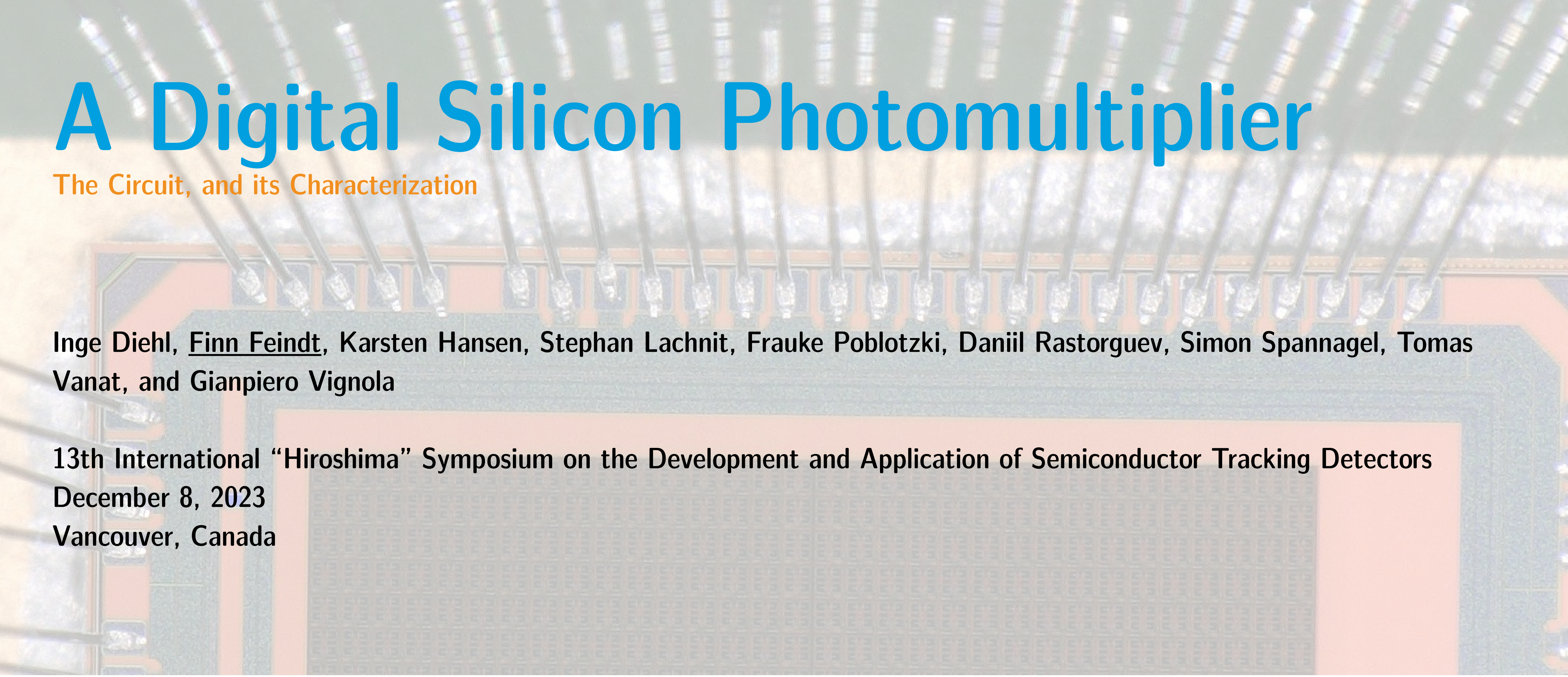
DESY.



A Digital Silicon Photomultiplier

The Circuit, and its Characterization

Inge Diehl, Finn Feindt, Karsten Hansen, Stephan Lachnit, Frauke Poblotzki, Daniil Rastorguev, Simon Spannagel, Tomas Vanat, and Gianpiero Vignola

13th International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors
December 8, 2023
Vancouver, Canada

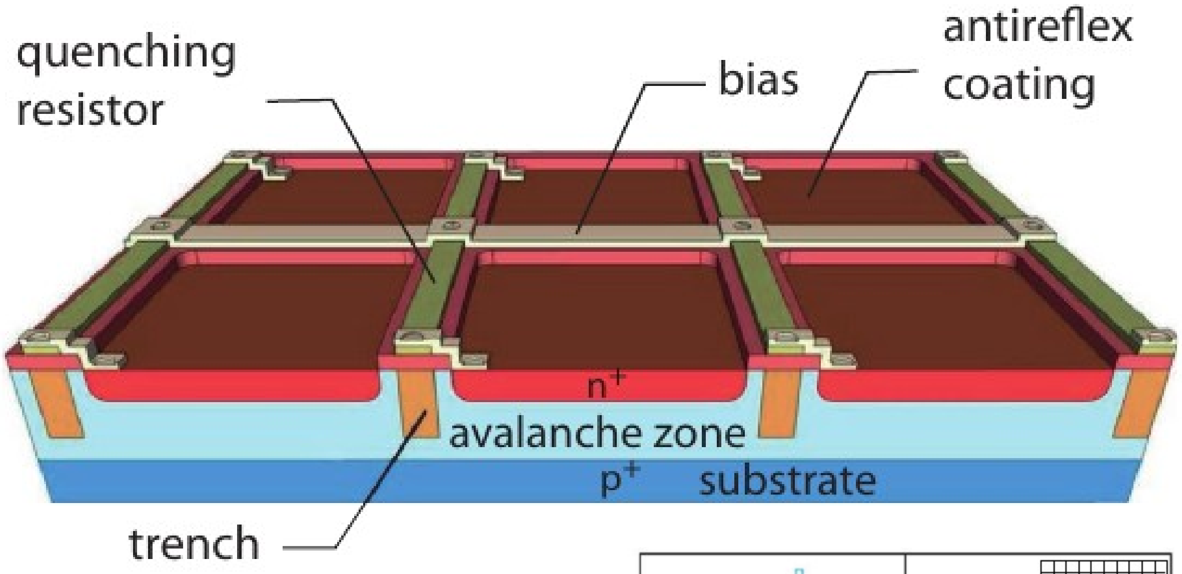
Motivation

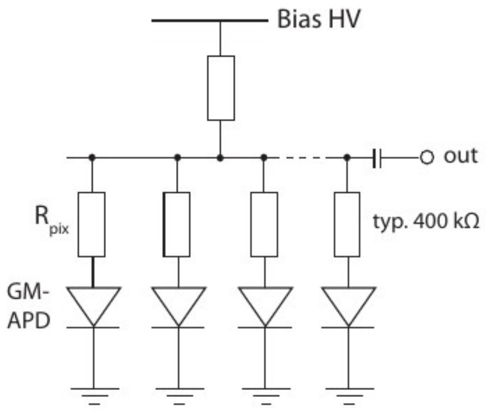
For Digital SiPMs

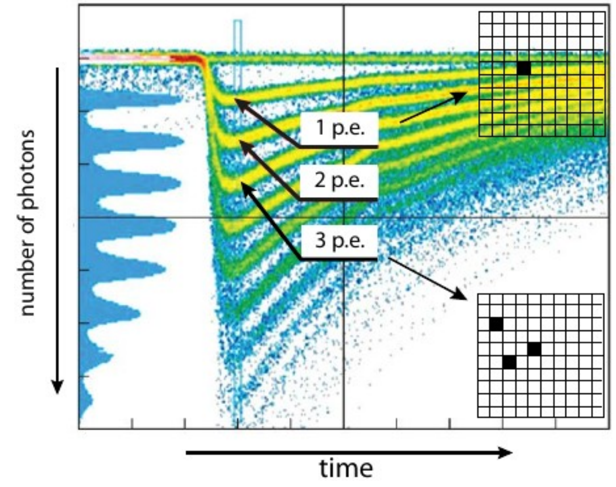
Silicon Photomultipliers

Digital Devices with ~~Analog~~ Digital Readout

- Array of SPADs (Single-Photon Avalanche Diodes), sizes between 15 and 70 um
- Single photon detection efficiencies reach O(50 %)
- Fast peaking time, reaching time resolutions of few 10 ps
- Typically with analog readout of all SPADs in parallel
- More light: number of firing SPADs approx. proportional to photon flux (within some constrains)
- BUT: The information a single SPAD provides is DIGITAL
- Add CMOS circuitry
  - No loss of information by digitizing SPAD signals
  - Profit from digital signal processing
  - E.g. resolve position of firing SPADs



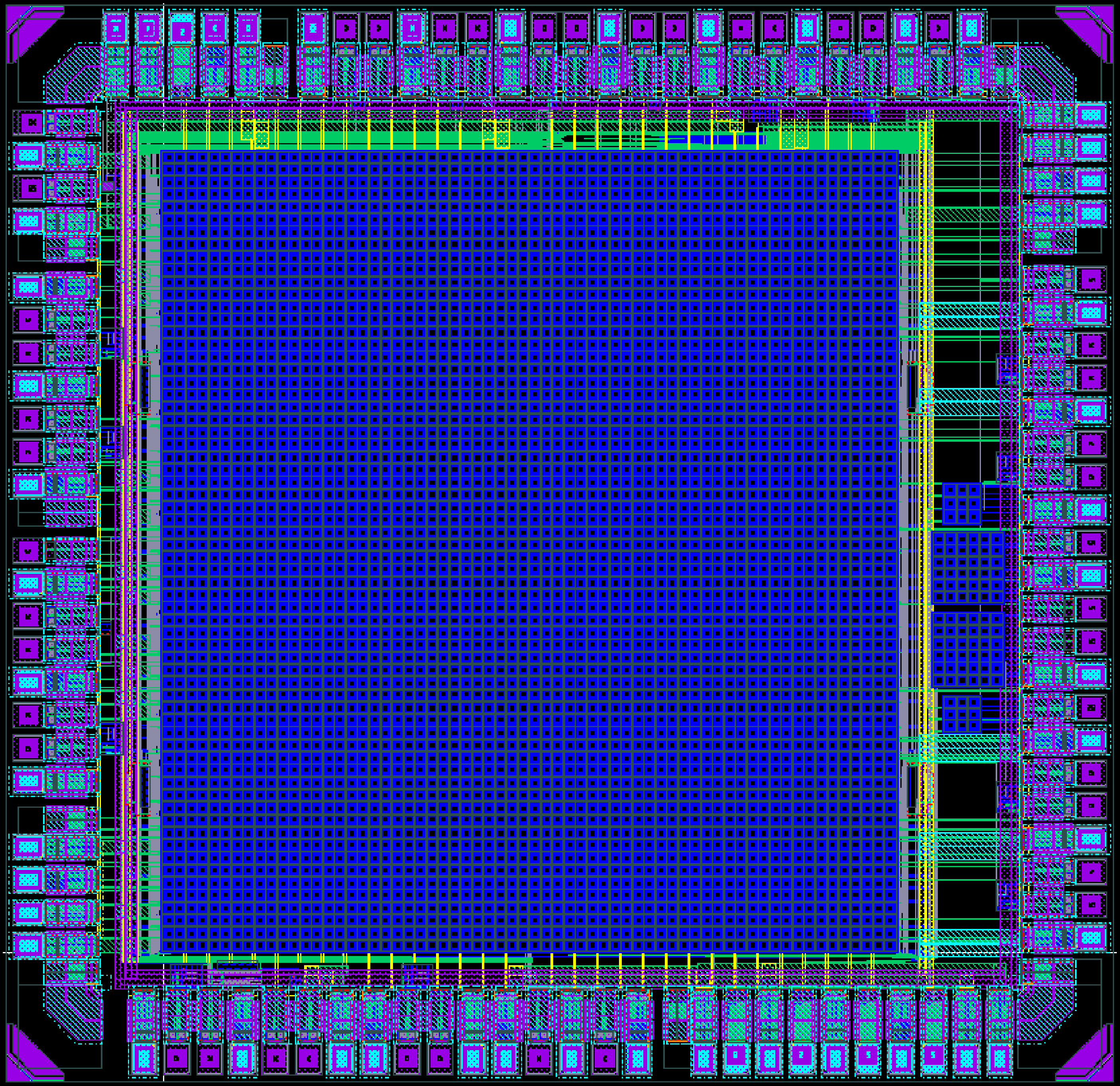




[H. Kolanoski and N. Wermes]

The Circuit

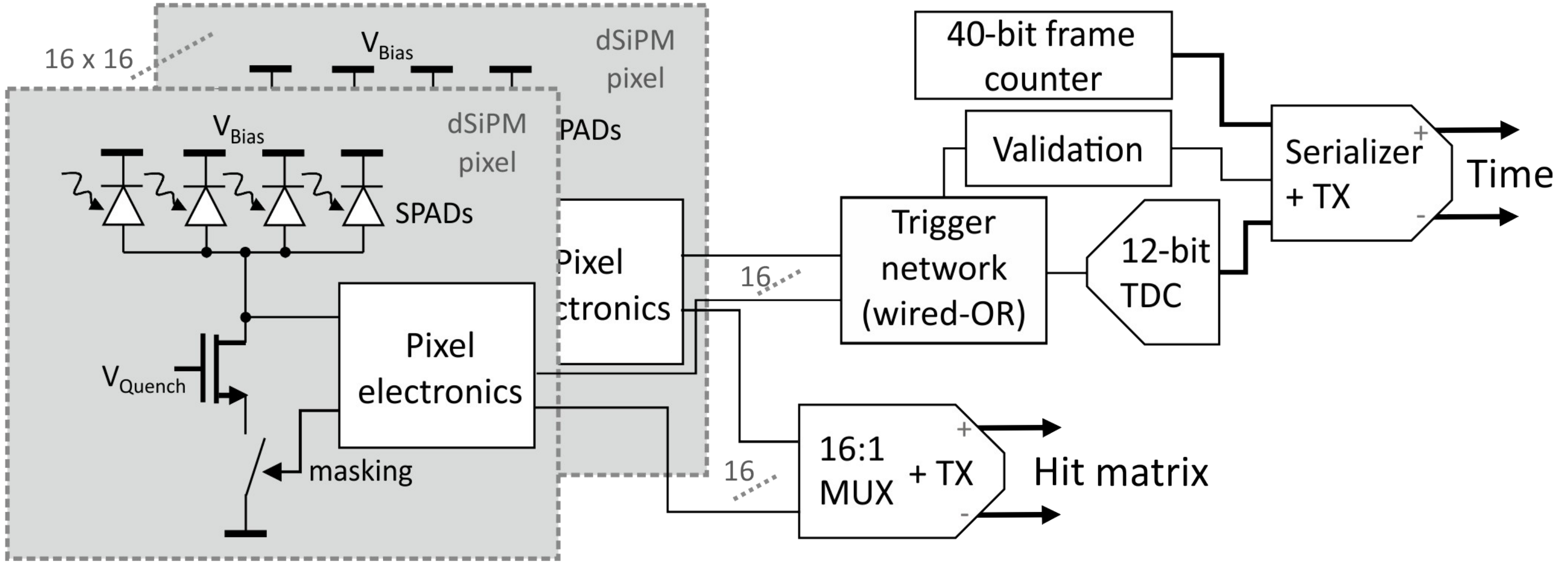
A Digital Silicon Photomultiplier –
Designed in LFoundry's 150-nm CMOS



The Readout Scheme

Key Components

- Four SPADs make a pixel
  - Variable quenching resistance (V_{quench})
  - Masking (pixel not powered)
  - 2-bit hit counter (2 readout modes)
  - Wired-or connection to quadrant TDC
- 16x16 pixels form quadrant unit with
  - 12-bit TDC, time stamps of 1st firing pixel per frame; configurable validation logic
  - Per-frame hit-matrix readout

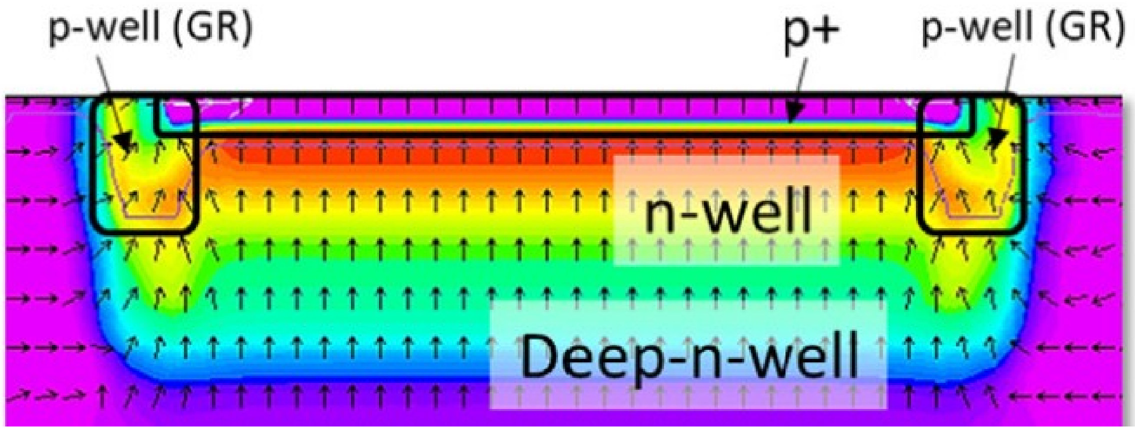


- This looks like a pixel detector! Can we operate it like a pixel detector?
- What are its MIP detection properties? Efficiency? Spatial and temporal resolution?
- Are 4D tracking applications feasable?

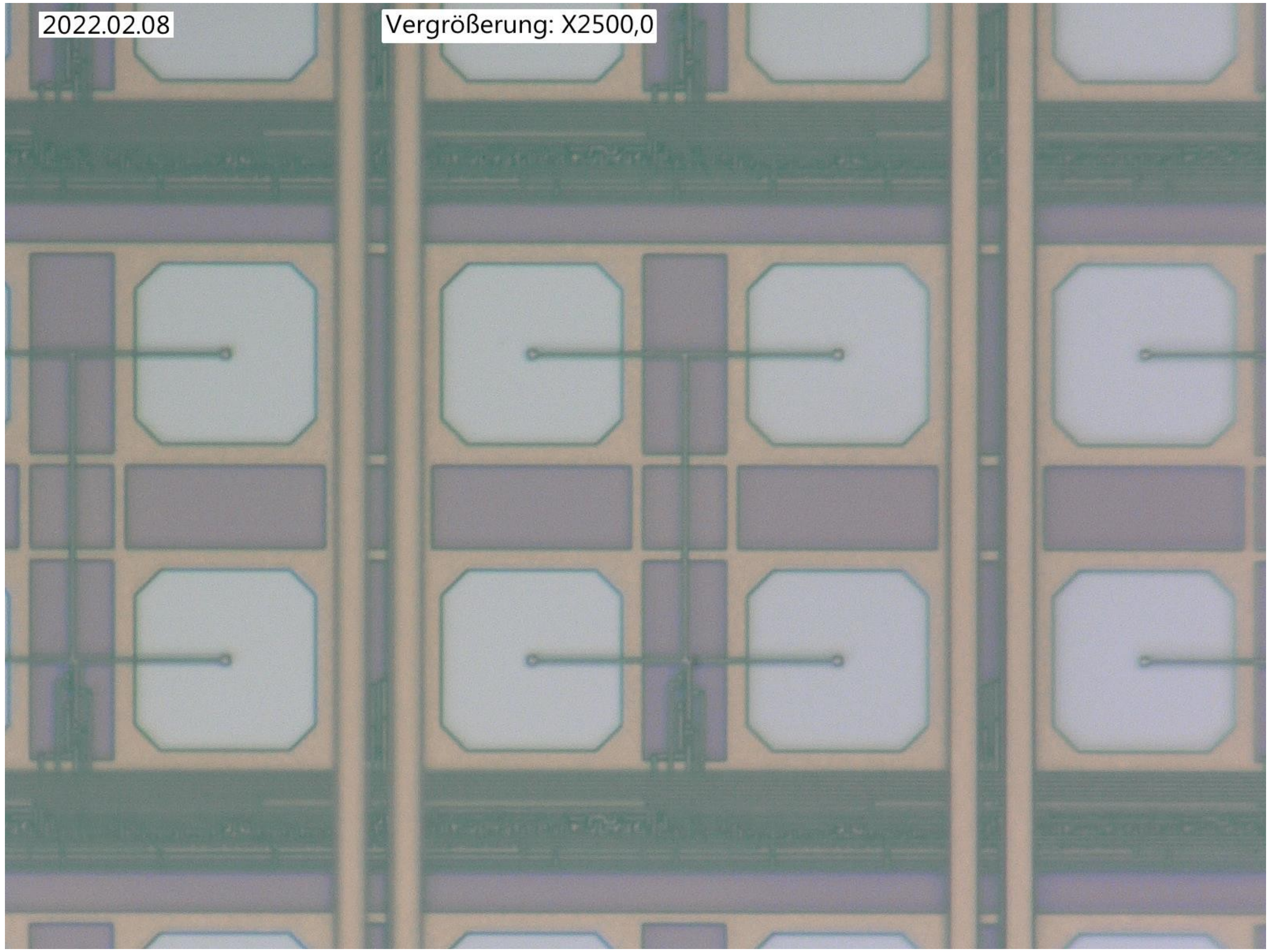
The Pixel

Four SPADs Make a Pixel

- Four library p+/n-well SPADs, 20 x 20 um^2, in parallel
- Surrounded by cathode and p-well ring for cross-talk minimization
- Pixel area 69.6 x 76 um^2, fill factor 30 %
- Shared front-end below SPAD group



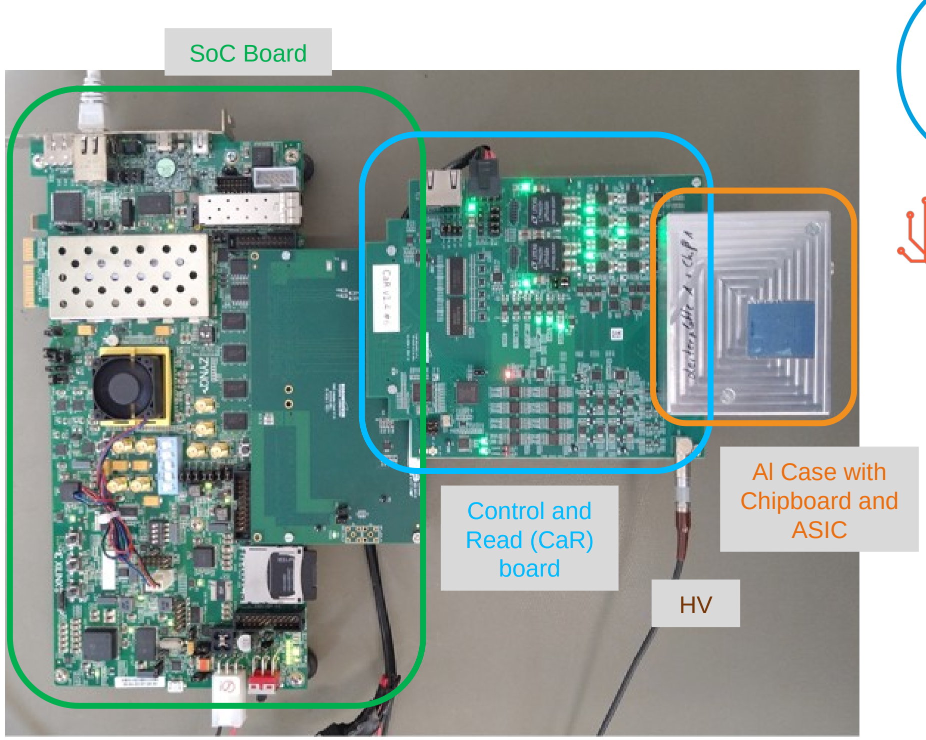
Example of a p+/n-well SPAD in a CMOS process
[F. Acerbi and S. Gundacker]



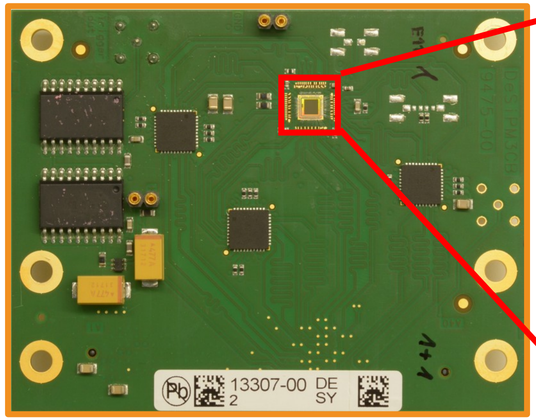
Caribou

A Versatile Readout System

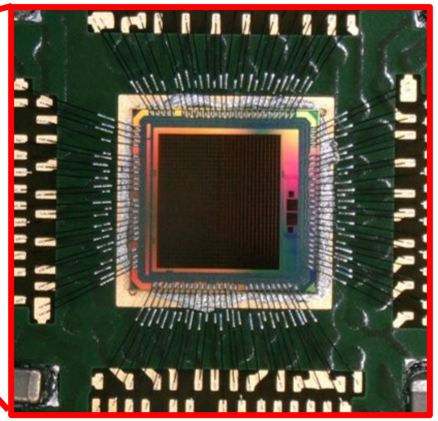
- Developed by CERN, BNL, and DESY
- Fast, simple and low-cost implementation & tests of sensors, already 16 devices e.g. ATLASPix, CLICTD, …
- System on Chip (SoC) Board – CPU and FPGA on same die
  - A CPU runs DAQ and control software
  - An FPGA runs custom hardware for data handling and detector control
- Control and Readout (CaR) Interface Board
  - Physical interface from the SoC to the sensor
  - Peripherals needed to interface and run the chip: power supplies, ADCs, voltage/current references, LVDS links, etc.
- Chip Board – passive & detector-specific components



Caribou DAQ System



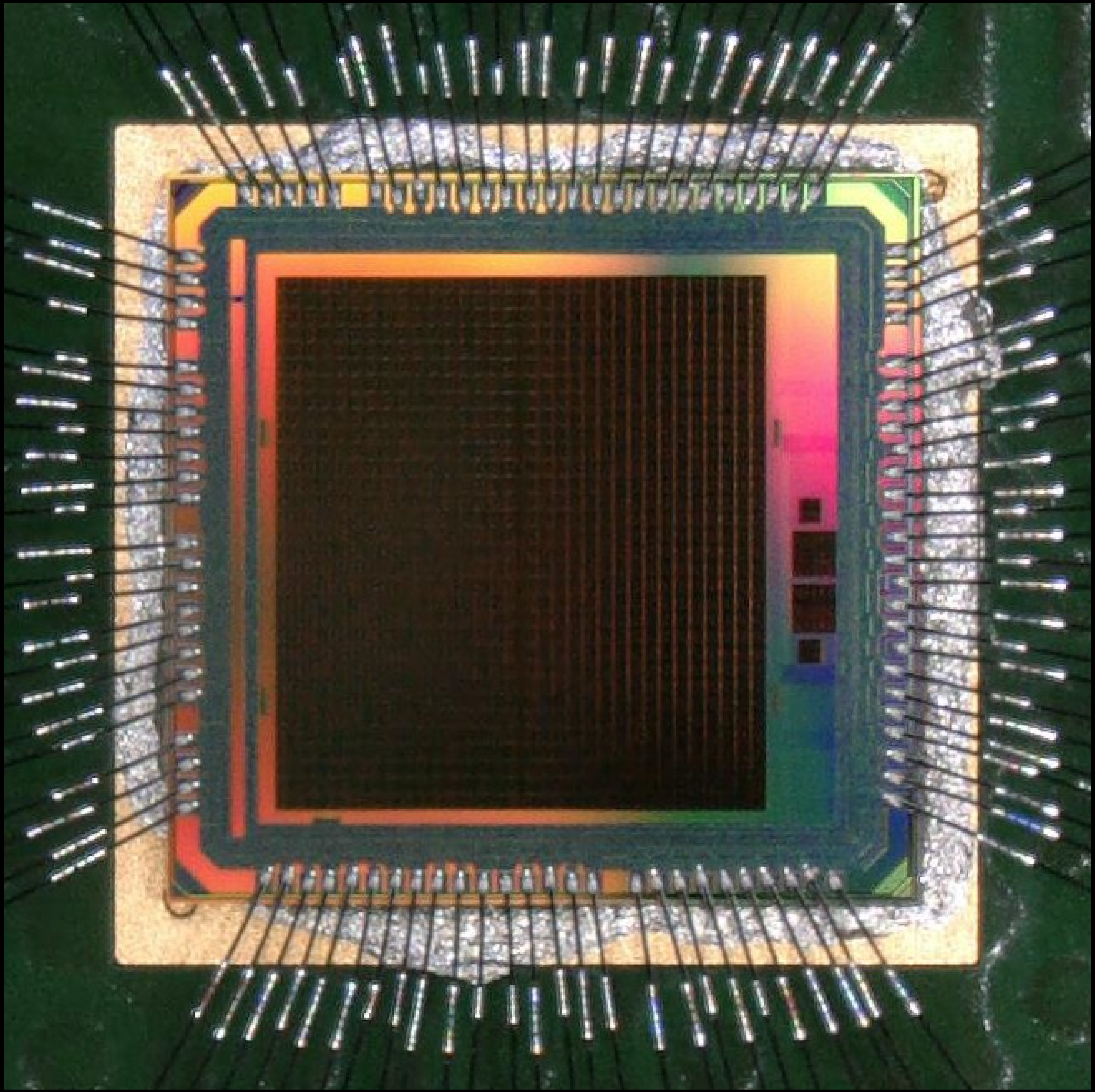
Chip Board



Chip Glued & Bonded

Characterization

Laboratory



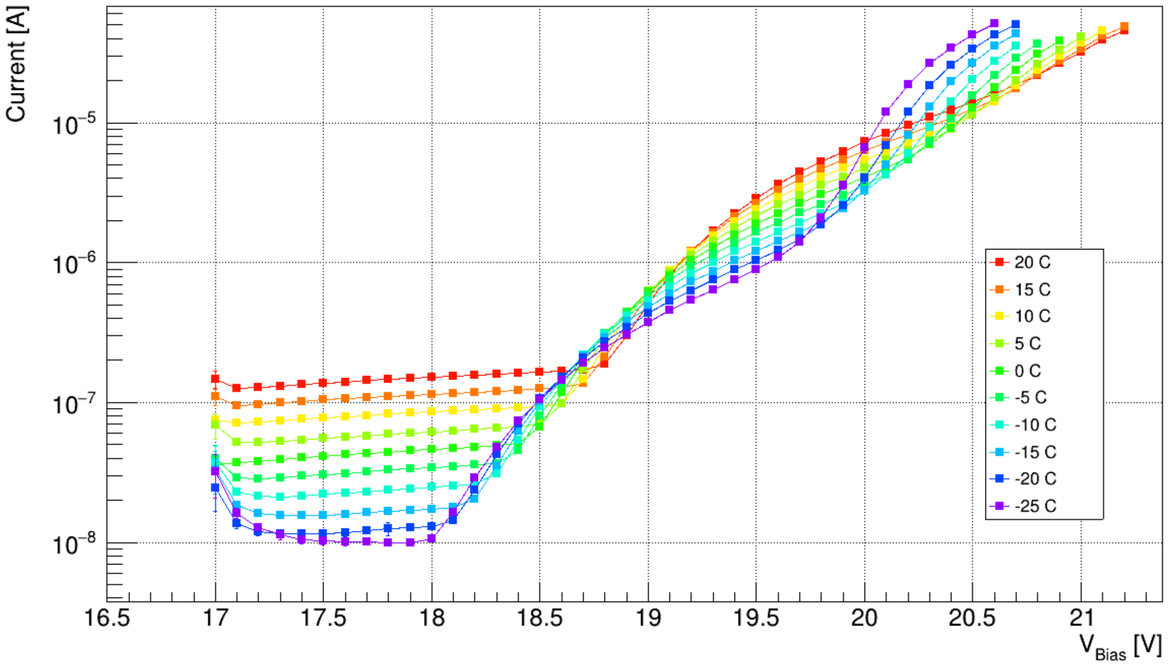
Lab – IV and Breakdown Voltage

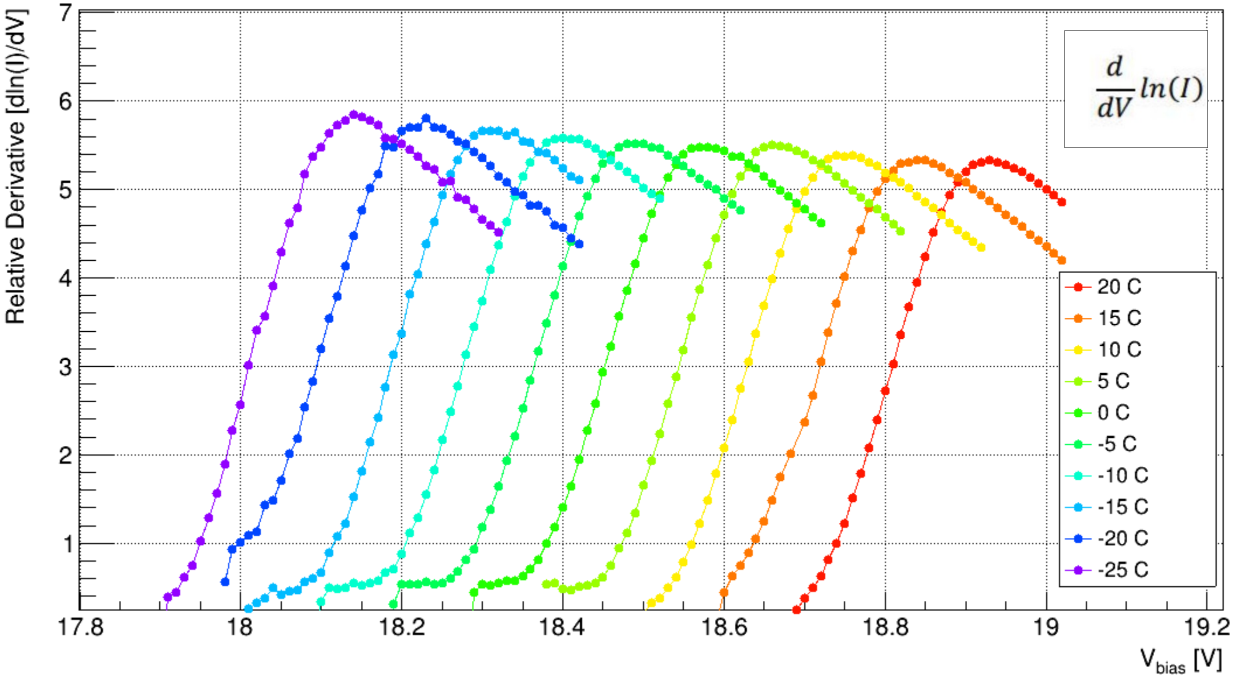
Because Breakdown is what we Need

Reaching Geiger mode

- Scanning the bias voltage in the breakdown region
- Different temperatures (climate chamber, humidity ~ 0%)
- Shift of breakdown voltage with temperature visible
- Avoid secondary breakdown for operation

- Various definitions of breakdown voltage around
- We used the “relative derivative“
- Measured breakdown as a function of temperature
- 18.9 V at 20°C and about 20 mV/K

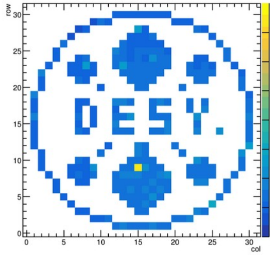




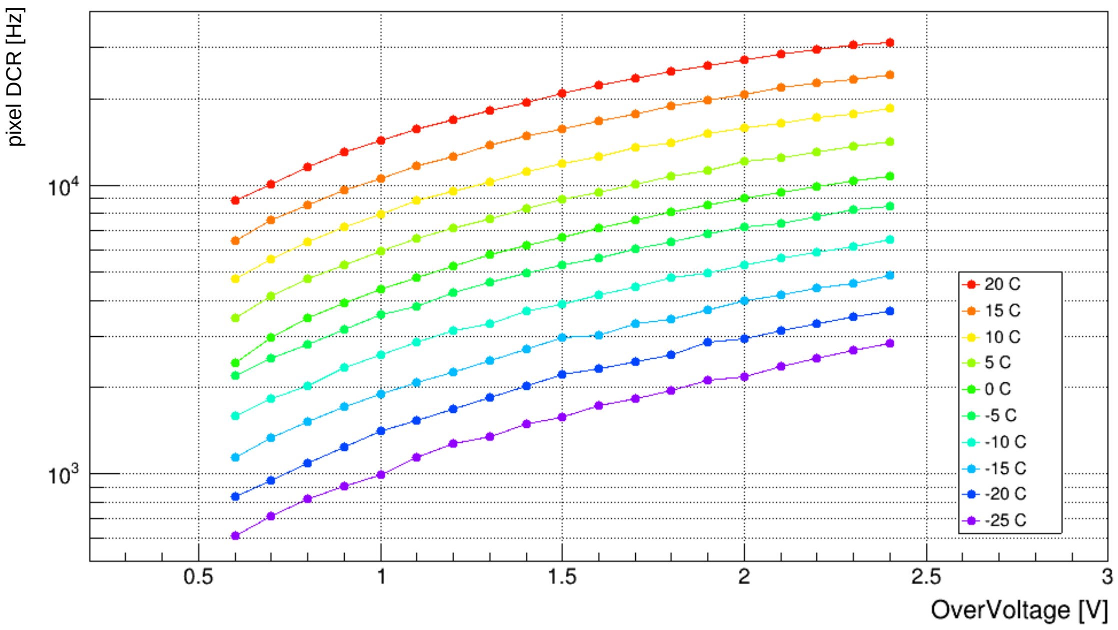
Lab – DCR

Dark Count Rate

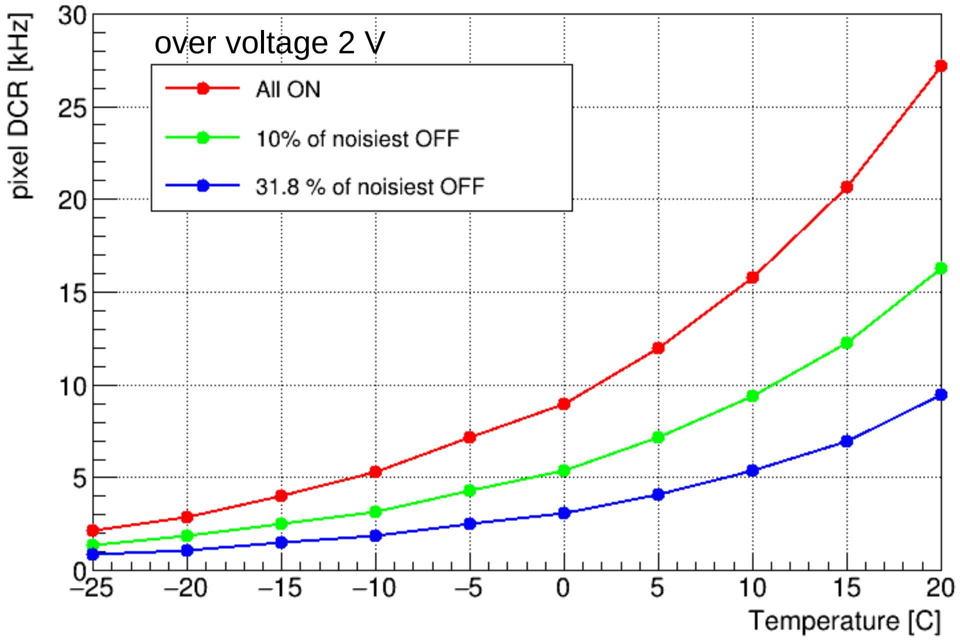
Thermal excitation → carriers → discharge



- Reading frames in dark environment
- Strong dependence on temperature and over voltage
  - Cooling helps!
- 10^4 Hz per pixel corresponds to 6.25 Hz/um^2



- Pixel masking helps!
- Masking noisiest 10 % reduces noise by about 40 %
- Observed also an impact on leakage current
  - Interesting case: single pixel determines breakdown

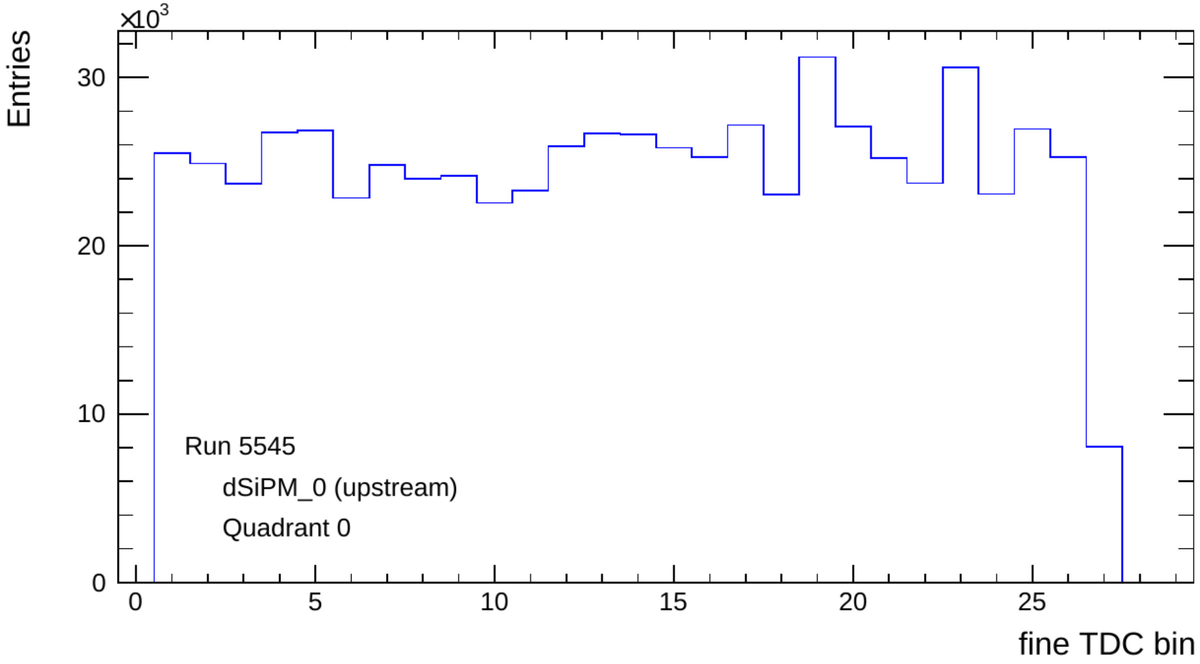


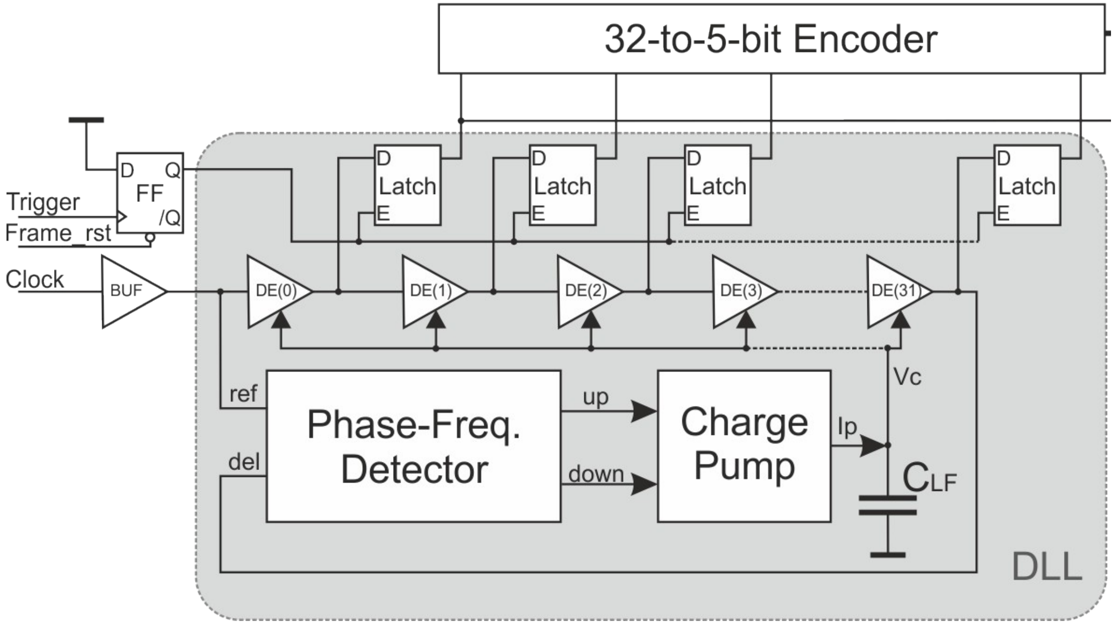
TDC Characterization

Measuring TDC Bin-Width Variations

- Studying the fine TDC with nominal binning of 77 ps
- Expecting constant occupancy (on short time scale)
- Variations are due to delay variations
- Not exploiting full dynamic range of 32 bins!

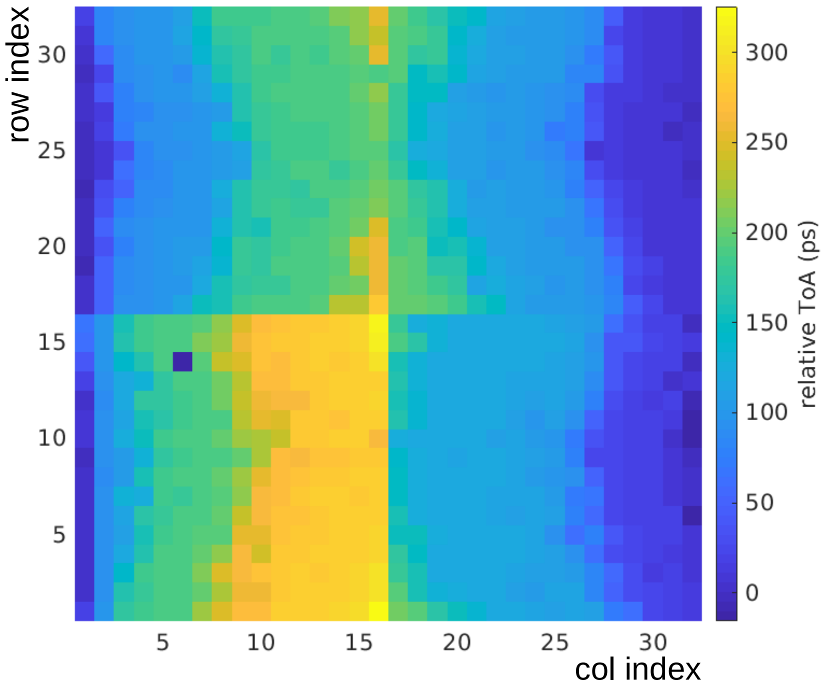
- Find corrections statistical code density analysis
- The width of a bin corresponds to its fraction of the total entries times the clock period (~2.5 ns)
- Mean bin width 93.1 ps





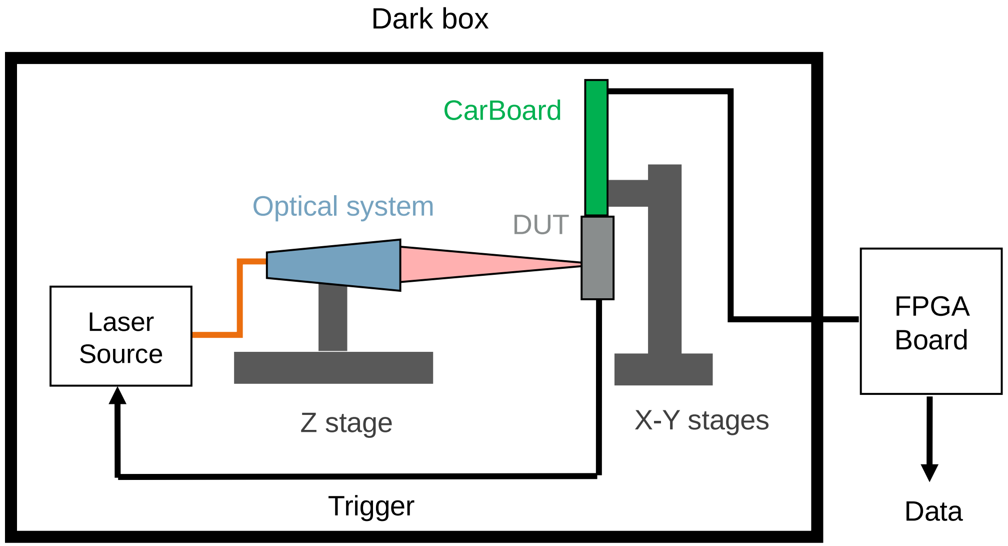
Laser Measurements

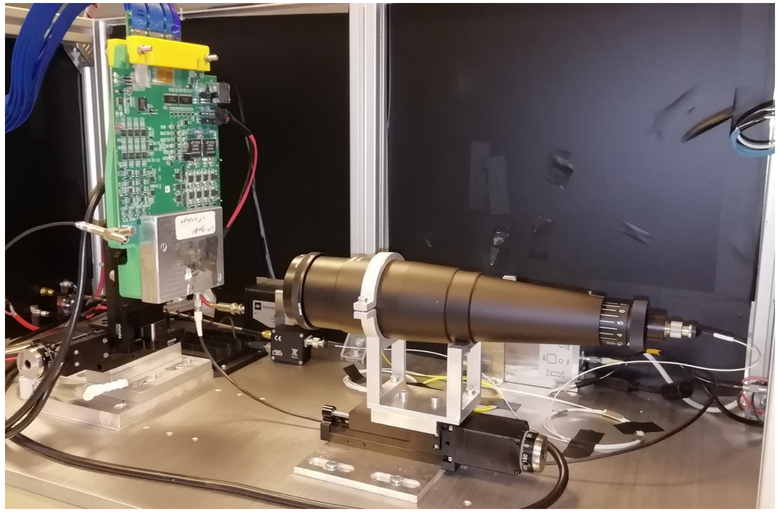
Measuring Propagation Delays



Setup

- DUT placed on an x-y stage; laser optical system on a z-stage
- 1054 nm pulsed laser; focus width $<$ 10 um in beam waist
- Laser in sync. with the DAQ clock
- Scan chip pixel-by-pixel, measure Time of Arrival (ToA)





- Clear function of distance to TDC
- Different offsets for each quadrant

Characterization

Beam Tests

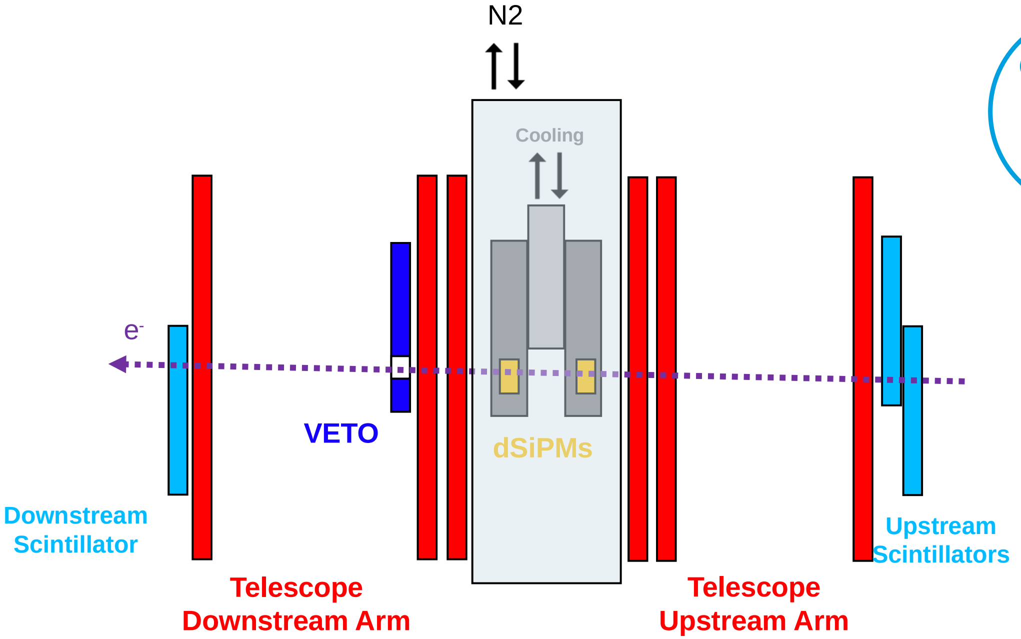
reddit.com/r/ScientificArt/

Our Setup

Evolving…

Setup in March 2023

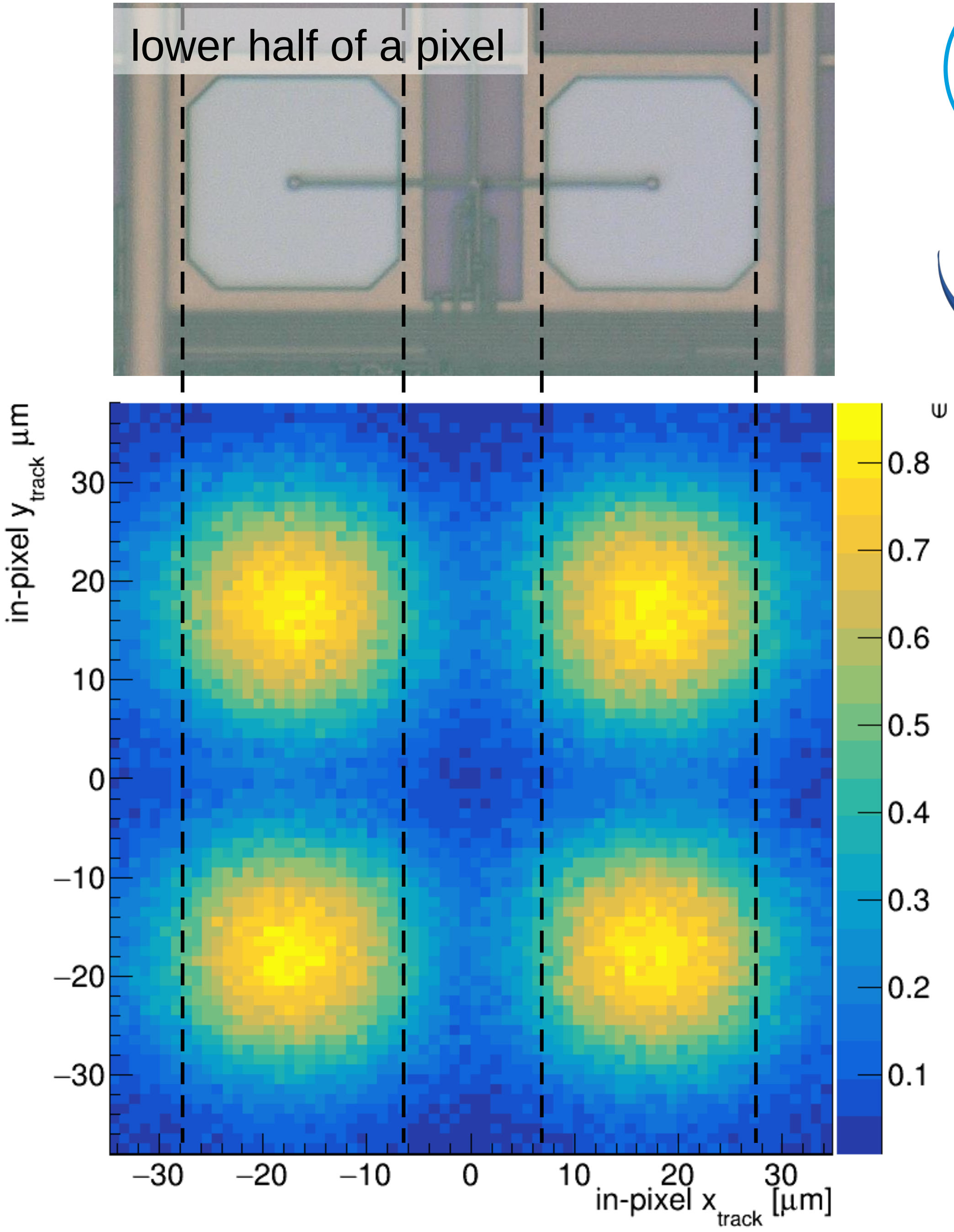
- Main goal: measure time resolution
- Triggering using 3 scintillators in coincidence
  - 4th scintillator with hole vetoes tracks out of acceptance
- For the time resolution measurement we take 2 dSiPMs
  - Not easy to find time reference better than 100 ps
  - Assume 2 DUTs have similar resolution
    - Derive residual $\Delta t = t_{DUT1} - t_{DUT2}$
    - DUT resolution $\sigma_{DUT} = \sigma_{\Delta t} / \sqrt{2}$
- Custom cold box to allow for temperatures down to -5°C
- Estimated track resolution around 4 um



Hit Detection Efficiency

Fill Factor Limited

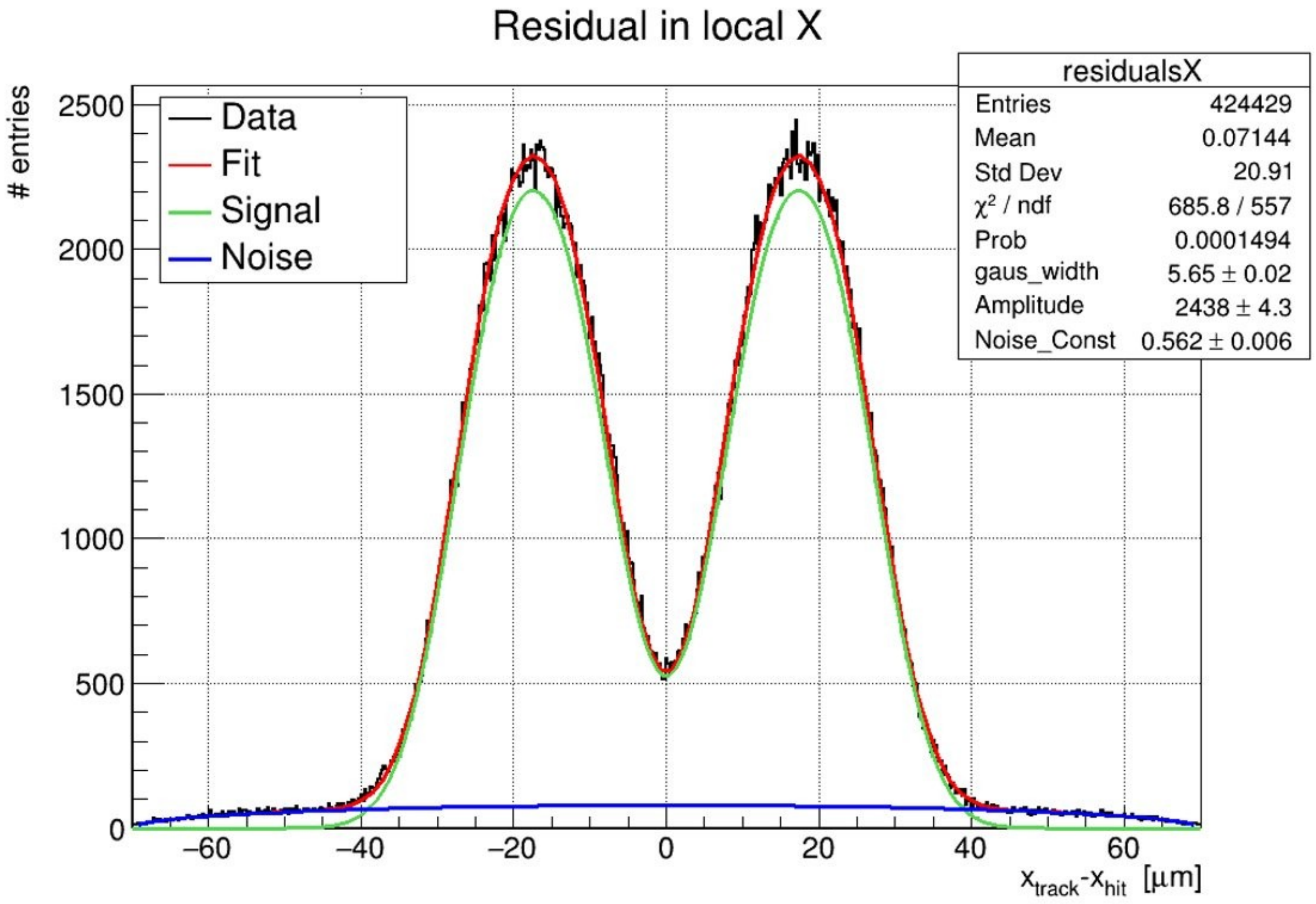
- Analysis using Corryvreckan
  - Reconstruct tracks using the beam telescope
  - Associate hits on DUT using spatial cuts
  - $E = N_{assoc} / N_{reco}$
- In-pixel efficiency
  - Inefficient outside of SPAD region
  - Smearing due to track resolution (larger than expected)
- Over all efficiency – determined by fill factor
  - About 30 %, corrected for dead time and fake hit contributions
  - Small voltage dependence above breakdown observed



Spatial Resolution

Determined by Pixel Size

- Difference between reconstructed hit and interpolated track position $\Delta x = x_{track} - x_{hit}$
- Double peak feature due to in-efficient region between SPADs (remember previous slide!)
  - Added Corryvreackan feature: Define arbitrary fit function for DUT alignment MR
- Unavoidable contribution from dark counts (circular background distribution)
- Signal described by double box convolved with Gaussian
- Does the track resolution explain the width of the Gaussian?
- Achieve spatial resolution on the order of 20 um

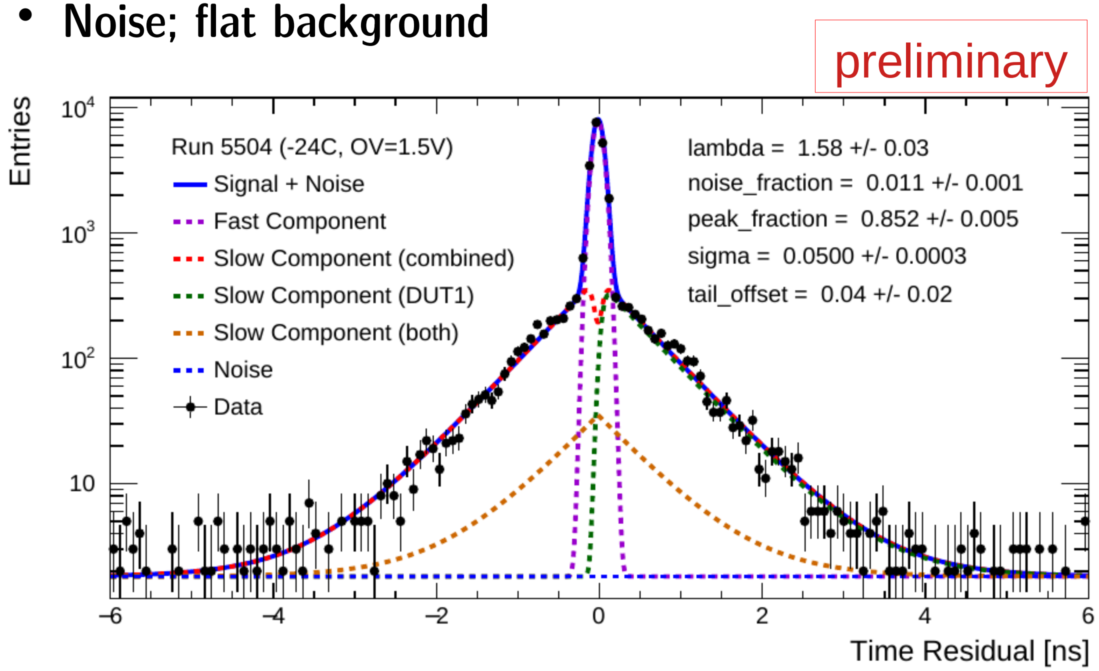


Time Residuals

Measuring the Time Resolution

Time residual between two dSiPMs $\Delta t = t_{DUT1} - t_{DUT2}$

- Each of them contributes 3 cases
  - Fast signal; Gaussian with width between 35 and 55 ps
  - Slow signal; exponential tail (about 15 %)
  - Noise; flat background

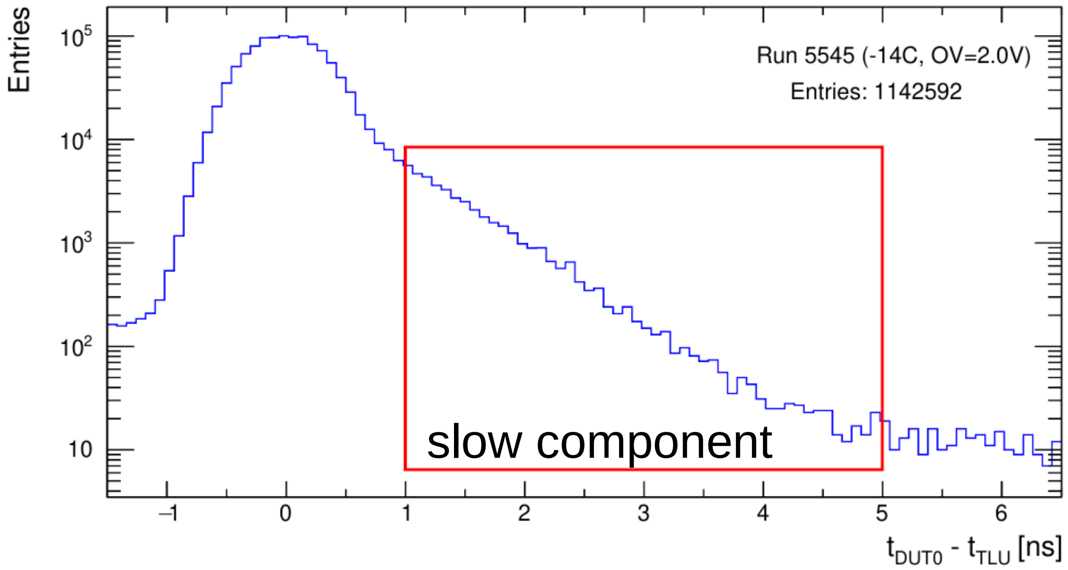


Time Residuals

Measuring the Time Resolution

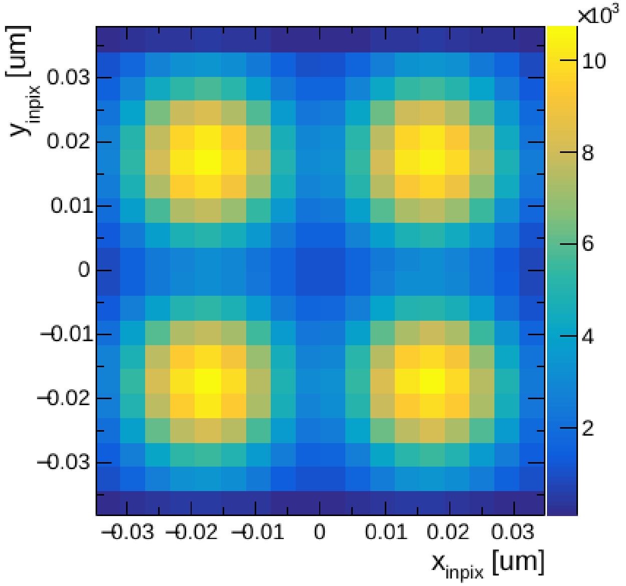
Time residual between dSiPM and ref. $\Delta t = t_{DUT0} - t_{TLU}$

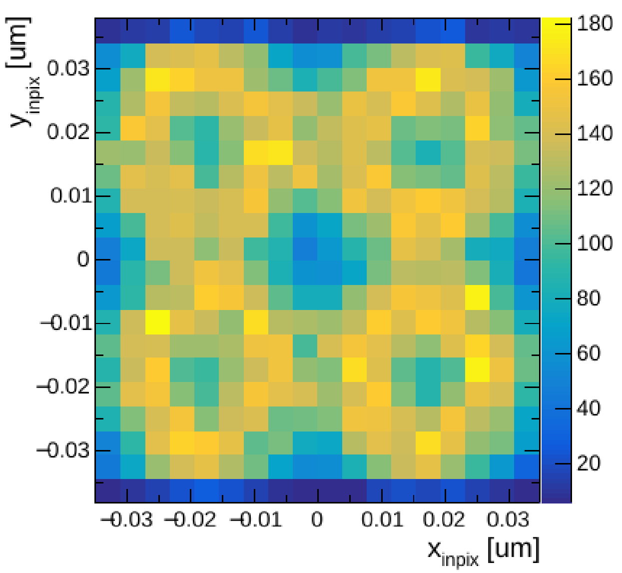
- Fast signal; dominated by time reference
  - Trigger scintillator + TDC in AIDA TLU
- Slow signal; slow DUT response



Origin of the tails

- Left: Intercepts of tracks with associated hits
- Right: same, but only for slow component
- Slow response associated to SPAD edges
- Also visible in laser measurements





MIP Timing

Timing Plane Application

- Spatial and temporal resolution are promising
- Hit detection efficiency too low
  - 30 % fill factor probably not practical
- Fill factor can be optimized but will always be limited
- F. Carnesecchi, et al. increased MIP detection efficiency of SiPMs due to Cherenkov effect in encapsulation
  - We started studies in that direction!
    - Keep spatial resolution on the order of pitch
    - First photon counts → suppress tails in timing
    - How much will the efficiency increase?
    - How much will it cost in material budget?

Example: encapsulated Hamamatsu SiPMs

Summary

Yes, like a pixel detector!

Introduced a digital silicon photomultiplier produced in an LFoundry‘s 150-nm CMOS process

Test-beam characterization

- Hit detection efficiency (MIPs): > 30 %
- Spatial hit resolution (MIPs): ~ 20 um
- Temporal resolution (MIPs): ~ 50 ps

Submitted first paper on circuit design and laboratory characterization (already available on ArXiv)

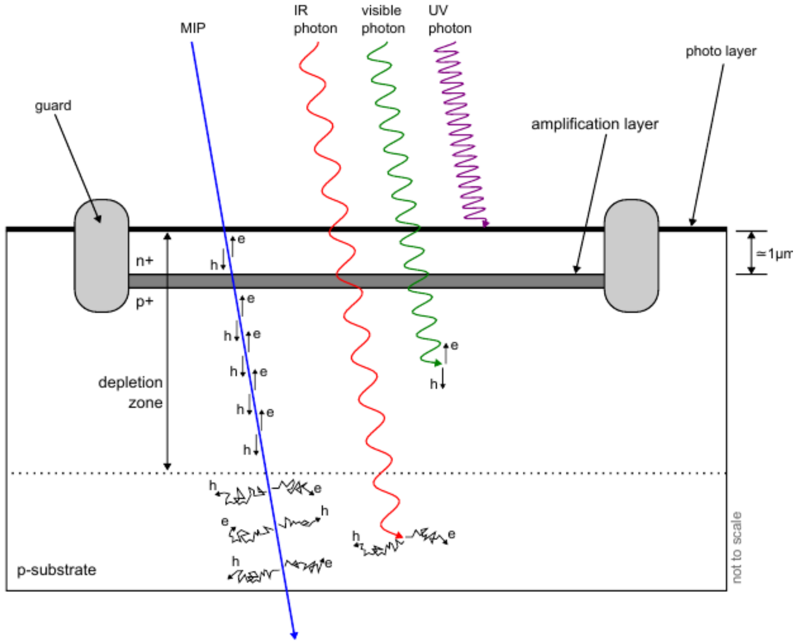
We are eager to test dSiPM + radiator in the beam!

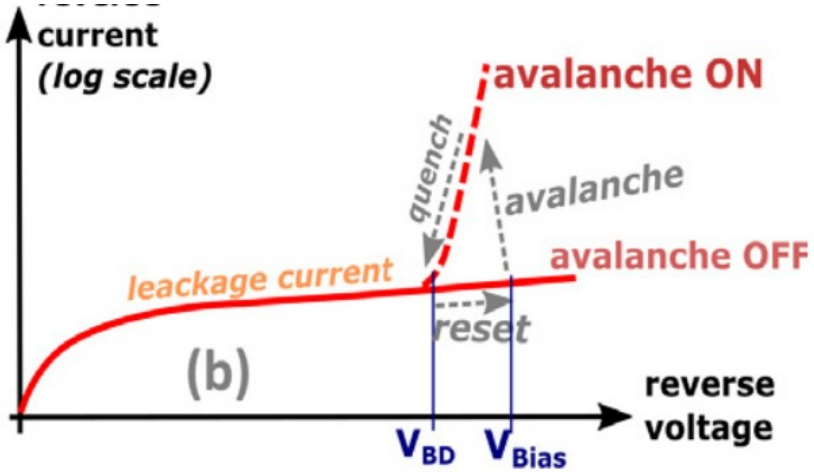

dSiPM

A Single Photon Avalanche Diode

Basic Building Block of a SiPM

- Strong doping gradient generates strong filed → Geiger mode amplification
- Quenching of discharge by lowering the bias voltage (quenching resistor)
- Gain on the order of 10^5 to 10^6 → counting device sensitive to single photons
- Photon interactions (optical energy range)
  - Exciting single electron from to conduction band
  - Penetration depth between 0.1 um (blue) and 10 (red) um
- Photon detection efficiency: fill factor x quantum efficiency x breakdown probability
- Electron interactions (GeV energy range, close to minimum)
  - 50 to 100 electron-hole pairs per micrometer
  - Deposition along electron trajectory



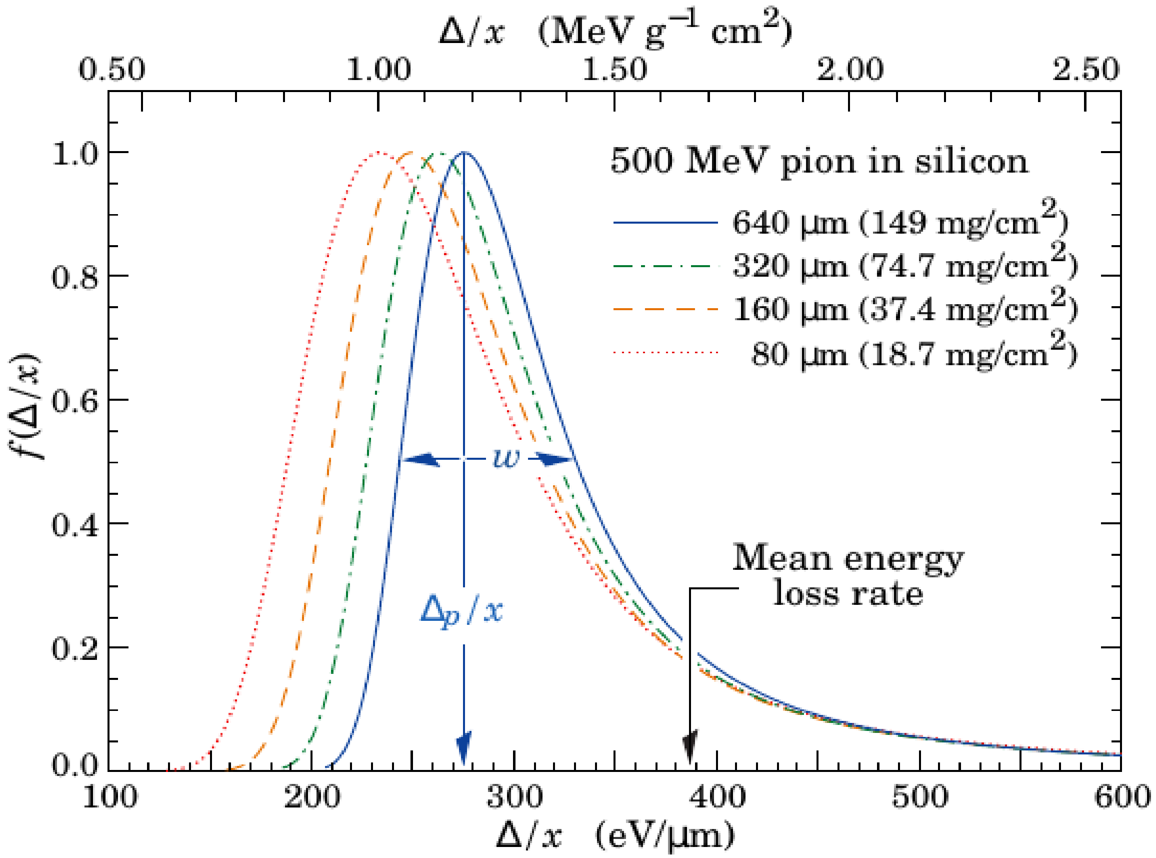


[F. Acerbi and S. Gundacker]

Charged Particles

And Their Interaction with ~~Matter~~ Silicon

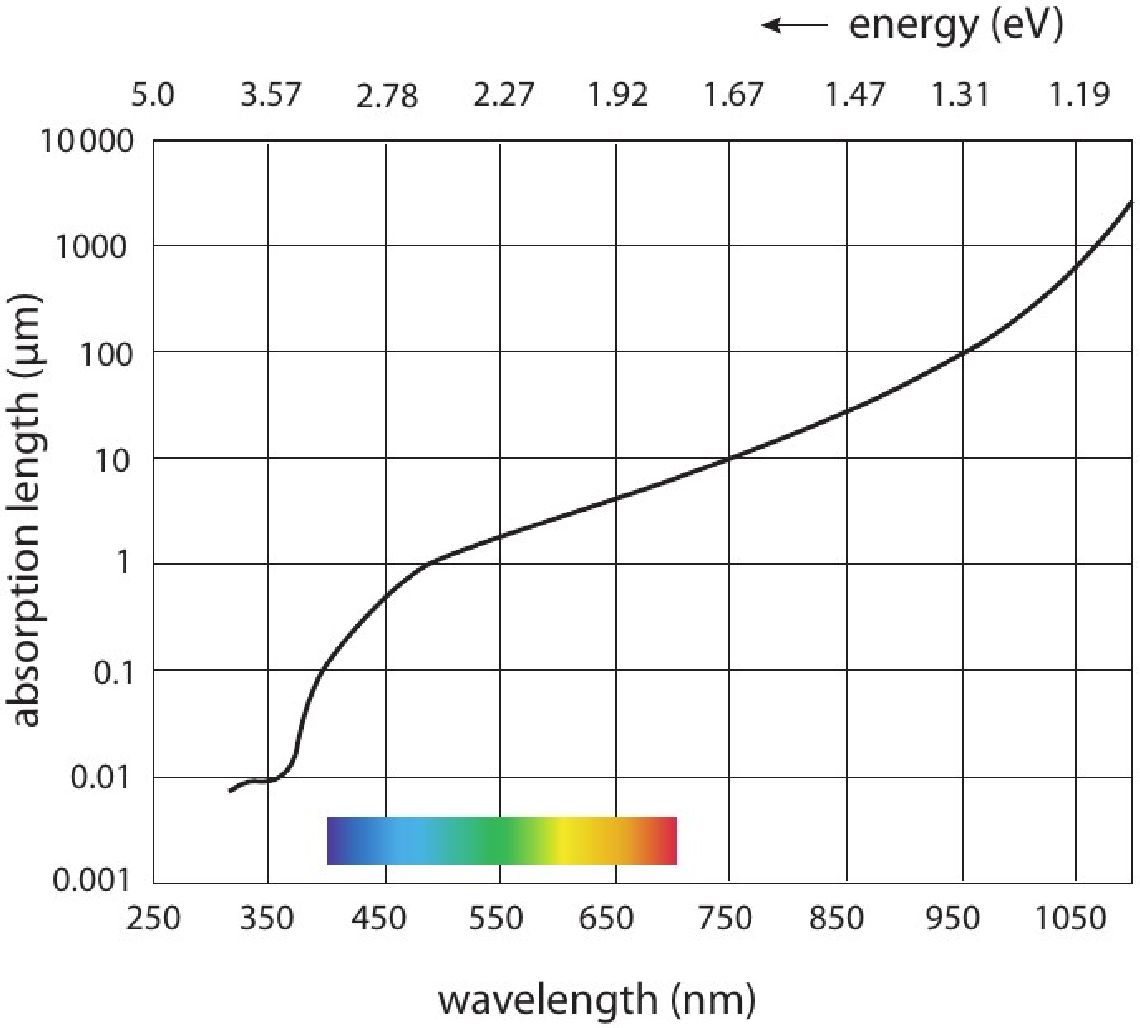
- Electrons (GeV energy range, close to minimum)
  - Energy loss dominated by ionization and excitation
  - Radiative losses below 1 %, limited contribution to signal in thin Silicon detectors
  - Straggling functions are highly skewed due to rare large energy depositions
  - Mean ionization energy 3.67 eV per electron-hole pair
  - Signal on the order of 50 to 100 electron-hole pairs micrometer (depends on material thickens)
  - Deposition along electron trajectory
- Similar for other charged particles around energy loss minimum (MIPs)



Optical Photons

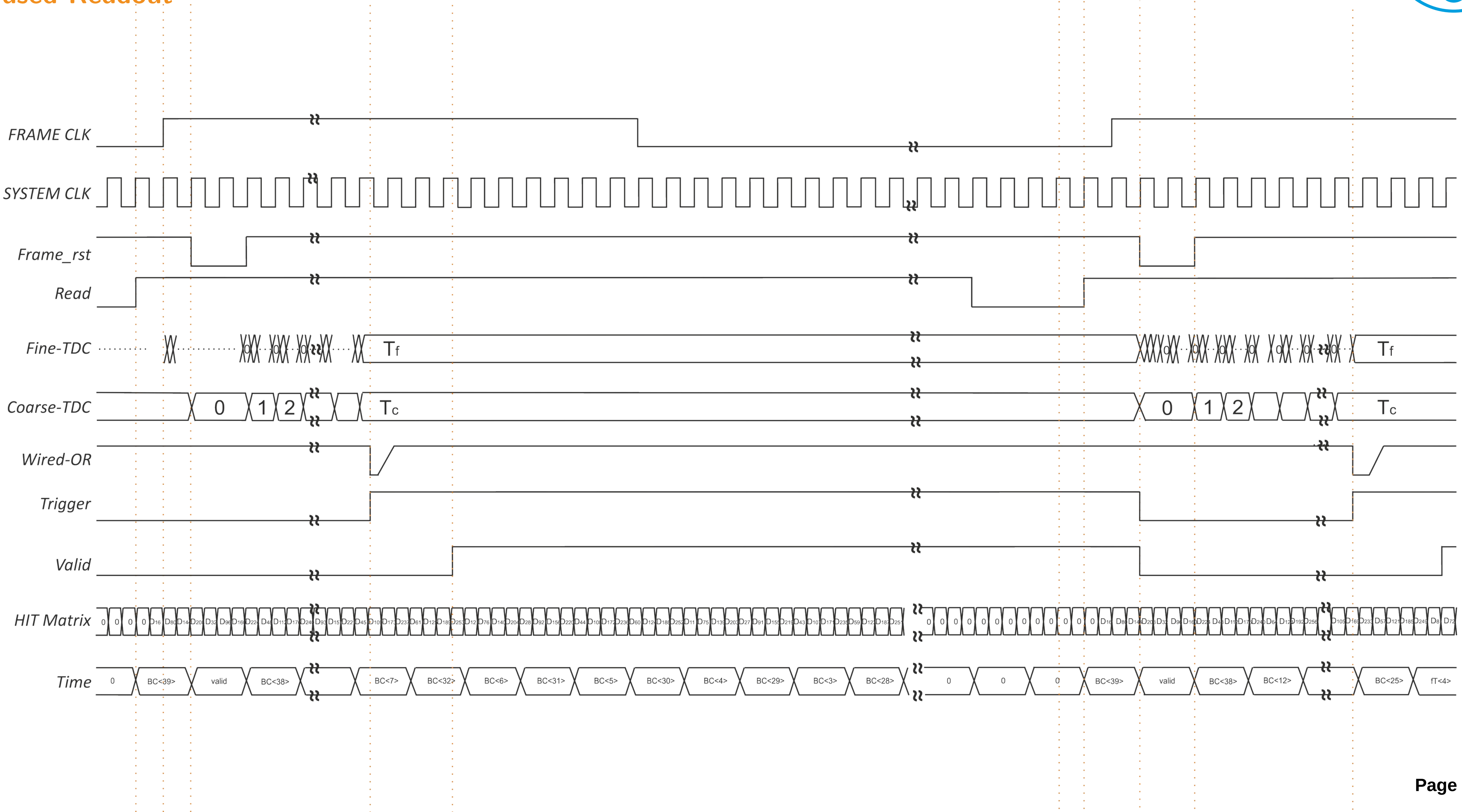
And Their Interaction with ~~Matter~~ Silicon

- Photons (optical energy range)
  - Internal photo effect: dominant contribution from 1 eV to several 10 keV [cw]
  - Exciting 1 electron from valance to conduction band
  - Minimal energy (band-gap) 1.12 eV, corresponding wavelength 1100 nm (UV)
  - Indirect band-gap transition requires phonon interaction
    - Strong rise in absorption probability to 3.4 eV
    - Temperature dependence
  - Penetration depth between 0.1 and 10 um



Timing Diagram

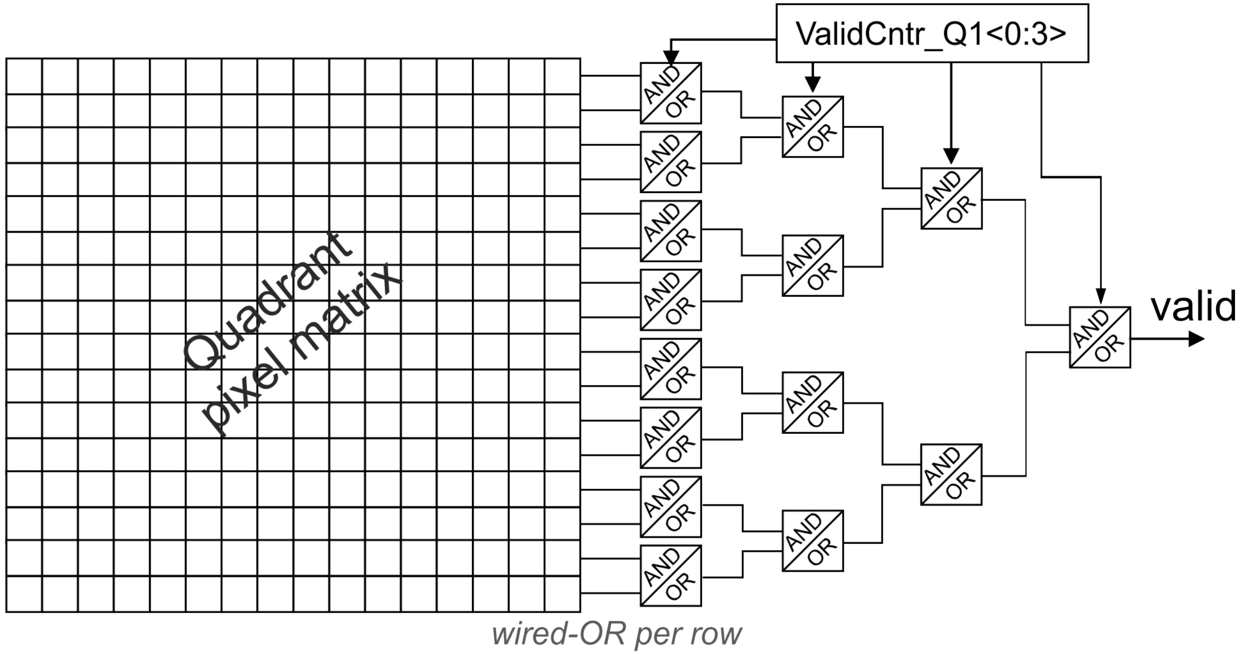
Frame Based Readout



Validation Logic

Suppressing Noise

- Implemented for each quadrant separately
- Hit within a row generates „true“ for said row
- Cascade of AND/ OR operations between rows
- Allows to select certain hit patterns
    - E.g. *at least 1 hit in each row*
    - Or *at least 1 hit per row in a pair of rows*
- Helps to discard noise hits if certain signal patterns are expected

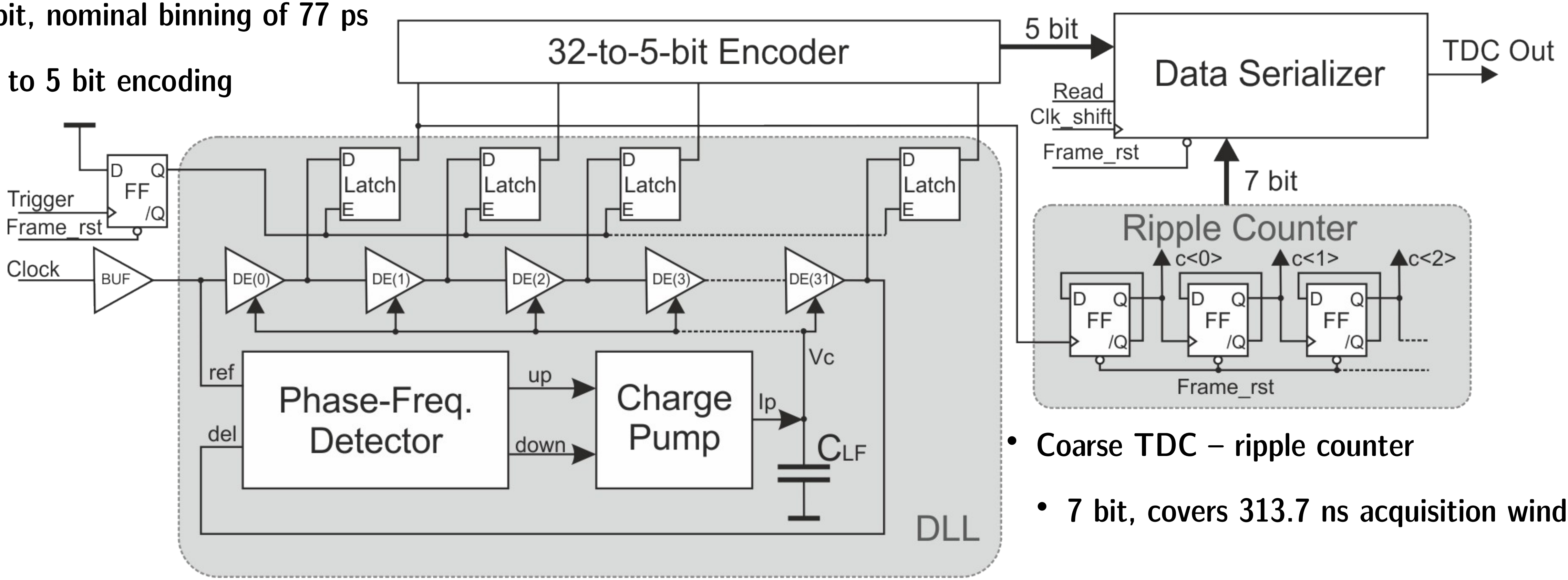


TDCs

Time Digital Converters

- Fine TDC – taped delay line with delay locked loop
  - 32 delay elements
  - 5 bit, nominal binning of 77 ps
  - 32 to 5 bit encoding

- Frame clock 3 MHz defines readout frames 333 ns
- System clock 408 MHz used in coarse and fine TDC



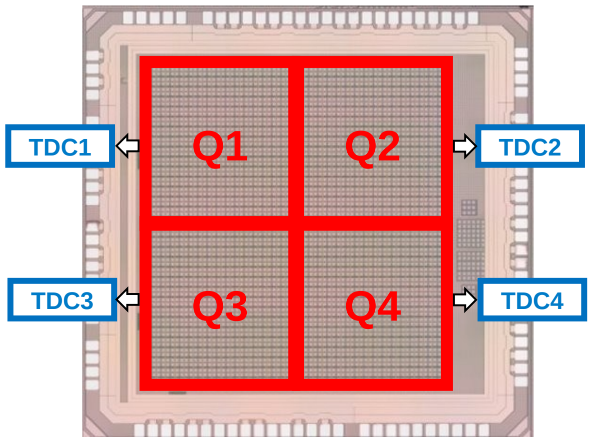
- Coarse TDC – ripple counter
  - 7 bit, covers 313.7 ns acquisition window

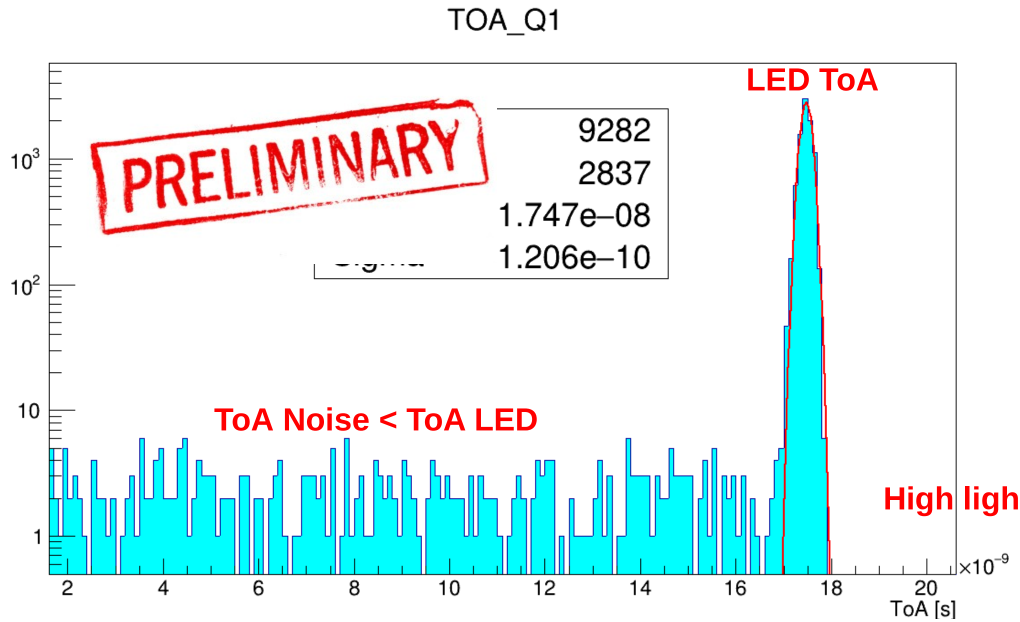
First Timing studies with LED

Preliminary Results

Timing performance

- From Preliminary LED studies
- TR of the whole system reported
- Quadrant TOA: σ ~120 ps
- Time differences bw Quadrants: σ ~160 ps
- No correction for propagation delays

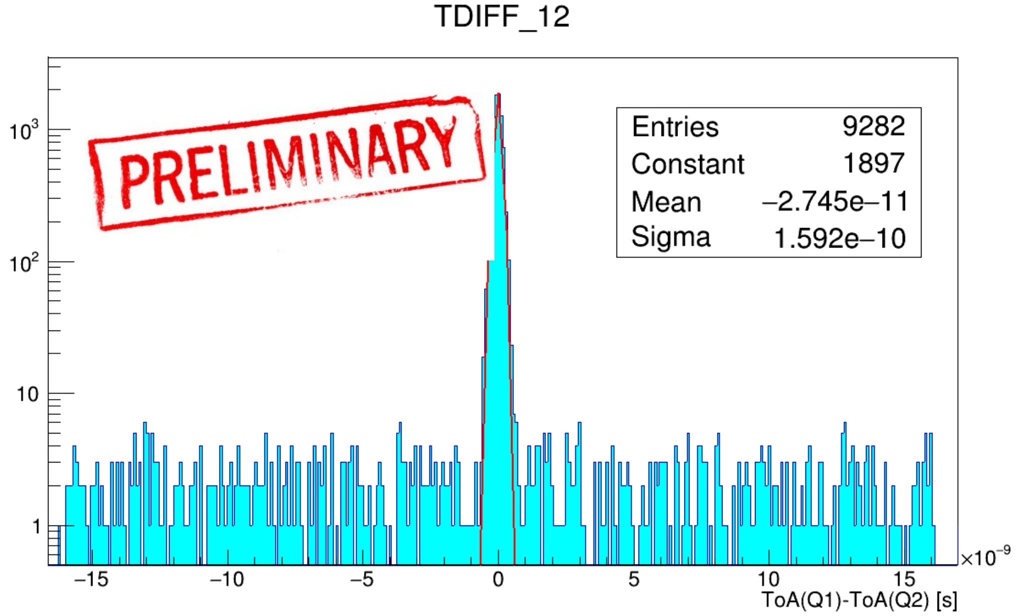




LED ToA

ToA Noise < ToA LED

High light effect

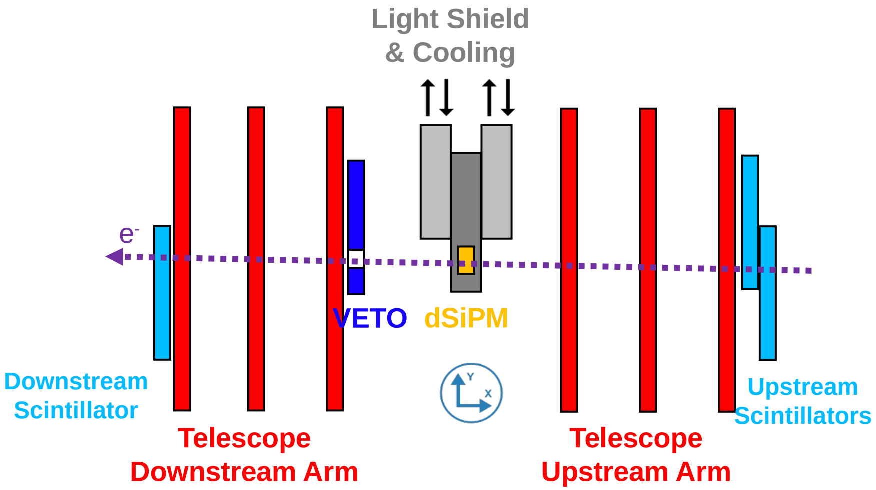


Our Setup

The First Shot

Setup in May 2022 – proof of concept, integration test

- Triggering using 3 scintillators in coincidence
  - 4th scintillator with hole vetoes tracks out of acceptance
- Track time resolution O(1ns) (scintillator + TLU TDC)
- Estimated track resolution around 5 um
- Temperature stabilization ~ 25° C (no cold box)



Light Shield & Cooling

e^-

VETO

dSiPM

Y

x

Downstream Scintillator

Telescope Downstream Arm

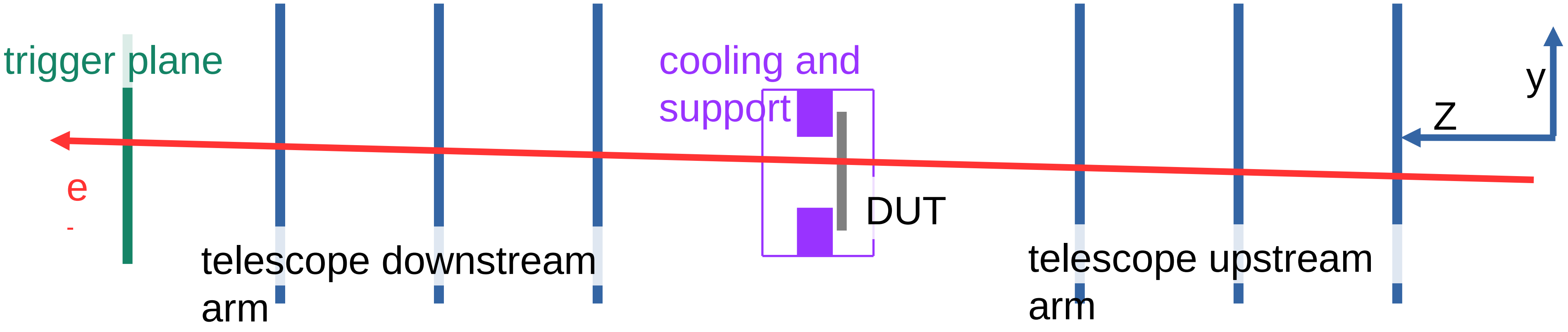
Telescope Upstream Arm

Upstream Scintillators

May 2022

Beam Test – Introduction

Test Bench for Particle Detectors – The Tracking Detector Case



Components

- Beam (DESY II 5 GeV, SPS, MAMI;)
- Tracking system, 6 planes of pixel detectors
- E.g. scintillators for timing and triggering
- Device Under Test

Goals

- Prove/ test integration of prototypes
- Performance characterization
  - Detection efficiency
  - Resolution in space, time, (energy)

Reconstruct individual charged particles – time and position information

Alignment

Material Budget Imaging

DUT- Trigger Alignment With High Dark Count Rate

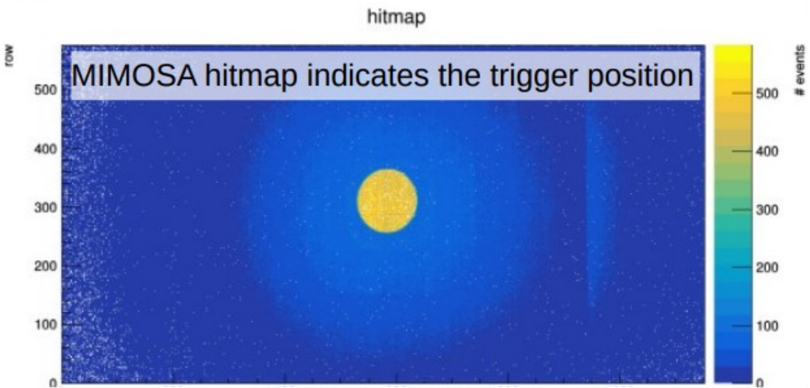
- DCR/MIP event distinction impossible before alignment
- dSiPM too noisy to use self trigger

Material Budget Imaging (MBI)

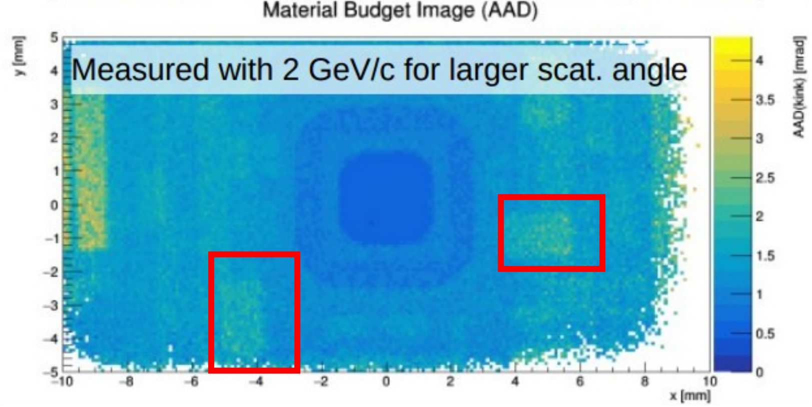
- Amount of scattering is proportional to the thickness of the scattering medium in radiation lengths
- Plot width of scattering angle distribution in DUT-plane

Evaluation of MB using Corryvreckan

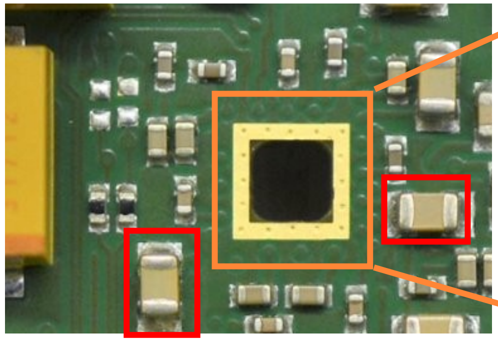
- Maximize multiple Coulomb scattering
- Use the straight line approximation for tracks in the two arms of the beam telescope (TrackingMultiplet)
- Material budget image obtained in global coordinates



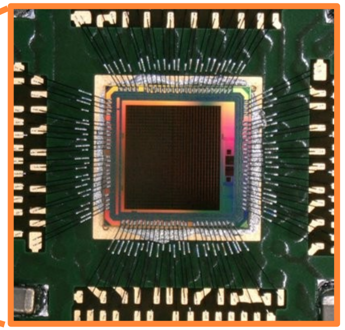
MIMOSA hitmap indicates the trigger position



Measured with 2 GeV/c for larger scat. angle



Chipboard (back)



Chip glued & bonded (front)

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