The Tangerine Project: Monolithic Active Pixel Sensors Development in a 65 nm imaging process

An overview of the Tangerine Project at DESY

Manuel Alejandro Del Rio Viera on behalf of the Tangerine collaboration
26 September 2022

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DESY.

The Tangerine Project

TowArds Next GEneRation SIlicoN DEtectors

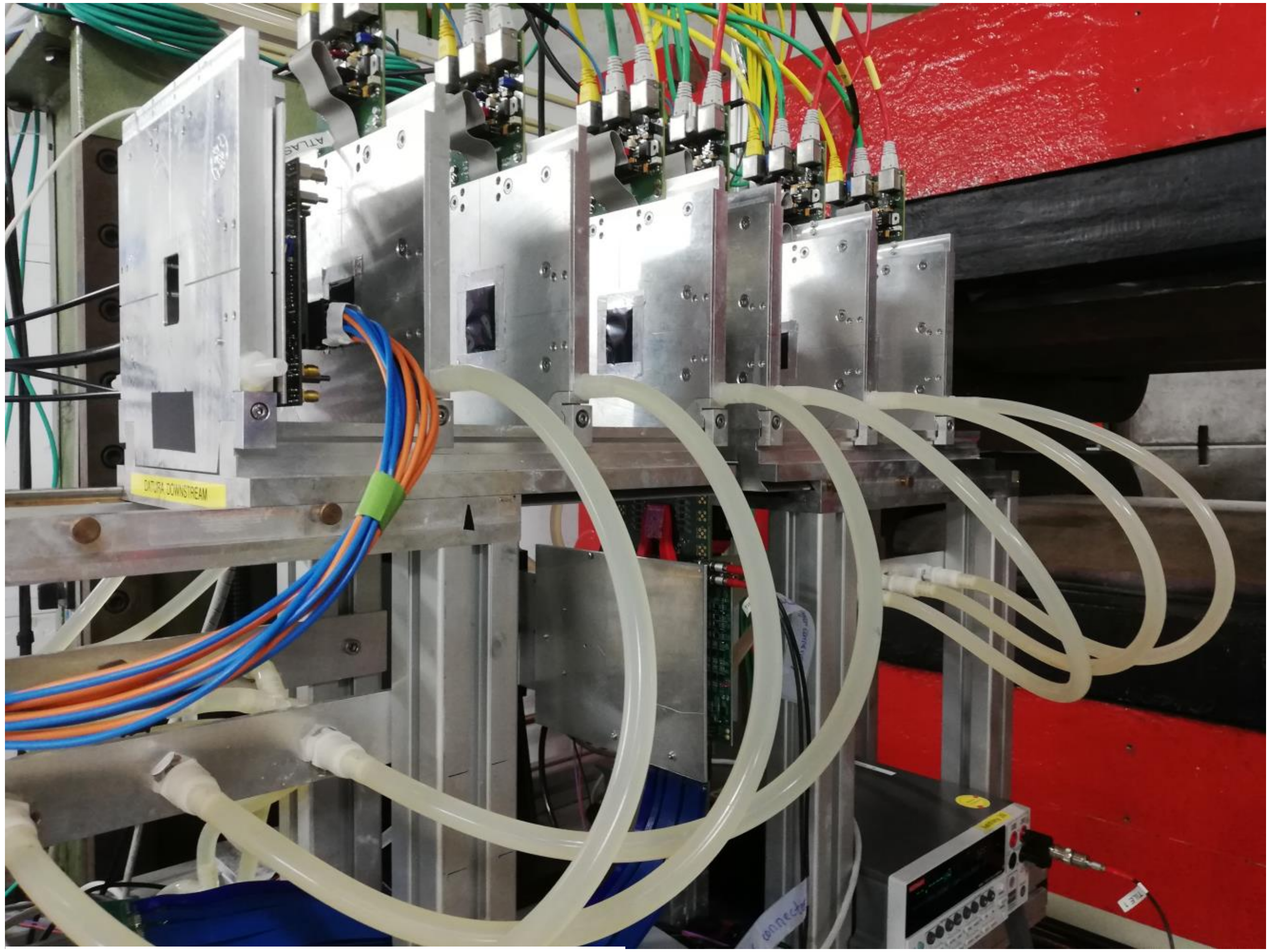
The **goal** of the Tangerine project is to develop the next generation of monolithic silicon pixel detectors using a 65 nm CMOS imaging process.

Requirements

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

- **Application**: Beam Telescopes
- Funded by Helmholtz Innovation Pool and DESY

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



MIMOSA Beam Telescope at DESY

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RESEARCH FOR GRAND CHALLENGES

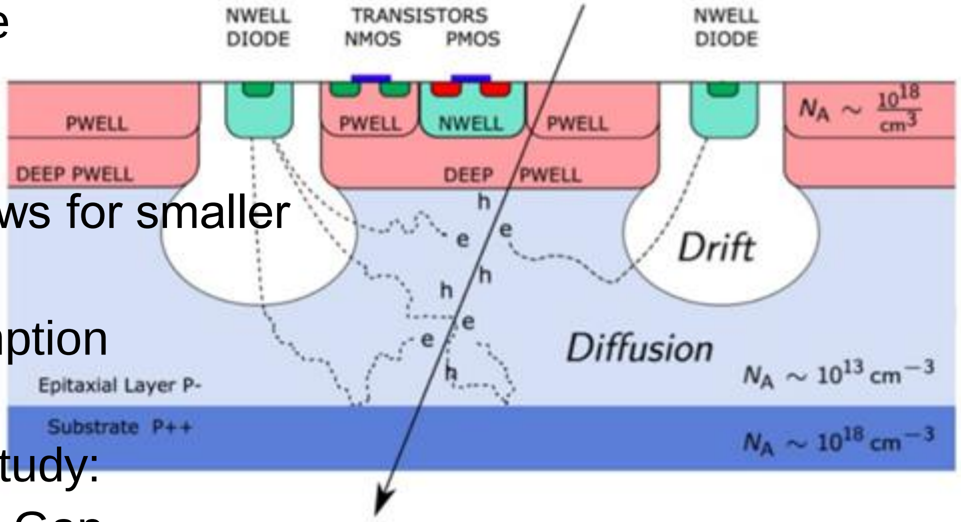
Advantages of the Monolithic Active Pixel Sensor

In a 65 nm imaging process

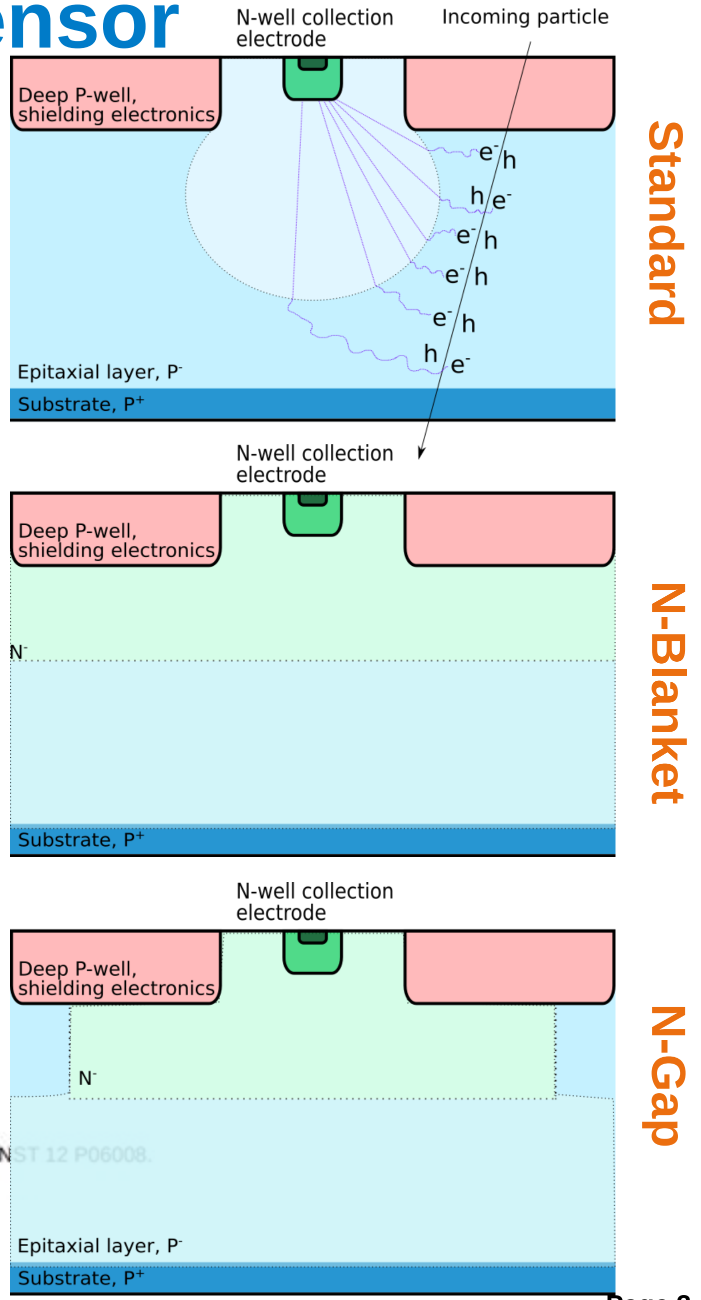
Monolithic Active Pixel Sensors (MAPS)
- Low Material Budget
- Reduce production cost and complexity compared to hybrid sensors
- Thin sensors → Reduce multiple Coulomb scattering
- Smaller collection electrode

65 nm process allows:
- Higher logic density → Allows for smaller and more complex pixels
- Decrease in power consumption

Three different layouts under study:
- Standard, N-Blanket and N-Gap



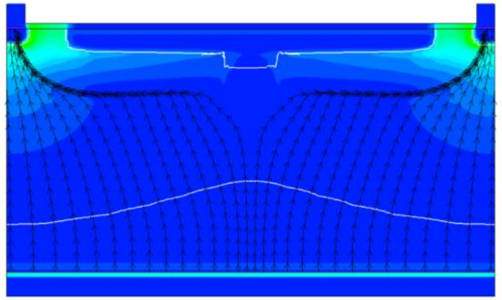
H. Pernegger et al. 2017, "First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors", JINST 12 P06008.



Workflow of the project

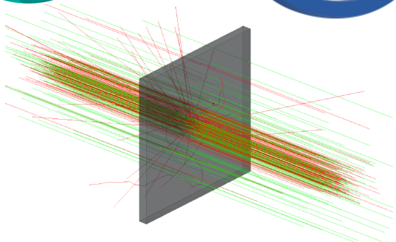
From device simulations to test beams

Device Simulations → Monte Carlo Simulations → Lab and Test Beam Characterization → ASICs Design



Device Simulations (TCAD) allow to optimize the layouts that characterize a sensor

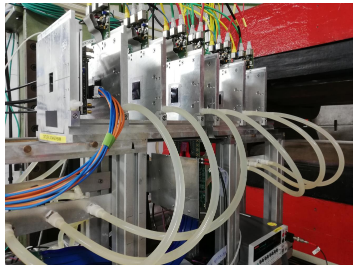
- Electric Fields
- Process Simulations
- Capacitance
- Weighting Potentials



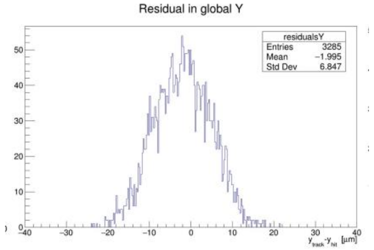
Monte Carlo Simulations allow for greater statistics and to analyze detector performance

- Efficiency
- Cluster Size and Resolution
- Pulses

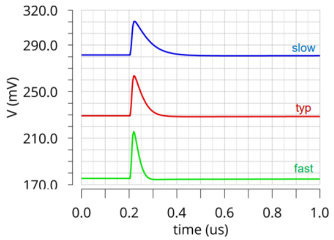
Test the performance of the sensors



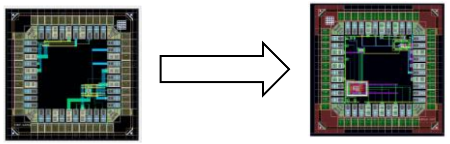
Compare data with simulations



Testing electronics and design prototypes



Resulting feedback is used for the next prototype



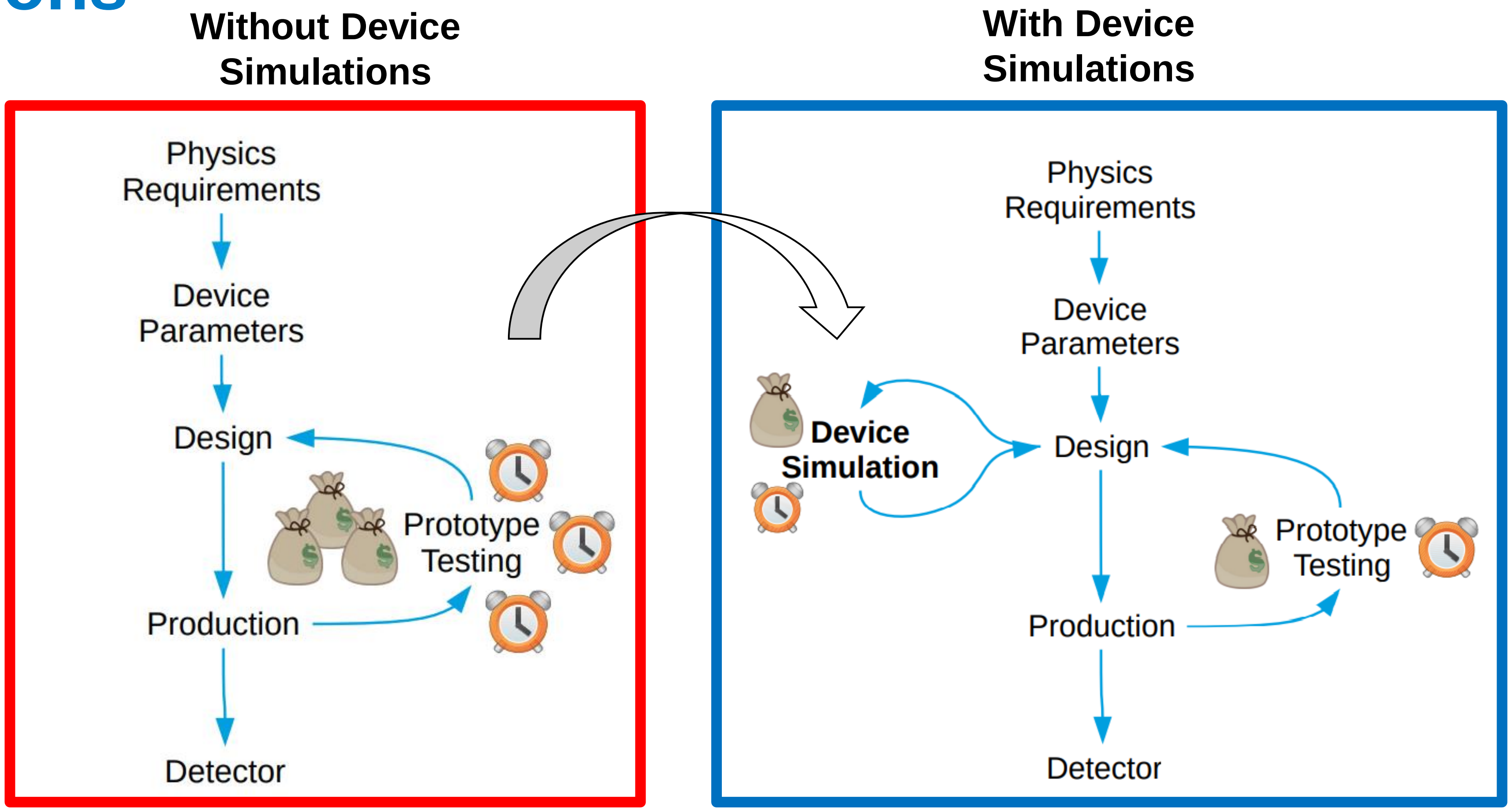
The Tangerine Project: Simulations

Device Simulations

Motivation

The main advantages that the use of TCAD simulations provides are the **reduced cost** and **time** on the prototype phase.

On top of that, it allows for a better understanding of the sensors.



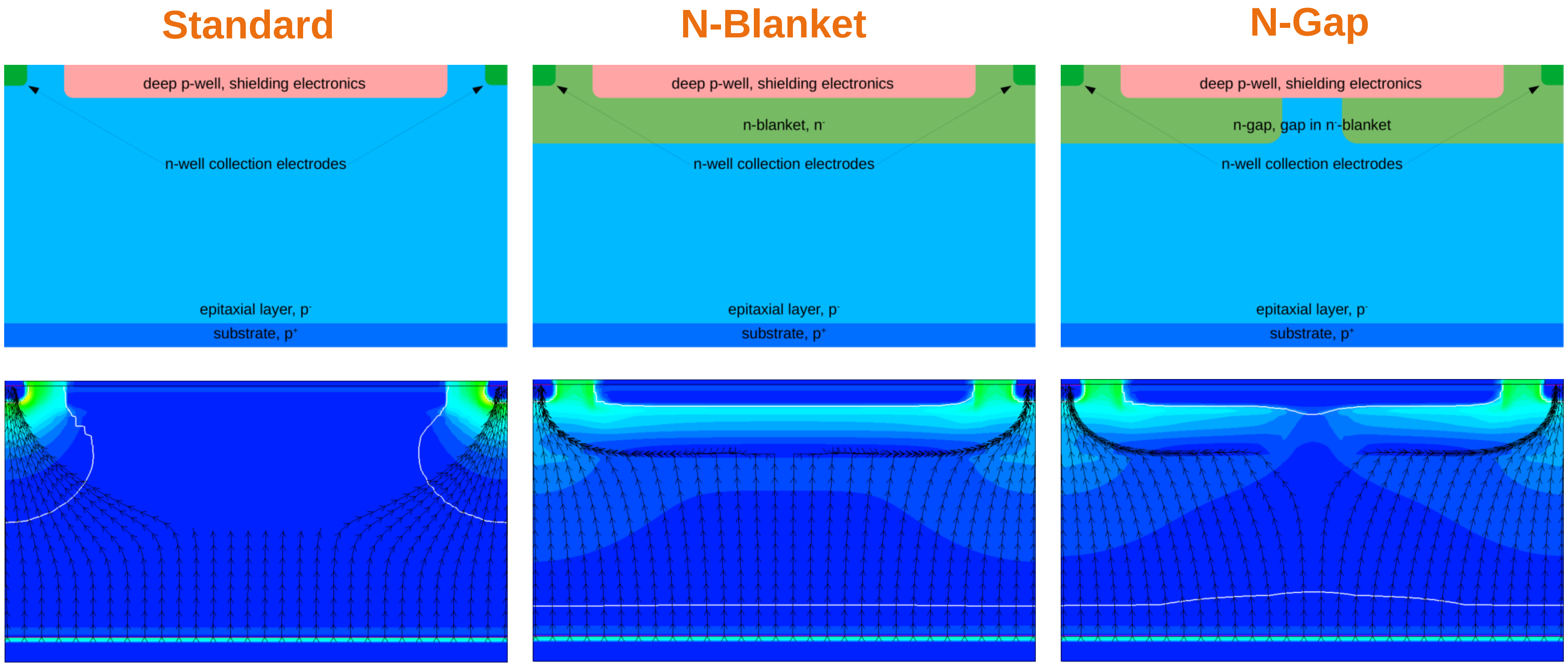
Device Simulations

Technology Computer-Aided Design (TCAD)

TCAD simulations allow to optimize the parameters that characterize a sensor

Using generic doping profiles, these simulations can provide useful information on how different parameters affect the sensor behavior.

Depending on the layout, different parameter scans can be performed.



Optimize parameters → Improved performance

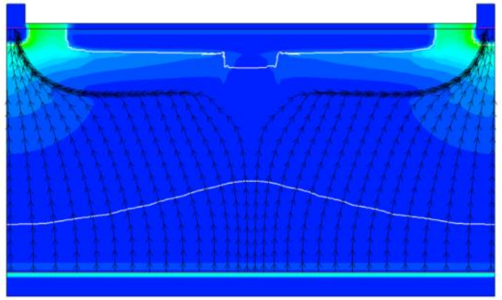
Better understanding of the physical processes!

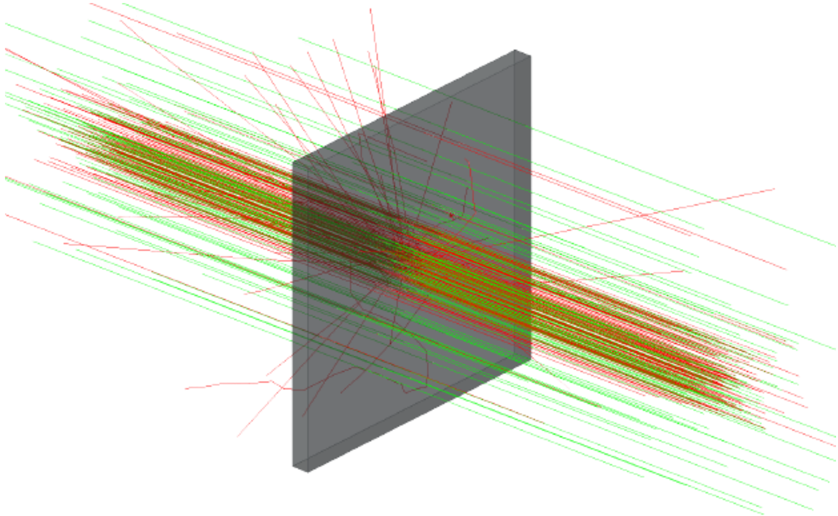
Monte Carlo Simulations

Motivation

The **main advantage** that Monte Carlo simulations provide is the **reduced simulation time** compared to the TCAD only approach.

By combining the TCAD profiles with the **Allpix Squared** framework, we can produce results with enough **statistics** (within a reasonable amount of time) which can give an insight of the performance of the sensors.

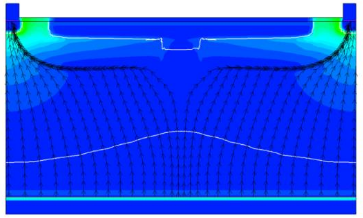


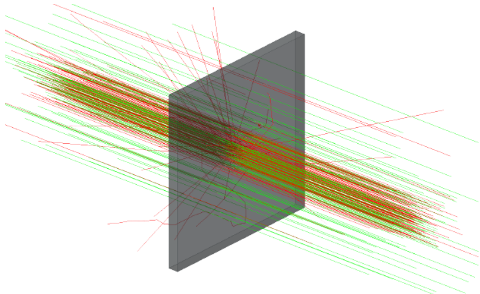


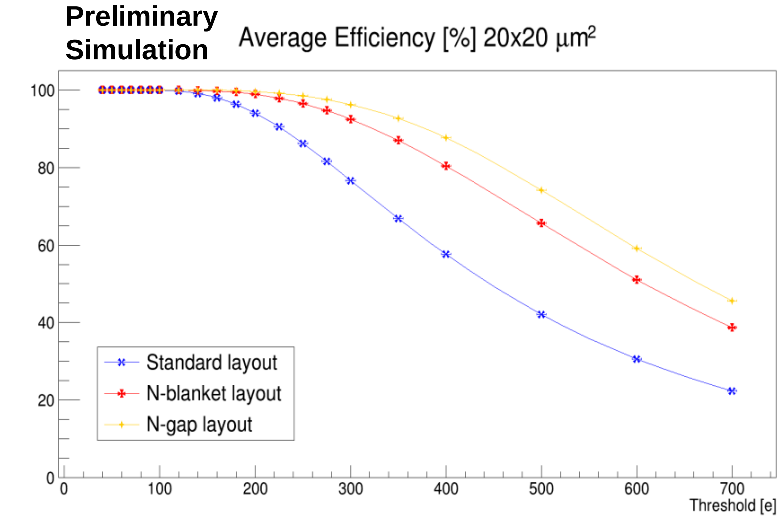
Monte Carlo Simulations

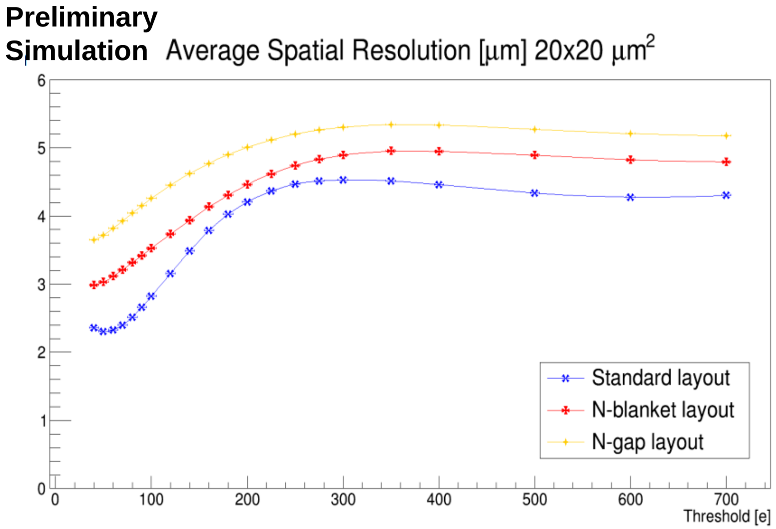
Procedure and Results

1. A particle is shot through the sensor
2. Physics processes: Diffusion, Drift, Ionization, Recombination...
3. Repetition (Same energy and direction)
4. Analysis









Quantities we can compare with experiment data!

The Tangerine Project:
Test Beam

Tangerine MLR1

October 2021

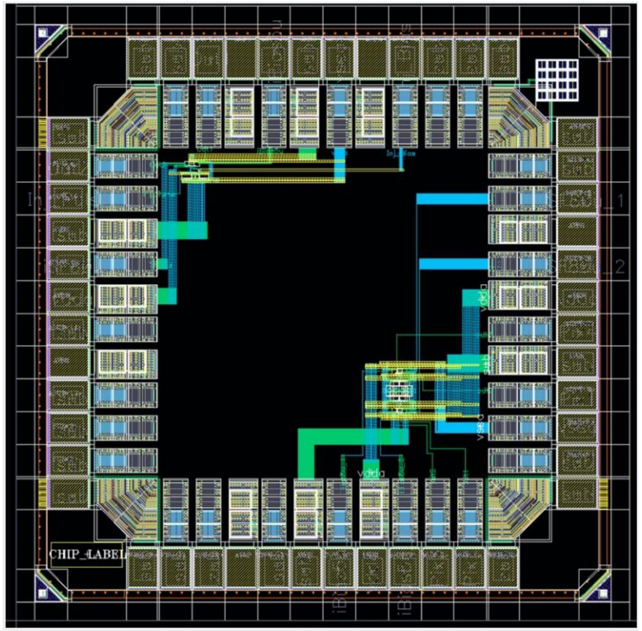
The Multi Layer Reticle (MLR1) Test Chip contains:

- 2 different CSA for evaluation of performance [with charge injection] (top-left)
- Block of 2x2 16 µm pixel with analog readout for pixel characterization (bottom-right)

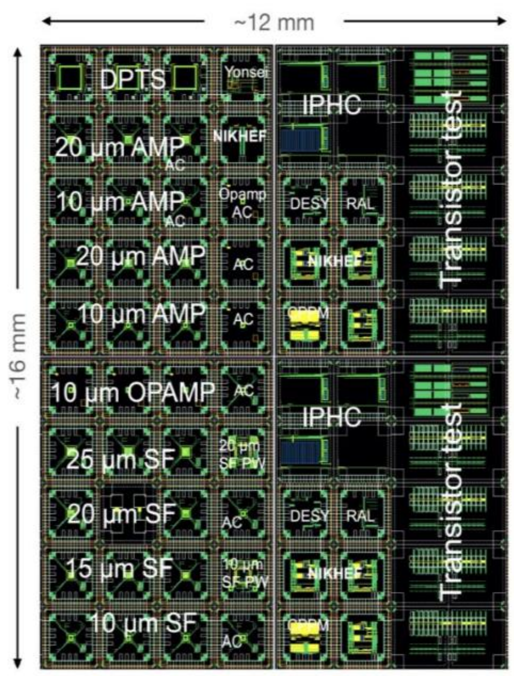
2x2 Pixel Matrix with Charge Sensitive Amplifiers (CSA) :

- **Gain**: 80 µV/e- , Cf = 2fF (typ)
- **Sensing Node**: N well hexagon 1.2µm diameter
- **Pitch**: 16 µm
- **Outputs**: 4 analog read-out
- **Aim**: Pixel characterization

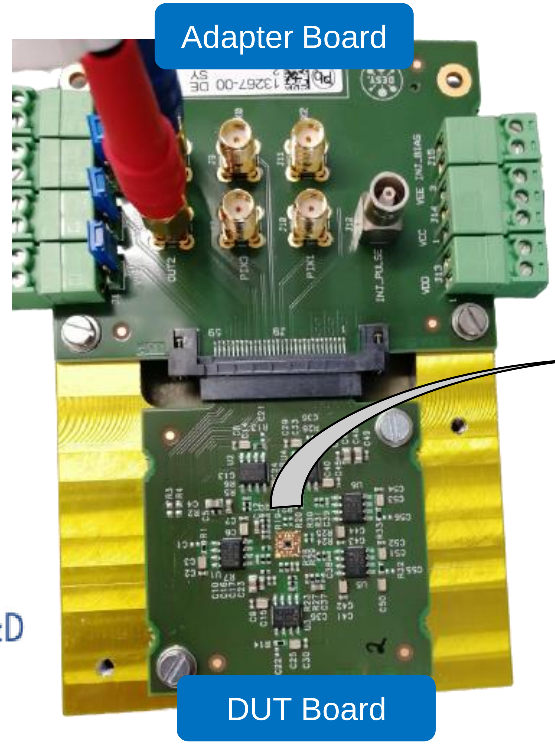
Thanks to **CERN EP R&D** for all the support in the submission and test beam.



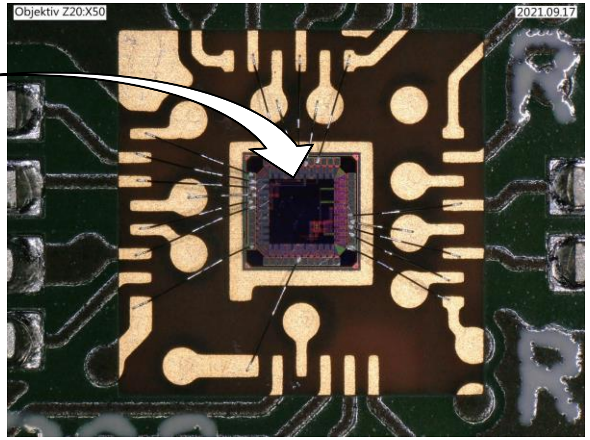
MLR1 production



expect O(500) dies per wafer



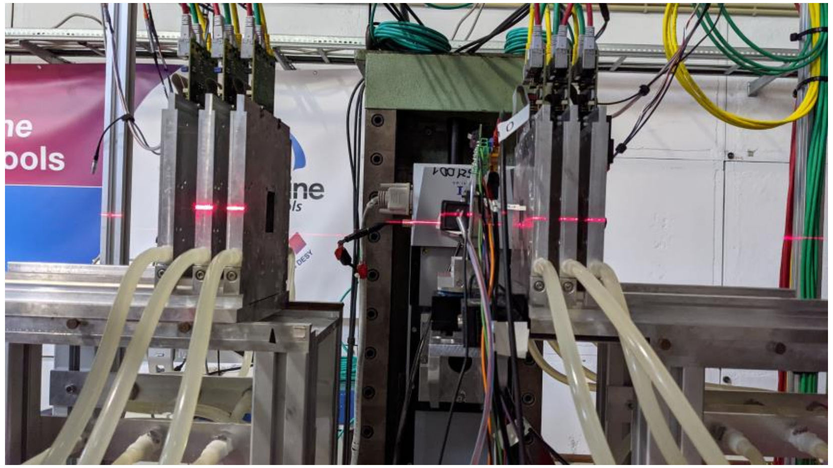
MLR1 Test Chip



MLR1 Test Beams Summary

DESY II, CERN SPS and MAMI Microtron

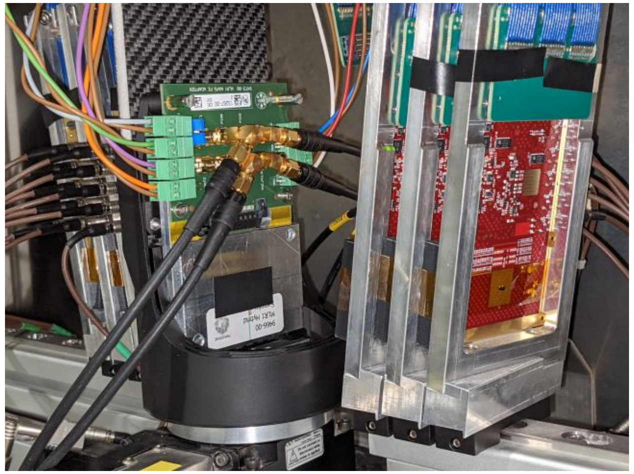
Thanks to **CERN EP R&D** for all the support in the test beam and **ALICE** for the ALPIDE telescope.



DESY II
18 Oct – 01 Nov 2021

- Electron beam of 5 GeV
- Oscilloscope readout for 4 pixels
- Self triggered by DUT (or scope channel)
- Few events per hour

Gained confidence with the setup and obtained preliminary results

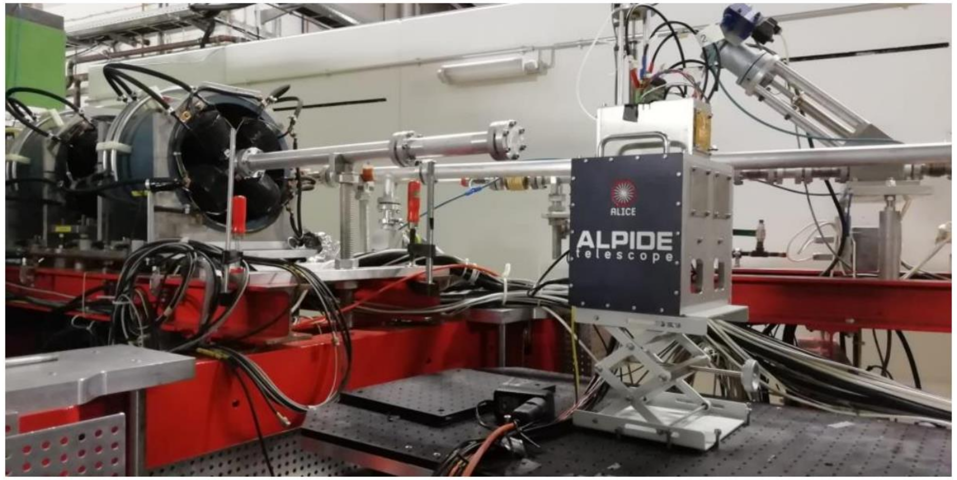


CERN SPS
10 – 15 Nov 2021

- 120 GeV high intensity Pions
- Pixel structure recognizable after track reconstruction (shown later in the test beam results)

Hit rate lower than expected → Found a sensor layout issue that affected the efficiency of device

Fixed for next submission



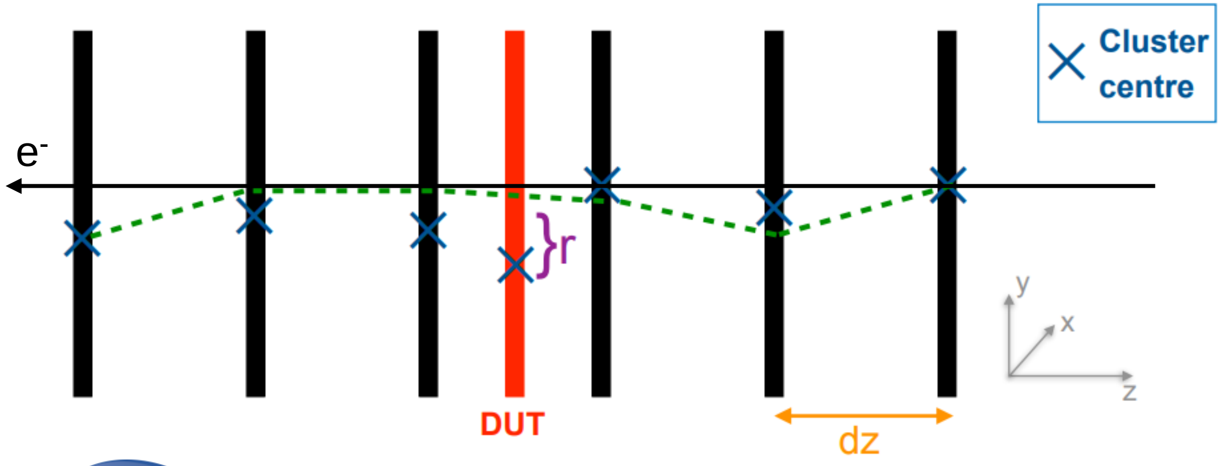
MAMI Microtron
2 – 6 Dec 2021

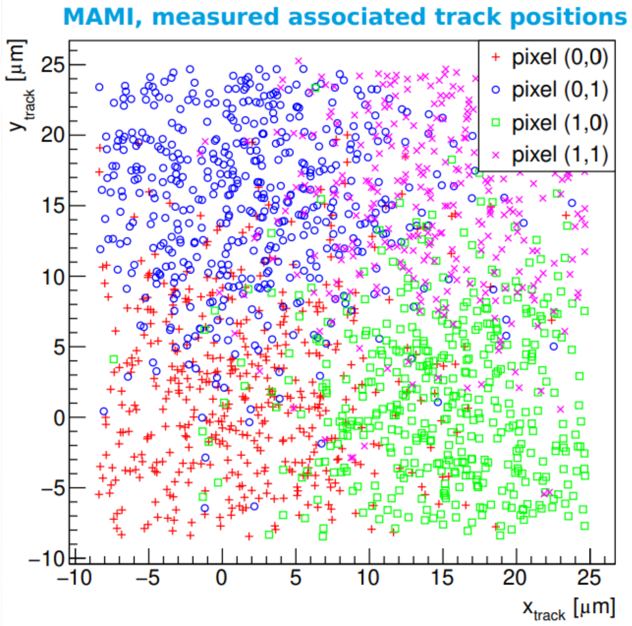
- Electron beam of 855 MeV
- Trigger rate of a few Hz
- Bias and current scans (for pixels and CSA)

Goal of the MLR1 Test Beam: Study parameters of the CSA

MLR1 Test Beam Results

Corryvreckan Analysis



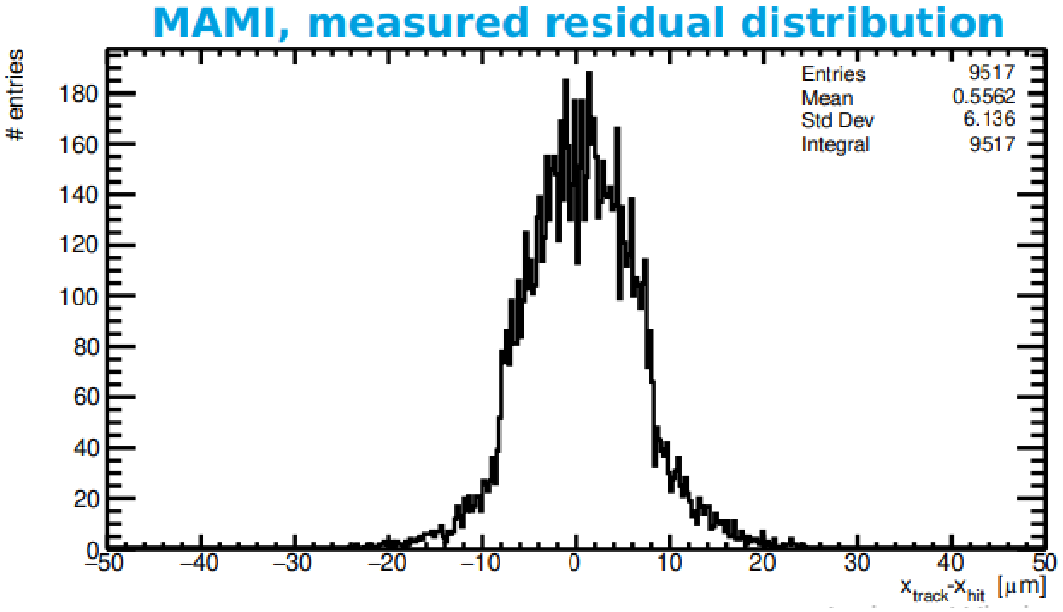


After reconstruction, pixel structure is recognizable through the associated tracks

Corryvreckan reconstructs the **particle tracks** using the information of the **hits** and its **associated clusters**

Residuals (Difference between positions from track interpolation and DUT measrements) **~ 6 µm** is dominated by low beam momentum

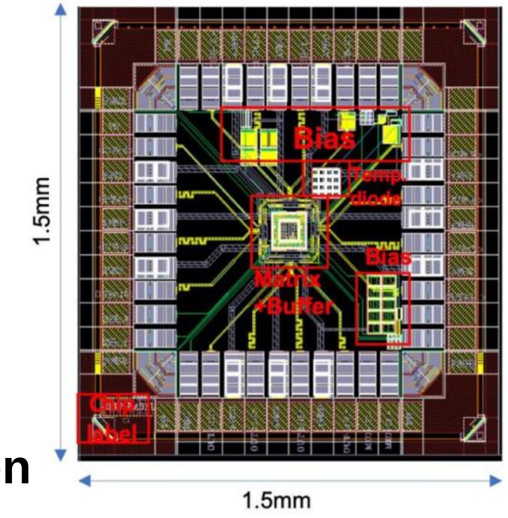
Main results come from MAMI Test beam due to rate



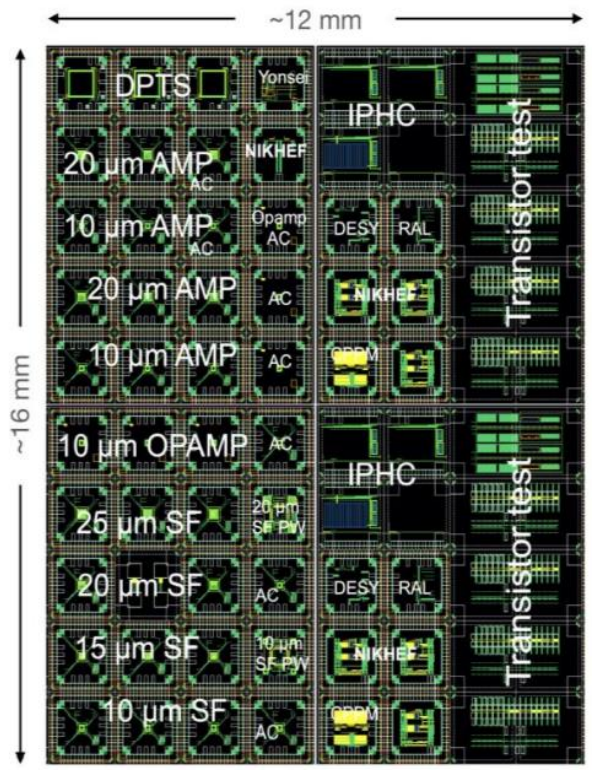
Analogue Pixel Test Structures (APTS)

Tangerine Overview

- Test-Chip in **65nm CMOS** imaging technology
- MLR1 production
- 4x4 Pixel Matrix
- Pixel pitch **15 & 25** µm
- **3 layouts** (Standard, N-Blanket and N-Gap)
- **Direct analogue readout** of 16 channels
- Allows studies on **charge collection/distribution**

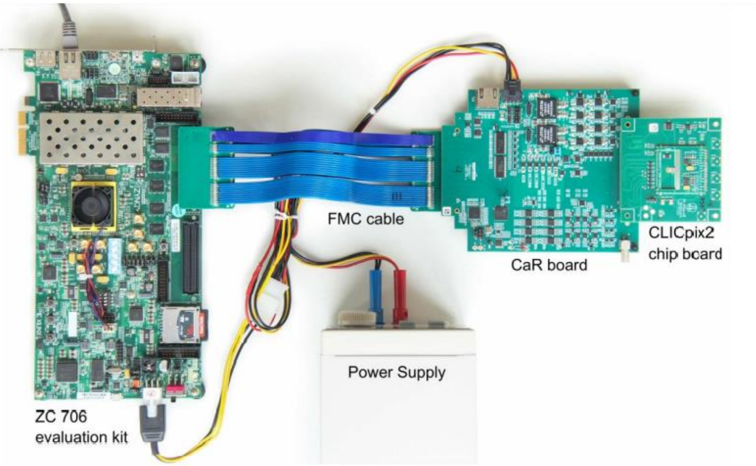


MLR1 production



expect O(500) dies per wafer

Goal: Test the different layout performance



Thanks to **Eric Buschmann** and **CERN EP R&D** for all the support.

APTS Test Beams Summary

MAMI Microtron and DESY II

MAMI Microtron
11 – 15 April 2022

- Electron beam of 855 MeV
- Trigger rate of ~ 150 Hz
- Test of different layouts

Helped to test the DAQ system, gain confidence with the ALPIDE setup and develop analysis chain

DESY II
13 Jun – 4 Jul 2022

- Electron beam of 5 GeV
- Trigger rate of ~ 50 Hz
- Test of different layouts
- Voltage scans on pwell and psub performed

Data will improve our knowledge on the different layouts and how they are affected by voltage

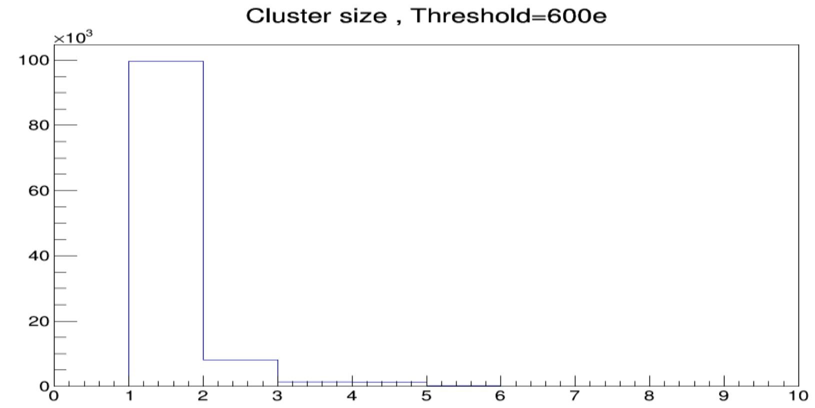
Valuable data obtained for comparison with simulations for the next steps

APTS Test Beam Preliminary Results

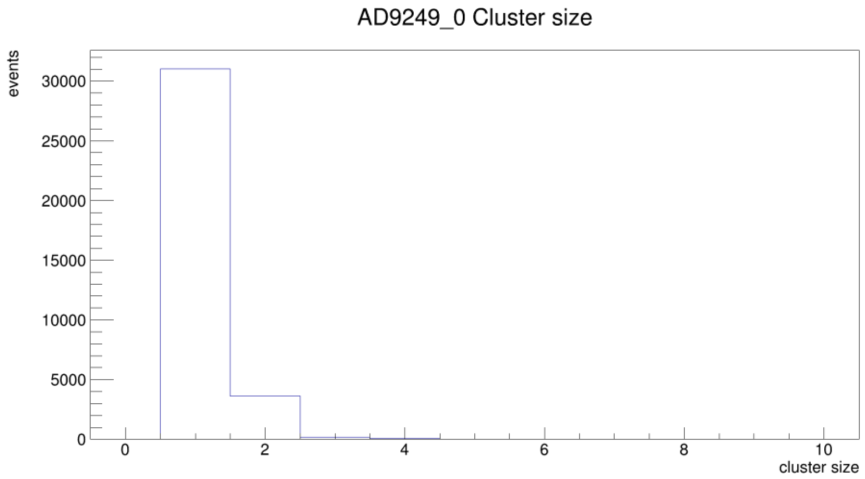
N-Gap 25 µm APTS sample

Cluster Size

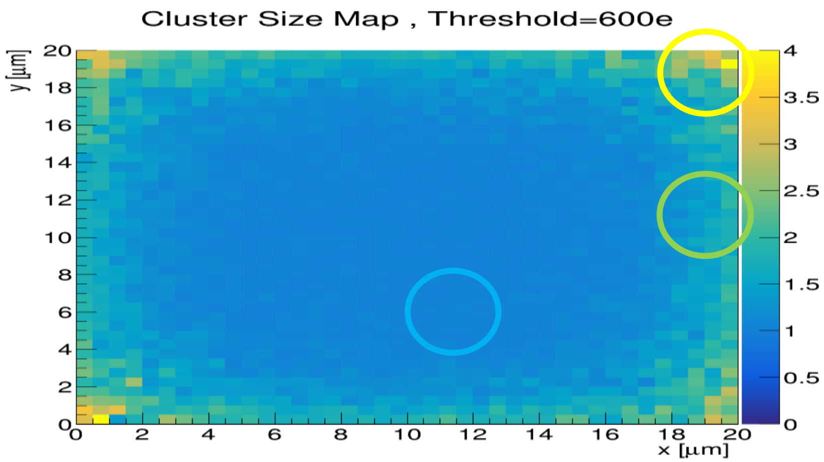
Preliminary Simulation



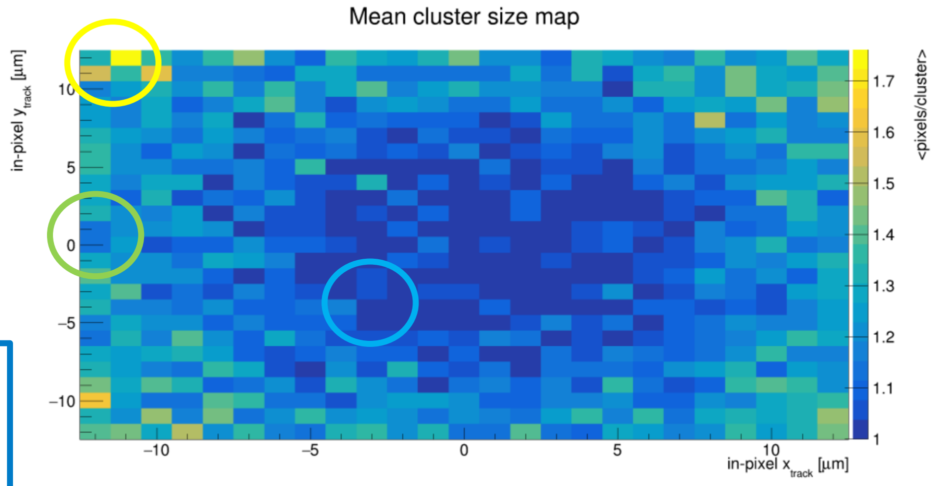
Preliminary Data Analysis



Preliminary Simulation



Preliminary Data Analysis

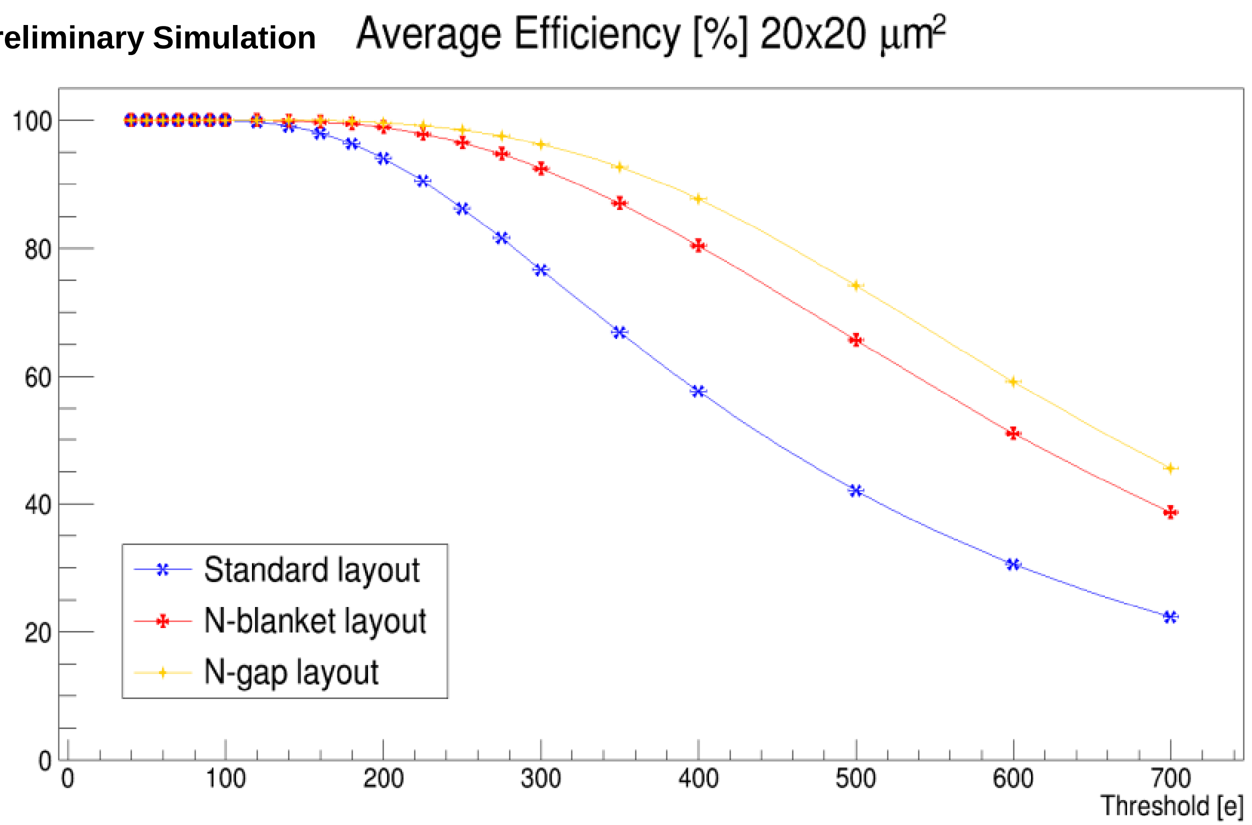


Trend aligns with what we expected from the simulations! (Qualitatively)

APTS Test Beam Preliminary Results

Efficiency

Preliminary Simulation



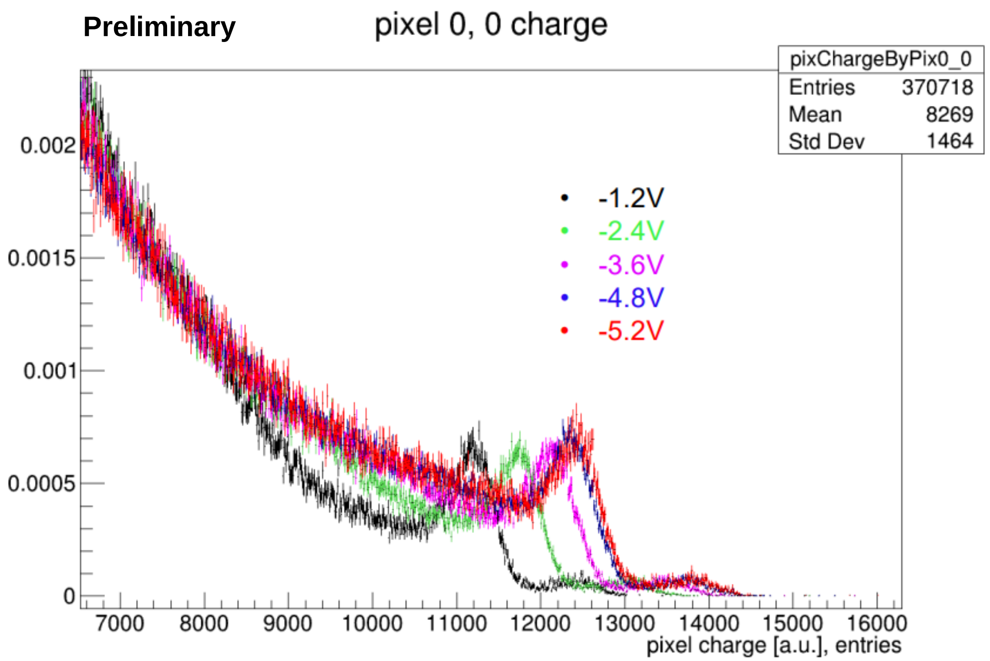
Preliminary Data Analysis

Standard ~ 84.2% (± .9%) < N-Blanket ~ 93.2% (± .7%) < N-Gap ~ 98.4% (± .4%)

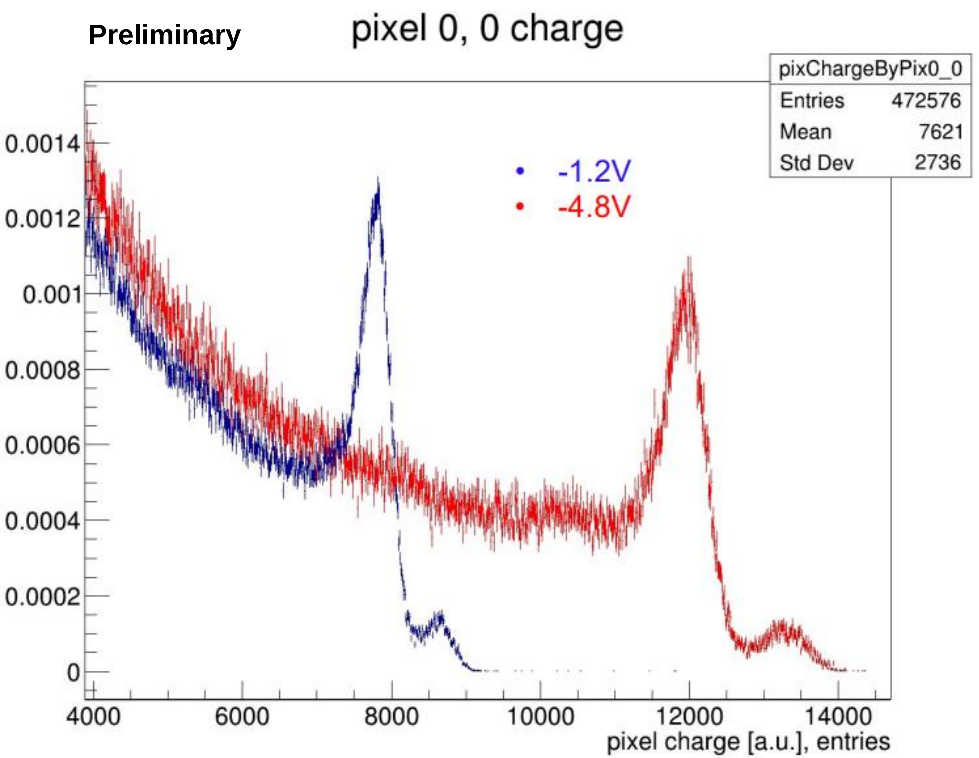
Trend aligns with what we expected from the simulations!

APTS Iron-55 Source Measurements

Layouts Pixel Charge Calibration



Standard



N-Blanket

There is significant difference between the layouts' behavior at different voltages → This due to a difference in the capacitance

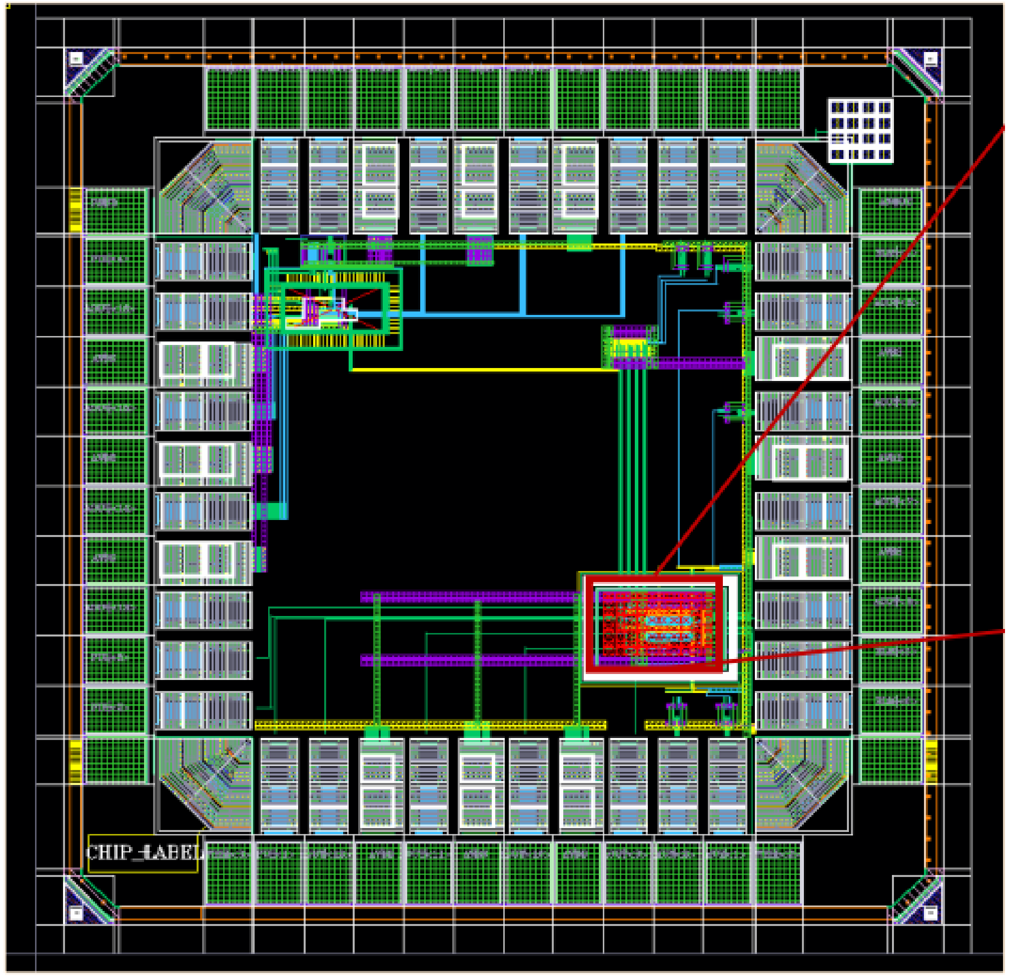
The Tangerine Project:
Work in Progress

Tangerine Project: Work in Progress

Tangerine ER1 Prototype

The next Tangerine prototype has been **submitted to CERN**:

- 2x2 35x25 μm^2 matrix with **all analogue in pixel functionality**
- **N-Gap layout** with 2.5 and 4 μm gap
- External access to **CSA and discriminator output**
- Slow-Cntrl to adjust **threshold** & Krummenacher Bias
- Single front-end with charge injection



Tangerine Project: Work in Progress

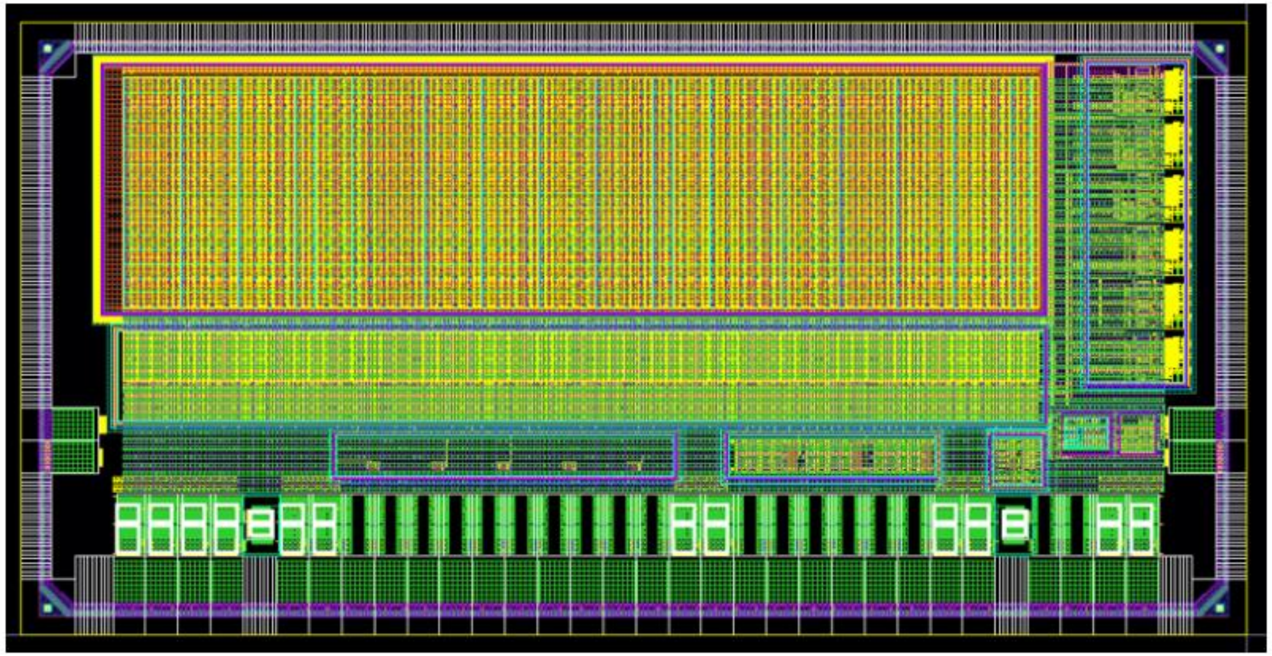
H2M (Hybrid-to-Monolithic)

A collaboration between DESY, CERN and IFAE the **Hybrid-to-Monolithic** (H2M):

- 3 x 1.5 mm^2 , 64 x 16 square pixel, 35 µm pitch
- 8-bit counter per pixel

4 acquisition modes:

- ➢ Time of Arrival (ToA)
- ➢ Time over Threshold (ToT)
- ➢ Photon counting
- ➢ Triggered binary readout

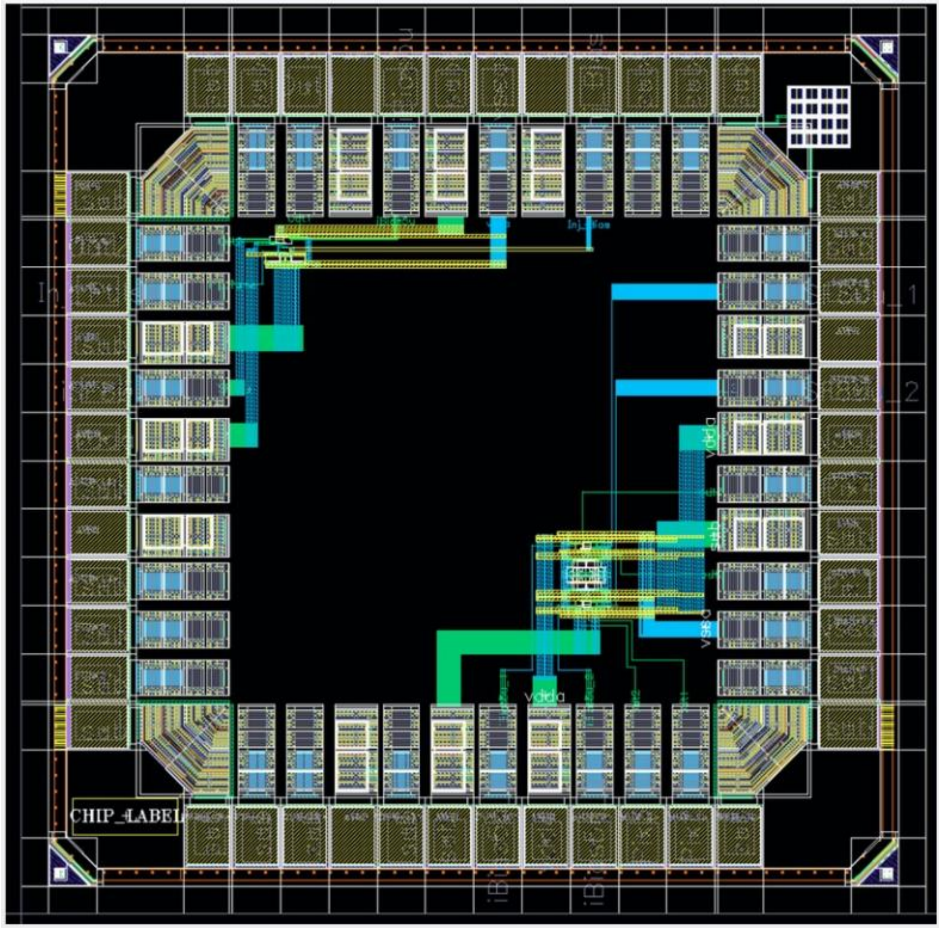


Conclusions

Tangerine: Towards the future

MLR1 Test Chip:

- A 65 nm CMOS pixel detector was for the first time developed and investigated at DESY
- Detailed **waveform analysis** was performed, as well as **tests on the CSAs**
- The results increased our understanding of the process and allowed to improve the next prototype submission **next prototype submission**



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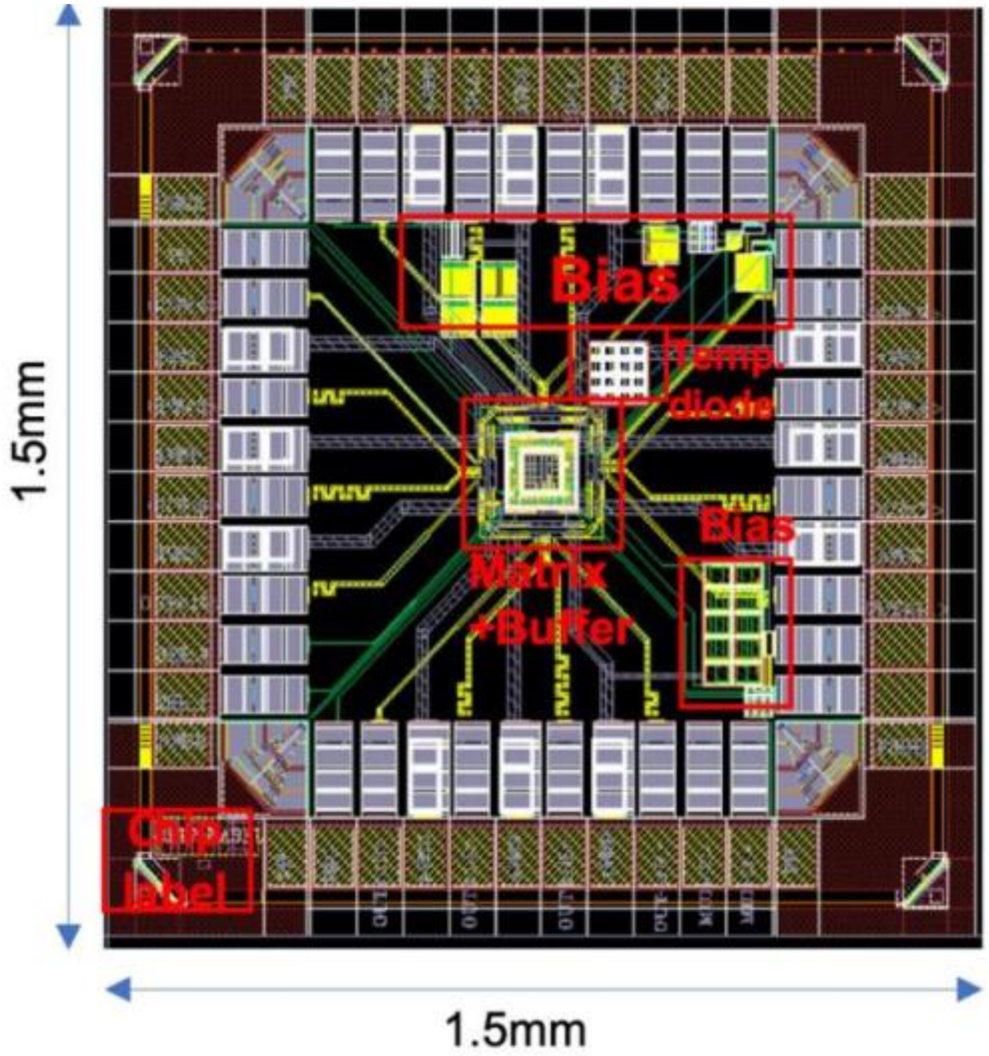
Conclusions

Tangerine: Towards the future

APTS:

- Provided us with a better understanding on the **behavior** of the **different layouts**
- Calibrations studies were performed to check for the best possible parameters configuration
- Lots of data are still being analyzed, and even preliminary analysis gave sensitive results
- **Confirm the MAPS technology** as **good candidate** for the next generation of pixel detector for beam telescopes
- Results are very promising and will allow us to compare with **simulations**



Thank you for your time!

Contact

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