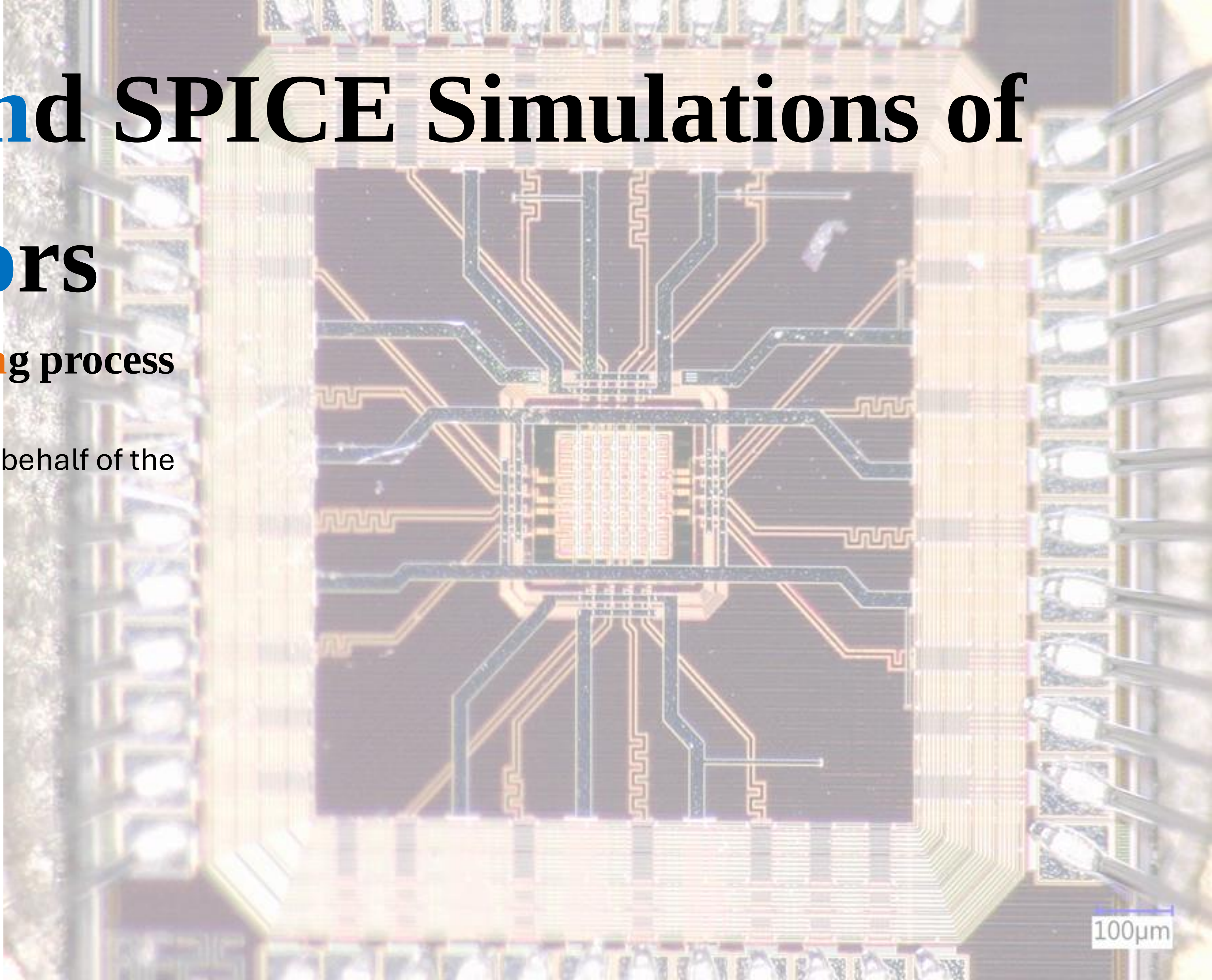
Transient and SPICE Simulations of silicon sensors

in the 65nm CMOS imaging process

Manuel Alejandro Del Rio Viera on behalf of the TANGERINE Group at DESY

5th Allpix Squared User Workshop

Oxford, May 2024



HELMHOLTZ

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

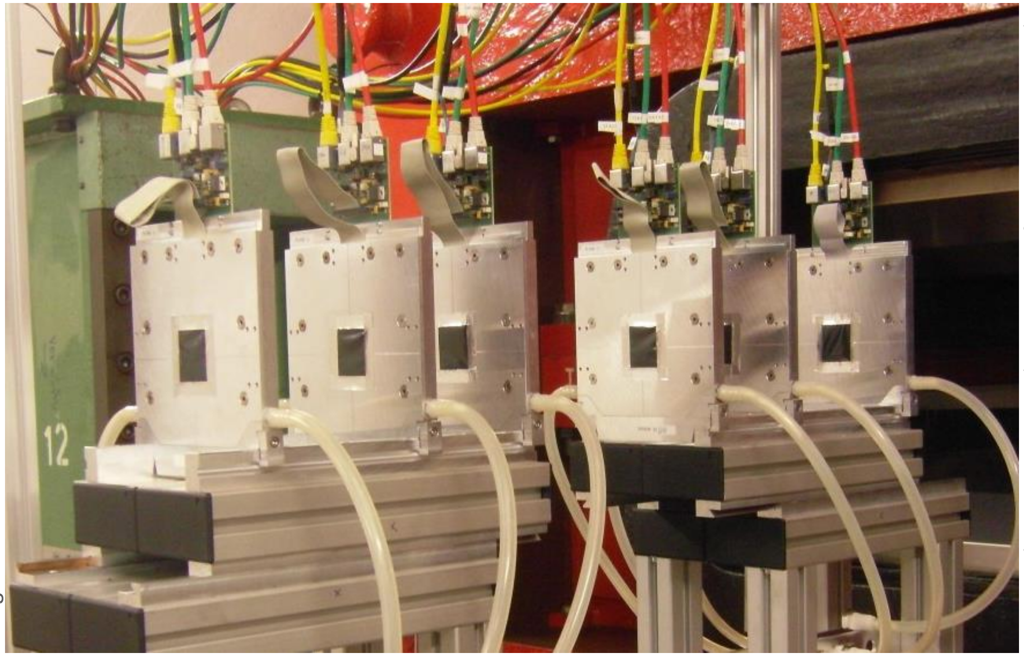
We investigate the potential for the following applications:

- **Trackers for future e^+e^- Colliders**
- **Reference detector at DESY-II test beam upgrade**

Requirements

- Spatial Resolution ~ 3 µm
- Time Resolution ~ ns
- Low material budget ~ 50 µm silicon (compared to hybrid sensors)

Image:DESY



https://newsline.linearcollider.org/2011/08/18/the-impact-of-ilc-detector-rd/desy-beam-telescope/

MIMOSA Telescope at the DESY II Facility

Motivation of these studies

To understand the process better and improve on

- Study the time resolution we might achieve with this process

1. Understand how this is affected by the sensor and the electronics
2. Understand where the limitations come from (sensor, electronics)

- For the sensor, in particular study how the particle incident position affects amplitude, timing, charge collection time…

→ **Simulation studies help to start to answer these questions**

Tools that we use in our simulations

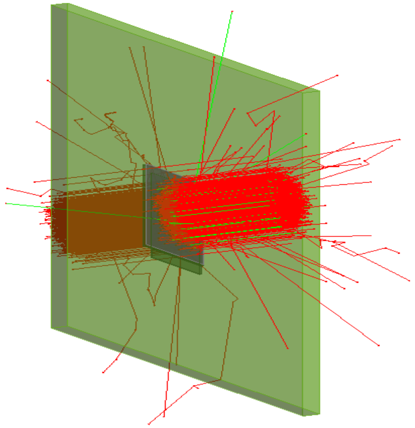
Technology **C**omputer-**A**ided **D**eisgn

SYNOPSYS®
Silicon to Software™

+

Allpix Squared: a Monte Carlo simulation framework for semiconductor detectors

- High statistics Monte Carlo simulations of semiconductor detectors
- Full detector simulation chain, from energy deposition and charge carrier propagation to signal digitization
- Integration with GEANT4 and TCAD.
- Development carried out at DESY
- Detailed documentation and continuous support

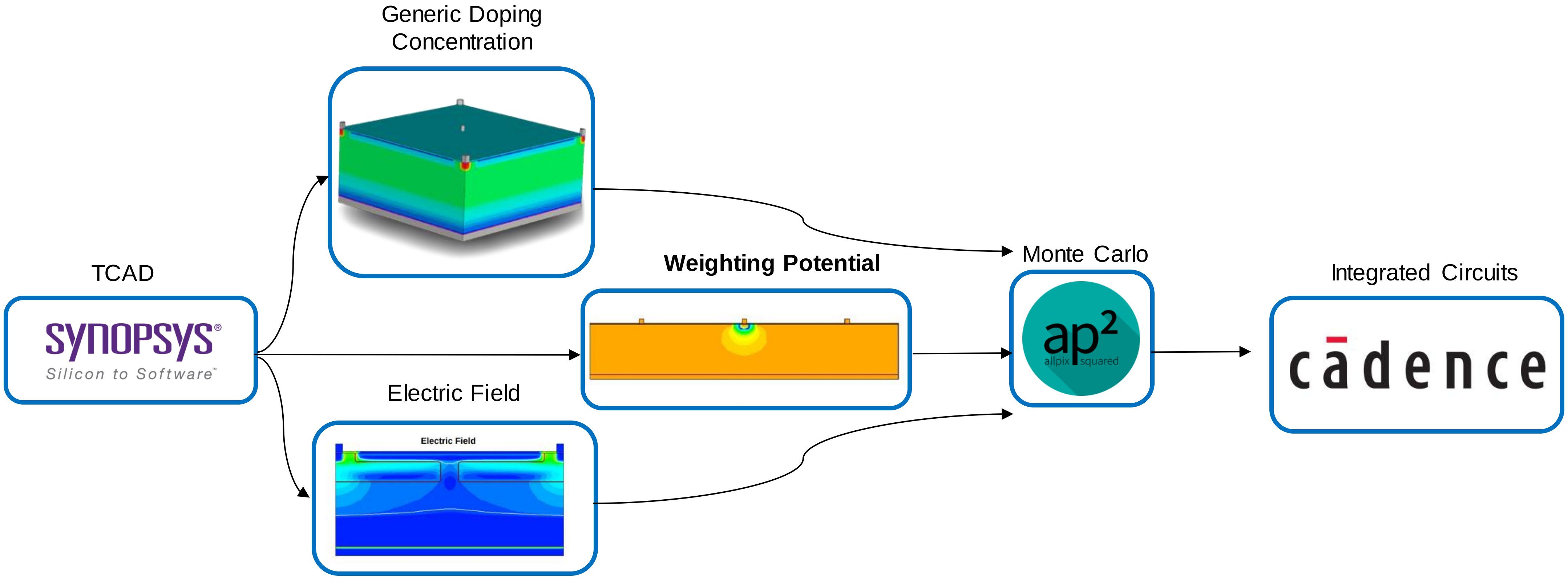


Particle beam passing through a single sensor in Allpix^2

Transient Simulations

Simulation Workflow

- Transient simulations allow us to study the **time evolution** of the response of a sensor, i.e. the **signal** evolution which is exactly what we want to achieve for our sensors.
- Electric field and generic doping profiles are imported into the Allpix Squared framework. This allows to produce **high statistics** simulations saving time compared to transient simulations in TCAD.
- In order to simulate the electronics, the **output signal** from Allpix Squared is imported into CADENCE

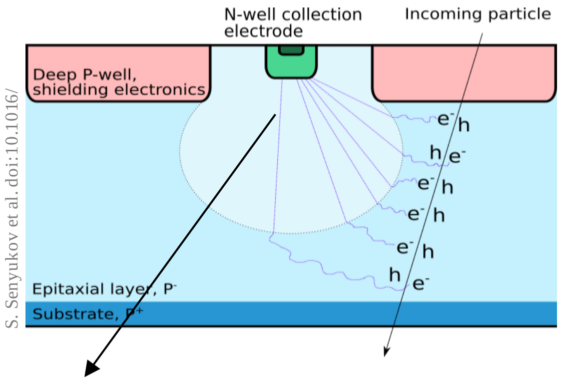


Electric field in thin silicon sensors

Designs

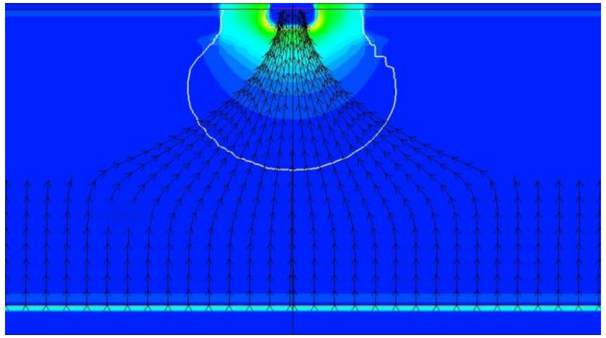
Standard

Layout geometry

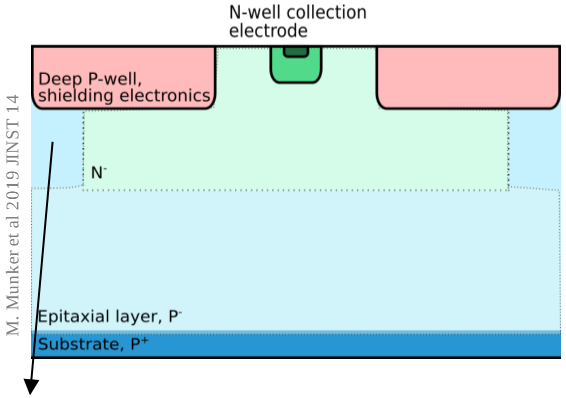


Drift predominates inside depleted region and **diffusion** outside

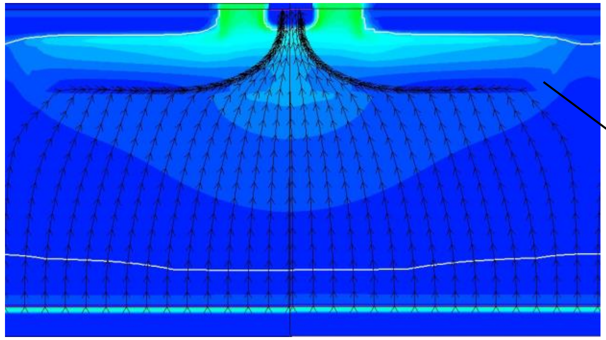
Electric Field lines



N-Gap



Gap in Continuous N-type Implant
Speed up charge collection

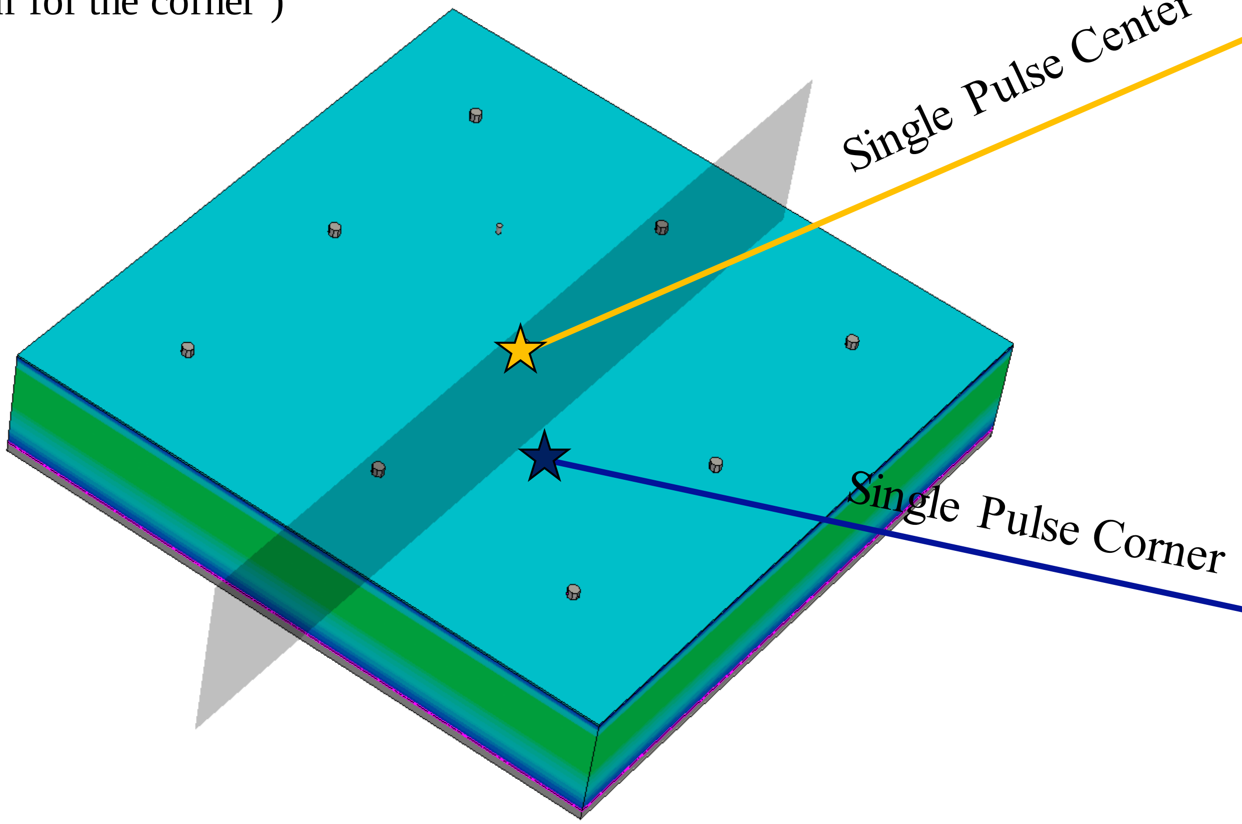


The electrons follow the direction of the **stream lines**

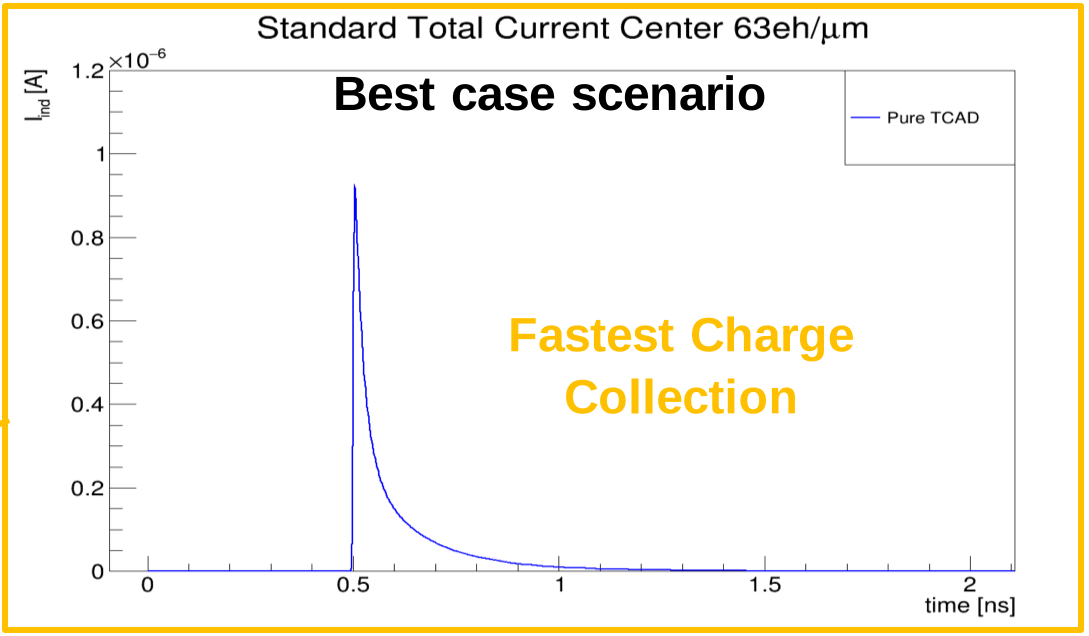
TCAD + Allpix^2 Simulations

Two extreme cases under study – Standard Layout

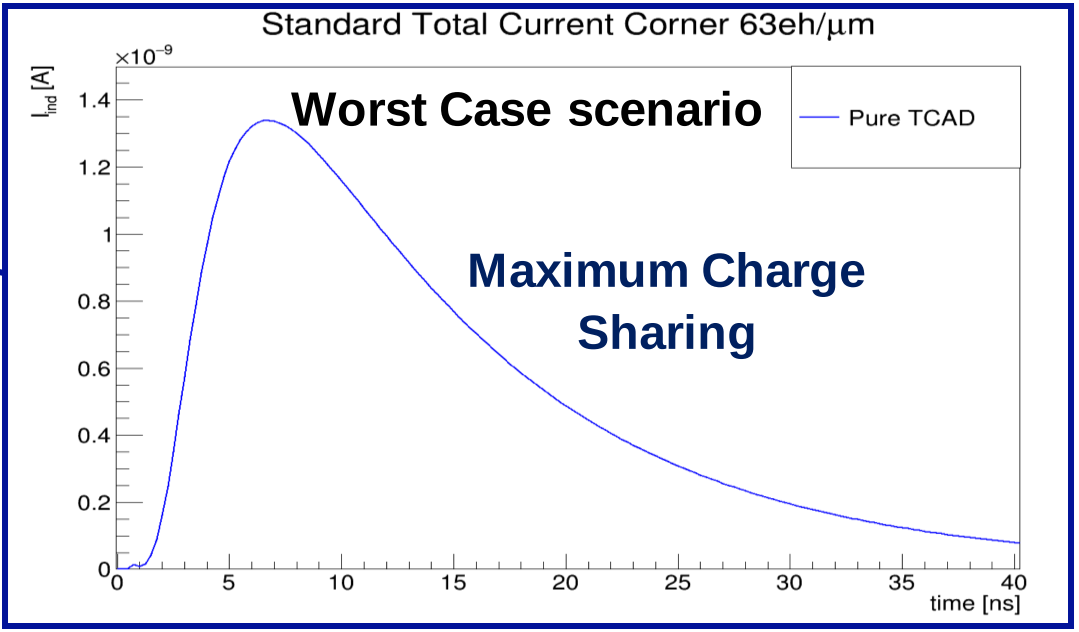
- Charge carriers injected alongside the pixel **corner** or **center**
- Fixed amount of charge carriers **63 eh/µm**
- Average of pixels over threshold calculated (One for center and four for the corner)



3x3-cell model in TCAD



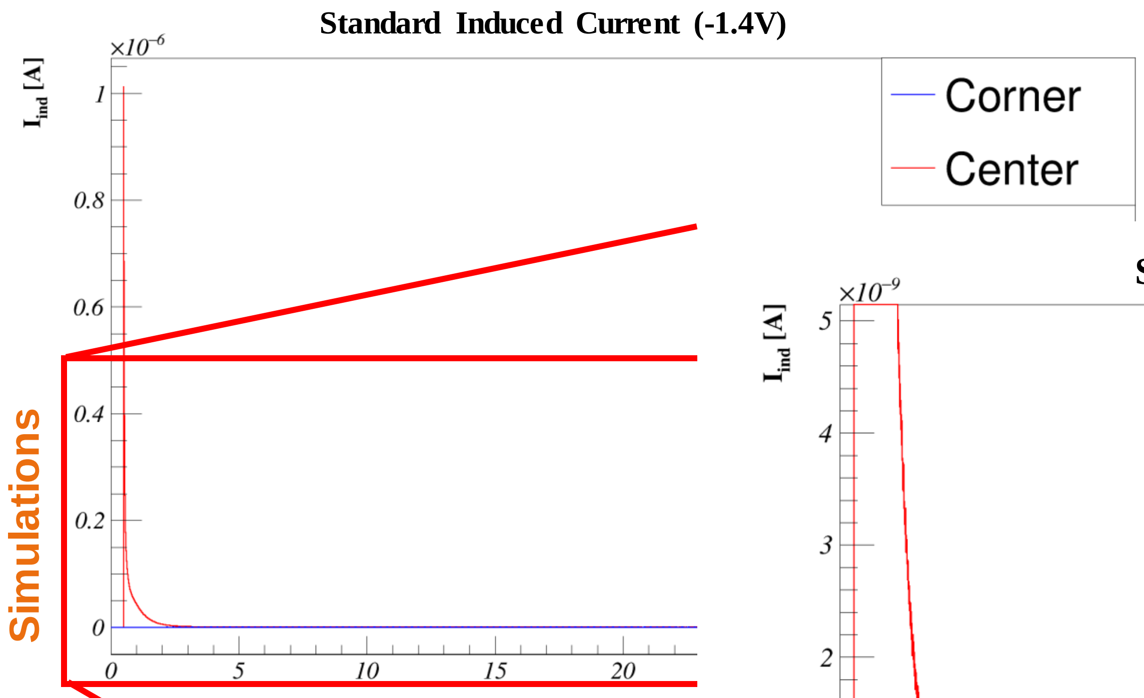
Not same time scale!

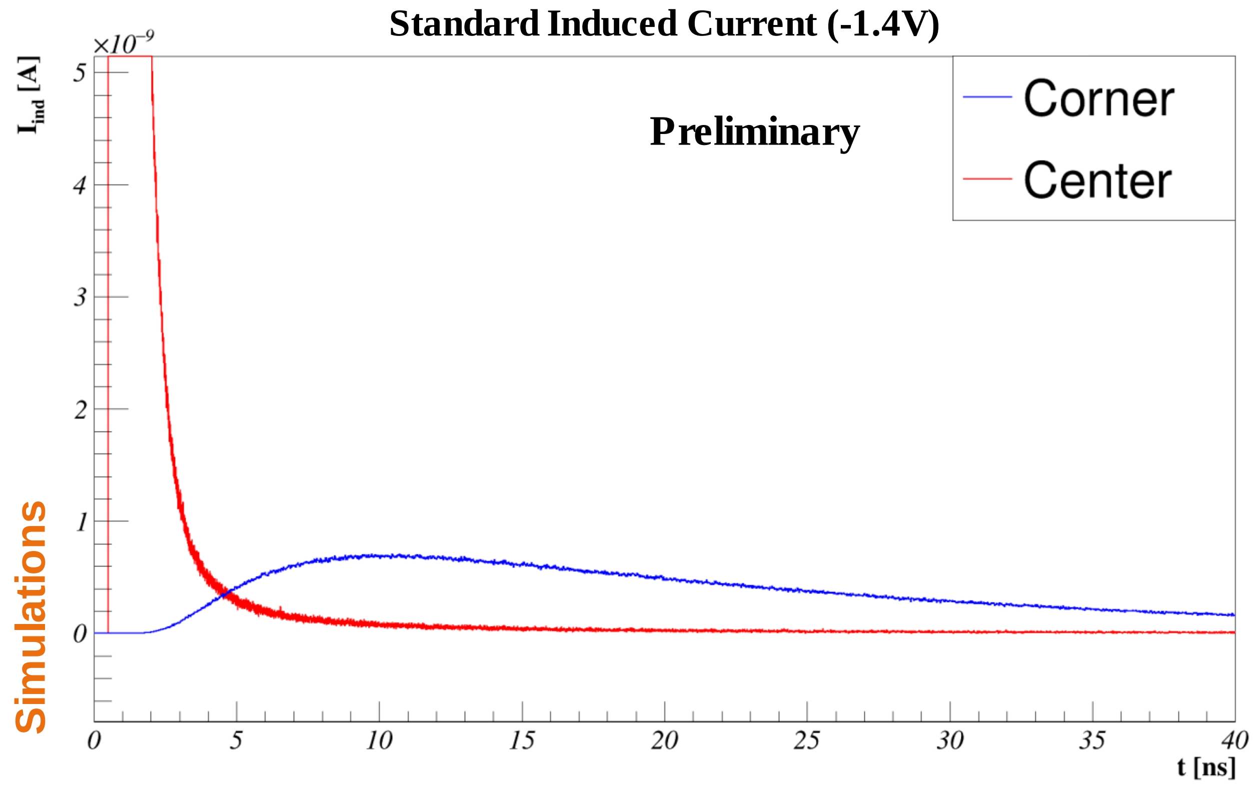


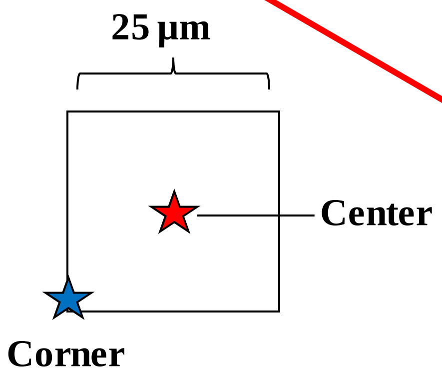
Detector response simulation

Standard Layout → No electronics included

- **Pulse duration** depends heavily on particle incident position
- Charge collection time ~ **5 ns** for center incidence and > **40 ns** for corner incidence
- Peak ratio of three orders of magnitude



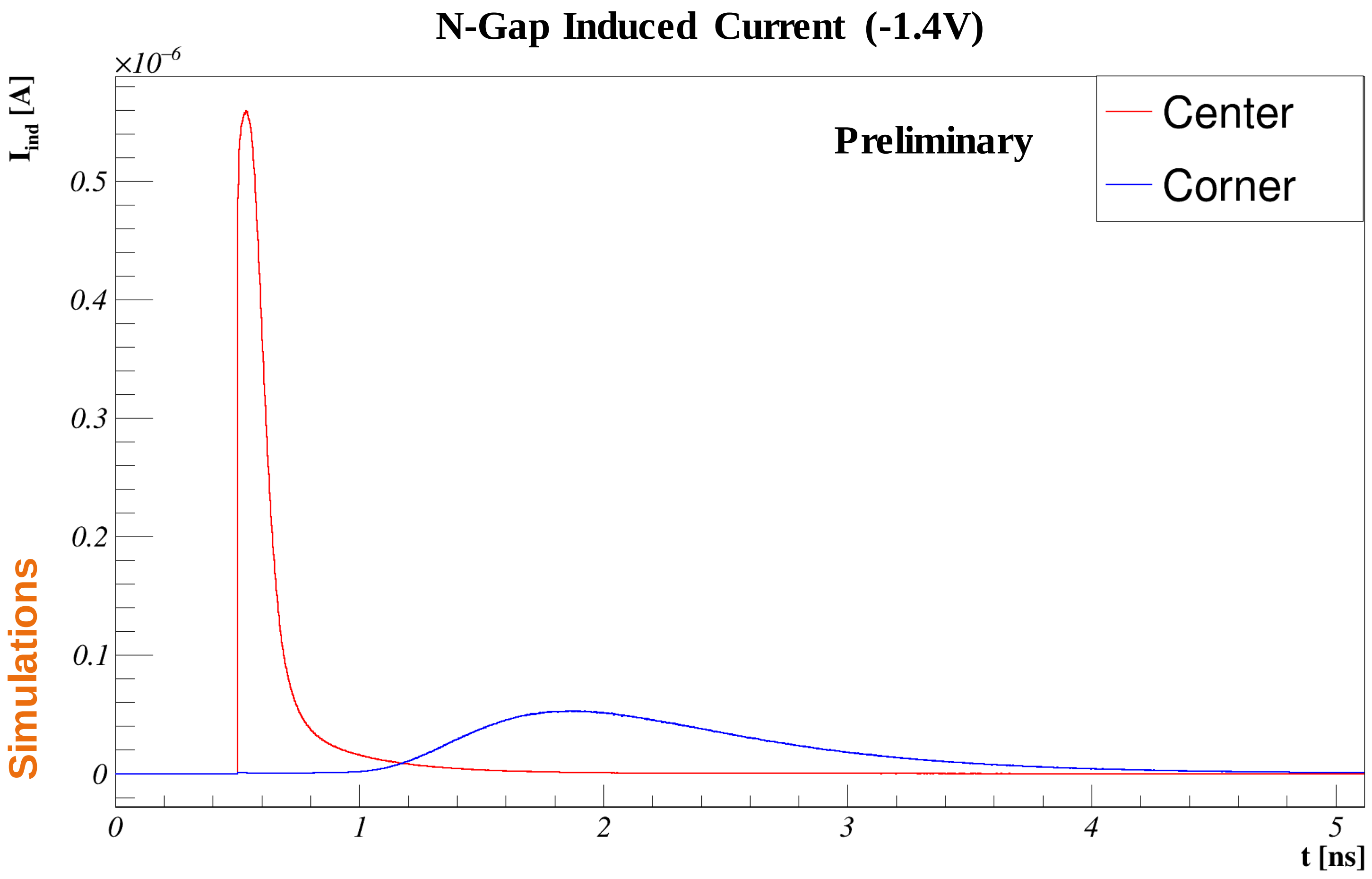




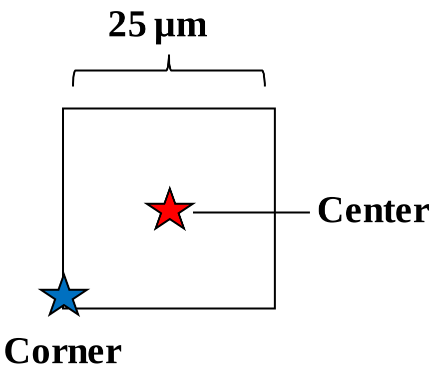
*Charge collection time defined as time when signal reaches a value of 10^{-13} A

Detector response simulation

N-Gap Layout → No electronics included



- **Pulse duration** difference not as marked
- Charge collection time < **5 ns** independent of incidence position
- Same order of magnitude peak of the signals

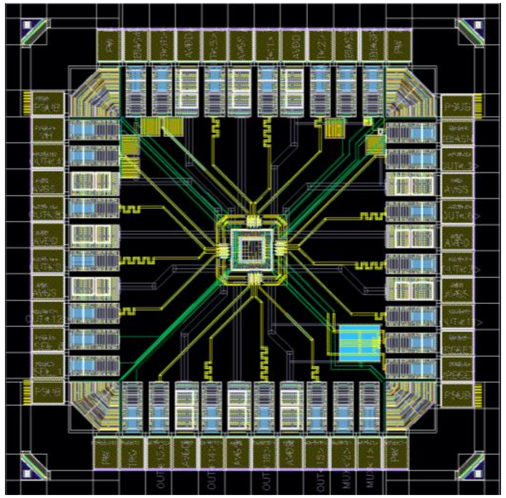


Detector response understood →

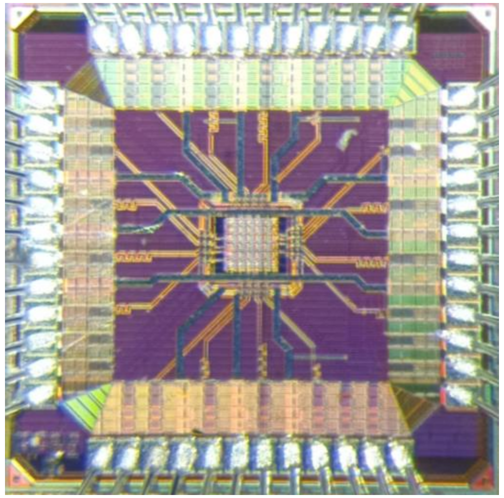
Next step: Study the electronic response (**technology dependent**)

Sensors in MLR1 production

Analogue Pixel Test Structures (APTS)



ASIC Design



Prototype

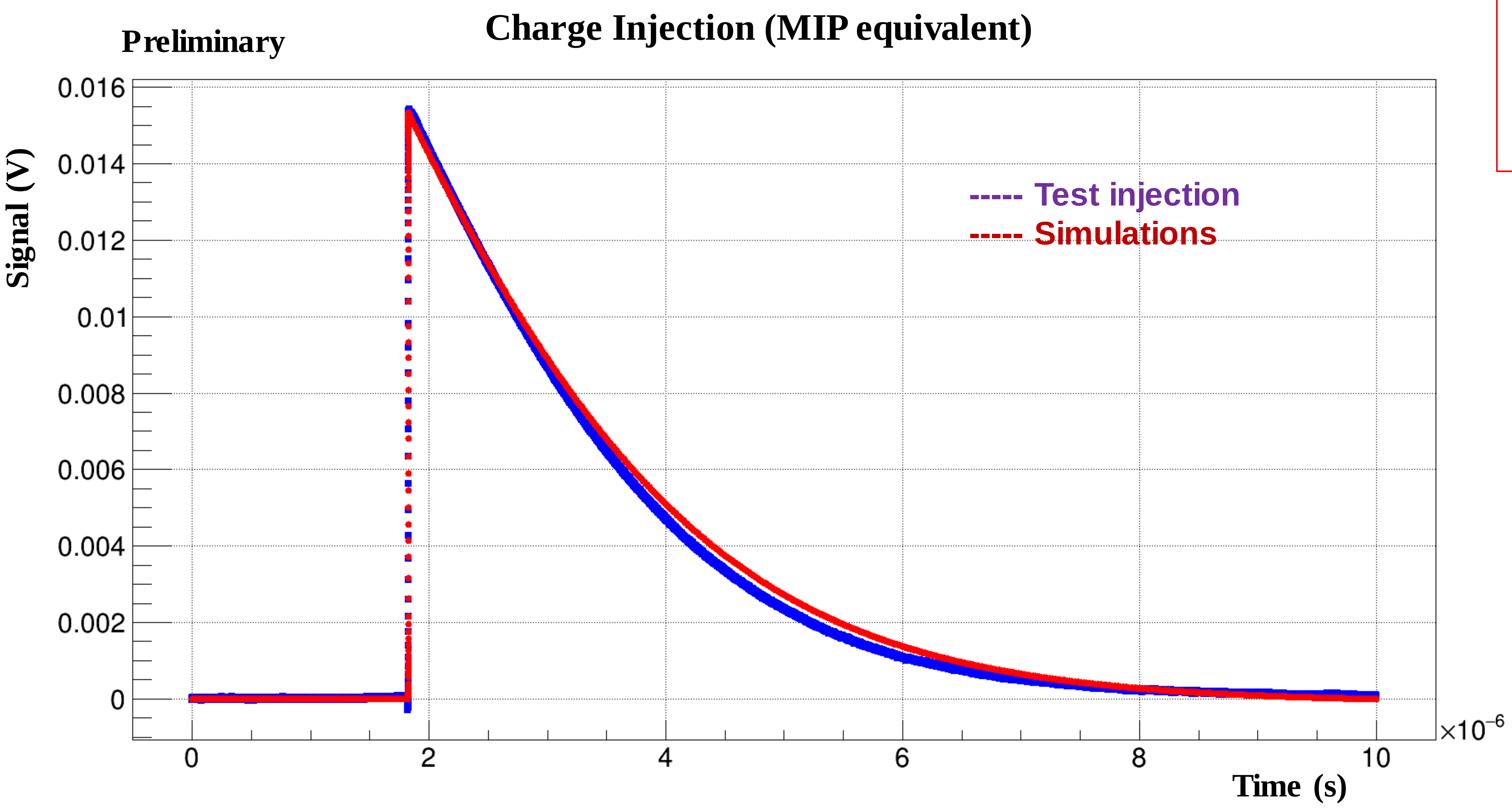
- Designed at **CERN** (**DESY** involved in the lab and TB characterization)
- 4x4 pixels structure with analogue output
- **Charge injection capacitor for testing purposes**
- Different sensor pitches from 10 µm to **25 µm**
- Different sensor layouts: **Standard**, Modified and **N-Gap**
- Two versions of the output buffer
  - The focus of this talk will be on the **Source Follower** version.

Objective:

- Study the sensor layout physics
- Obtain data samples during test beam and lab measurements
- Calibration studies so simulations can be compared with data

Comparison with SPICE simulation

Laboratory Measurements + Simulations



Average pulse obtained through charge injection.

Chip settings

IBIASN 400 uA
IBIASP 40 uA
IBIAS3 500 uA
IBIAS4 6 mA
IRESET 1 uA
VRESET 0.48 V
PWell/PSub -1.2 V

Used in the simulations as well

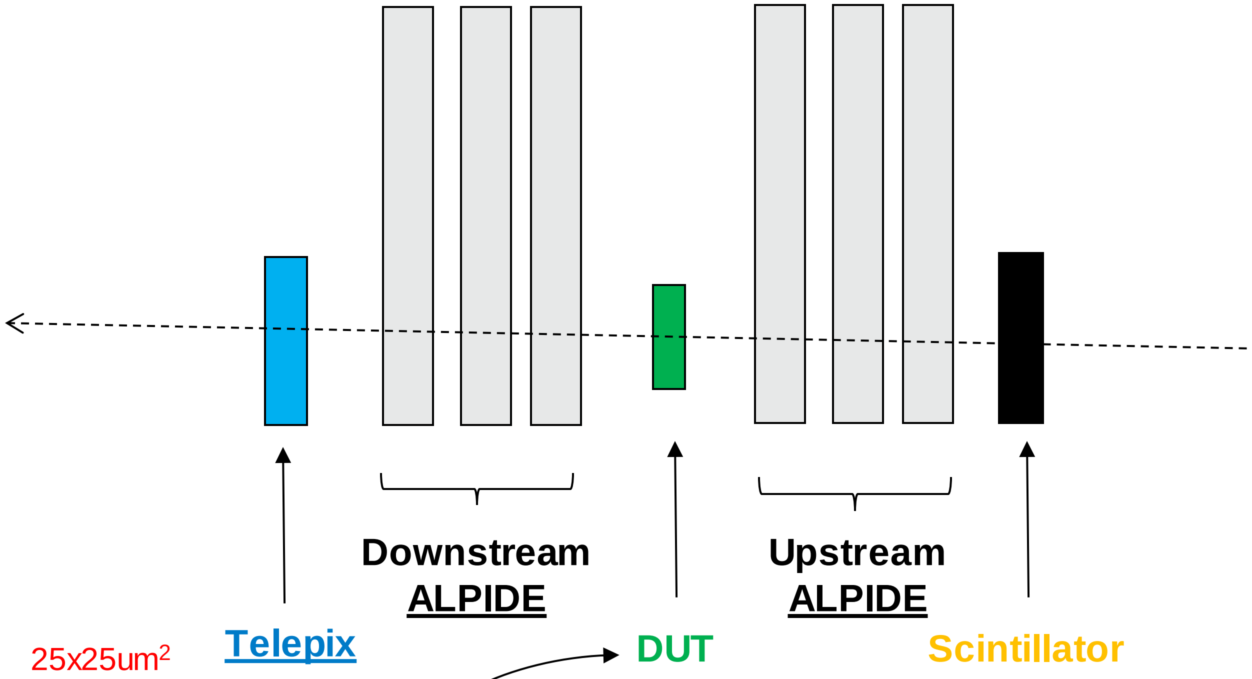
25x25um^2
Standard

Test Beam Setup (June & December 2023)

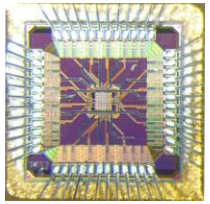
DESY II Test Beam Facility

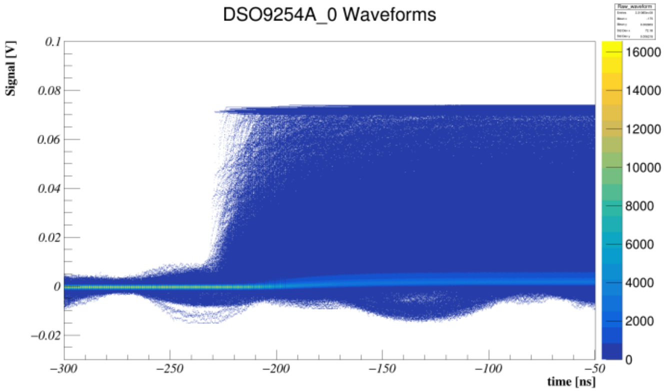
- Telepix and scintillator used in coincidence as trigger, and the former as **time reference**
- Telepix **masked** used to reduce trigger area
- NIM logic used along with TLU to introduce a BUSY signal while the oscilloscope records data

Motivation: Obtain waveforms associated with a track and a rise time

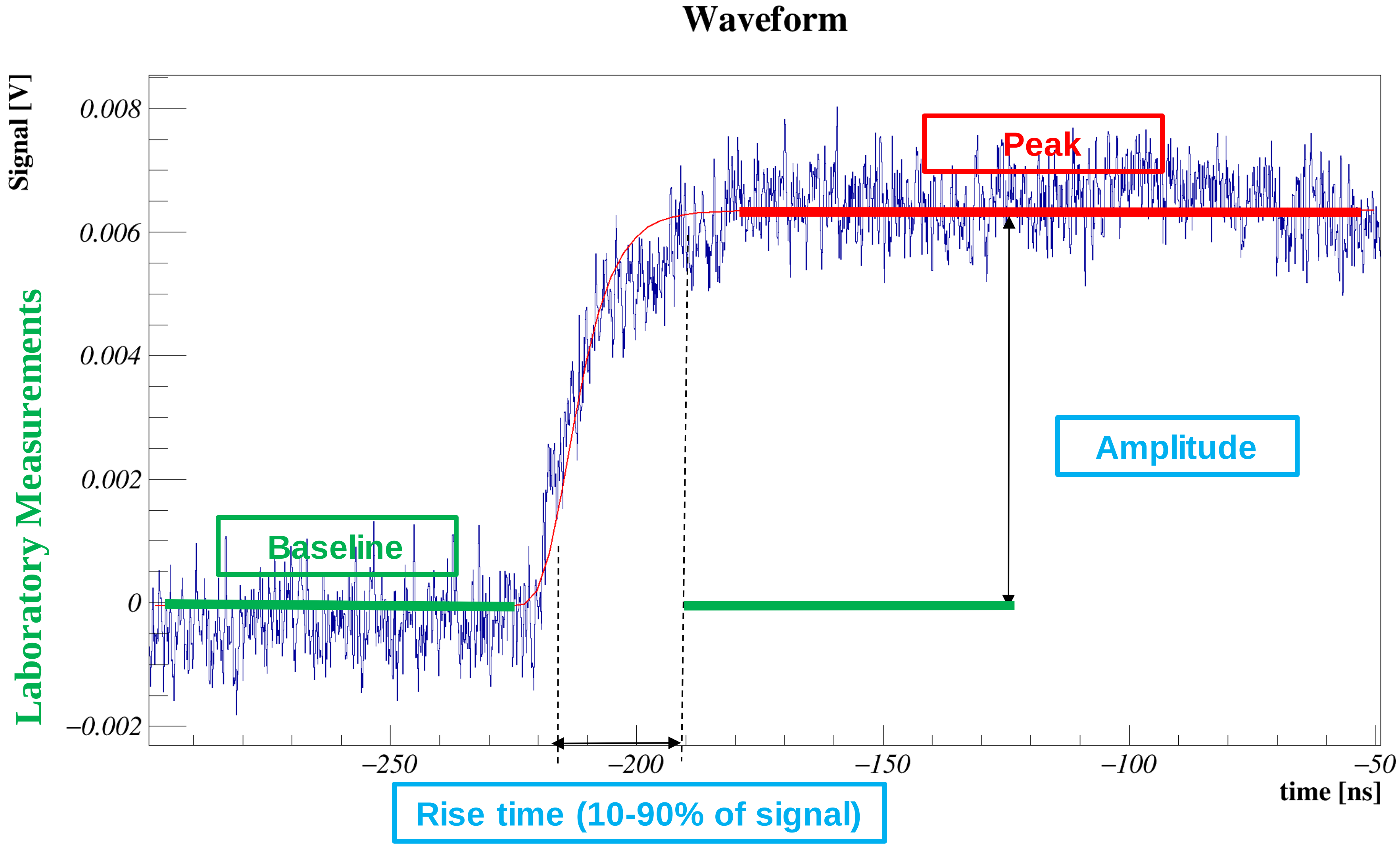


25x25um^2
Standard and N-Gap





Waveform Simplified Analysis (Without amplification)



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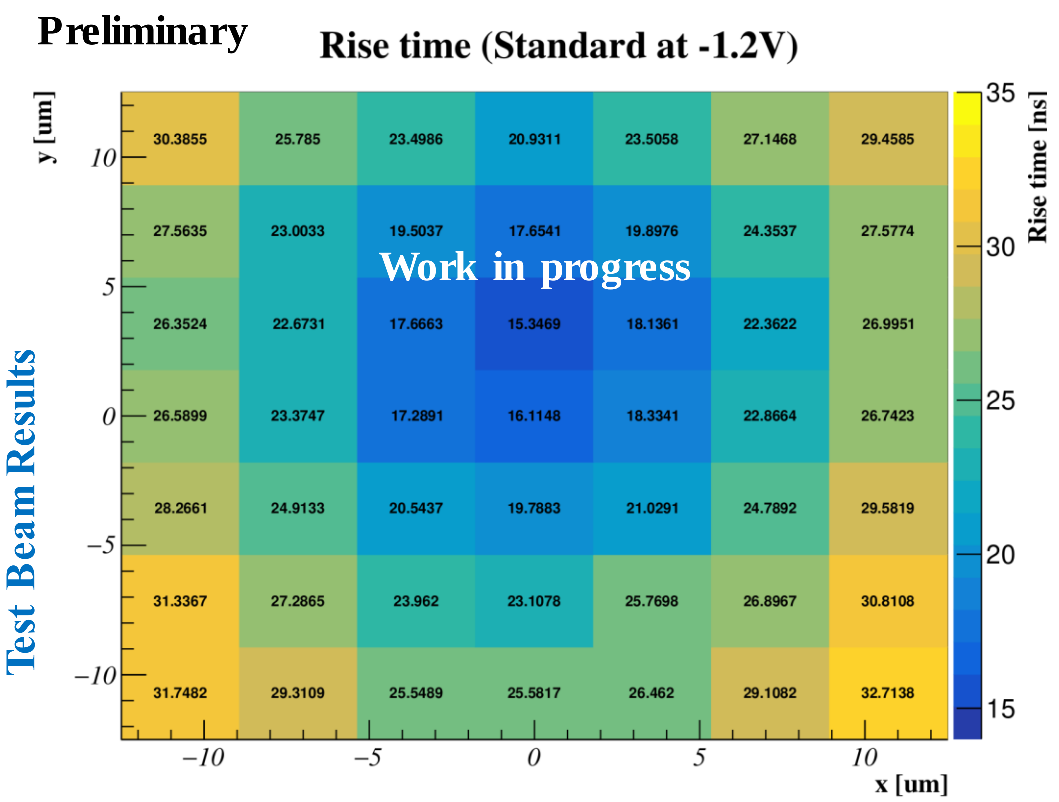
IRESET 1 uA
VRESET 0.48 V
PWell/PSub -1.2 V

$25x25um^2$
Standard

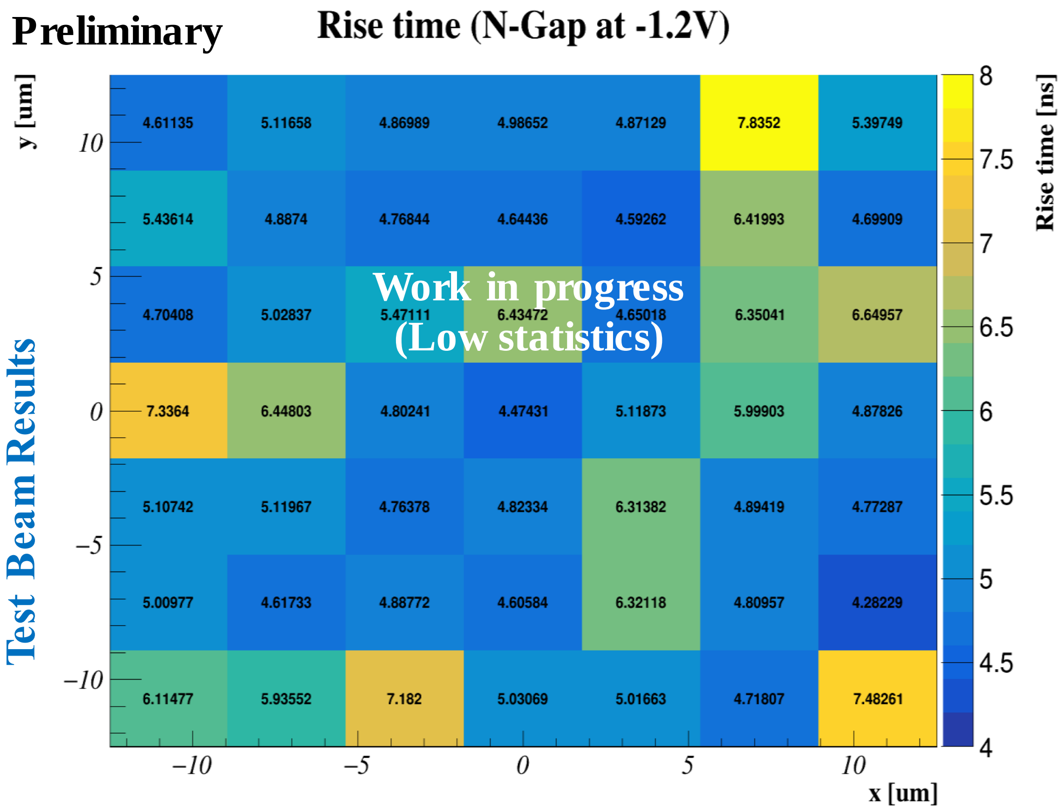
The rise time* is an intrinsic quantity of the electronics response due to the signal induced in the detector. This can be directly compared to simulations

*Dominated by the electronics, but consist in a convolution of the electronics response and transient from the detector.

In pixel rise time distribution (Qualitative trend values)



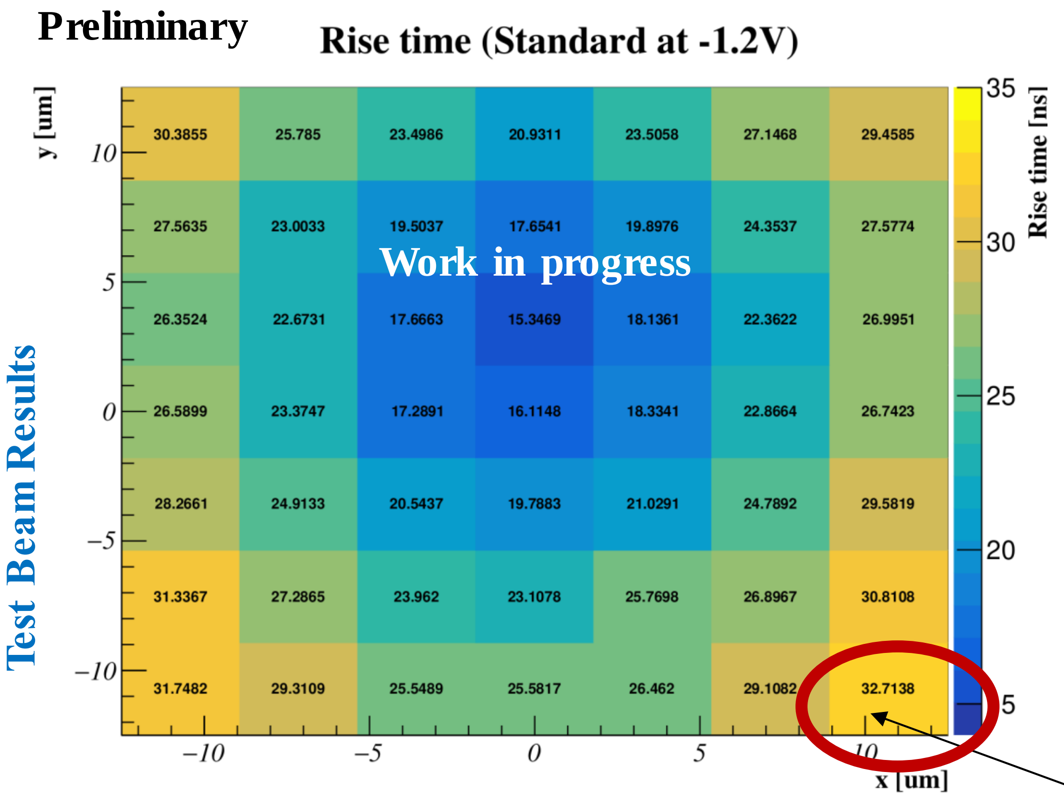
- Clear dependence of particle incident position and rise time



- Uniform rise time distribution regardless of incident position

Note that the spatial resolution for ADENIUM telescope for 4 GeV ~ 3-4 μm

In pixel rise time distribution (Qualitative trend values)



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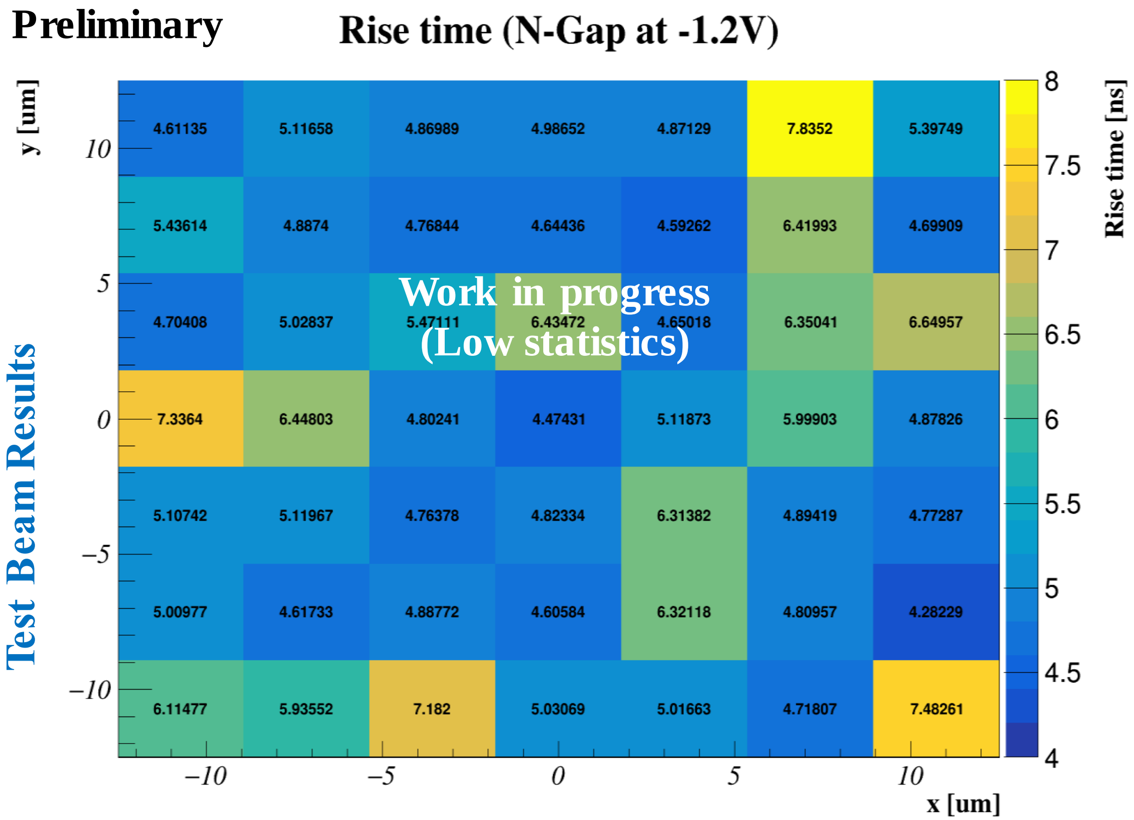

- Uniform rise time distribution regardless of incident position

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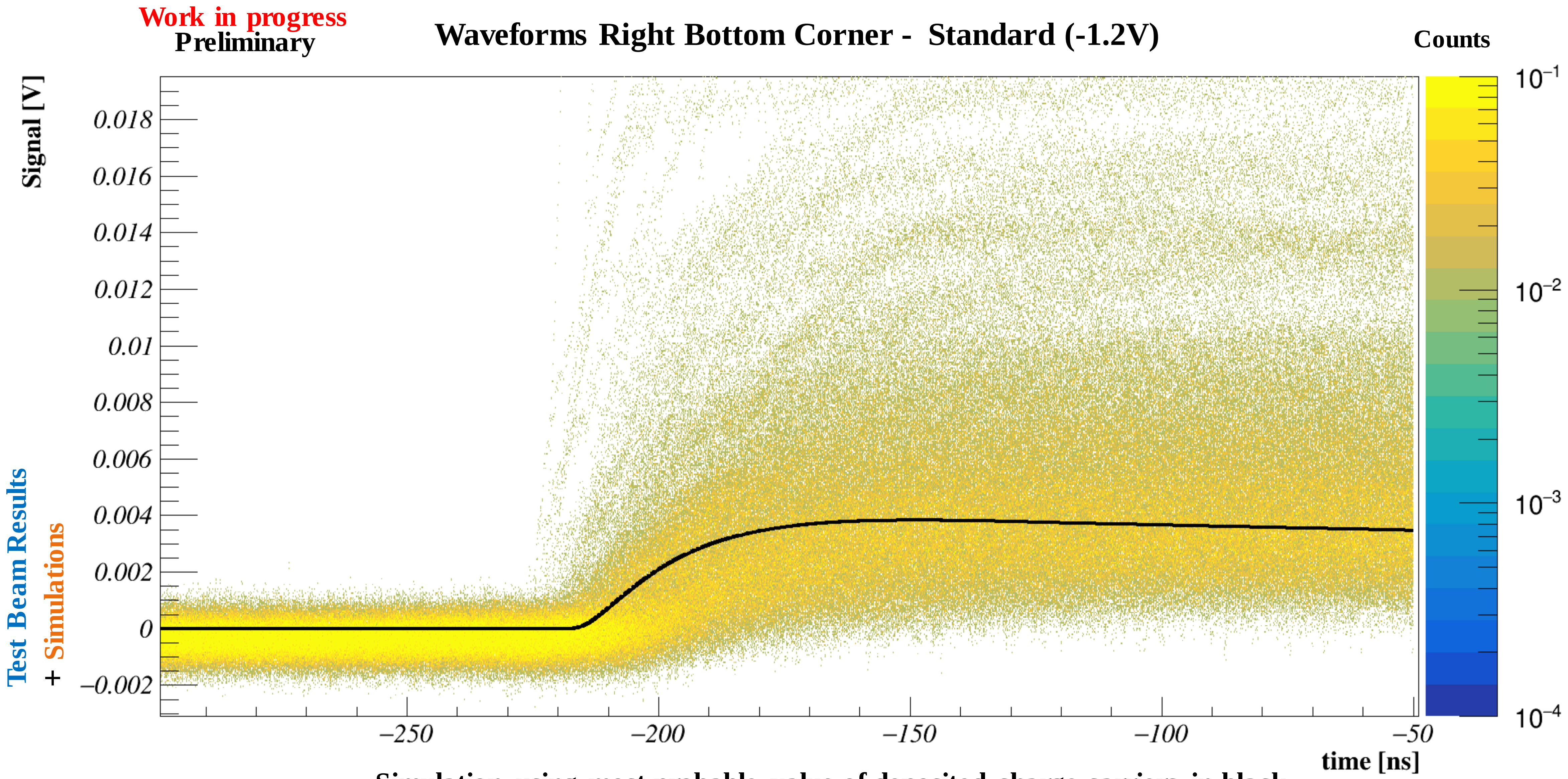
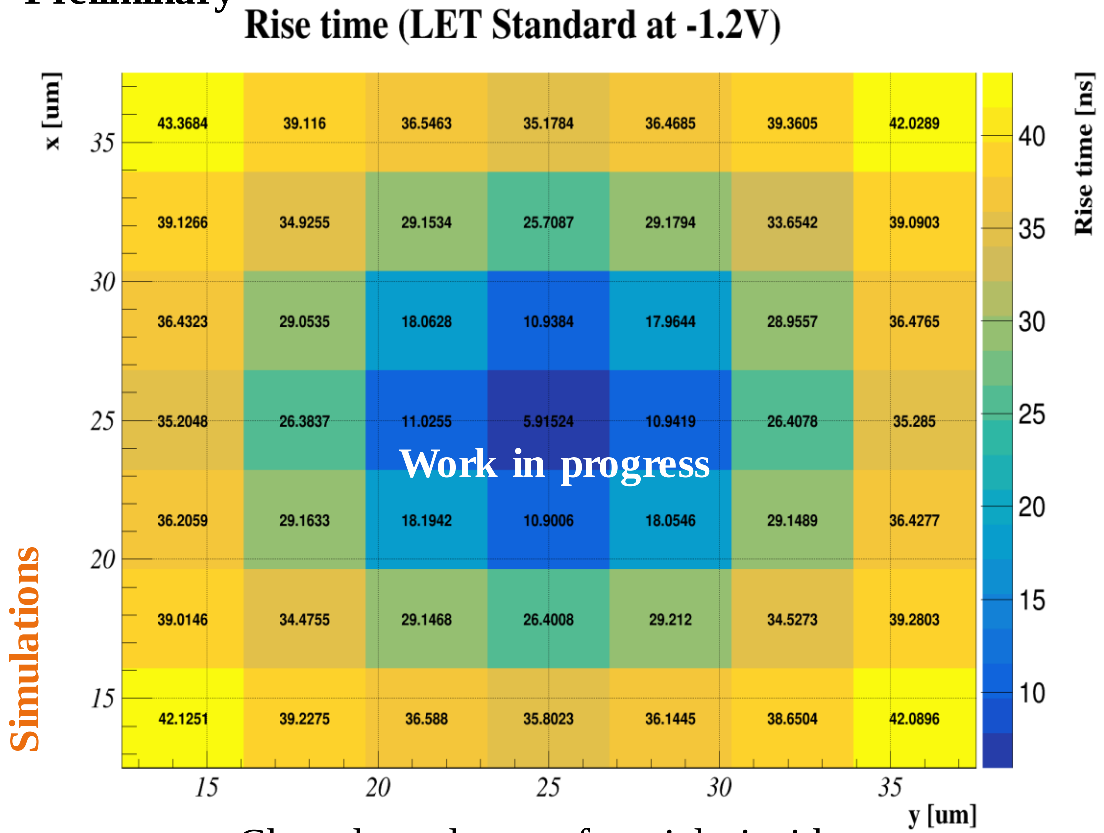
Waveforms in the corner of the pixel – Standard Layout



Simulation using most probable value of deposited charge carriers in black

In pixel rise time distribution (Qualitative trend values)

Preliminary



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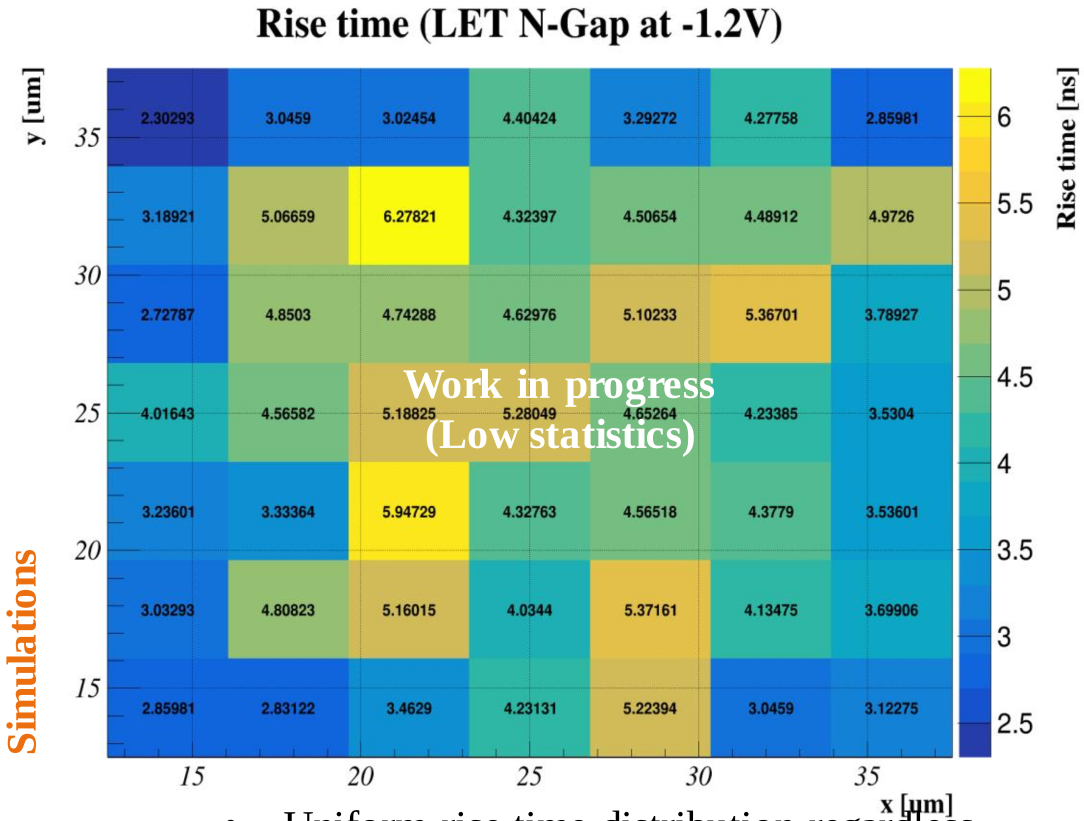
Preliminary



- Uniform rise time distribution regardless of incident position

Caveats:

- LET injection of 63 eh/um at the center of each bin.
- Not including Landau fluctuations, variation in the number of charge deposits...
- The result of 1000 pulses used as input in the SPICE simulations
- A single pulse used in the low statistic case

Summary and Outlook

Summary

- The Tangerine group investigates the **65 nm CMOS imaging** technology

- Simulations are a powerful tool to predict and understand the behavior of new detector technology

- Simulations, lab measurements and test beams were performed in order to understand how the incident position affects the charge collection time, amplitude, rise time and thus the **timing performance**

- Large differences between rise time distributions between both layouts with trends predicted by simulations

Outlook

- Improve robustness of analysis (Amplitude and rise time fluctuations depending of definition)
- Reproduce laboratory and test beam results through simulations
    - Same conditions as in test beam that include Landau fluctuations, variation in the number of charge deposits...
    - Inclusion of noise at the input node of the SPICE simulations