Test Beam Characterization of a Digital SiPM in 150 nm CMOS Imaging Technology

Towards 4D-Tracking with High Gain Silicon Detectors

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Hamburg, 19 Apr 2023

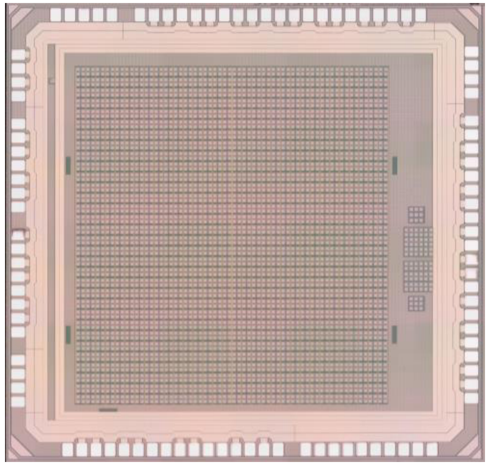
HELMHOLTZ UNIVERSITÄT BONN DESY.

Introduction

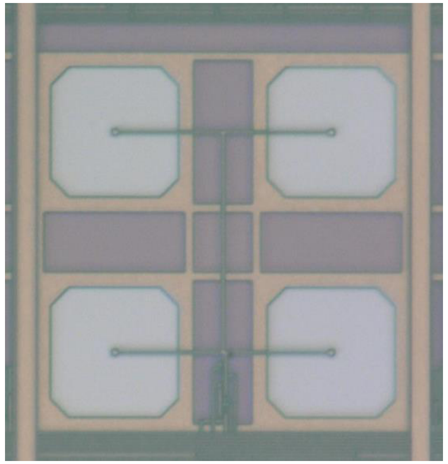
4D-Tracking with a digital SiPM

DESY Digital SiPM

- Active area: 2.2 x 2.4 mm^2
- Pixel pitch: 69.6 x 76.0 μm^2 (Binary resolution ~20 μm)
- Sensor Thickness: 280 μm (Standard for LF's MPW run)
- 4 shared 12-bit TDC (<100 ps binning)
- SPAD timing is intrinsically good (Geiger mode)



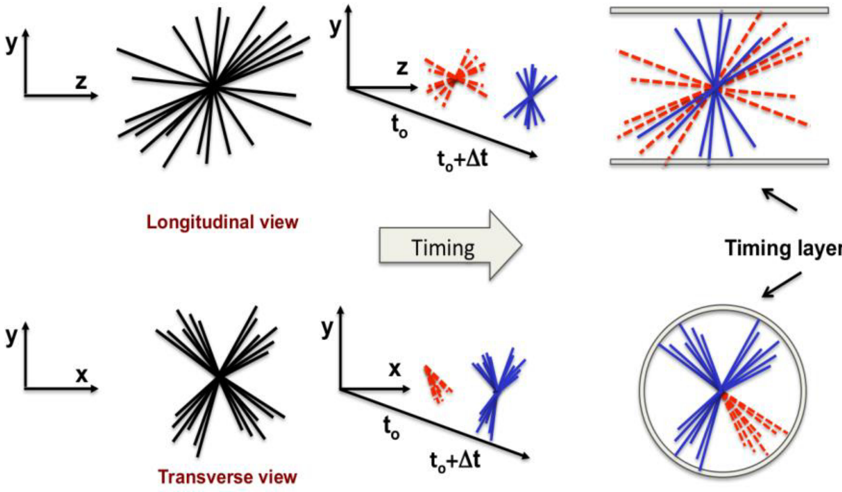
Microscope picture of the Chip



Digital Pixel: 4 SPAD Structure

4D-Traking

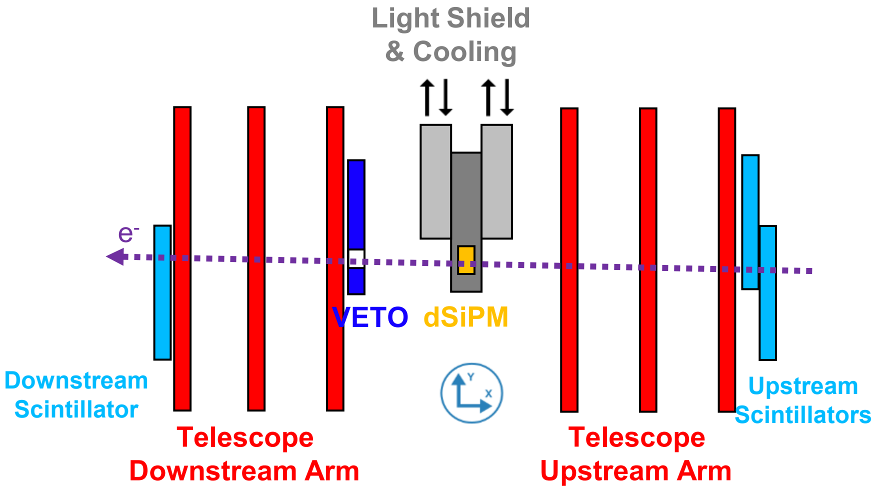
- Trackers able to perform the concurrent measurements of the spatial and temporal coordinates in MIP detection
- Key R&D for future high-energy physics experiments
- Needed in high pileup conditions to assign tracks to events

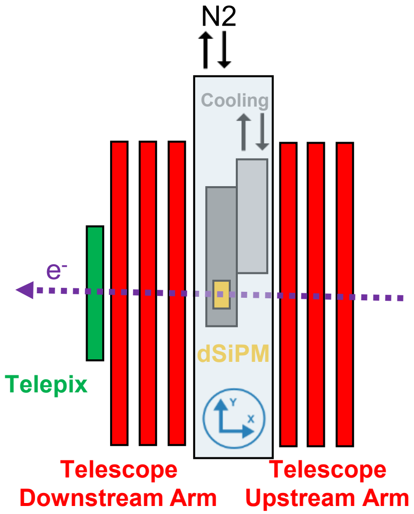


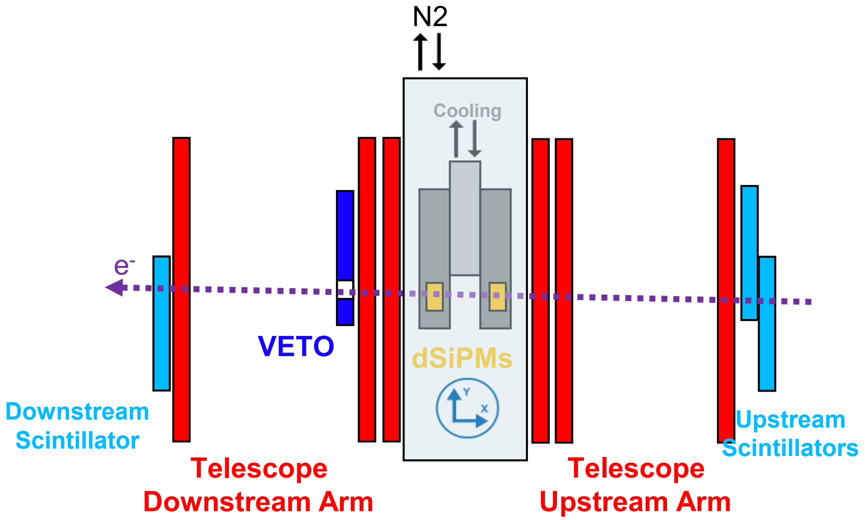
DOI 10.1088/1361-6633/aa94d3

Test Beam Setups

DESY-II Test Beam Facility





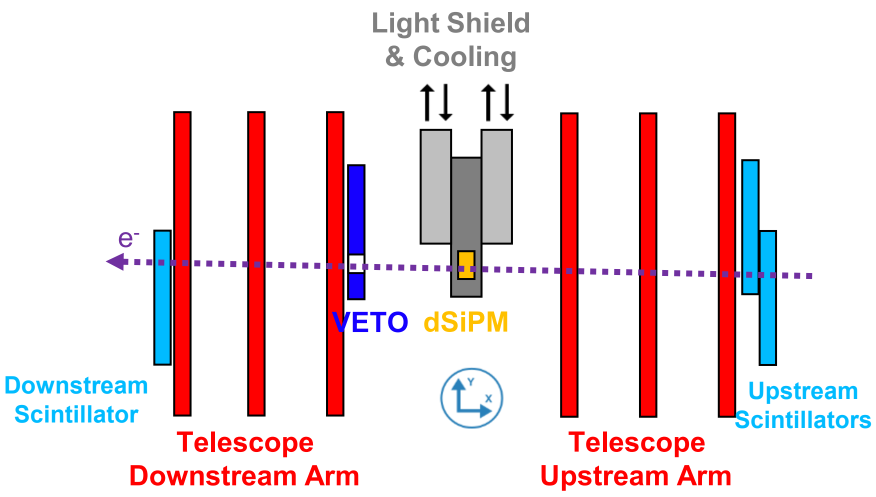


Test Beam Setups

DESY-II Test Beam Facility

May 2022

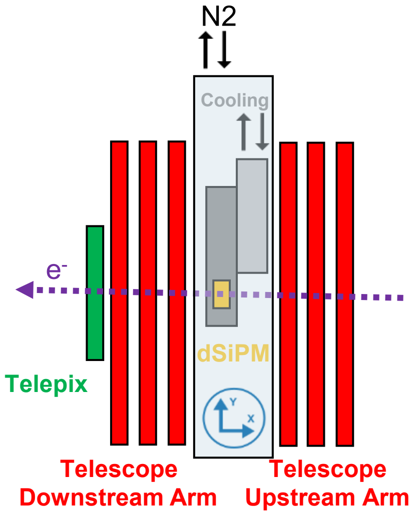
- **Goal:** Implementation of dSiPM in a TB setup, hardware & software tests
- **1 DUT** on XYstage **+ Mimosa Telescope**
- **Active cooling** stable at ~25°C on chip
- Trigger with scintillators + PMT + VETO



October 2022

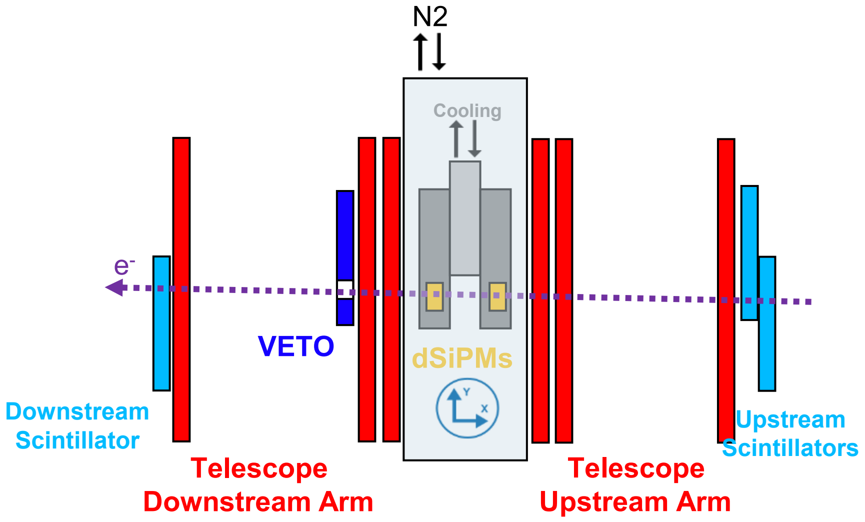
- **Goal:** Improve cooling, temperature scans in TB, evaluation of efficiency & spatial resolution
- **Active cooling** down to ~0°C on Chip
- Better **trigger coverage** using Telepix

See Arianna BTTB11 Talk



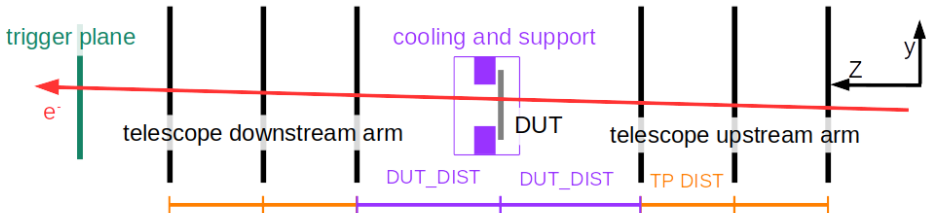
March 2023

- **Goal:** dSiPM time resolution studies, further investigations of efficiency & spatial performances
- **2 dSiPMs aligned**
- Active cooling down to -5°C on chip



Telescope Geometry

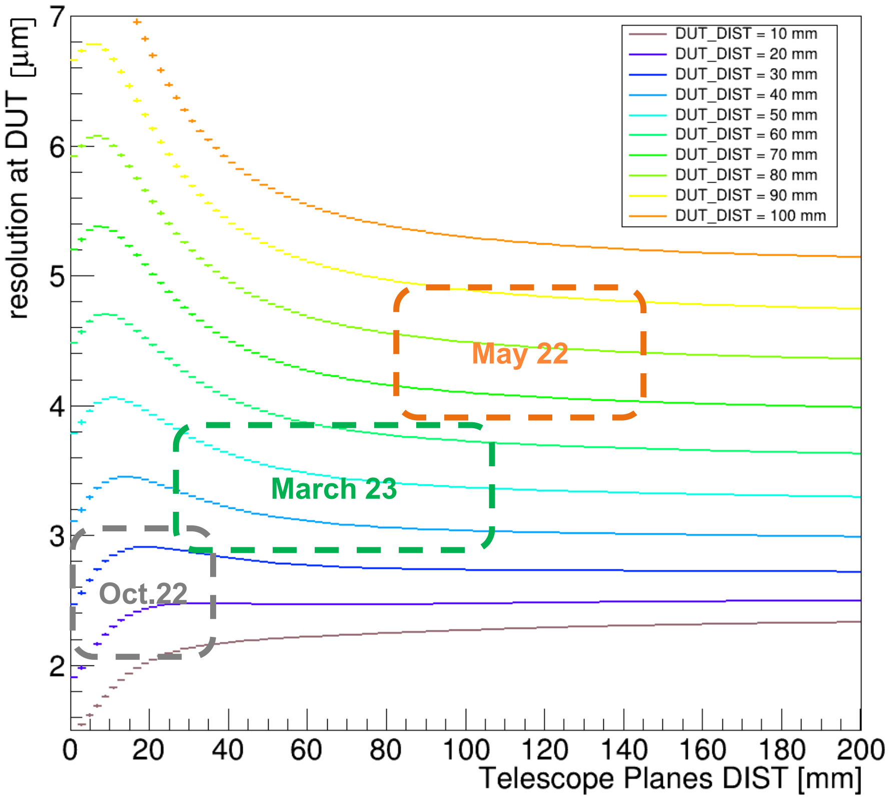
Maximization of the Track Resolution

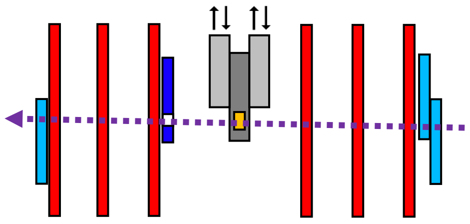


Simulation of the Track Resolution at DUT z-Position

- Evaluated using GBL **track resolution calculator** DOI 10.5281/zenodo.48795
- All **scattering materials** included in the simulation (silicon, protections, etc)
- The simulation tool provides an estimate of the **expected track resolution**

MIMOSA_Telescope + dSiPM Track Resolution at DUT

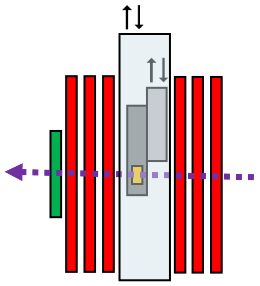




May 2022

- Mechanical limit on DUT_DIST
- Opted for **long arms**
- Estimated GBL resolution:

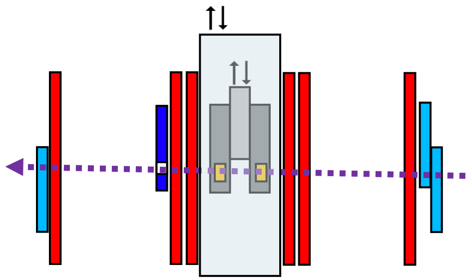
~ 5 um



October 2022

- Small DUT_DIST
- Opted for **short arms**
- Estimated GBL resolution:

~ 2-3 um



March 2023

- Higer Material Budget
- Opted for a **hybrid solution**
- Estimated GBL resolution:

~ 3-4 um

Trigger Plane

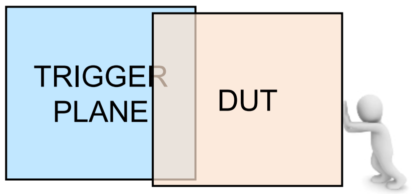
Scintillators & Telepix

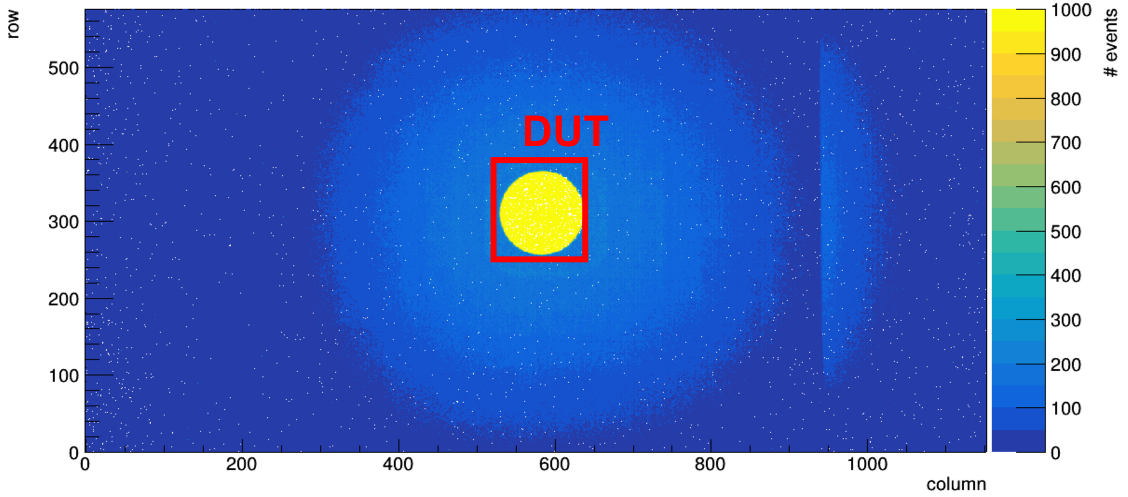
Making the Most of Beam Time

- Maximize **event rate** on DUT (trigger not too small & efficient)
- Minimize unnecessary **Event Storage & dead time** due to busy of detectors (trigger not too big)
- Trigger plane as **close** as possible to the DUT (especially with low momentum beam)
- Perform a good relative **alignment** of DUT & Trigger plane

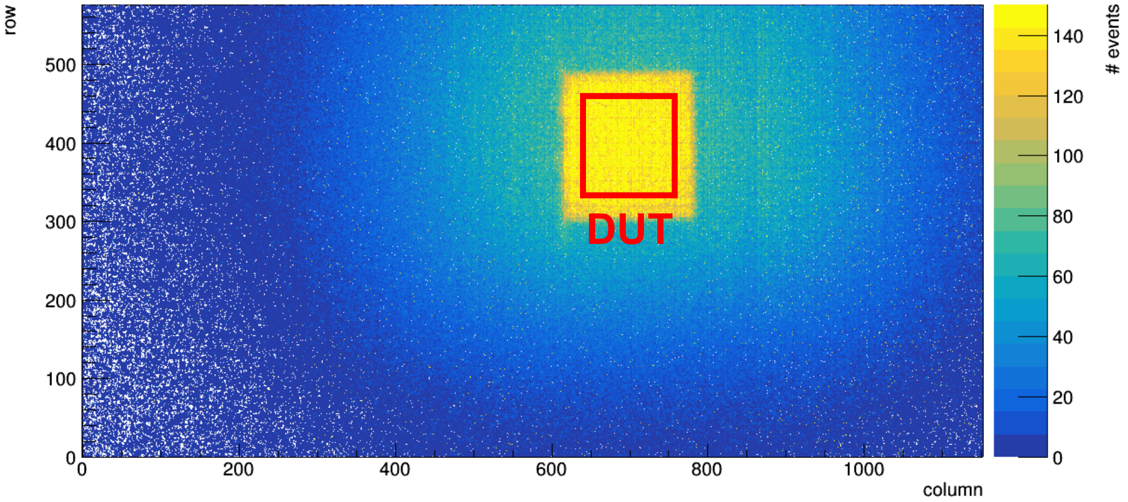
DSiPM TBs Trigger Approach

- Scintillator scheme + veto (May 2022 & Mar 2023)
  - Circular trigger region of **~2 mm diameter**
- Telepix plane with mask (October 2022) See Arianna BTTB11 Talk
  - Trigger region of **~3.0 x 3.4 mm^2**





Hitmap on the Telescope reference plane using Scintillators + VETO as trigger



Hitmap on the Telescope reference plane using Telepix ROI as trigger

DUT & Trigger Alignment

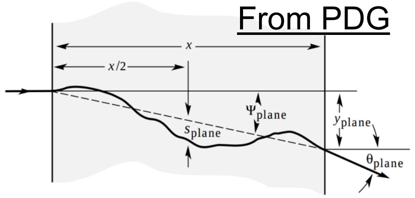
Material Budget Imaging

DUT- Trigger Alignment With High Dark Count Rate

- DCR/MIP event distinction impossible before alignment
- DSiPM self-trigger can not be used to identify the DUT position

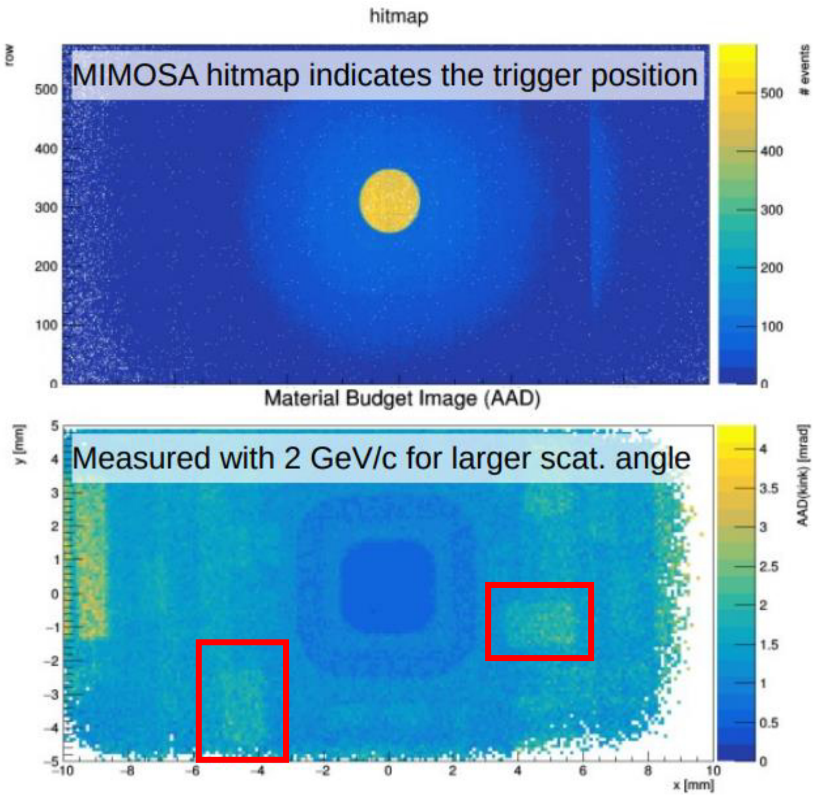
Material Budget Imaging (MBI)

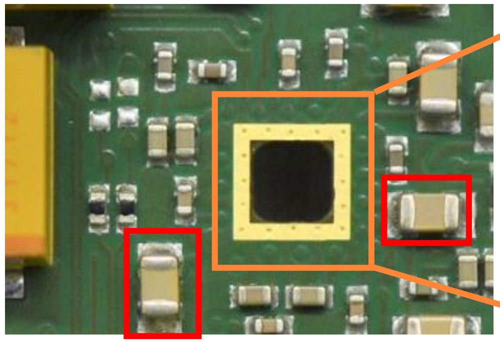
- Scattering angle is proportional to the thickness of the scattering medium in radiation lengths $\theta_{plane} \propto \frac{x}{X_0}$
- The MBI can be used to align trigger & DUT with high accuracy



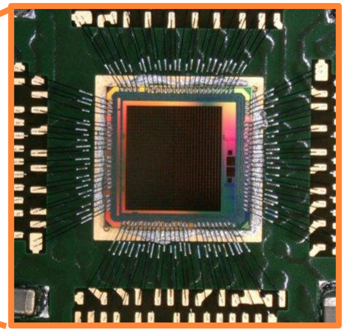
Evaluation of MB Using Corryvreckan

- Set **low particle momentum** to maximise multiple Coulomb scattering
- Use the **straight line** approximation for tracks in the two arms of the beam telescope (TrackingMultiplet)
- Evaluate the material budget at the DUT z-position using the **widths of the scattering angle** distribution (AnalysisMaterialBudget)
- The material budget image obtained in Corry global coordinates





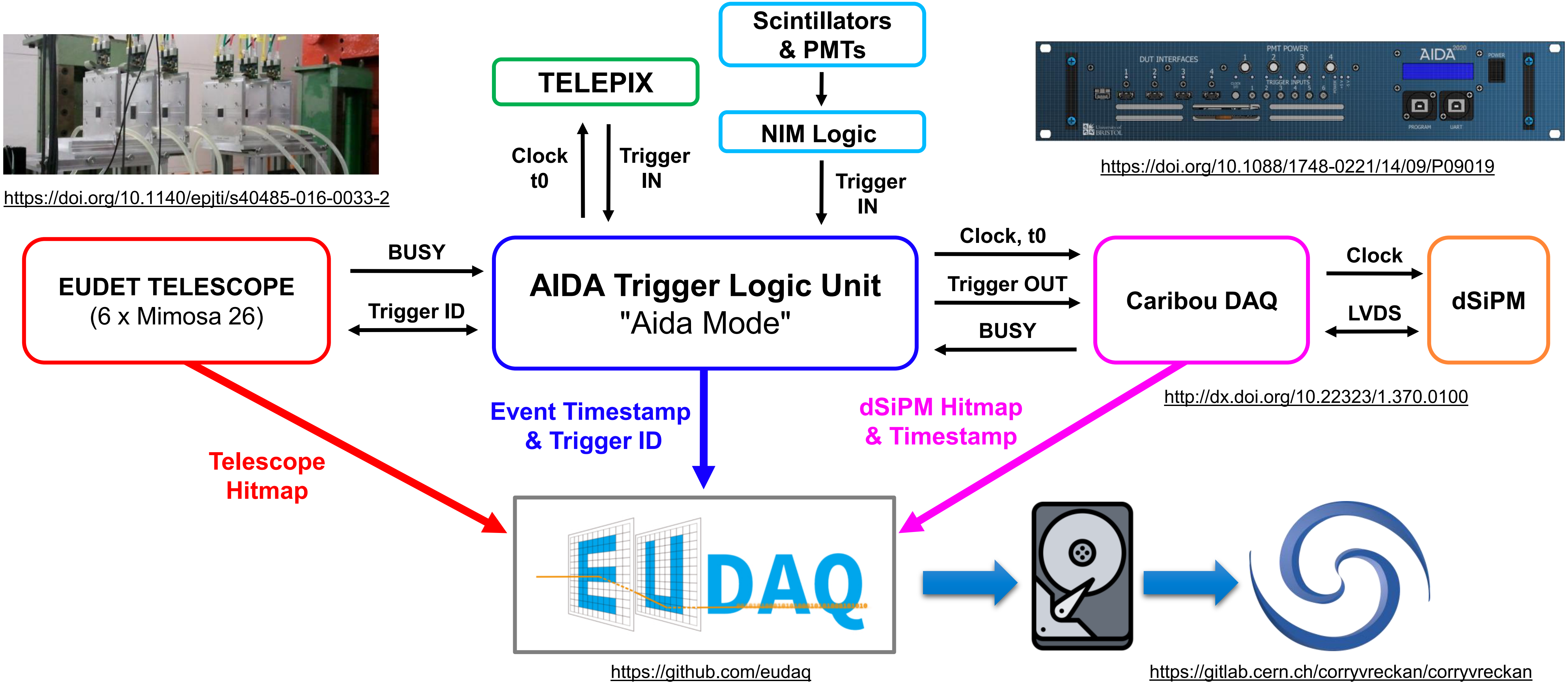
Chipboard (back)



Chip glued & bonded (front)

DAQ System in Test Beam

AIDA TLU Core

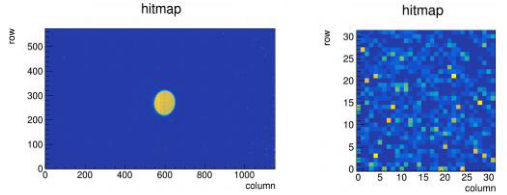


Analysis Chain

Using Corryvreckan

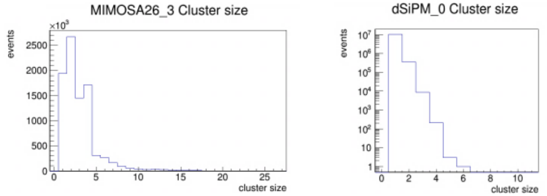
Data Decoding

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



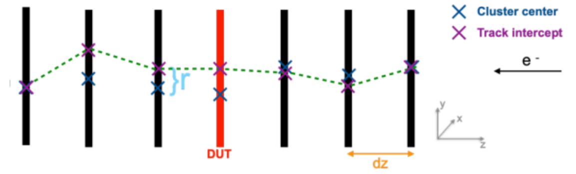
Clustering

Clusters of hits in the reference telescope and DUT are identified



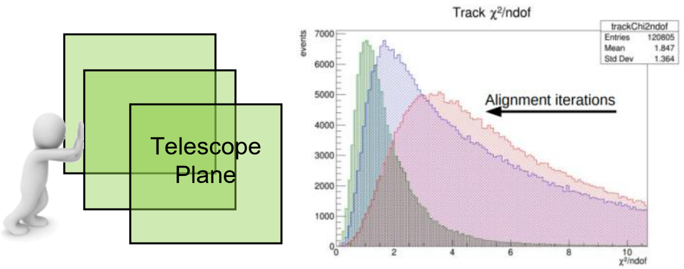
Tracking *

Tracks are reconstructed using telescope clusters + spatial & temporal cuts



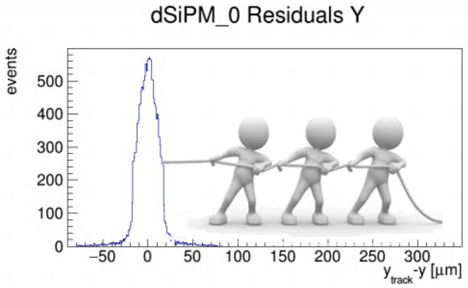
* **Telescope Alignment**

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



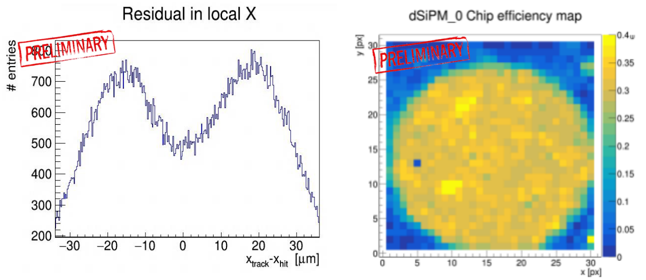
dSiPM Alignment

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



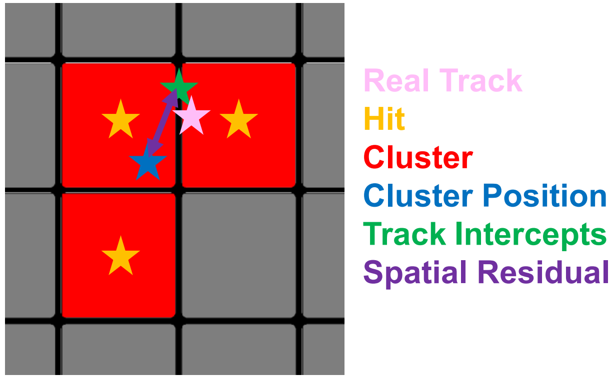
DUT Association & analysis

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



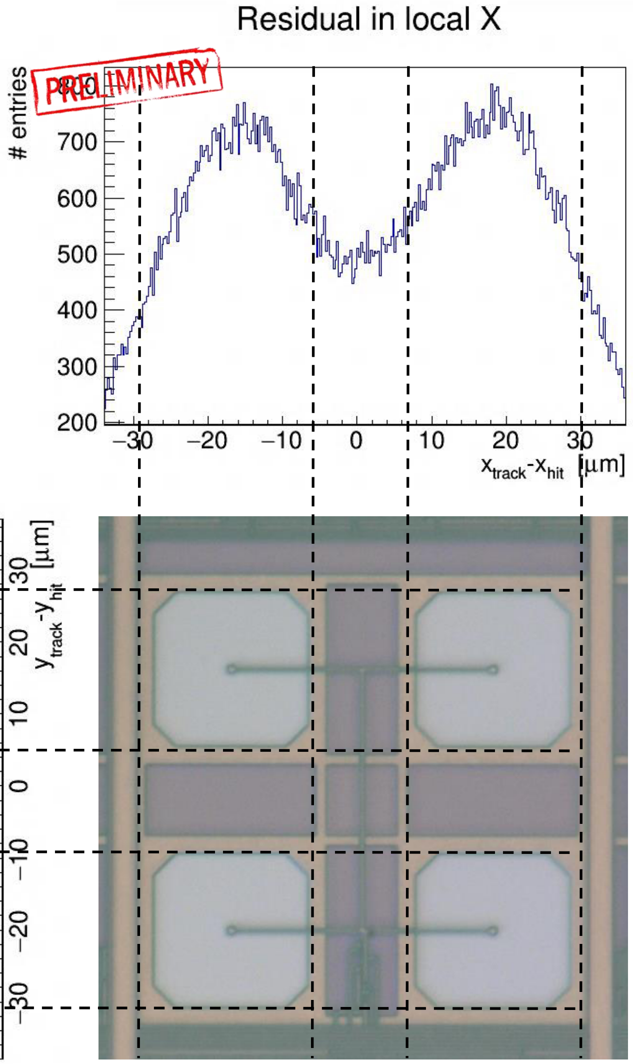
Spatial Resisuals

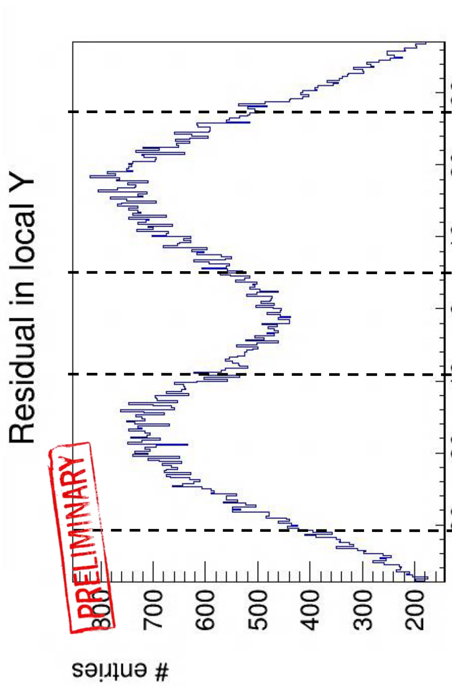
Not Gaussian



DSiPM Spatial Residuals

- Defined as the difference between Cluster position in DUT and interpolated track in the same z-position
- **Double-peak structure** due to inefficient in-pixel regions
- Proves **pixel scale resolution of** the dSiPM $\mathcal{O}\left(pitch/\sqrt{12}\right)$





Microscope picture of a pixel

How to deal with non-Gaussian residuals in Corry

- Standard [AlignmentDUTResidual] in Corry does not work properly
- Expect a Gaussian distribution of spatial residuals
- **Redefinition of spatial residual** in [AlignmentDUTResidual]:

$$Residual_{x/y} = TI - CP$$

$$Residual_{x/y} = \left(\left| TI - CP \right| - [\,0\,] \right) \times sign\left(TI - CP \right)$$

Corryvreckan Merge request !597

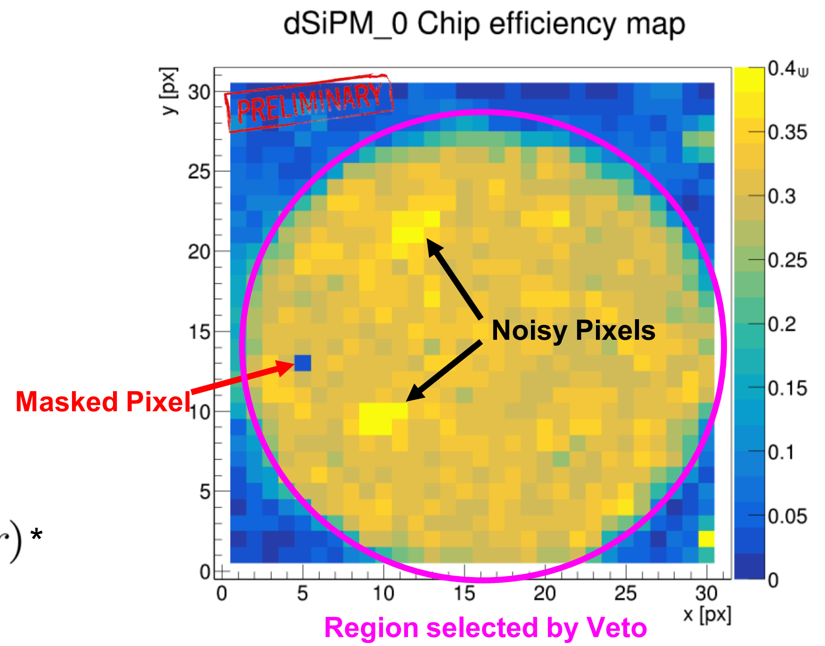
TI = Track Intercepts, CP = Cluster Position
[0] = 17.6 µm in x & 19 µm in y

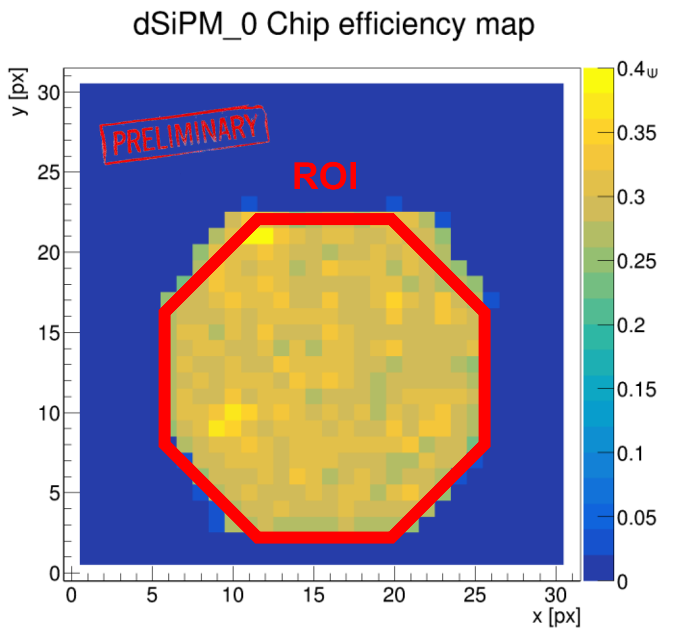
Efficiency

In MIP Detection

Chip Efficiency

- **Trigger** circular shape is visible
- **Noisy & masked** pixels are visible
- For efficiency study a **Region of Interest** is used
- Chip total **Efficency in MIP detection** $\mathcal{O}(fill\ \ factor)$ *

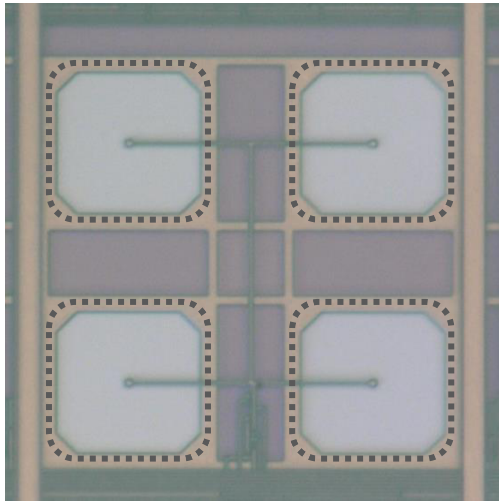


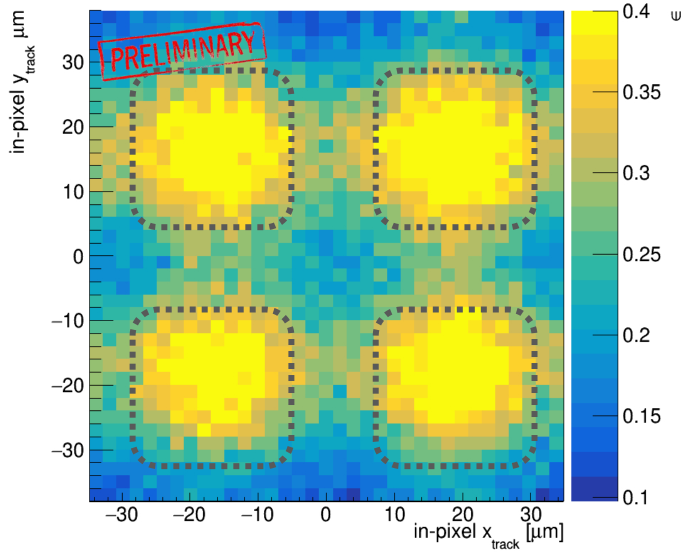


In Pixel Efficiency

- Evaluated in the ROI
- The efficient area can be associated with the **SPAD position**
- **Track resolution** affects reconstructed shapes
- Track resolution at the DUT **> 5 µm** (es from May 22 TB)
- Efficiency $\mathcal{O}(fill\ \ factor)$ *

*Impact of noise & systematics under investigation





Time Residuals

Promising Results

Time Residuals

- Defined here as the difference between the track time stamp (TLU+trigger) and the hit time stamp (dSiPM TDCs)
- Time **correlation** between dSiPM hit & associated tracks confirmed
- **Width** dominated by trigger reference time resolution

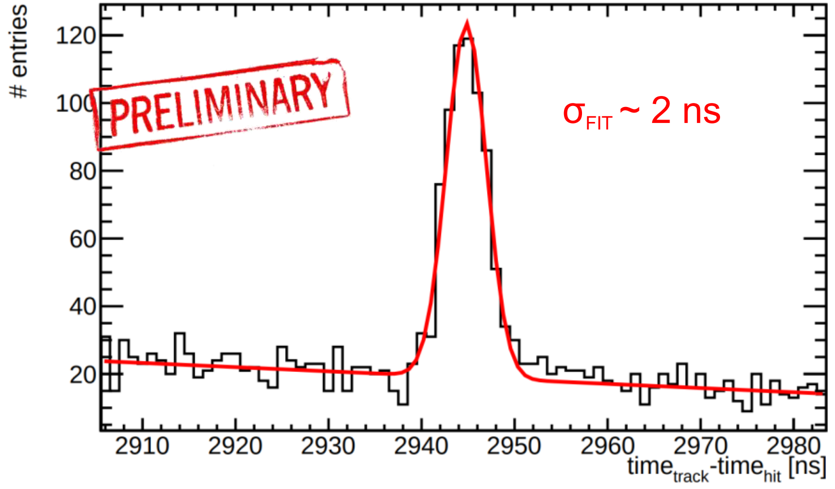
Test Beam October 2022

- Time track sampled by TLU time to digital converter
- Trigger was given by **Telepix** (distribution with **~ 2ns**)
- Time residual distribution dominated by the reference time resolution

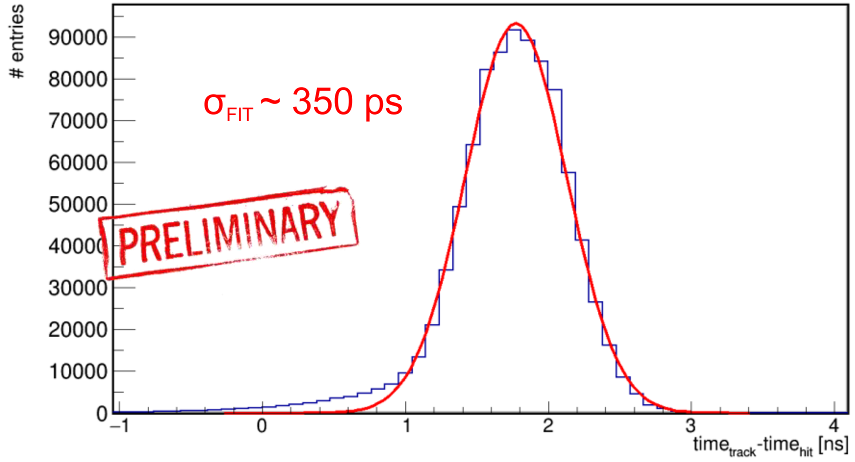
Test Beam March 2023

- Trigger was given by **scintillators + PMTs + veto**
- Time residual distribution with **~350 ps**
- Ongoing data analysis for dSiPM resolution evaluation

$$\sigma^2_{FIT} = \sigma^2_{TLU} + \sigma^2_{Telepix} + \sigma^2_{dSiPM}$$



$$\sigma^2_{FIT} = \sigma^2_{TLU} + \sigma^2_{Scint+PMT+VETO} + \sigma^2_{dSiPM}$$



Summary

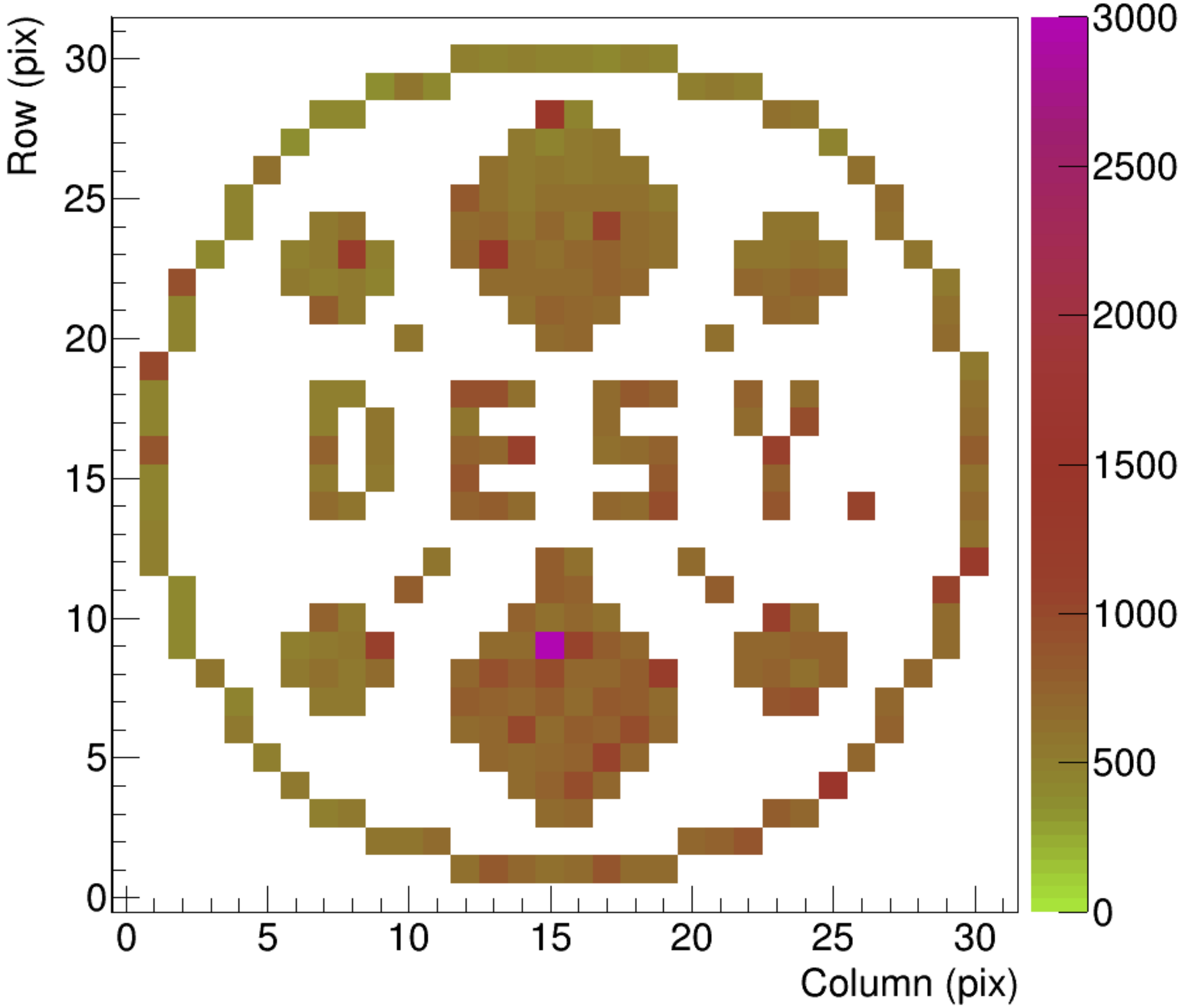
A promising R&D project

Results from Test Beam

- DESY dSiPM was successfully **integrated in DESY-II** test beam setup
- **Three different TBs** already carried out with continuous hardware & software improvements
- **Material Budget Imaging** technique used for DUT alignment in high noise condition
- Pixel scale **spatial resolution** proved & **efficiency** $\mathcal{O}(fill\ factor)$

Ongoing studies

- Evaluation of **systematics & noise** effect on results
- **Timing performances** of the prototype are currently being studied using test beam data and laser setup
- Investigation of possible solutions to **improve efficiency**
- Ongoing research of **possible applications**



Dark Events Hitmap whit DESY logo Mask applied

Thank you.

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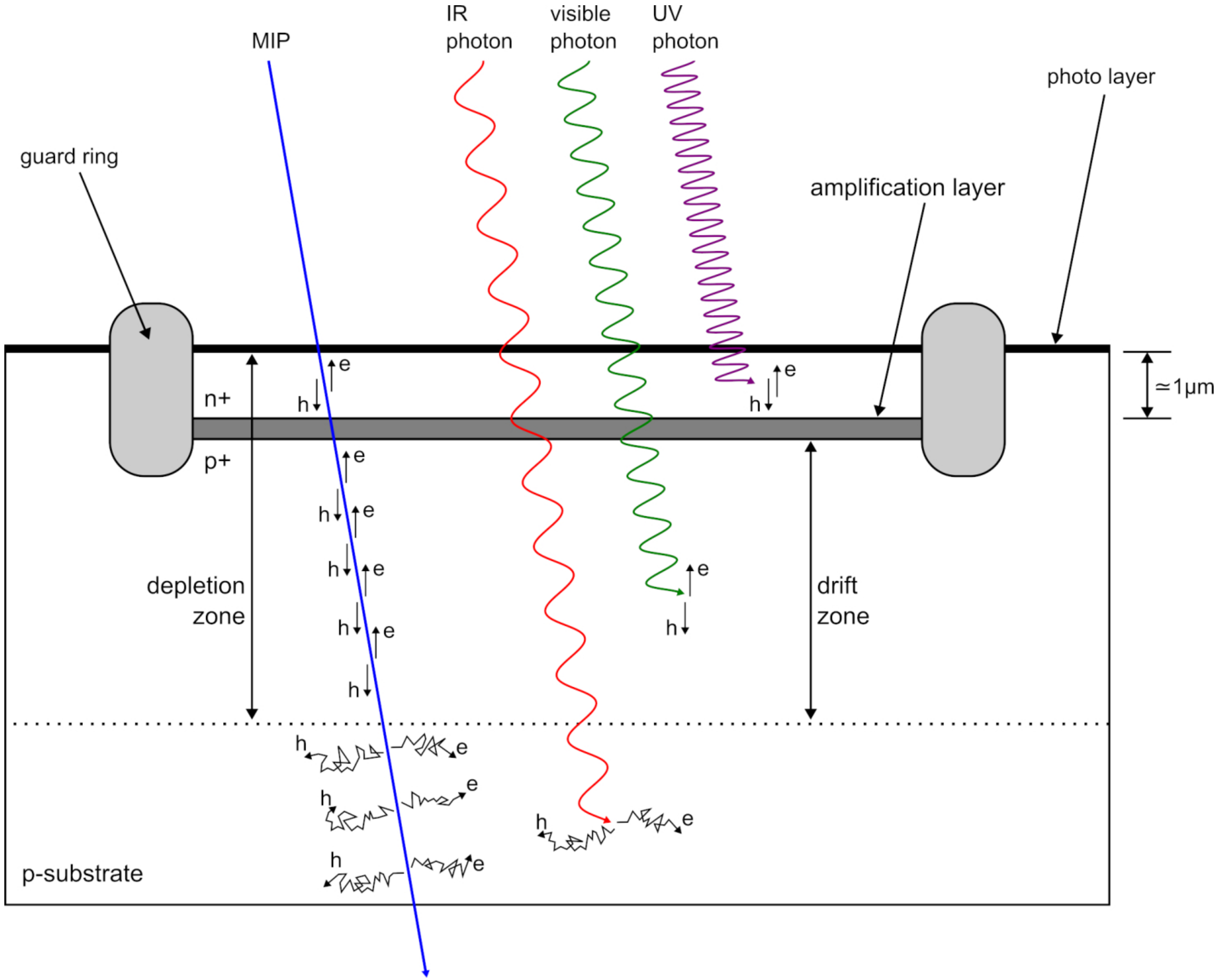
DESY TEST BEAM.

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).

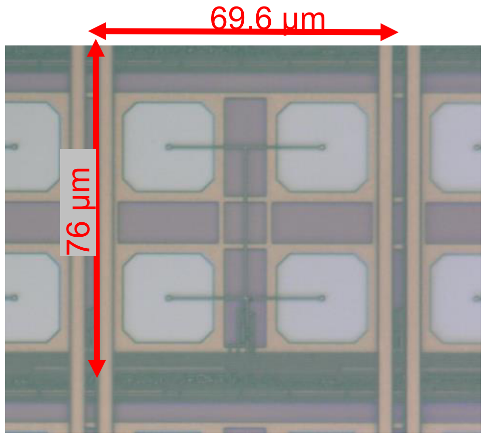
SPAD & MIP detection

Electron-hole production in all the path

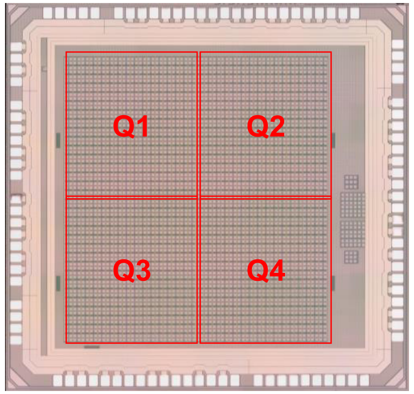


DESY dSiPM

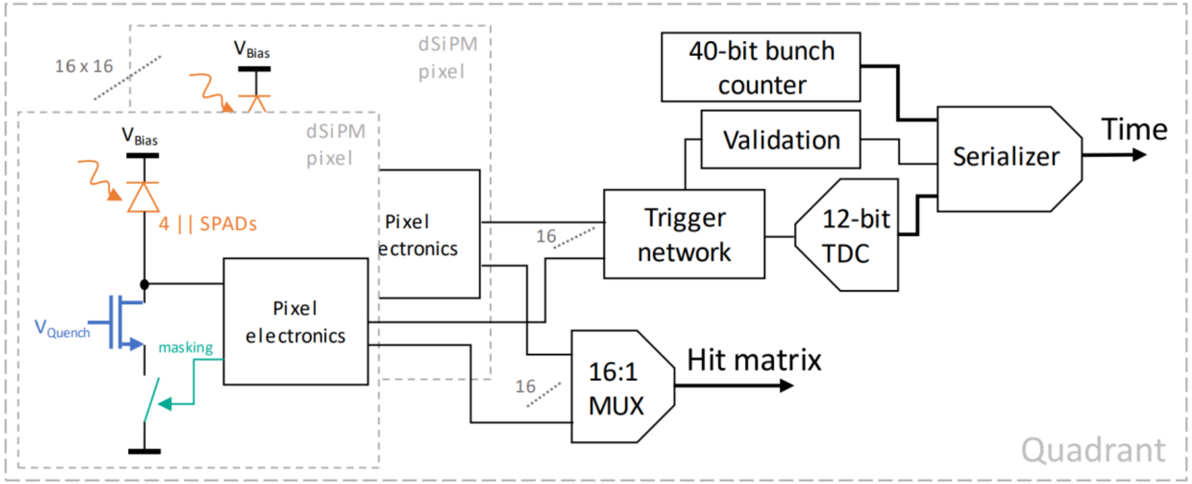
Details



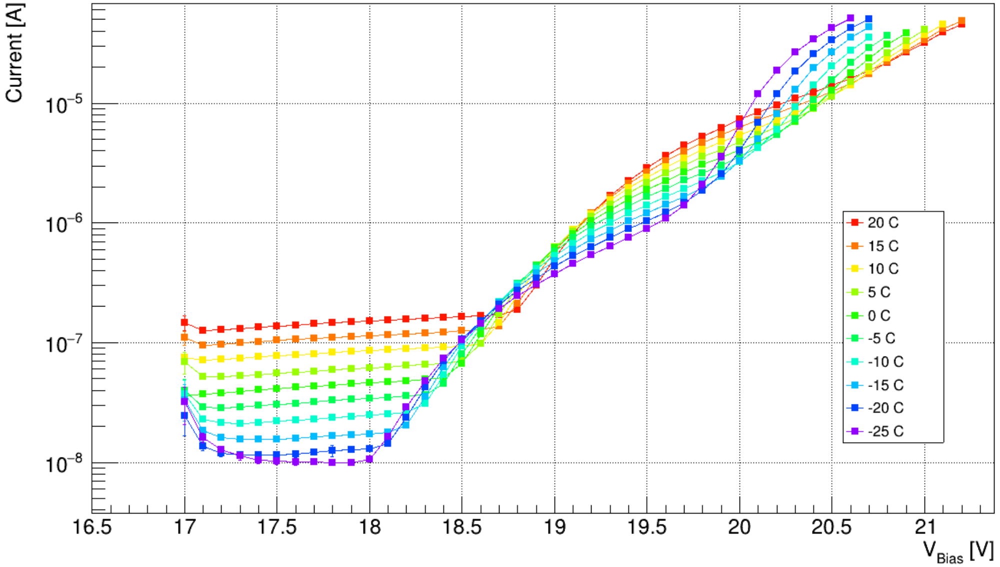
Microscope picture of a pixel



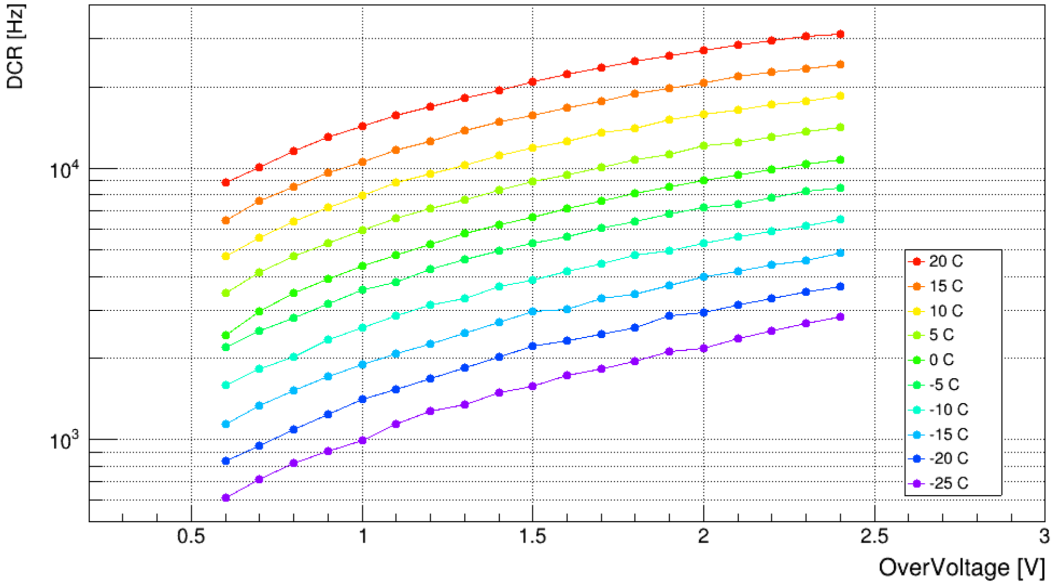
Microscope picture of the Chip



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



IV curves (Full Matrix), Temperature Scan



Dark Count Rate (per pixel), Temperature Scan

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

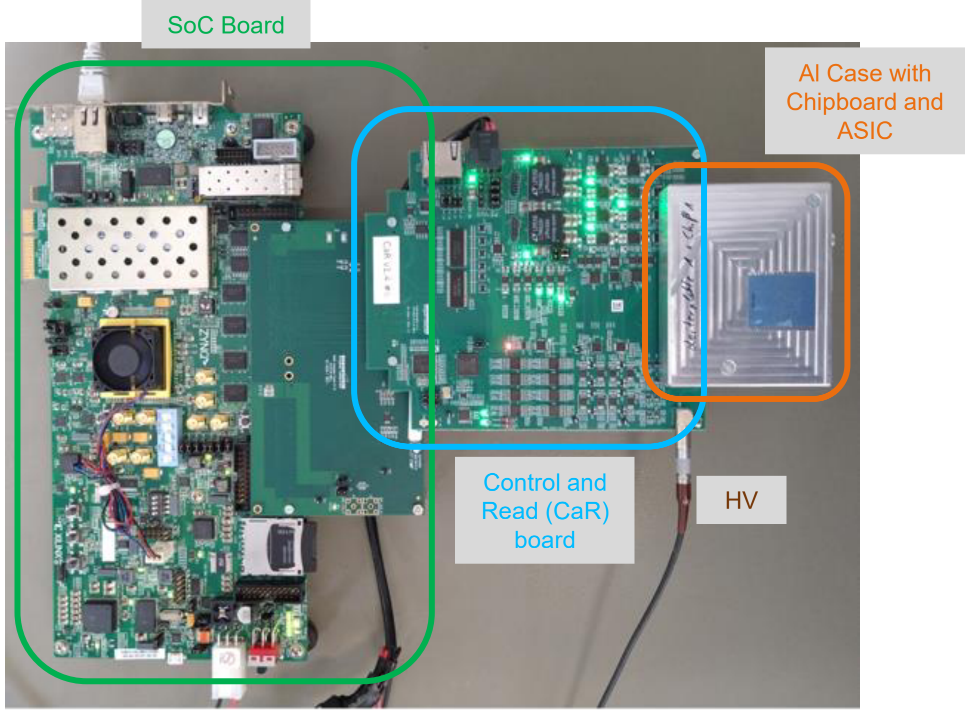
Control and Readout (CaR) Interface Board

- 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.

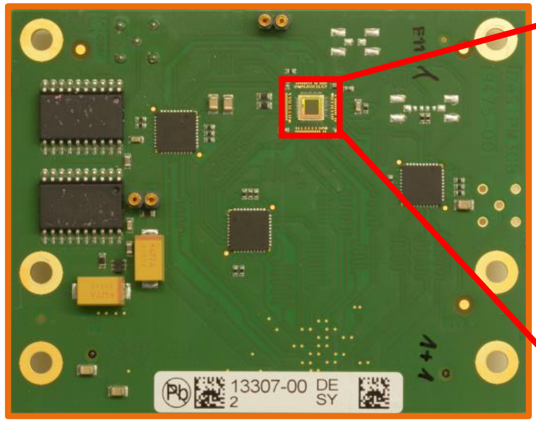
Chip Board

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

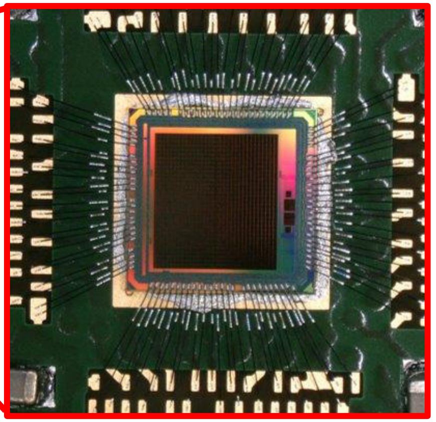
http://dx.doi.org/10.22323/1.370.0100
https://gitlab.cern.ch/Caribou/



Caribou DAQ System



Chip Board



Chip Glued & Bonded

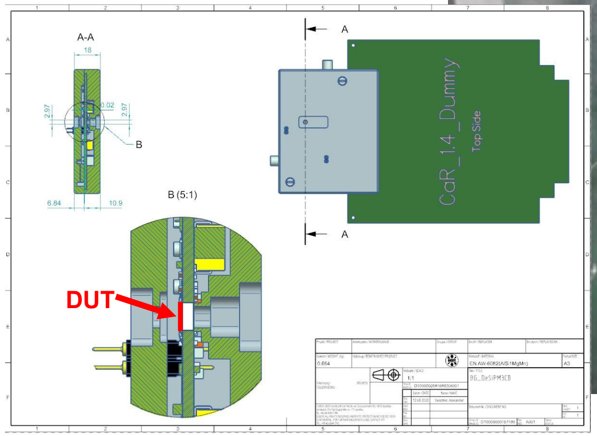
Cooling

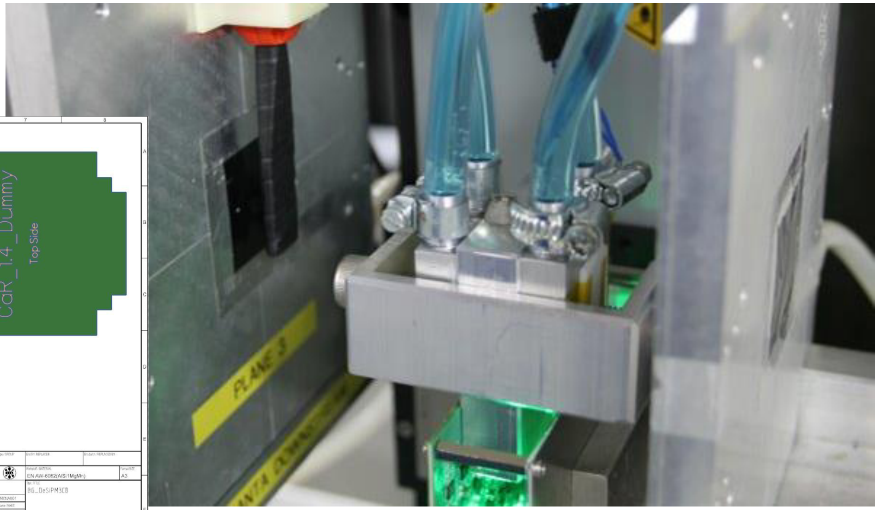
Silicon oil + N2 dry Box

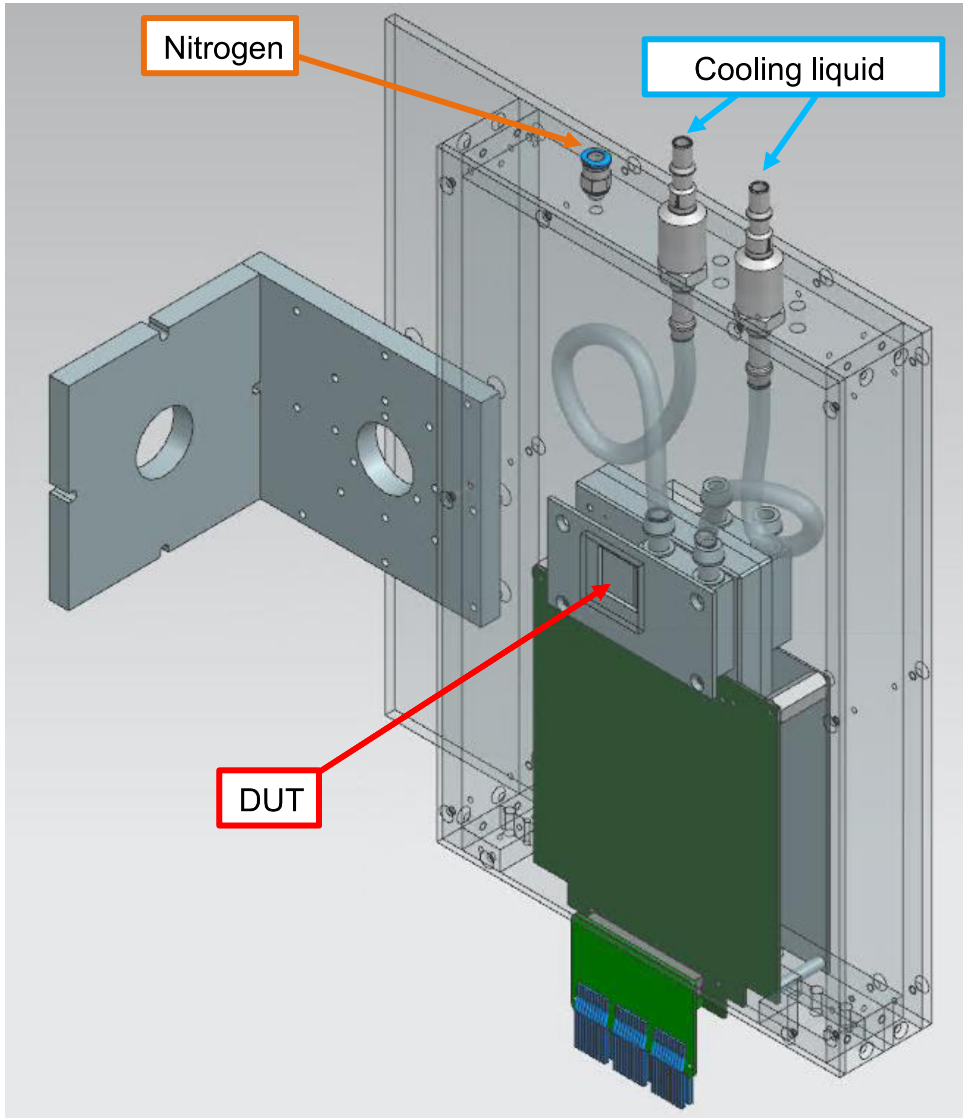
Cooling components

- Aluminium case that acts as heat sink and light shield
- Active cooling with Silicon oil down to ~ -5°C on chip
- Plastic Box filled with N2 to avoid condensation

  (Nitrogen available in all DESY-II Test Beam lines)







DUT & Trigger Alignment

Material Budget Imaging

DUT- Trigger alignment With high Dark Count Rate

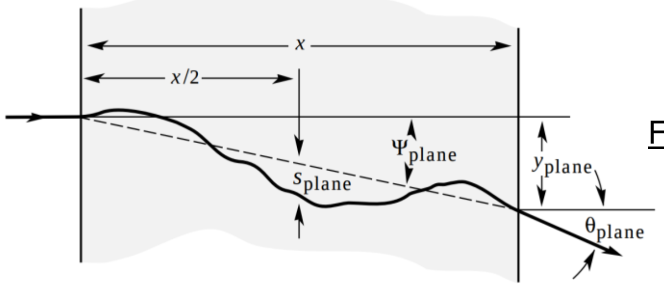
- DCR/MIP event distinction impossible before alignment
- DSiPM Self trigger can not be used to identify DUT position

Material Budget Imaging (MBI)

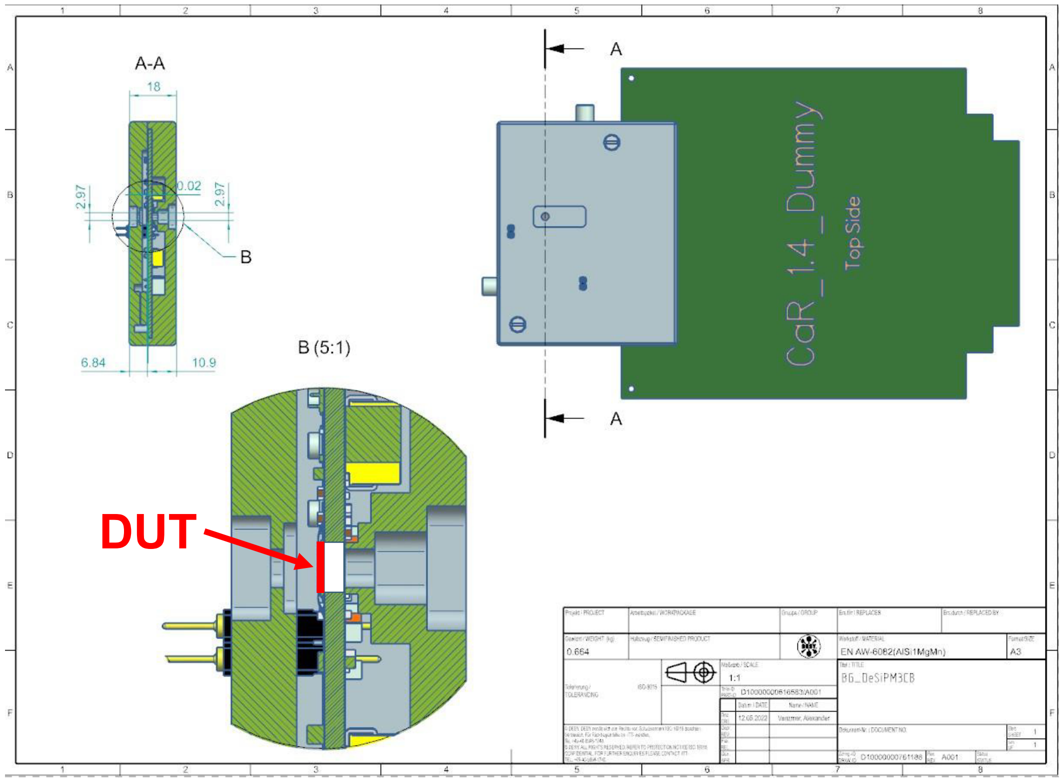
- Material Budget is minimized in the position of the DUT
- Evaluation of MBI measuring the Scattering angle:

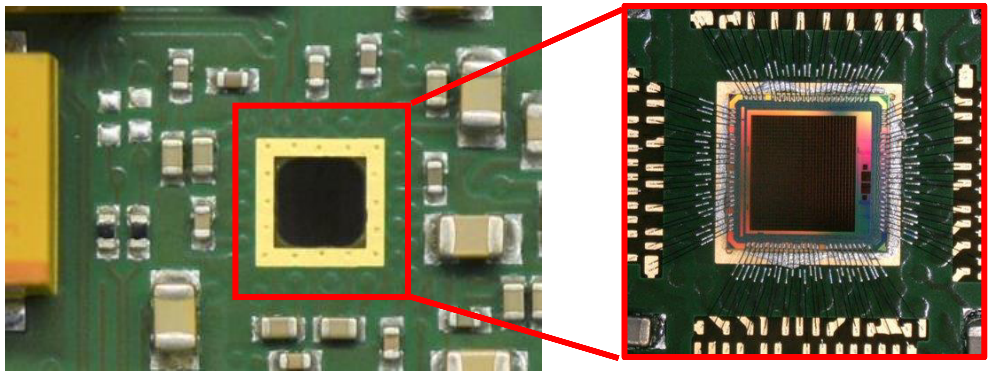
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

Thickness of the scattering medium in radiation lengths



From PDG





Chip Board (Back) *Chip Glued & Bonded (Front)*