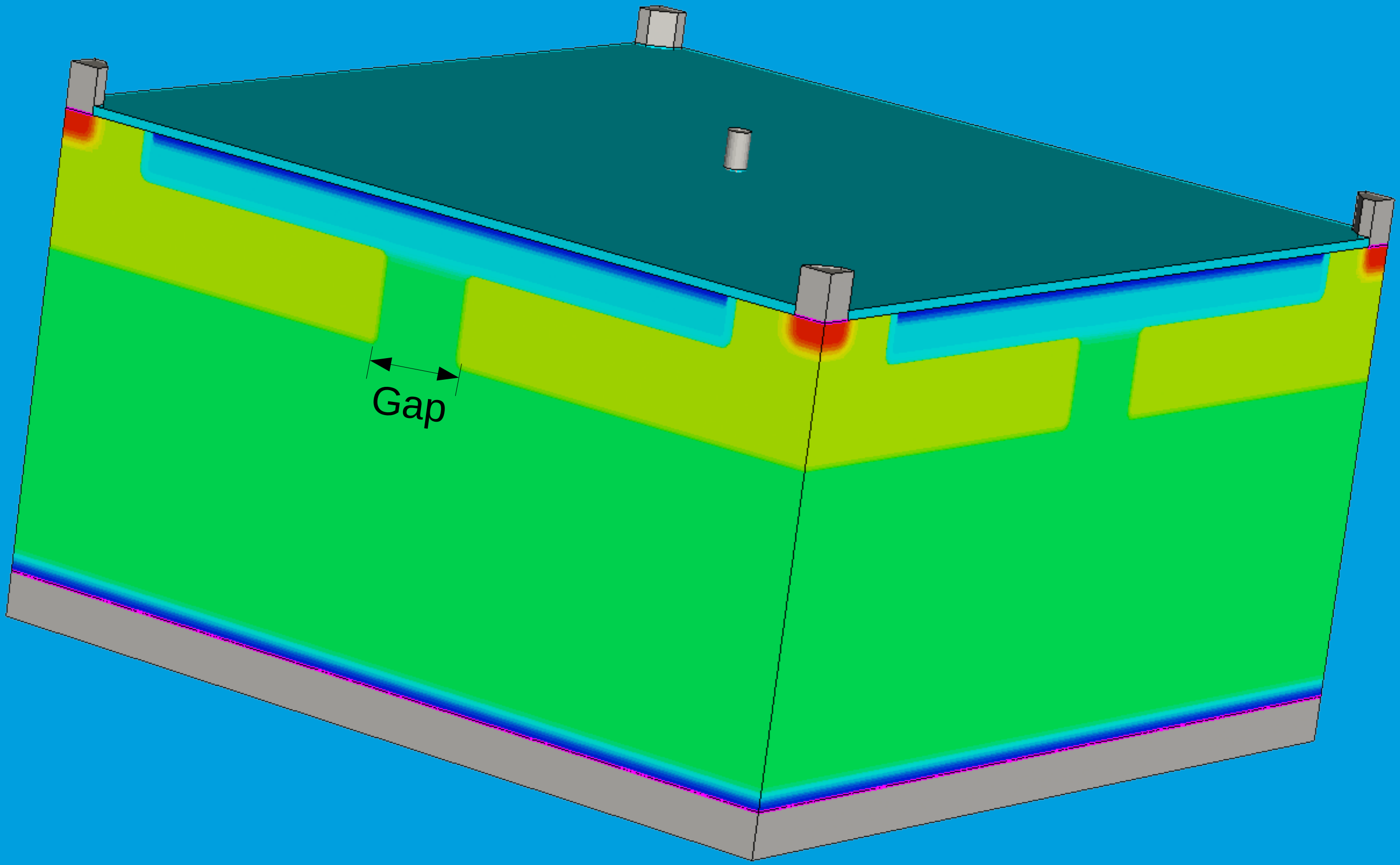




By L. Mendes

Results for N-blanket with gap Layout

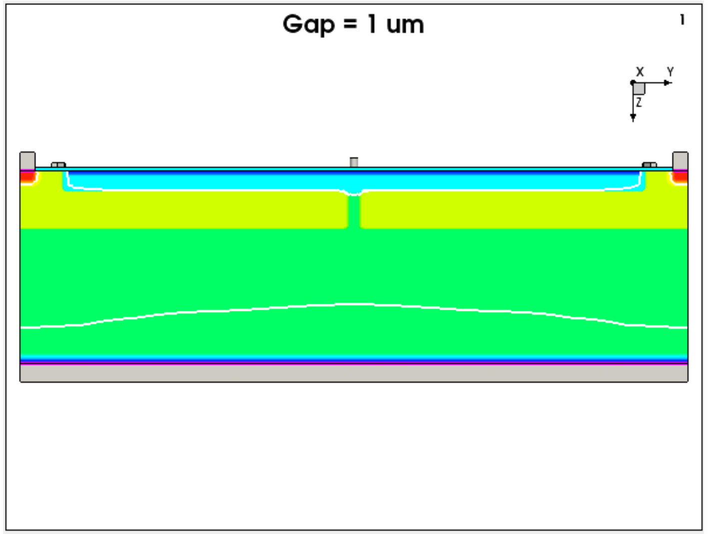
- Gap size

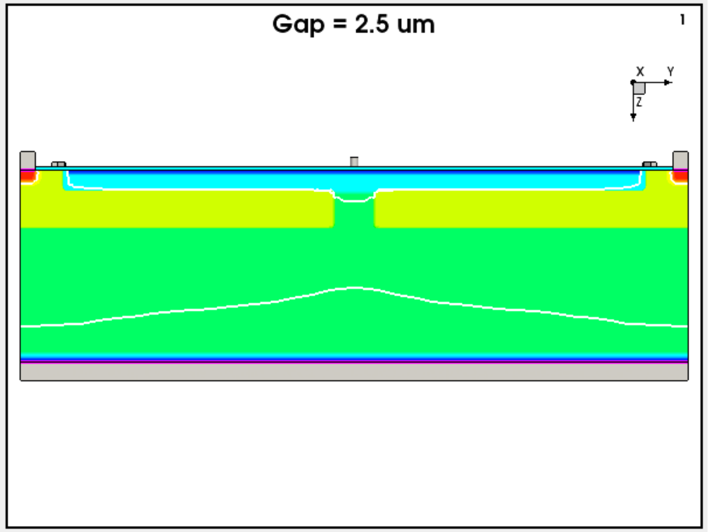


Results for N-blanket with gap Layout

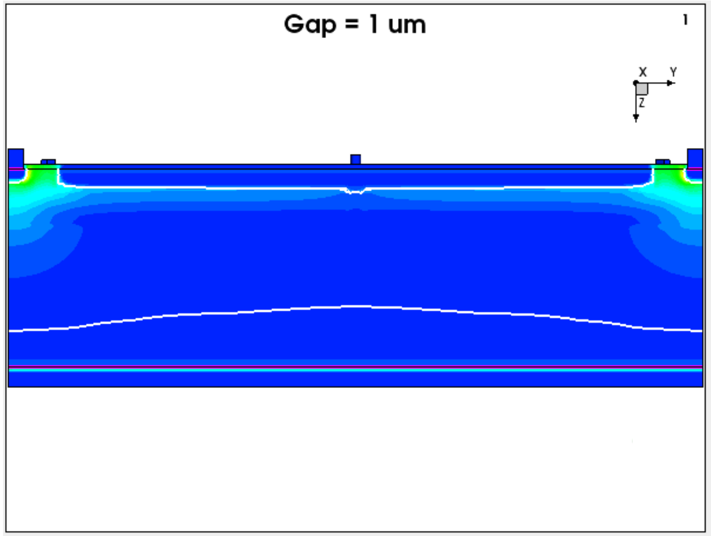
- **n-blanket gap size**: varied from 1 – 4 µm, chose 2.5 µm as most sensible value.

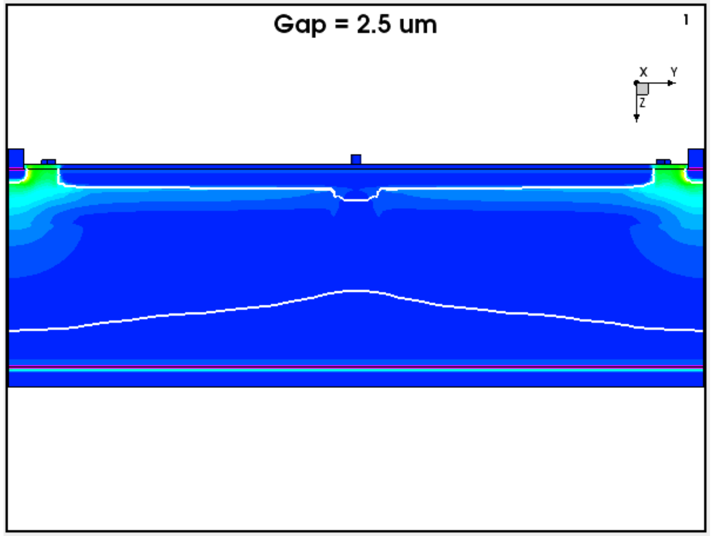
Doping Concentration



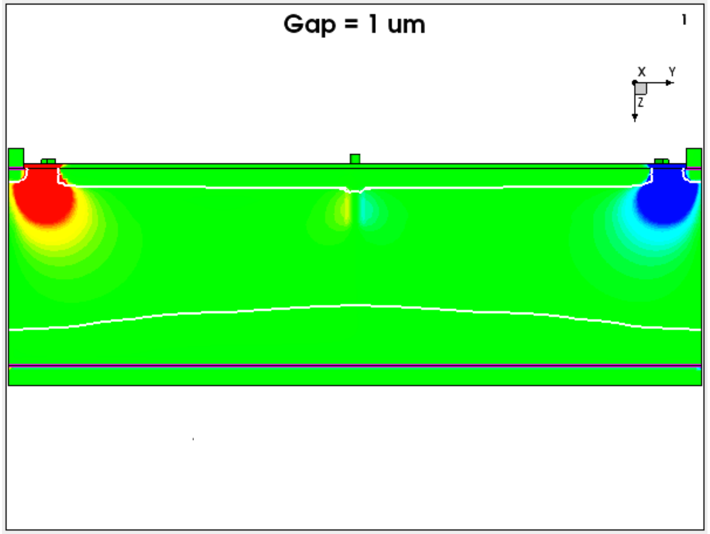


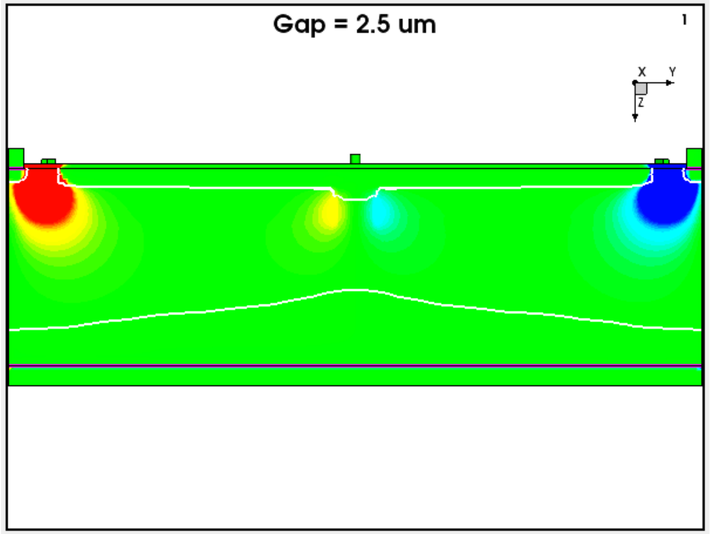
Electric Field





Lateral Field

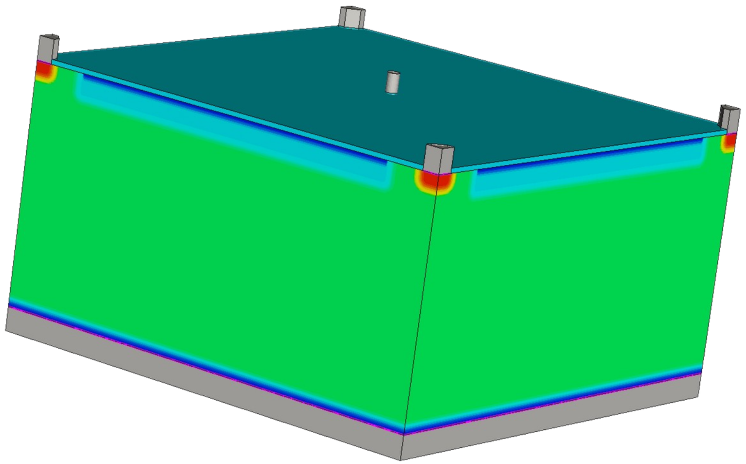


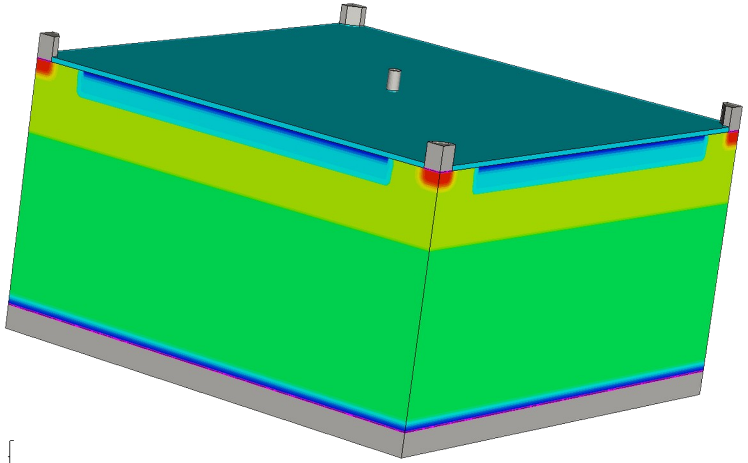


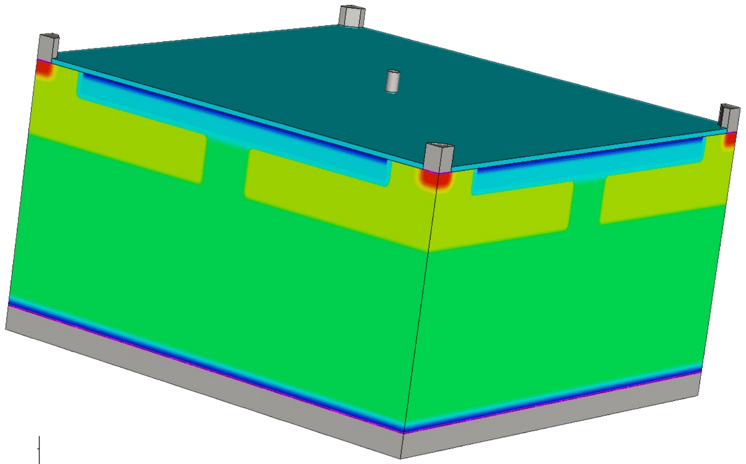
All Layouts After Tuning Parameters

Standard Layout | **N-blanket Layout** | **N-blanket with Gap Layout**

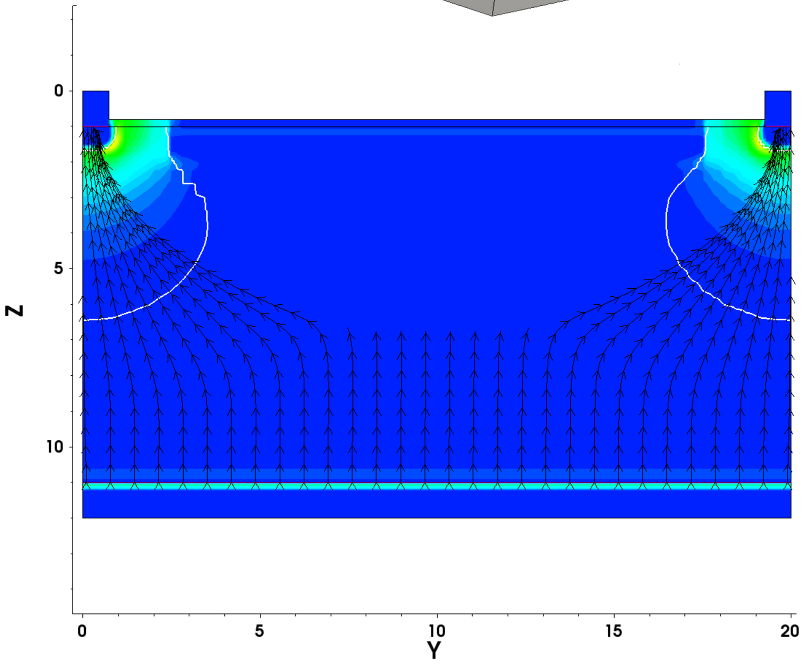
Doping Concentration

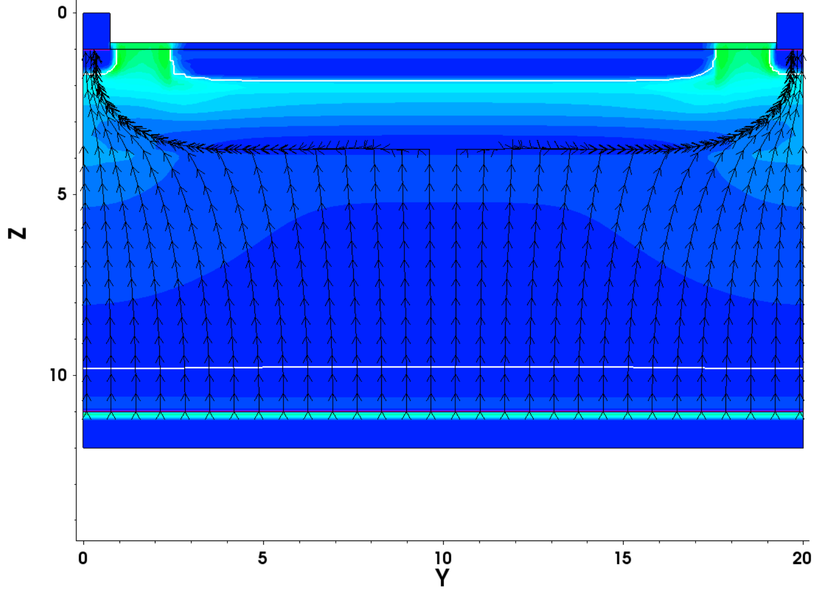


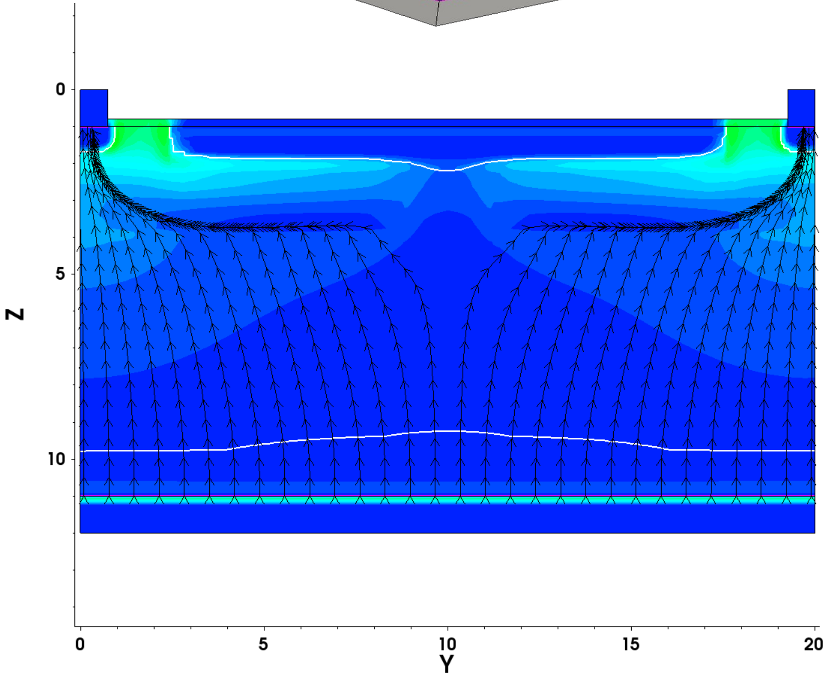




Electric Field and Streamlines

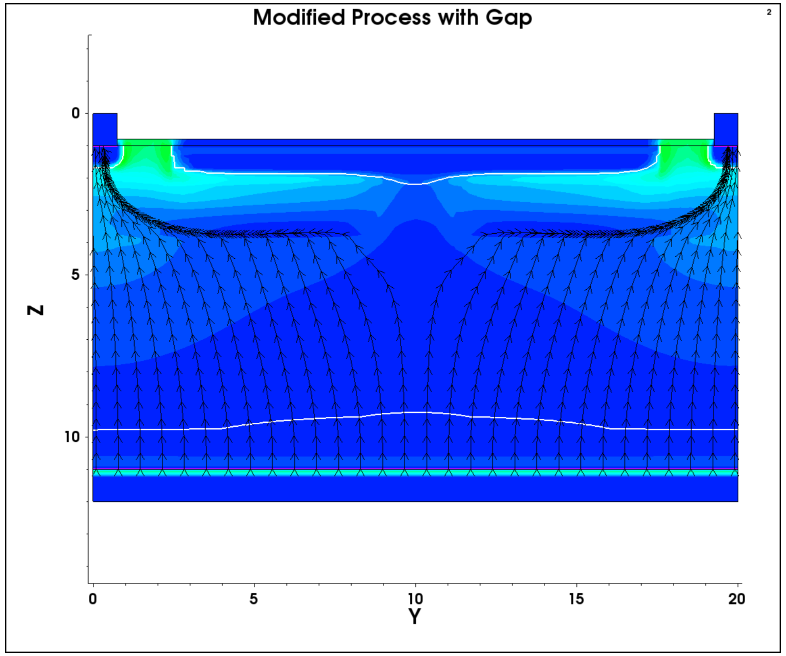


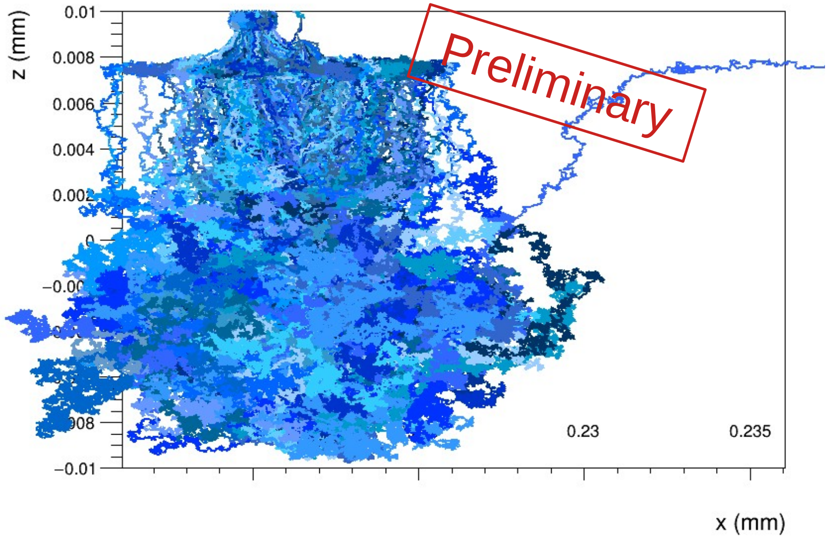




Conclusions from Tangerine Simulations

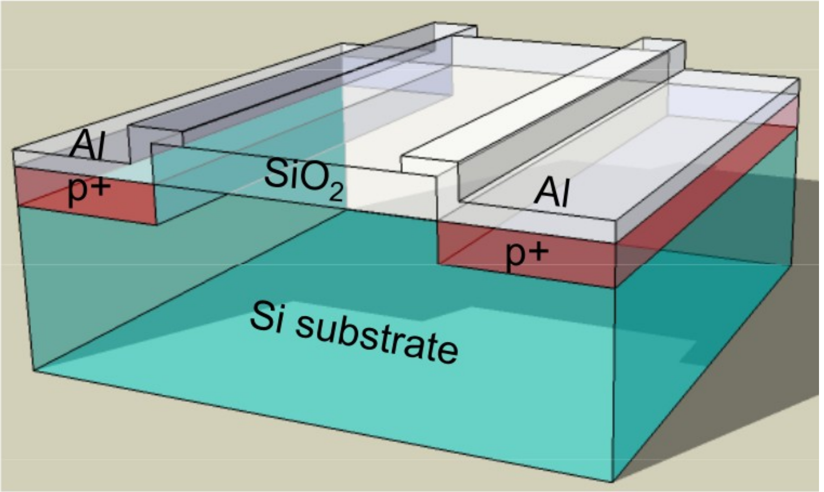
- TCAD simulations using generic doping profiles have provided very useful insights for sensor optimization.
- Sensor layouts: standard, n-blanket and n-blanket with gap.
- Scans: pitch, p-well opening, substrate and p-well bias, n-blanket gap size…
- Understood effect of parameters on electric field and depleted volume.
- Established sensible values for some parameters.
- Complemented with Monte Carlo Simulations using Allpix² (H. Wennlöf, M. A. Del Rio Viera, S. Ruiz Daza).





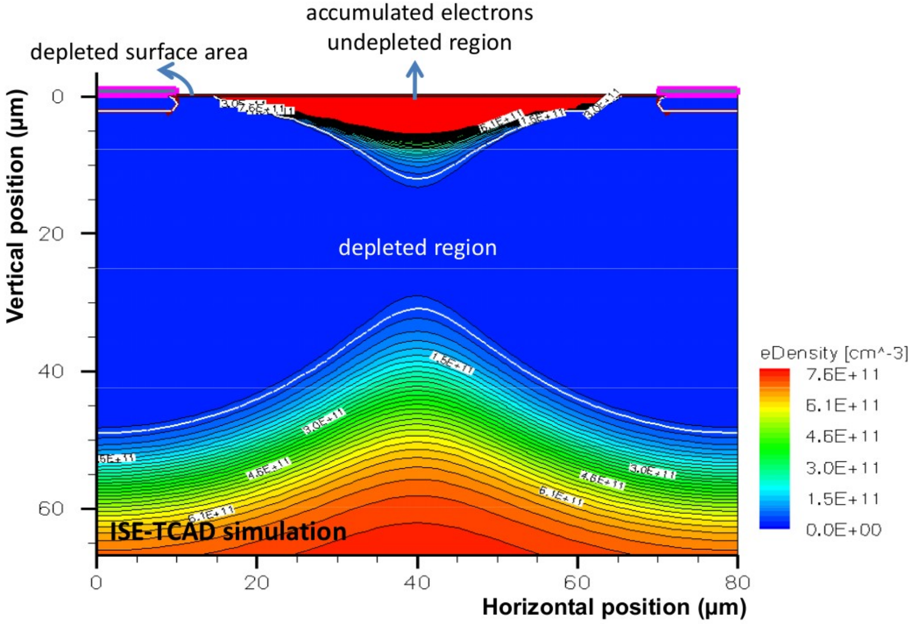
AGIPD Sensor Development for XFEL (UHH)

- Proposed p+n Si pixel detector capable to withstand a dose of up to 1 GGy of 12 keV X-ray for three years operation.
- Studies: radiation damage and breakdown voltage.

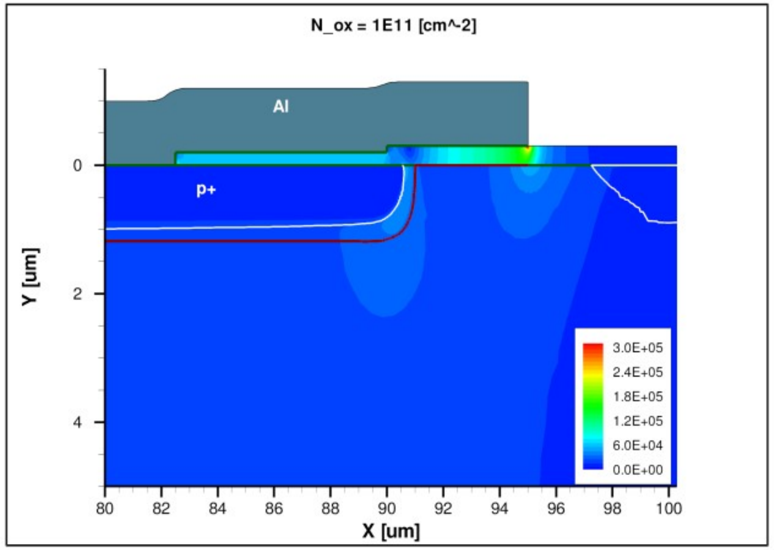


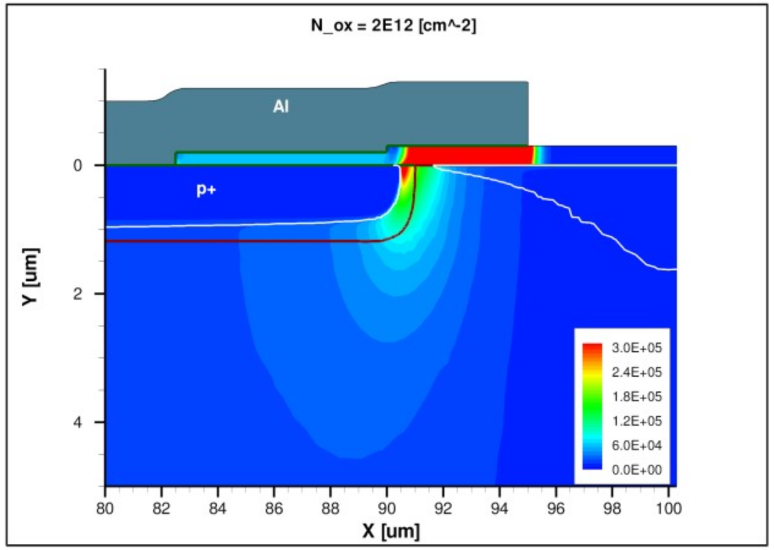
R. Klanner[1], E. Fretwurst[1], I. Pintilie[2], J. Schwandt[1], J. Zhang[1], A. Srivastava[1], T. Poehlsen[1].
[1]Institute for Experimental Physics (UHH), Germany
[2]National Institute of Materials, Romania

Electron Density of irradiated sensor



Electric Field at same bias for different density of oxide charges

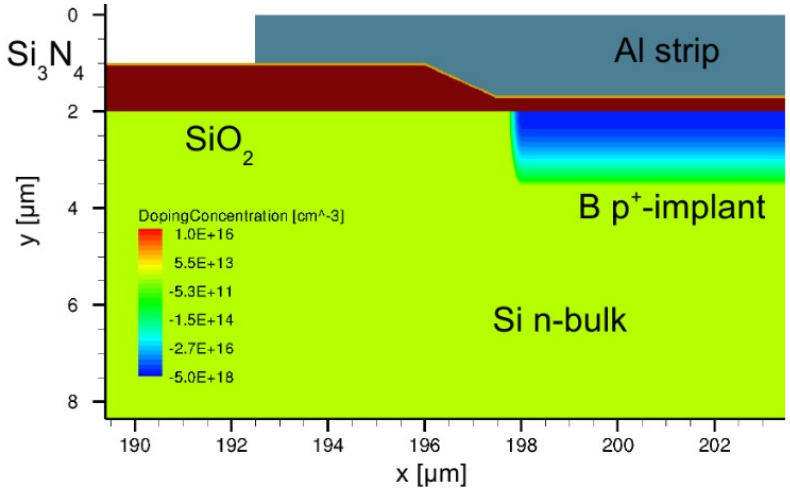




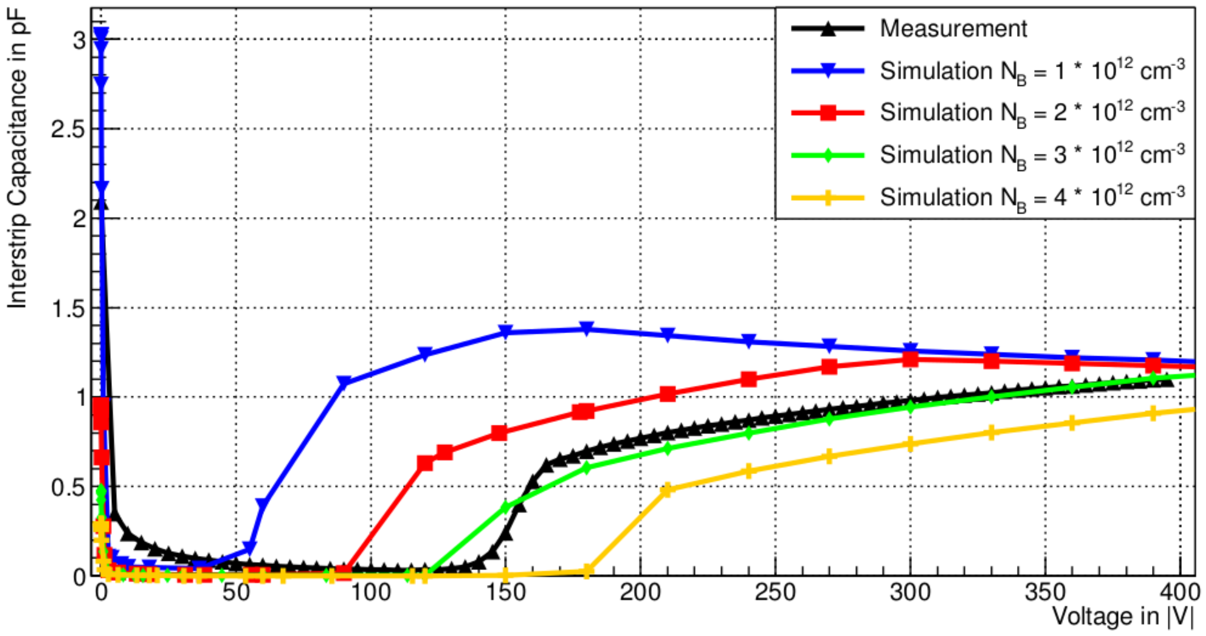
Multi-geometry Silicon Strip Detectors for CMS (DESY)

- Test sensor used to study the inter-strip capacitance for the CMS tracker upgrade.
- Studies: inter-strip capacitance, cross-validation with other software and measurements.

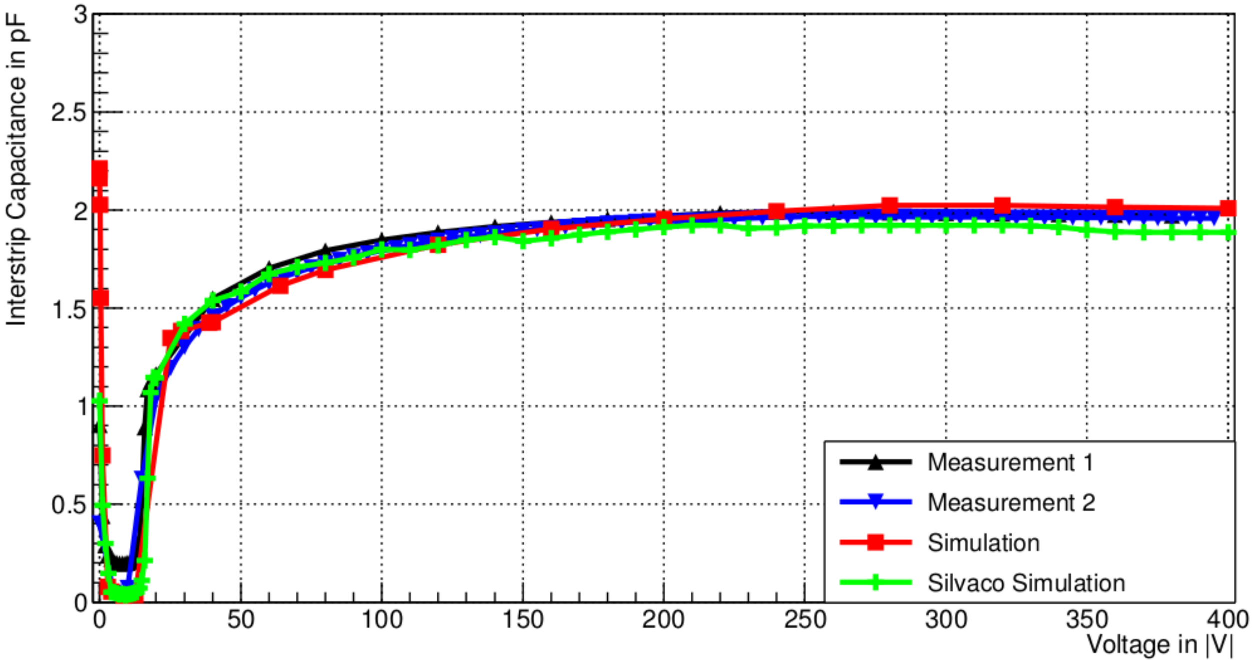
Eichhorn, T. 2015, “Development of Silicon Detectors for the High Luminosity LHC”, PhD Thesis, Universität Hamburg.



Inter-strip capacitance for different n-bulk doping concentration



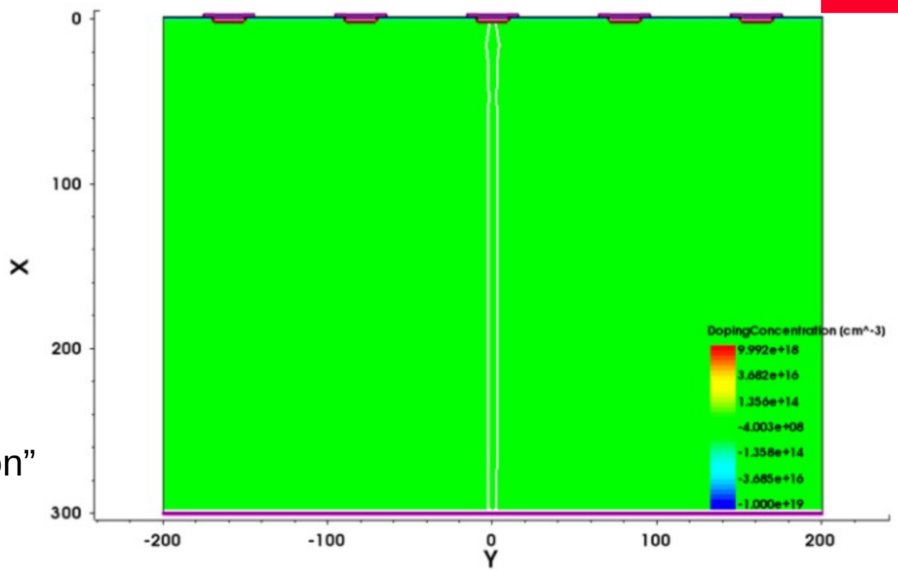
Cross-validation Synopsys, Silvaco and measurements



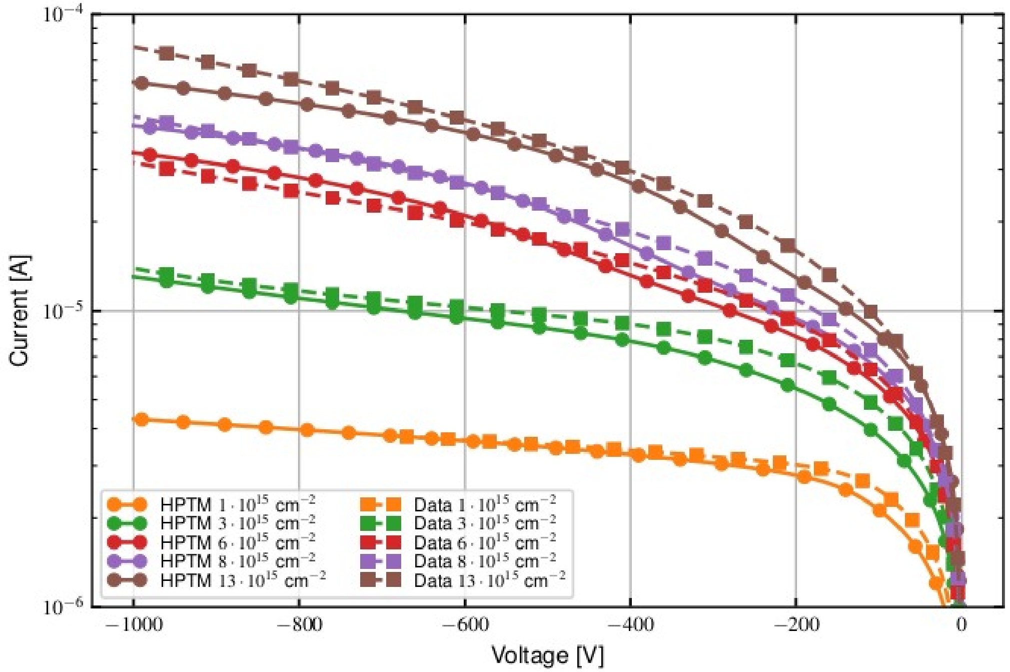
The Hamburg Penta Trap Model(UHH)

- Proposed and validated a new accurate bulk radiation damage model using I-V, C-V and CCE measurements from irradiated samples with 24 GeV/c protons.
- Studies: I-V, C-V, CCE.

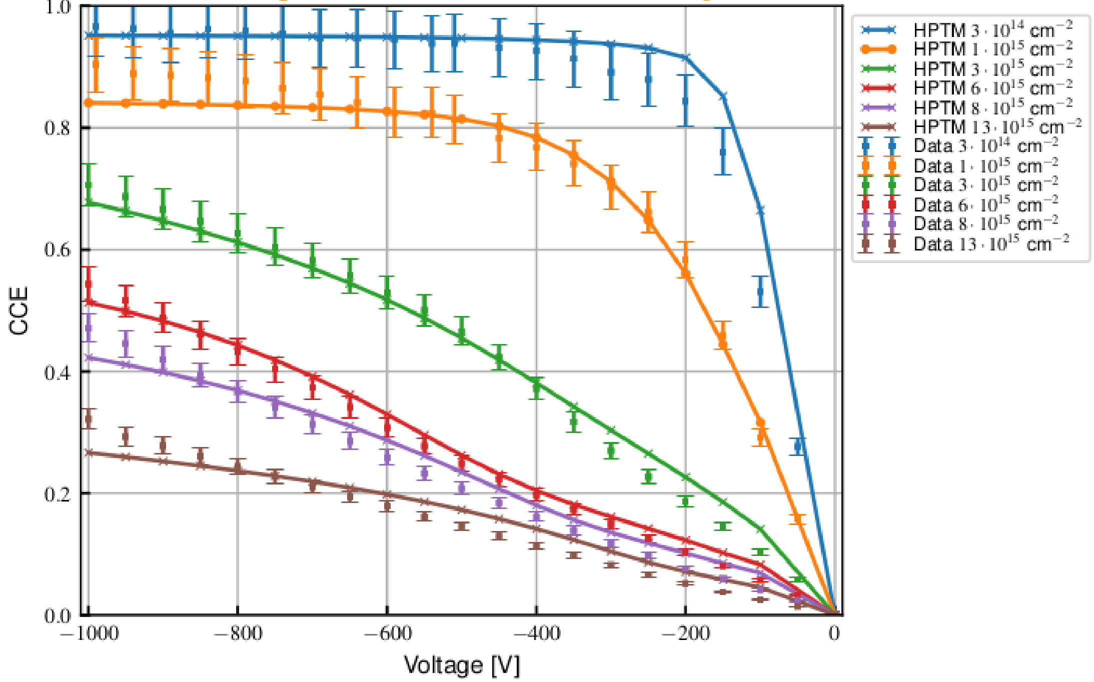
J. Schwandt, E. Fretwurst, E. Garutti, R. Klanner, C. Scharf, Georg Steinbrueck, 2018, “A new model for the TCAD simulation of the silicon damage by high fluence proton irradiation”



I-V Curve

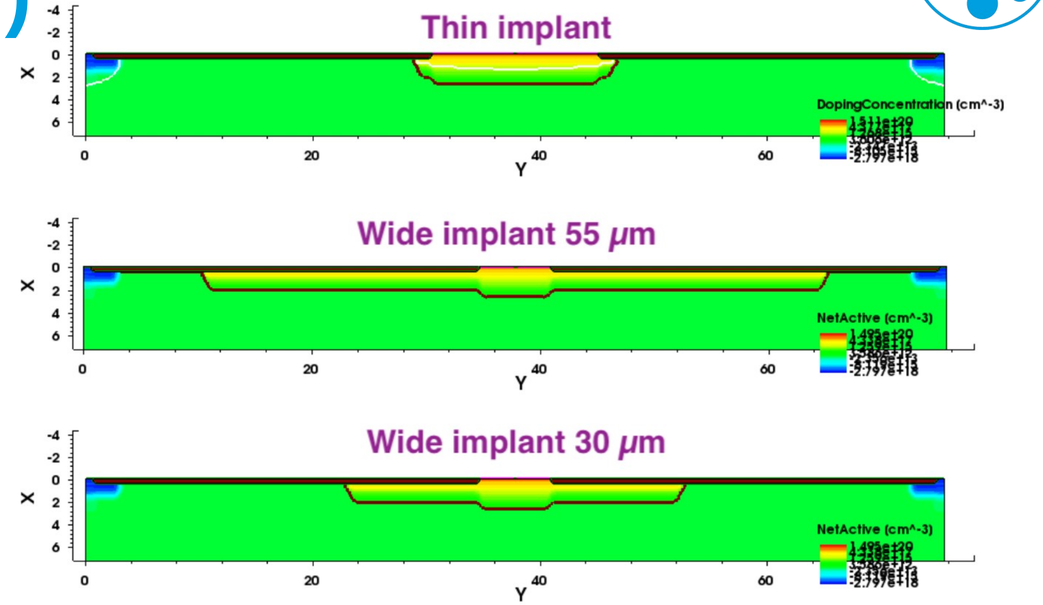


Charge Collection Efficiency

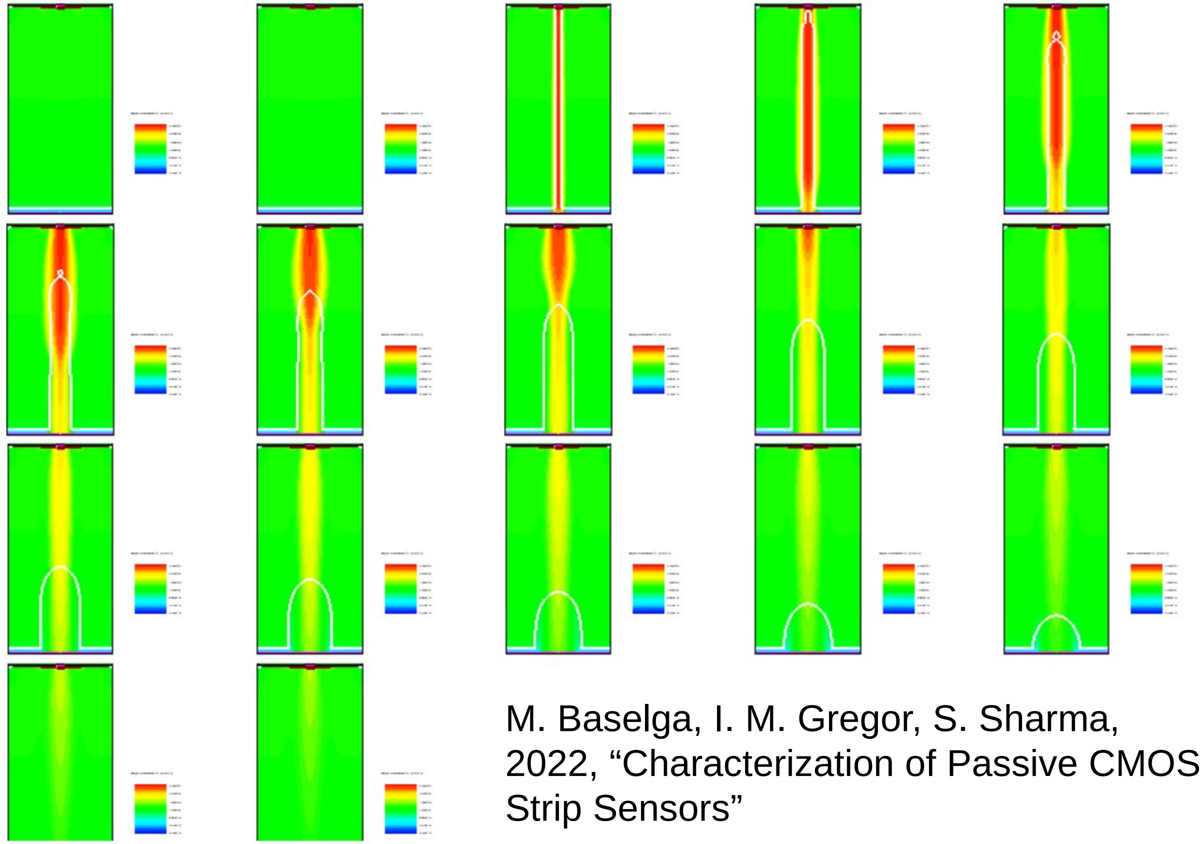


Passive Strip CMOS Detectors (DESY)

- Study on CMOS strip sensors to possibly cover larger areas than CMOS pixel sensors.
- Studies: charge collection and CV curves for three strip designs.

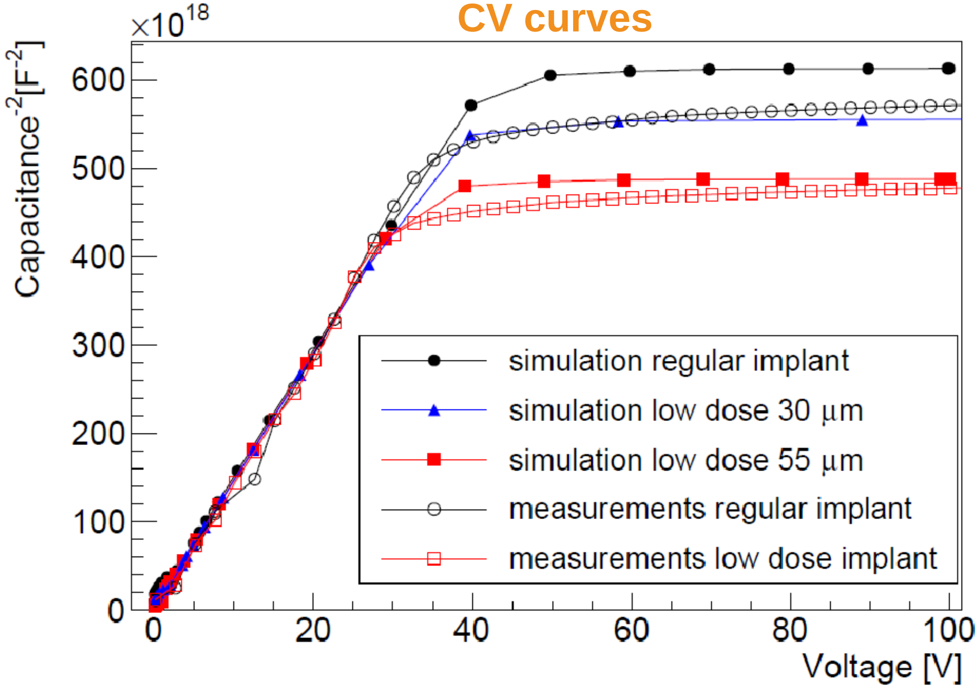


Electron density for transient simulation (wide implant 30 μm)



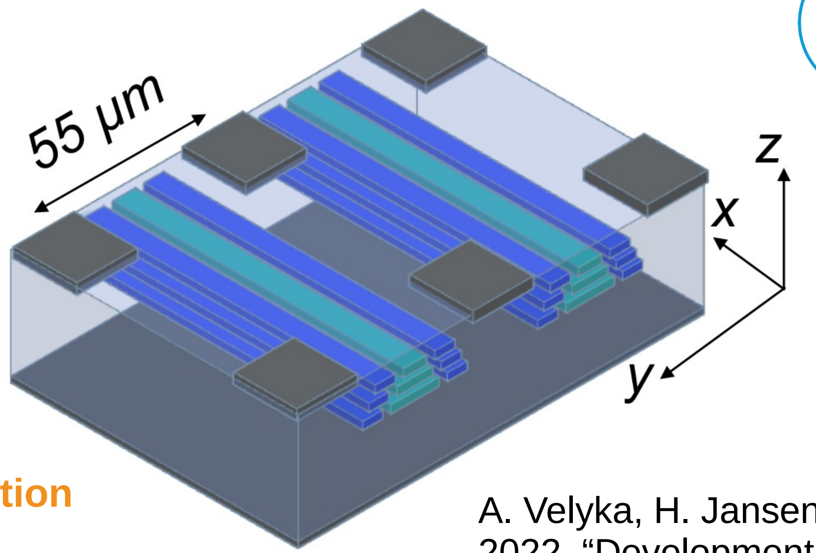
M. Baselga, I. M. Gregor, S. Sharma, 2022, “Characterization of Passive CMOS Strip Sensors”

CV curves



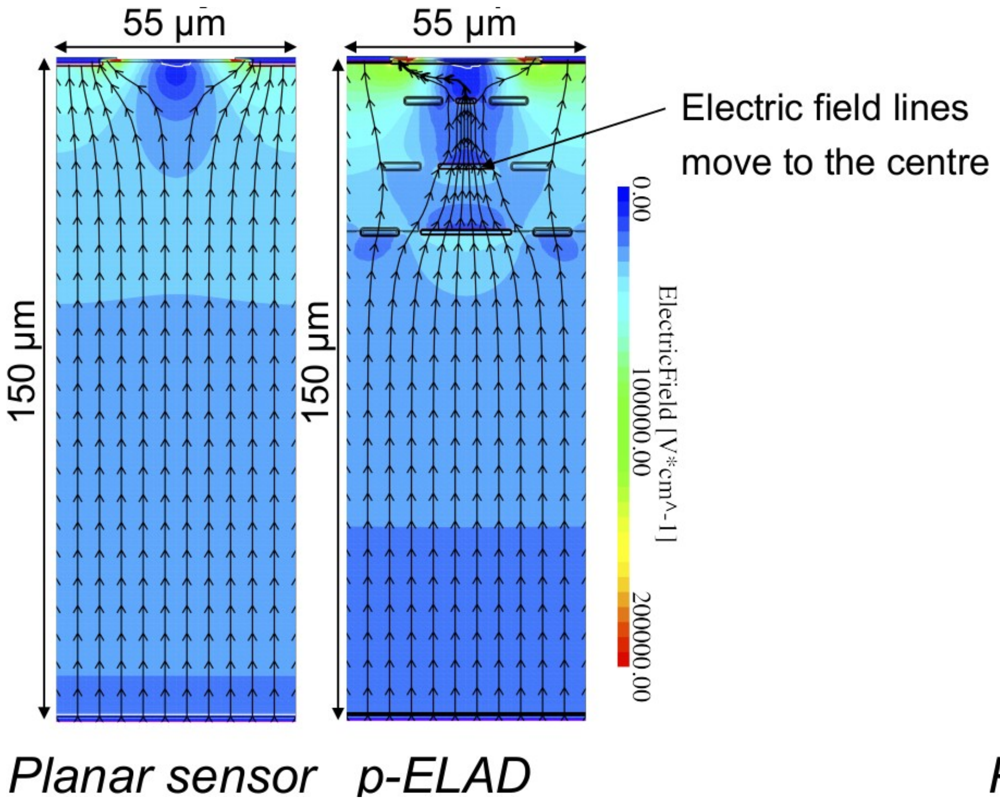
Enhanced Lateral Drift Sensors (DESY)

- Improving position resolution by locally engineering the electric field to induce lateral drift of charges, and adding a multiplication layer.
- Studies: electric field and transient simulations.

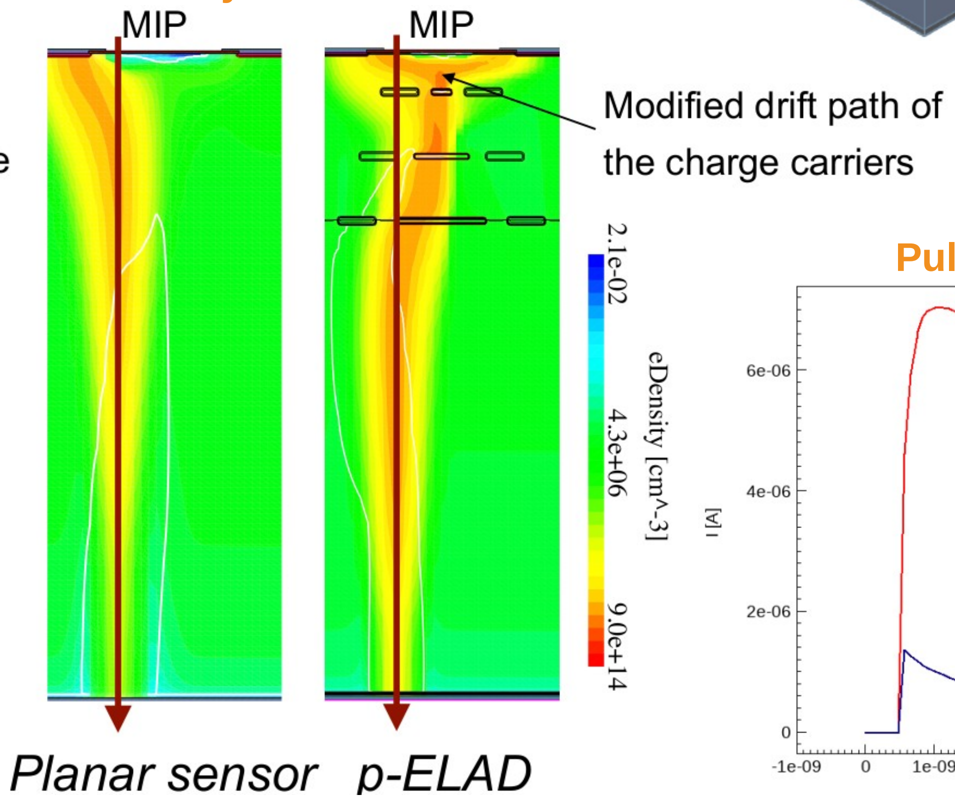


A. Velyka, H. Jansen, 2022, "Development and simulations of Enhanced Lateral Drift Sensors"

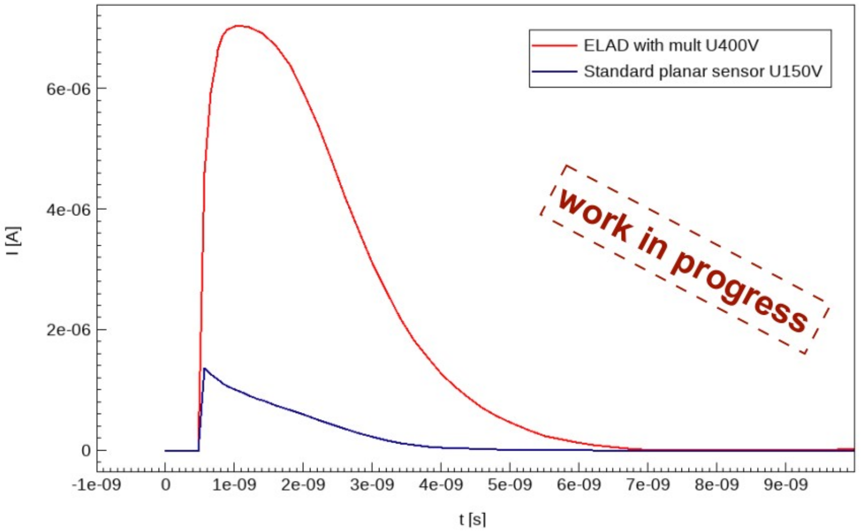
Electric Field



Electron density for transient simulation



Pulse from transient simulation



Conclusion

- TCAD is a very powerful tool to simulate semiconductor devices.
- Used in HEP for the past ~20 years.
- Important for development, characterization and optimization of semiconductor detectors.
- Compatible with Monte Carlo simulations.
- Valuable examples of our home-made TCAD sensor simulations.

Thank you!