The Tangerine project: Development of high-precision 65 nm silicon MAPS

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for the Tangerine collaboration

24/4 -24

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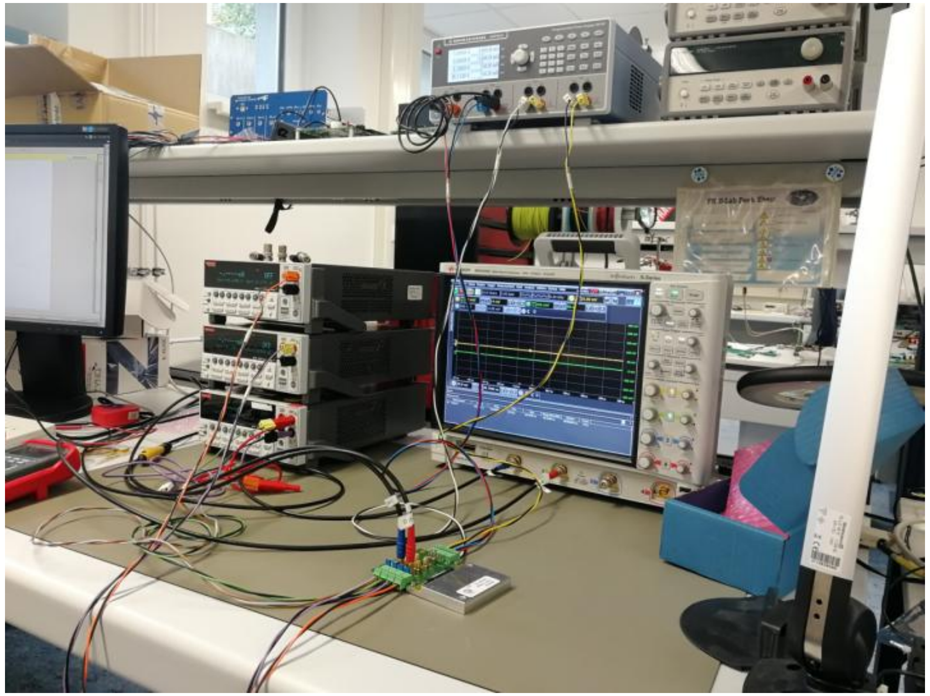
Outline

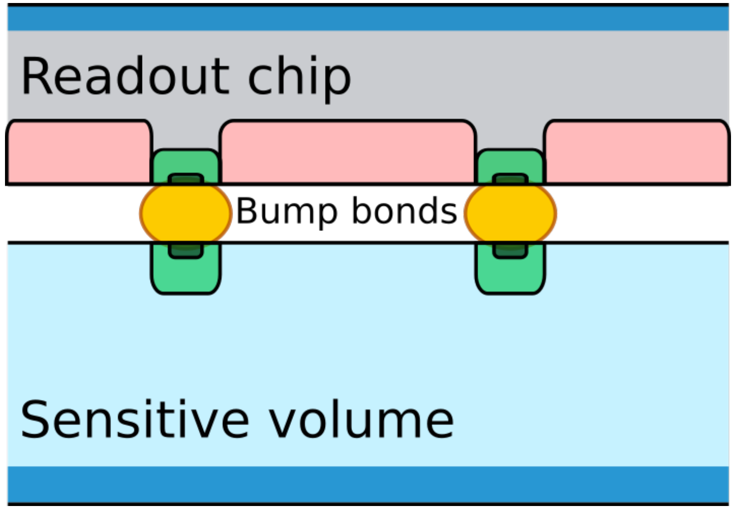
- Introduction
  - Monolithic active pixel sensors
  - The Tangerine project
- Sensor design
- Sensors and sensor testing
- Simulation studies
  - Methodology
  - Results
- Conclusions and outlook



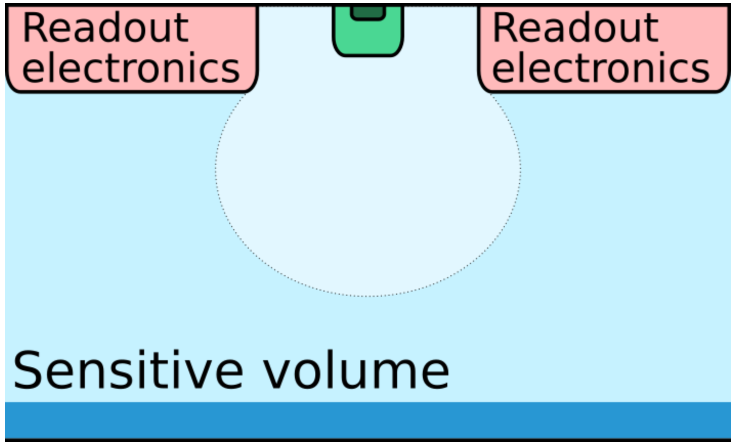
Monolithic active pixel sensors (MAPS)

- MAPS combine **sensitive volume and readout electronics in a single volume**
  - This enables lower material budget, reduced complexity, and reduced production cost compared to hybrid sensors
  - A low material budget is **essential** for particle tracking applications
- MAPS have made significant progress in recent years
  - First MAPS used in the STAR experiment
  - Currently used in ALICE; the **ALPIDE chip**
  - The MALTA and MonoPix developments: developed as candidates for ATLAS
  - Current developments for the next ALICE tracker upgrade and the EIC
  - Large collection electrode MAPS prototypes widely investigated (e.g. MuPix, MightyPix, TelePix, ...)

Hybrid sensor sketch

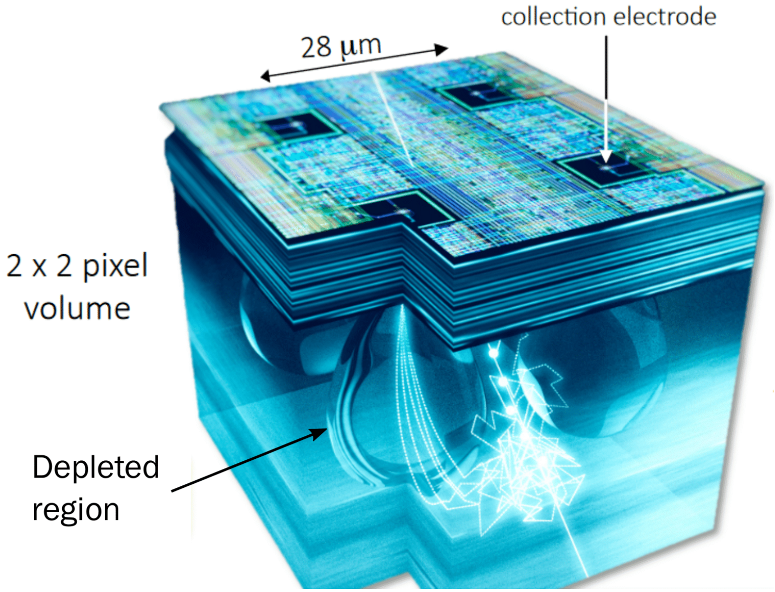


Monolithic sensor sketch



Monolithic active pixel sensors (MAPS)

- The ALPIDE chip is the current state-of-the-art MAPS sensor installed in a collider experiment
  - It utilises a development allowing for a **small collection electrode**, which reduces both detector noise and power consumption
  - The ALPIDE chip is made using a 180 nm CMOS imaging process
- Recently, access has been granted to a 65 nm CMOS imaging process, and this is envisioned to be used for the next ALICE inner tracker upgrade sensor
- The 65 nm process allows a **higher logic density** compared to previously used processes, leading to reduced pixel size or more in-pixel functionality
  - It also allows for decreased power consumption, and **stitching** for large-area sensor production
  - The process is so far **unused in particle physics applications**, however. It is **crucial** to test it



Artistic view of the ALPIDE chip cross section. Figure from here

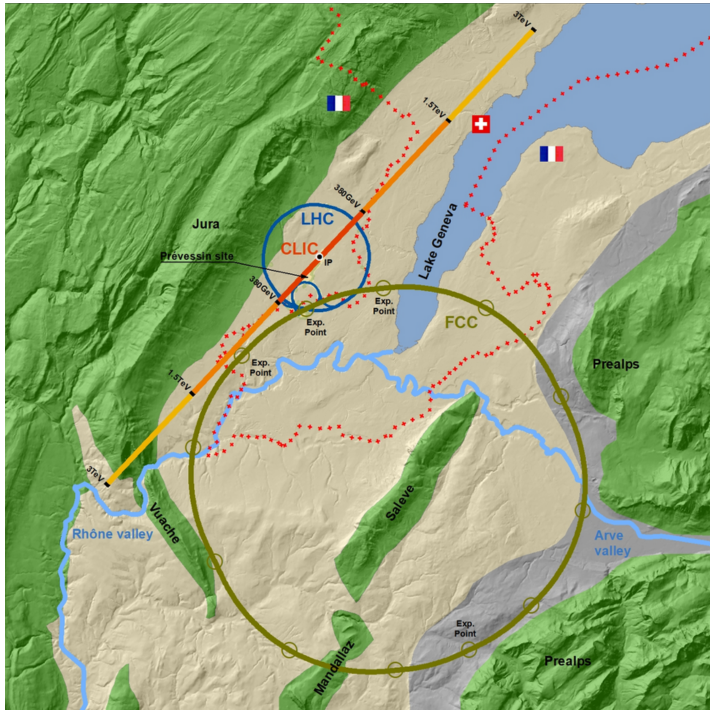
The Tangerine project (Towards next generation silicon detectors)

- Started in 2021 with the aim of **developing and investigating particle detection sensors in new silicon technologies**
- This presentation focuses on Work Package 1 of the project; **monolithic active pixel sensors** in a novel CMOS imaging technology (65 nm)
  - The project encompasses all aspects of sensor developments: electronics design, sensor design, prototype test chip characterisation
- The goal is development of a sensor with **high precision and low material**
  - Spatial resolution below 3 µm
  - Time resolution of less than 10 ns
  - Very low material budget, corresponding to at most 50 µm of silicon (0.05% X/X_0)
  - Per-pixel charge measurement
- Primary initial goal: development of a sensor for telescope use, for test beams
  - This will **demonstrate the capabilities of the 65 nm technology in a particle physics context**

Possible future applications

- Lepton colliders, e.g.
  - CLIC
  - ILC
  - FCC-ee
- Electron-ion collider
  - Synergies, at least (same CIS technology developments)
- Test beam reference system
- Common denominator: radiation damage is **not much of an issue**

CLIC: https://home.cern/science/accelerators/compact-linear-collider



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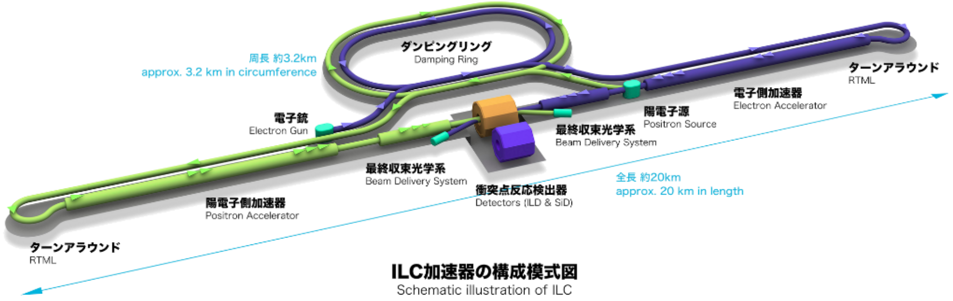
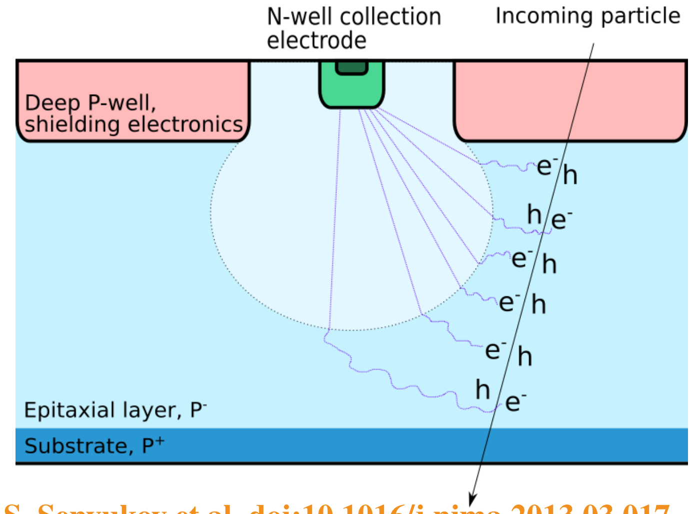


https://www2.kek.jp/ipns/en/research/ilc/

Sensor design

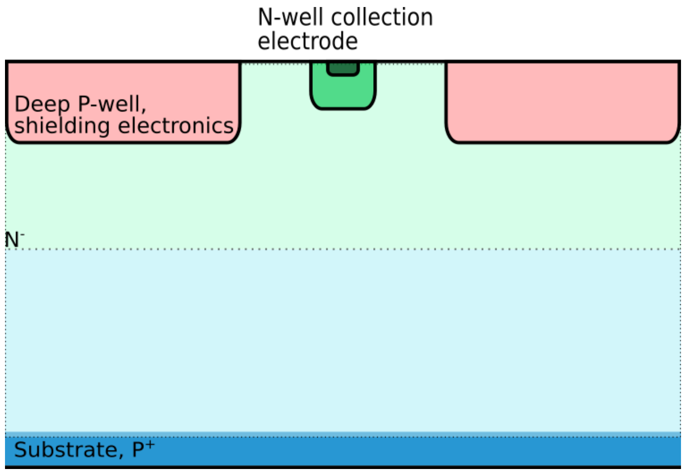
- The sensor design comprises both sensitive volume and electronics design
- For the sensitive volume design, there are three available layouts (all with a **small collection electrode**) originally designed for a 180 nm CMOS imaging process:

- Standard layout
  - ALPIDE-like



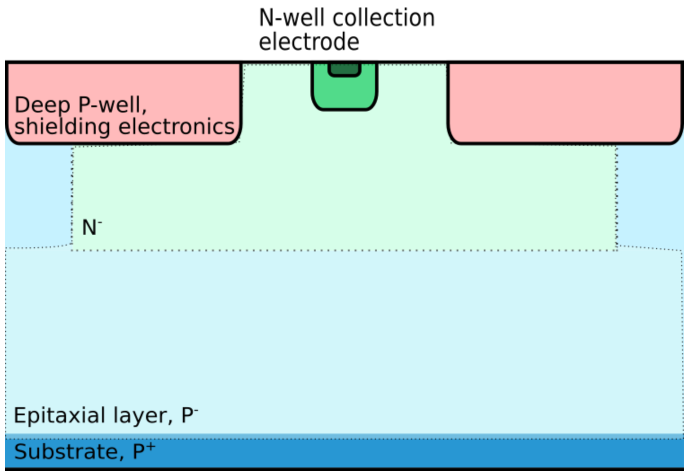
S. Senyukov et al. doi:10.1016/j.nima.2013.03.017

- N-blanket layout
  - Blanket layer of n-doped silicon, creating a **deep planar junction**



W. Snoeys et al. doi:10.1016/j.nima.2017.07.046

- N-gap layout
  - Blanket n-layer **with gaps at pixel edges**

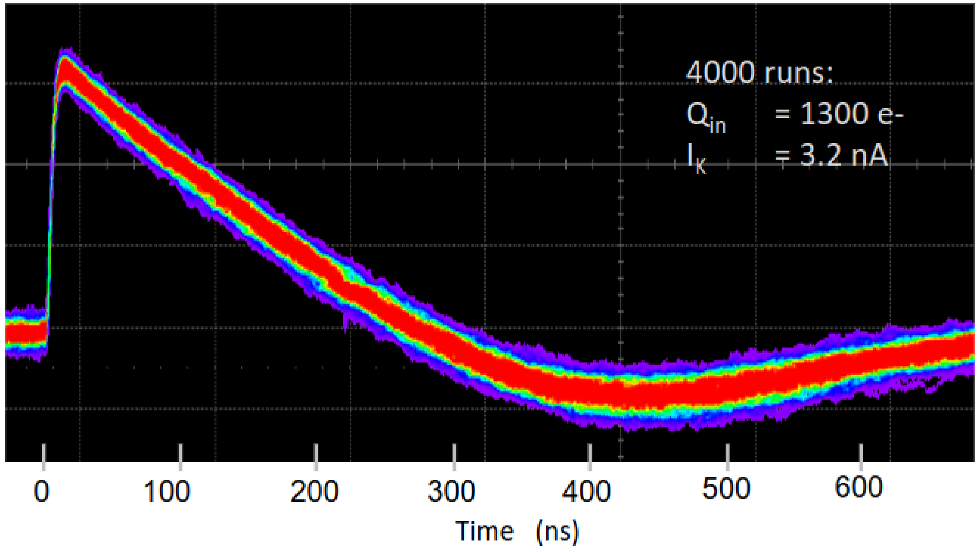


M. Münker et al 2019 JINST 14 C05013

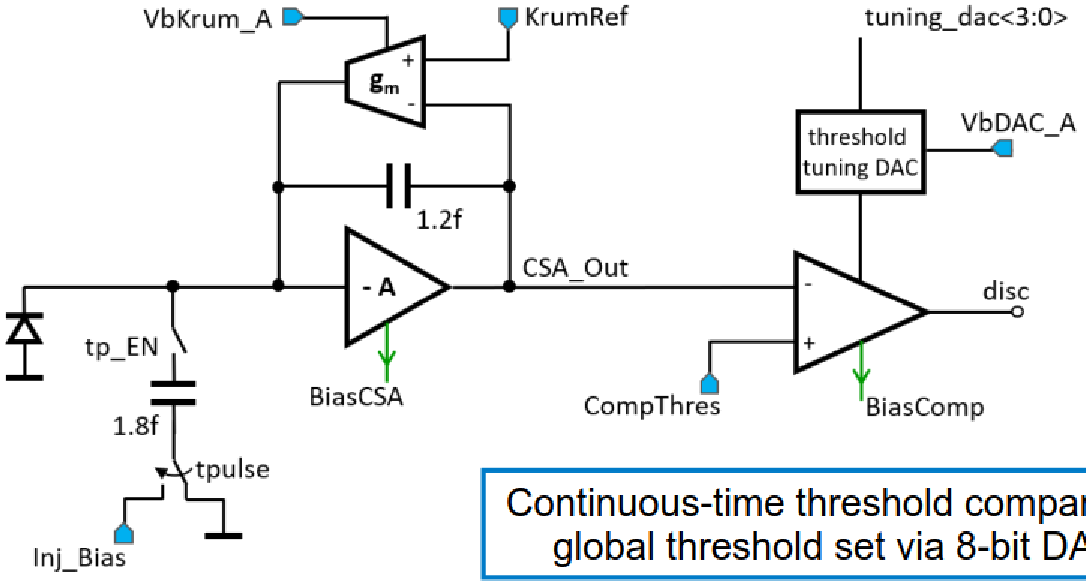
Sensor design at DESY

- Design of an analog front-end with a **charge-sensitive amplifier** circuit
  - **Krummenacher type feedback network** for continuous **reset** and **leakage current compensation**
  - Higher Krummenacher current -> faster return to baseline
- Comparator with tunable threshold in each pixel

CSA Output



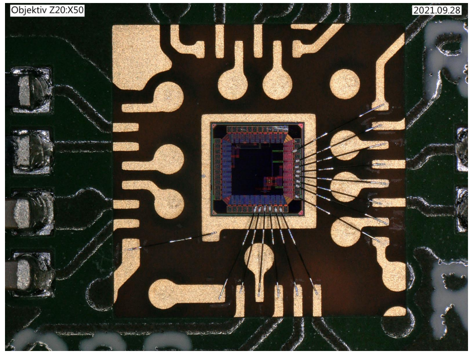
Sensor diode



Global biasing DAC to adjust tuning step size

⇒ Processing of comparator output by digital pixel logic

Continuous-time threshold comparator: global threshold set via 8-bit DAC



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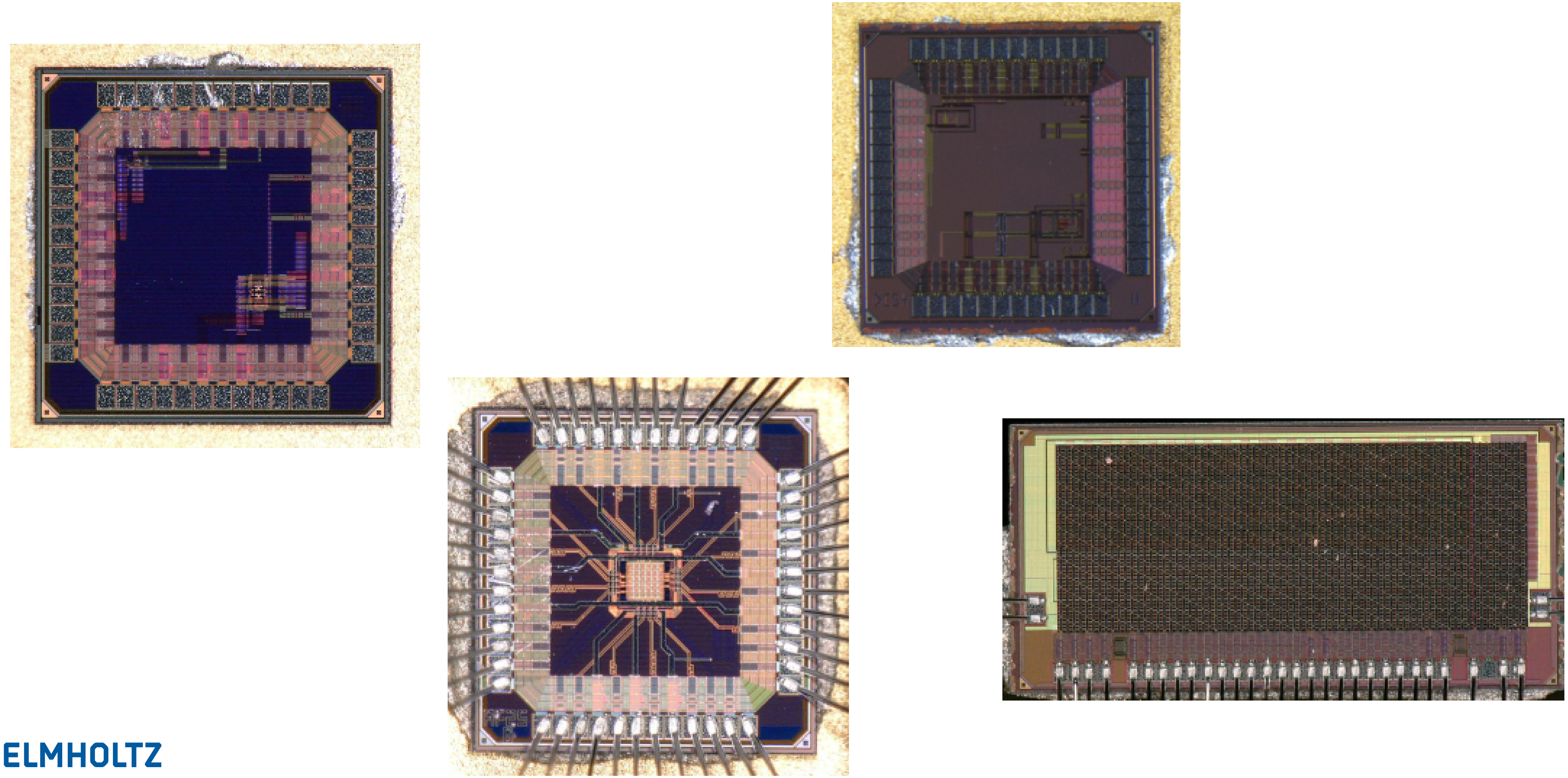
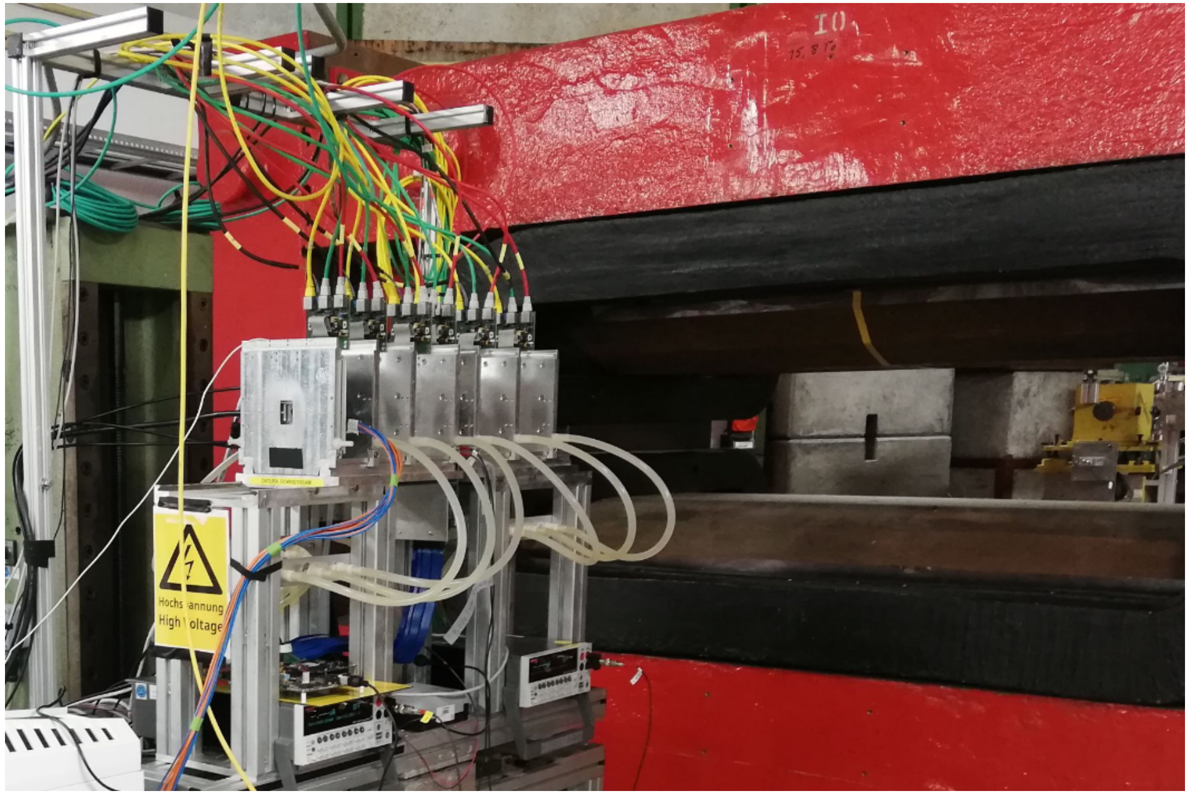
Sensors and sensor testing



HELMHOLTZ

Lab measurements and test beams

- Measurements performed with **x-ray sources** (mainly iron-55) in labs, and with **particle beams** at test beam facilities
- Test beams at DESY
  - MIMOSA26 or ALPIDE reference telescope
    - Provides **particle hit position** information
    - Six planes
    - Device under test in the middle
    - DUT mounted on motion stages
  - 5 GeV **electron beam**
  - Trigger plane with **configurable RoI** (TelePix)
  - **Corryvreckan** used for analysis



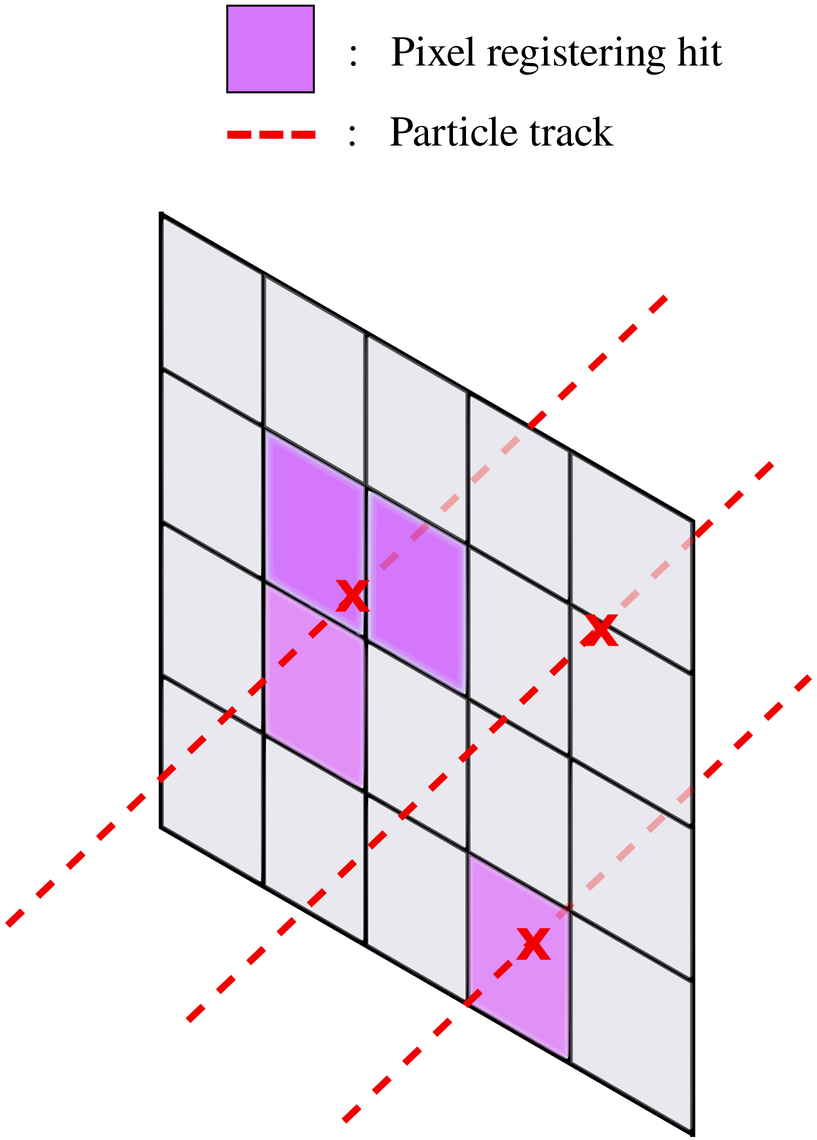
Example observables for sensor characterisation

Cluster size

- **Number of pixels that register hits for a single incident particle** (charge sharing)
- This will depend on the position of the incident particle, but with a **large number of particles** a mean value can be found, as well as the cluster size versus hit position
- Varies with threshold value

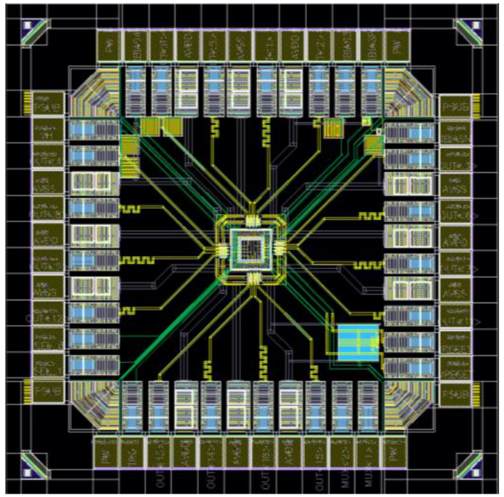
Efficiency

- Denotes the **fraction of particles incident on the sensor that produce a signal in the sensor**
- Goes between 0 and 1
  - If all particles traversing the sensor produce a signal, the sensor is 100% efficient
  - Desirable to have **as high as possible**
- Strongly related to threshold value
- Can find mean efficiency across the sensor, and look at efficiency versus hit position

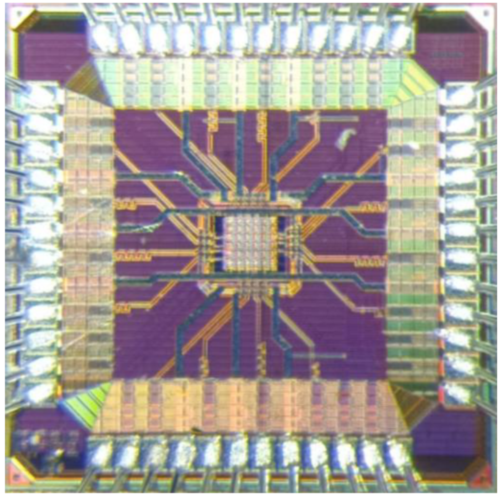


Analog Pixel Test Structure (APTS)

- Test chip designed at CERN
  - 4x4 active pixel matrix
  - Several versions and layouts available
    - Different pixel layouts and sizes
    - Different output buffers
- Tests carried out at several labs, including DESY
  - Focused on the **source follower** output buffer, and the **standard** and **n-gap** pixel layouts
  - Main focus on a 25x25 µm^2 pixel size
- At DESY: integrated with the **Caribou** readout system, on a new chip board



ASIC Design

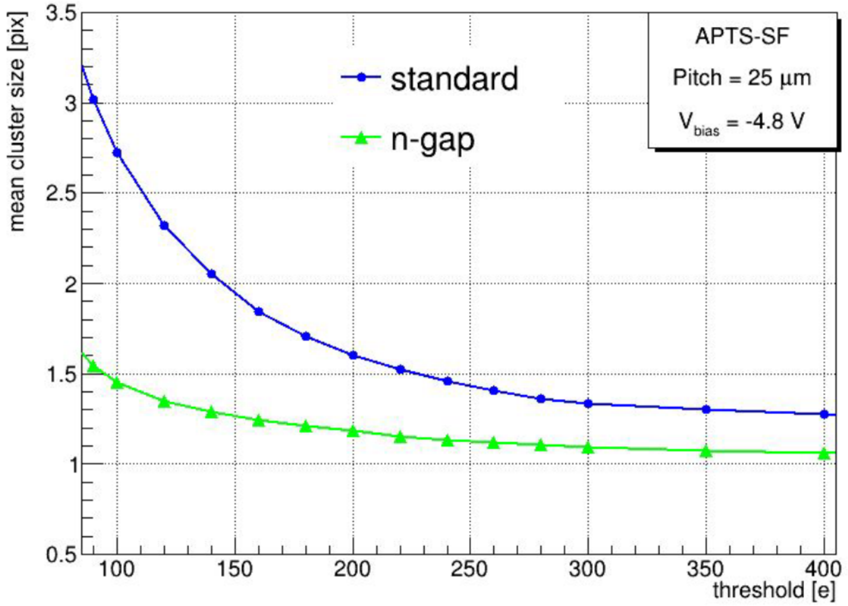


Prototype

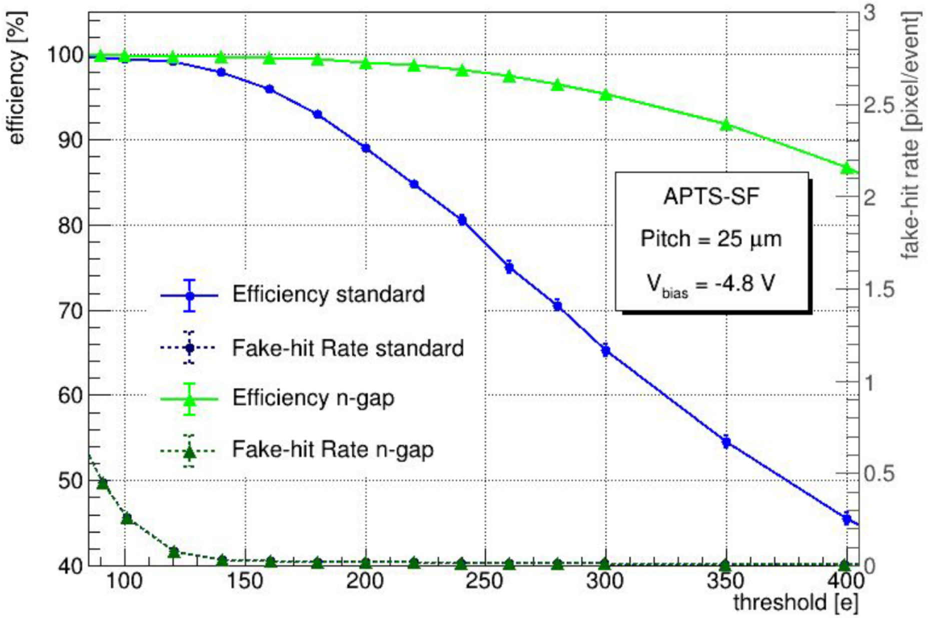
APTS labs and testbeams

- Comparisons made of different layouts under different biasing conditions
- Example results shown on the right, comparing the **standard and n-gap layouts**
- Cluster size reduced with increasing threshold
- Standard layout has **more charge sharing**, due to undepleted region at pixel edges
- Detection efficiency decreases as threshold increases
- N-gap layout **maintains efficiency to higher thresholds**, due to increased depletion and lateral electric field component
  - Trade-off between cluster size and efficiency

Mean cluster size



Mean efficiency



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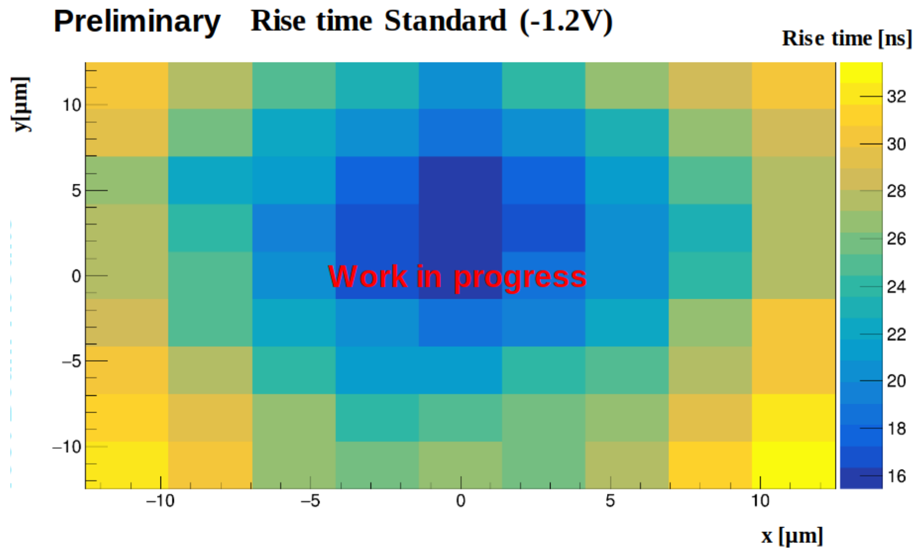
APTS labs and testbeams, timing results

- Goal: understand the signal generation and possible time resolution of the sensor
- Rise time of **signal pulses** investigated for the four inner pixels, using a fast oscilloscope
- Can study the rise time for **different particle incidence positions**, giving information about the charge collection behaviour
- Figures show in-pixel rise time distributions for the standard and n-gap layouts
  - Standard layout shows a **clear difference** between centre and corner incidence
    - Undepleted outside of a bubble around the collection electrode
  - N-gap layout **faster and more uniform**
    - Fully depleted, and charge pushed towards electrode



Preliminary Rise time Standard (-1.2V)

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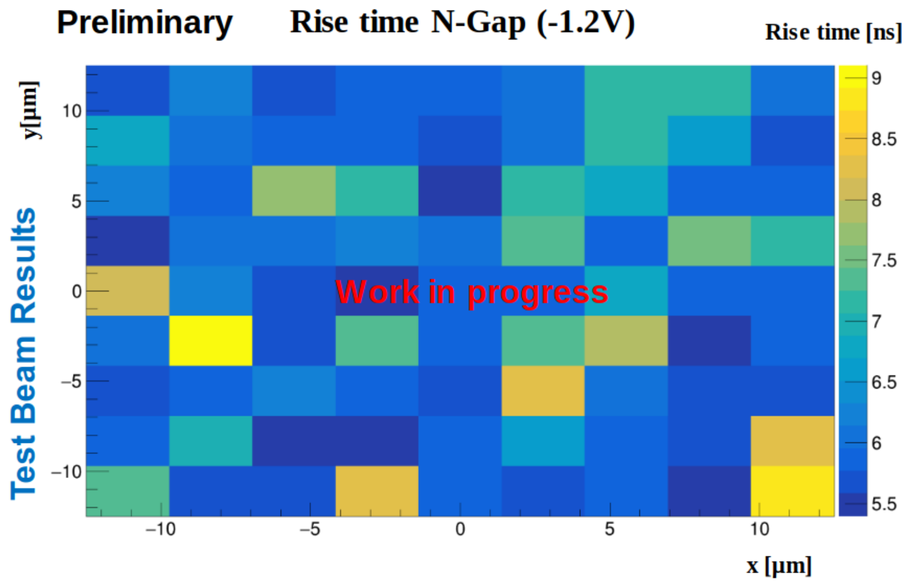


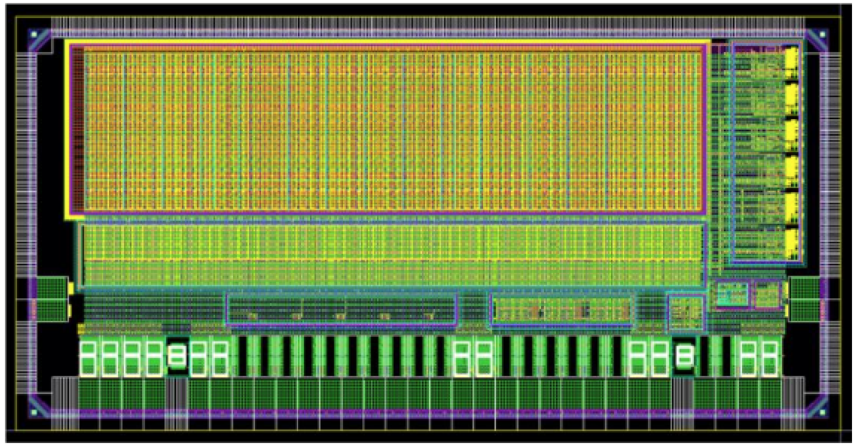
Preliminary Rise time N-Gap (-1.2V)

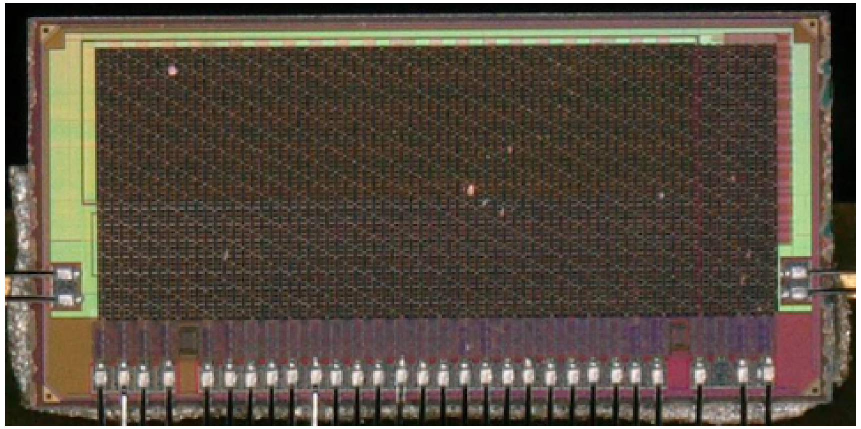
Test Beam Results

H2M from the ER1 submission - current chip

Hybrid-to-Monolithic

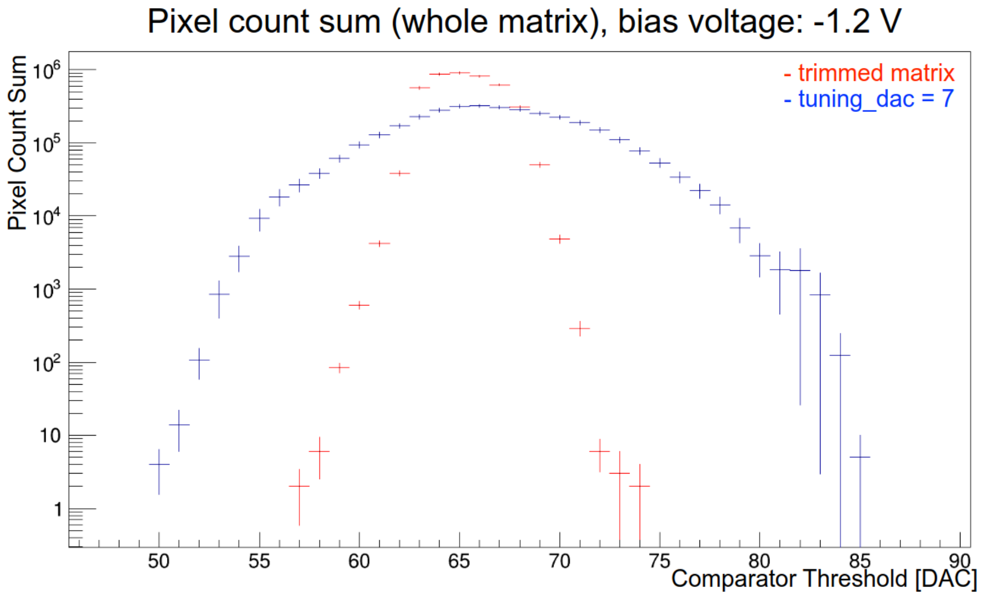
- Goals of the sensor:
  - Study challenges of porting a **known hybrid pixel detector architecture** into a monolithic chip
  - Exercise digital-on-top design flow and methodology in monolithic process
  - Design and test a compact digital cell library
- Several institutes collaborating in the development
  - Analog part **designed at DESY**
  - Prototype testing done at DESY and CERN
- Sensor specifications:
  - 64x16 pixels, of 35x35 μm^2 size and in the n-gap layout
  - Full analog and digital FE in each pixel
  - 4 (non-simultaneous) acquisition modes; 8-bit ToA, 8-bit ToT, photon counting, and triggered

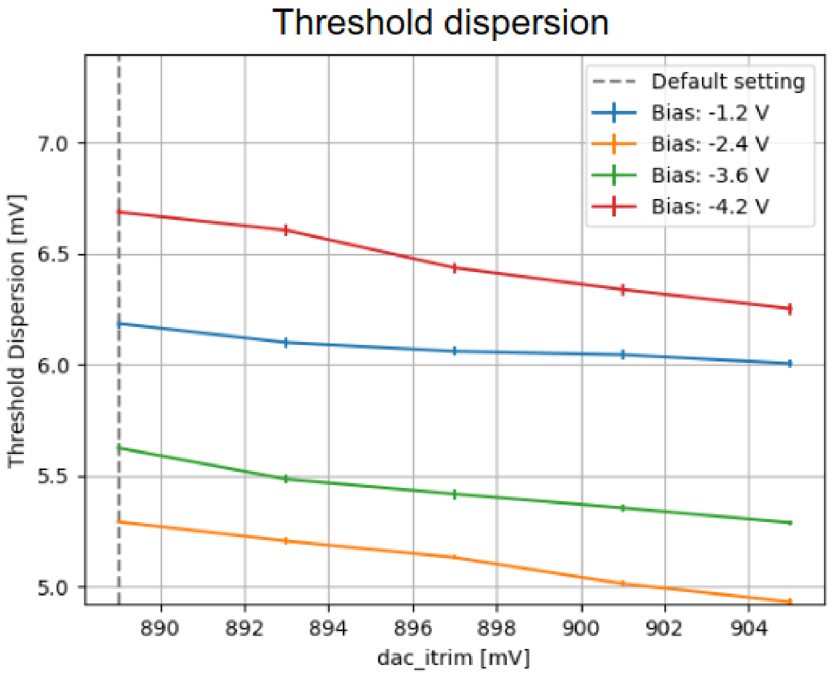




H2M results - tuning

- Per-pixel **threshold trimming** possible using a 4-bit register
  - Used to **counter pixel-to-pixel variations**
  - Reducing threshold dispersion makes sensor response more uniform, allowing for a lower threshold
  - Performed using **intrinsic noise**
- Front-end parameter optimisation
  - Global biasing currents can be varied, and their impacts on noise and threshold dispersion observed
  - The goal is to find an **optimised working point**
  - Varies with different **chip bias settings**
  - In the end a **compromise** between low threshold dispersion and high amount of tunable pixels





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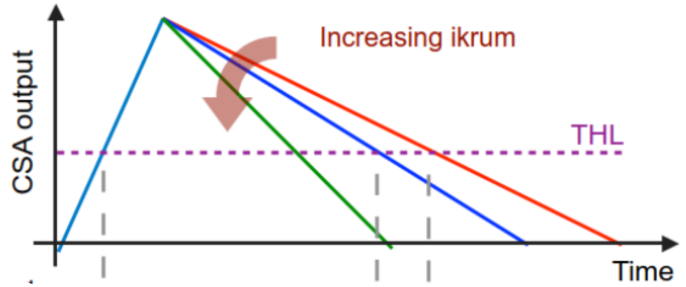
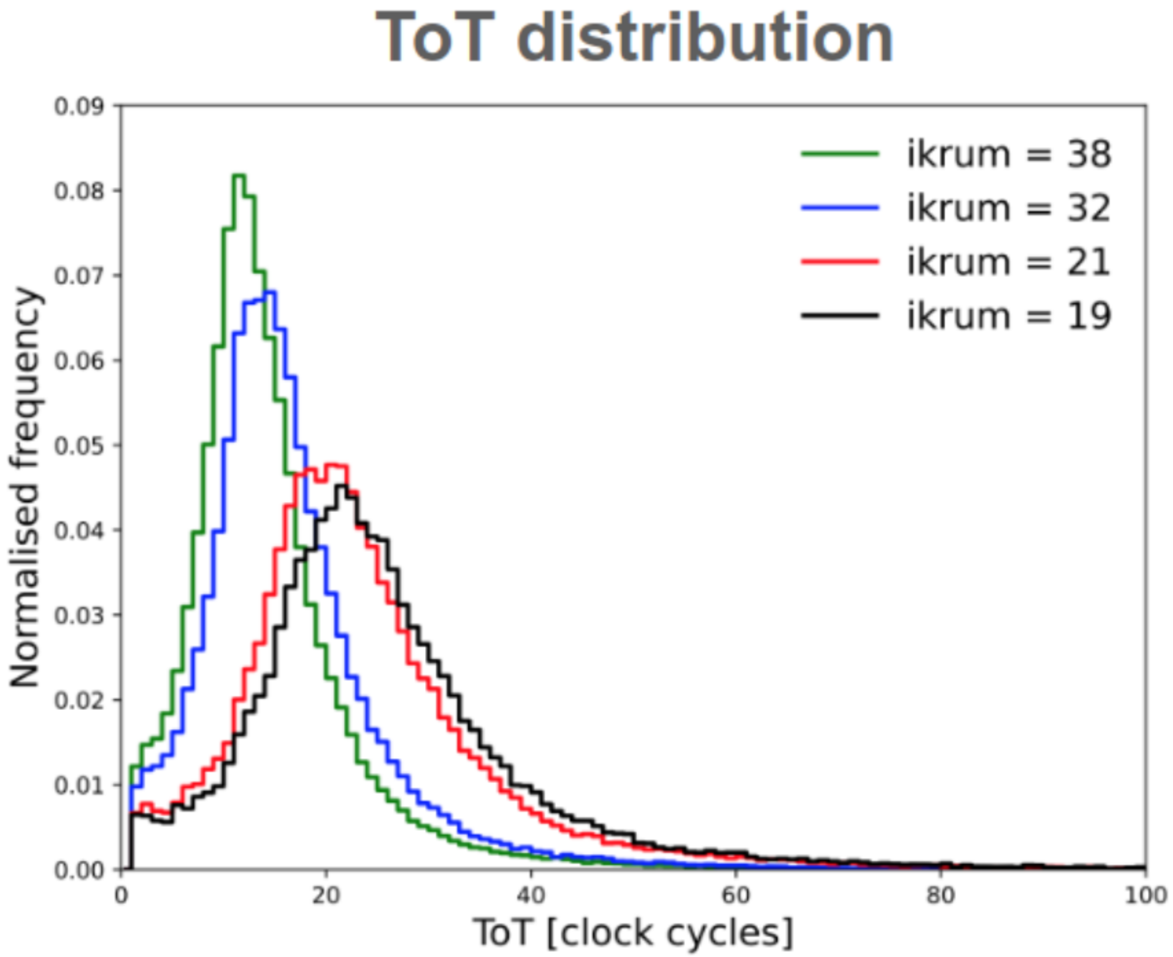
H2M results - test beam



- Several test beams carried out, investigating the different acquisition modes
- Figure shows **time-over-threshold spectrum** for different Krummenacher currents
  - Reminder: ToT **proportional to collected charge**
  - Higher I_{Krum} means **faster return to baseline** for the signal
- Results **qualitatively follow expectations:**
  - Landau-like distribution
  - Lower ToT with higher Krummenacher current
- H2M is a **fully-functioning** advanced monolithic digital-on-top sensor in a 65 nm CMOS imaging technology!
  - Some things left to understand, however



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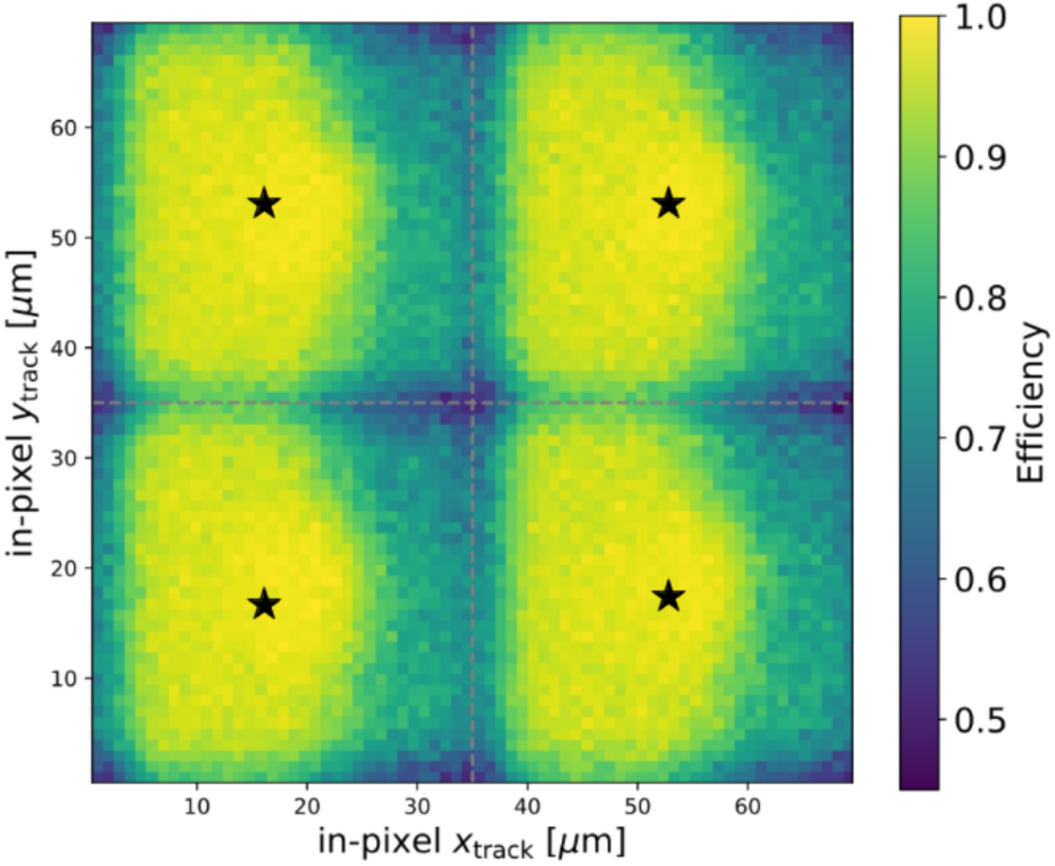
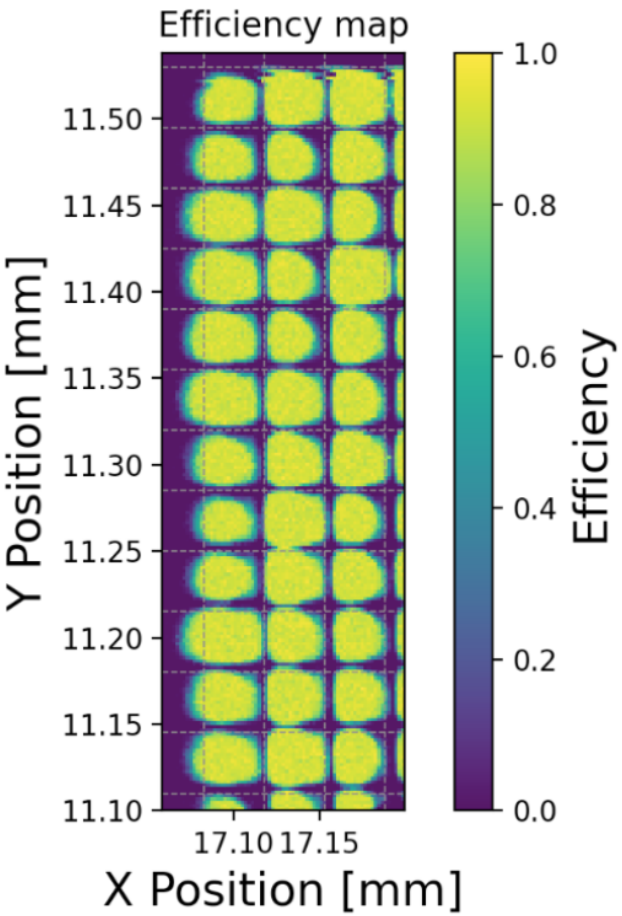
H2M results - test beam and laser setup: efficiency

- Efficiency displays an **unexpected pattern**
- Asymmetric low-efficiency region
- Reproduced both at test beam and laser deposition measurements
- Leading theory: related to **electric field perturbations** below the deep p-well, caused by the internal n-wells
  - Mitigation strategies discussed in preparation of the next submission
- New chip working point being investigated; may **reduce pixel-to-pixel variations**

In-pixel efficiency, test beam



In-pixel efficiency, IR laser



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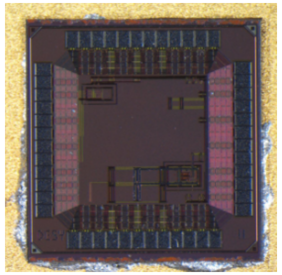
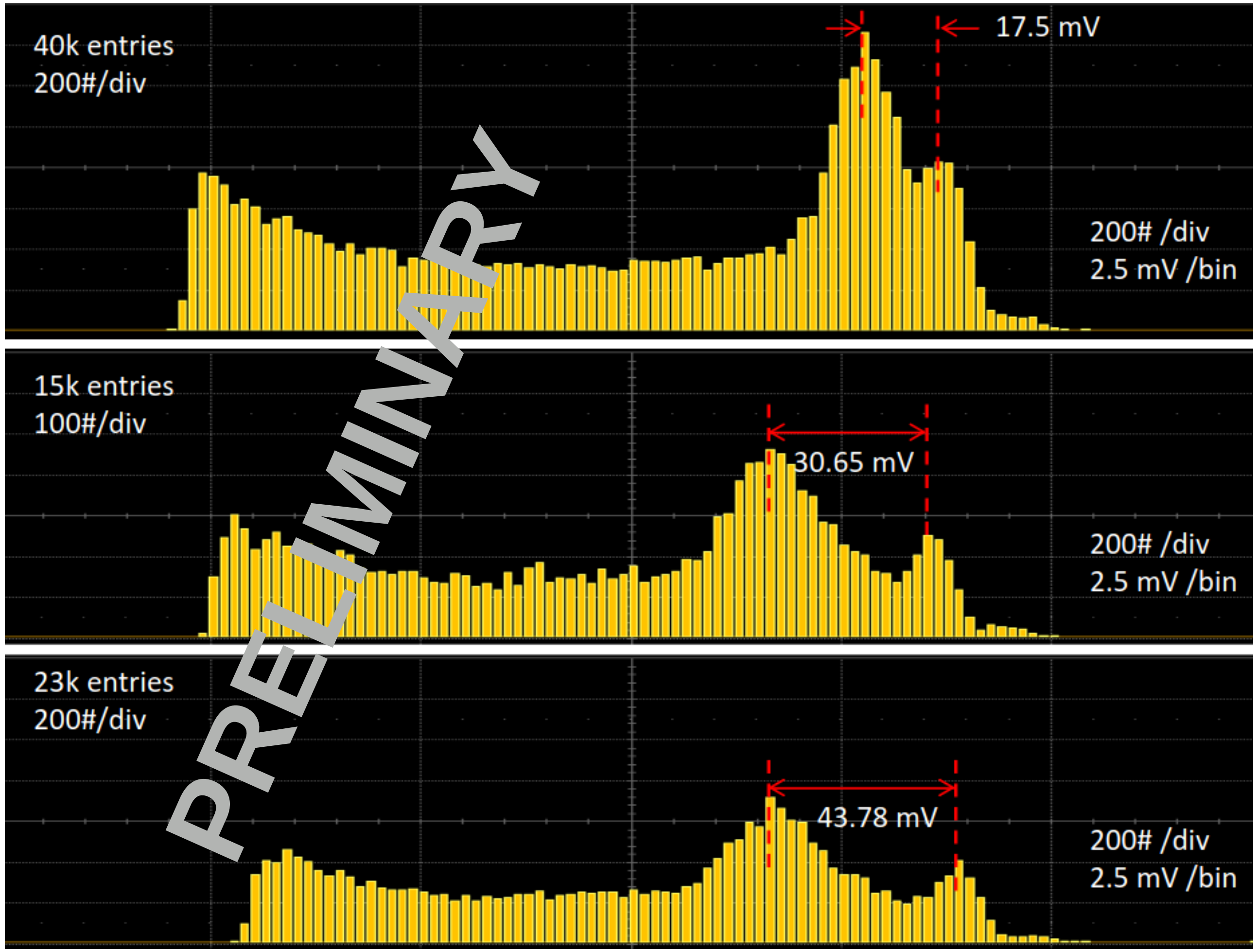
DESY ER1

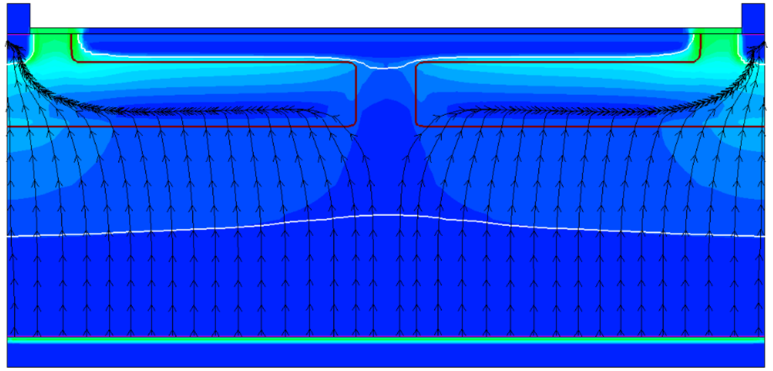
- Same analog part as in H2M, but **more detailed control possible**
- 2x2 matrix with **rectangular pixels** of size 35x25 µm^2
- N-gap layout with **two different gap sizes;** 2.5 µm and 4 µm
- Initial tests with **iron-55**
  - Signal amplitude results are **unexpected!**
  - Two-peak structure, but **not** K_α and K_β
  - Peaks shift with increasing I_{Krum}
- Reminder: higher I_{Krum} means faster return to baseline
- Theory: deposits far from pixel centre get **collected slowly**, so some charge **drains away before peaking**

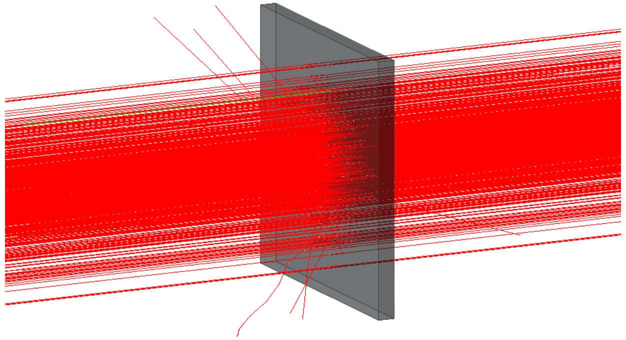


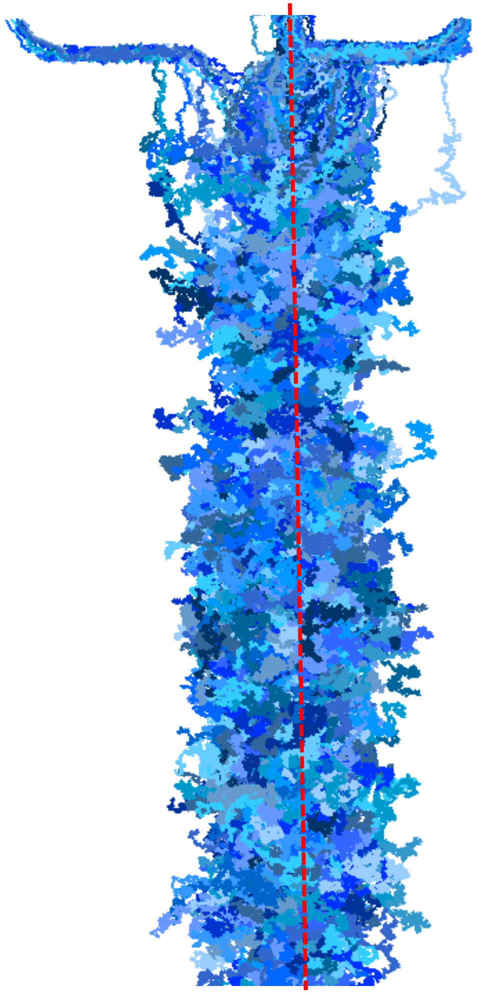
Increasing Krummenacher current



Simulations



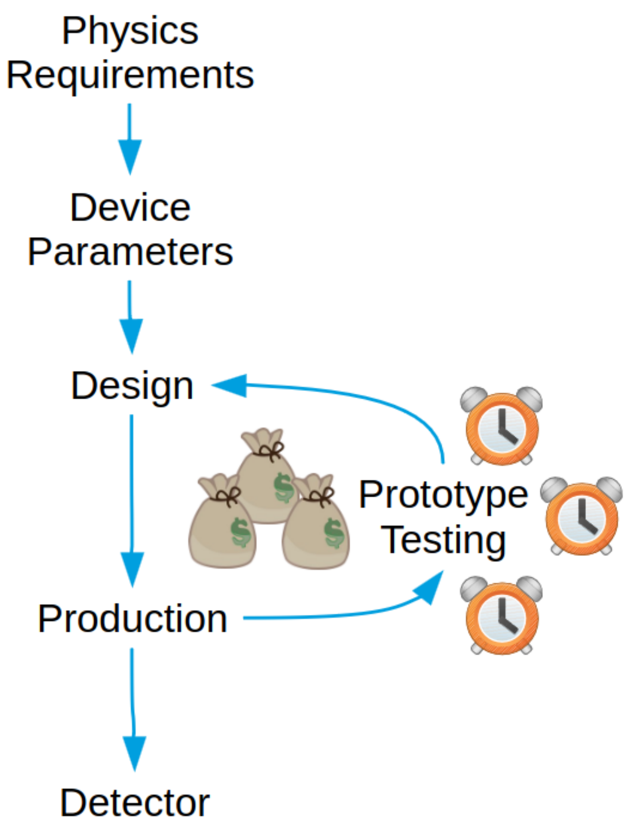




Motivation for simulations

- A way to **understand and predict** sensor behaviour
- Computing power is **relatively cheap** nowadays
  - Simulations are cheaper and faster than prototype production
- Simulations also help in providing a **deeper understanding** of measurement results
- A combination of **detailed simulations** and **prototype testing** can be used to efficiently **guide the way** in sensor developments

Old workflow example



Physics Requirements

Device Parameters

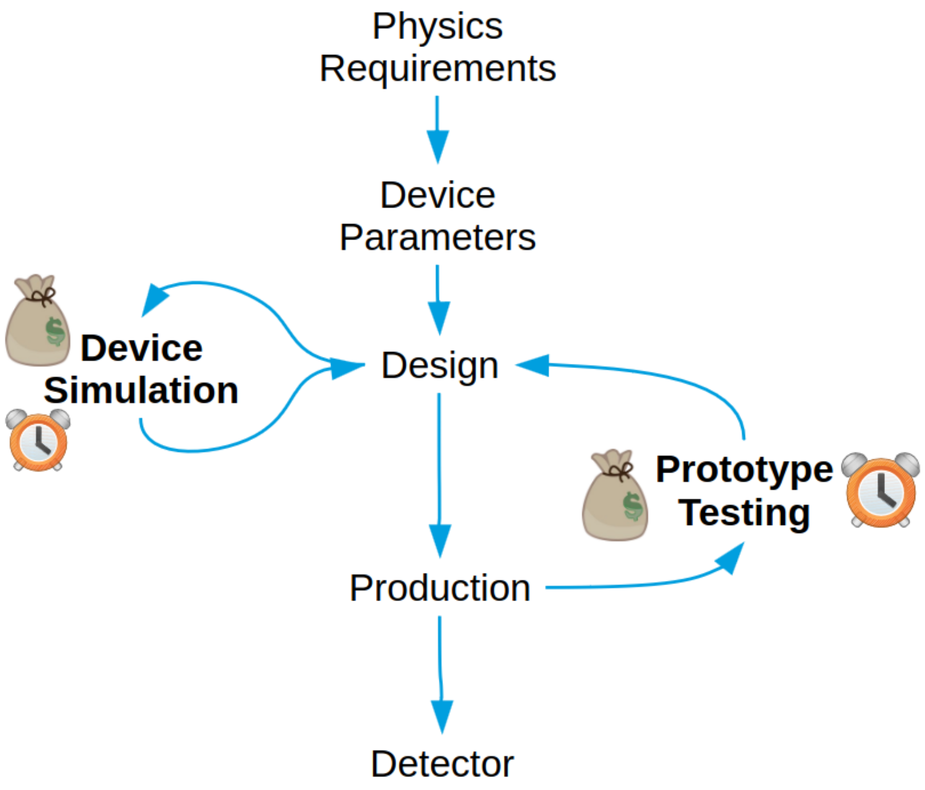
Design

Production

Detector

Prototype Testing

Current workflow example



Physics Requirements

Device Parameters

Device Simulation

Design

Prototype Testing

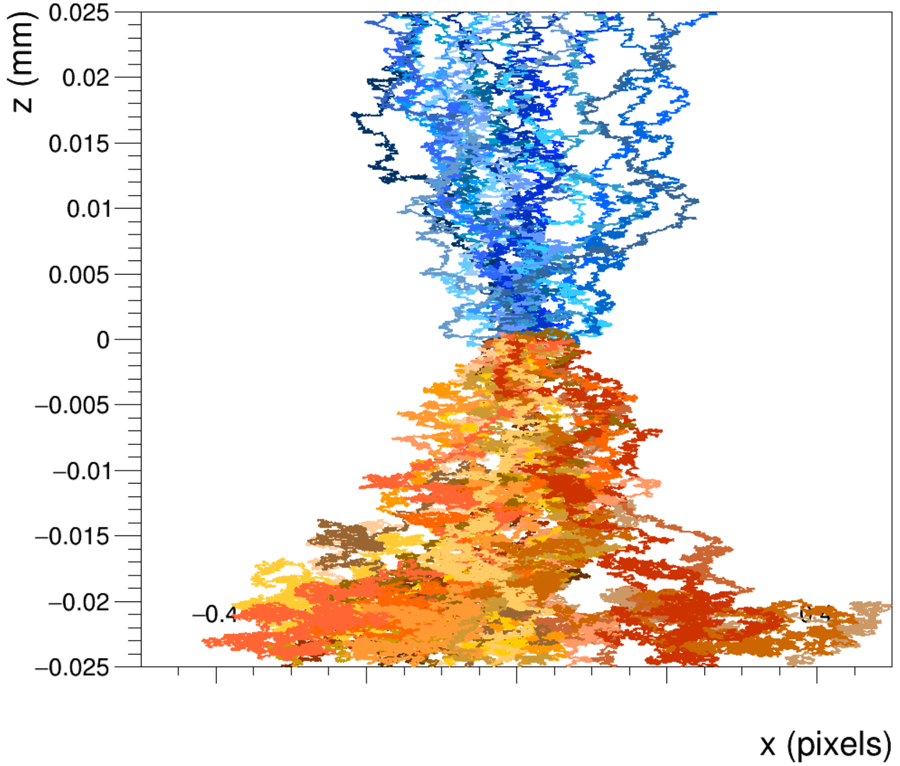
Production

Detector

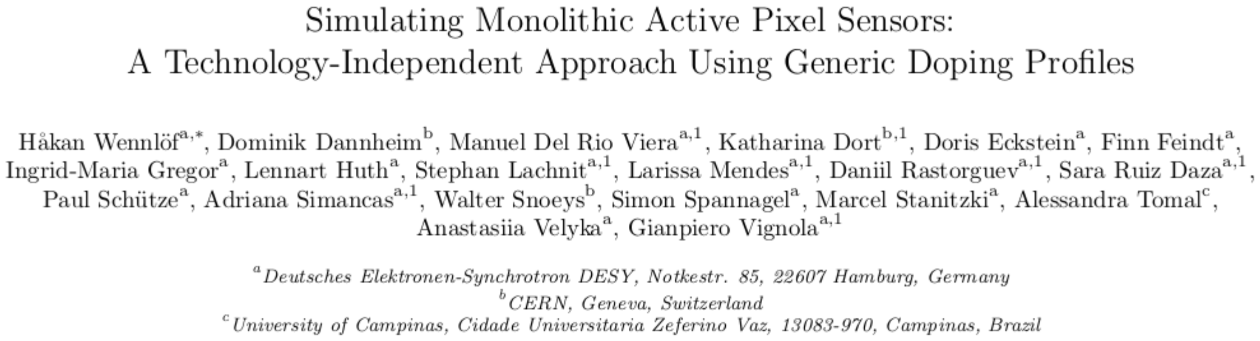
Figures by A. Simancas, BTTB10

Silicon sensor simulations

- **Goal:** Accurate simulation of the **charge collection behaviour** in the sensitive volume
  - Enables **prediction of sensor performance** (e.g. resolution, efficiency)
  - Done by simulating the **movement of electron-hole pairs** created by an interacting particle
- **Issue:** The access to manufacturing process information may be **very limited**
  - The Tangerine project for example utilises a commercial CMOS imaging process - detailed process information is **proprietary**
- **Solution:** development of a **technology-independent simulation approach using generic doping profiles**
  - Currently writing a **paper** describing the approach, serving as a **toolbox** for such simulations



Simulated motion of individual electrons and holes deposited in the centre of a silicon sensor with a linear electric field



Simulating Monolithic Active Pixel Sensors:
A Technology-Independent Approach Using Generic Doping Profiles

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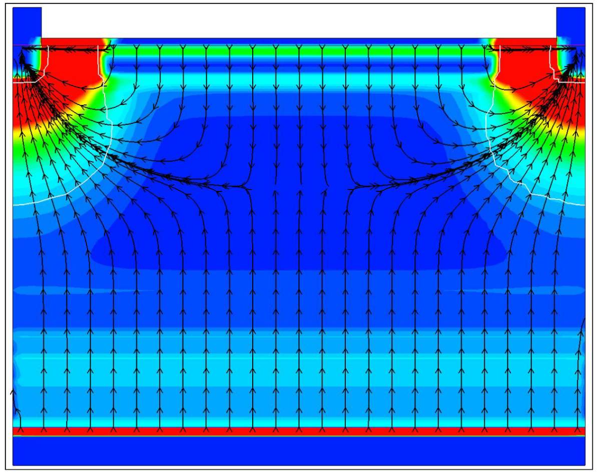
Tools used in the simulation approach

Sentaurus TCAD

SYNOPSYS®
Silicon to Software™

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

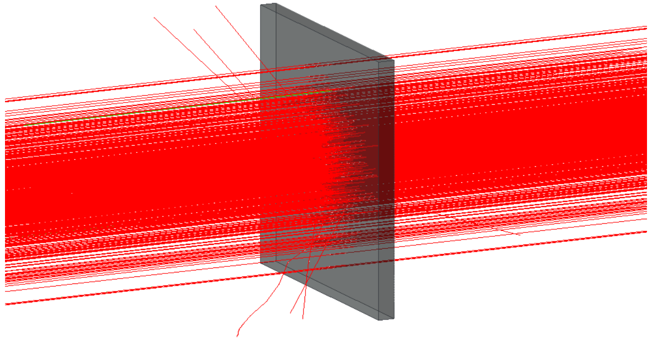
- Models semiconductor devices using **finite element methods**
- Calculates realistic and accurate **electric fields and potentials** from doping concentrations



Example electric field in TCAD

Allpix Squared: a Monte Carlo simulation framework for semiconductor detectors
https://allpix-squared.docs.cern.ch/

- Simulates **full detector chain**, from energy deposition through charge carrier propagation to signal digitisation
  - Interfaces to **Geant4** and **TCAD**
- Simulation performed **quickly** - allows for **high-statistics** data samples across a full detector

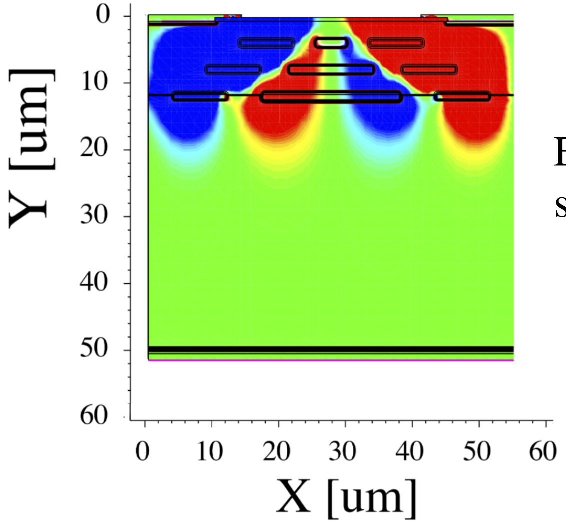


Particle beam passing through a single sensor in Allpix²

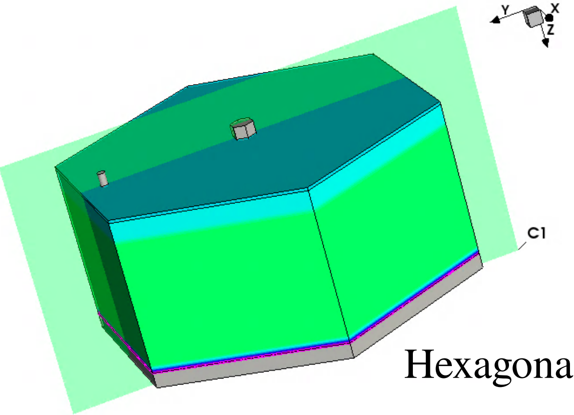
TCAD

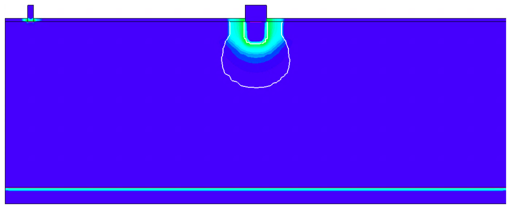
Technology computer-aided design

- Models **semiconductor devices** in 2D or 3D, and numerically solves equations using provided information
  - By providing doping information, e.g. **electric fields** and **weighting potentials** can be calculated
  - Capacitances, I-V and C-V curves, and transient properties can be extracted
- **Fabrication steps** in semiconductor manufacturing can be simulated
- Different pixel geometries and layouts can be simulated in **great detail**
- Some example resulting electric fields shown on the right

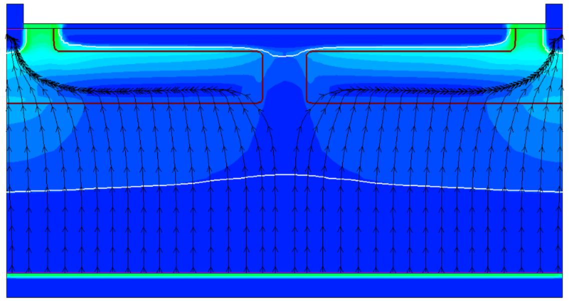


Enhanced Lateral Drift sensor simulation, A. Velyka





Hexagonal pixel simulation, L. Mendes



Rectangular pixel simulation, A. Simancas

Allpix Squared

A Monte Carlo simulation framework for semiconductor detectors

- Simulates **charge carrier motion** in semiconductors, using **well-tested** and **validated** algorithms
  - Includes different models for e.g. charge carrier mobility, lifetime and recombination, trapping and detrapping
  - Support for several semiconductor materials and pixel and sensor geometries
- Provides a **low entry barrier** for new users
  - Simulations are set up via **human-readable configuration files**
- **Steady development** over many years
  - Framework is **easily extendable** and **widely used**
  - **Open-source**, and written in **modern C++**
  - Version 3.0.3 released on December 14th 2023
- User workshop presentations hold many example applications

Website and documentation:
https://allpix-squared.docs.cern.ch/

```
[AllPix]
number_of_events = 10000
detectors_file = "telescope.conf"

[GeometryBuilderGeant4]
world_material = "air"

[DepositionGeant4]
particle_type = "Pi+"
number_of_particles = 1
source_position = 0um 0um -200mm
source_type = "beam"
beam_size = 1mm
beam_direction = 0 0 1

[ProjectionPropagation]

[SimpleTransfer]

[DefaultDigitizer]
```

Minimal simulation configuration example

Quick aside: Allpix Squared workshop 2024

- Held in **Oxford, 22nd to 24th of May**
- https://indico.cern.ch/e/apsqws5
- Basic **registration is free**, but lunches and workshop dinner can be provided for a fee
- In-person registration deadline: **4th of May**
  - If you want to present something: talk to me or anyone form the organising committee, and we can sort it out
  - Abstract submission is still open
- Workshop brings together the Allpix Squared community for discussions and presentations
  - Developers, users, and **curious people** welcome!

UNIVERSITY OF OXFORD

5th Allpix² User Workshop

22-24 May 2024
University of Oxford, UK

Organisers
Daniel Hynds
Paul Schütze
Simon Spannagel
Håkan Wennlöf

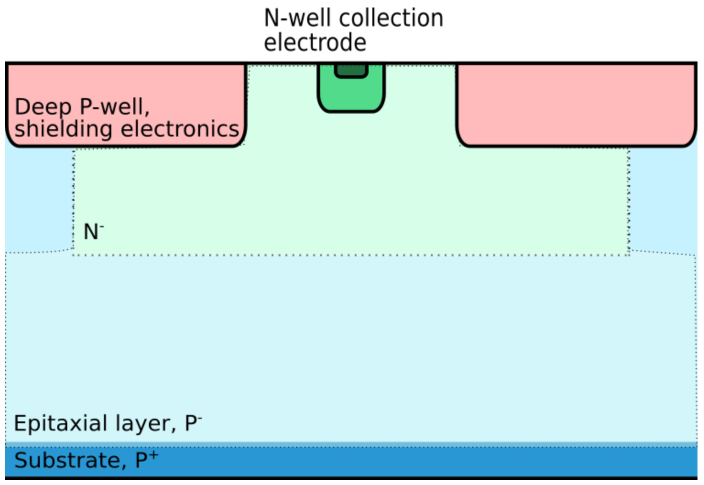
https://indico.cern.ch/e/apsqws5

Abstract deadline: 22 April
Registration deadline: 4 May

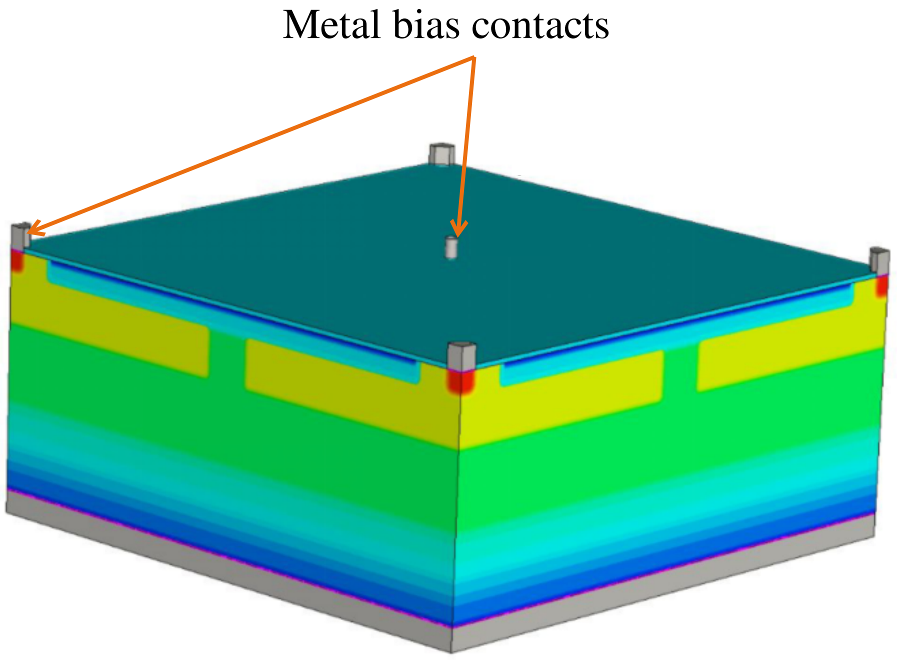
Silicon simulation layout and assumptions

Using the Tangerine project as an example

- High-resistivity **epitaxial layer** grown on low-resistivity **substrate**
- Approximate doping concentrations can be found in **published papers** and theses, that have been approved by the foundry
  - The **exact values are proprietary information**, however
- Doping wells are simulated **without internal structure** and as flat profiles
  - Small collection n-well in the centre of the pixel
  - Deep p-well holding the in-pixel CMOS electronics
- **3D geometry** simulated, including **metal bias contacts** and **Ohmic contact regions** in the silicon



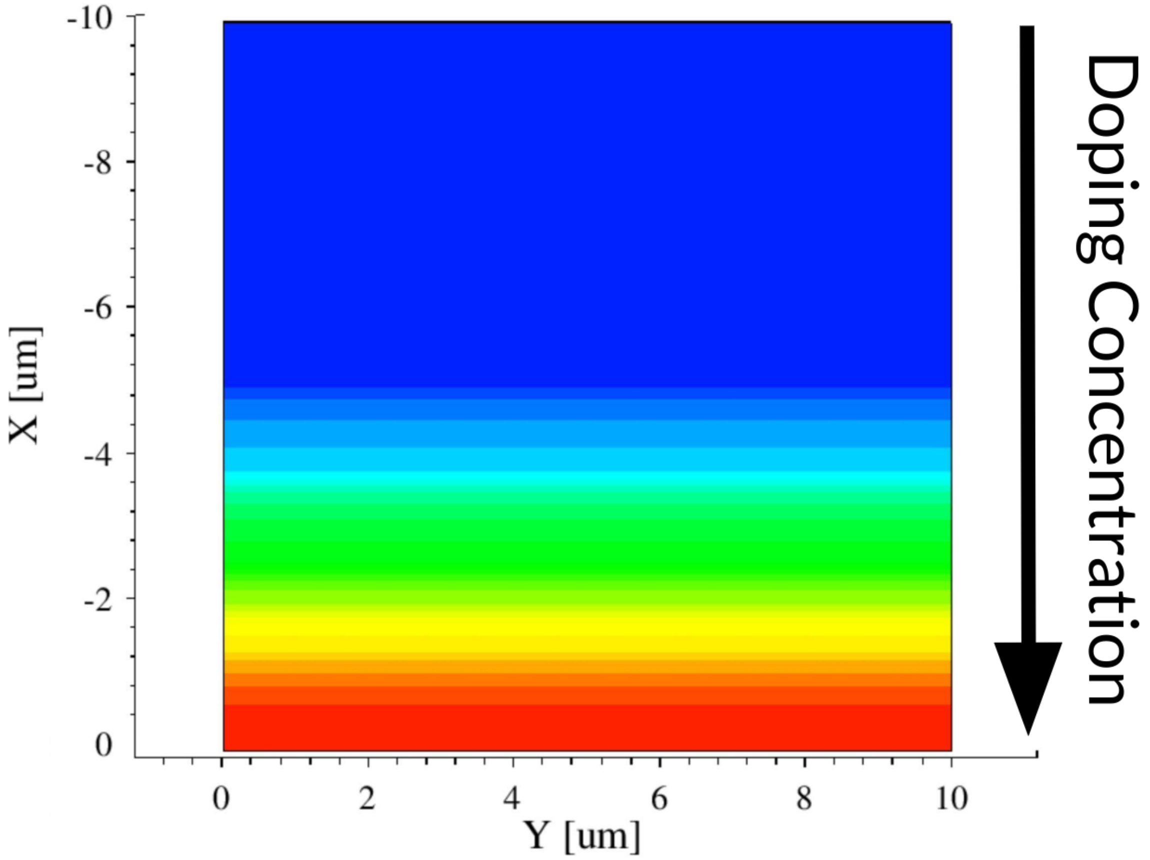
“N-gap layout”, M. Münker et al 2019 JINST 14 C0501



Finite element method simulations using TCAD

Using the Tangerine project as an example

- Using TCAD, **doping profiles** and **electric fields** are simulated
  - Studies are made observing the **impact of varying different parameters**, such as well doping concentrations and mask geometries
- Starting by creating the **geometry and doping regions**
  - Doping geometry is **further refined** by simulating diffusion between regions at reasonable **sensor production process temperatures**
    - Gives a continuous interface between epi and substrate
- Device simulations used to simulate **electric fields**, **electrostatic potentials**, and performing **transient simulations**

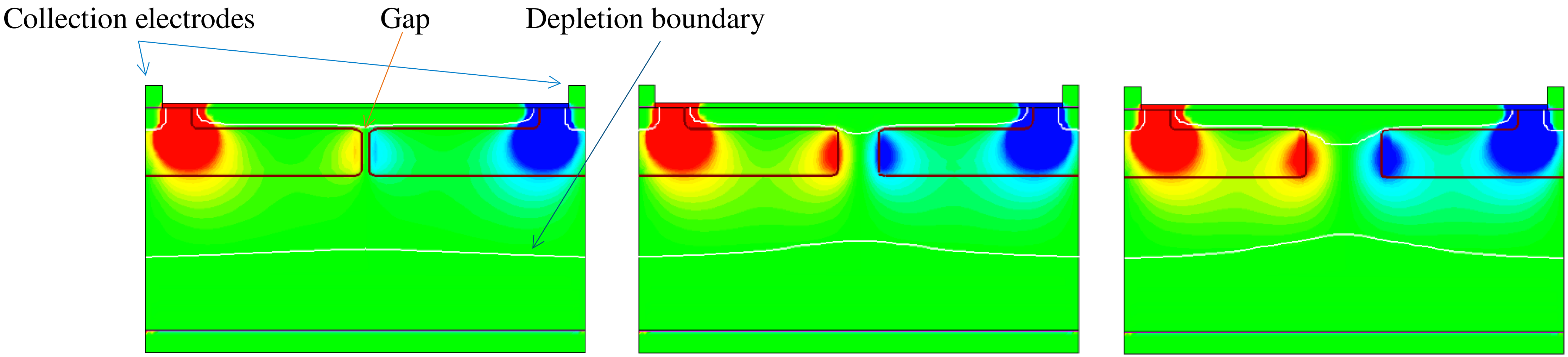


Process simulation result, showing dopant diffusion between substrate and epitaxial layer

Finite element method simulations using TCAD

Example study: impact of n-gap size on electric field

- The gap in the n-gap layout is introduced to give a **lateral electric field at pixel edges**
- The magnitude of the field depends on the **size of the gap**
  - A small gap makes the lateral components cancel, and a large gap leads to a low-field region
- Figures show simulation results for the **lateral electric field** (red and blue) for different gap sizes

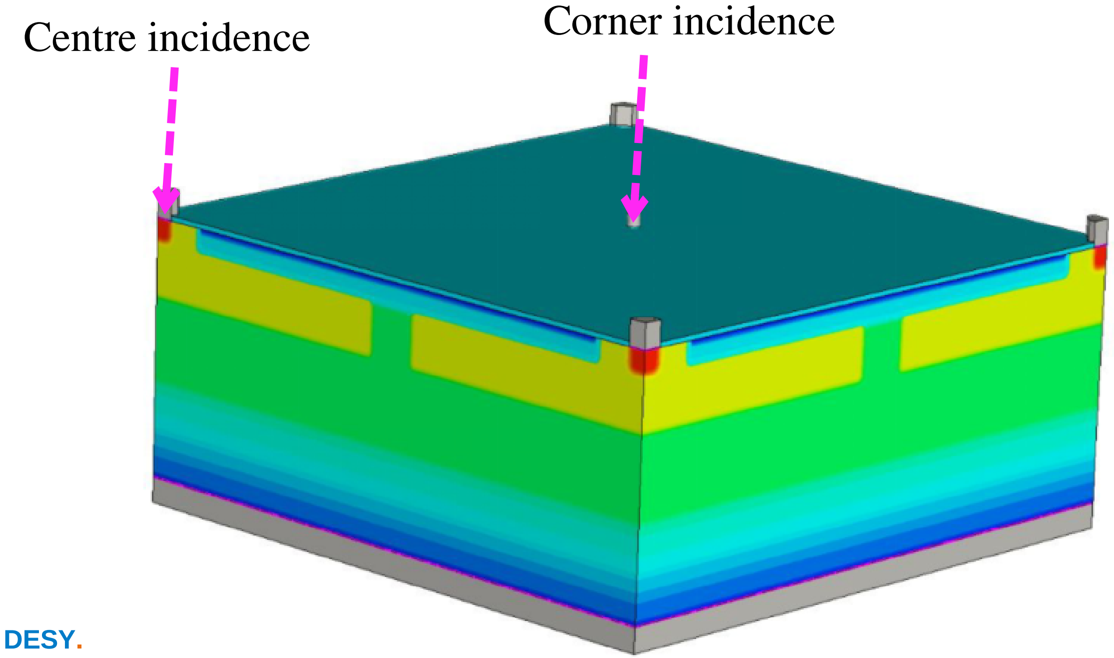


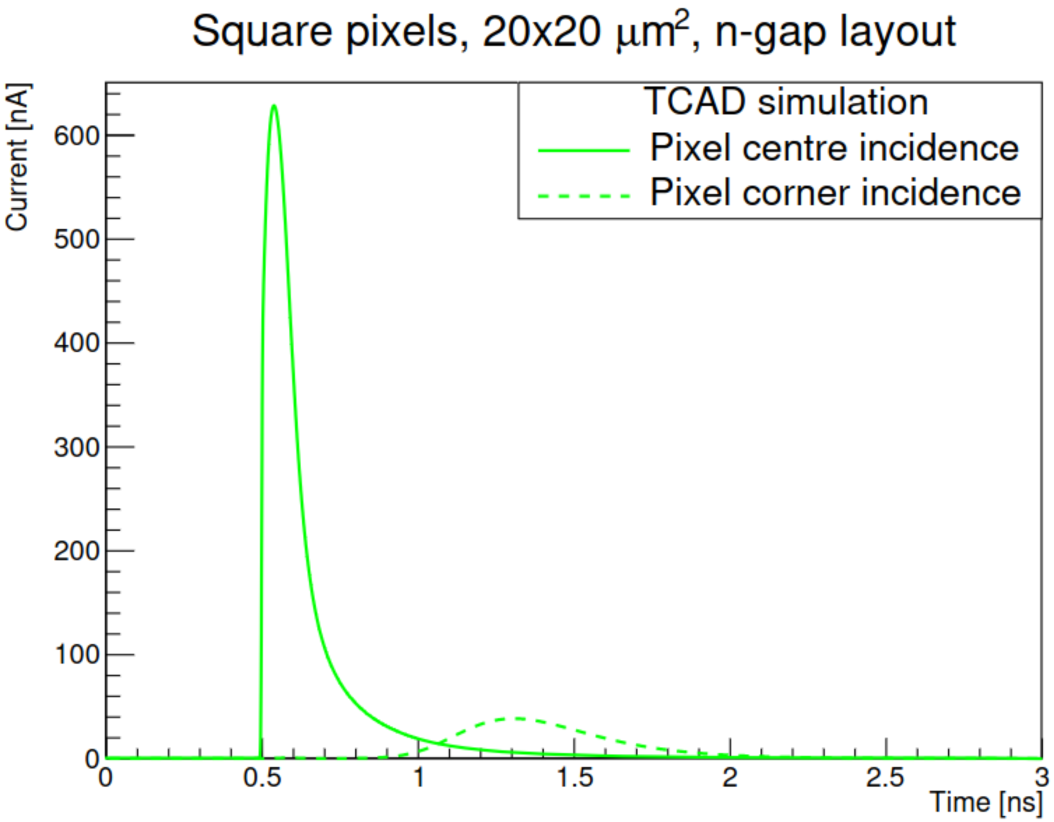
(a) 1 µm gap (b) 2.5 µm gap (c) 4 µm gap

Finite element method simulations using TCAD

Transient simulations

- Extracting the **time-dependent induced signal** on the collection electrodes, from traversal of a MIP
- Investigating both **pixel corner** incidence and **pixel centre** incidence
  - Gives indication of "worst case" and "best case" particle hit scenarios

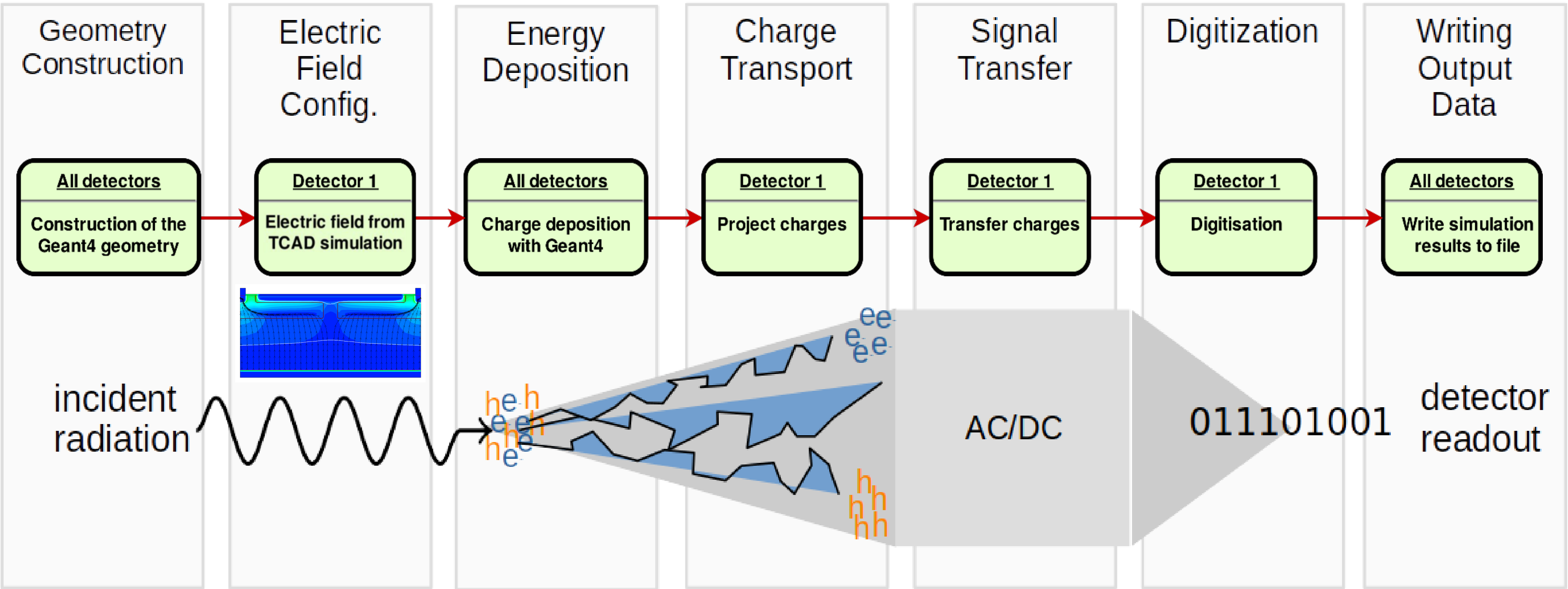




Transient pulses for pixel centre and corner incidence

Monte Carlo simulations using Allpix^2

- **Flexible** and **modular** framework, describing each part of **semiconductor signal generation and propagation**
- Allows import of **TCAD fields and doping profiles**
  - Allpix^2 and TCAD make a **powerful combination**; fast and detailed simulations possible, allowing high statistics



Geometry Construction
All detectors
Construction of the Geant4 geometry

Electric Field Config.
Detector 1
Electric field from TCAD simulation

Energy Deposition
All detectors
Charge deposition with Geant4

Charge Transport
Detector 1
Project charges

Signal Transfer
Detector 1
Transfer charges

Digitization
Detector 1
Digitisation

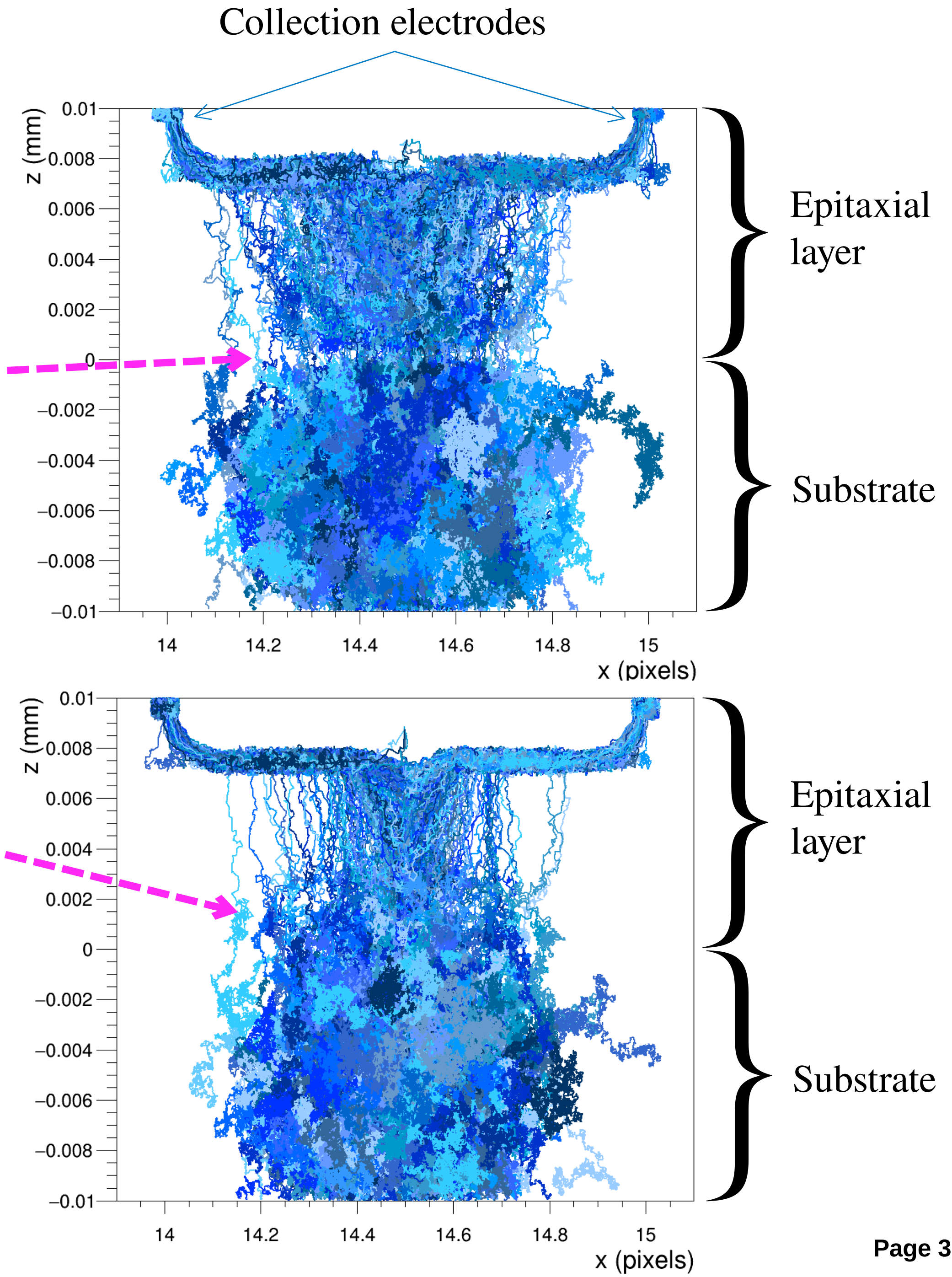
Writing Output Data
All detectors
Write simulation results to file

Figure from S. Spannagel, BTTB10, and A. Simancas, 4th Allpix Squared User Workshop

Monte Carlo simulations using Allpix²

Impact of dopant diffusion simulation

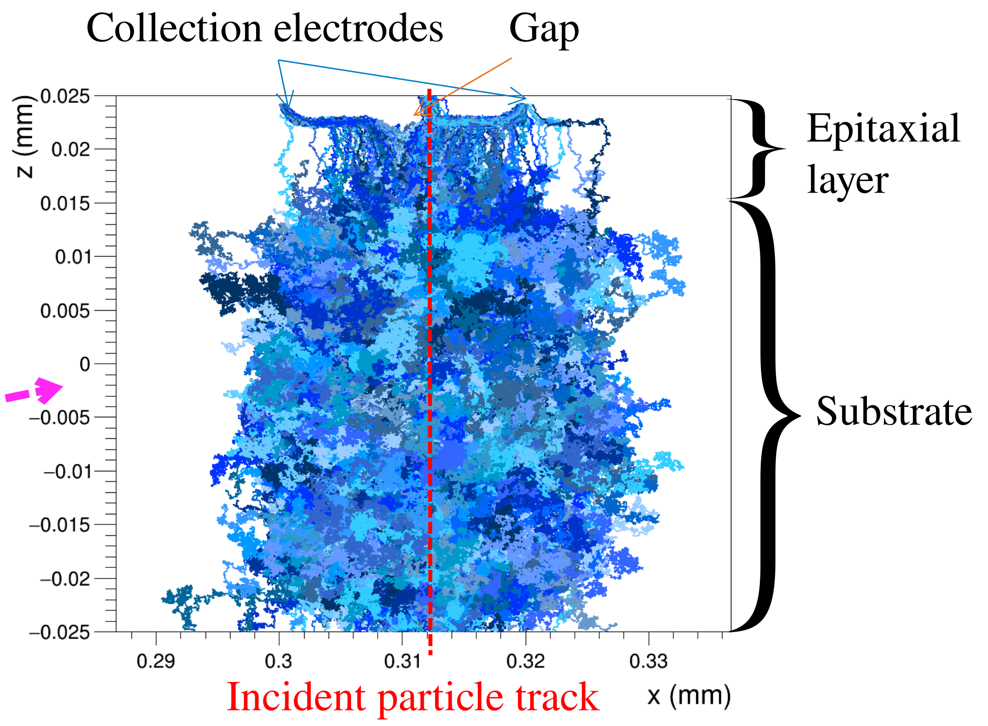
- Linegraphs to demonstrate charge carrier movement
- Without simulated dopant diffusion, a **significant electric field appears** in the epitaxial layer-substrate interface
  - This is **unphysical**
- With simulated dopant diffusion (see slide 28), there is a **smooth transition region** rather than a step function
  - More natural, and provides a better match to data

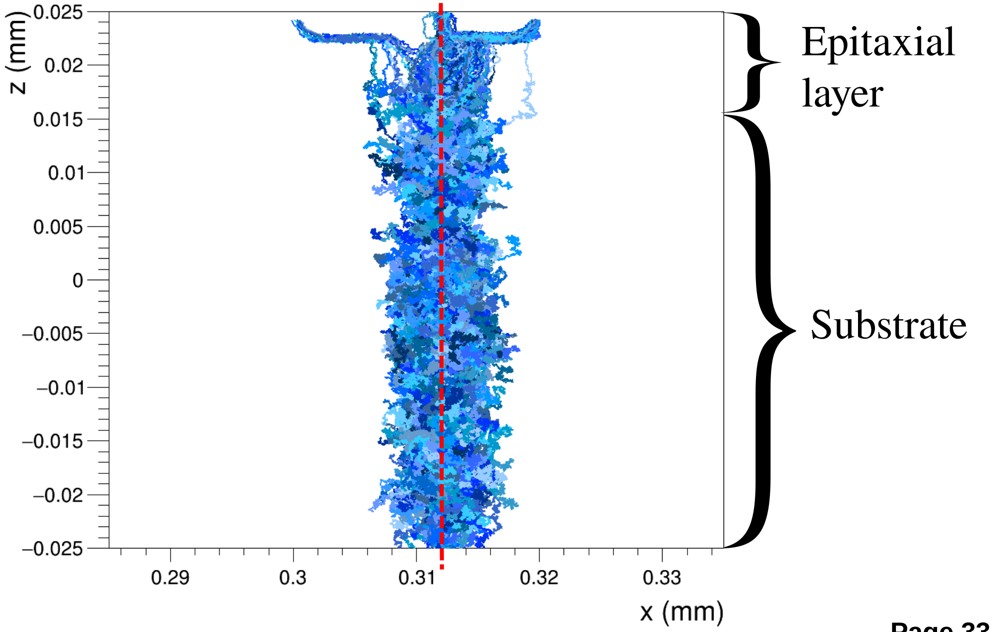


Monte Carlo simulations using Allpix^2

Impact of mobility model

- Physical parameters and models can easily be **exchanged**
- Example: **mobility models** in silicon
  - Jacoboni-Canali model is **doping-independent**
    - Sufficient for describing charge propagation in low-doped regions
    - In high-doped regions (e.g. substrate) diffusion is unphysically large
  - Extended Canali model (including the Masetti model) is **doping-dependent**
    - Describes charge carrier motion well also in highly-doped regions
- Linegraphs show the **propagation paths of individual charge carriers**
  - Each blue line is the path of a single electron

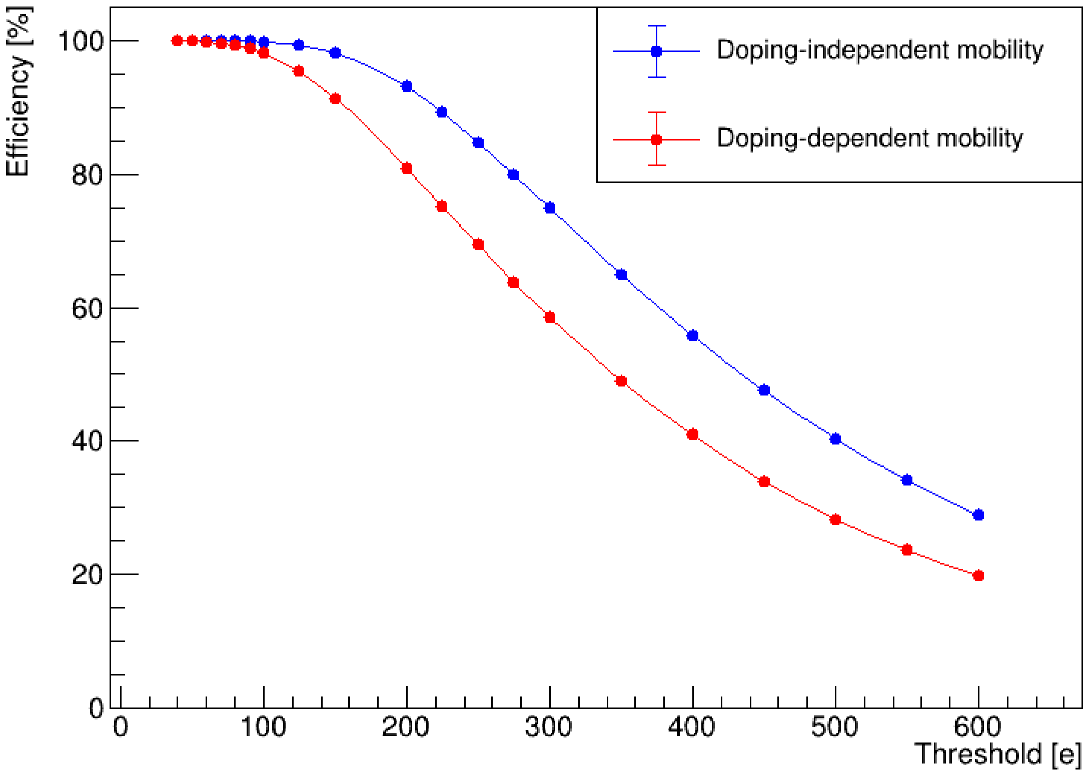




Monte Carlo simulations using Allpix^2

Impact of mobility model

- Mobility model also impacts **final observables**
- High-statistics simulations allow extraction of observables such as cluster size, resolution, efficiency
- Figure shows **sensor efficiency vs detection threshold**, for two different mobility models
  - Simulation carried out with a DESY II-like beam of electrons
  - Each point corresponds to 500 000 events, so the statistical error bars are very small
- The doping-independent mobility model **over-estimates efficiency**, due to an excess of charge collected from the highly-doped substrate

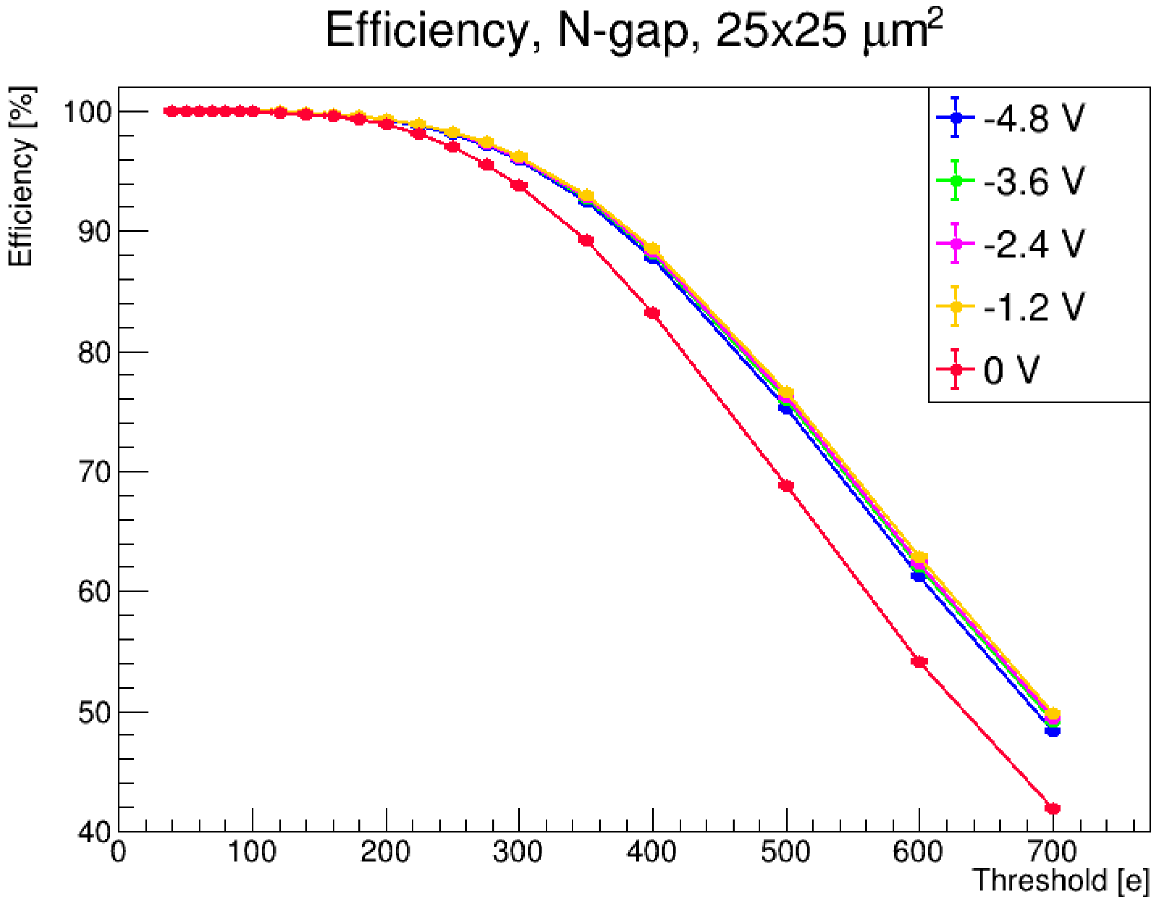


Sensor efficiency vs threshold for two different mobility models

Allpix^2 combined with TCAD

Example result from the Tangerine project

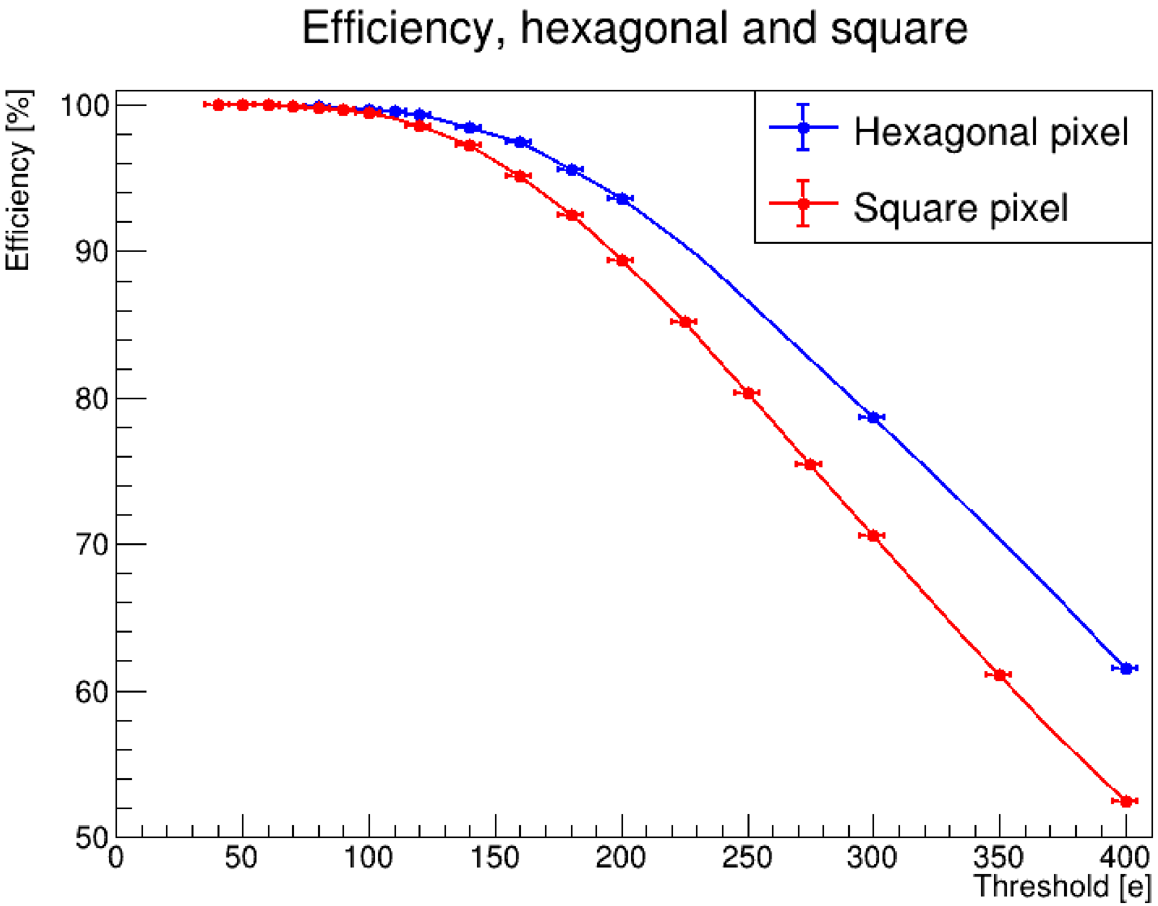
- High-statistics simulations allow extraction of observables such as cluster size, resolution, efficiency
- Sensor **mean efficiency versus detection threshold**, for different bias voltage
  - Simulation carried out with a DESY II-like beam of electrons; many events (500 000), so statistical error bars are small
- The trend is as expected:
  - Efficiency **decreases as threshold increases**
  - The sensor reaches its **full efficiency** potential already at -1.2 V
- 0 V deviates from the others by being less efficient as threshold increases, most likely due to **incomplete depletion**



Allpix^2 combined with TCAD - different pixel geometries □ ⬡

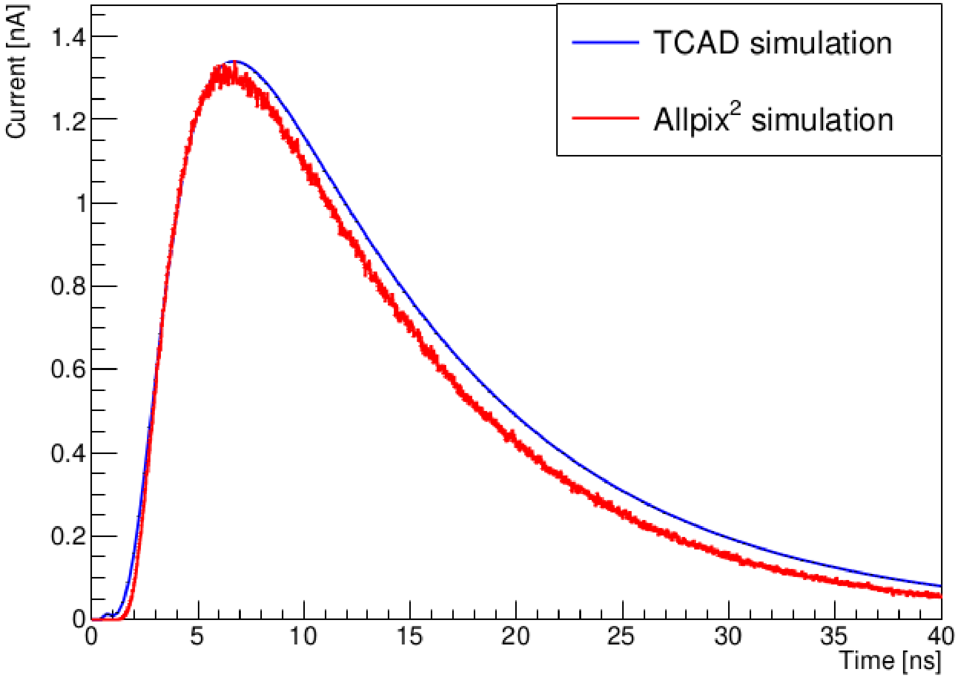
Example result from the Tangerine project

- Simulations allow for comparison of the performance of different sensor geometries
- A hexagonal layout leads to **reduced charge sharing in pixel corners** and a reduced distance from pixel boundary to pixel centre
  - Allows efficient operation at higher thresholds, and possibly better spatial resolution
- Tests have been performed comparing square pixels and hexagonal pixels, **maintaining the pixel area**
  - The space available for readout electronics thus remains the same per pixel
- Figure compares hexagonal pixels 18 µm corner-to-corner, and 15x15 µm^2 square pixels, in the standard layout (ALPIDE-like)



Transient simulations, comparing TCAD and Allpix^2

- Generating weighting potentials for use in Allpix^2, from the electrostatic potentials from TCAD
  - Using Allpix^2 for the transient simulations gives a **lower computational cost**, and allows use of **Geant4 energy deposition**
- First step: compare Allpix^2 results to TCAD results
  - Allpix^2 results are the average of 10 000 events, TCAD is a single event
  - Same settings are used for charge carrier creation and mobility
  - Results in general agreement
- Allows for simulation of sensor **time response**

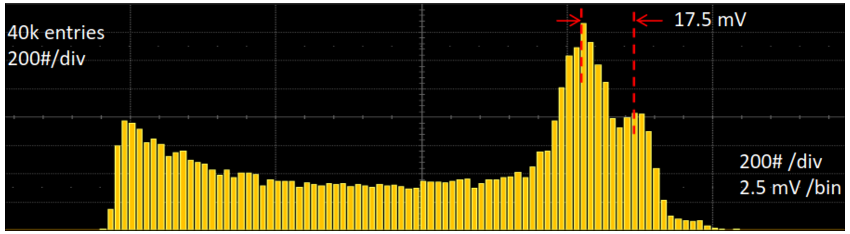


(a) *Standard* layout

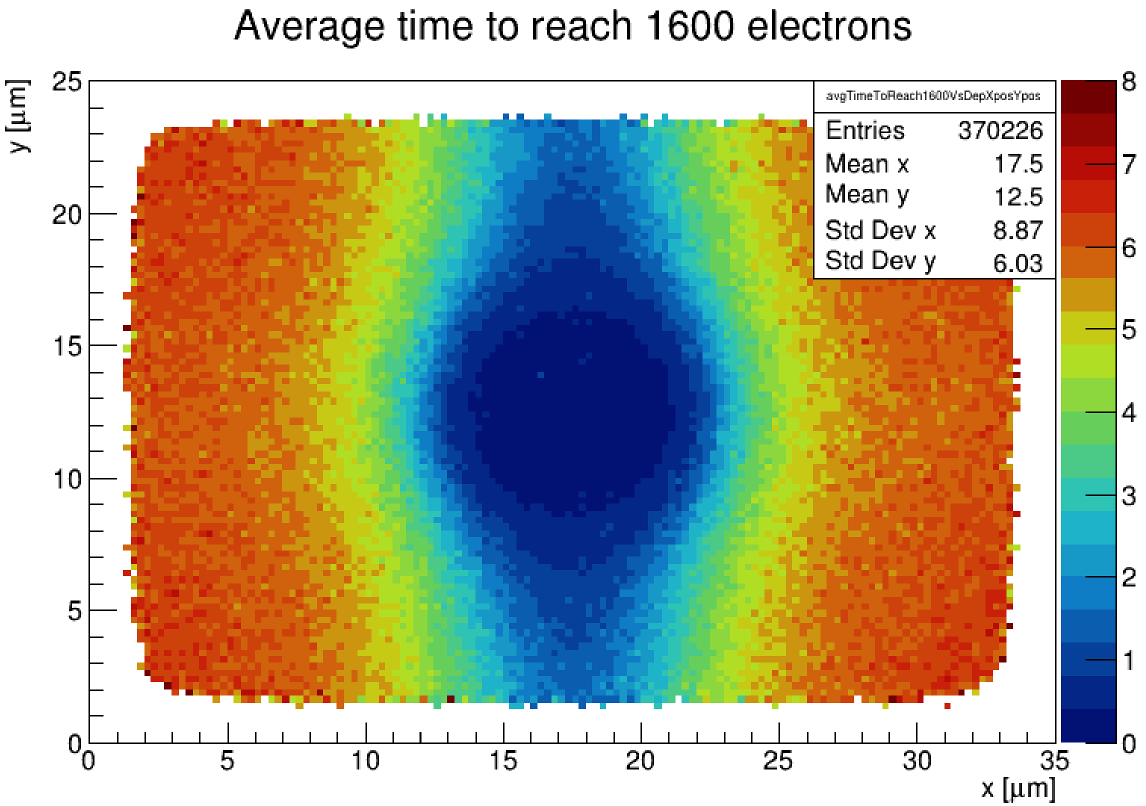
Allpix^2 combined with TCAD - Charge collection time of DESY ER1

Example result from the Tangerine project

- Reminder: higher Krummenacher current (i.e. faster return to baseline) leads to **two-peak structure** of single-energy x-ray (see slide 19)

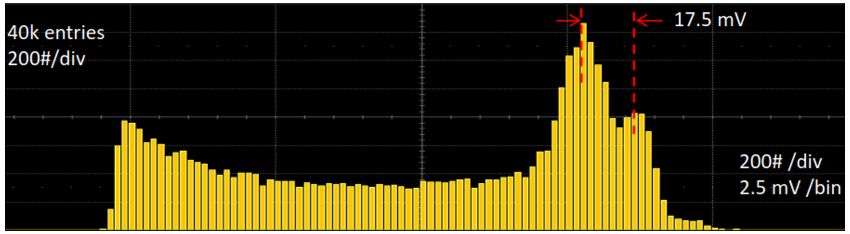


- Charge deposition simulated over a full pixel, with 1640 electrons in each point
- Plot shows time taken to collect 1600 electrons
- There are **clear regions of different collection time**
- This can explain the two-peak structure seen in lab tests
  - Slower collection means that **more charge drains away** before peaking, leading to a **lower maximum amplitude**



Allpix^2 combined with TCAD - Charge collection time of DESY ER1

Example result from the Tangerine project



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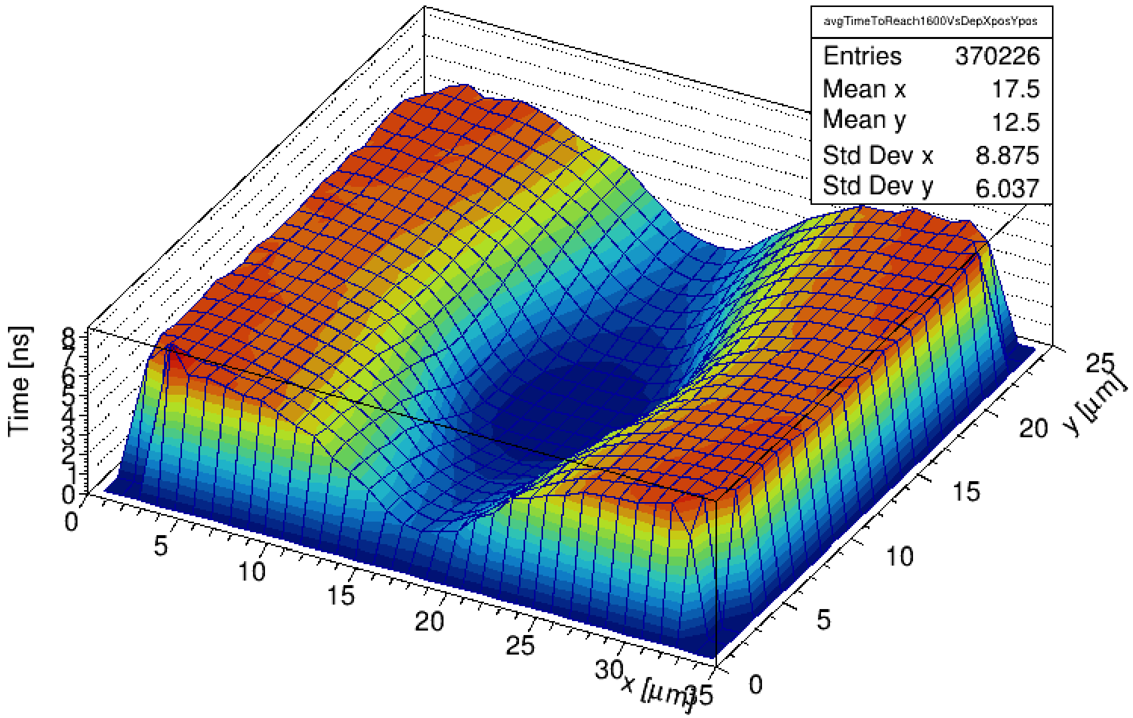
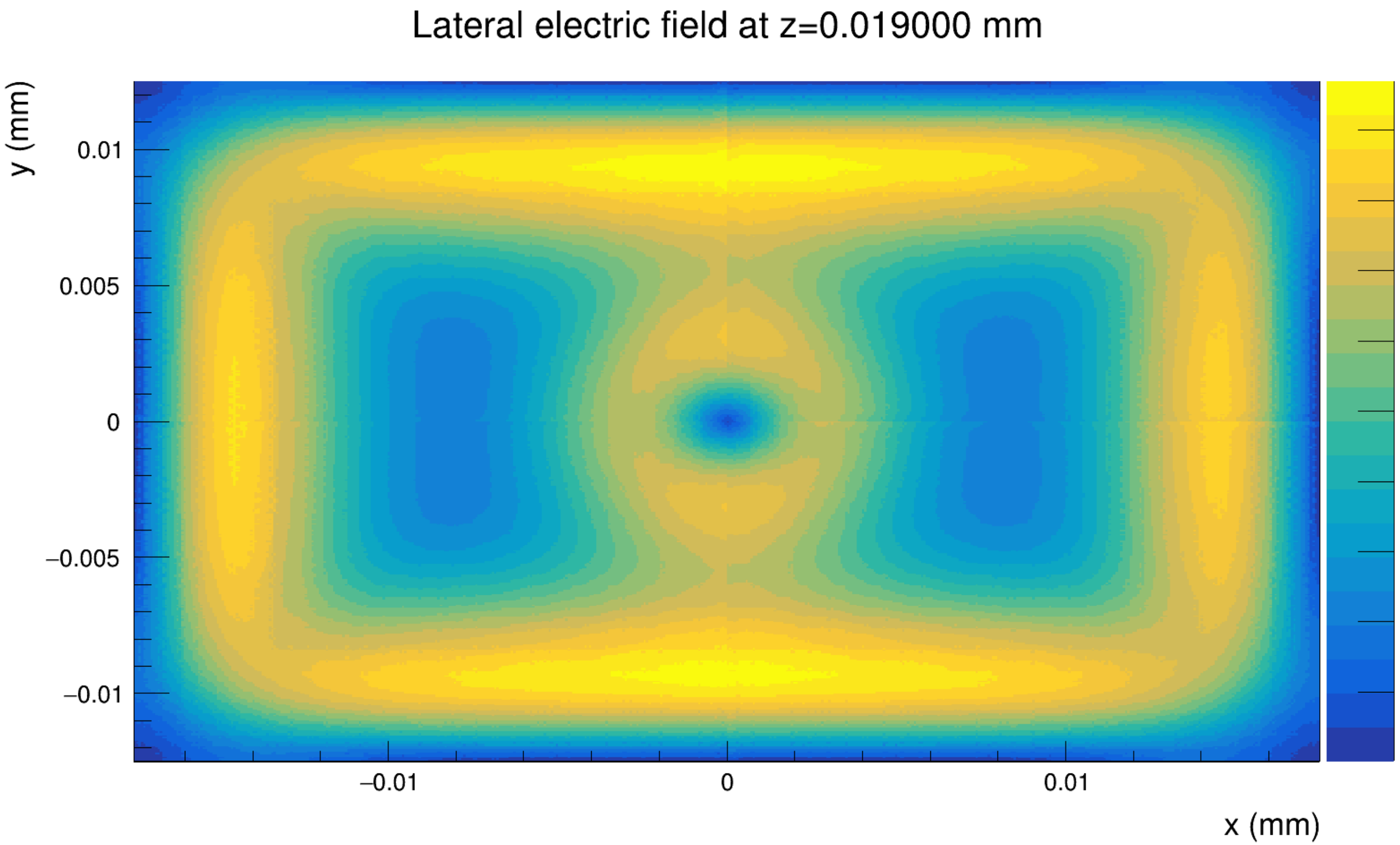
Average time to reach 1600 electrons



Allpix^2 combined with TCAD - Charge collection time of DESY ER1

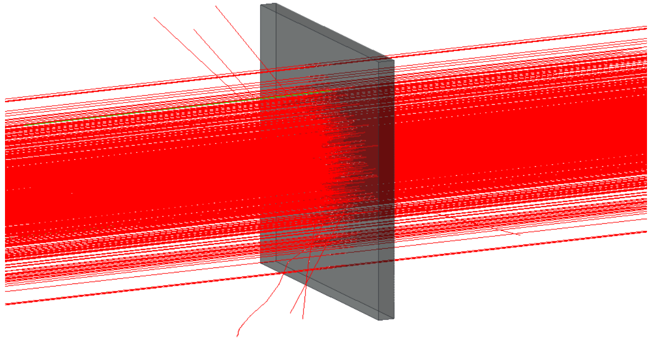
Example result from the Tangerine project

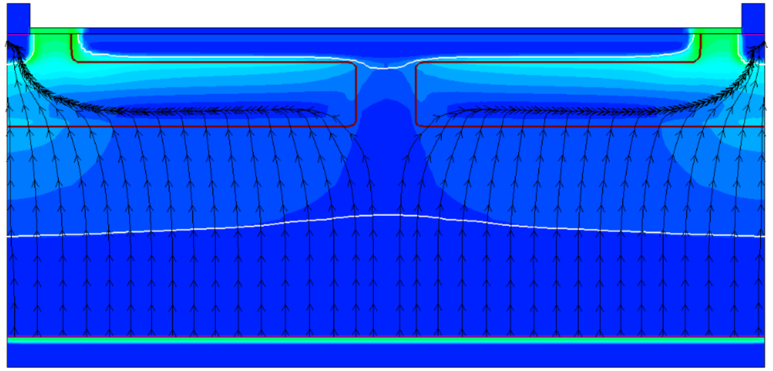
- Lateral electric field magnitude
- In x, we have **a region with low field** between gap and collection electrode
- This is also in y, but **much smaller due to the smaller distance** - we never go as low as in x
- This leads to overall faster charge collection, as charges are **constantly pushed** towards the collection electrode
- Simulations are a **powerful tool** for providing **understanding** of results



Simulations compared to data

Does the procedure *actually* work?





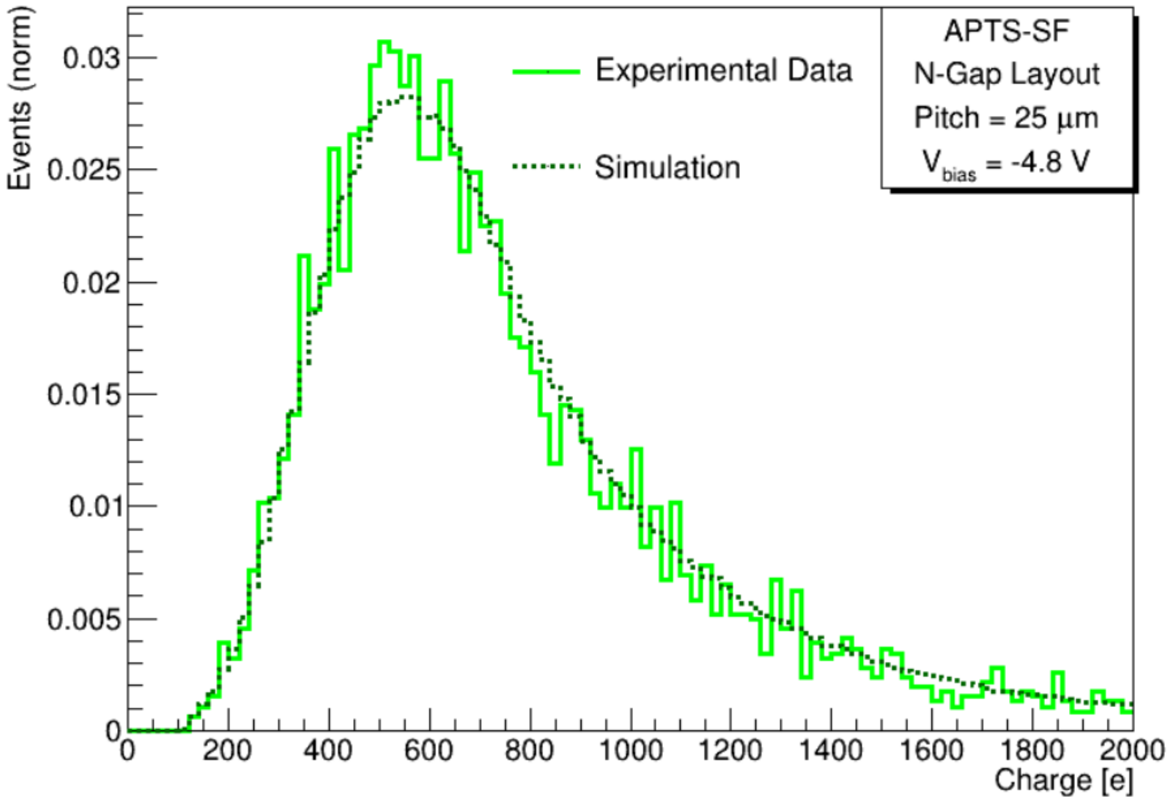
HELMHOLTZ

Allpix^2 combined with TCAD - Preliminary comparison to data

Example result from the Tangerine project

- Testbeams have been carried out at DESY, and comparisons made to simulations
- Results from the "Analog Pixel Test Structure" (APTS)
  - N-gap layout
  - 25x25 μm^2 pixel size
  - 4x4 pixel matrix
  - -4.8 V bias voltage
- The trend between simulations and data **matches well**

Cluster charge distribution



https://arxiv.org/abs/2402.14524

Allpix^2 combined with TCAD - Preliminary comparison to data

Example result from the Tangerine project

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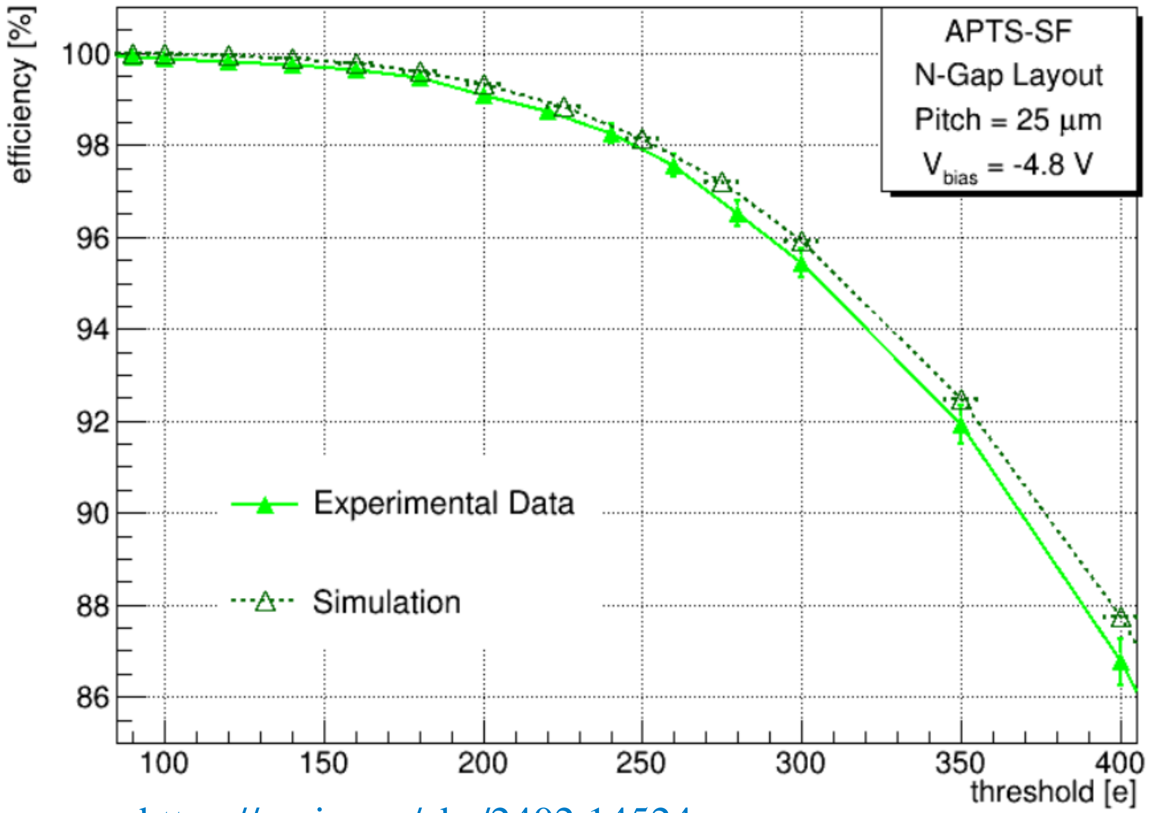
- Results from the “Analog Pixel Test Structure” (APTS)
  - N-gap layout
  - 25x25 µm^2 pixel size
  - 4x4 pixel matrix
  - -4.8 V bias voltage
- The trend between simulations and data **matches well**
  - Error bars on the simulated results are purely statistical here
- In conclusion, the developed **simulation procedure works well**, without any proprietary information

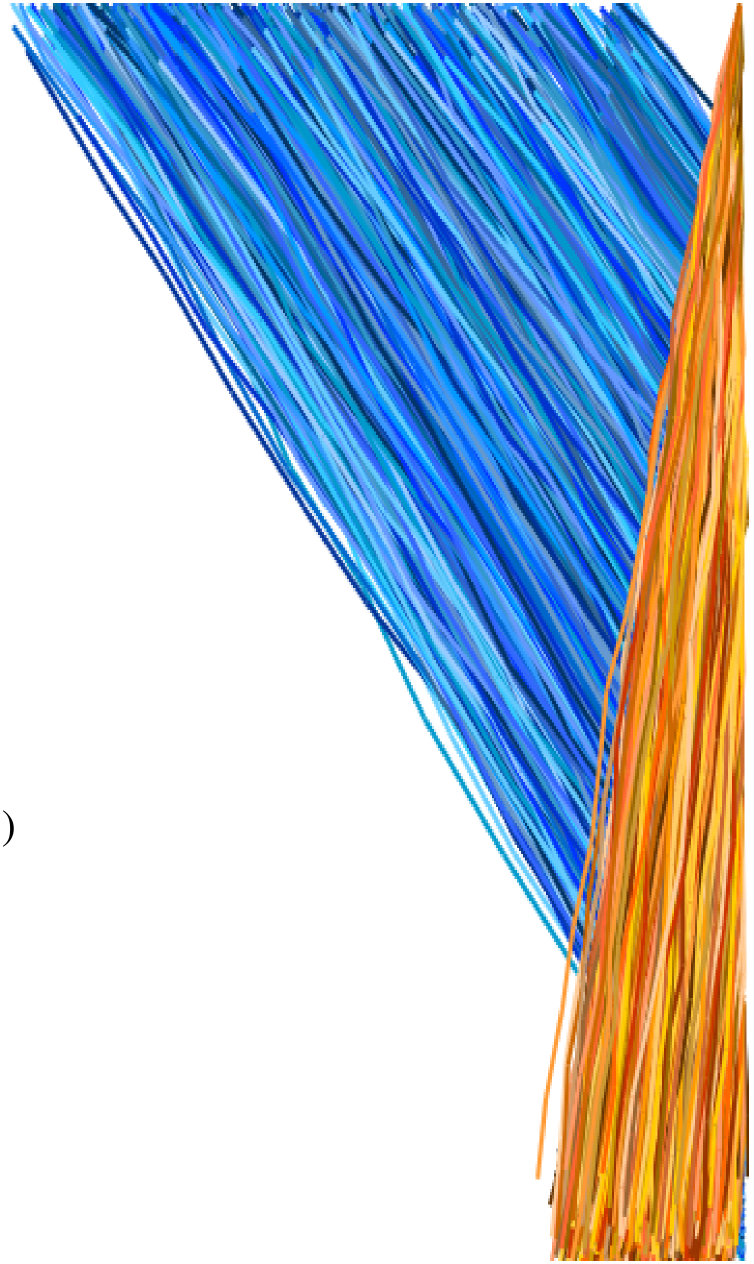
Mean efficiency vs threshold



https://arxiv.org/abs/2402.14524

Conclusions and outlook

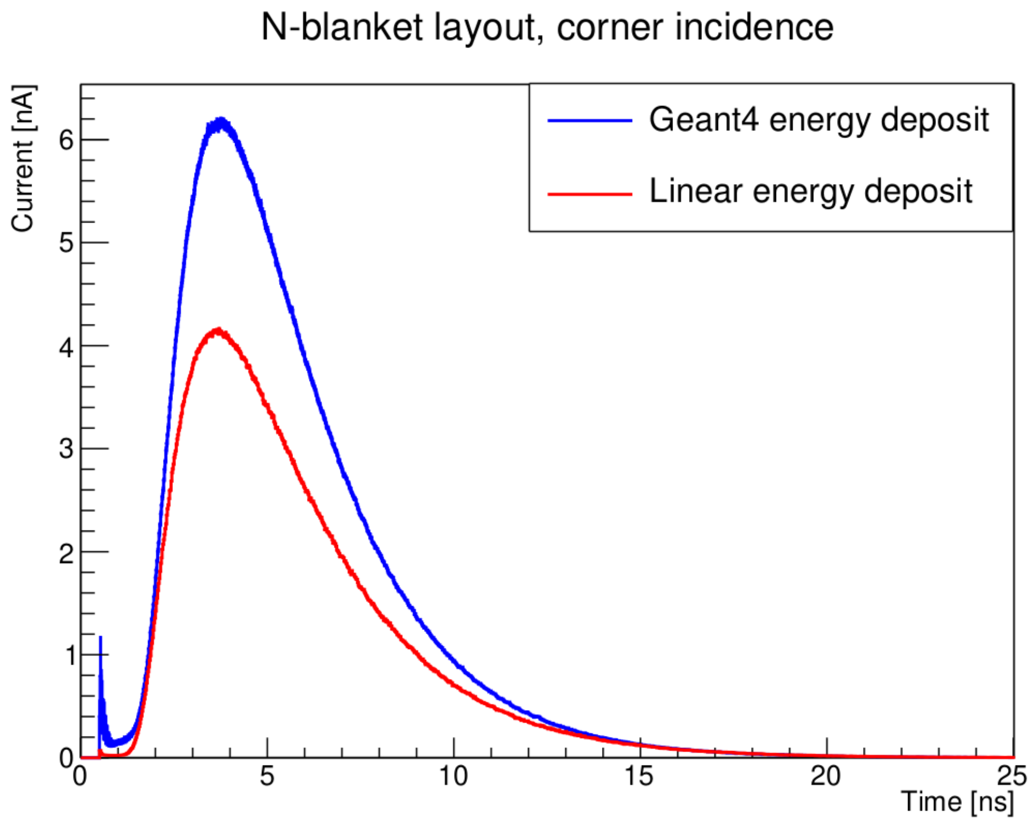
- The Tangerine project is **successfully participating in investigation of a 65 nm CMOS imaging process** for particle physics applications
- Prototypes have been **designed and tested** within the project
- Simulations are a **powerful tool** for sensor understanding and development
  - A technology-independent approach using generic doping profiles has been developed for silicon sensor simulations; a **generic toolbox**, free from proprietary information
- Next steps for **sensor testing**:
  - Continue characterising H2M, figuring out where the unexpected behaviour comes from
  - Further characterise the DESY ER1 chips (a new master's student has started work on this)
- Next steps for **simulations**:
  - Properly define the **uncertainties of the simulation results** and perform **further comparisons to data** to validate the predictive power of the simulations
  - Allpix Squared is developing, and will be **instrumental in DRD3 simulations**
- The Tangerine project has a **proposed succession** within the DRD3 framework



Backup slides

Transient simulations, comparing linear energy deposition to Geant4

- Using the n-blanket layout
- Each signal is the average of 10 000 events, incident in the pixel corner
- Geant4 energy deposition includes stochastic effects, while linear deposit generates 63 electron-hole pairs per µm



The Tangerine project: published references

- The Tangerine project: Development of high-resolution 65 nm silicon MAPS
  - https://doi.org/10.1016/j.nima.2022.167025
- Towards a new generation of Monolithic Active Pixel Sensors
  - https://doi.org/10.1016/j.nima.2022.167821
- Developing a Monolithic Silicon Sensor in a 65 nm CMOS Imaging Technology for Future Lepton Collider Vertex Detectors
  - https://arxiv.org/abs/2303.18153