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# A novel LGAD design with continuous gain layer: MARTHA

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# FCC-ee Requirements for LGADs

## Operational Context:

- Lepton Collider: No pile-up & and radiation damage issue compared to the LHC environment
- Driven by physics performance: Timing significantly improves Particle Identification

## Integration Possibilities:

- One option: Replace at least one tracking layer by a precise timing layer
  - Requires 100 % fill-factor and granularity comparable to the tracker resolution 30 μm
  - Minimum material budget

## Performance Requirements vs. Tech Status:

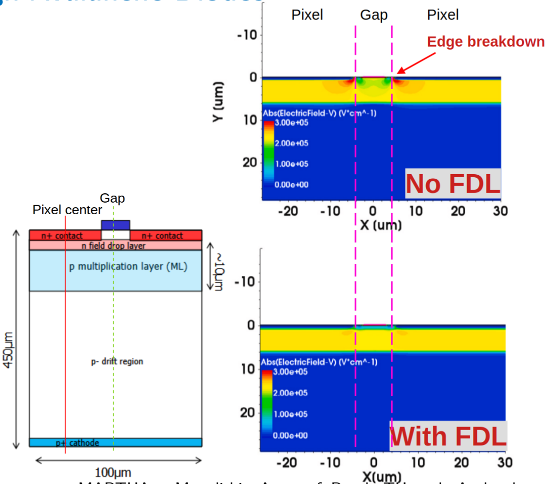
- Target Timing Performance: 20 ps to 40 ps time resolution
  - Easily achievable by most standard LGAD designs
- Fill-Factor:
  - Standard LGADs: Efficiency $<$100 %, no gain in gap regions, pitch $>$500 μm

# The MARTHA Concept

## MARTHA - Monolithic Array of Reach THrough Avalanche Diodes

- LGAD design optimized for photon science
  - Timing behaviour not optimized
- Continuous multiplication layer (ML)
  - Enables inter-pixel detection of particles
- n-doped field drop layer (FDL)
  - Prevents edge breakdown
- MOS-Structure to separate pixels
  - Highly convenient for prototypes
  - Will be replaced by shallow implant in future generations

**This design offers 100 % fill-factor**

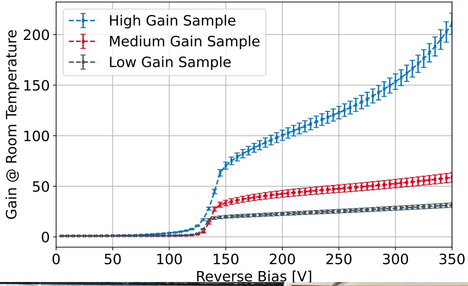



MARTHA - Monolithic Array of Reach THrough Avalanche photo diodes - R.H. Richter et al.

# Structures

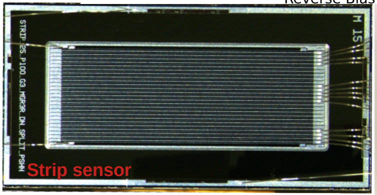
## MARTHA was designed and produced at Semiconductor Laboratory of the Max Planck Society

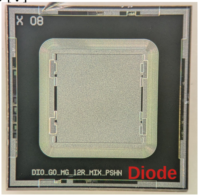
- First structures 450 µm thick
  - Driven by photon science applications
- Three different gain options (Low, Medium, High)
- Various test structures on the wafer
  - **Strips, Diodes, Pixel Sensors**




## This presentation:

- MIP efficiency studies on strip sensors
  - Strip sensors: 100 µm pitch
- MIP timing resolution studies on diodes
  - Diodes



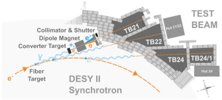



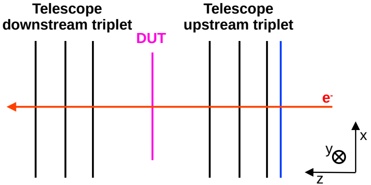
# Efficiency Studies with Strip Sensors

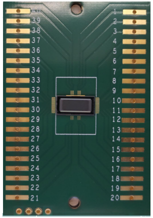
# Test Beam Setup

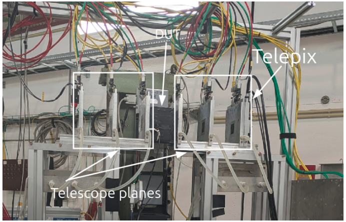
## Overview:

- DESY II Test beam line 24 @ 5 GeV (electrons)
- **Tracking:** Beam telescope, MIMOSA26 planes ($t_{\text{int}} = 115\,\mu s$)
- **Trigger:** TelePix2 (Pitch: $165\,\mu m \times 25\,\mu m$)
- **DUT:** MARTHA strip sensor (Pitch: $100\,\mu m$ Gap: $3\,\mu m$)
  - Low gain sample: Bias: $-350\,V$, MOS: $-14\,V$
  - Three strips are read out
  - Neighbouring strips grounded
  - Custom readout boards
  - Custom EUDAQ2 Producer
  - Amplifier: Cividec, 40 dB amplification
  - CAEN DT5742 digitizer, 500 MHz
    5 GS/s, 16+1 trigger channels



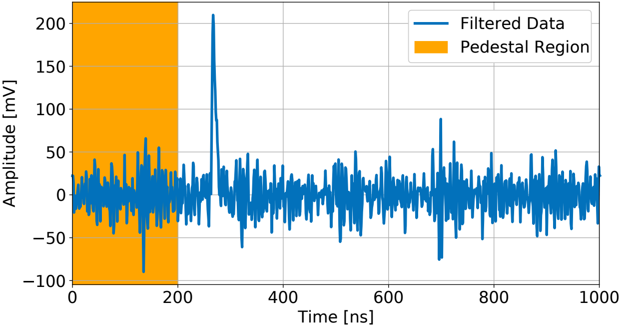



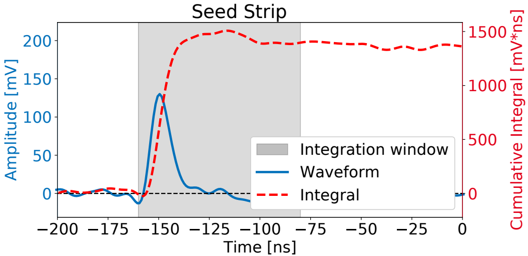



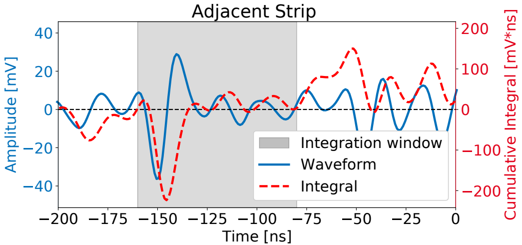


# Waveforms

- Signal interpretation challenging due to noise
  - 80 MHz low-pass filter on middle strip
  - Software filtering for edge strips
- Baseline subtraction on first 200 ns
- Charge estimation via waveform integration

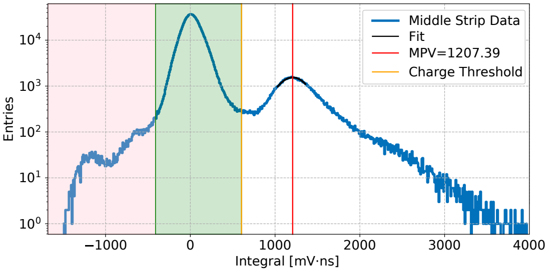


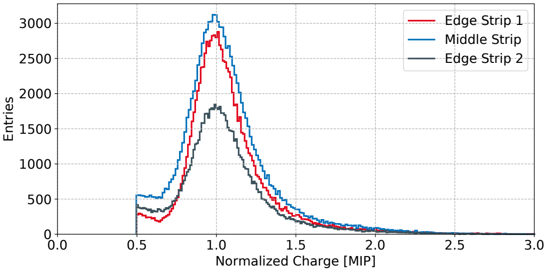



# Strip Charge

- Amplifier gain varies between used amplifiers
- Charge normalized to MIP (MPV of the distribution)
- Initial charge cut at 0.5 MIP
  - Prevents noise association during alignment
  - Threshold can be lowered for subsequent steps



# Cluster Size

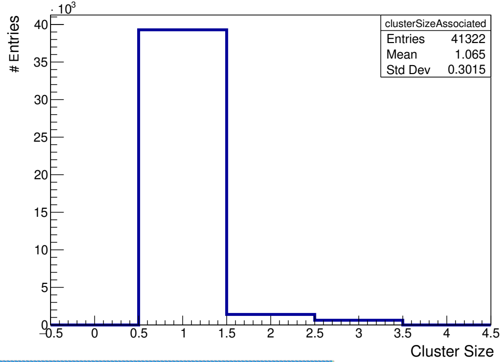
- Dominated by cluster size 1 due to perpendicular incidence

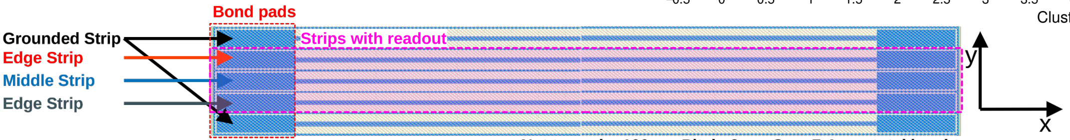
**Central Strip:**

- Only channel capable of recording cluster size 3 both direct neighbours are read out

**Outer Strips:**

- Geometrically capped at cluster size 2 due to missing adjacent readout channels
- Incomplete clusters on outer strips lead to systematically lower reconstructed cluster charge



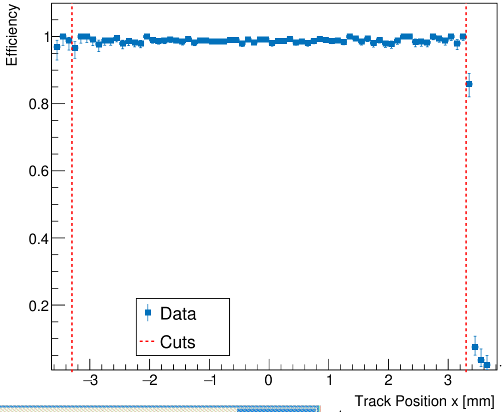



Not to scale: 100 µm Pitch, 3 µm Gap, 7.4 mm total lenght

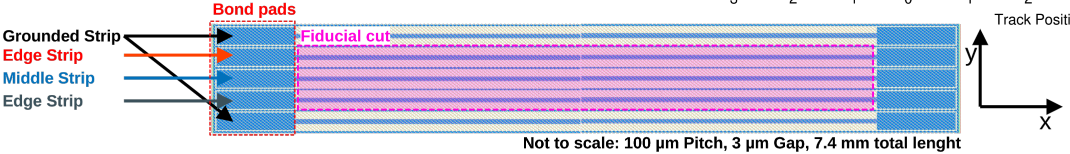
# Fiducial Cut

## Efficiency is defined as:

$$\epsilon_{\text{hit}} = \frac{N_{\text{Track}}^{\text{DUT}}}{N_{\text{Track}}}$$

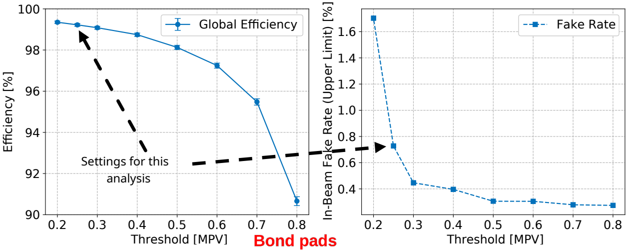



- Symmetric cut in $x$ to exclude bond pad region
  - Efficiency drop is visible only on one edge due to a global alignment ambiguity
- Symmetric 10 µm cut in $y$
  - Prevents artificial efficiency loss due to charge sharing with unread strips

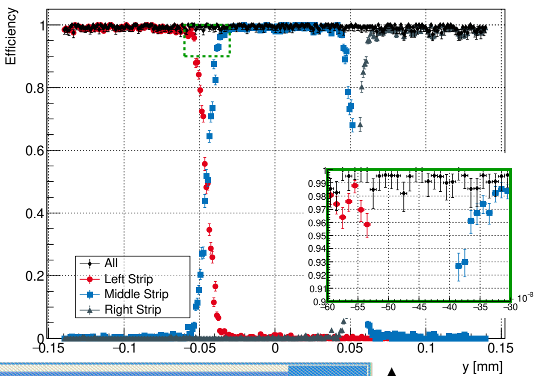


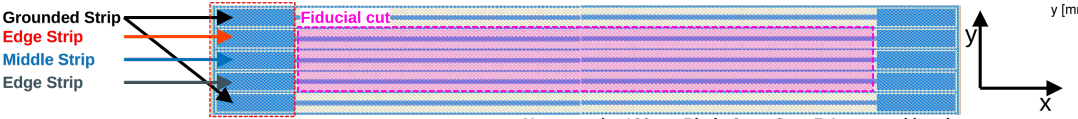
# Efficiency Results

- Global efficiency: 99.22(4) %
- No loss of efficiency in the gap regions




−350 V, −14 V MOS, 0.25 MPV Threshold

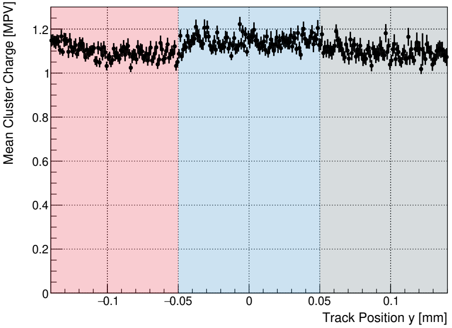


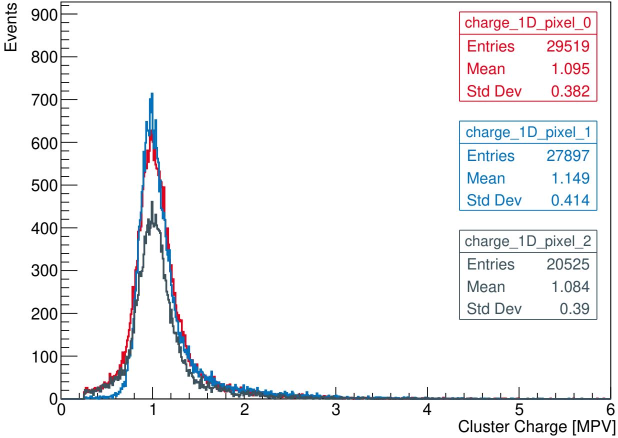




**Not to scale: 100 µm Pitch, 3 µm Gap, 7.4 mm total lenght**

# Charge

- Low-charge tail for edge strips
  - Adjacent strip information is missing
- Slight drop in charge for edge strips
- Charge is homogenous over strips



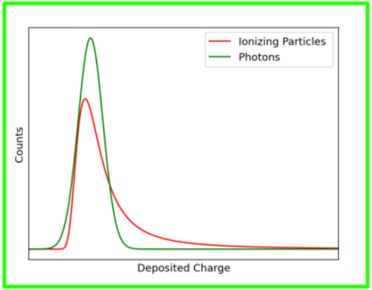
# Timing Resolution Studies on Diodes

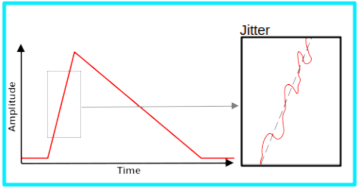
# LGAD Timing Resolution

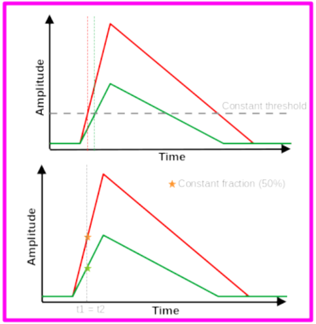
## What affects LGAD timing resolution?

$$\sigma^2_{LGAD} = \boxed{\sigma^2_{Landau}} + \boxed{\sigma^2_{Jitter}} + \boxed{\sigma^2_{Timewalk}}$$

$\approx t_{Rise}/SNR$



# Test Beam Setup



## Goal:

- Determine MIP timing resolution

## Readout:

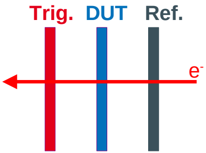
- Amplifier: Cividec, 40 dB amplification
- CAEN DT5742 digitizer - 5 GS/s

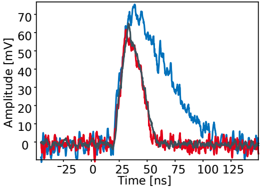
## Beam energy: 3 GeV

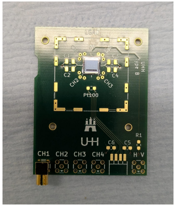
## Data taking:

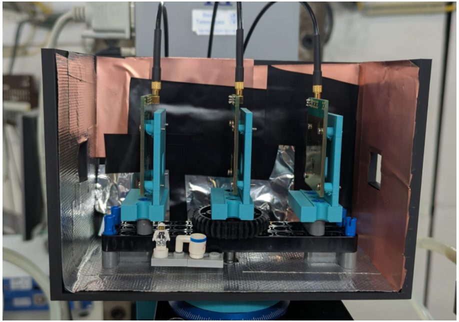
- Fixed threshold on trigger
- Fixed bias on trigger and reference
- Bias scan −200 V to −350 V on DUT in 25 V steps

## Data selection: Coincidence of three



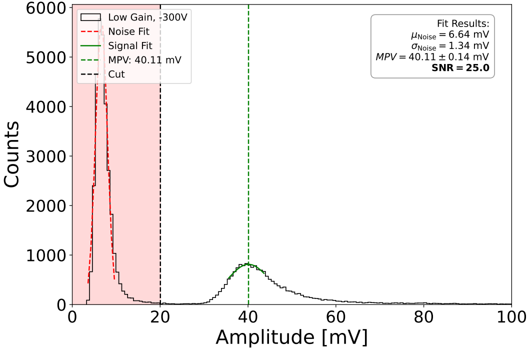



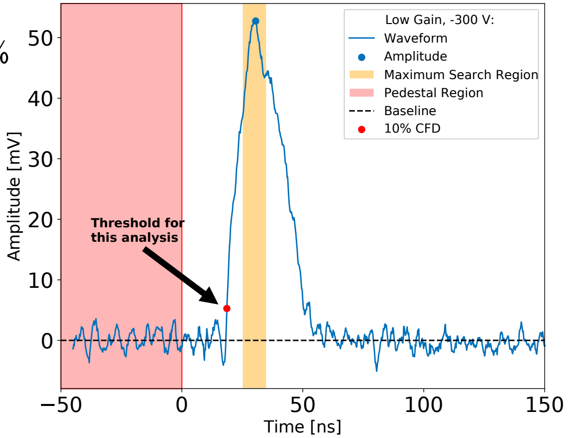



# Waveform Analysis Overview

- Pedestal region to subtract offset
- Amplitude cut at 50 % MPV
- Threshold crossings estimated by software constant fraction discrimination @ 10 %



# Determining Timing Resolution

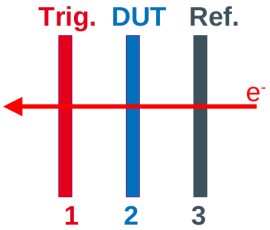
## Considering a system of three LGADs:

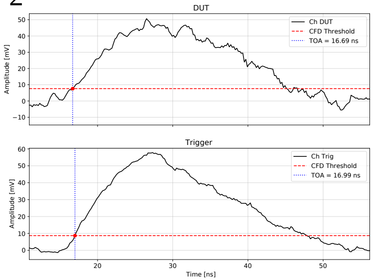
- The time residual of one set of LGADs is given by:

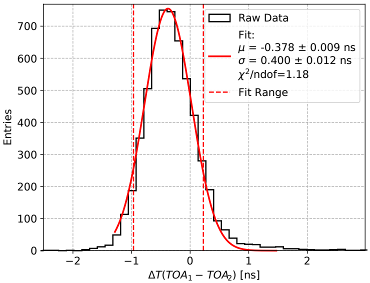
$$\sigma_{2,3}^2 = \sigma_2^2 + \sigma_3^2$$

- By analysing a system of three LGADs this can be separated:

$$\sigma_2^2 = \frac{1}{2}(\sigma_{2,3}^2 + \sigma_{2,1}^2 - \sigma_{3,1}^2)$$



# Timing Resolution

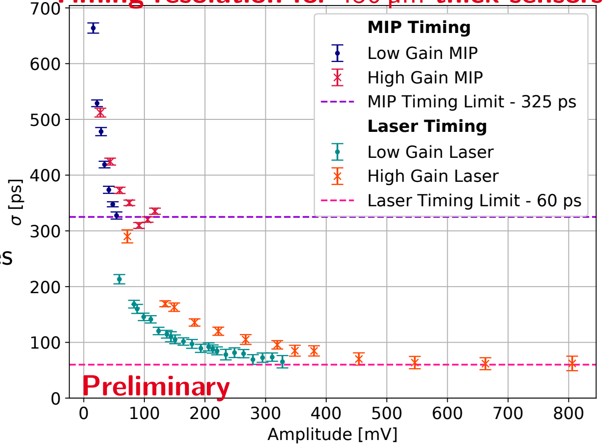
## MIP Timing Results:

- Both samples reach ≈325 ps
  - Within expectations for 450 µm thick sensors
  - Limited by Landau fluctuations

## Laser (1060 nm) Timing Results:

- Both samples reach ≈60 ps
  - Absence of Landau fluctuations isolates the limits set by jitter and sensor geometry

**Timing resolution for 450 µm thick sensors**

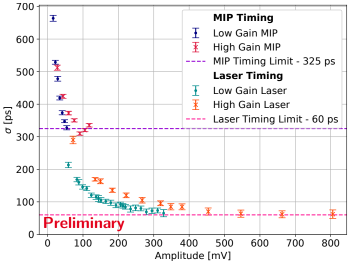


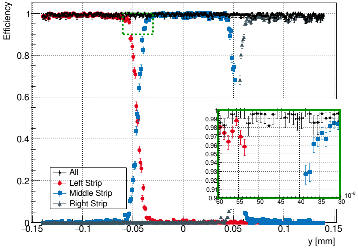
# Summary

- MARTHA is a new LGAD concept featuring a **continuos gain layer**
- Current samples are optimized for photon science on 450 μm substrate
- Global efficiency of 99.22(4) % has been achieved
  - No loss of efficiency was observed in gap region
- MIP timing resolutions of ≈ 325 ps have been achieved
  - Laser timing resolutions ≈ 60 ps

## Towards FCC-ee Requirements:

- **Tracking ready:** High fill factor possible @ 100 μm pitch
- **Next step:** Thinning the substrate to ∼ 50 μm to reach target timing performance ∼ 30 ps



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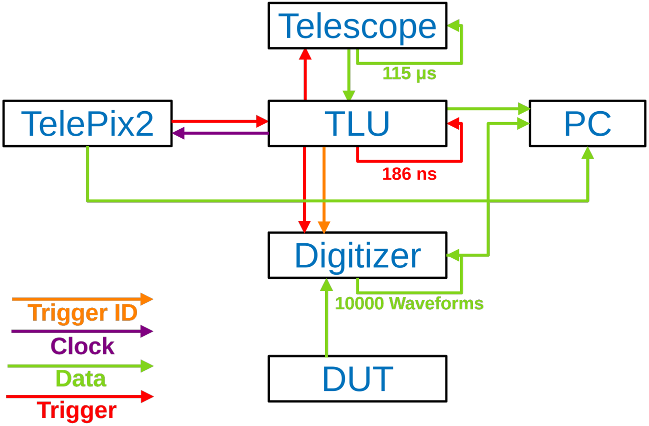
# Backup

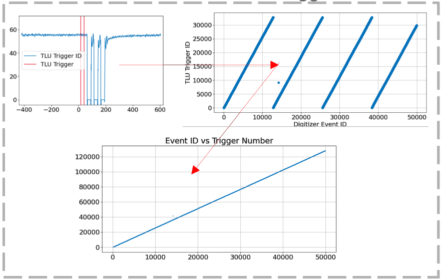
# Data Acquisition

## Online data acquisition



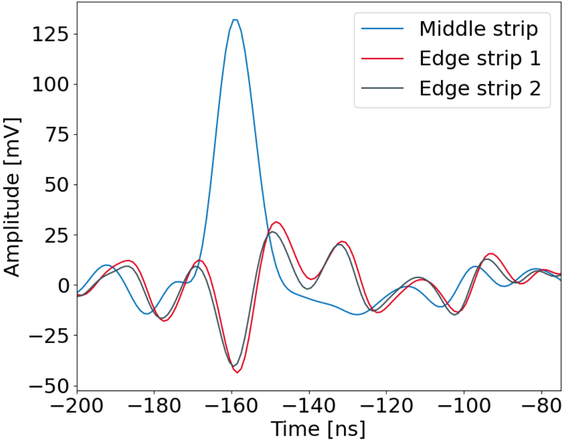

## Offline event matching

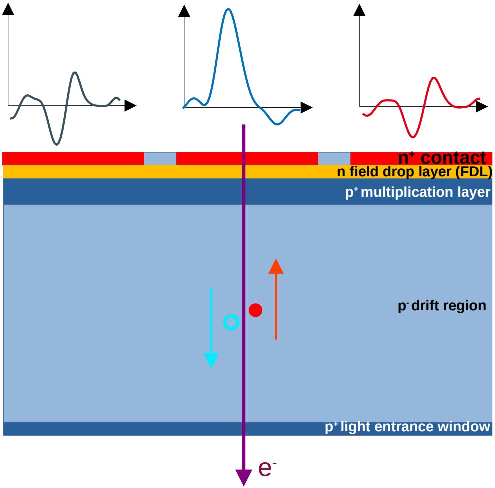
**From raw waveforms to TriggerIDs:**




Data analysis performed with Corryvreckan

# Waveforms


Middle strip
Edge strip 1
Edge strip 2
125
100
75
50
25
0
−25
−50
−200
−180
−160
−140
−120
−100
−80
Amplitude [mV]
Time [ns]


n+ contact
n field drop layer (FDL)
p+ multiplication layer
p- drift region
p+ light entrance window
e-

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# Gain Measurements

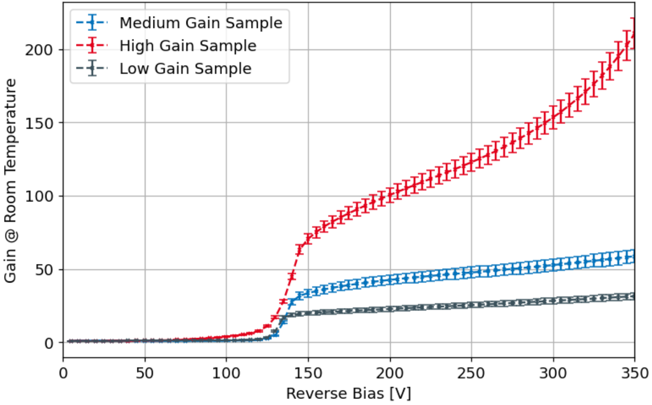
## Goal: Determine homogeneity of the .

- Multiple diodes over different wafers
- Gain is determined from IV-Curves

**Photocurrents:** $I_{\mathrm{Photo}} = I_{\mathrm{Light}} - I_{\mathrm{Dark}}$

**Gain:** $\mathrm{Gain} = I_{\mathrm{Photo}} / \overline{I}_{\mathrm{Photo},\,[20\text{–}90\,\mathrm{V}]}$

- MARTHA LGADs show substantially higher gain than other LGADs
- 20 - 100 @200 V

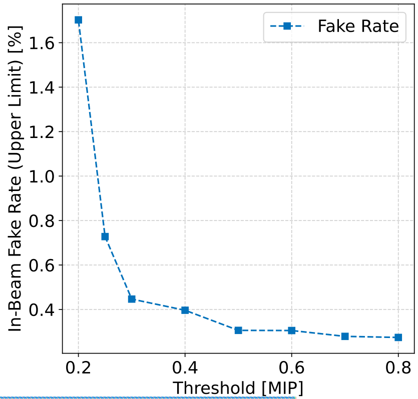


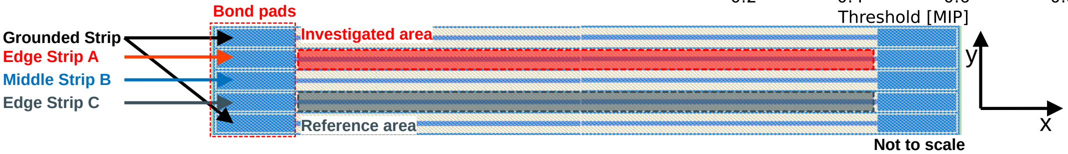
# In-Beam Fake Rate (Upper Limit)

## In-Beam Fake Rate (Upper Limit):

$$P_{Fake} = \frac{N^{Strip\ A}_{Track\ \ B+Hit\ \ A+Hit\ \ B}}{N^{Strip\ \ B}_{Track\ \ B+Hit\ \ B}}$$

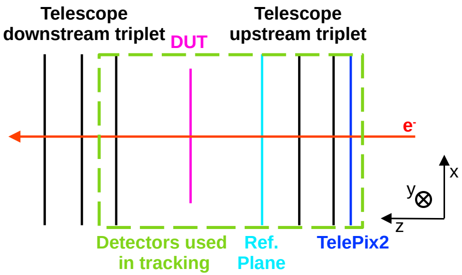
- Active-beam conditions: secondaries, $\delta$-electrons, beam background + electronic noise
- True electronic fake rate under beam conditions is below this estimate

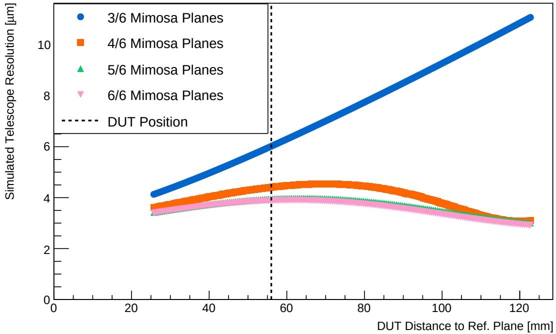


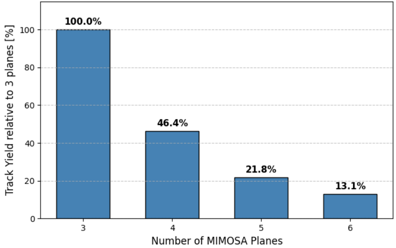



# Tracking

- Track reconstruction: General Broken Lines
- 4/6 telescope planes + TelePix2 (timing ref)
  - Best compromise (track yield vs. resolution)
- DUT associated in additional analysis step



# Amplitudes and Noise

- Medium gain sample excluded based on unstable amplitude behaviour
- SNR $\approx$ 13-26 for low gain sample - SNR $>$ 20 for high gain sample