First test-beam result on MAPS prototypes in 65 nm process

Tangerine project at DESY

Gianpiero Vignola, on behalf of the Tangerine Collaboration

BTTB10, Lecce, 22 Jun 2022

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UNIVERSITÄT BONN

DESY.

Tangerine Project overview

New Pixel Detector for Beam Telescopes

- **Goal**: Design a monolithic pixel detector in 65nm CMOS imaging technology
    - **Main application**: beam telescope
    - **Potential applications**: e^+ e^- colliders, etc.
- Requirements:
    - **Position resolution**: ~ 3µm
    - **Rate capabilities**: 1 MHz particle rate
    - **Time resolution**: ~ 1-10 ns
    - **Energy measurement** via ToT
    - **Low material budget**: < 0.05% X/X_0
- Founded By InnoPool & DESY
- Tangerine project start in Sep. 2020

MIMOSA Beam Telescope, DESY II Test Beam Facility

DESY.

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RESEARCH FOR GRAND CHALLENGES

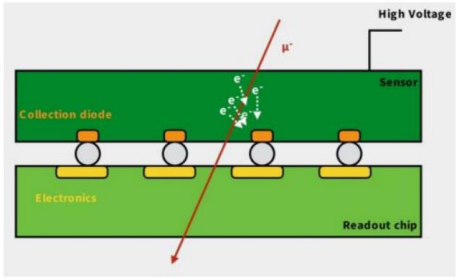
TowArds Next GEneRation SIlicoN DEtectors

Tangerine Project overview

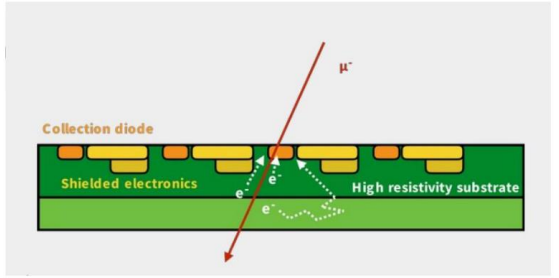
Why Monolitic Active Pixel Sensor in 65 nm CMOS imaging process?

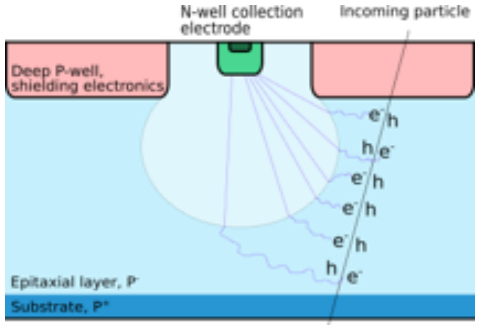
- **Reduce**: Material budget, Production cost & Complexity
- Recent improvements thanks to **ALICE ITS & MALTA**:
  - 180 nm CMOS imaging process
  - Small collection electrode (reduce noise and power consumption order ~ 40 mW cm^{-2})
  - Spatial resolution ~ 5 µm
- Three layouts under study for the **sensitive volume design**: Standard, N-blanket, N-gap
- **65 nm process** allows:
  - Higher logic density -> small pixel pitch and/or increase in-pixel functionality (fast CSA, in-pixel ToT)
  - Further decrease in power consumption

Hybrid Sensor Sketch

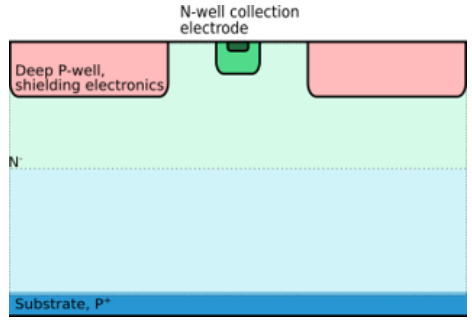


Monolitic Sensor Sketch

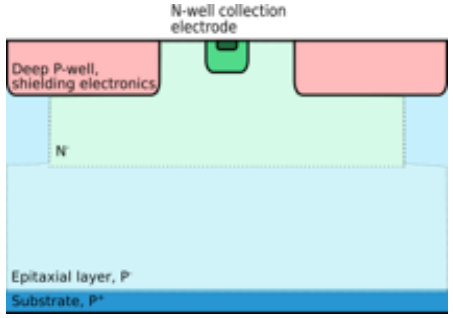




Standard



N-blanket



N-gap

Tangerine Project overview

Workflow: from simulations to test-beam

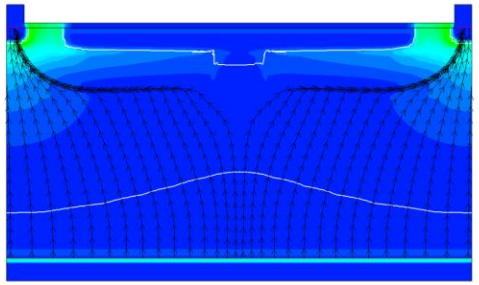
Device Simulation → **MC Simulation** → **Lab & Test-beam characterization of prototypes**

Sentaurus TCAD

SYNOPSYS® Silicon to Software™

Tune Geometrical parameters to optimize Electrical Characteristics:

- I-V, C-V curves
- Electric fields
- Weighting potentials
- Pulse shape

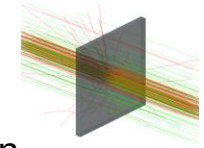


See: Adriana Simancas BTTB10

ap² allpix squared

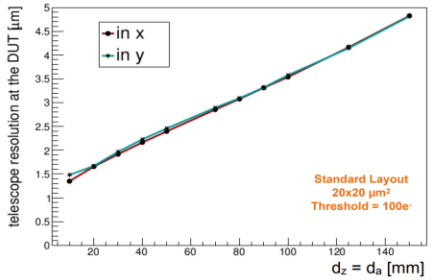
Simulate the full response of the sensor

- Efficiency
- Cluster Size
- Spatial Resolution



See: Manuel A.D.R.Viera BTTB10

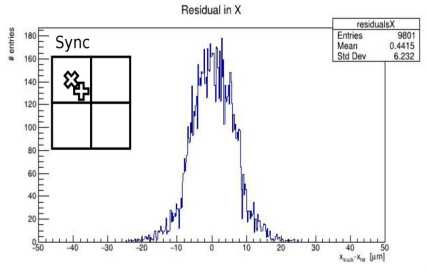
Simulation of test beam telescope



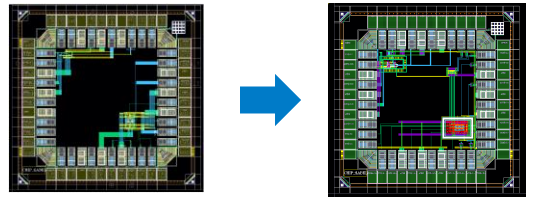
See: Sara Ruiz Daza BTTB10

ROOT Data Analysis Framework

Compare measurements with simulations



Tune the design of the next prototype



Tangerine MLR1 Chip Details

2 Test structures

DESY MLR1 timetable

- Chip design 2020
- Submitted to foundry Dec-2020
- prototype in Hamburg October 2021

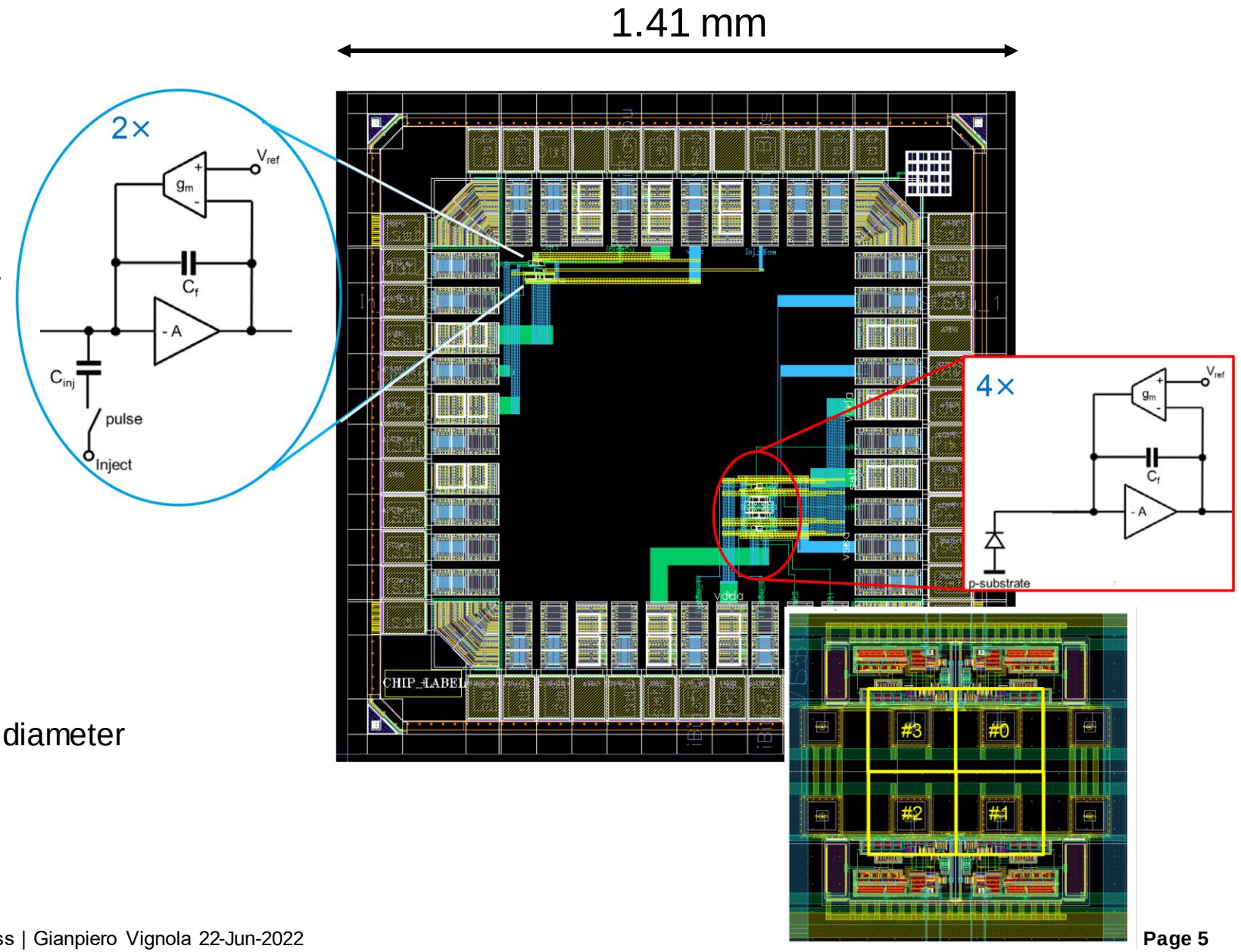
2 CSAs with different gains

a) feedback cap 1.5fF → 107µV/e
b) feedback cap 2.0fF → 80 µV/e-

- Use Charge injection as stimulus
- No Pixel diode
- **Aim**: Evaluation of CSA performance

Block of 2x2 pixel with CSA

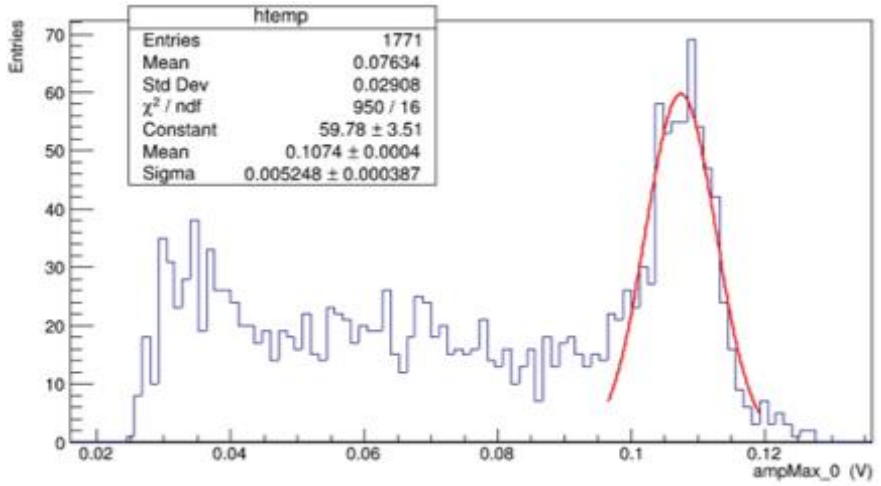
- **Gain**: 80 µV/e- , Cf = 2fF (typ)
- **Sensing node**: nwell hexagon 1.2µm diameter
- **Pitch**: 16 µm
- **outputs**: 4 analog read-out
- **Aim**: Pixel characterization

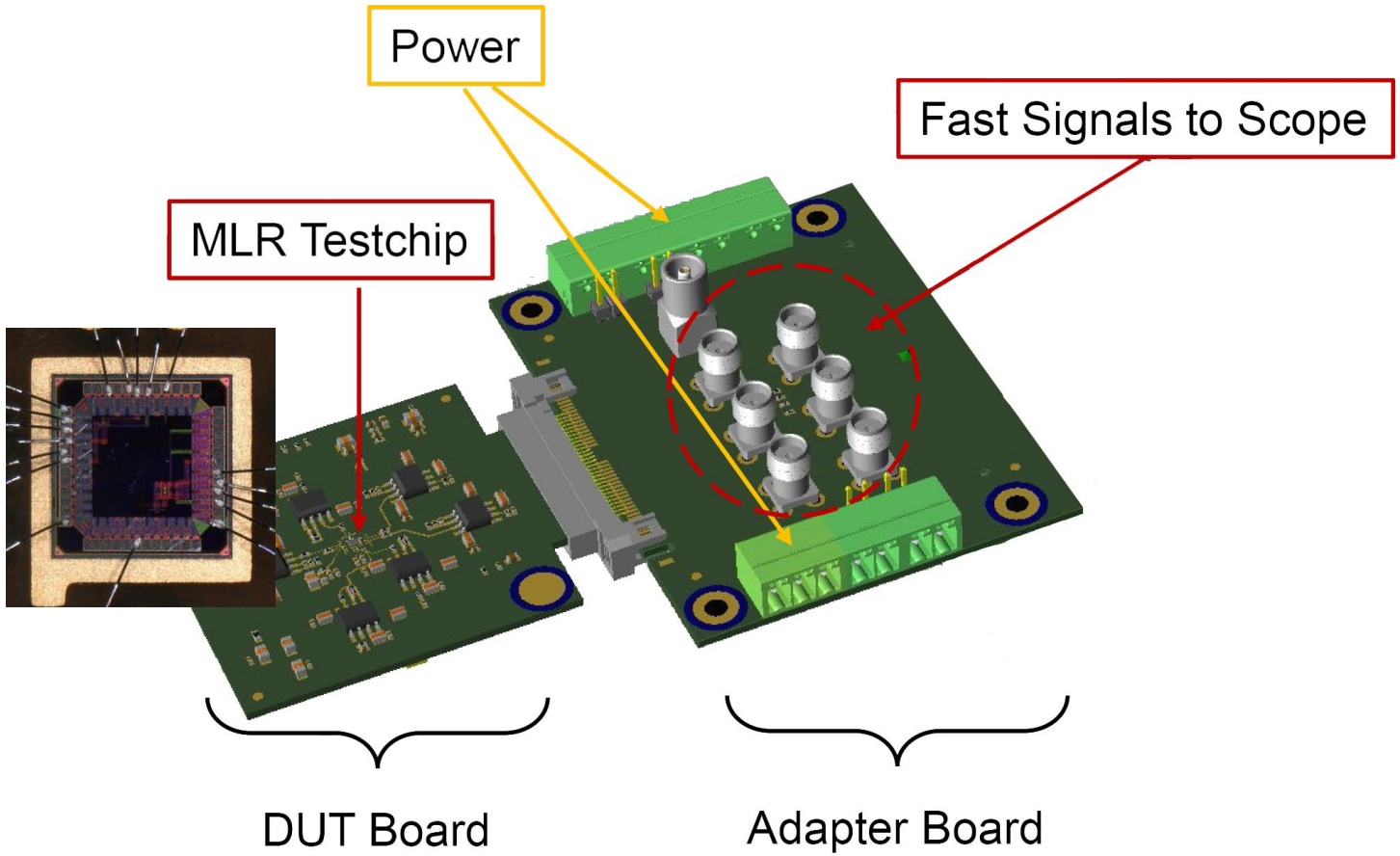


Tangerine MLR1 Chip at DESY

October 2021

- MLR1 Chip arrived at DESY in early October 2021
- Chip glued and bonded on **DUT board**
- First **tests on CSAs** comparing them with simulations. Evaluation of: Gain, Delay, Rise Time, Falling edge
- First waveforms obtained with Fe^{55} source





DESY Test Beam

18 Oct – 01 Nov 2021

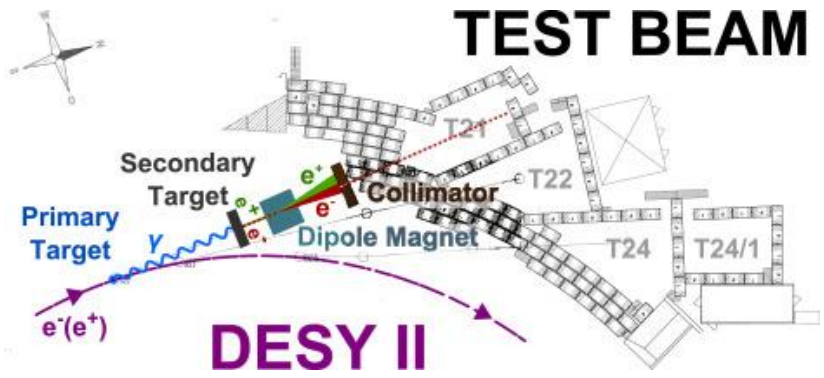
Setup

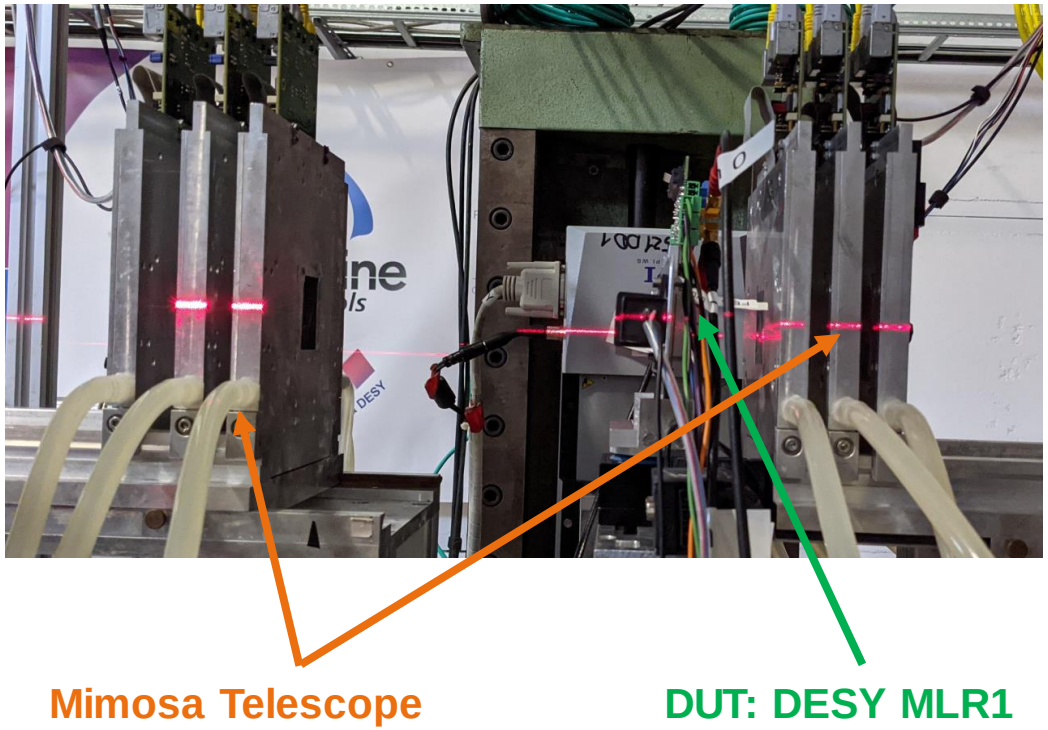
- **Electron beam**, 2-5 GeV
- Oscilloscope based Read-out of 4 pixels
  Full waveforms stored (4GHz 10 Gs/s)
- **Mimosa telescope** used for track reconstruction
- **Self-Trigger** of MLR1 (OR of Scope Channels)

Results

- **Event rate**: 1 event every 5-15 minutes
- **MIP response**: order of 50 mV
- **Rise time**: 5-10 ns
- **Slew rate**: on the order of mV/ns

Rate too low at DESY Facility, gained confidence with the Chip & preliminary results



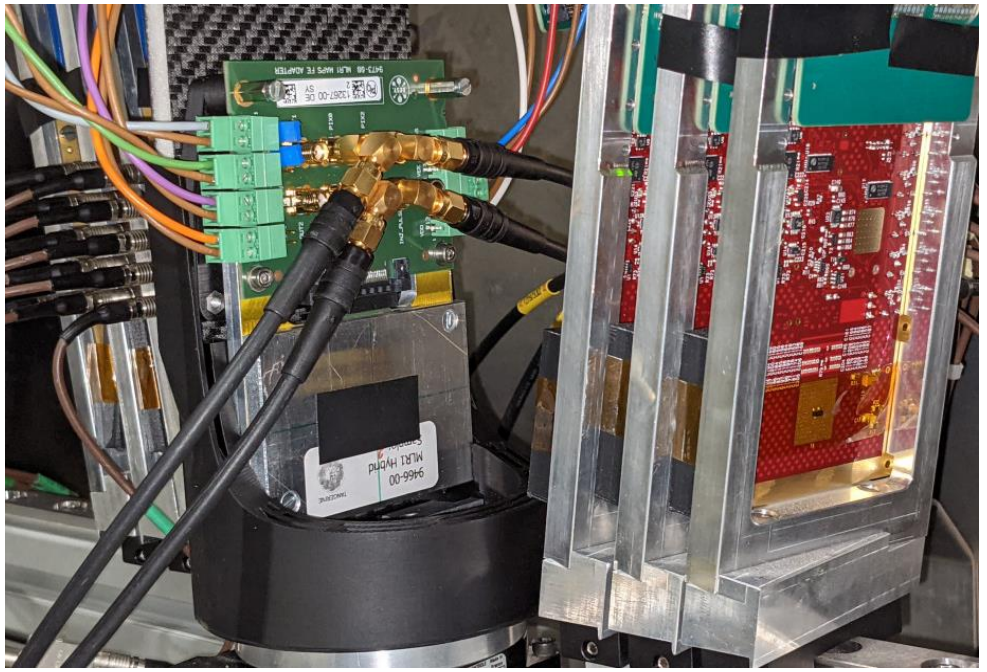


CERN Test Beam

SPS, 10 – 15 Nov 2021

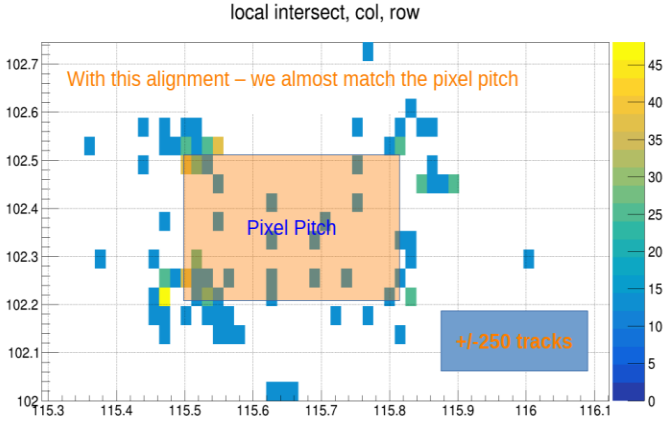
Setup

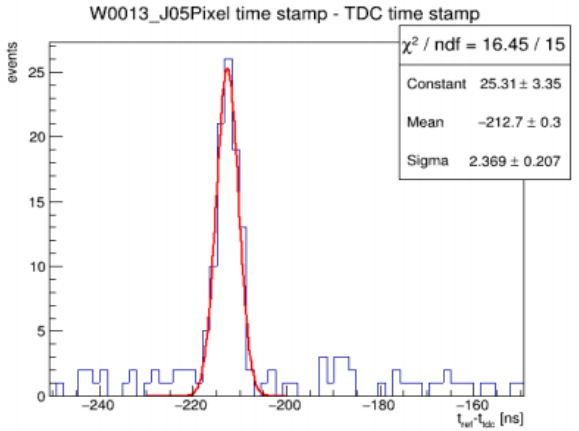
- **Pion beam**, 120 GeV, 1e6 per spill
- Oscilloscope based Read-out of 4 pixels
  Full waveforms stored (4GHz 10 Gs/s)
- **Timepix3 telescope** used as reference
- **Self-Trigger** of MLR1 (OR of Scope Channels)



Results

- Scope trigger correlate nicely in time -> **time resolution** ~ few ns
- After tracks reconstruction **pixel structure** is recognizable
- **event rate** extremely lower than expected!





Discovered a sensor layout issue in DESY MLR1 Chip that affect the efficiency of device

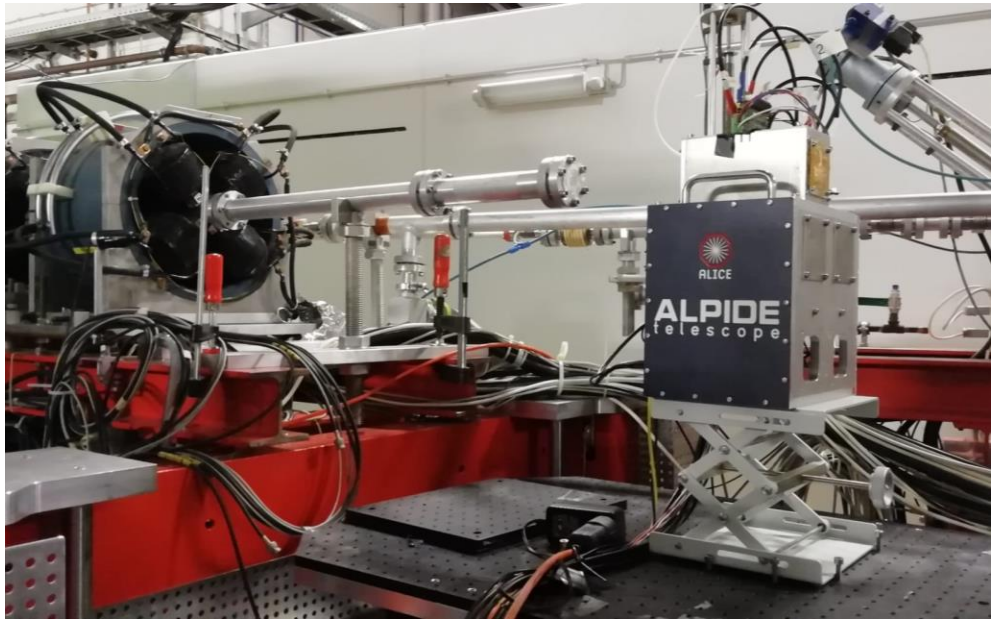
Thanks to the SPS testbeam support team

Mainz Test Beam

MAMI Microtron, 02 – 06 Dec 2021

Setup

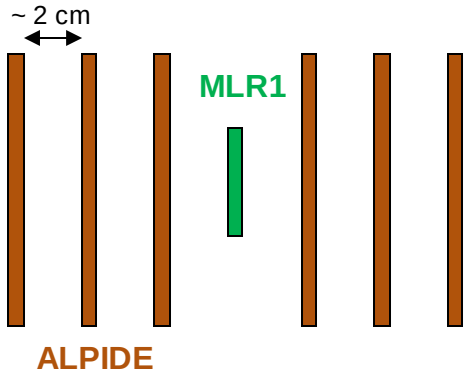
- **Electron beam**, 855 MeV
- **Beam Imax**: ~ 100 µA
- **Beam size**: ~ 1mm^2
- **ALICE ALPIDE Telescope** used as reference
- **Self-Trigge**r of MLR1 (OR of Scope Channels)

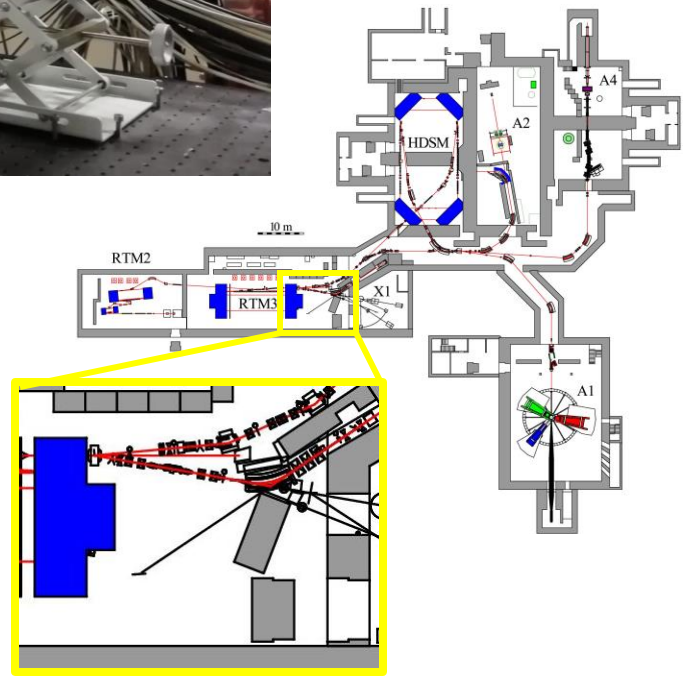


Results

- Recorded events: **> 500k** (few µm^2 of active area)
- Bias & Current scans on Pixel & CSA
- **Detailed Waveform analysis**

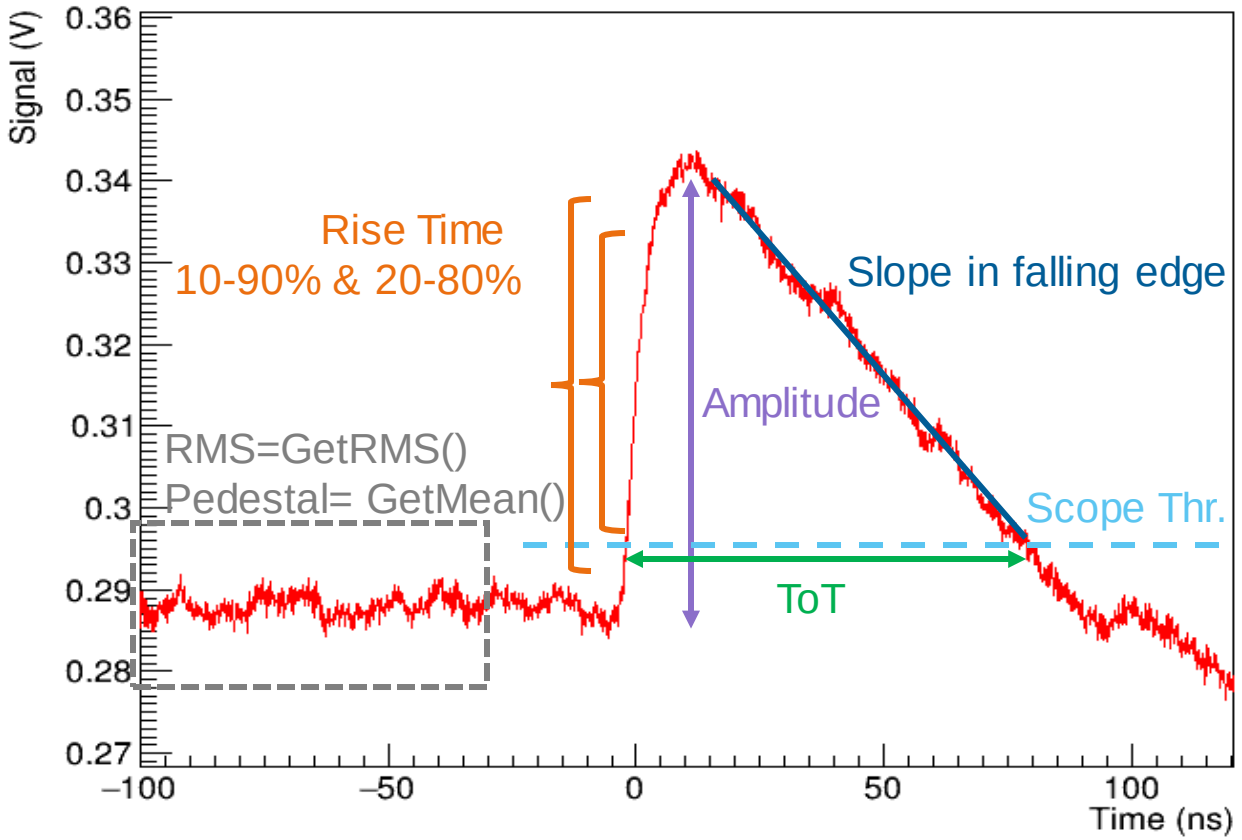
Thanks to the MAMI testbeam support team

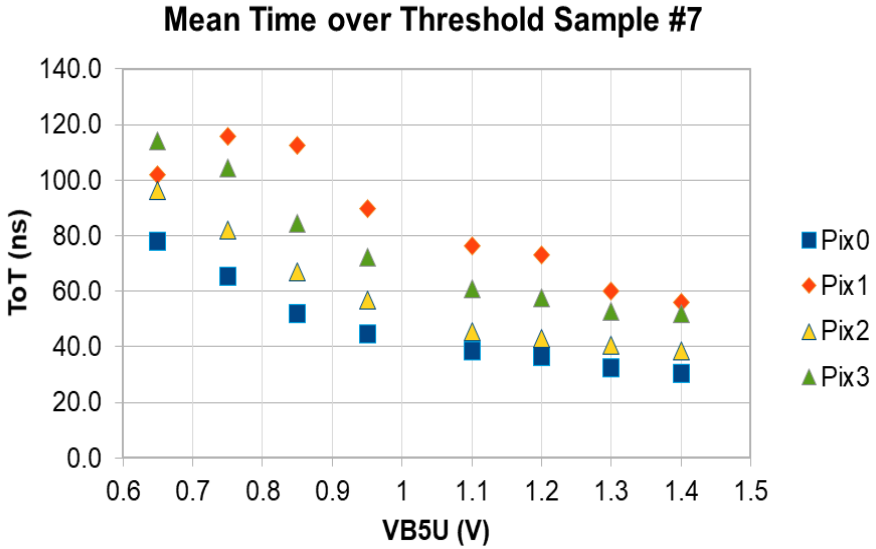


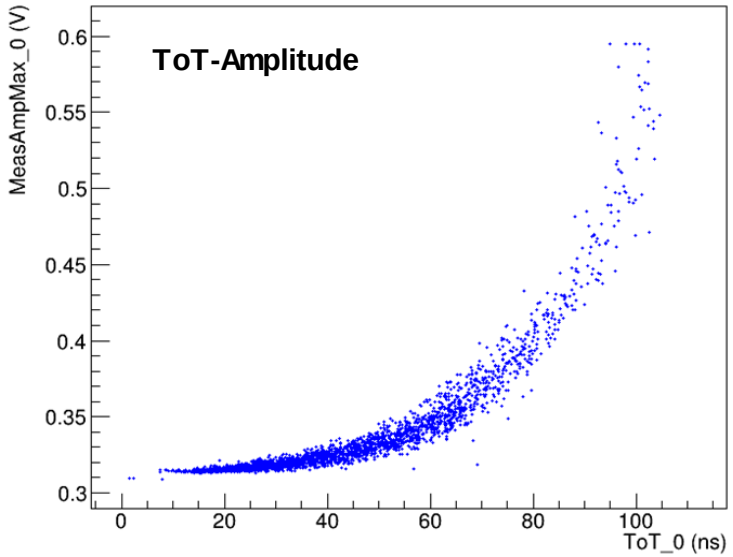


Mainz Test Beam: Results

Waveform Analysis with ROOT

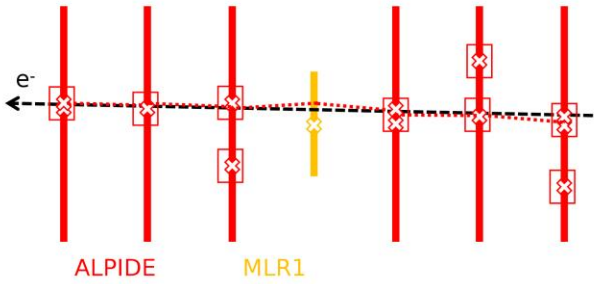






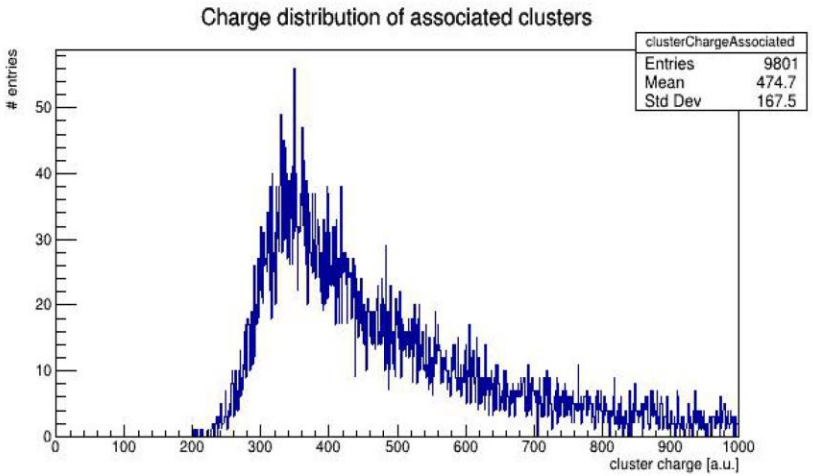
Mainz Test Beam: Results

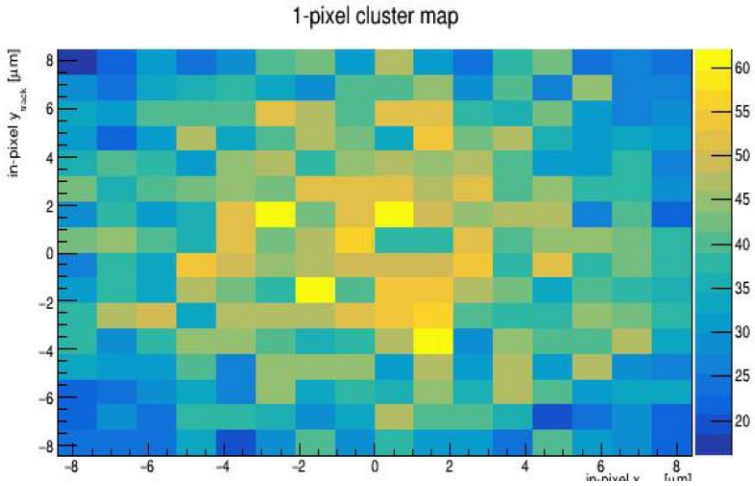
Corryvreckan Analysis

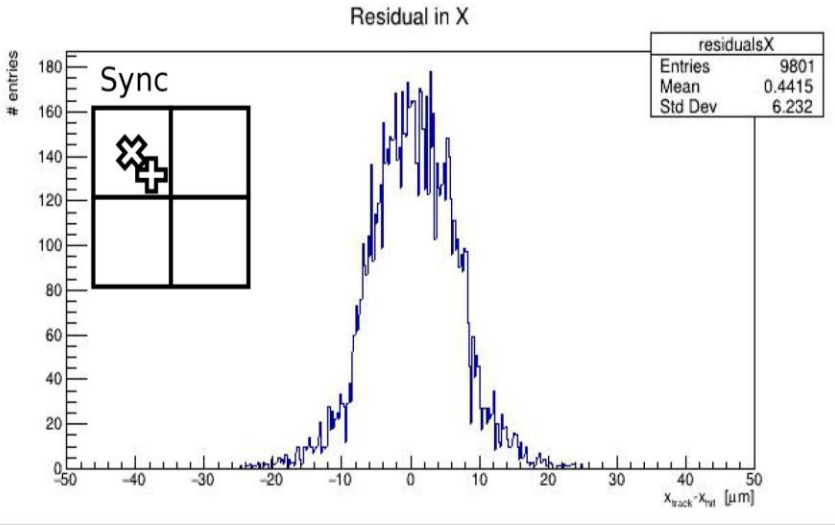


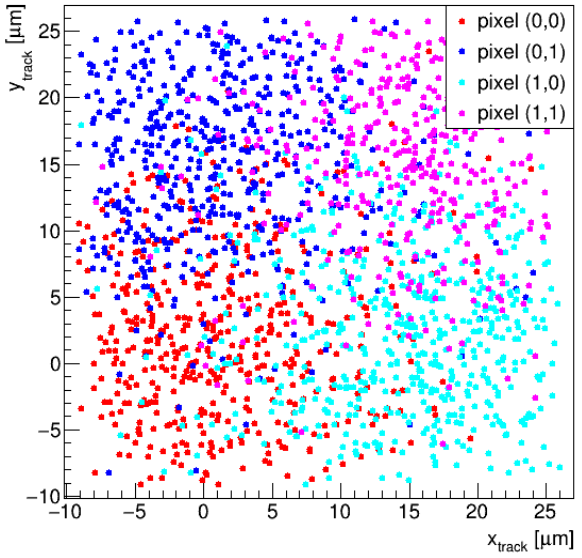
- Corryvreckan uses hit ⛒ (pixels above threshold) and Clusters ▯ (groups of adjacent hits) to recontruct particles trajectories ····

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







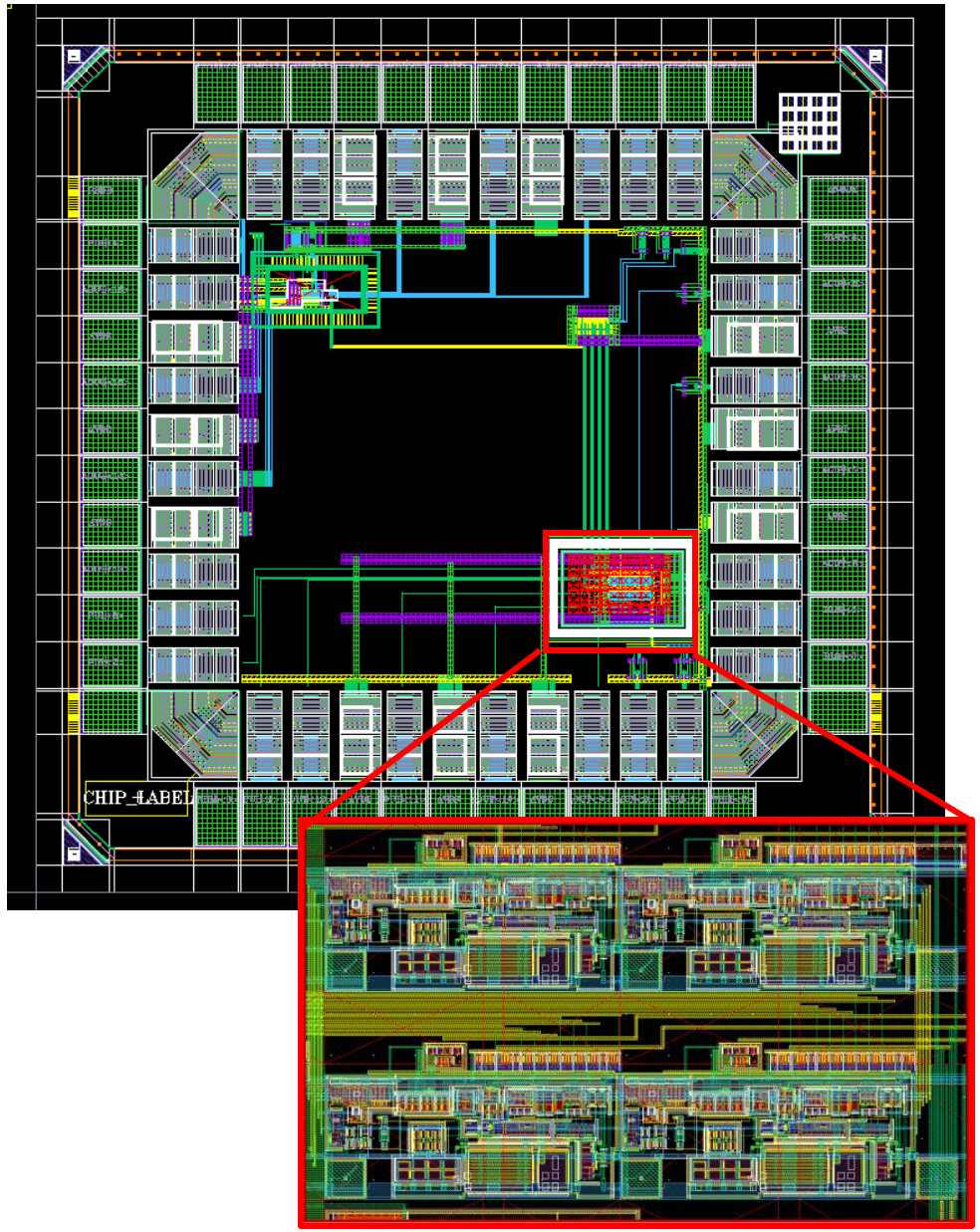


Work in progress & next

not only MLR1

Design of the **next TANGERINE prototype** submitted (ER1 Submission):

- 4x4 pixel (35x25 µm^2) matrix with **all in pixel functionality**
- External access to **CSA** and **discriminator** output
- N-blanket with gap layout with 2.5 µm and 4 µm gap
- Single Front-End with Injection
- Expected in Hamburg in early 2023



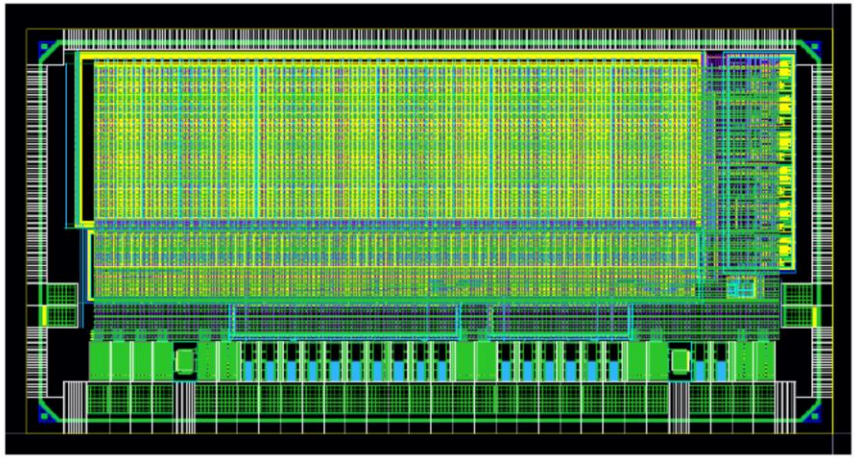
Work in progress & next

not only MLR1

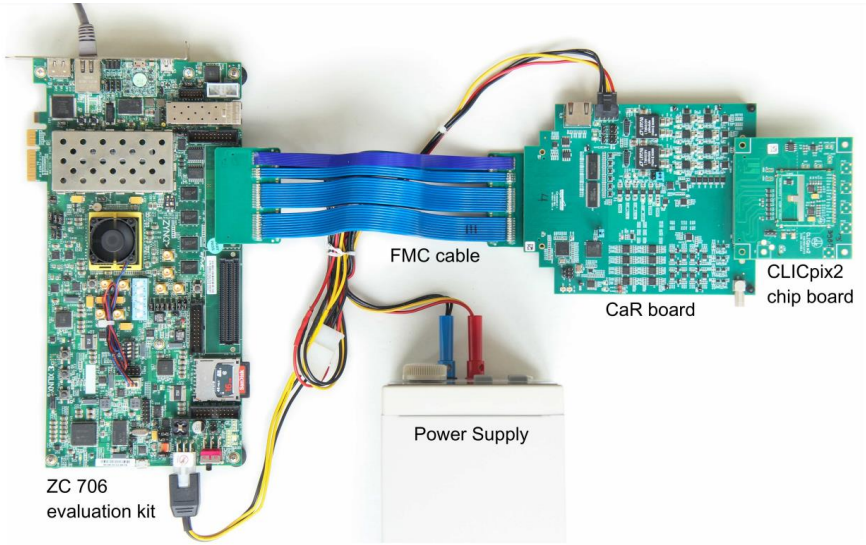
H2M (Hybrid-To-Monolithic):

- Collaboration of DESY, CERN and IFAE
- 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

- Expected in Hamburg in early 2023 (ER1 Submission)



H2M ASIC design



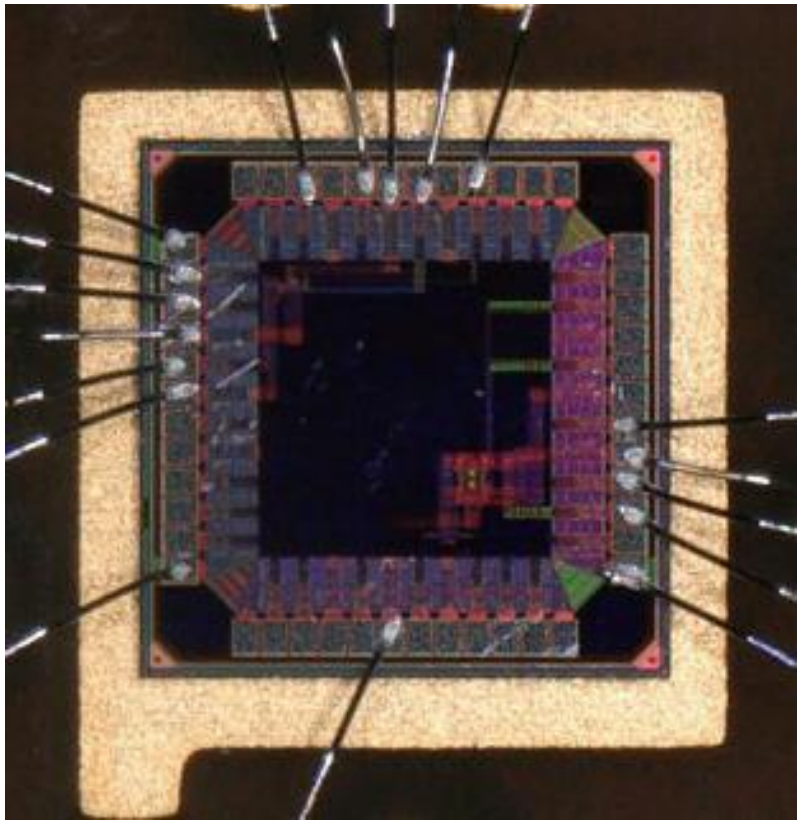
http://dx.doi.org/10.22323/1.370.0100

Conclusions

Results from the tangerine MLR1 Chip

TowArds Next GEneRation SIlicoN DEtectors

- A 65 nm CMOS pixel detector was for the **first time** developed & investigated at DESY
- DESY MLR1 Chip allowed the **first tests on designed CSAs** with the direct study of the waveforms
- Results of the studies on MLR1 allowed improvements in the **next prototype**
- The Tangerine group is now focused on TCAD studies, Allpix^2 simulations & test on other MAPS prototype in preparation of **next submissions**
- Results of Tangerine MLR1 Chip confirm the **MAPS** technology as **good candidate** for the next generation of pixel detector for beam telescopes
- Thanks for the great support from **CERN EP R&D** in MLR1 submission



Thank you

Contact

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Synchrotron DESY

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Backup

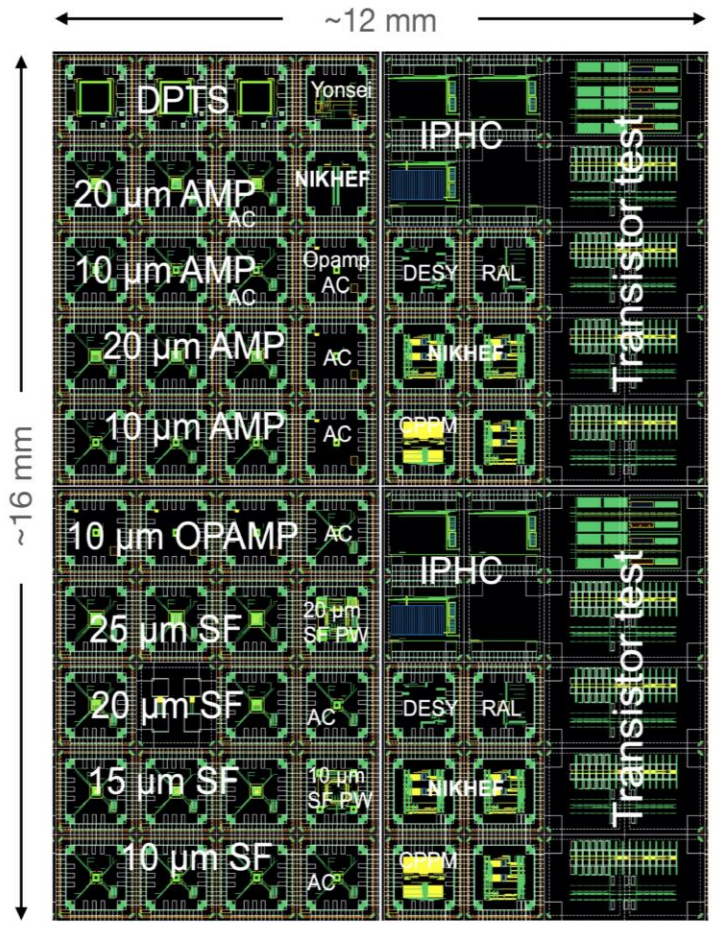
MLR1 production

Multi Layer Reticle 1

- **Wafer** divided up into “sites” of 1410x1410 µm for different test chips **shared** between DESY, CERN, RAL, Nikhef, etc.

- TJ 65nm ISC Process limitations in MLR1:
  - Only 3+1 metal layer
  - 10µm epitaxial layer

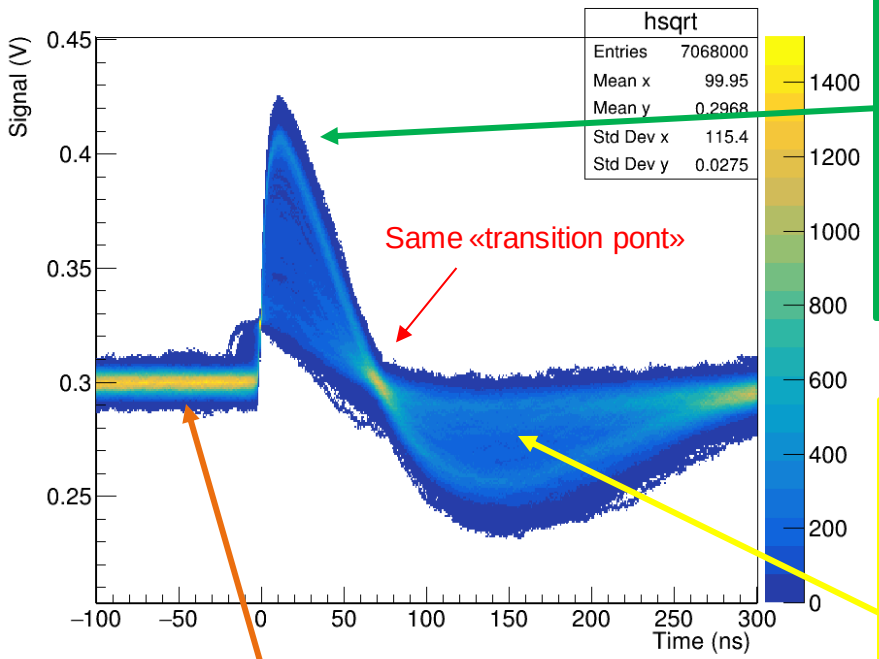
- MLR1 timetable:
  - Design submitted Dec-2020
  - MLR1 at CERN June 2021
  - DESY MLR1 in Hamburg October 2021

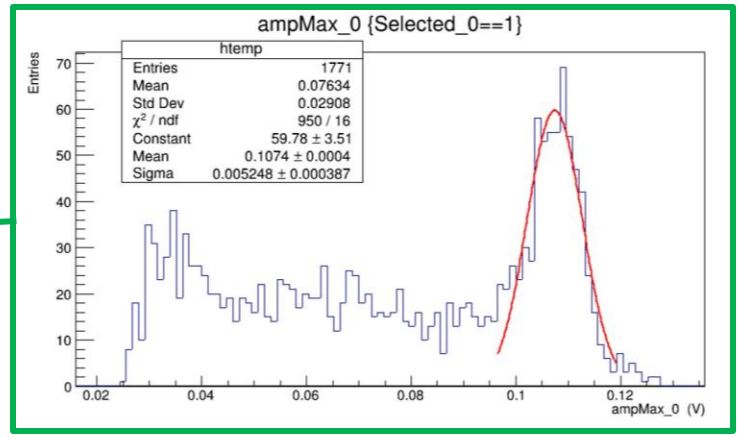


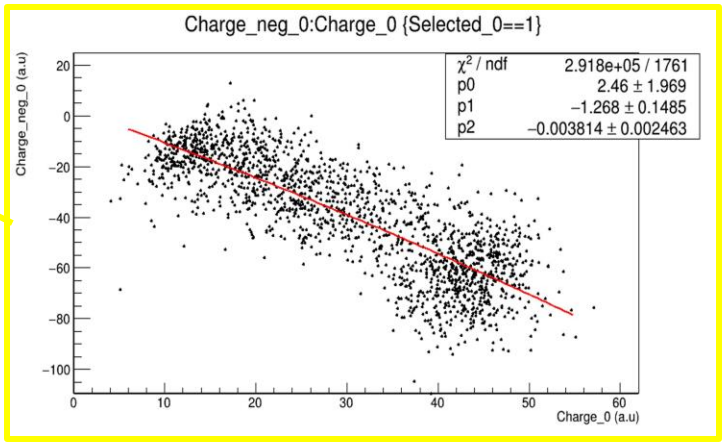
expect O(500) dies per wafer

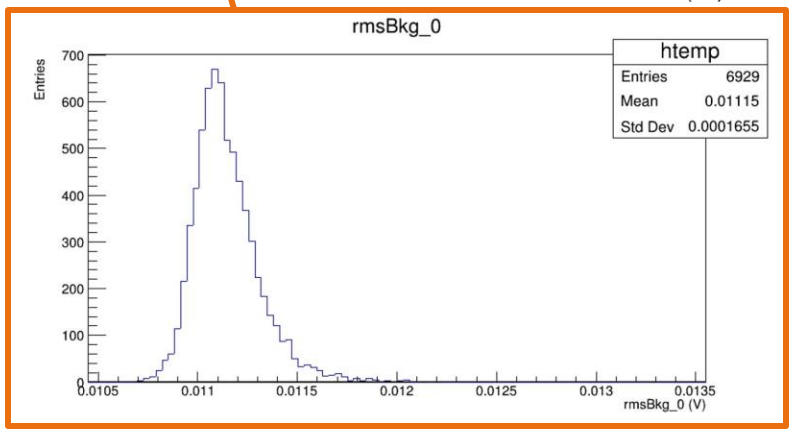
Fe^{55} source studies

October-November 2021







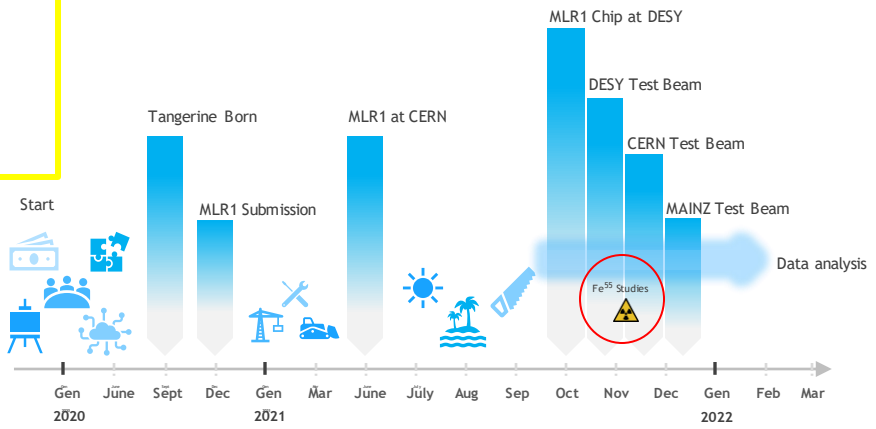


Example reported:

- Sample ID: 4 pixel 0
- Exposure time: ~ 1 night
- # Trigger: 6929 (all 4 channels)
- Thresholds: 20 mV over noise

Signal amplitude Expected:
(@ Christian Reckleben)

- K_α: 5.8 keV → ~ 1590 e-
- @ Cf = 2fF ±10% → ~ 127 mV
- Gain 1.33 → ~ 168 mV ±10%

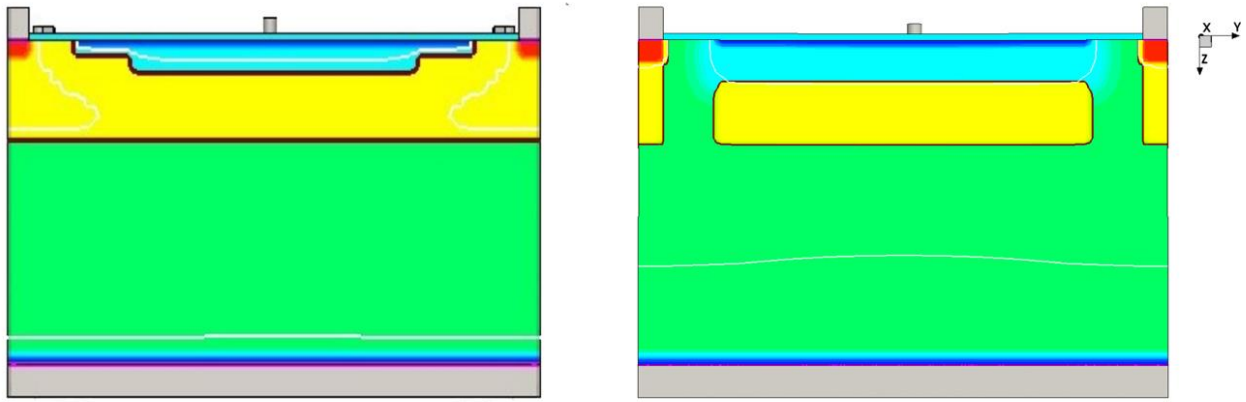


MLR1 Real Chip

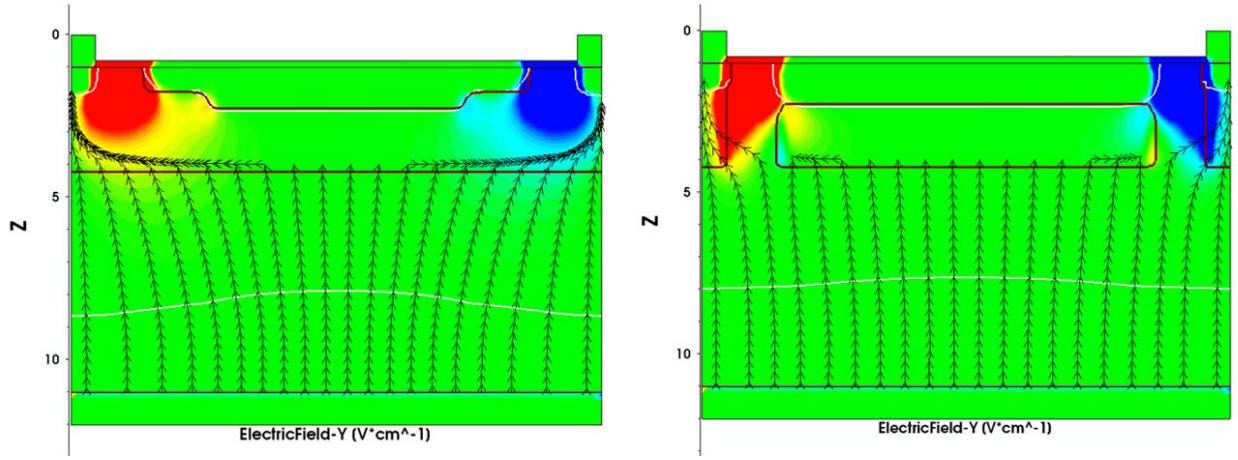
Explanation for the low efficiency of the chip

- The very low rate at DESY and CERN prompted an in-depth analysis of the MLR1 chip
- After Interactions with CERN people involved in MLR1 production, a sensor layout issue in DESY MLR1 Chip was found
- TCAD simulations confirmed that the chip cannot perform as expected
- The **expected efficiency is now ~ 0.5%**

Doping Concentration



Lateral Electric Field



Expected MLR1 Pixel **Real MLR1 Pixel**

@ A. Simancas

Mainz Test Beam: Results

Waveform Analysis with ROOT, sample #7

- IB5U scan (amps bias current) 4-14 µA (VB5U 0.65 - 1.4 V)
- VSUB scan (pwell sub voltage, sensor cathode) 1.25 - 2.2 V