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

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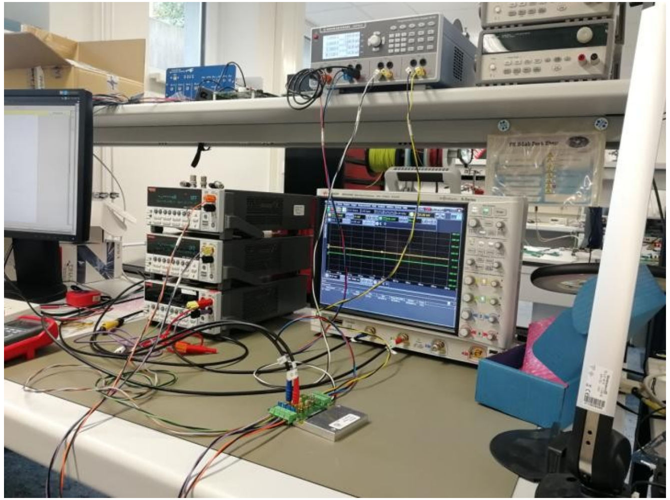
for the Tangerine collaboration

24/2 -22

Outline

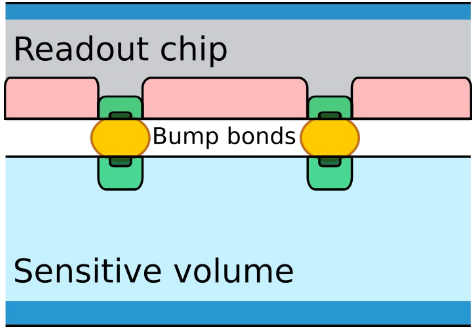
- Introduction
  - Monolithic active pixel sensors
  - The Tangerine project
- Sensor design
- Lab and testbeam investigations
- Simulation studies
- Conclusions and outlook



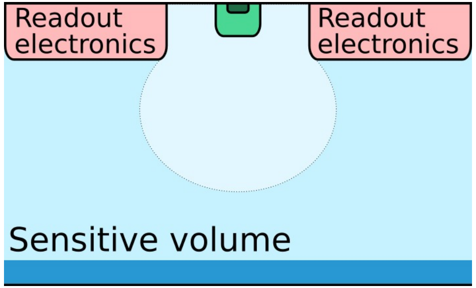
Monolithic active pixel sensors (MAPS)

- 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: candidates for ATLAS
  - Current developments for the next ALICE tracker upgrade and the EIC

Hybrid sensor sketch

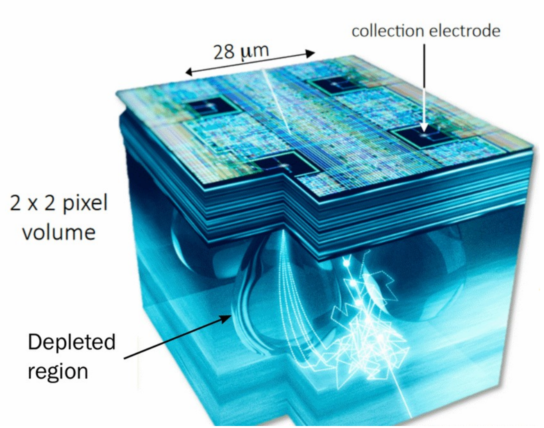


Monolithic sensor sketch



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 relatively recent 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
  - 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**

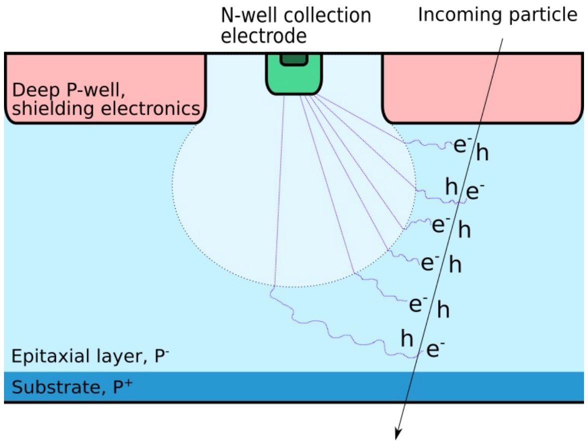
The Tangerine project (Towards next generation silicon detectors)

- 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 (2023): development of a sensor for telescope use, for testbeams
  - This will **demonstrate the capabilities of the 65 nm technology in a particle physics context**

Sensor design

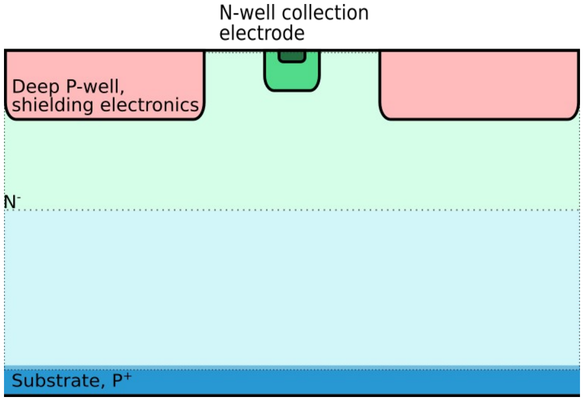
- The sensor design comprises both sensitive volume and electronics design
- For the sensitive volume design, there are three available processes (all with a small collection electrode) originally designed for a 180 nm CMOS imaging process:

- Standard process
  - ALPIDE-like



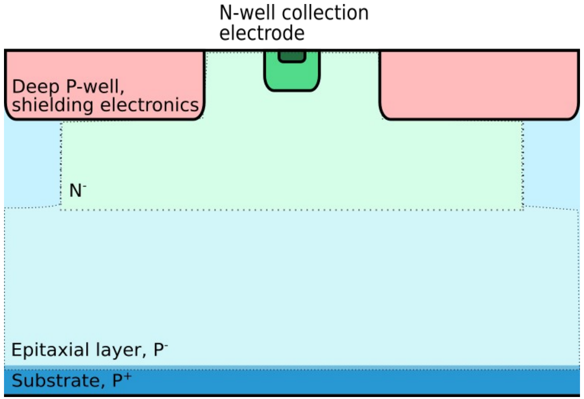
S. Senyukov et al. doi:10.1016/j.nima.2013.03.017

- Modified process
  - 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 process
  - Blanket n-layer **with gaps at pixel edges**

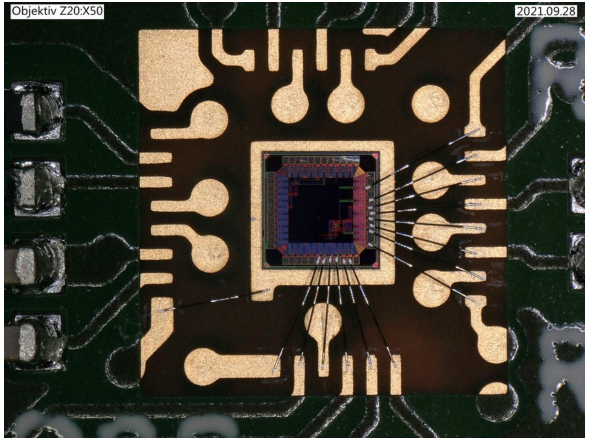


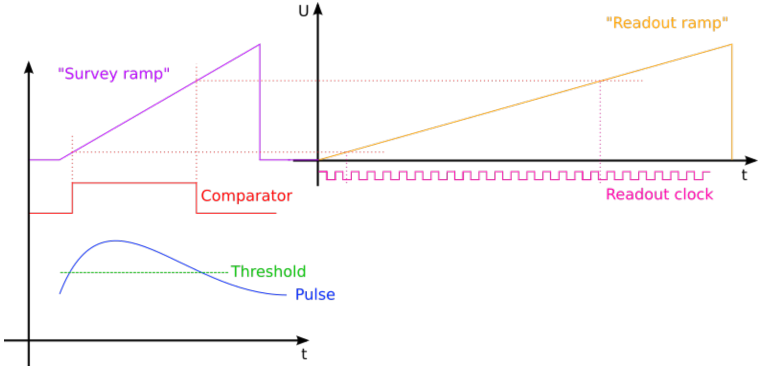
M. Münker et al 2019 JINST 14 C05013

Current sensor architecture

The DESY “MLR1” chip

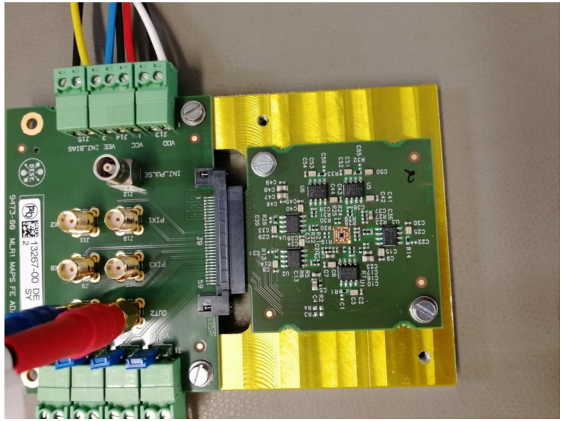
- The main purpose is to test a newly designed **charge-sensitive amplifier** circuit
  - Two amplifier variants are available, each with a Krummenacher type feedback network for continuous reset and leakage current compensation
- Also contains a 2x2 pixel matrix with analogue readout
  - Pixel size: 16.3x16.3 μm^2
- Electronics and readout design for future submissions is **ongoing**
  - Final target matrix size: 256x256 pixels
  - Each pixel is intended to have a **signal amplitude readout** via a time-over-threshold measurement
    - One suggestion is to achieve this by sending analogue “ramps” from the periphery to each pixel, and through this store the threshold crossings of a pixel for later readout





Sensor prototype characterisation - How to test?

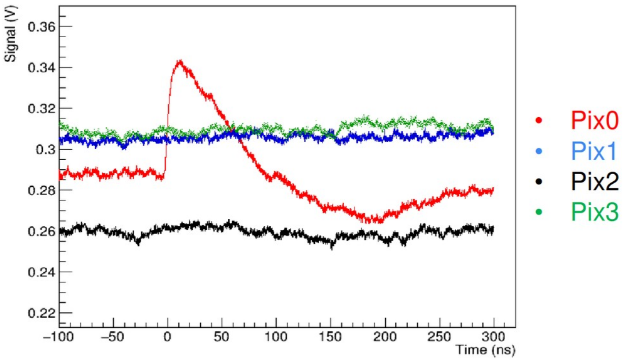
- Tests performed in **labs** and at **testbeams**
- Lab tests performed using radioactive sources and current injection pulses
  - Makes it possible to extract **signal waveforms** from the prototype chip
- Testbeams performed at accelerator facilities
  - A beam of particles is shot through the sensor
  - Using a “telescope” made up of reference planes, the particle track position at the sensor can be extracted
    - This can provide measurements of sensor detection efficiency and resolution, and figures of merit for different in-pixel hit positions
  - Initial goal of the Tangerine project: create reference planes for a new telescope for testbeam usage



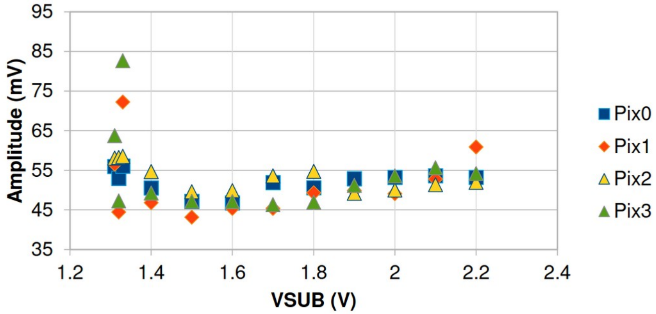
Lab results - Waveforms

- The analogue pixel signals can be read out, and the output can be used to investigate the behaviour of the in-pixel charge-sensitive amplifiers
- Tests performed using a ^{55}Fe source in the lab, and electrons from a testbeam facility
- Different bias voltages and control currents are used on the chip, to investigate their impact on waveform parameters
- Example: the signal amplitude for different bias voltages (labelled VSUB)
  - All four pixels shown
  - Each data point has approximately 2500 events
- These are the first results of a 65 nm MAPS at DESY!

Typical analogue output for a hit in the 4-pixel matrix (image by G. Vignola)

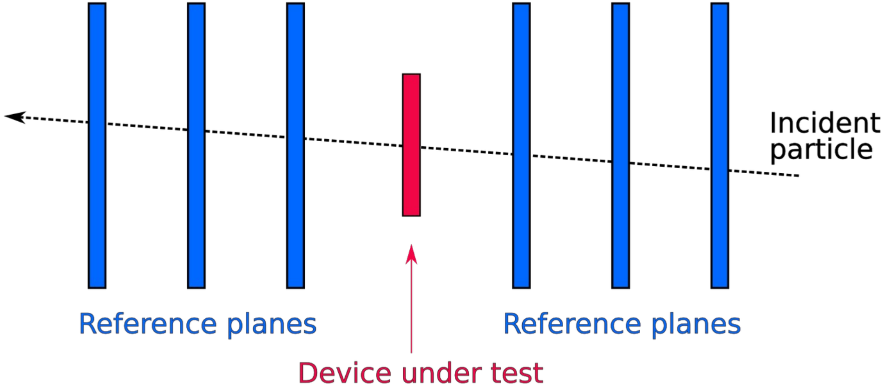


Mean amplitude for different sensor bias voltages (image by G. Vignola)

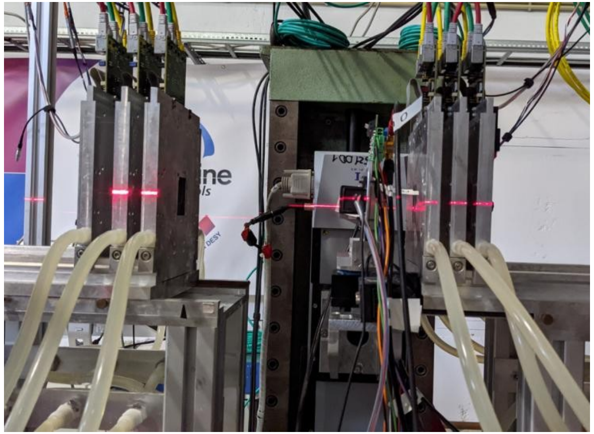


Testbeam setup

- The device under test is surrounded by reference planes (which form a telescope)
- A beam of particles is shot through the reference planes and the device under test
- A **reference track** is reconstructed by using particle hit data from the reference detector planes



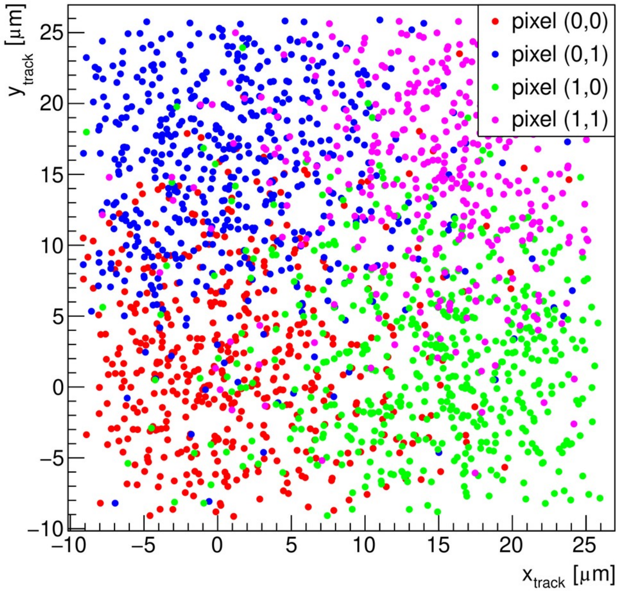
- Device under test placed between reference planes
  - Can thus find **particle position at device under test** from using the reconstructed track



Testbeam - MAMI

- Testbeam in autumn 2021 at the Mainz Microtron (MAMI)
  - Provides a very **small beamspot**, approximately 1 mm^2
  - Electron beam energy relatively low; 0.855 GeV
  - High beam current (up to 100 μA), giving a **high hit rate**
- Tests performed mainly on the 4-pixel matrix of the DESY MLR1 chip
  - Design needs some correction to perform well, but issues are understood, and lessons can still be learned about sensor operation in a testbeam
- Image shows interpolated track positions at the sensor, for tracks associated to a hit in a certain pixel (colour coded)
- The four different pixels have **distinct regions**
  - The current sensor design thus works as a **pixellated sensor**, even if design updates are needed to reach high efficiency

Pixel matrix hit positions, associated with hits in different pixels (image by F. Feindt)



Sensor simulations

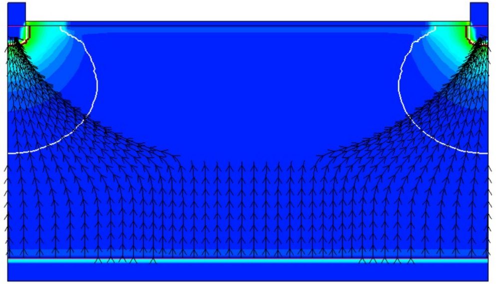
- The electric fields in the investigated sensor types are highly non-linear, so **detailed electric field simulations** are performed using technology computer-aided design (TCAD)
  - Numerically solves equations using **sensor doping information**
    - **Note:** the exact doping concentrations used at the silicon foundry are not available to this project, so **generic doping profiles** are used, and varied to gain insight into how sensor performance is affected by different parameters
  - Different pixel geometries and layouts can be simulated in great detail
- **High-statistics Monte Carlo simulations** are performed using Allpix^2
  - The simulated electric field and doping concentration from TCAD can be imported, and used in simulations for **each pixel in a pixel matrix**
  - Simulations of the **full pixel hit chain** can be carried out relatively quickly
    - This involves charge deposition, individual charge carrier behaviour, and digitisation
- Together TCAD and Allpix^2 are a **powerful combination**! Detailed sensor behaviour and performance can be simulated accurately with high statistics

Sentaurus TCAD

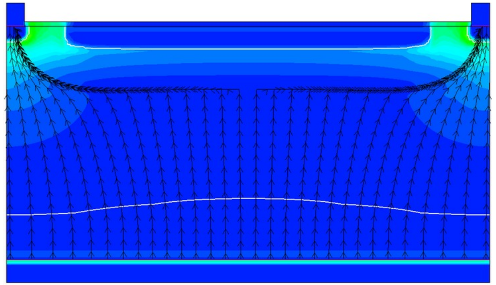
Detailed electric field simulations using TCAD

- Using **estimates** of doping concentrations of different parts of the sensor, in-pixel electric fields are simulated
  - The estimated concentrations are not related to any real process, but the studies give insight into the effect of varying different parameters of the pixel geometry
- Different doping concentrations are investigated and evaluated, and electric fields produced for different geometries, conceptually similar to the three processes developed for the 180 nm sensors (see slide 6)
- Some aspects in the sensor design can be controlled (such as the n-gap size), and some are fixed. The simulation studies endeavour to optimise the sensor performance by changing non-fixed aspects
- The figures below show example electric field magnitudes, streamlines, and depletion boundaries for the three main investigated geometries

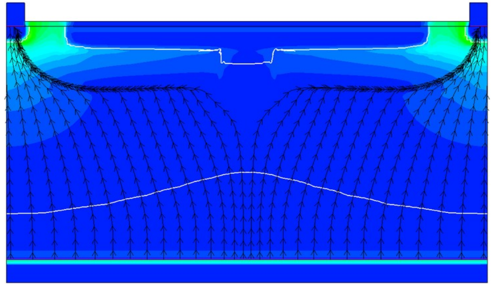
Standard process



Modified process



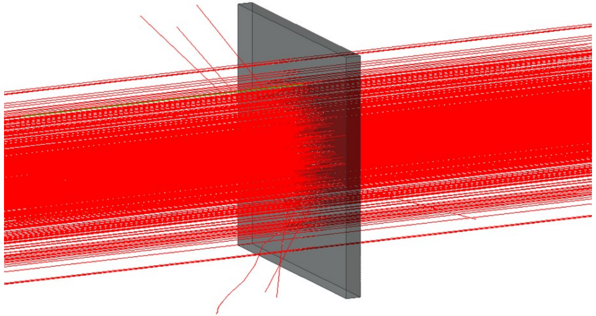
N-gap process



High-statistics Monte Carlo simulations using Allpix²

- Using **Allpix²** to generate incident particles and simulate their energy deposits in a **pixellated sensor model** (via an interface to GEANT4)
  - Each pixel in the sensor model contains the electric fields and doping concentrations from TCAD
- Deposited energy generates electron-hole pairs, and the individual **charge carrier propagation** is simulated
- This finally gives the **charge** per incident particle event that reaches the collection electrode **in each pixel**
- A threshold is then set in simulations, to exclude pixels that would not produce a hit with this threshold level
  - Noise is also added to the signal in this step
- The Monte Carlo truth information is stored along with the simulated per-pixel output, and analysis is performed

- Allpix² allows the simulation of a particle hit to be performed quickly, and thus makes it practical to generate **many particles hitting many different sensor positions**
  - High-statistics data are obtained
  - Makes it relatively easy to test and compare different configurations and setups
- The framework is well-tested and validated against known data and experiments, e.g. for small collection electrode MAPS sensors; https://www.sciencedirect.com/science/article/pii/S0168900220303181?via%3Dihub



Particle beam passing through a single sensor, in Allpix²

Figures of merit for study

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

Cluster size

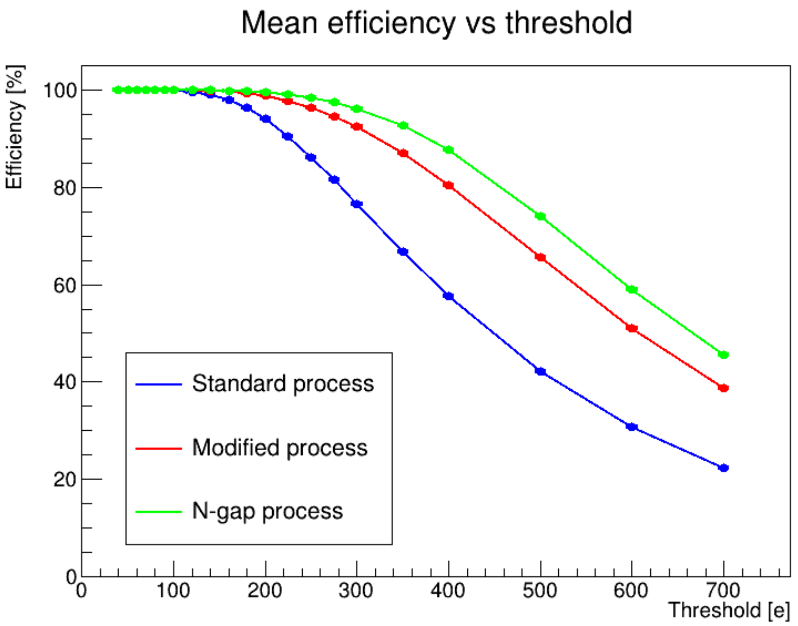
- Number of pixels that register hits for a single incident particle (charge sharing)
- This will depend on the position of the incident particle, but with a **large number of particles** a mean value can be found, as well as the cluster size versus hit position

Spatial resolution

- Comparing the incident particle position to the reconstructed particle position on the sensor
- In the simulations so far, this is done by comparing the Monte Carlo truth position to a charge-weighted **mean position of a cluster** of pixels
- Doing this for many events creates a distribution of values
    - Spatial resolution taken to be the RMS value of the central 99.73% of the distribution

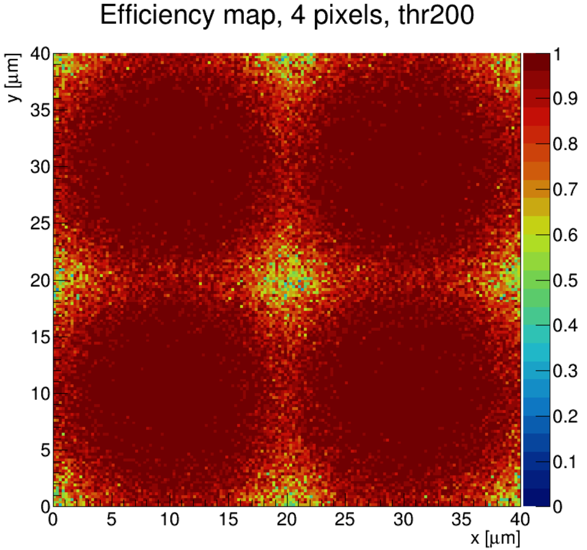
Example study: process comparisons for a 20x20 μm² pixel size

- Comparing the performance of the three different sensor process variations (see slide 6)
- Simulating a 5 GeV electron beam, incident head-on on a single pixellated sensor
  - 500 000 single-electron events per data point
    - Error bars are thus very small
- Varying pixel hit threshold, and plotting figures of merit versus threshold value
- Figure shows **mean efficiency** in the sensor for different threshold values
  - Colours indicate different processes
  - The modified process and the n-gap process have a larger operating margin than the standard process

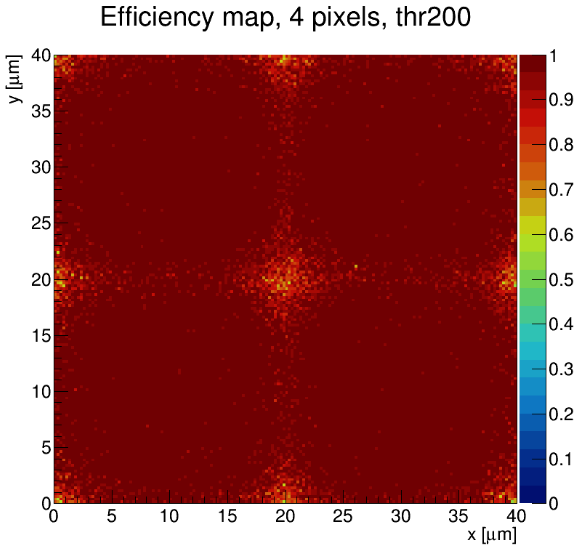


In-pixel efficiency maps

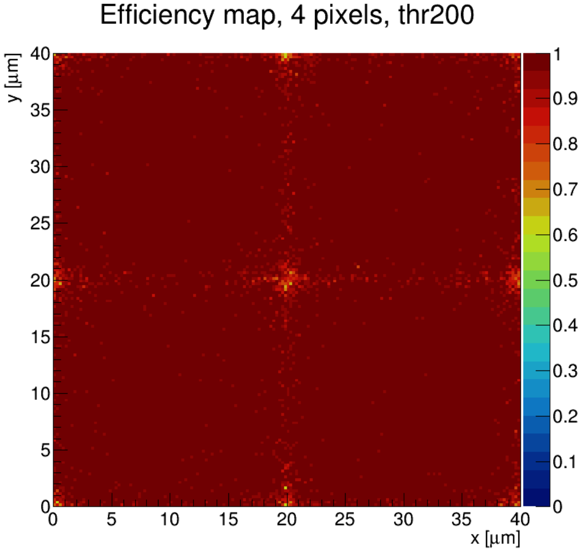
Standard process



Modified process



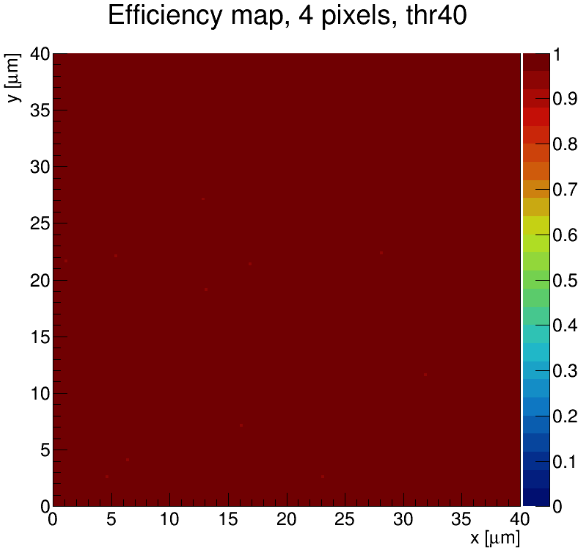
N-gap process



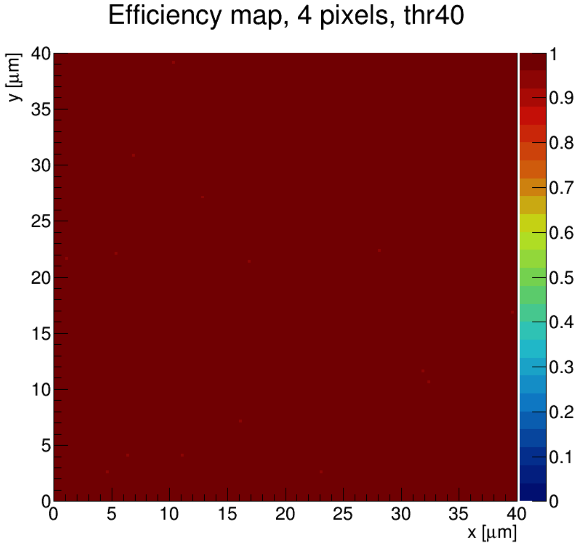
- Map of the in-pixel efficiency of 4 pixels, at a threshold of 200 electrons
- Red means 100% efficient
  - The standard process thus loses more efficiency **at pixel edges and corners** compared to the other processes

In-pixel efficiency maps, gifs (see .pptx file in presentation mode for them in motion)

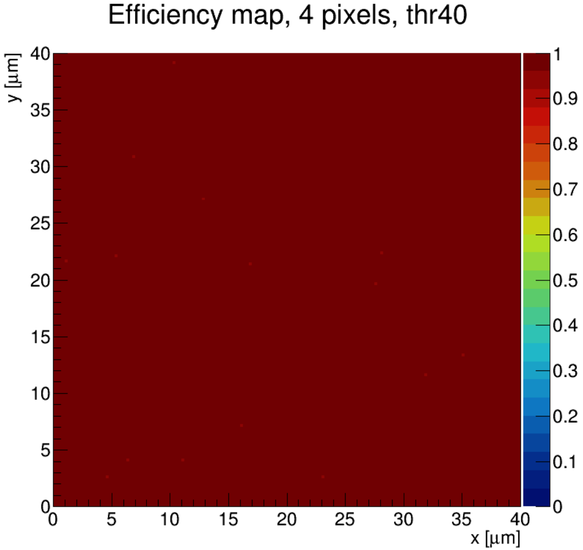
Standard process



Modified process



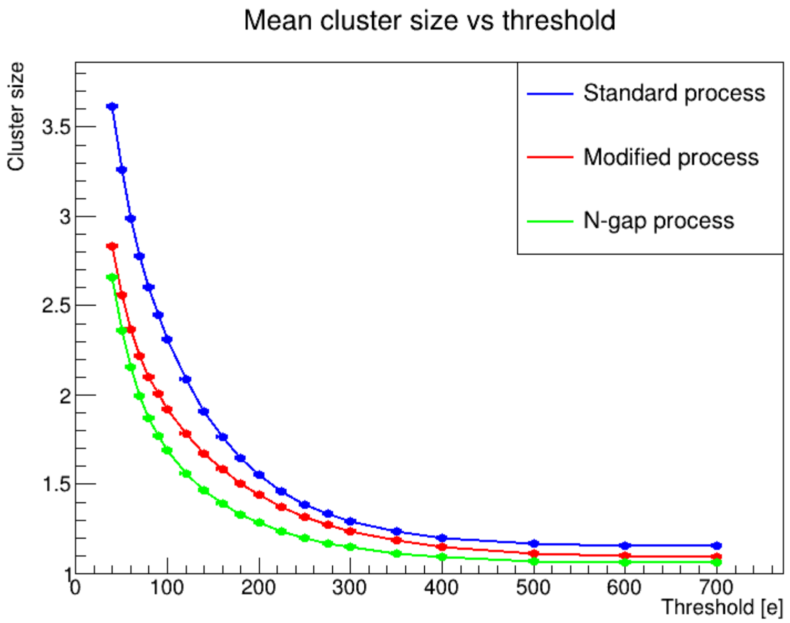
N-gap process



- From this, it is clear that the standard process loses efficiency at lower thresholds than the other two
- It is also clear that the modified process loses the square shape of the efficient region (i.e. efficiency at pixel corners) at lower thresholds than the n-gap process

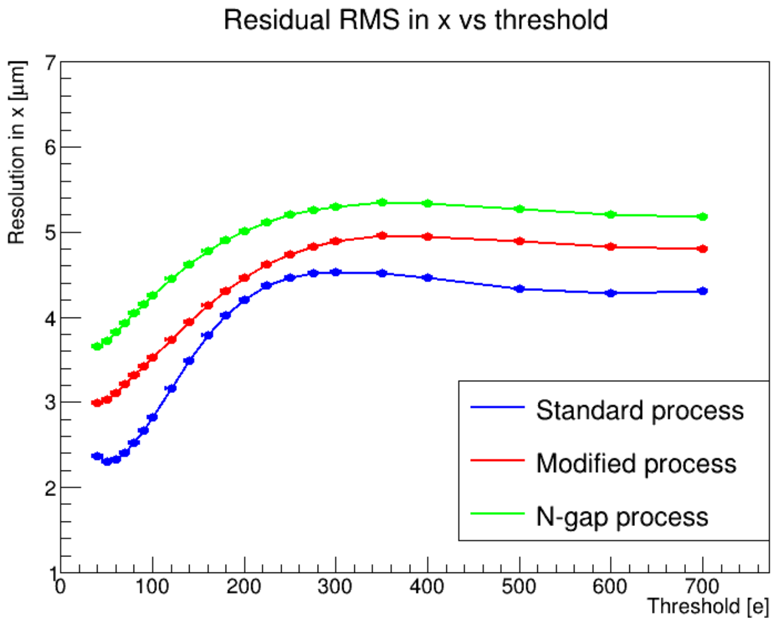
Example study: process comparisons for a 20x20 μm² pixel size

- The figure shows the **mean cluster size** of the sensor, for different threshold values
  - I.e. the number of pixels that register a signal for an event
- This number tends to 1 as threshold increases, as the charge generated by a traversing particle will eventually not be enough to register as a hit in more than one pixel
  - A MIP is expected to generate a signal of approximately 700 electrons in a 10 μm thick sensitive volume
- The standard process has a larger cluster size than the others, due to the **larger undepleted volume at pixel edges**
  - This leads to charges moving by diffusion, and thus a larger charge cloud



Example study: process comparisons for a 20x20 μm² pixel size

- The figure shows the sensor **spatial resolution** in the x direction, for different threshold values
  - As the simulated pixel in this case is square and symmetric, it looks identical in the y direction
- The resolution relates to cluster size, as the reconstructed hit position is taken as a pixel **charge-weighted mean cluster position**
  - The standard process thus has the best spatial resolution of the three
    - However, the efficiency of the standard process is lowest



- Conclusion: A **balance** needs to be reached between efficiency and resolution
  - The threshold should be kept as low as possible, but what is possible depends heavily on the electronics design and noise
- Using the method of combining TCAD simulations and Monte Carlo simulations, we can **quickly produce high-statistics data of different situations**

Other simulation studies performed

- Comparisons of different **doping concentrations** in different parts of the sensor
- Comparisons of **different pixel sizes**
- Comparisons of different **bias voltage configurations**
- Studies of different **in-pixel geometries**; e.g. different extents of the gap in the n-layer
- Studies of **hexagonal pixels** are beginning
  - Work has been ongoing with generic doping profiles in TCAD for a while, and will soon be studied using Allpix^2

- There is **significant progress in understanding the impact of different parameters**, and the conceptual design of a new sensor is being converged on!

Current status and future work

- We have tested the first prototype chip (MLR1) thoroughly
    - Both lab tests and testbeam measurements have been performed
    - In-pixel inefficiencies have been found, but are well understood
- Starting tests on an analogue pixel test structure, to compare sensor flavours and see if simulation results match reality
- Testbeam in Mainz again in April, and testbeam at DESY in June
    - Will test the analogue pixel test structure further
- Simulations using generic doping profiles already give insights for use in sensor optimisation
- Currently preparing for our next sensor submission! “Engineering Run 1” is on the way, and will hold the next iteration of our chip
    - Testing new things in electronics; improved electronics design and sensor design
- Conclusion: **there are exciting times ahead!**

Backup slides

The Tangerine collaboration

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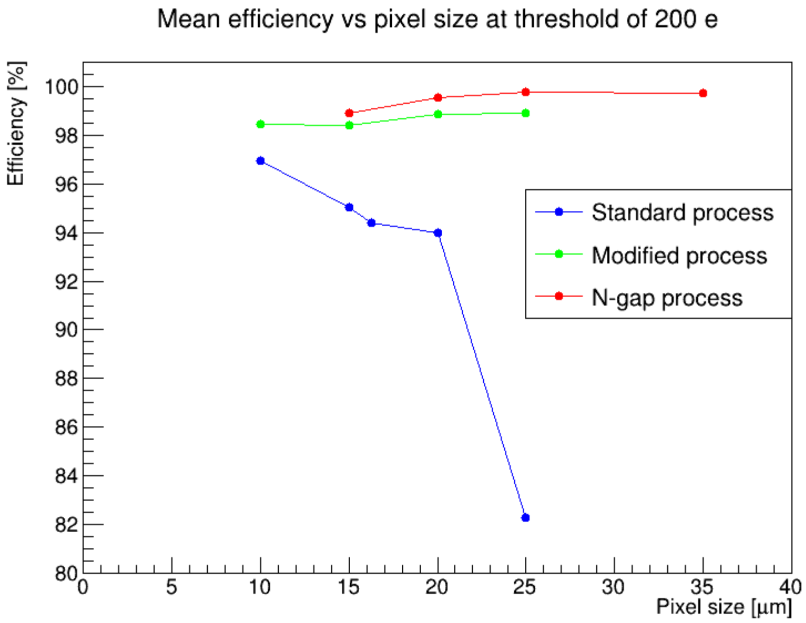
- [1] DESY, Germany, [2] University of Bonn, Germany, [3] University of Campinas, Brazil, [4] University of Wuppertal, Germany

- Project funded by the Helmholtz Innovation Pool, 2021 - 2023

Example study: process comparisons for more pixel sizes

Efficiency

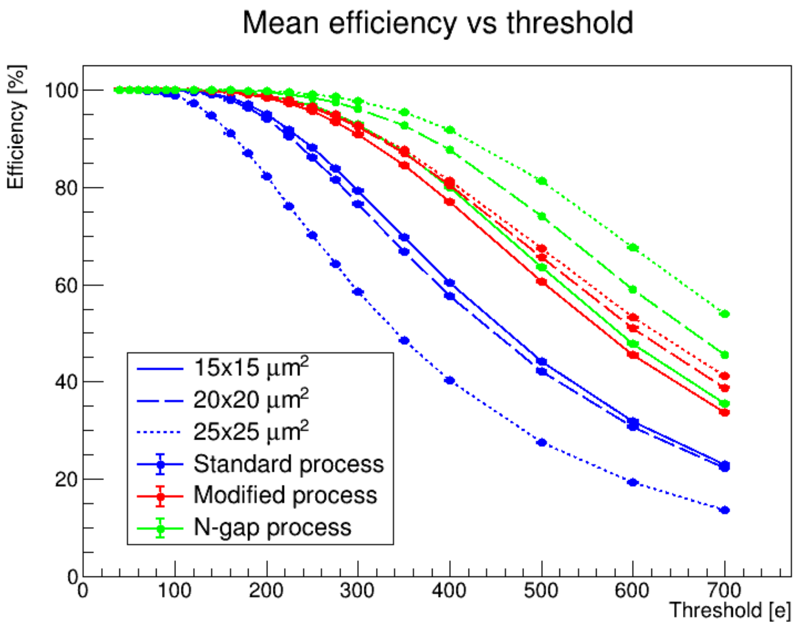
- Figure shows **mean efficiency** for different **pixel sizes** for the different processes
- The standard process efficiency drop severely at pixel sizes larger than 20x20 µm2
- The other two keep efficiency high (and even increasing) as pixel size increases, with the n-gap process being the most efficiency
  - The n-gap process is designed to eliminate inefficiencies at pixel edges and corners, which becomes more important the larger the pixel size is



Example study: process comparisons for more pixel sizes

Efficiency

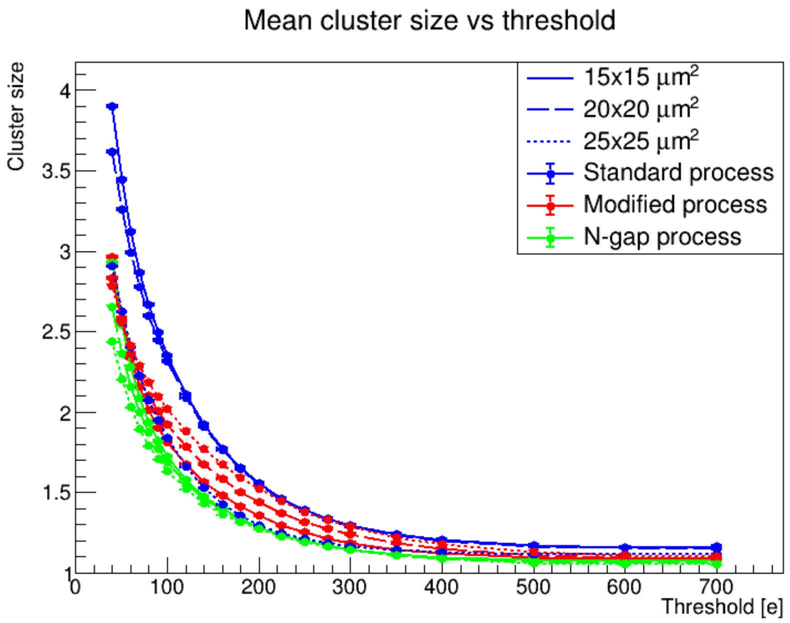
- Figure shows **mean efficiency** in the sensor for different threshold values
  - Colours indicate different processes
  - Different line styles indicate different pixel sizes



Example study: process comparisons for more pixel sizes

Cluster size

- Figure shows **mean cluster size** of the sensor for different threshold values
  - Colours indicate different processes
  - Different line styles indicate different pixel sizes



Example study: process comparisons for more pixel sizes

Spatial resolution

- Figure shows **spatial resolution in x** of the sensor for different threshold values
  - Colours indicate different processes
  - Different line styles indicate different pixel sizes