Characterization of a digital SiPM in 150 nm CMOS Imaging Technology

First Characterization & Results

Inge Diehl, Doris Eckstein, Finn Feindt, Ingrid-Maria Gregor, Karsten Hansen, Stephan Lachnit, Frauke Poblotzki, Daniil Rastorguev, Simon Spannagel, Tomas Vanat, **Gianpiero Vignola**

Trento, 02 Mar 2023

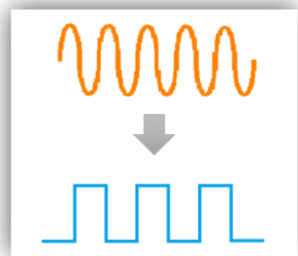
HELMHOLTZ

UNIVERSITÄT BONN

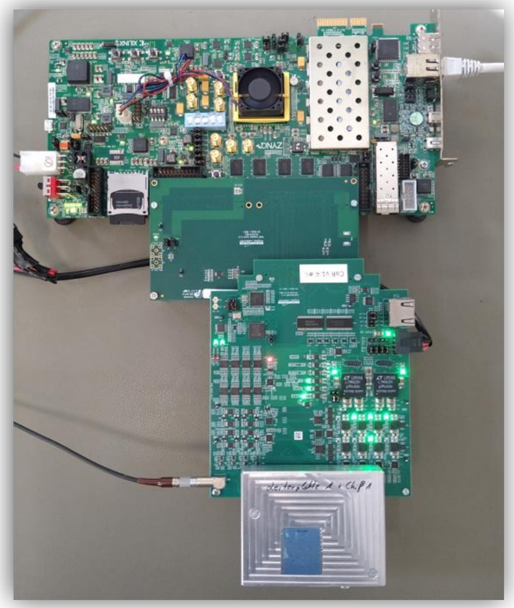
DESY.

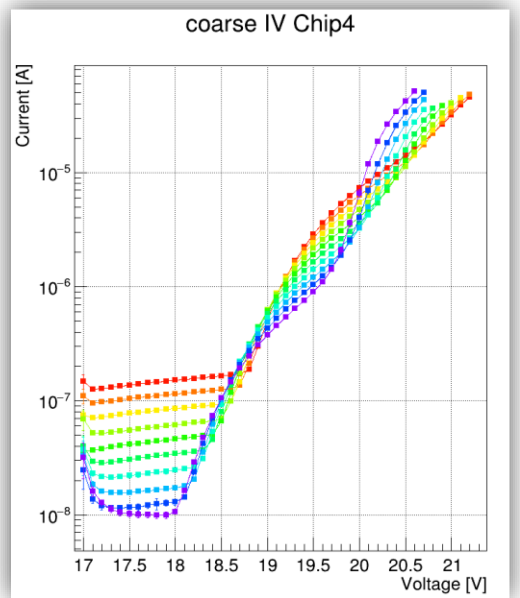
Overview

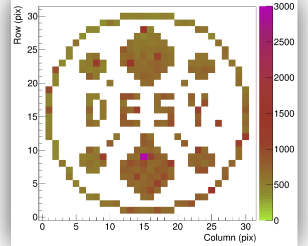
dSiPM ongoing studies



Introduction







Summary

Sensor & DAQ

- DESY dSiPM Specifications
- Pixel Design & Readout
- DAQ Chain

Laboratory Characterization

- IV Curves & Dark Count Rate
- Quenching & Pixel Masking

Test Beam studies

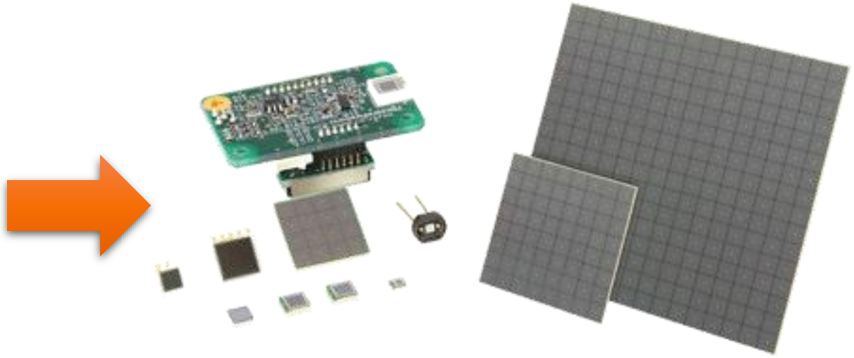
- DESY-II TB Setup
- First Results

Introduction

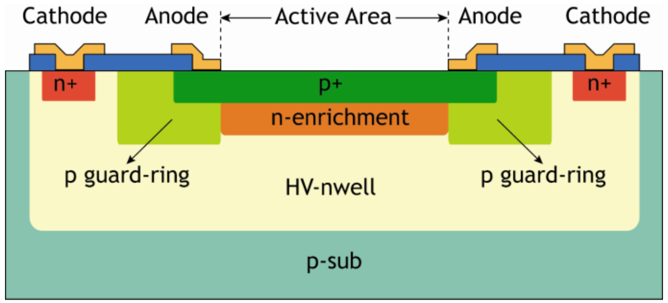
What is a Silicon PhotoMultiplier

- Solid state **single photon** detectors
- Array of Single Photon Avalanche Diodes (SPADs) with pitches in the range **10-100 µm**
- **High Internal Gain (~10^6)** thanks to High doped amplification region
- Signal **proportional** to the number of photons that hit the sensor
- **High quantum efficiency**
- **Low power consumption**
- **Insensitive to magnetic fields**

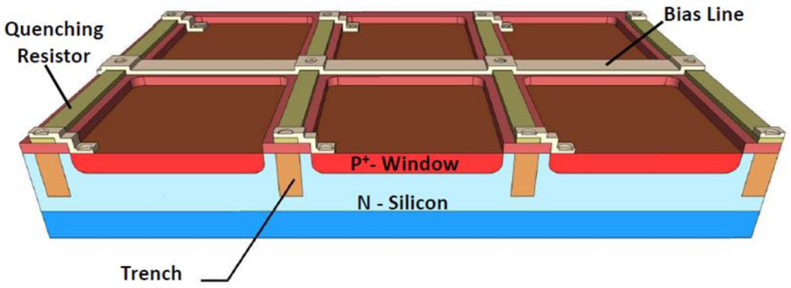
Photomultipliers



SiPMs



Schematic structure of SPAD (Fraunhofer IMS)



Typical SiPM design (KETEK)

Introduction

Analog vs Digital SiPMs

Project Goals

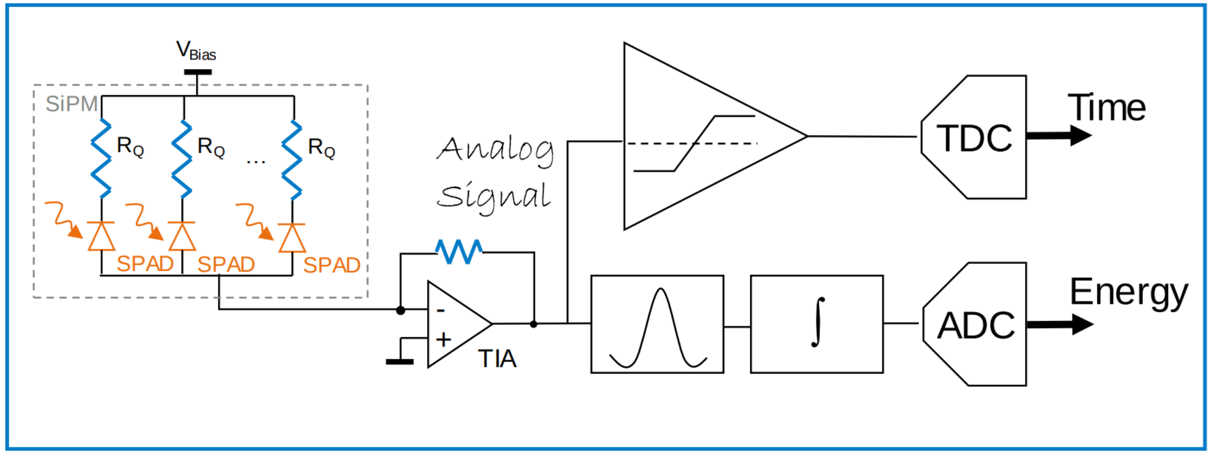
- Investigate CMOS SPADs performances & possibilities
- Possible Applications:
  - Optical Fibre Read-Out
  - 4D-Tracking

Why digital?

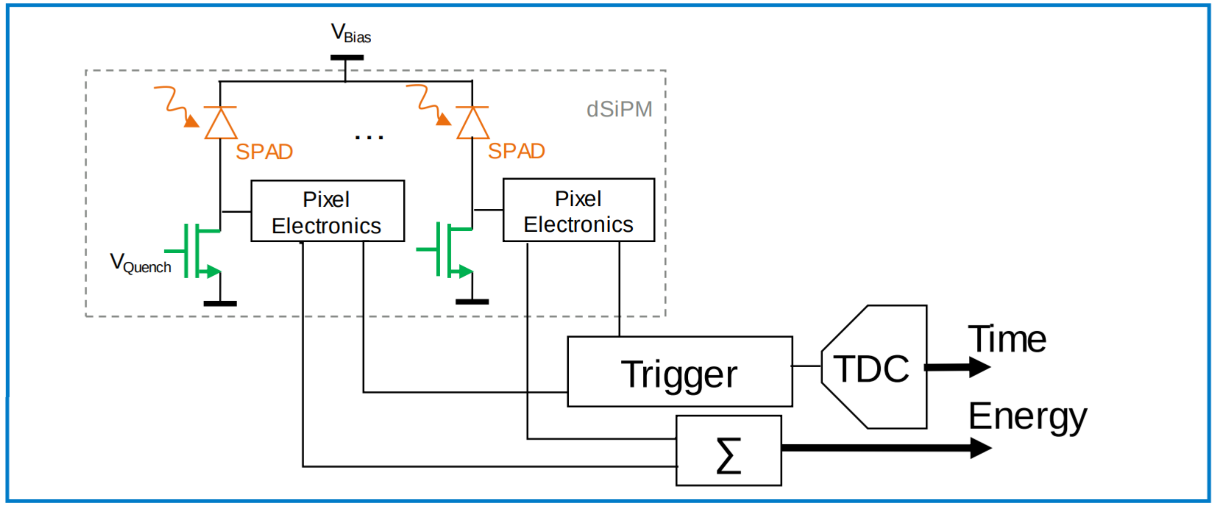
- Small quenching circuitry
- Inverter as event discriminator
- In-pixel/in-Chip Hit counting
- Masking & Hit map readout

Commercial CMOS processes

- Sensor & electronics in the same Chip
- Direct photon detection (Monolithic: no backside processing)
- Low-cost R&D (Available in Multi Project Wafer)
- High volume production



Schematic representation of the readout chain of an Analog SiPM



Schematic representation of the readout chain of a Digital SiPM

DESY dSiPM Specifications

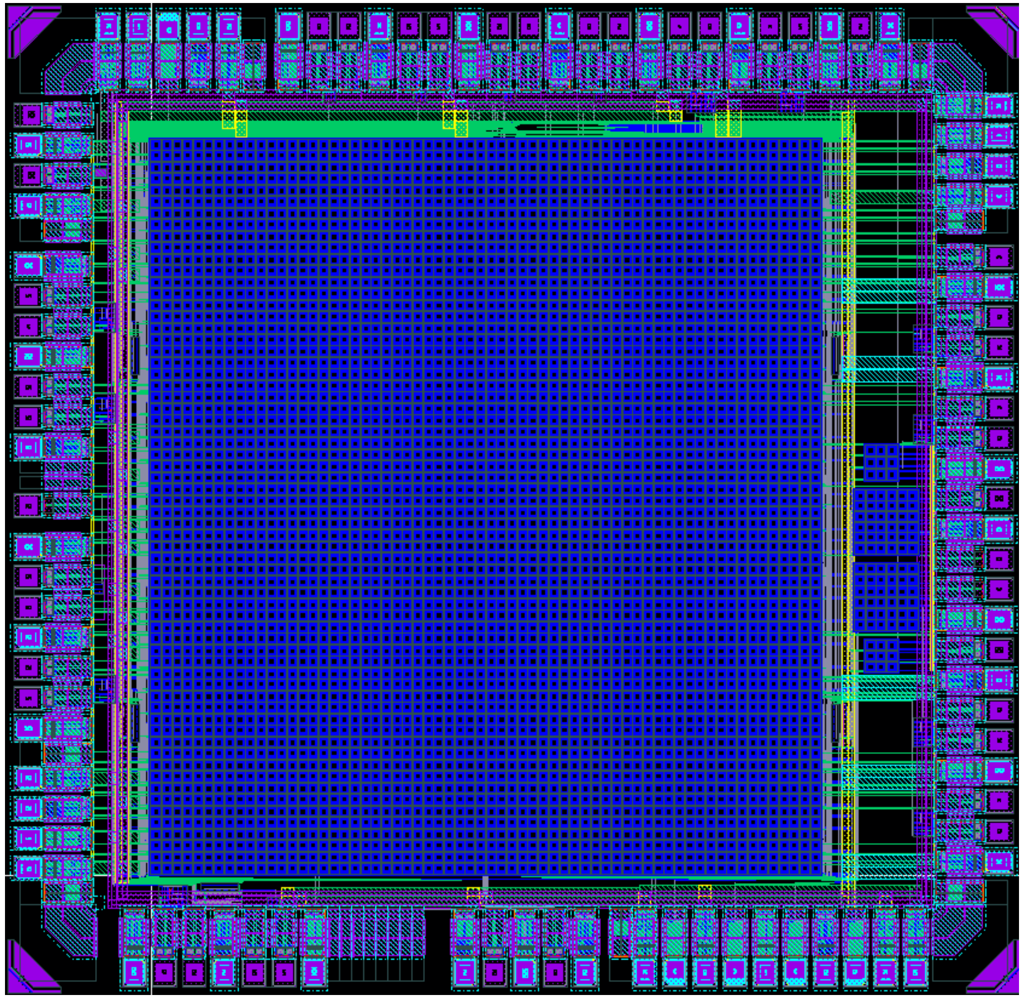
ASIC in LF 150 nm CMOS

Layout

- In LFoundry 150 nm CMOS Technology
- Main matrix: 32 x 32 pixels
- Sensor area: 2230 x 2430 µm^2
- Test structures in the Chip periphery

Features

- Full hit matrix readout and timing measurements
- 4 x 12-bit TDCs with <100 ps timing resolution
- Pixel masking
- 2-bit in-pixel hit counting
- Validation logic whit adjustable settings
- Readout is Frame based (3 MHz frame rate)



ASIC Design of the DESY dSiPM

Pixel Design & Readout

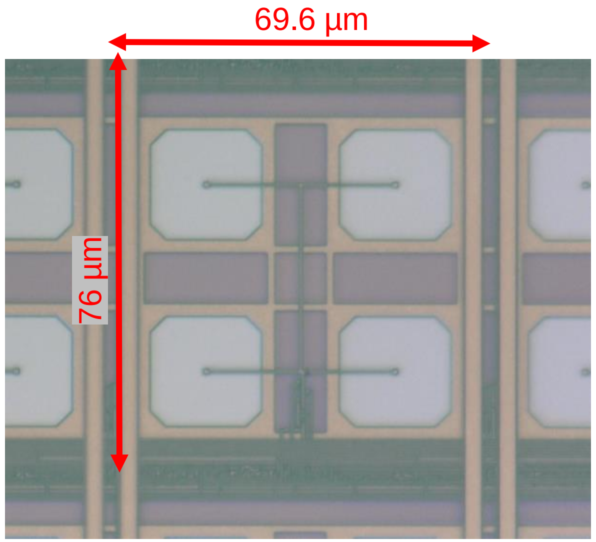
4 SPAD Layout

Pixel Layout & electronics

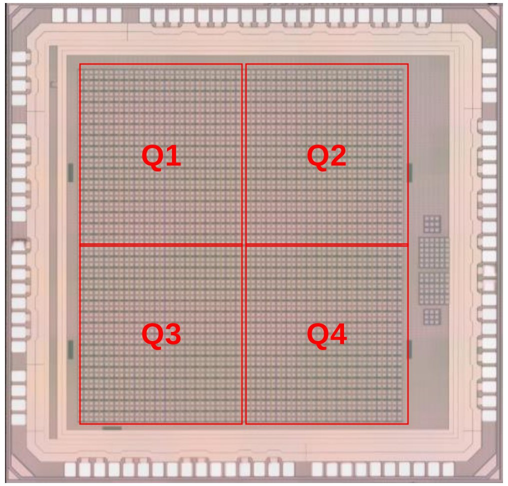
- 4 SPADs sharing one Frontend and additional readout electronics
- Fill factor ~30% (limited by SPAD dimension available)
- Quenching Transistor (V_{Quench})
- Masking Circuitry
- In-pixel Hit counter

Readout concept

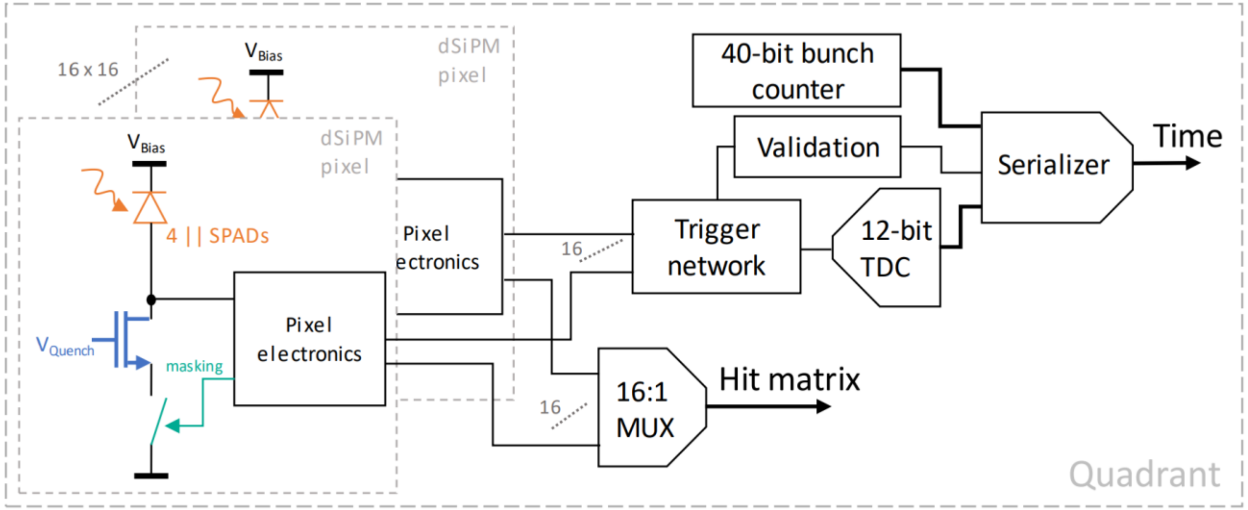
- The ASIC is divided into four identical quadrants (16 x 16 pixel units)
- Outputs of all pixels are combined in a wired-OR
- The fastest pixel signal triggers a running 12-bit TDC
- Validation logic to discard undesirable events
- The Hit matrix is readout via a 16-to-1 multiplexer



Microscope picture of a pixel



Microscope picture of the Chip



Readout concept of a 16-by-16 pixel unit (Quadrant)

DAQ Chain

Caribou System

Caribou

- Versatile readout system developed by CERN, BNL, DESY and University of Geneva
- Allows fast, simple and Low-cost implementation & tests of sensors
- Already used for: ATLASPix, CLICTD, DPTS, FASTPIX, etc.

SoC Board

- An embedded CPU runs DAQ and control software
- An FPGA runs custom hardware for data handling and detector control

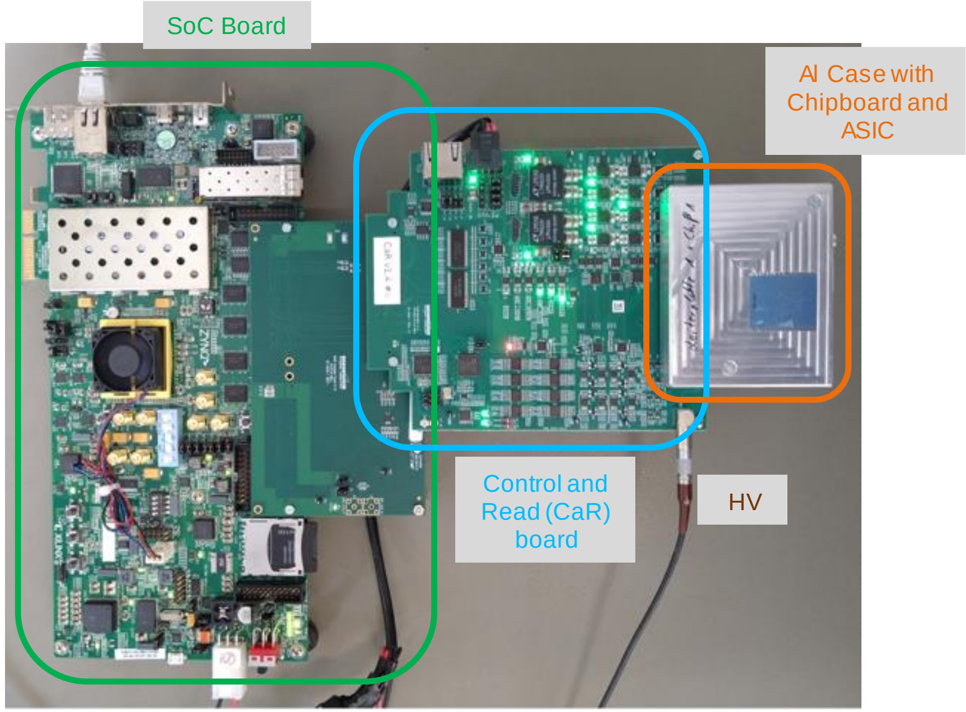
Control and Readout (CaR) Interface Board

- Provides physical interface from the SoC to the detector chip
- Contains all peripherals needed to interface and run the chip: power supplies, ADCs, voltage/current references, LVDS links, etc.

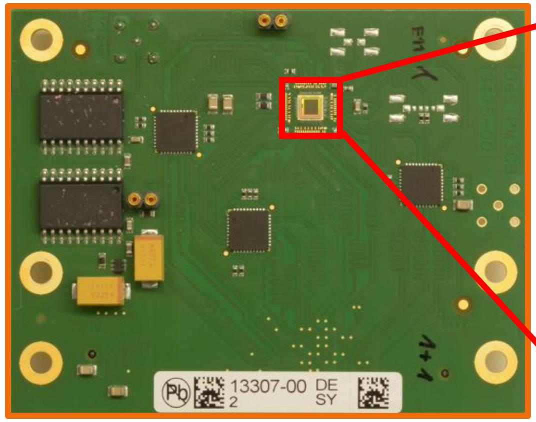
Chip Board

- Passive & detector-specific components only
- DSiPM here glued & bonded
- Enclosed in Aluminum case that acts as heat sink and light shield

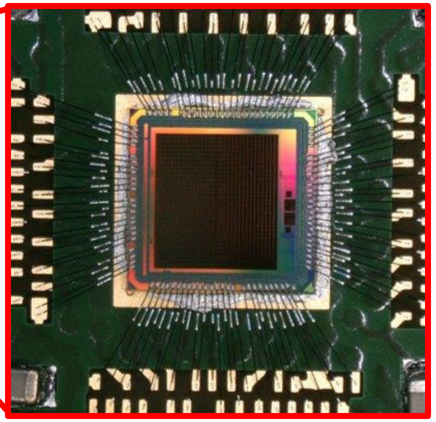
http://dx.doi.org/10.22323/1.370.0100
https://gitlab.cern.ch/Caribou/



Caribou DAQ System



Chip Board

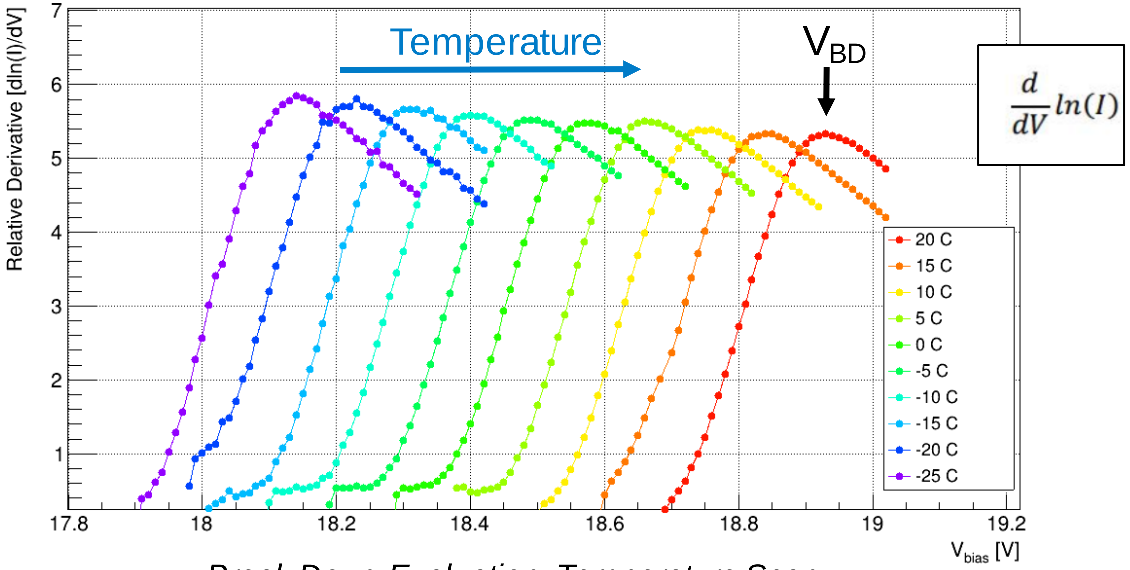


Chip Glued & Bonded

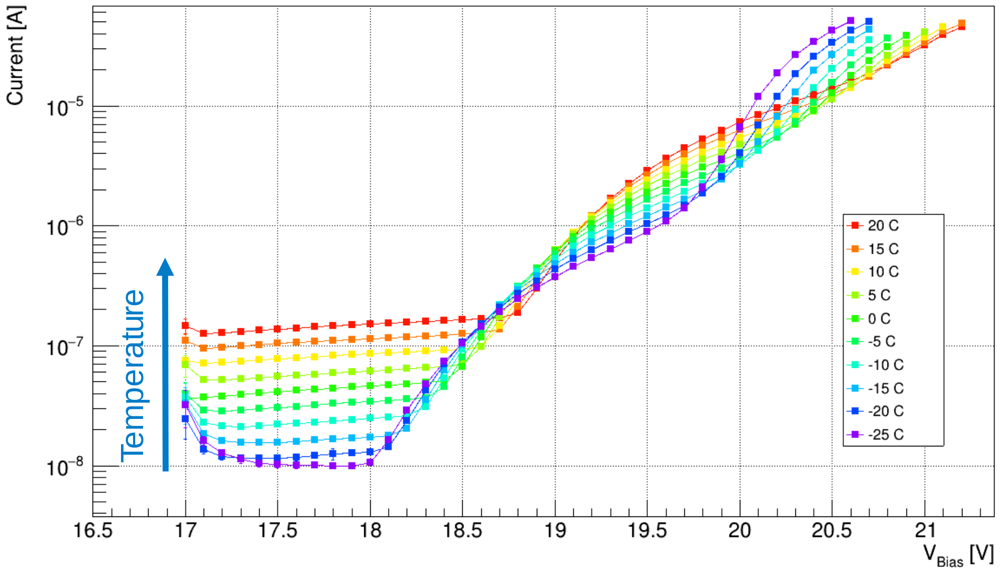
IV Curves & Dark Count Rate

Chip Characterization

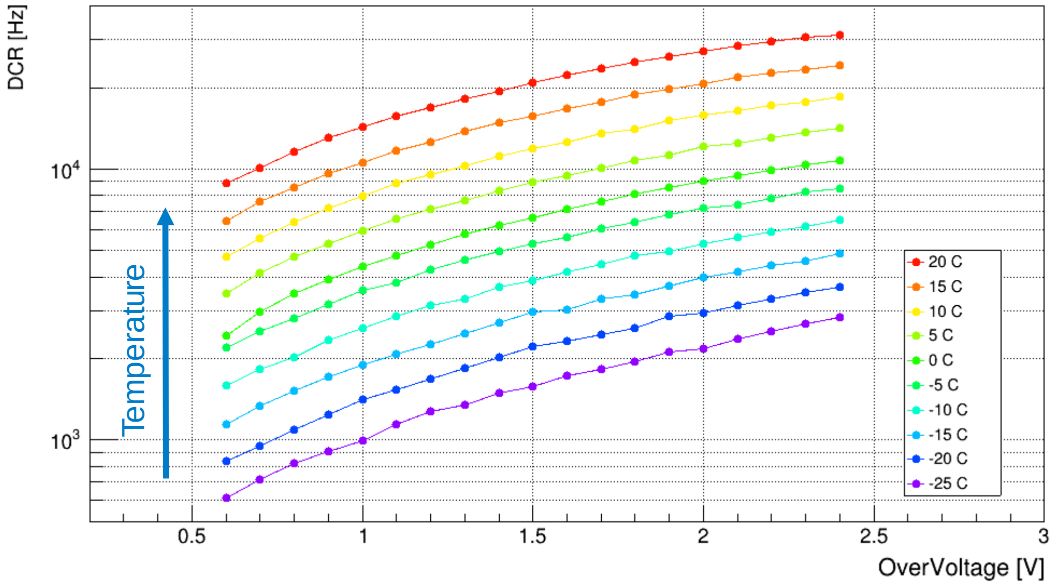
- Detailed characterization performed on several samples (Chip4 shown in figures)
- IV & Dark Count Rate studies performed whit controlled temperature (from -25 to 20 °C) and humidity (~ 0 %) in a dark environment
- Measurements compatible with expectations



Break Down Evaluation, Temperature Scan



IV curves (Full Matrix), Temperature Scan



Dark Count Rate (per pixel), Temperature Scan

Quenching & Pixel Masking

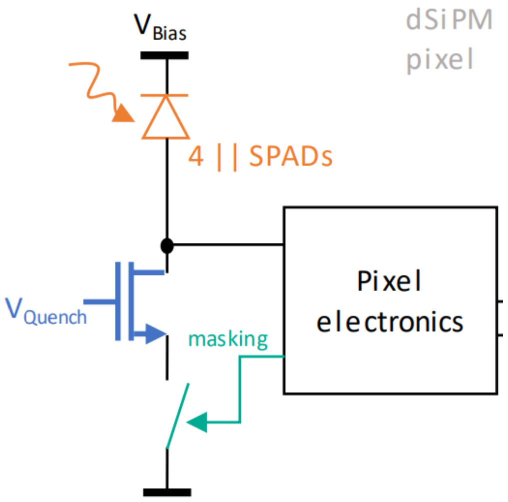
Two Peculiar Features

Quenching

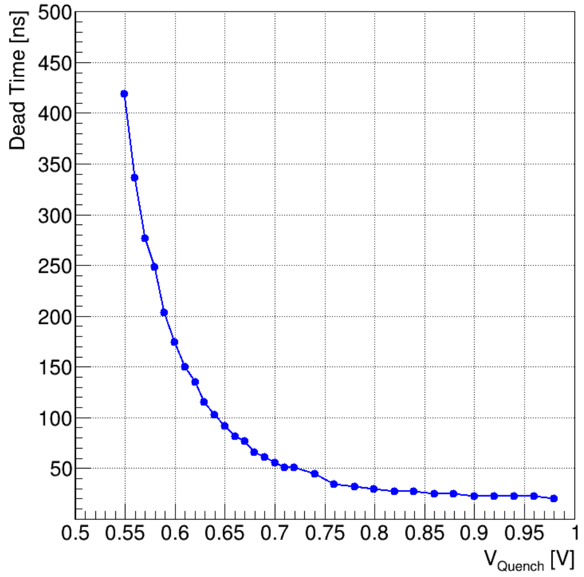
- The Pixel's quenching circuit consists of a single Transistor
- Acting on V_{Quench} is possible to tune the signal length
- Non-overlapping hits (up to 3) can be distinguished and counted within the frame (3MHz frame rate)

Pixel Masking

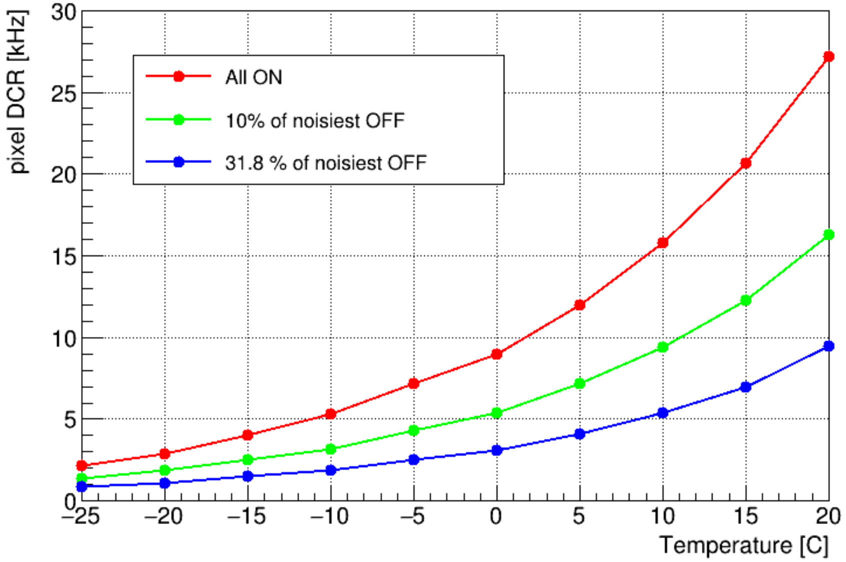
- Individual pixels can be disabled
- Allows deactivation of noisy/unused pixels (DCR & power consumption reduction)
- Allows in-depth characterization of SPAD arrays



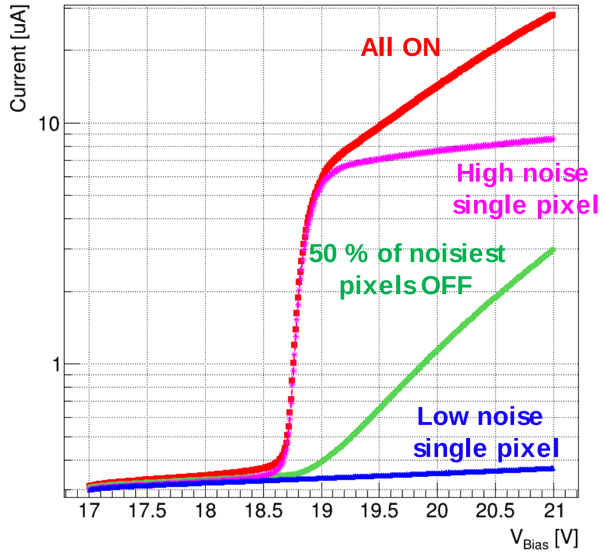
Pixel Circuit



Dead Time vs V_{Quench}



DCR whit different masks (2 OverVoltage)

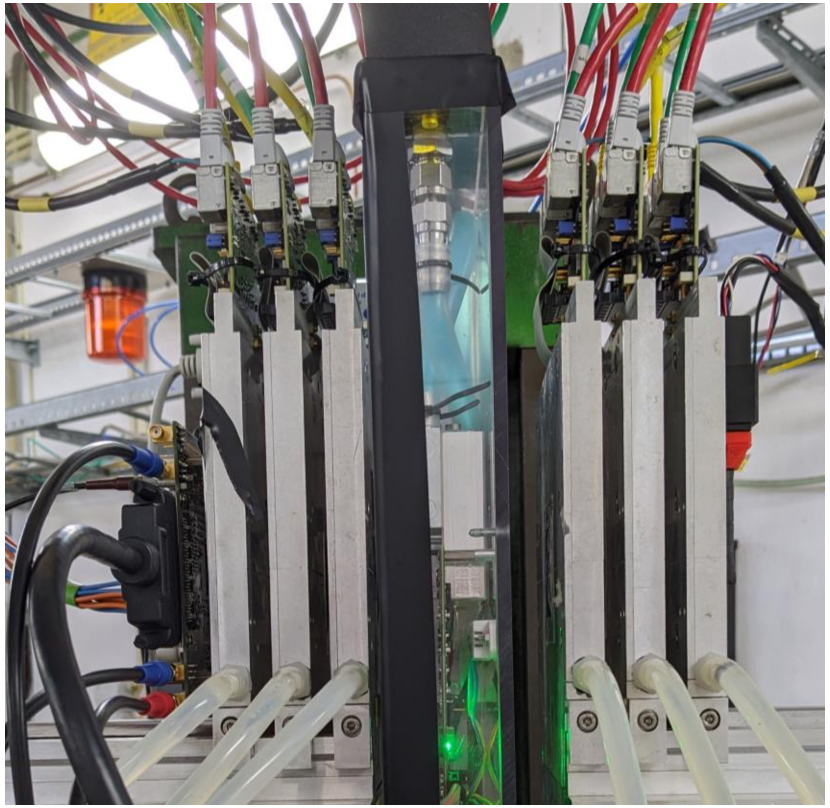


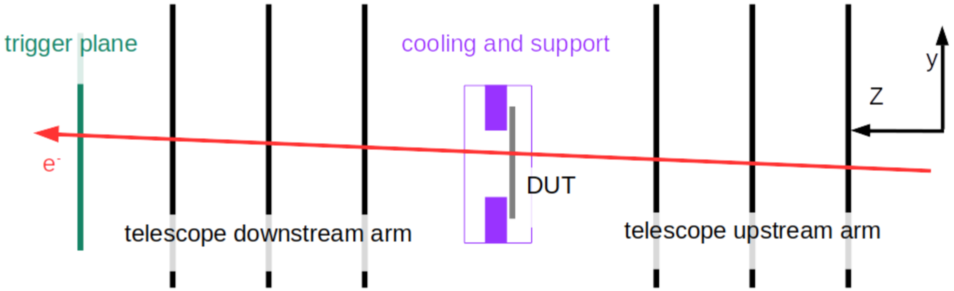
IVs whit different masks

DESY-II TB Setup

May and Oct. 2022

- Two Test Beam campaigns with Caribou+dSiPM at **DESY-II TB**
- **4 GeV/c** electron beam
- **6 beam telescope MIMOSA 26 planes** used for track reconstruction (Spatial resolution 3.24 µm per plane)
- Scintillators + PMT (in May) and Pixelated timing plane (in October) used as **Trigger reference**
- **Active cooling** to allow stable conditions & Temperature Scans (down to ~0 °C on Chip)
- **AIDA Trigger Logic Unit** (TLU) allowed synchronous operation of the involved detector systems
- Mechanics, cooling system and optical isolation was optimized to **maximize track resolution**
- Particle Track & time was reconstructed using Telescope data, dSiPM response in **MIP detection** can be investigated





DESY II Test Beam Setup

First Results

Work in progress

Time Residuals

- Defined as the difference between the Track time stamp (TLU+trigger) and the Hit time stamp (dSiPM TDC)
- Time correlation between dSiPM Hit & tracks confirmed
- Width dominated by Trigger time resolution (~ 2ns)

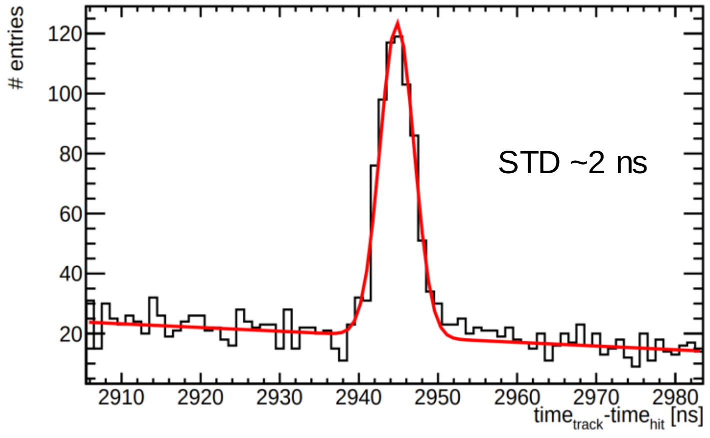
Spatial Residuals

- Defined as the difference between hit position in DUT and interpolated track in the same z-position
- Double-peak structure due to inefficient regions inside the pixels
- Proves pixel scale resolution of the dSiPM

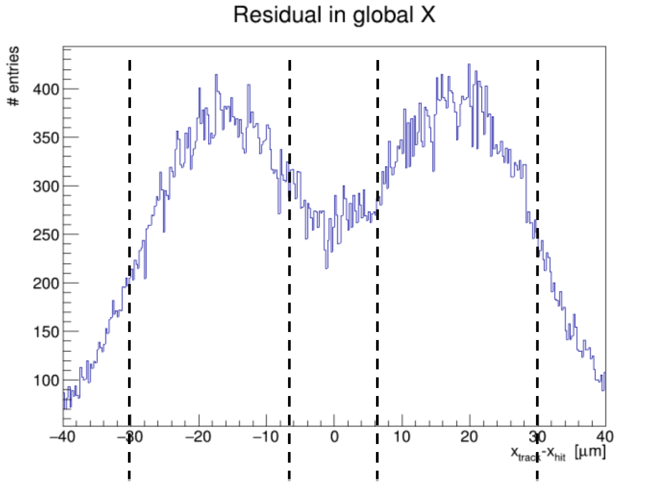
Efficiency

- The Efficient area can be associated to the SPAD position
- Track resolution at the DUT ~ 5 µm
- Chip Total efficency in MIP detection ~ O(Fill Factor)*

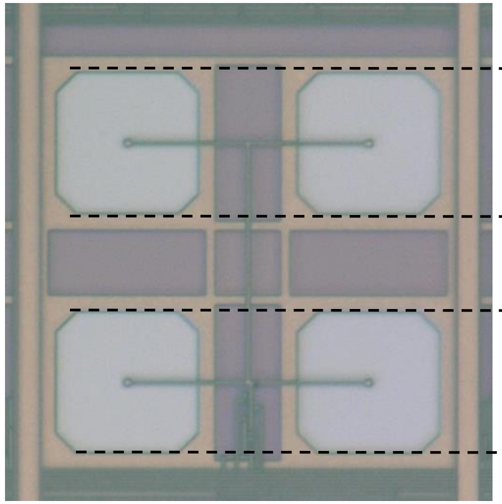
*Impact of noise & systematics to be studied



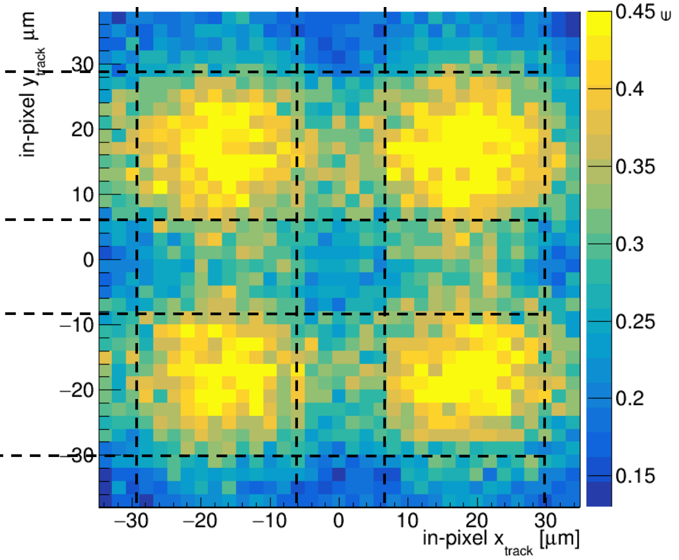
Example of Time Residuals



Example of Spatial Residuals



Microscope picture of a pixel



Example of In-pixel Efficiency Map

Summary

A promising R&D

Chips & Characterisations

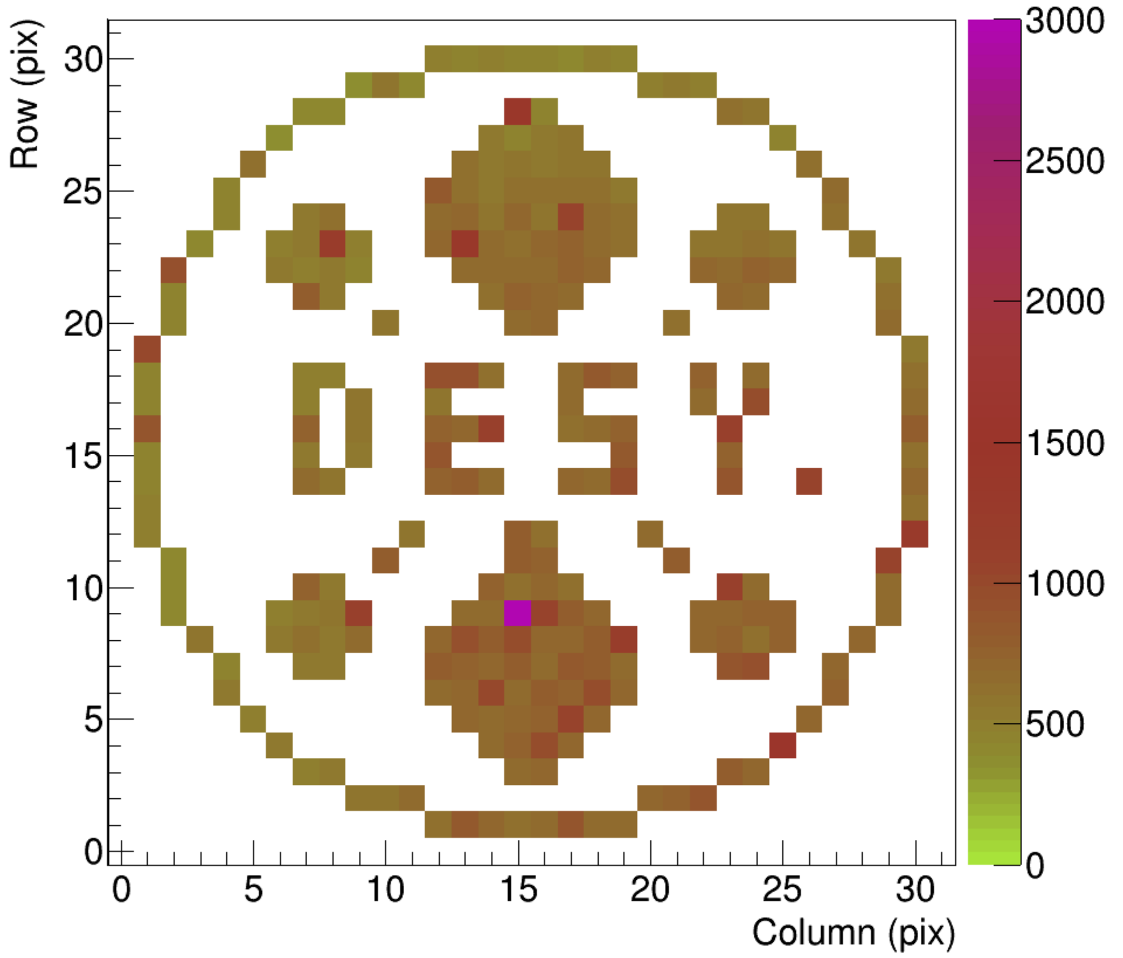
- A digital SiPM was designed at DESY in LFoundry 150 nm CMOS
- CMOS circuits are implemented in-pixel and in Chip periphery
- All characterisations performed to date are in line with the expected performances

Results from Test Beam

- DESY dSiPM was successfully integrated in DESY-II TB setup
- 4D-Tracking performances of the prototype are currently being studied

Project Plans

- Next TB with focus on dSiPM timing in a few days (13-27 Mar.)
    - 2 aligned DUT: time resolution using TOA difference
- Pixel & Subpixel scale laser studies
- Ongoing research of possible applications



Dark Events Hitmap whit DESY logo Mask applied

Thank you.

Gianpiero Vignola
gianpiero.vignola@desy.de

Deutsches Elektronen-Synchrotron DESY
Notkestraße 85, 22607 Hamburg
1C, O1.331, ATLAS

Additional characterizations

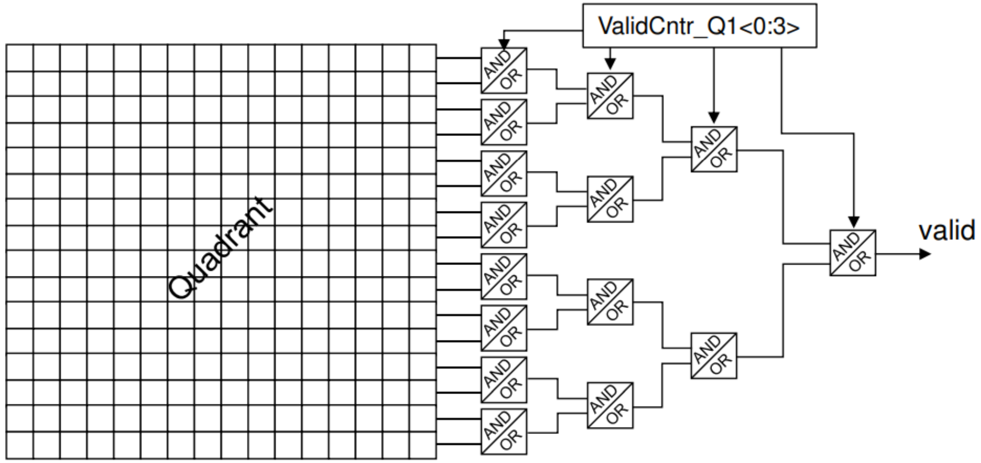
Validation Logic & Dead Time

Validation logic

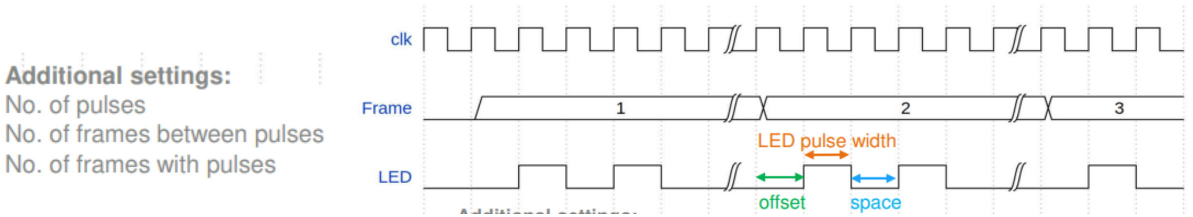
- A 4-step validation logic is implemented in every quadrant
- Every step can be configured to be an AND or OR gate
- A flag bit is generated for event validation within 2 ns
- Successfully validated using laser pulses and masking

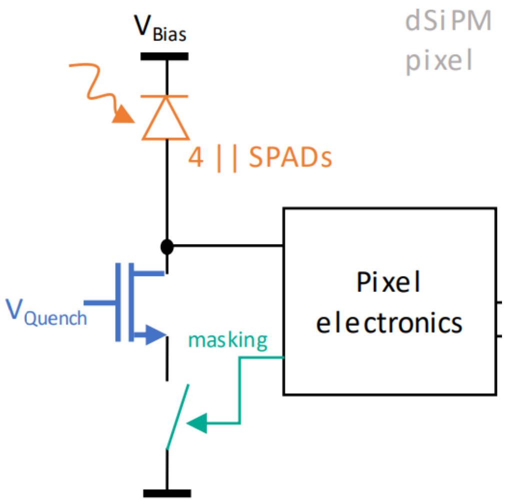
Quenching & Dead Time

- 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)

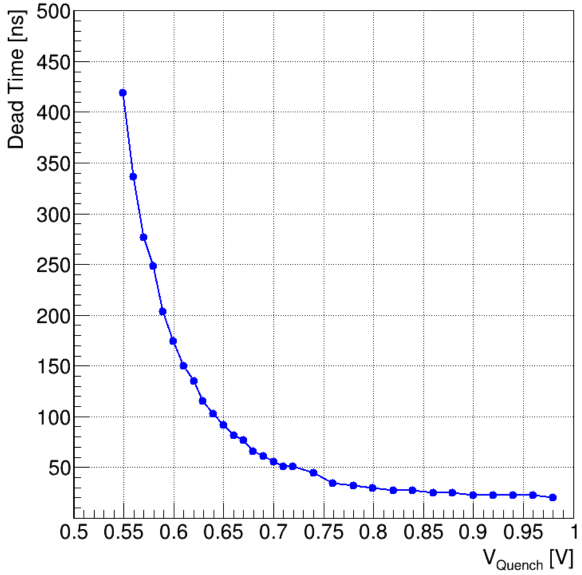


Schematic representation of the Validation Logic





Pixel Circuit



Dead Time vs V_{Quench} (chip4)

Laser Studies

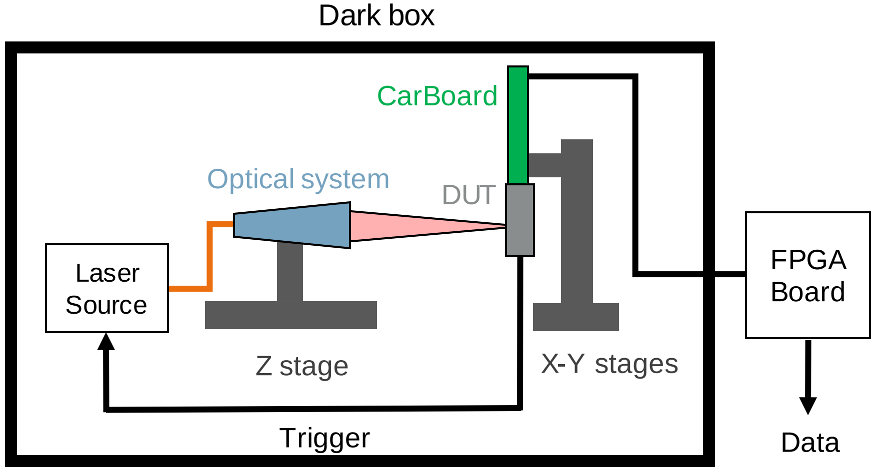
At sub pixel level

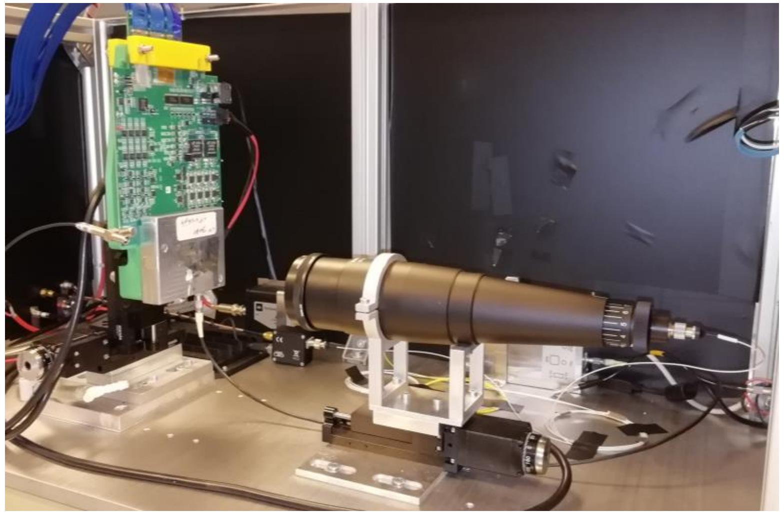
Setup

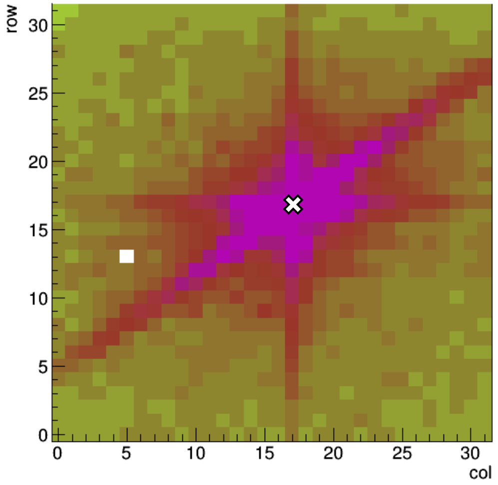
- DUT placed on an x-y stage
- Laser Optical System on a z-stage
- 1064 nm pulsed laser
- Laser in sync with the DAQ Clock

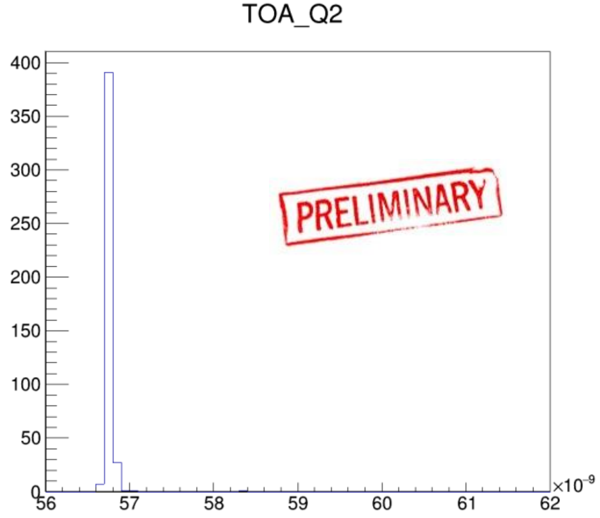
Ongoing & future studies

- Characterize Chip functionality
  - Tests on validation logic
  - Dead time evaluation
- Uniformity & delay of the array response
- Study time resolution/efficiency with 2D scan, investigating sub-pixel structure







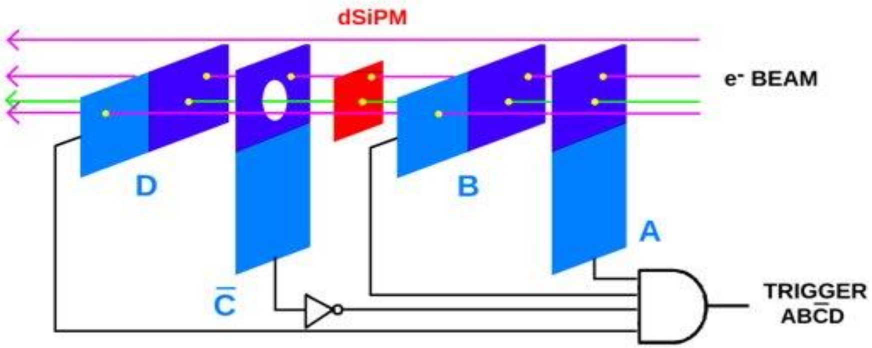


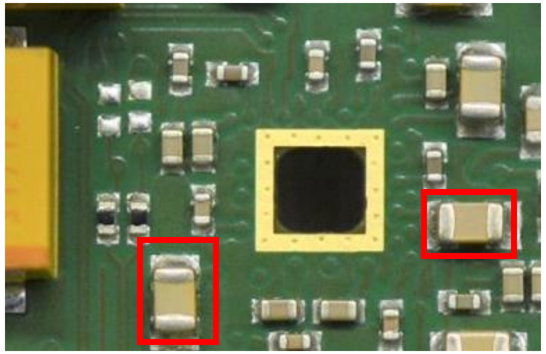
Time Of Arrival (TOA) of a single pixel in high light conditions (17-17)

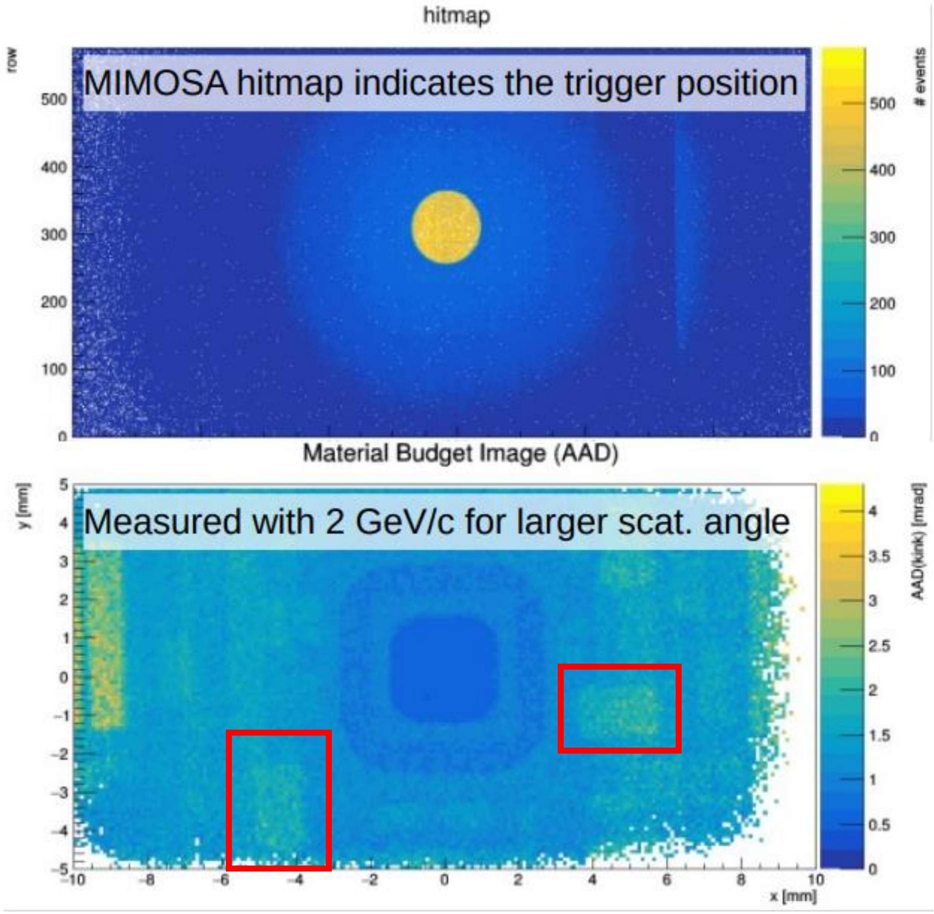
DUT & Trigger Alignment

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





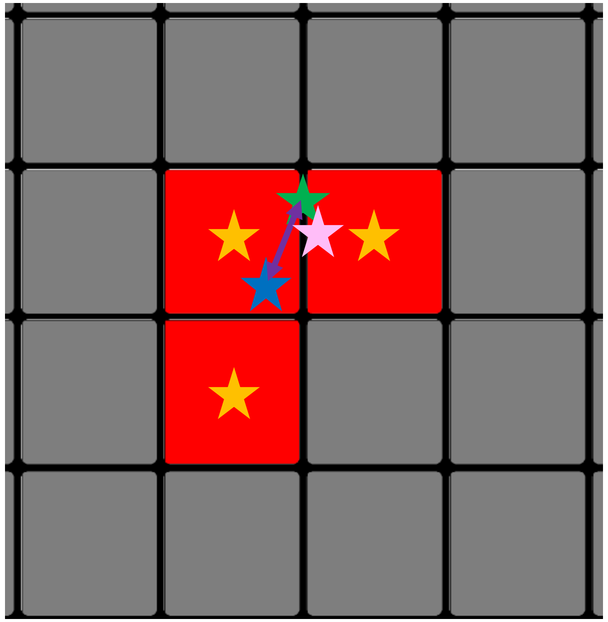


https://gitlab.cern.ch/corryvreckan/corryvreckan/-/tree/master/src/modules/AnalysisMaterialBudget

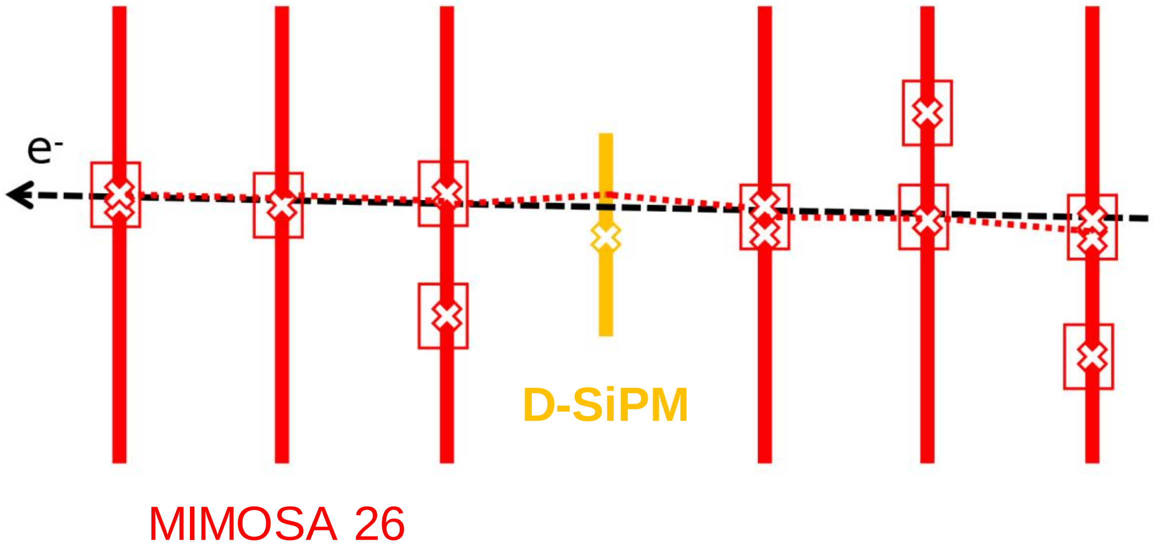
Software used for the analysis

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



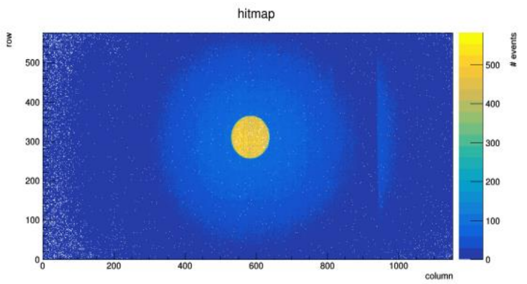
Analysis Chain

Using Corryvreckan

Data Decoding → **Clustering & Tracking** → **Alignment & DUT Association** → **DUT Association & Analysis**

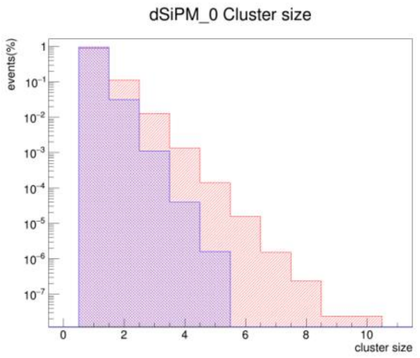
Data Decoding

- Raw Telescope & dSiPM data acquired in TB are decoded into a format accessible to Corryvreckan
- Hitmap and Timestamp is reconstructed event by event for each detector involved



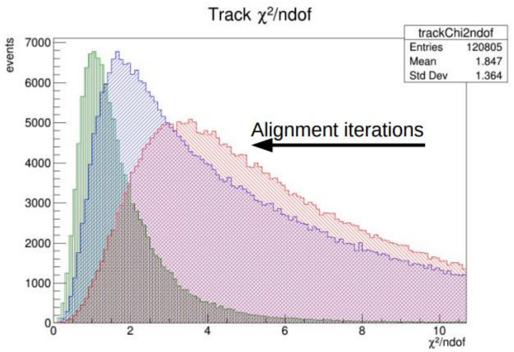
Clustering & Tracking

- Cluster of hits in the reference telescope are identified and used in the reconstruction of the MIP Track.
- Spatial and temporal cuts are applied to associate clusters with Tracks



Alignment & DUT Association

- Translations and rotations of the telescope and DUT planes are performed
- Multiple iterations maximize accuracy in tracks reconsrtuction



DUT Association & Analysis

- DUT clusters are associated with the reconstructed tracks
- The response of dSiPM in MIP detection is analyzed. it is possible to determine spatial resolution, temporal resolution, efficiency, Cluster size, etc.