Transient Simulations with TCAD and Allpix Squared

Manuel Alejandro Del Rio Viera on behalf of the TANGERINE Collaboration

SiDet R&D Meeting

April 11th 2023

HELMHOLTZ UNIVERSITÄT BONN

DESY.

The Tangerine Project

TowArds Next GEneRation SIlicoN DEtectors

Goal: Develop the next generation of monolithic silicon pixel detectors using a 65 nm CMOS imaging process

Requirements

- Spatial Resolution ~ **3 µm**
- Time Resolution ~ **1 -10 ns**
- Low material budget ~ **50 µm silicon**

Application: e^+e^- Colliders

- Funded by Helmholtz Innovation Pool and DESY

Part of the **Work Package 1 (WP1):** Monolithic pixel detectors in novel CMOS imaging technology

Future e^+e^- Colliders

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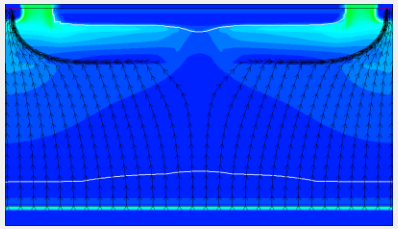
Workflow of the Project

From Device Simulations to Test Beams

Device Simulations (TCAD)

SYNOPSYS®



Allow to optimize the layouts that characterize a sensor

- Electric Fields
- Process Simulations
- Capacitance
- Weighting Potentials

Monte Carlo Simulations

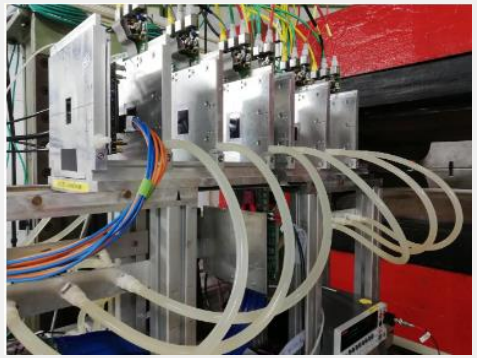
ap² allpix squared

Allow for greater statistics and to analyze detector performance

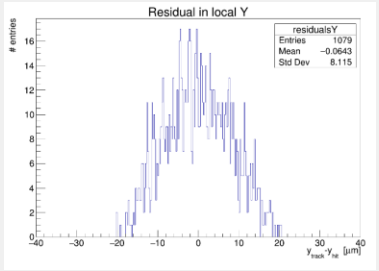
- Efficiency
- Cluster Size and Resolution
- Pulses

Lab and Test Beam Characterization

Test the performance of the sensors

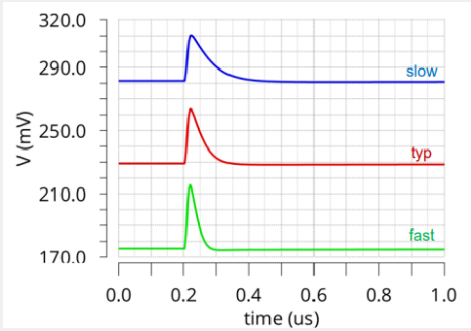


Compare data with simulations

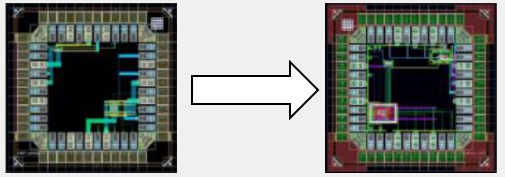


ASICs Design

Testing electronics and design prototypes



Resulting feedback is used for the next prototype



Allpix Squared + TCAD

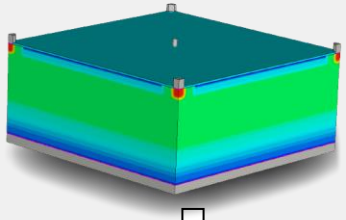
Transient Simulations - Full Detector Response

The **static** Electric Field, Doping Concentration and Electrostatic Potential Profiles are converted and imported into **Allpix Squared (APSQ):**

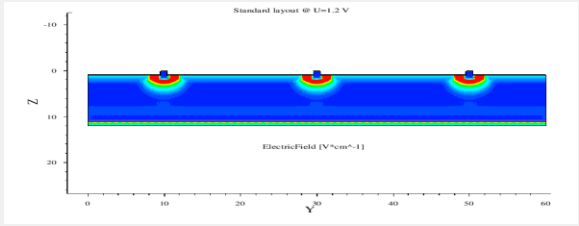
➞ **Combining the best of both : High statistics** and **accurate field modeling**

SYNOPSYS®

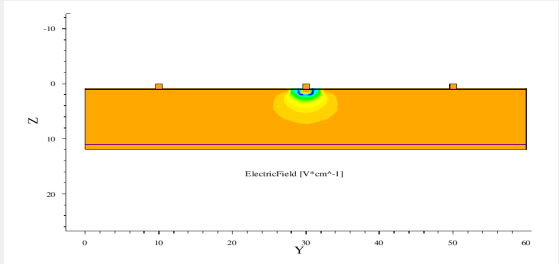
Generic Doping Profiles

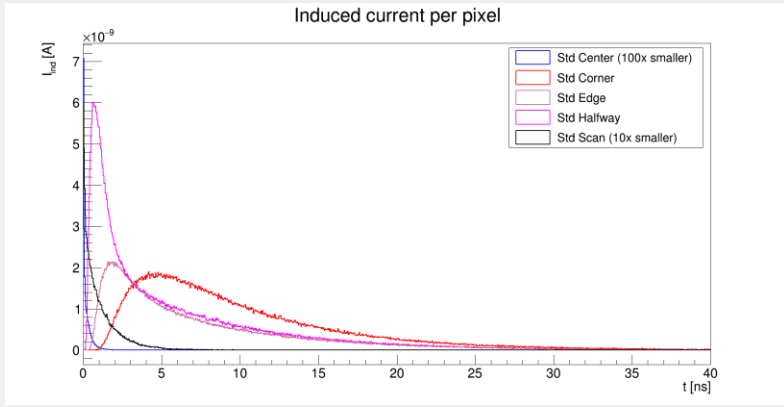


Electric Field



Weighting Potential





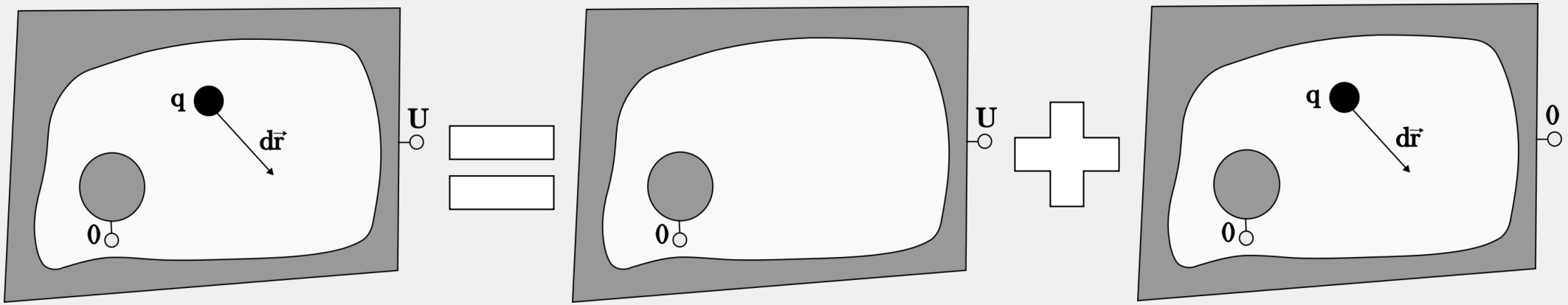
ap² allpix squared

Produce accurate pulses, and thus predict sensor and FE behavior!

Weighting Field: Shockley-Ramo Theorem

Basic Principle of Induced Signal in an electrode

See academic training lecture by W. Riegler (https://indico.cern.ch/event/843083/)



For a **static electric field, the energy:** $W_E = W_{E_0} + W_{E_q}$

No change in total field energy when charge is moving: $0 = dW_{E_0} + dW_{E_q} = UdQ + q\vec{E_0} \cdot d\vec{r} \rightarrow dQ = -q\frac{\vec{E_0}}{U} \cdot d\vec{r}$

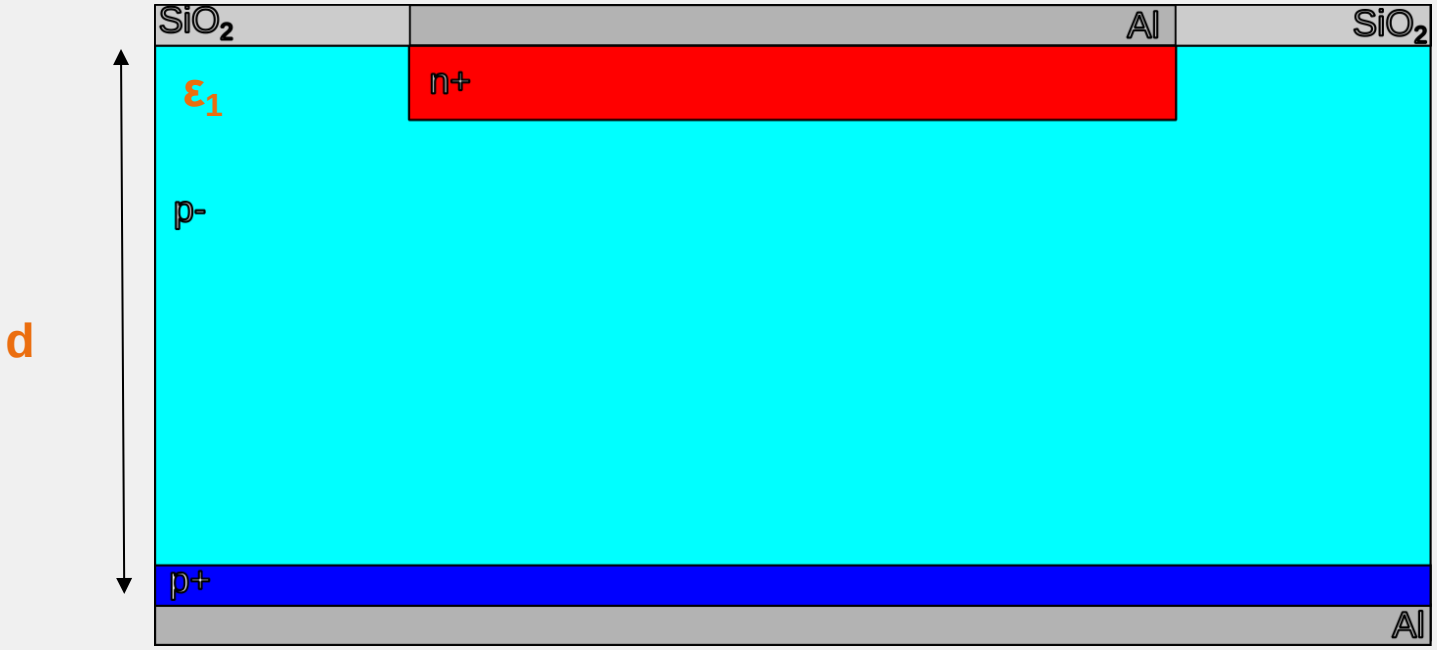
Solved by a **weighting field and a weighting potential**: $\varphi_w = \frac{\varphi_0}{U}\ ;\ \vec{E_w} = -\vec{\nabla}\varphi_w$

The induced current can be expressed by the **propagation of the charge in the weighting field** :

$$I_{ind} = q\vec{E} \cdot \vec{v}$$
$$Q_{ind} = q(\varphi_w(\vec{r}_{t_0}) - \varphi_w(\vec{r}_t))$$

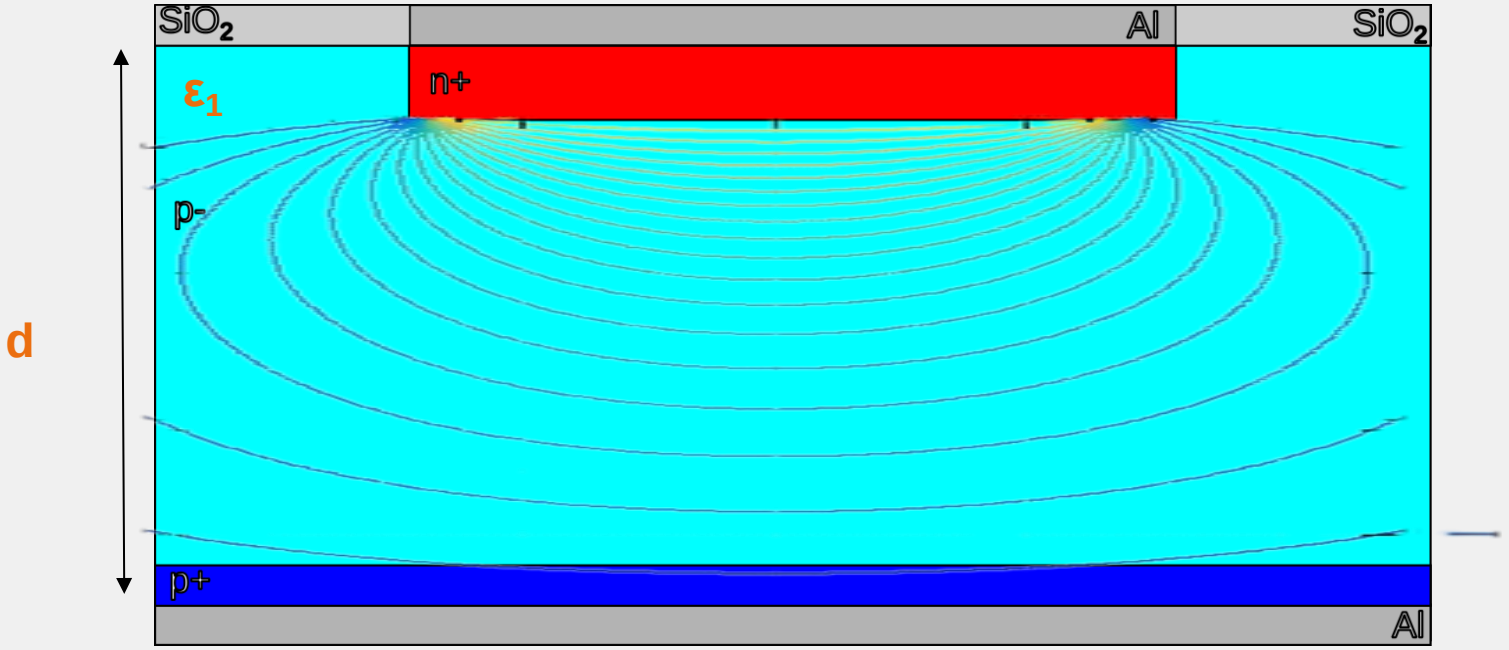
Shockley-Ramo's Theorem

Signal Formation on Silicon Sensors



Shockley-Ramo's Theorem

Signal Formation on Silicon Sensors



$$\varphi_w = \frac{\varphi_0}{U} \; ; \; \overrightarrow{E_w} = -\vec{\nabla}\varphi_w$$

Shockley-Ramo's Theorem

Signal Formation on Silicon Sensors

$$I_{ind} = q\vec{E} \cdot \vec{v}$$
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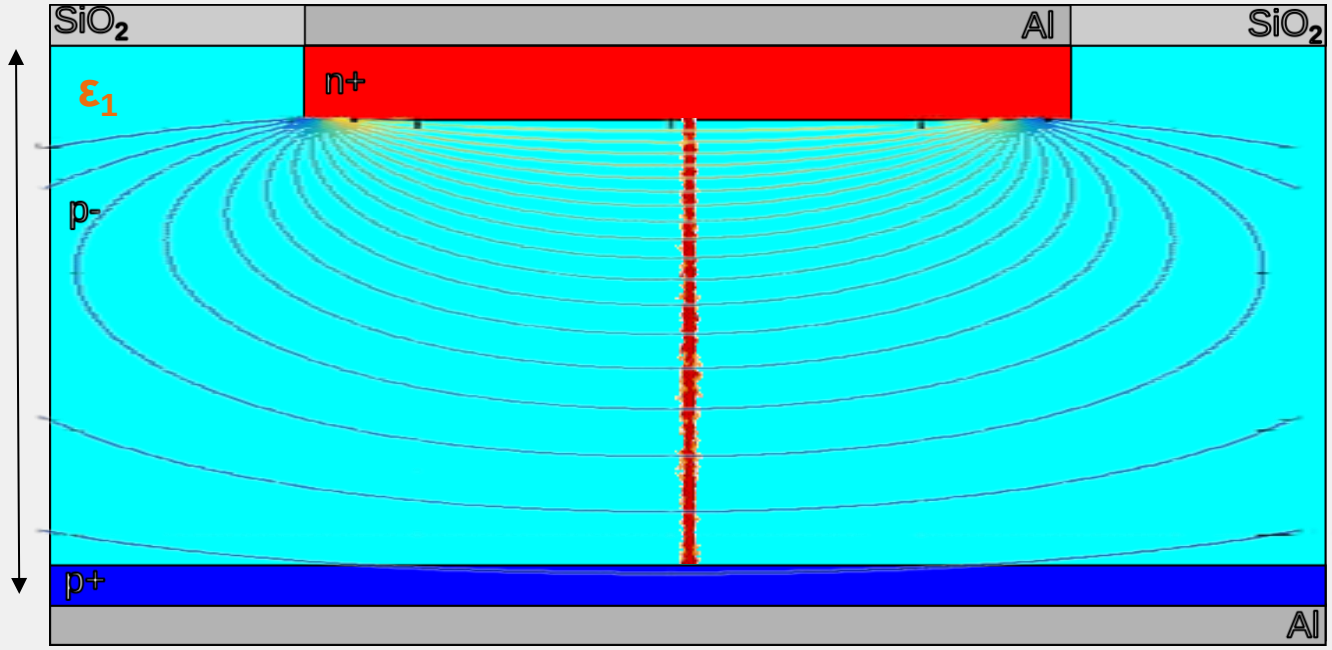
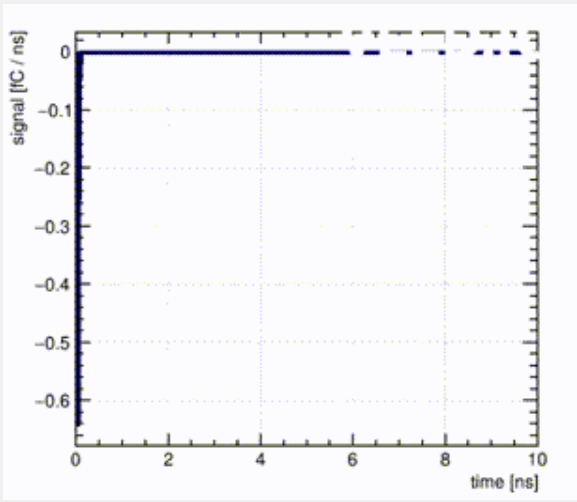
d





$$\varphi_w = \frac{\varphi_0}{U} \; ; \; \overrightarrow{E_w} = -\vec{\nabla}\varphi_w$$

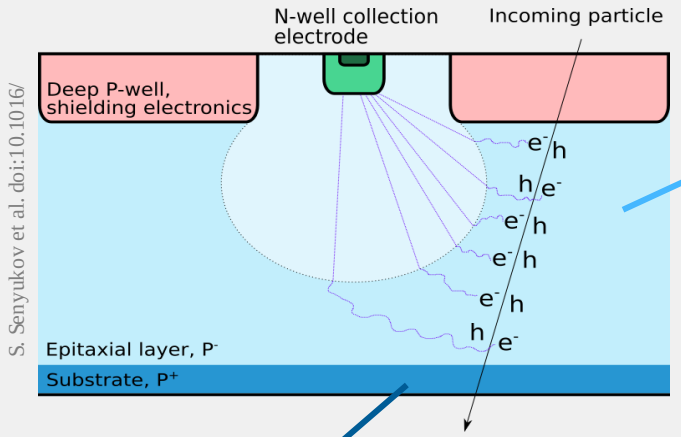
Recipe for a Transient Pulse

Sensor Layouts Under Study

Monolithic → Reduction of costs and material
65 nm process → Improved logic density of pixels and Power consumption → Material budget
Small collection electrode → Small capacitance → Improvement in S/N and Power consumption

Monolithic Active Pixel Sensors (MAPS)

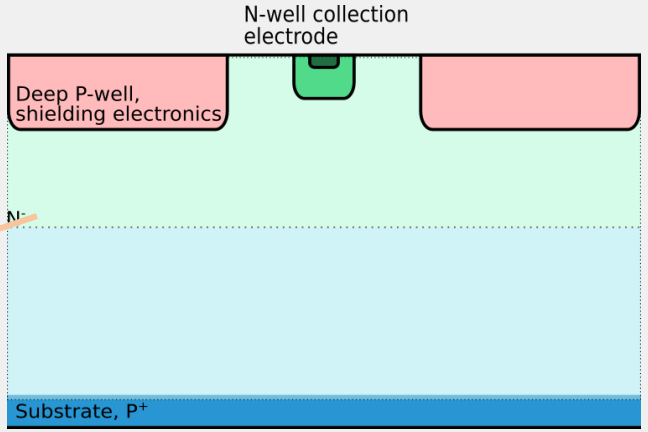
Standard



Epitaxial Layer
High Resisitivity

P-Subtrate
Low Resistivity

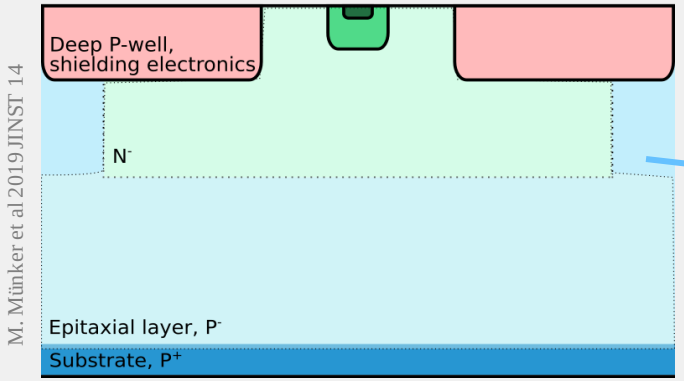
N-Blanket



Continuous
N-type Implant

Increase the depleted region

N-Gap

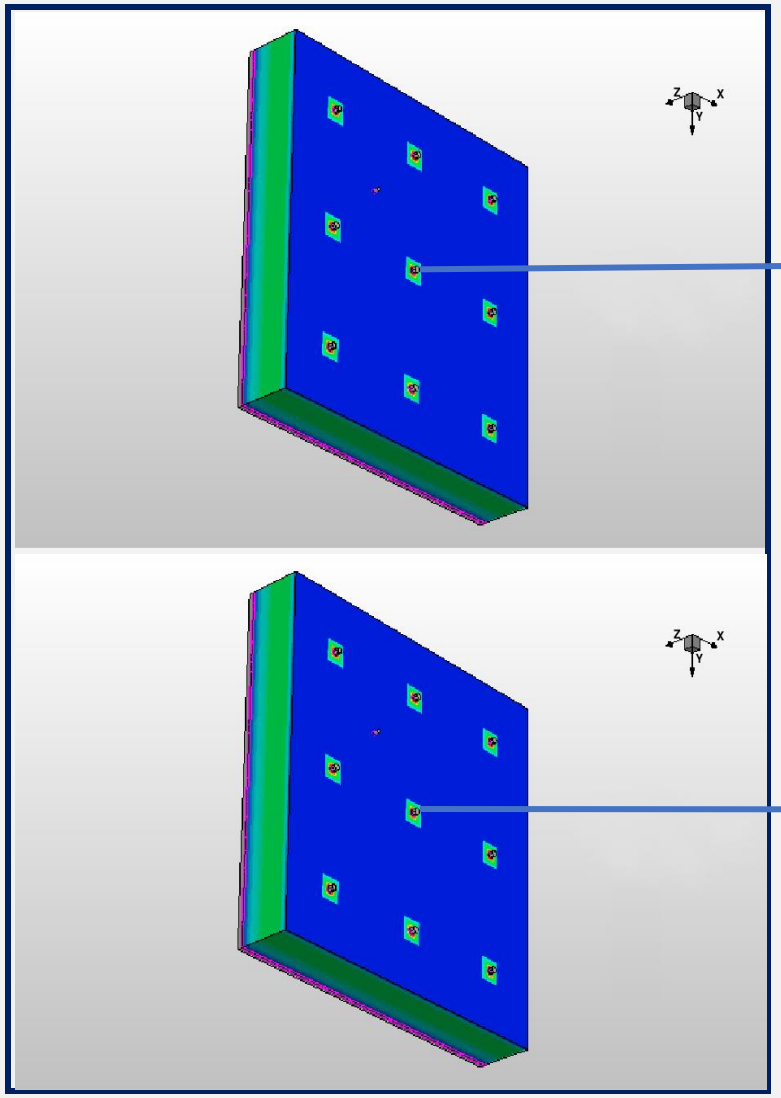


Gap in Continuous
N-type Implant

Speed up charge collection

Weighting Potential

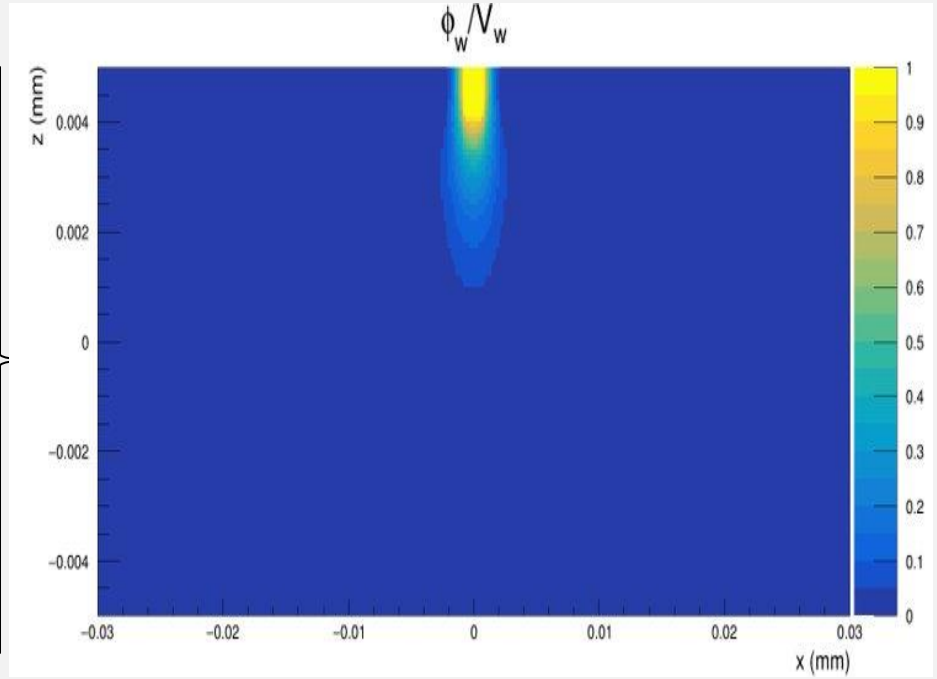
Recipe for a Transient Simulation



i.e. Voltage: -1.2 V

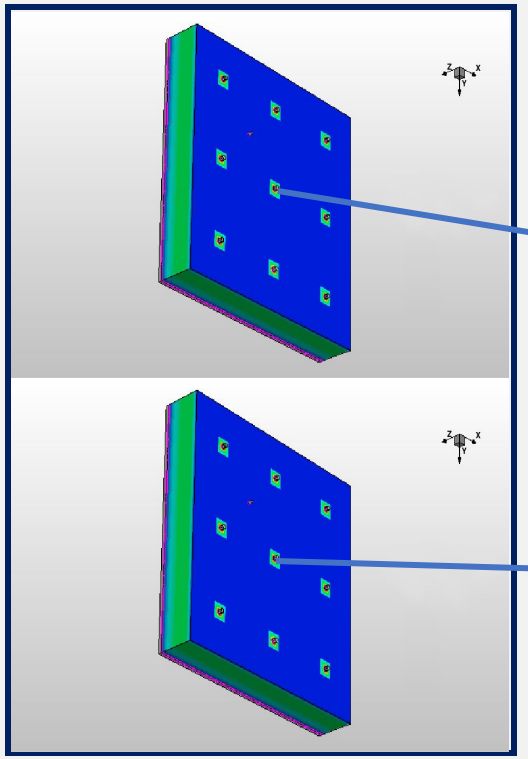
i.e. Voltage: -1.3 V

$$(\varphi_1 - \varphi_2)/\Delta U$$



Weighting Potential $(\varphi_1 - \varphi_2)/\Delta U$

Recipe for a Transient Simulation



i.e. Voltage: -1.2 V

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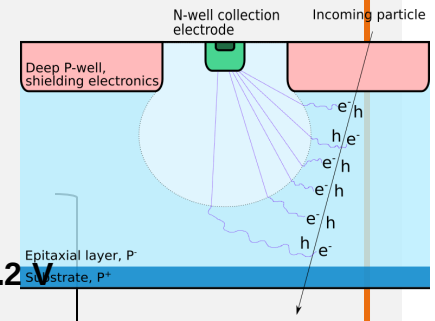
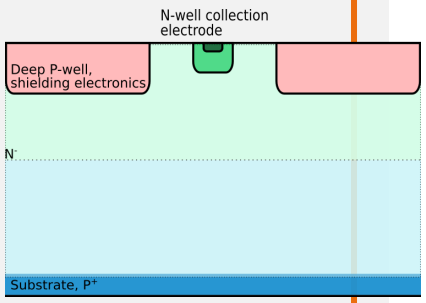
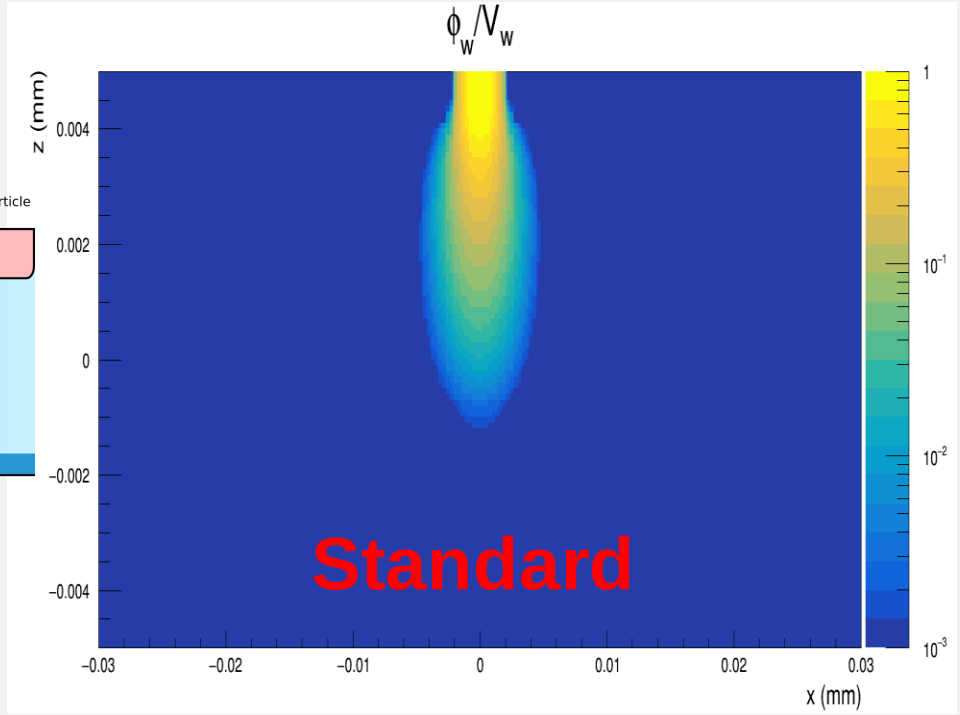
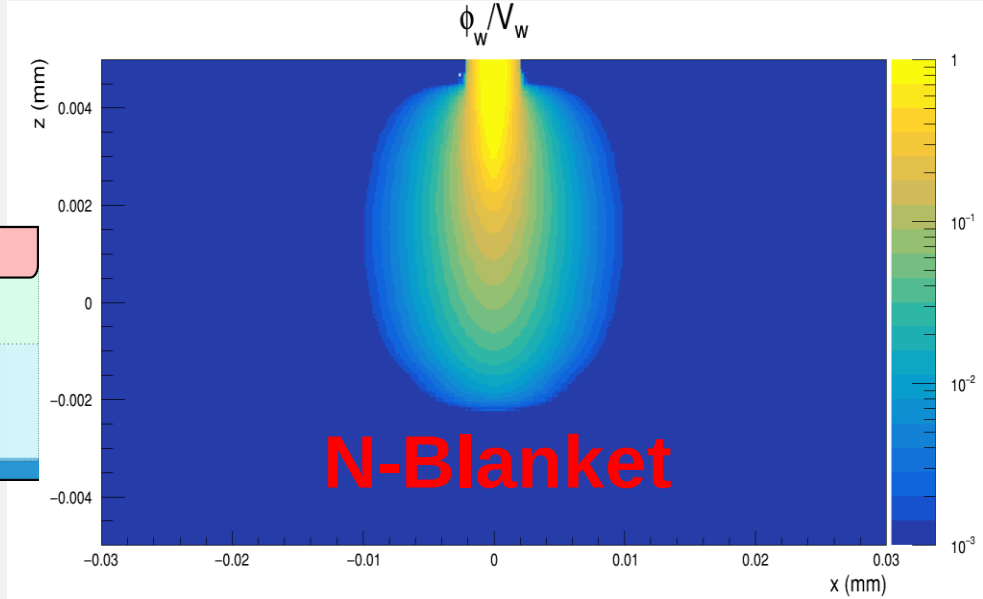




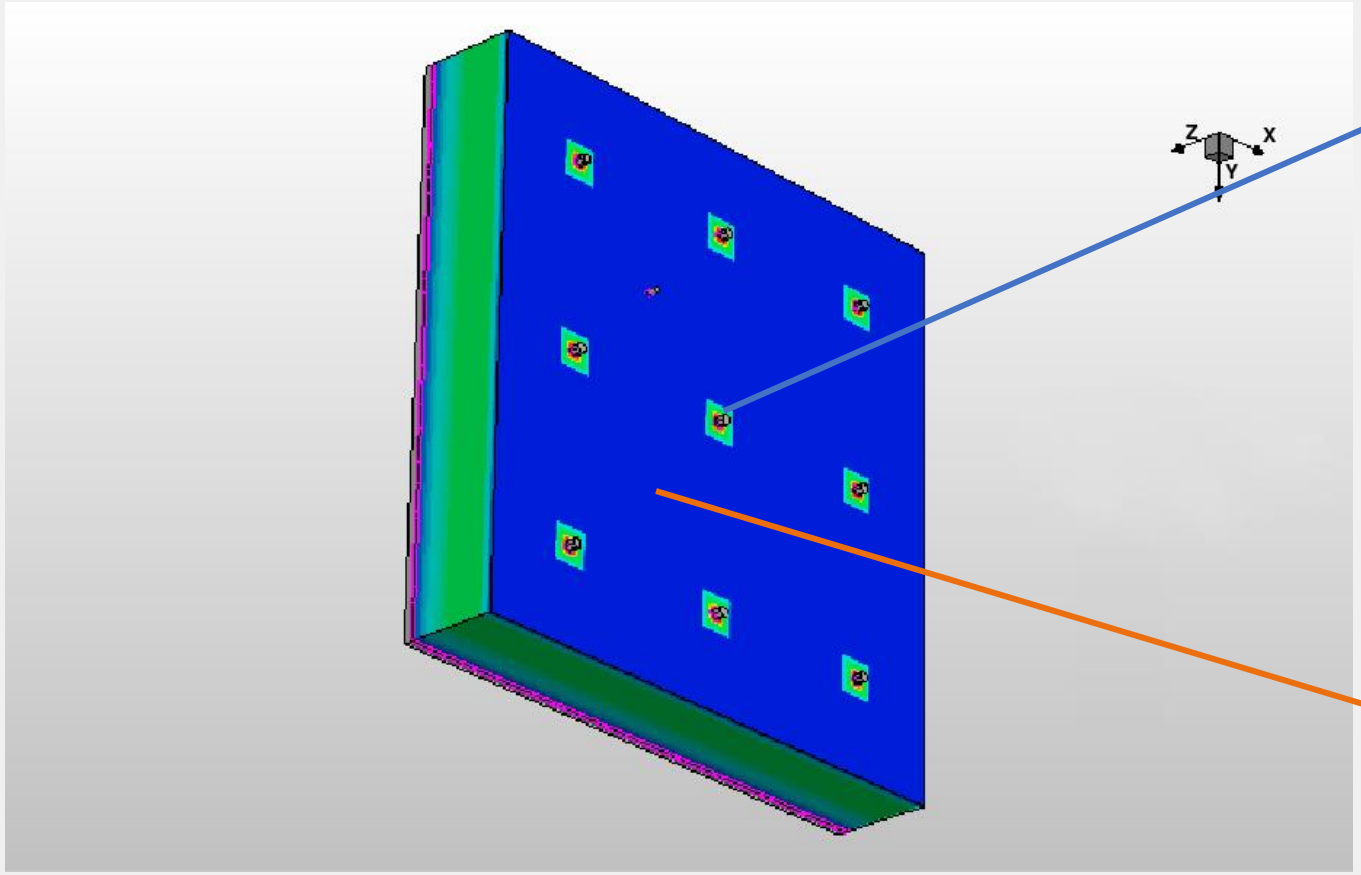
Geometry dependent!



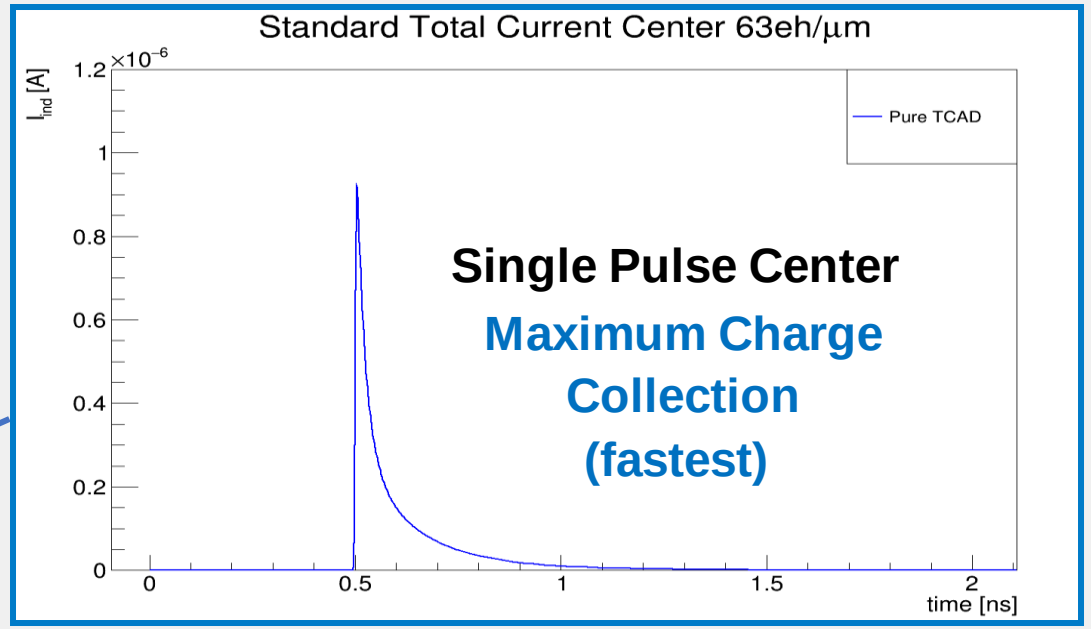


Technology Computer-Aided Design (TCAD)

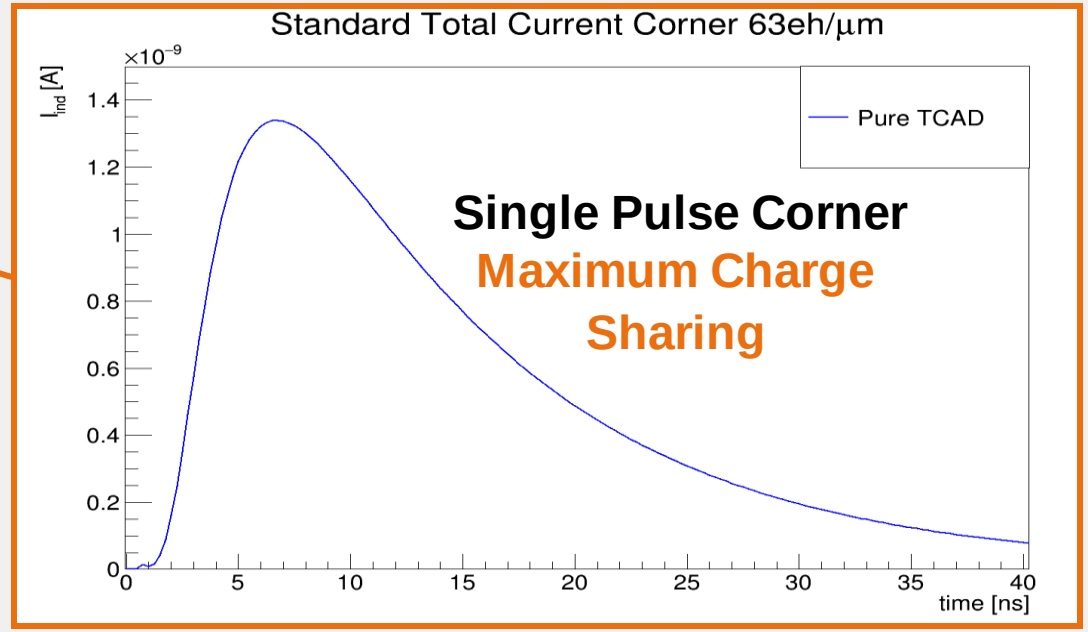
Transient Simulations - Full Detector Response



3x3-cell model



Not same time scale!



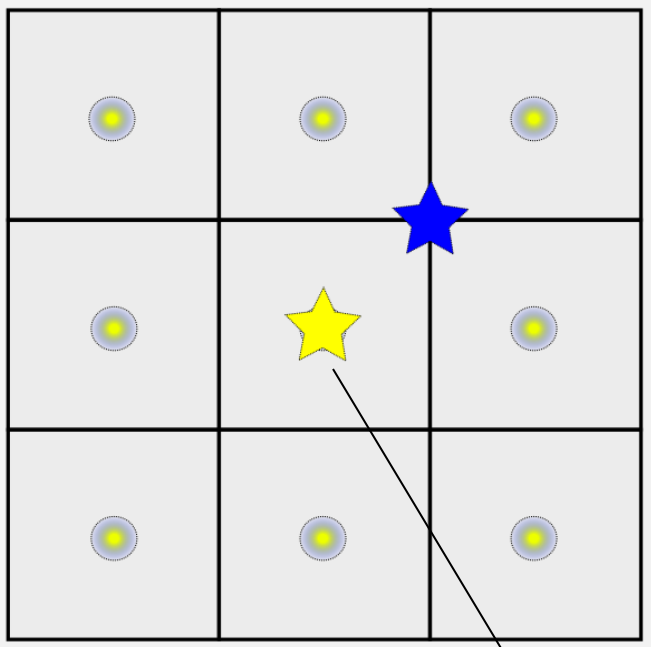
Validation with TCAD

TCAD + APSQ

- To **validate APSQ+TCAD simulations**, same simulation conditions as in transient TCAD are replicated:
  - Charge carriers injected alongside the pixel **corner** **or** **center**
  - Fixed amount of charge carriers: **Linear Energy Transfer (LET) 63 eh/µm**
  - Only the epitaxial layer is simulated: **10 µm**
  - Simulation repeated **<u>10000x</u>** times and the average pulse is calculated

Simulation Time

TCAD ~ days to weeks (Single Pulse)
TCAD + APSQ ~ hours



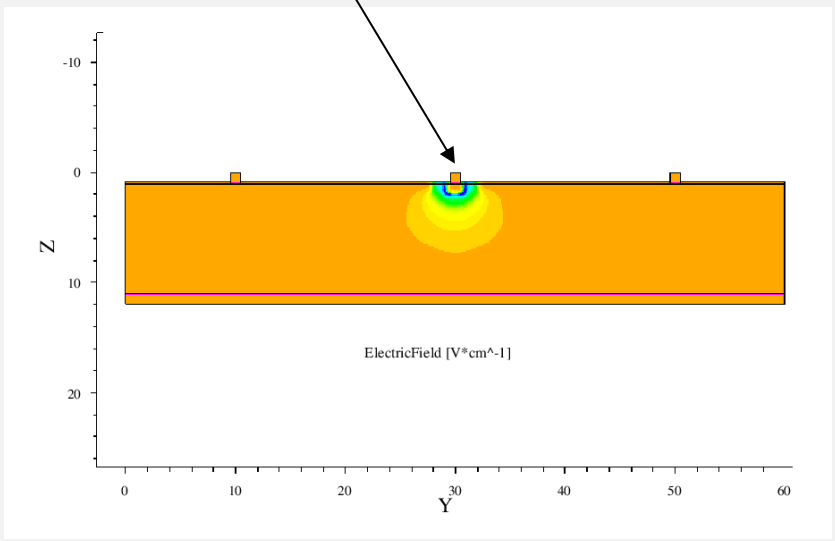
Charge injection at the **corner**

Charge injection at the **center**

Collection Electrode at +1.2 V

P-Well and P-Substrate at -1.4 V

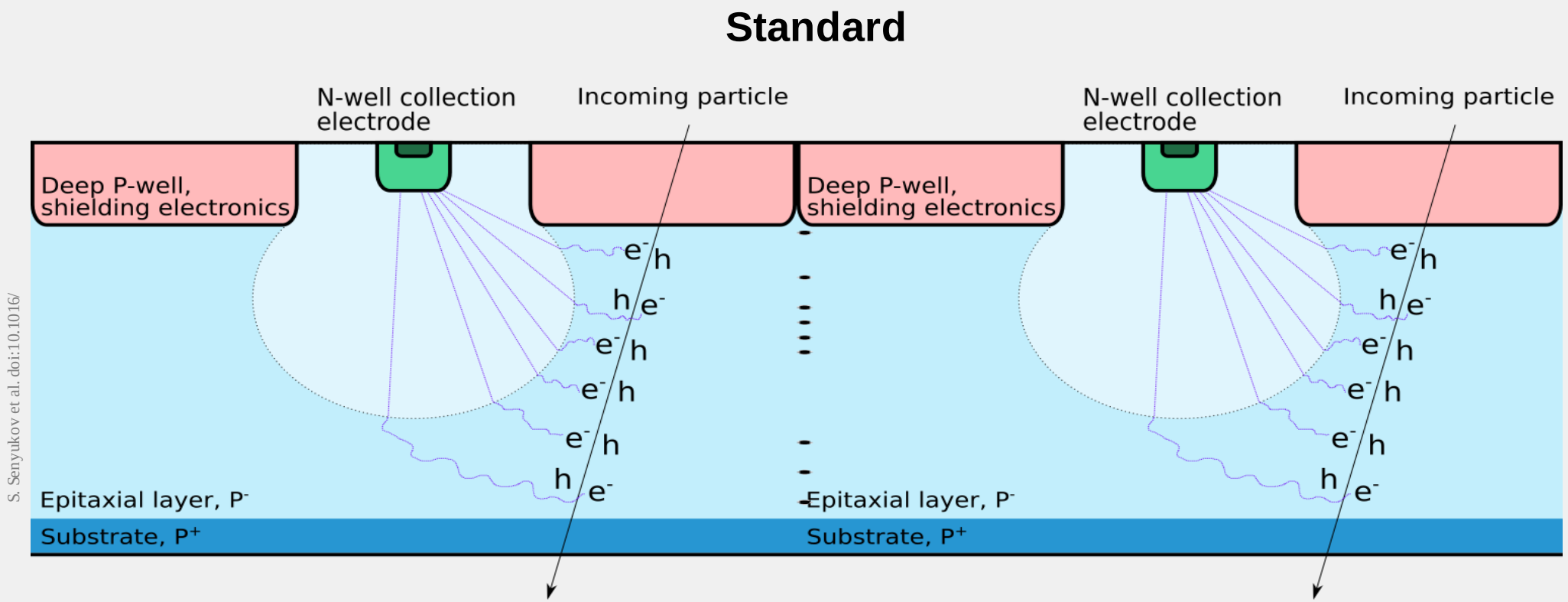
3x3 pixel matrix
20x20 µm² pitch



High weighting potential values are concentrated around collection electrode

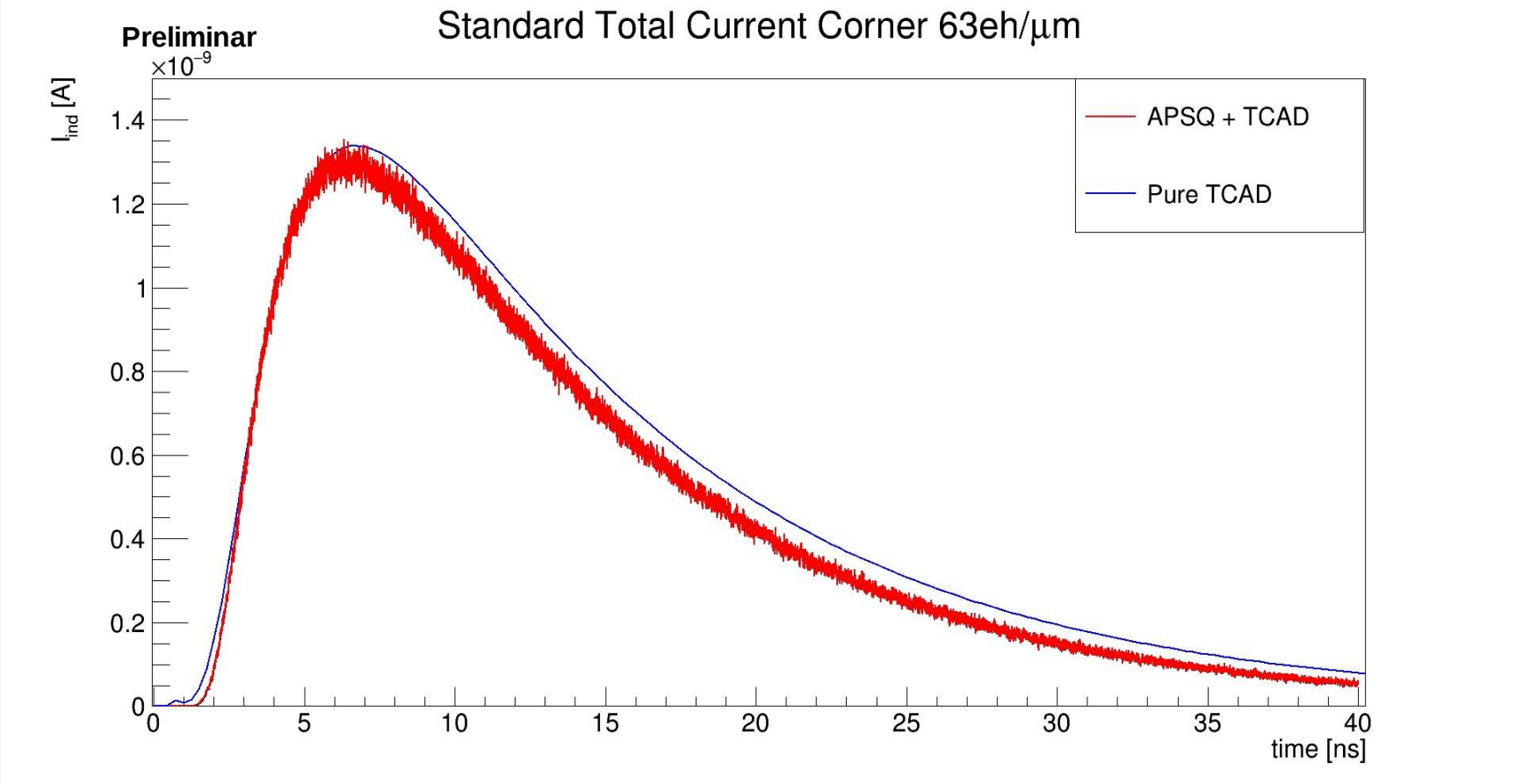
Standard Linear Charge Injection

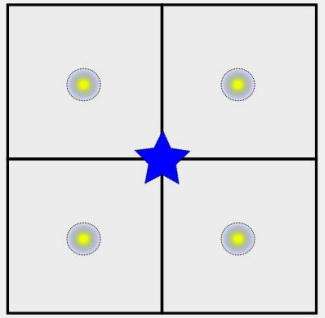
Monolithic Active Pixel Sensors (MAPS)



Validation – Corner Injection – Worst Case Scenario

Average Pulse Comparison

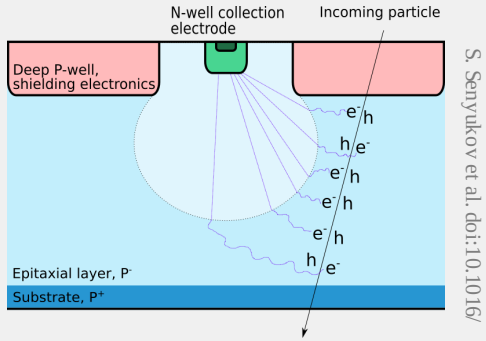




Charge injection at the **corner**

Collection Electrode at +1.2 V

P-Well and P-Substrate at -1.4 V



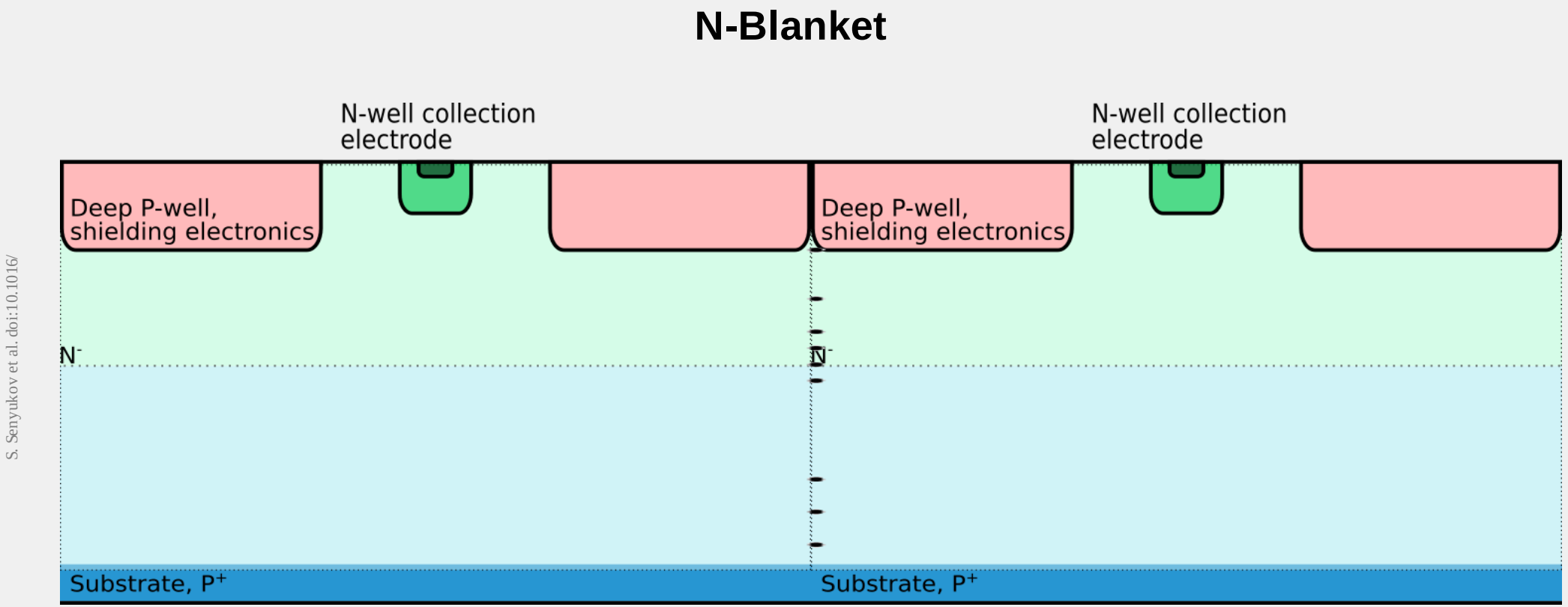
S. Senyukov et al. doi:10.1016/

Standard
Pulse duration ~ 40ns

Pure TCAD - 1 pulse
APSQ + TCAD – Average 10000 pulses

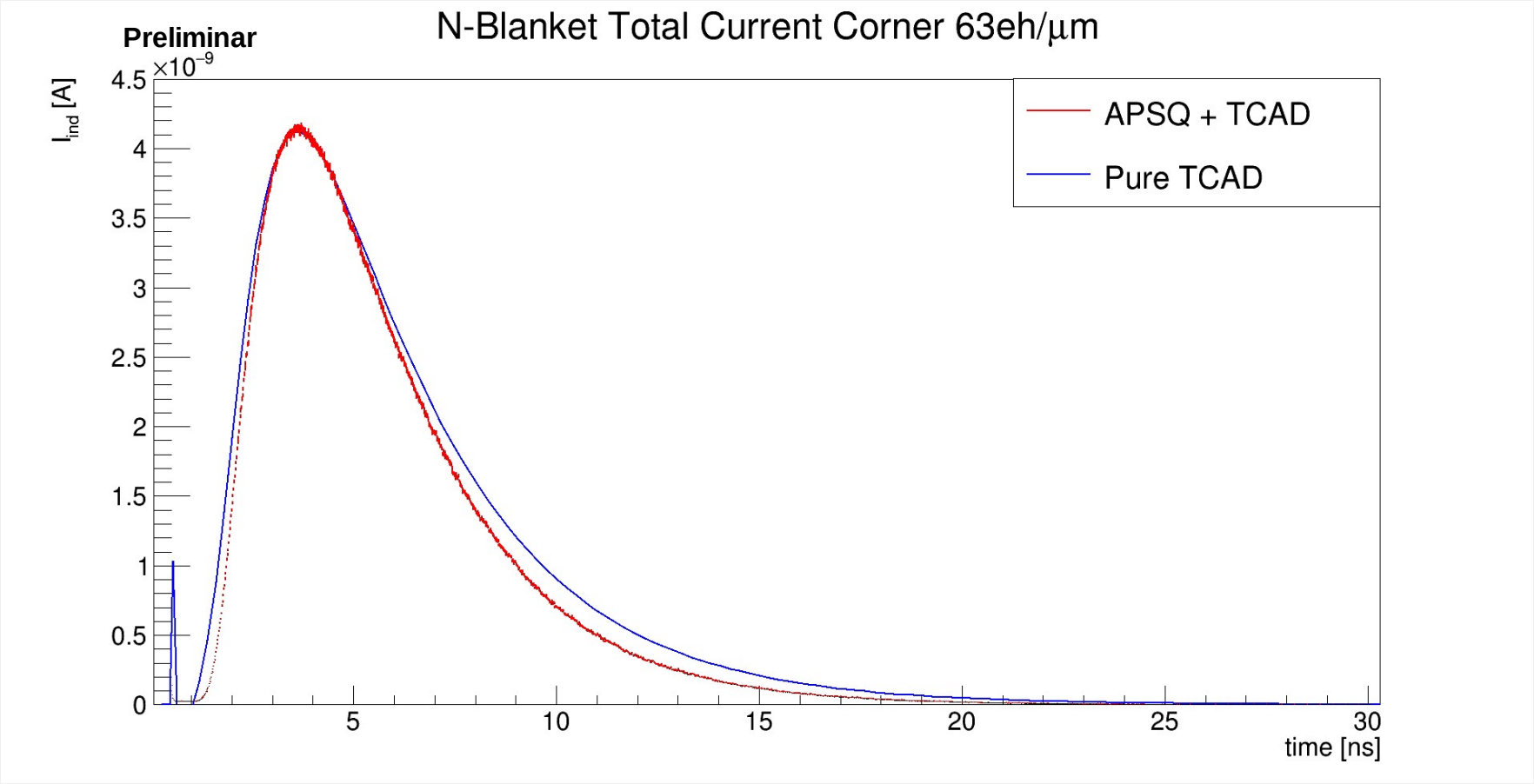
N-Blanket Linear Charge Injection

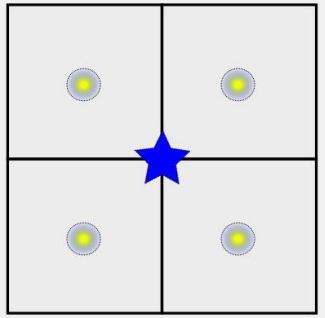
Monolithic Active Pixel Sensors (MAPS)



Validation – Corner Injection – Worst Case Scenario

Average Pulse Comparison

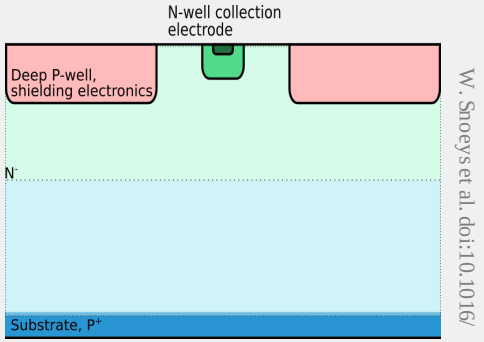




Charge injection at the **corner**

Collection Electrode at +1.2 V

P-Well and P-Substrate at -1.4 V

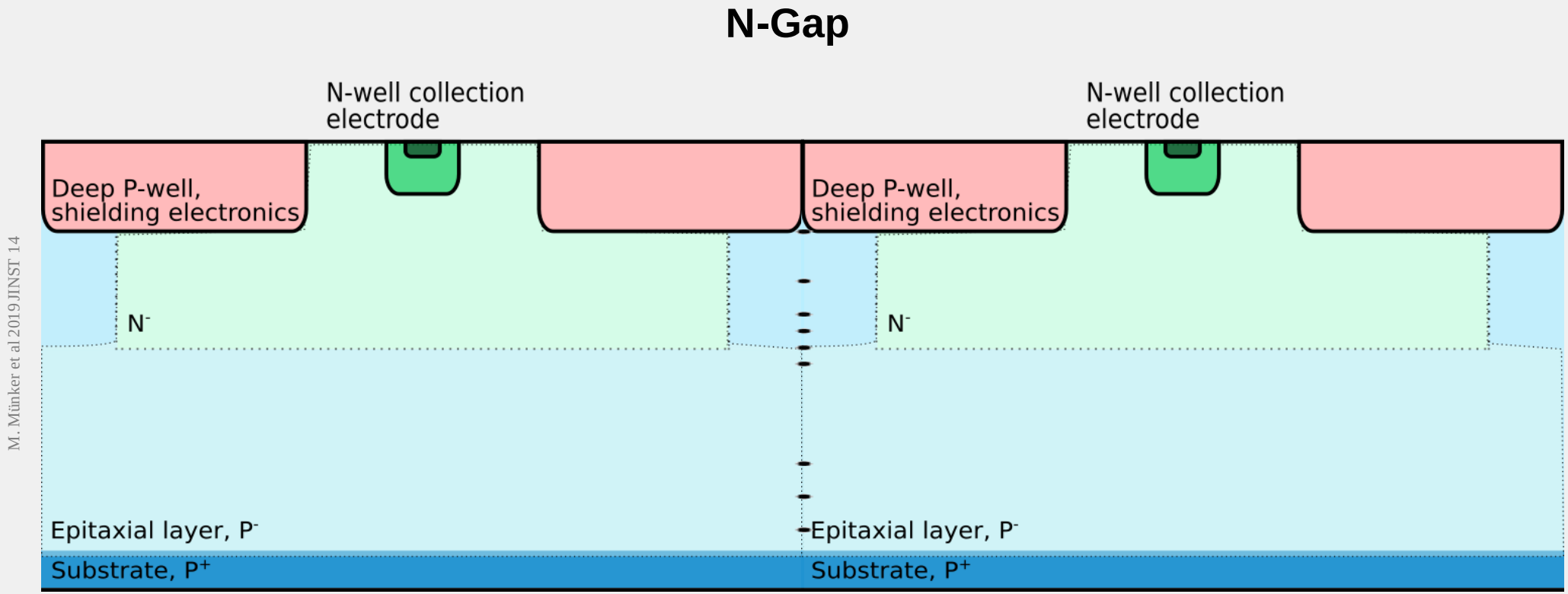


N-Blanket
Pulse duration ~ 25ns

Pure TCAD - 1 pulse
APSQ + TCAD – Average 10000 pulses

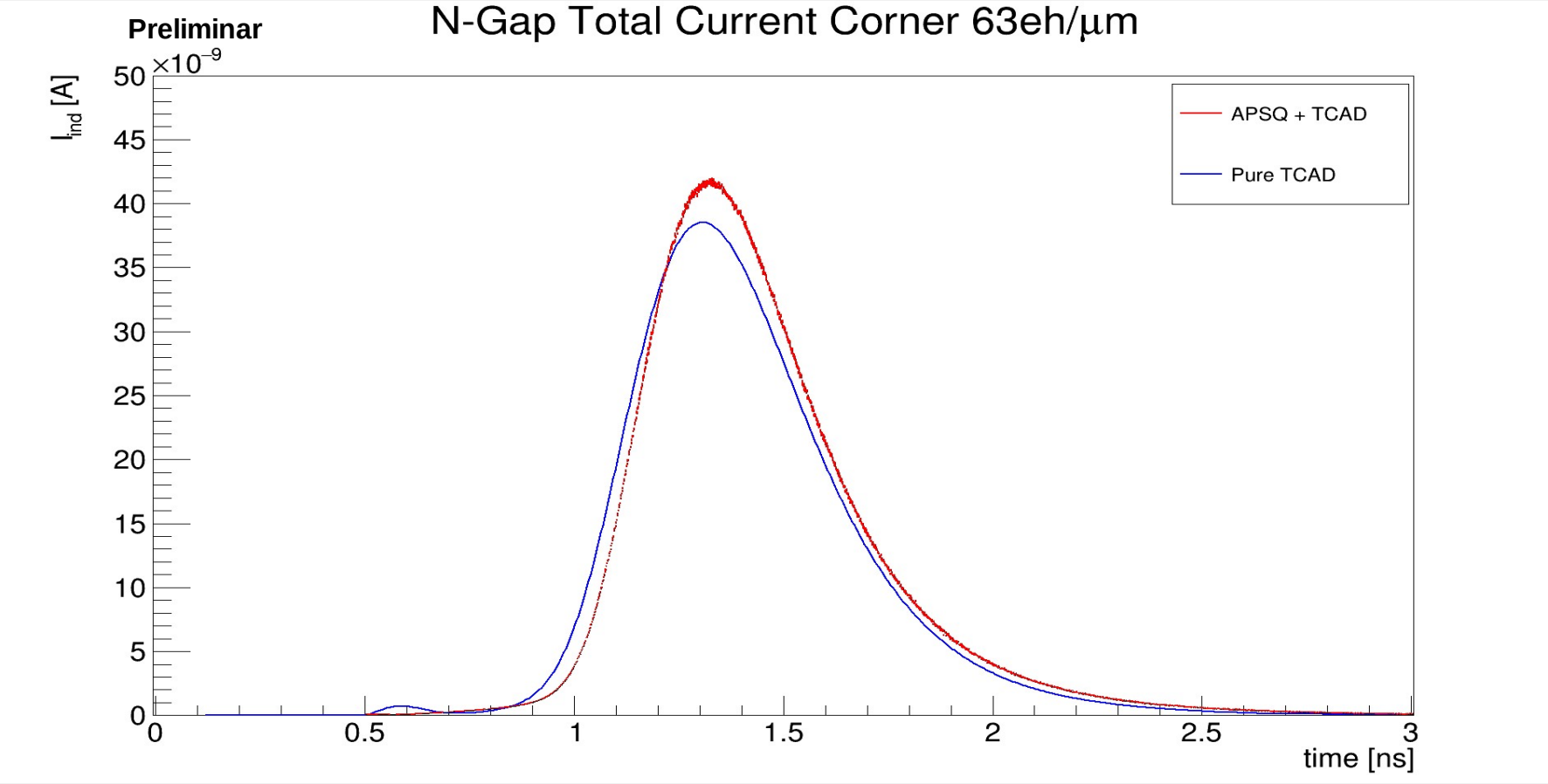
N-Gap Linear Charge Injection

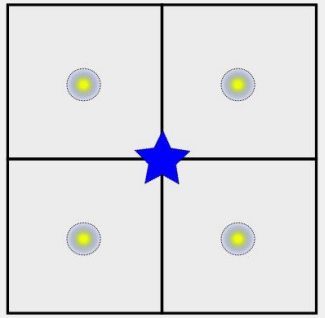
Monolithic Active Pixel Sensors (MAPS)



Validation – Corner Injection – Worst Case Scenario

Average Pulse Comparison

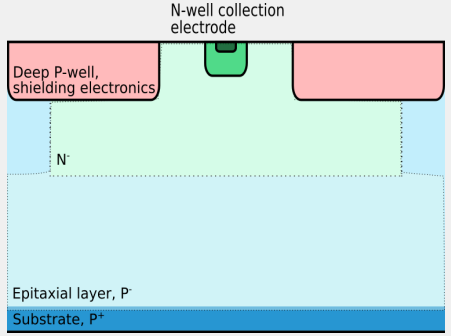




Charge injection at the **corner**

Collection Electrode at +1.2 V

P-Well and P-Substrate at -1.4 V



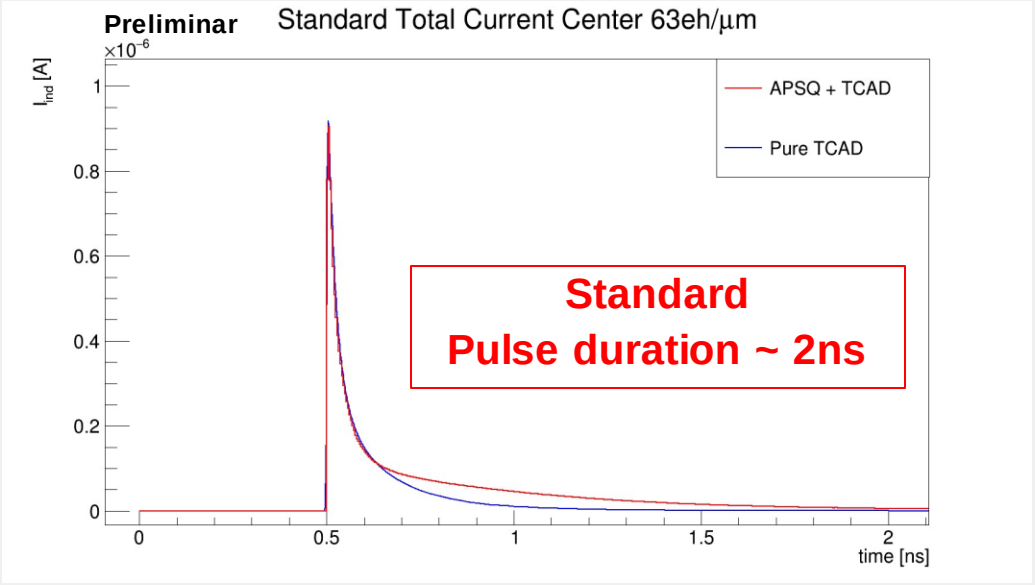
M. Münker et al 2019 JINST 14

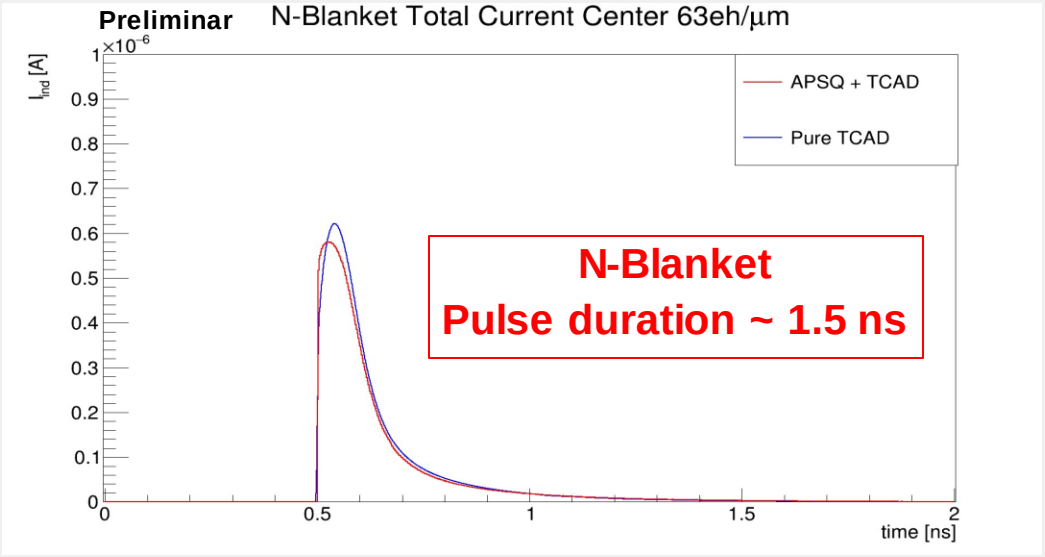
N-Gap
Pulse duration ~ 3 ns

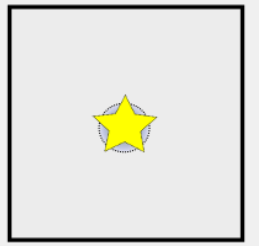
Pure TCAD - 1 pulse
APSQ + TCAD – Average 10000 pulses

Validation – Center Injection – Best Case Scenario

Average Pulse Comparison



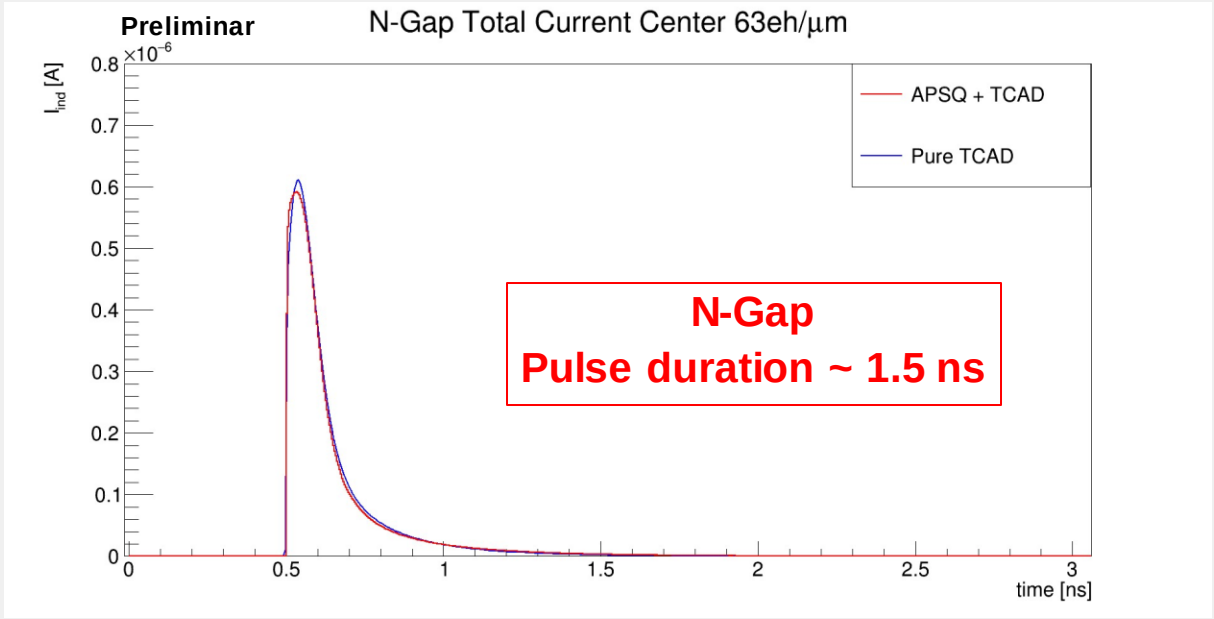




Charge injection at the **center**

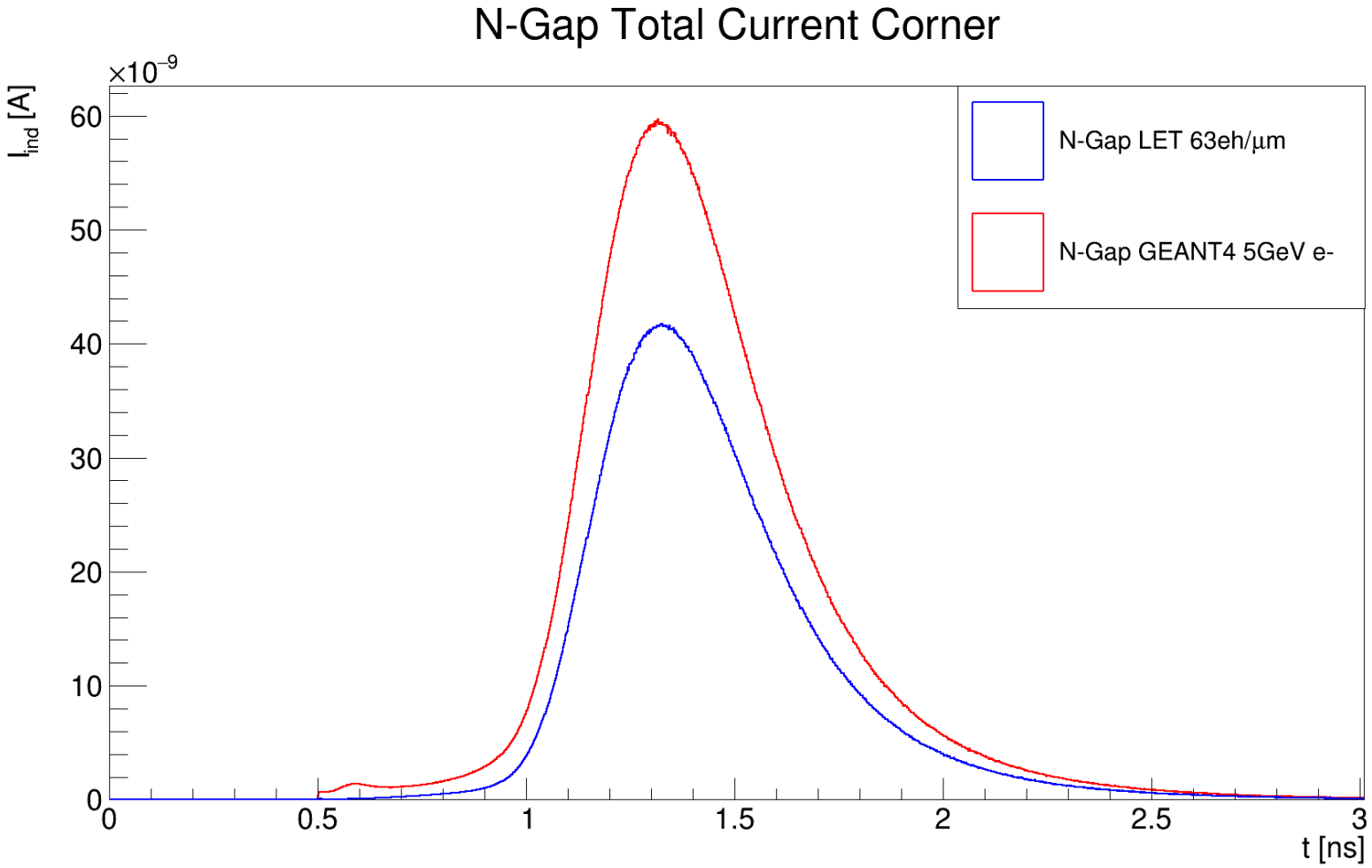
Collection Electrode at +1.2 V

P-Well and P-Substrate at -1.4 V



Pure TCAD - 1 pulse
APSQ + TCAD – Average 10000 pulses

Comparison GEANT4 – Corner Injection – Worst Case Scenario



We can proceed by shooting MIP particles and thus take into account **Landau fluctuations, secondary production, Photoabsorbtion Ionization...**

➞ **Sensor and Layout Scan**

➞ **Timing Performance**

Summary and Next Steps

What can we take away from these simulations?

- APSQ + TCAD pulses are getting **closer to a pure TCAD pulse**.
- Differences between layouts (**Pulse duration, Rise Time, Peak**)
- Eventually, only TCAD+MC simulations required (which can save resources and time)

What to do next and improve?

APSQ + TCAD (Landau fluctuations)

- Full sensor scans
- Different Pixel sizes
- Digitization
- Pulse Studies (TOA)

Lab Testing and Test Beam

- Waveform Analysis
- Different Pixel sizes and Layouts
- Pulse Studies (TOA)

Thank you for your time!

Contact

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