TestBeam Characterisation of DESY's Digital SiPM-IC

Towards CMOS Photo-Counters & 4D-Tracking

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Hamburg, 19 Jan 2024

HELMHOLTZ

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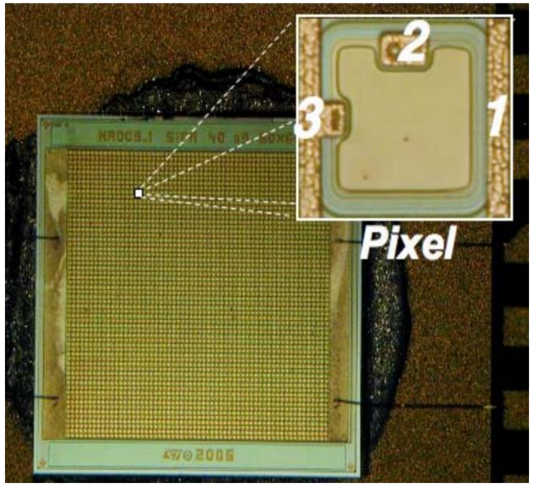
DESY.

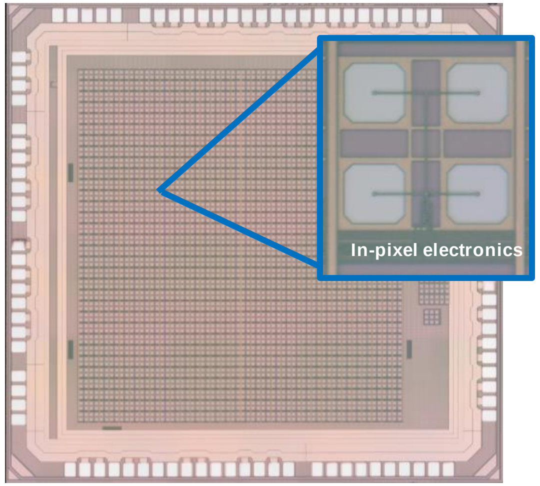
Motivation

Possible Application of CMOS SiPMs in HEP

As an alternative to analog SiPM

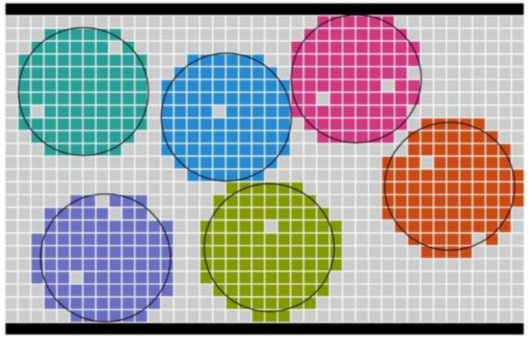
- Reduce complexity of DAQ chain with CMOS electronics
- New in-chip features:
    - Noise suppression
    - Photocounting & trigger logic
    - Parameters tuning (e.g. quenching tuning)
- Customized cost-effective solution in HEP



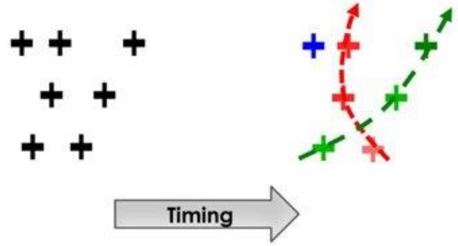


As candidate for new applications

- Multi-fiber readout in calorimetry
- 4D-Tracking of MIPs



https://doi.org/10.1016/j.nima.2022.167033



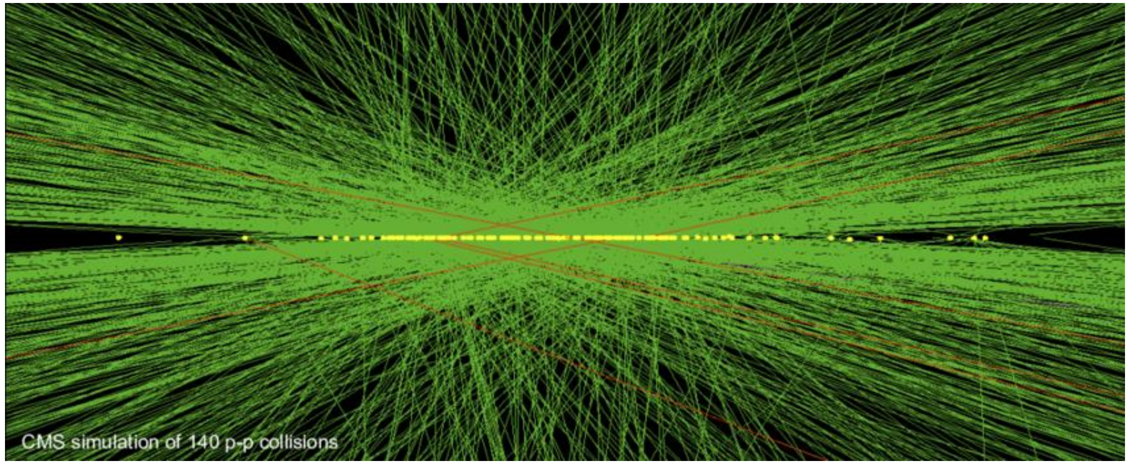
https://dx.doi.org/10.1088/1361-6633/aa94d3

4D-Tracking with SPADs

DESY dSiPM as Prototype

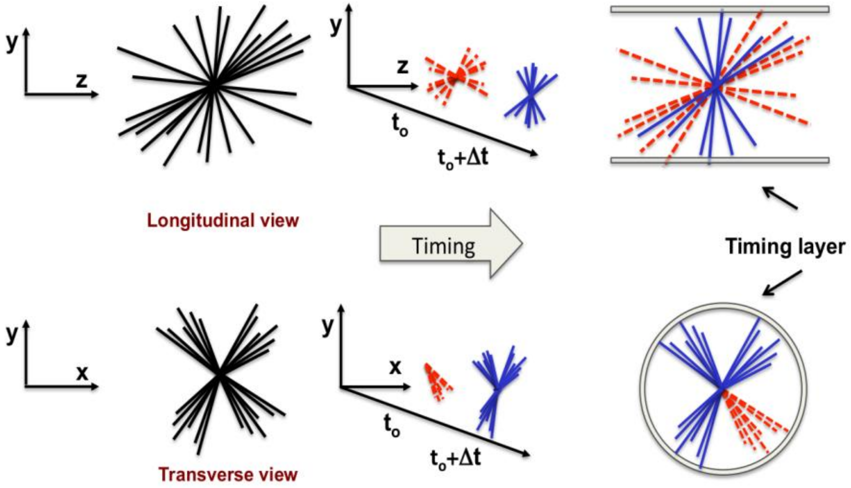
4D-Trackers

- Detector with excellent timing O(10s ps) and spatial O(10 µm) resolution
- Key R&D for future experiments
- Assign accurate timestamps to overlapping tracks



Is DESY dSiPM a 4D-Tracker prototype?

- Can we treat DESY dSiPM as a MIP detector?
- What are DESY dSiPM spatial resolution ?
- What are DESY dSiPM timing resolution ?
- What is DESY dSiPM efficiency in MIP detection?



DOI 10.1088/1361-6633/aa94d3

Is DESY dSiPM a MIP detector?

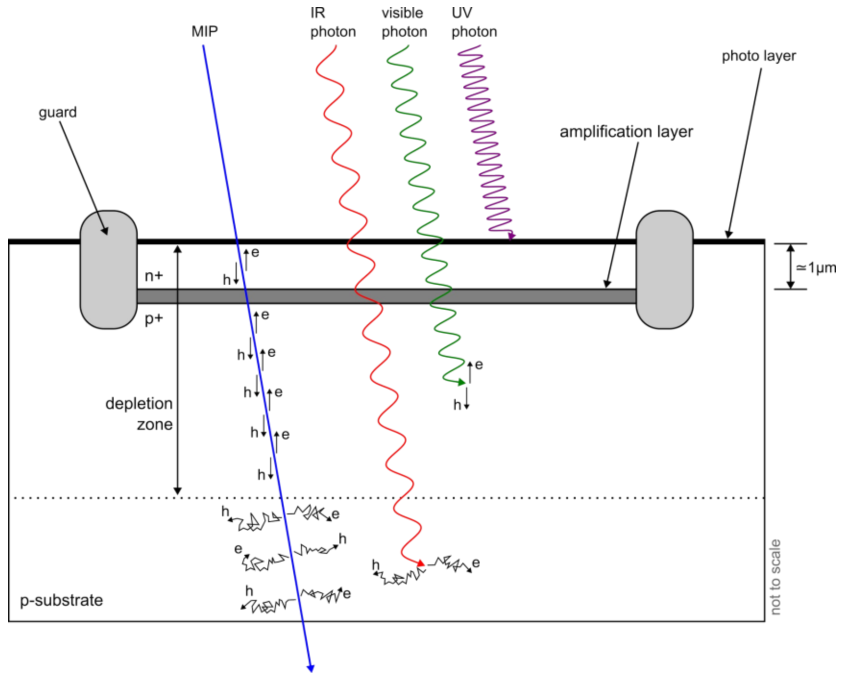
From TB in March 2023

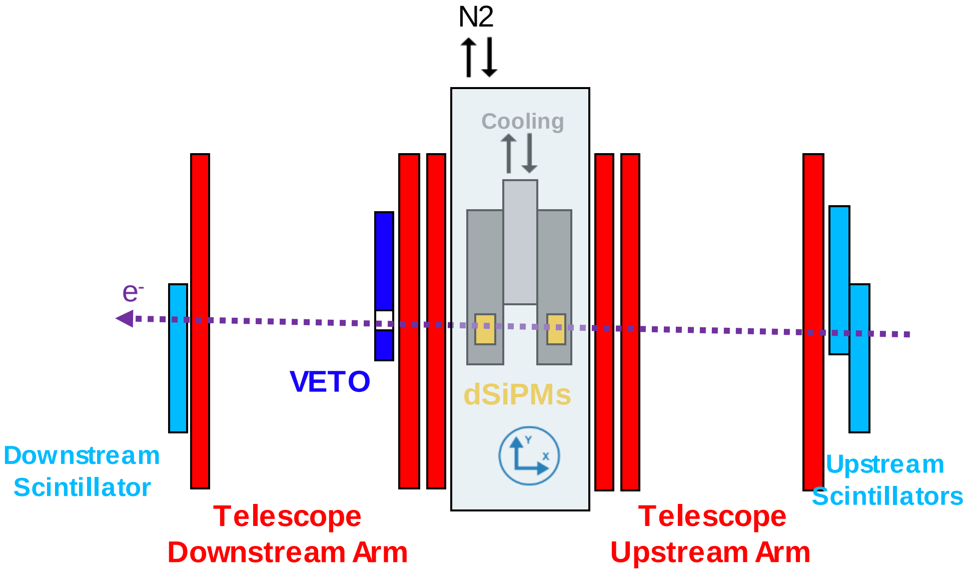
Direct MIP detection with SPADs

- Higher detection efficiency w.r.t. Photons (PDE)
- Main limit is the fill factor (30 % in DESY dSIPM)
- Binary information (Geiger mode device)
- No amplification needed (avalanche gain > 10^5)

DESY dSiPM in a testbeam setup

- DESY II with 4 GeV electrons
- EUDET telescope with 6 MIMOSA26 planes
- Triggering on scintillator+veto
- Trigger Logic Unit (TLU) & EUDAQ2 for system control
- Two dSiPMs (DUTs) to study coincidences



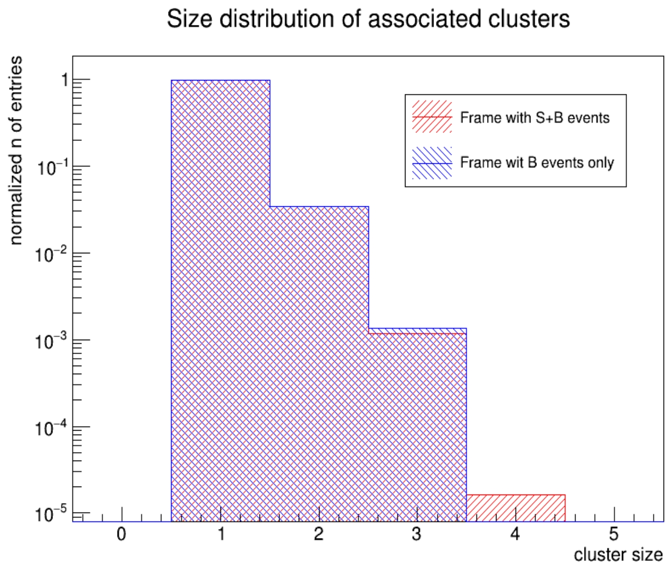


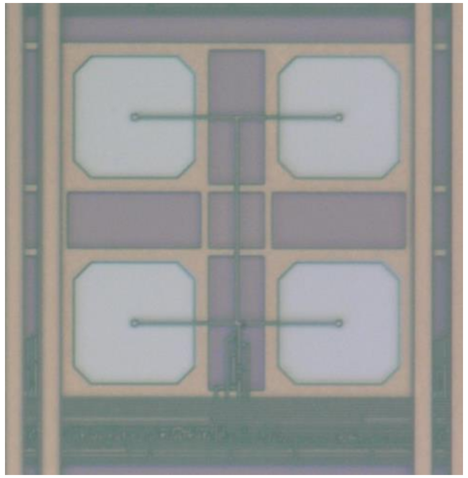
DESY dSiPM Spatial Performances

In MIP Detection

Associated cluster size

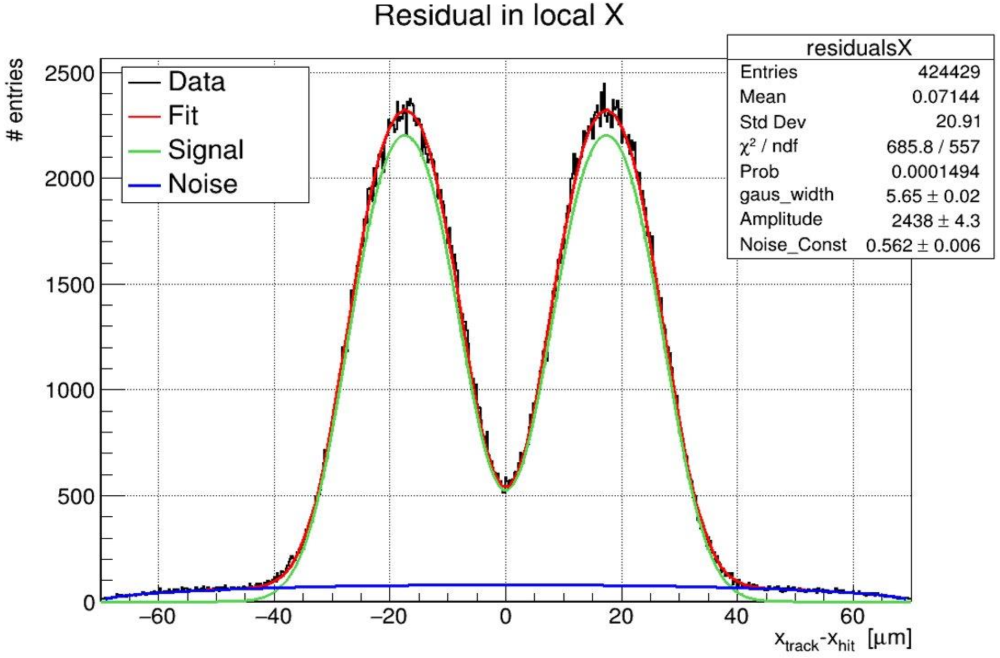
- Mainly one, no visible charge sharing
- Large gap between pixels to avoid crosstalk
- Cluster size of MIP and noise event compatible





Spatial residuals

- Defined as the difference between cluster position in DUT and interpolated track in the same z-position
- Double peak structure (inefficiency in the pixel centre)
- Small noise contribution (in blue)
- Std Dev of signal **~21 µm** in x and y (dominated by DUT resolution)
- Spatial resolution compatible with pitch/sqrt(12)



DESY dSiPM Timing Performances

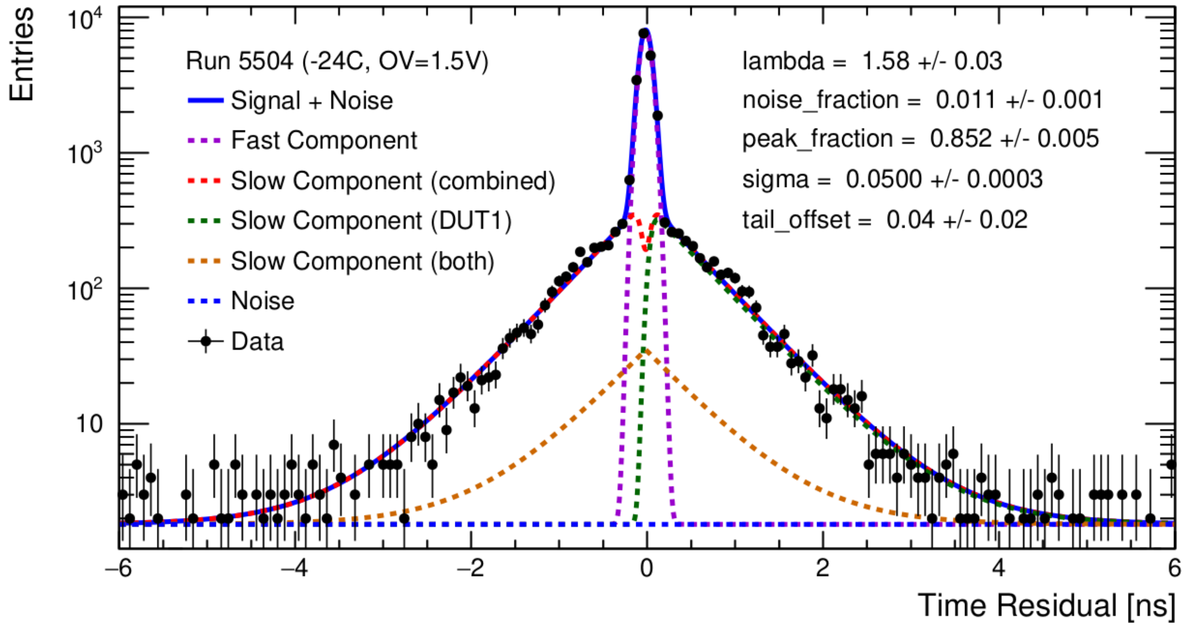
In MIP Detection

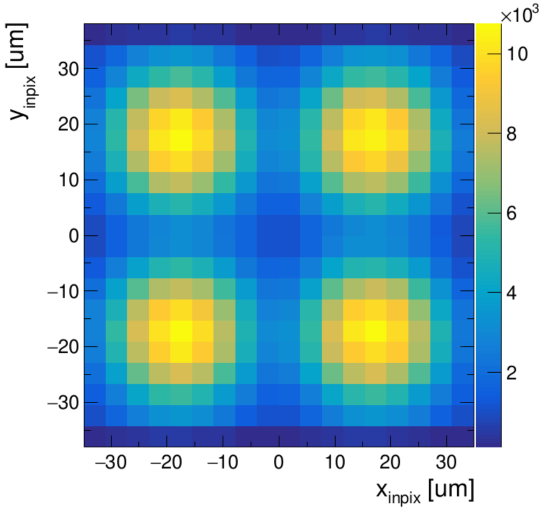
Time residuals

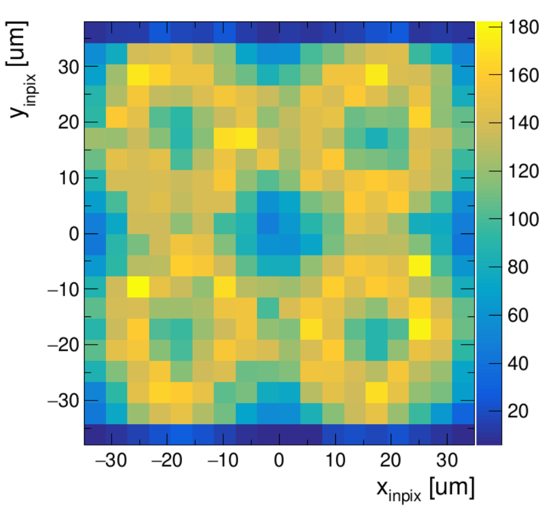
- Defined here as the difference between the DUTs timestamps (dSiPM1 – dSiPM2)
- Can be used to determine dSiPM + DAQ time res.
- Time resolution measured: **46 ± 5 ps**
- Limited mainly by TDC resolution (~95 ps)

Slow component

- The number above refers to the core of time residuals
- Slower component observed in the 15 % of the entries
- Visible as ns tails in time residuals
- Slow component correlated to SPAD periphery
- Probably due to MIP interaction in low E-field regions





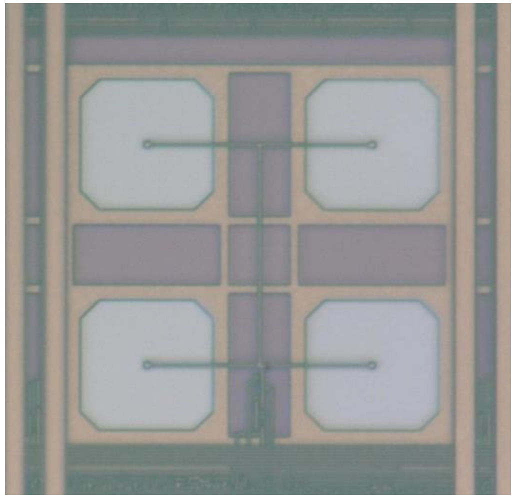


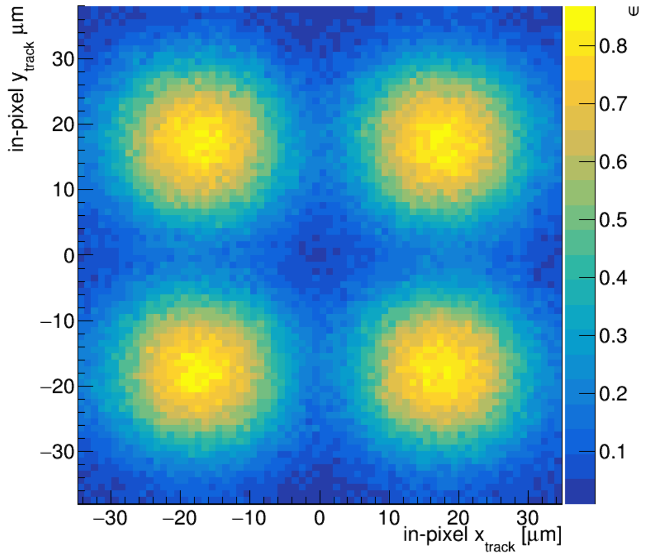
DESY dSiPM Efficiency

In MIP Detection

In direct MIP detection

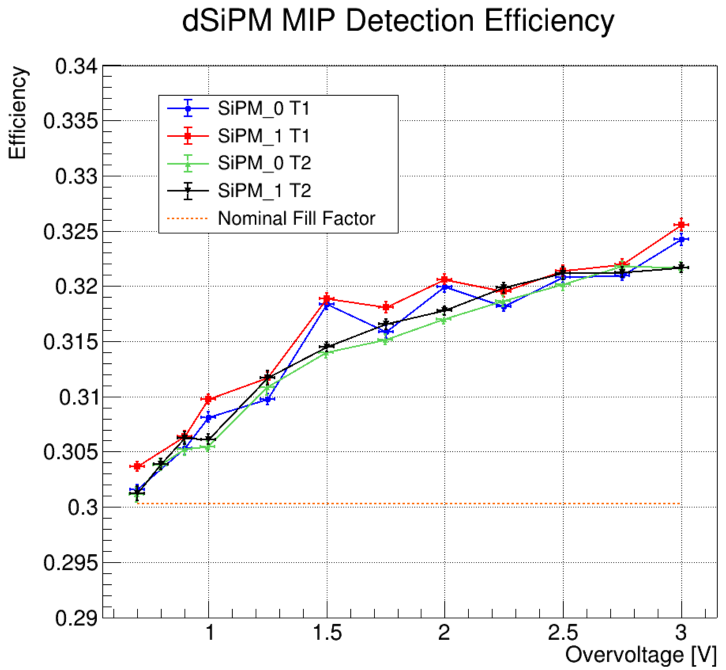
- Main limit is the fill factor (~30%)
- Maximum efficiency in the SPAD centre
- Track resolution O(4 µm)
- Measured value is slightly larger than the fill factor
- Small OV dependence
- No temperature/sample dependence observed





Overcome efficiency limits

- Along with the DCR represents the main limit for 4D-Tracking
- Use larger SPADs (and not 4 x small)
- Use design/processes with slimmer SPAD isolation
- Explore the coupling thin radiators (next slides)

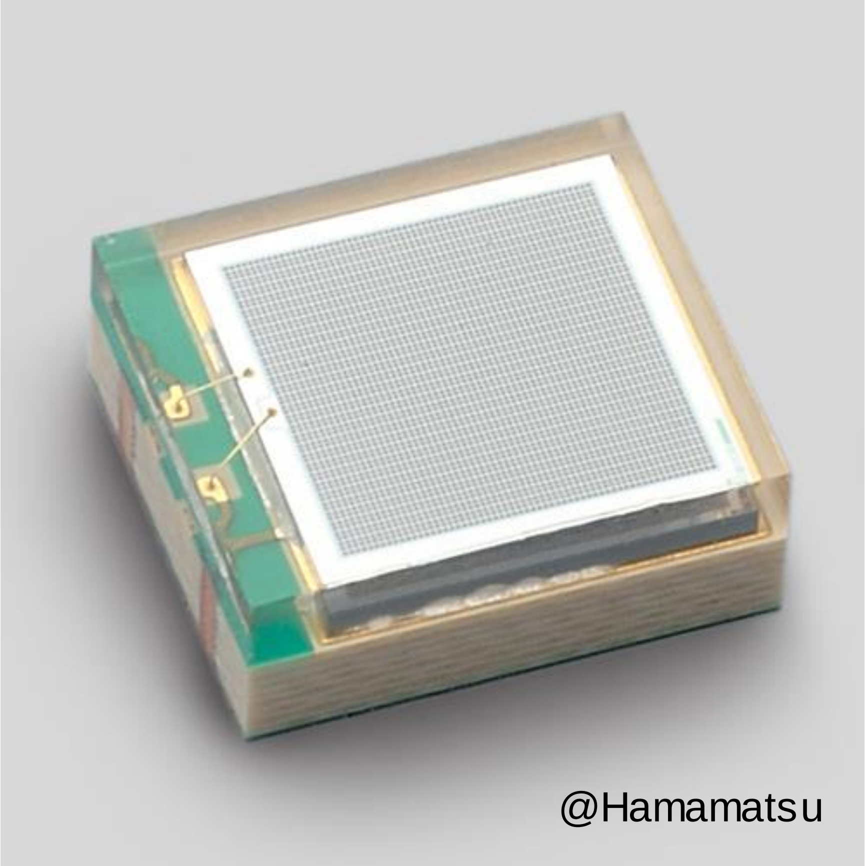


Possible Solution to Increase Efficiency

And "Reduce" DCR Noise

MIP detection with analogue SiPMs

- High detection efficiency observed while detecting MIP
- High number of SPADs firing
- Correlation between MIP response and SiPM packaging
- Effects attributed to Cherenkov light produced in commercial SiPMs protection materials (~0.6-1.5 mm Epoxy resin or Silicone)
- Benifits:
  - High efficiency of SiPM in direct MIP detection
  - Low DCR contamination (high threshold)
  - Multipurpose detector (single photon and MIP)



References

F.Carnesecchi, G.Vignola et al. *Direct detection of charged particles with SiPMs*, 2022

F.Carnesecchi, G.Vignola et al. *Understanding the direct detection of charged particles with SiPMs*, 2023

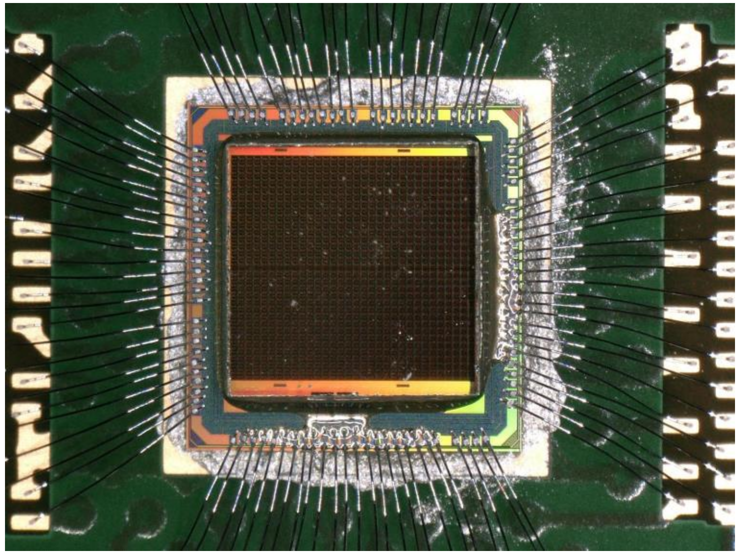
F.Carnesecchi, B.Sabiu et al. *Measurements of the Cherenkov effect in direct detection of charged particles with SiPMs*, 2023

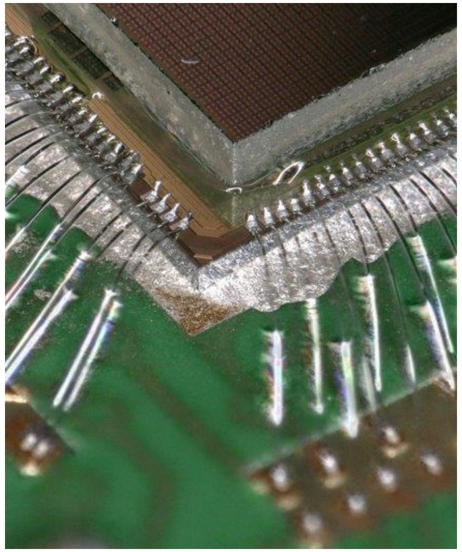
Thin LYSO Concept for DESY dSiPM

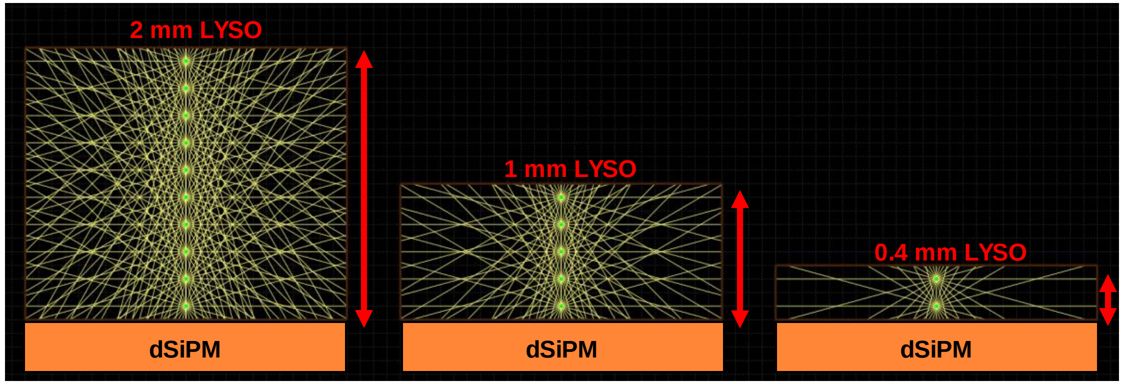
Increase Efficiency and "Reduce" DCR Noise, Towards 4D-Tracking

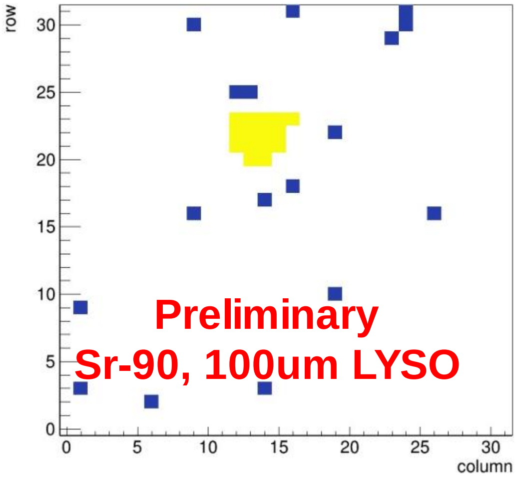
MIP detection with digital SiPMs

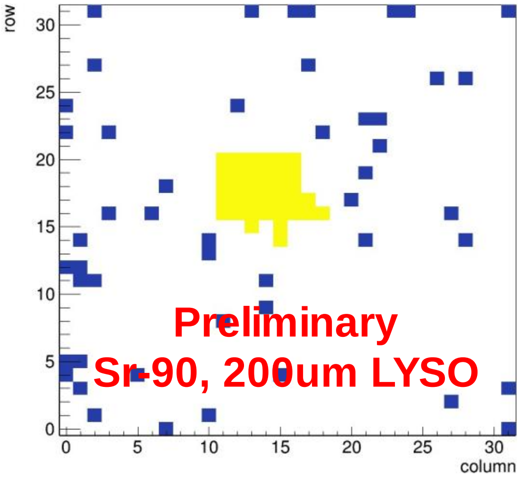
- Explore similar concept with the DESY dSiPM
- LYSO scintillators:
  - Higher number of photons/µm
  - Thinner converter -> cluster of photons
  - Preserve spatial resolution on DUT
- Promising simulations & Sr-90 preliminary results











Summary

DESY digital SiPM

CMOS SiPMs R&D

- dSiPMs can be an interesting alternative to analog SiPM in some HEP applications
- Combination of CMOS and SPAD electronics in the same silicon die opens new application possibilities

DESY dSiPM & 4D-Tracking

- Successively integrated into a test beam setup as particle detector
- Spatial resolution of the O(20 µm)
- Full-system timestamping with O(45 ps) time resolution
- Efficiency comparable to the fill factor
- dSiPM + LYSO: a promising approach to improve efficiency and reduce noise

Thank you.

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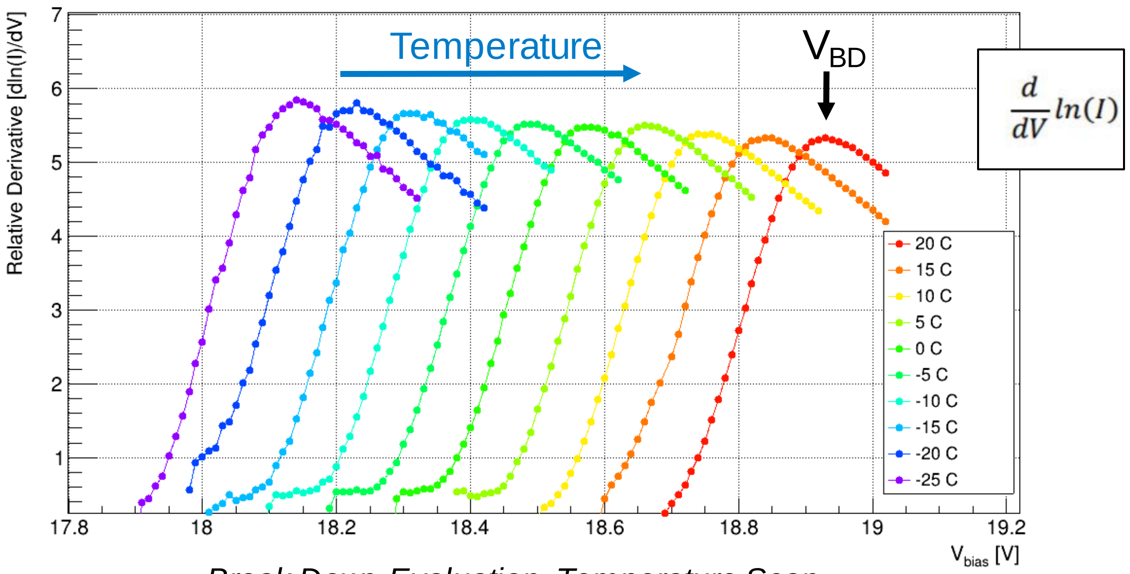
The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

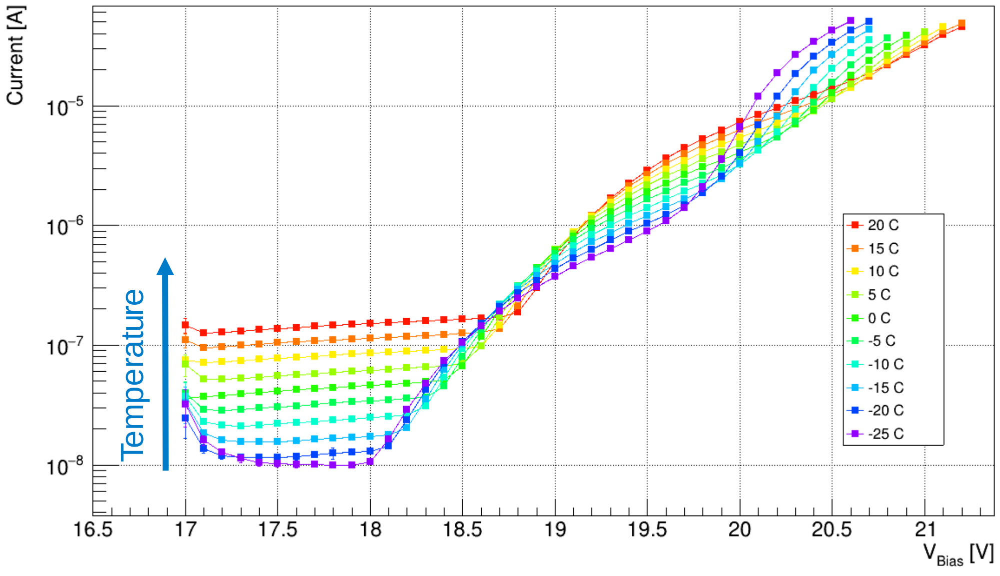
IV Curves & Dark Count Rate

Chip Characterization

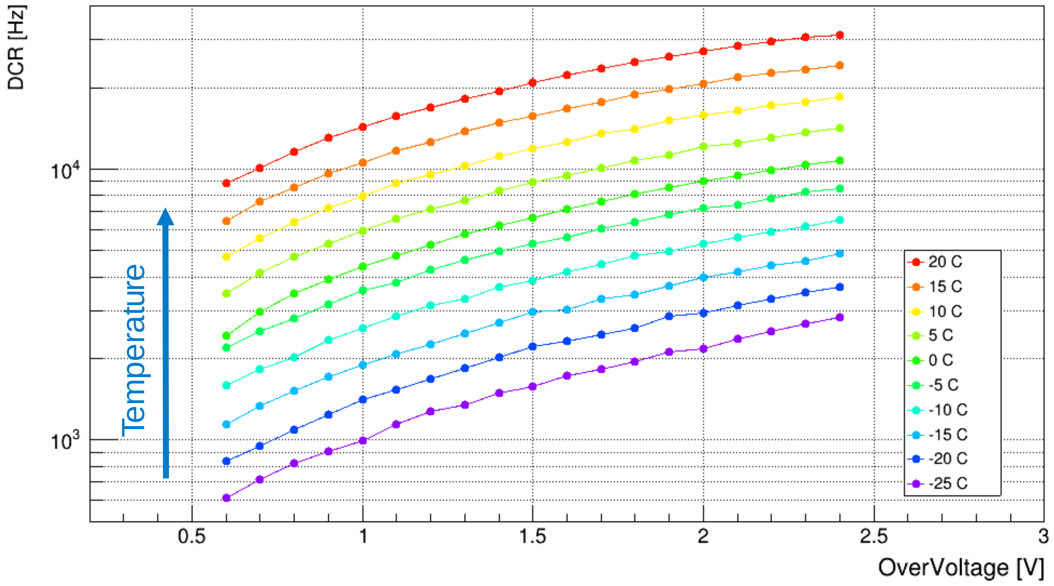
- Detailed characterization performed on several samples (Chip4 shown in figures)
- IV & Dark Count Rate studies performed whit controlled temperature (from -25 to 20 °C) and humidity (~ 0 %) in a dark environment
- Measurements compatible with expectations



Break Down Evaluation, Temperature Scan



IV curves (Full Matrix), Temperature Scan



Dark Count Rate (per pixel), Temperature Scan

Quenching & Pixel Masking

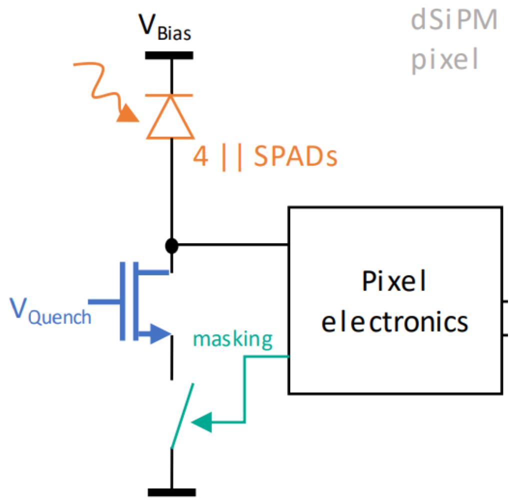
Two Peculiar Features

Quenching

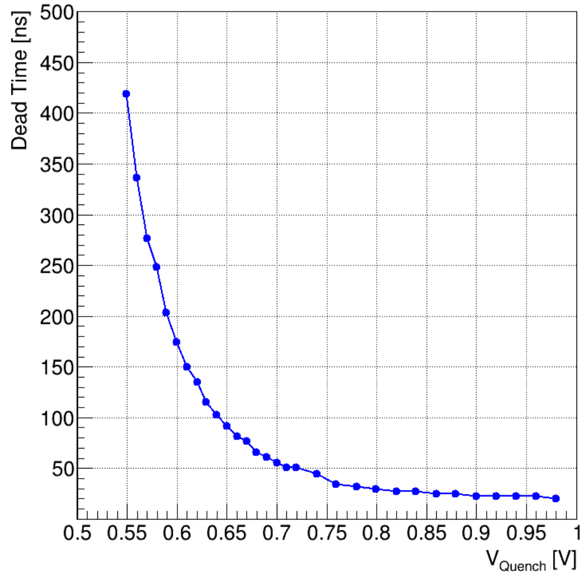
- The Pixel's quenching circuit consists of a single Transistor
- Acting on V_{Quench} is possible to tune the signal length
- Non-overlapping hits (up to 3) can be distinguished and counted within the frame (3MHz frame rate)

Pixel Masking

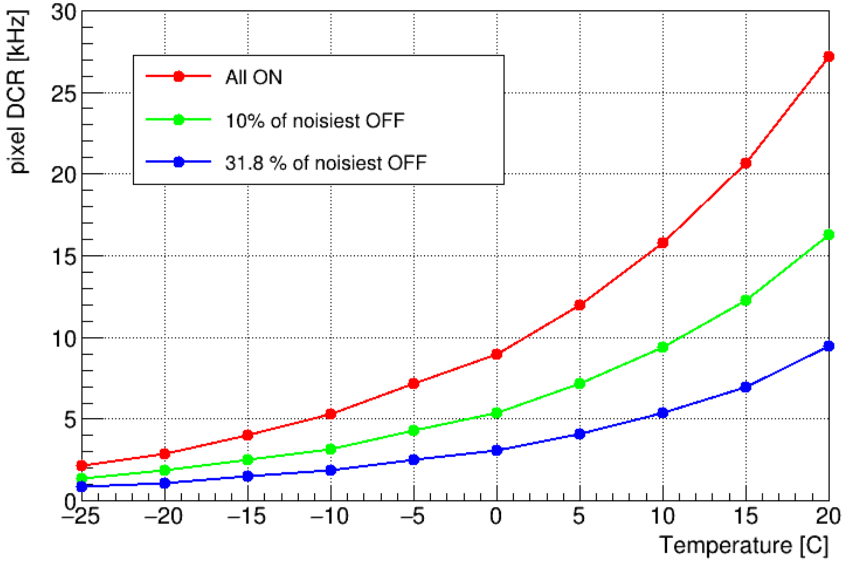
- Individual pixels can be disabled
- Allows deactivation of noisy/unused pixels (DCR & power consumption reduction)
- Allows in-depth characterization of SPAD arrays



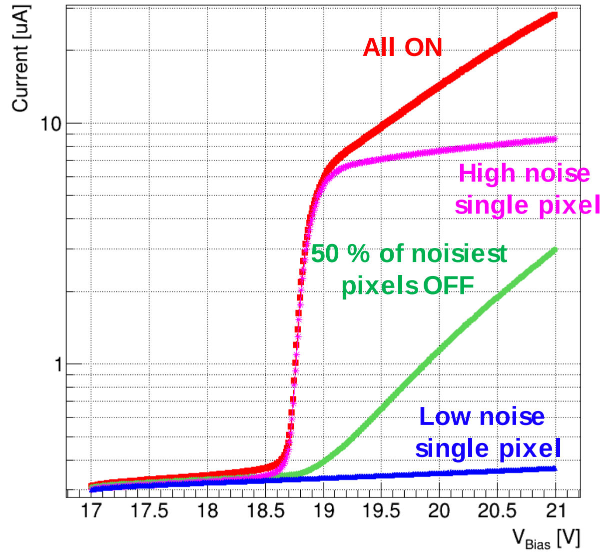
Pixel Circuit



Dead Time vs V_{Quench}



DCR whit different masks (2 OverVoltage)



IVs whit different masks

Additional characterizations

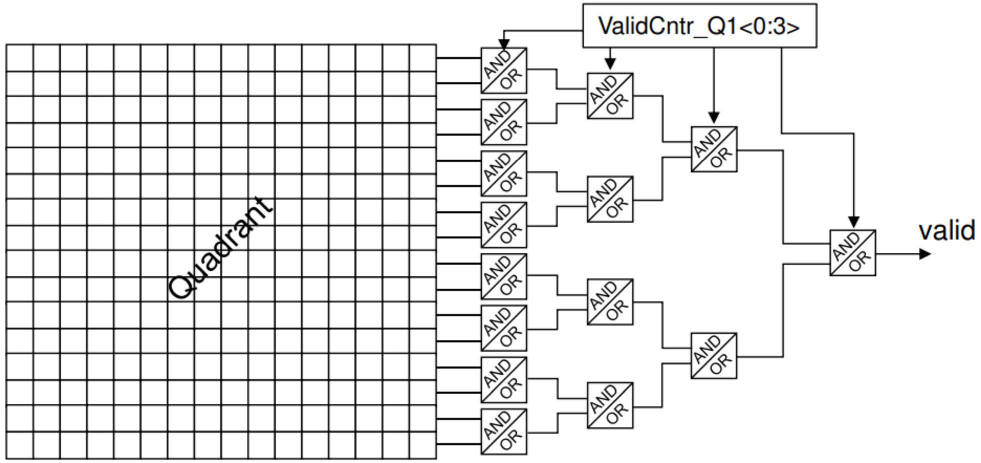
Validation Logic & Dead Time

Validation logic

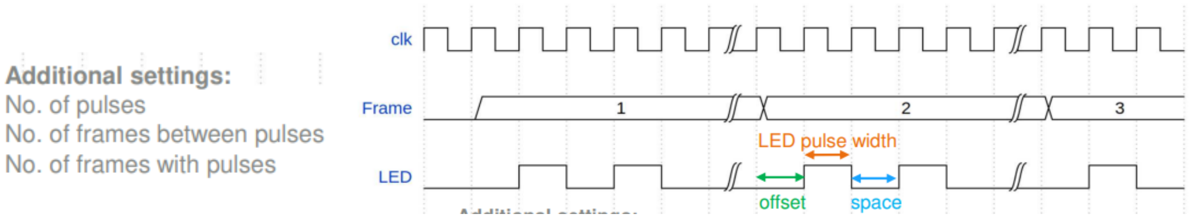
- A 4-step validation logic is implemented in every quadrant
- Every step can be configured to be an AND or OR gate
- A flag bit is generated for event validation within 2 ns
- Successfully validated using laser pulses and masking

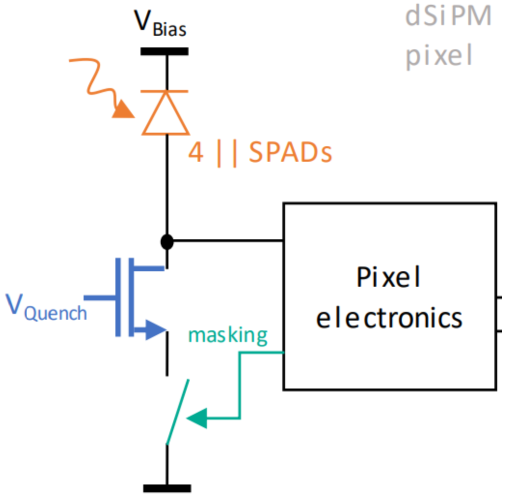
Quenching & Dead Time

- In 2-bit mode is it possible to count laser pulses within the frame
- Consecutive pulses can be distinguished only if the discriminator threshold is crossed (non-overlapping pulses)
- Pulse length can be tuned by acting on Vquench Transistor (Global Setting)

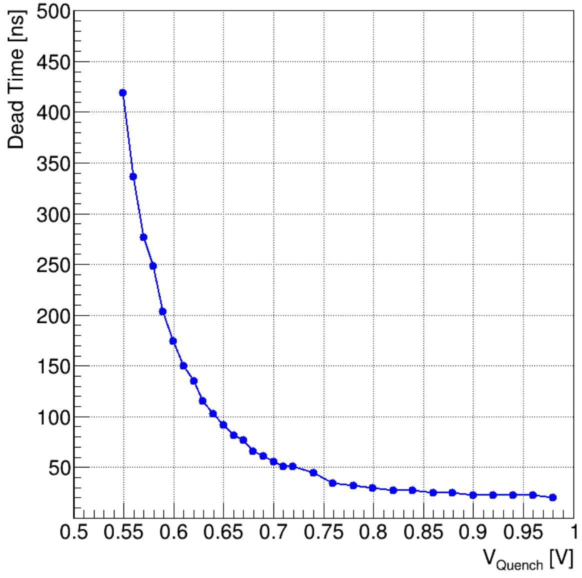


Schematic representation of the Validation Logic





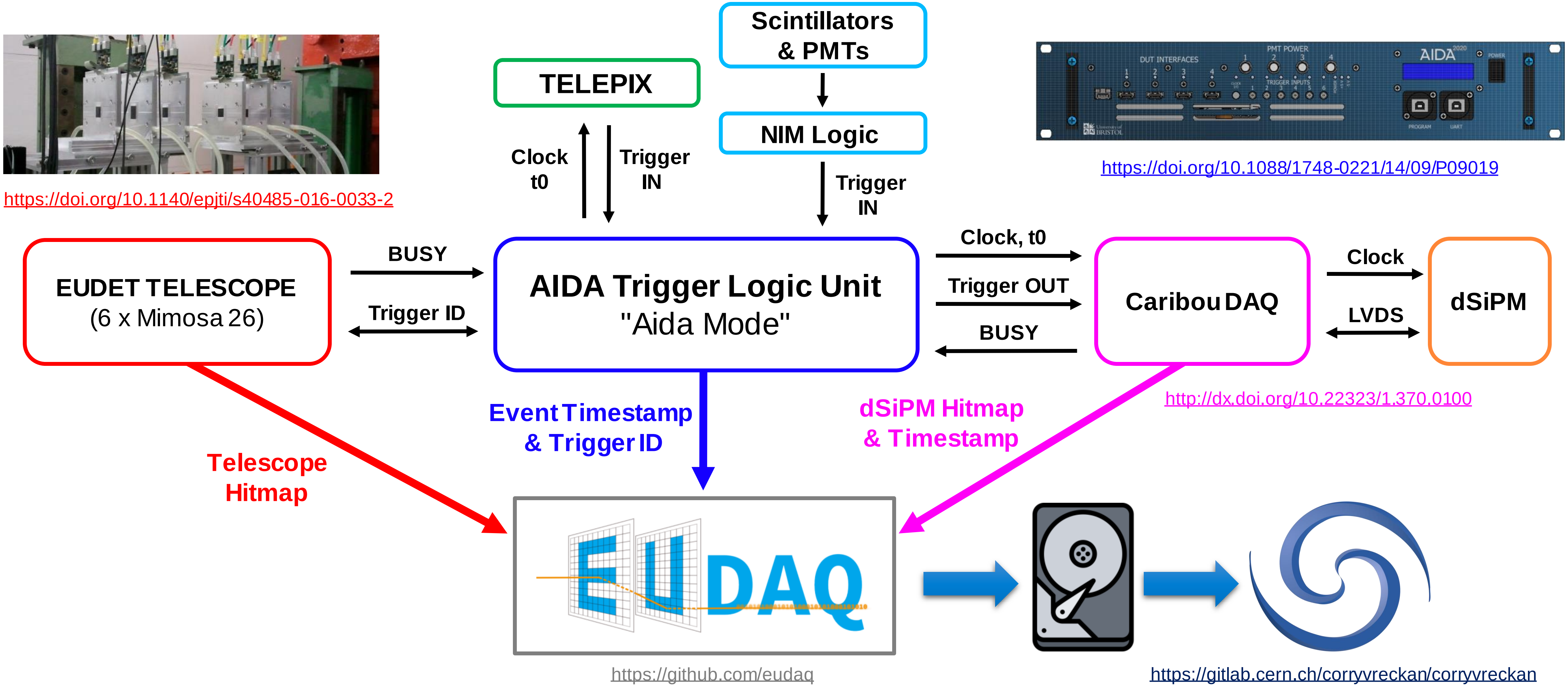
Pixel Circuit



Dead Time vs V_{Quench} (chip4)

DAQ System in Test Beam

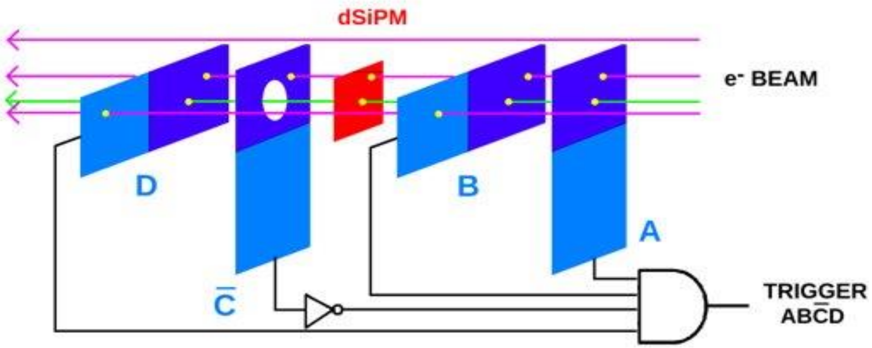
AIDA TLU Core

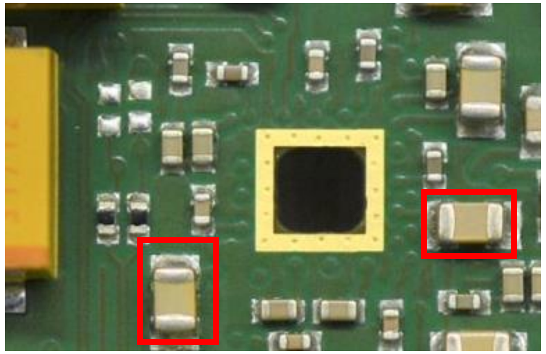


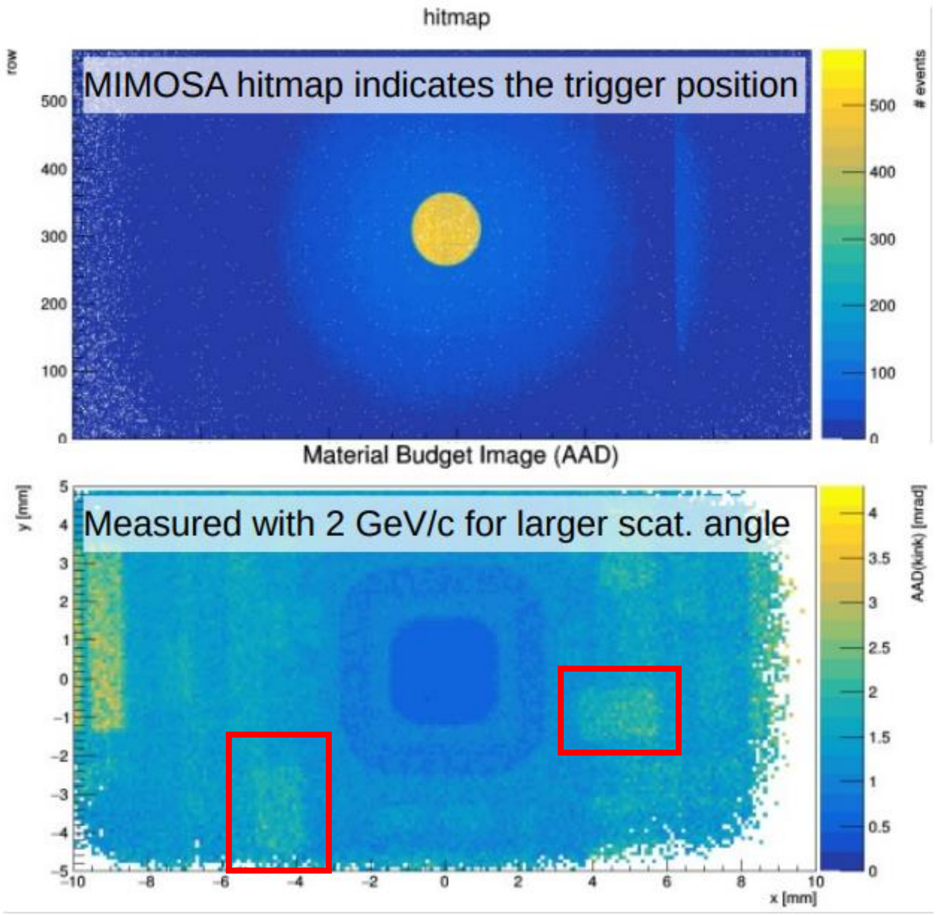
DUT & Trigger Alignment

A Peculiar Approach

- High DCR of dSiPM makes alignment of DUT and the trigger reference complicated (DCR/MIP event distinction impossible before alignment)
- Used Corryvreckan Material Budget Imaging (MBI)
- The software reconstructs the tracks and evaluates the scattering angle at the DUT z-position (proportional to Material Budget)
- The MB is minimized at the position of the dSiPM, which is then easily located



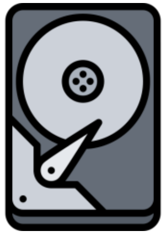




https://gitlab.cern.ch/corryvreckan/corryvreckan/-/tree/master/src/modules/AnalysisMaterialBudget

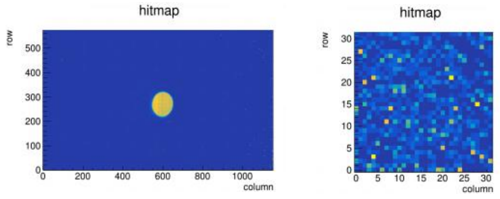
Analysis Chain

Using Corryvreckan



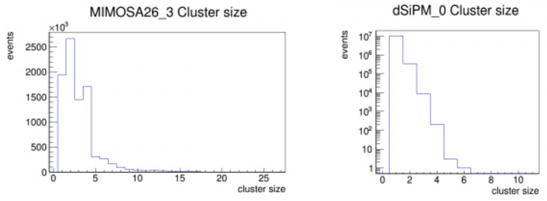
Data Decoding

Raw Telescope & dSiPM **data** are **decoded** into an accessible format



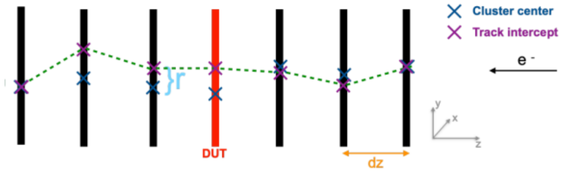
Clustering

Clusters of hits in the reference telescope and DUT are identified



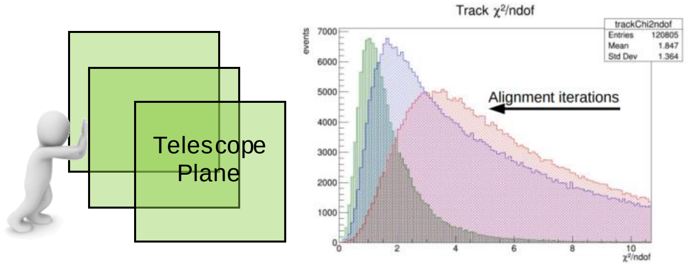
Tracking *

Tracks are reconstructed using telescope clusters + spatial & temporal cuts



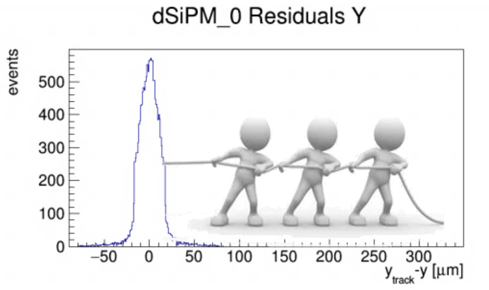
* Telescope Alignment

Software **translations and rotations** of the **telescope planes** are performed



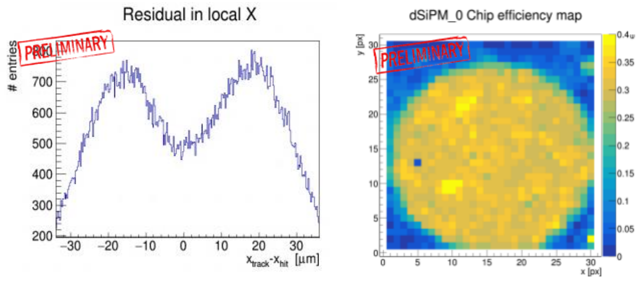
dSiPM Alignment

Translations and rotations of the **DUT** are performed to minimize unbiased residuals



DUT Association & analysis

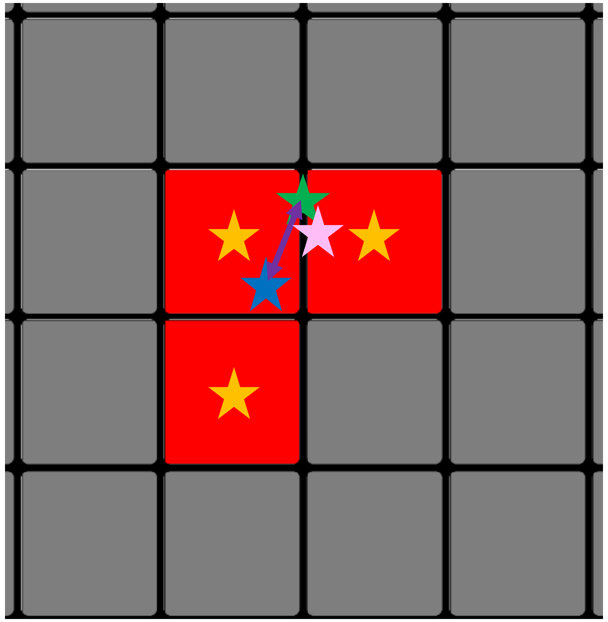
DUT clusters are associated with tracks & its **MIP detection response** is analyzed



Software used for the analysis

Corryvreckan

Corryvreckan use hit (pixels above threshold) and Clusters (groups of adjacent hits) to reconstruct particles trajectories



- Real Track
- Hit
- Cluster
- Cluster center
- Reconstructed Track
- Residuals