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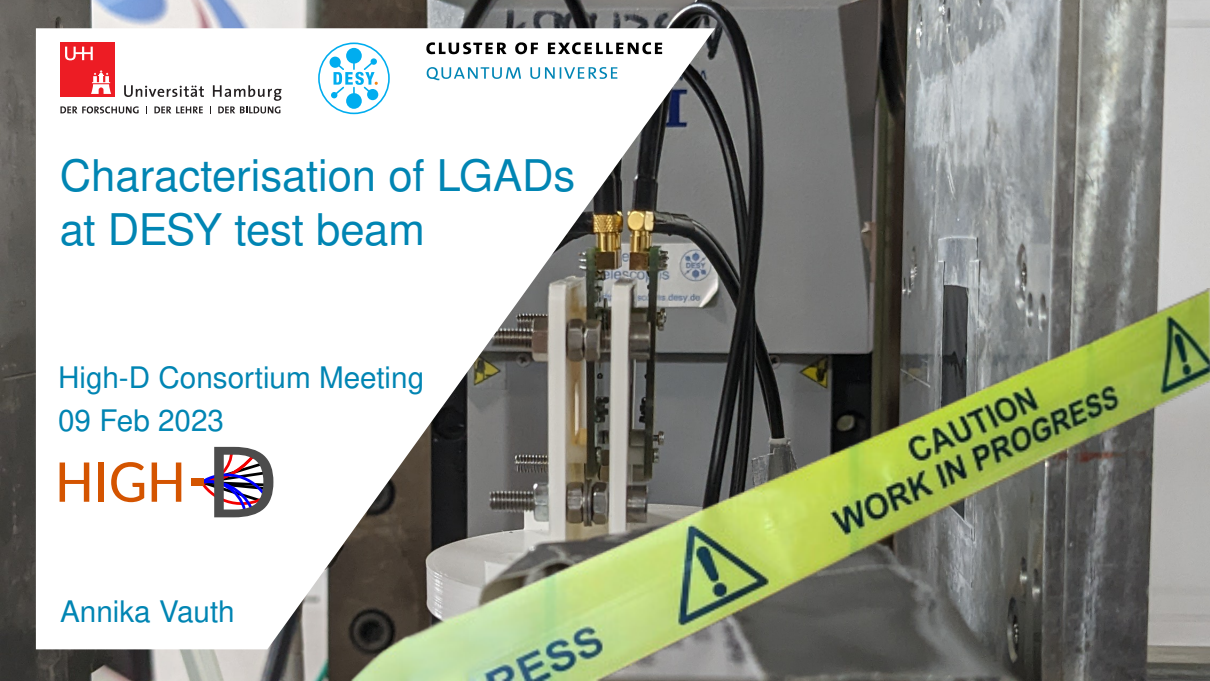
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Characterisation of LGADs at DESY test beam

High-D Consortium Meeting
09 Feb 2023

HIGH-D

Annika Vauth



LGAD projects: Timing layer

HEP detector R&D: dedicated beam tests for
conceptual / technical design, calibrations, commissioning, ...

→ DESY II Testbeam Faciliy

Integral part of test beam infrastructure: Beam Telescopes
Current EUDET-type telescopes:
Six planes of MIMOSA26 sensors
Intrinsic sensor resolution: $\sigma \cong 3\,\mu m$

Rolling shutter readout, readout cycle 115 µs

Add faster device for time stamping the tracks
→ LGAD timing layer

First LGAD samples

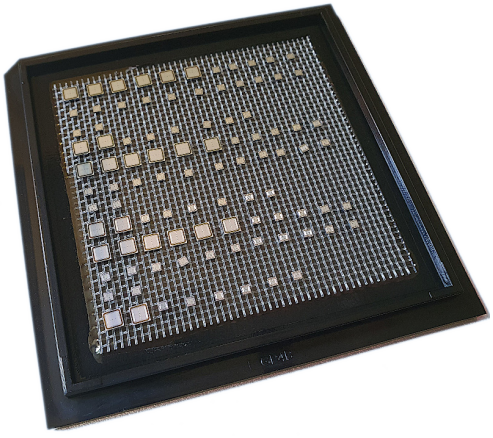
LGAD prototypes expected:

- TI-LGADs from FBK(*)
- i-LGADs from CMN

(*)received first test structures
FBK, trench isolated: test structures
45 µm substrate, trench depth “D2“, no carbon

Samples from three different wafers
(low/high diffusion, different trench processes)

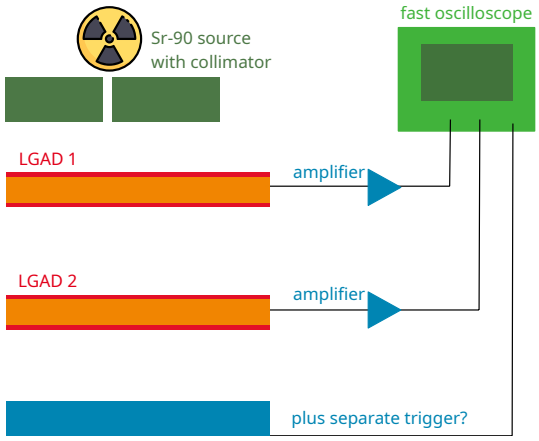
➤ The “big ones“:
4 mm x 4 mm, pixels 2x2 (1300 µm x 1300 µm)
all single trench, 18 with (6 without) gain



Time resolution measurement

One way to measure time resolution:

- Two LGADs (parallel to each other)
- Particle source
  (e.g. beta source with collimator)
- Each detector connected to an amplifier
- Signals fed into oscilloscope,
  triggers on signal in both
- Measure difference in arrival time Δt



Beta setup - analysis

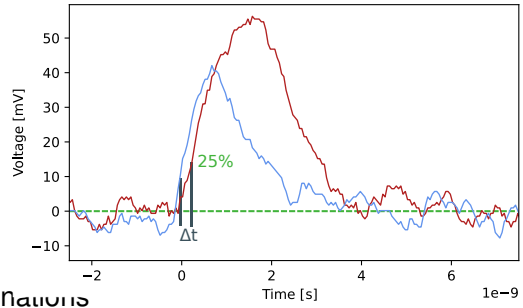
- Measure waveforms of two LGADs
- Apply constant-fraction-discriminator
- Determine time difference Δt
- Fit Δt distribution for many events
- Assuming no correlation:

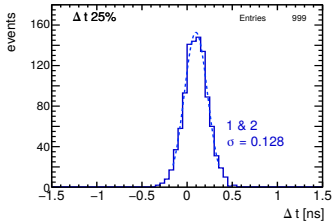
$$\sigma^2_{\text{system}-1-2} = \sigma_1^2 + \sigma_2^2$$

- Use three LGADs measured in three combinations

$$\sigma_1^2 = \frac{1}{2}\left(\sigma_{12}^2 + \sigma_{13}^2 - \sigma_{23}^2\right)$$

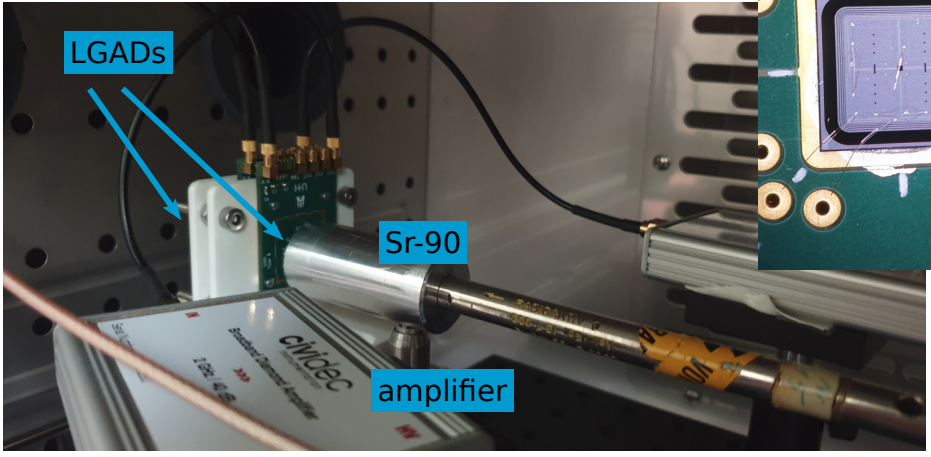
(and equivalent for the other two)

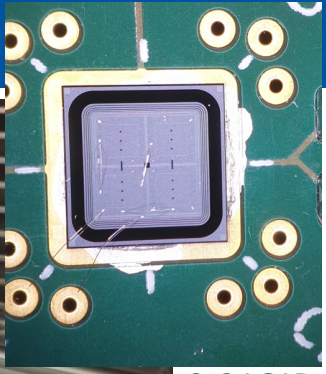




→ **can determine time resolution of all three LGADs**

Beta setup





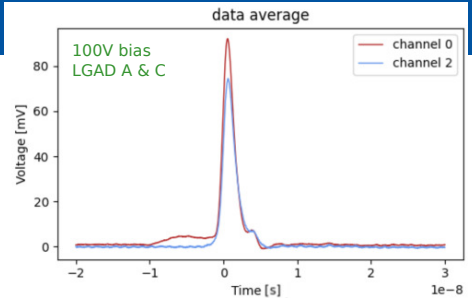
2x2 LGAD (pads bonded together)

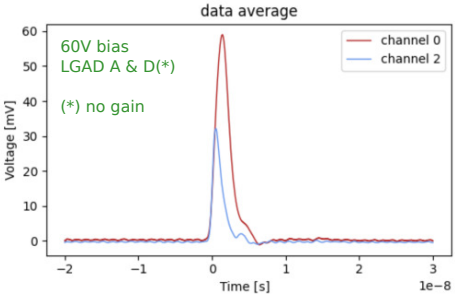
For more details: see report at last High-D meeting

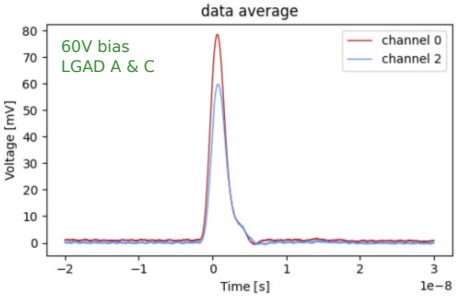
Beta setup: some signals

First tests with beta setup
Challenge: low trigger rate
1-2 hours for 1000 events

Idea: also perform some measurements at the testbeam



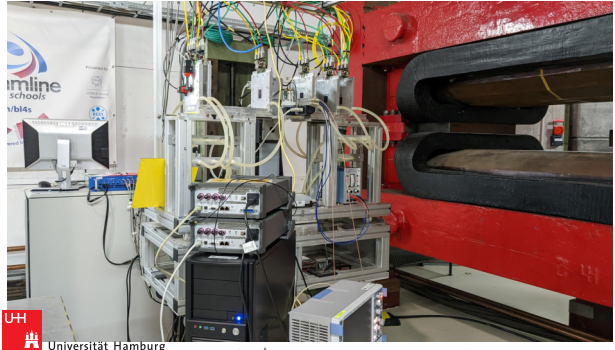


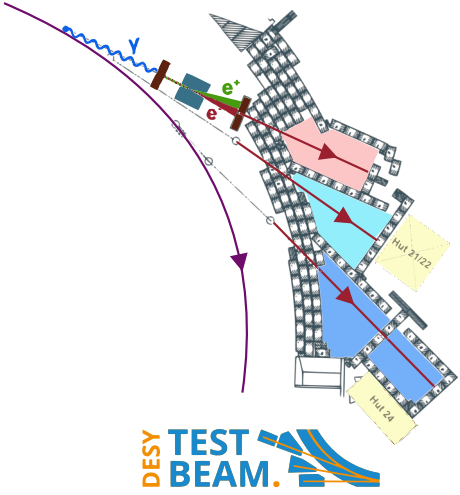


Testbeam at DESY

Testbeam time December 2022:

- $\sim$ 2.5 days area DESY II TB area 21
- Single electrons, beam energy used 2.8 GeV
- Together with Bohdan Dudar (DESY)



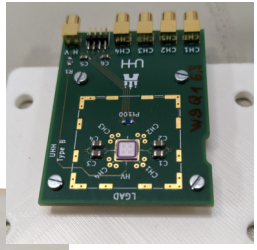


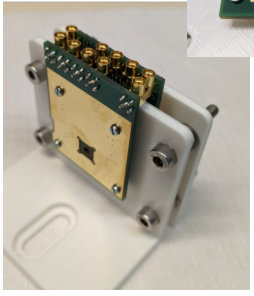
Data

Trigger on 40mV thresholds for signals within ± 2 ns coincidence window

Tested at the testbeam:

- A: W1 Q2 1,5 (p-dose B, high diff, trench P1, extended contact)
- B: W3 Q1 5,4 (p-dose A, low diff, trench P1, dot contact)
- C: W9 Q1 2,4 (p-dose B, high diff, trench P3, dot contact)





Combinations at the testbeam:

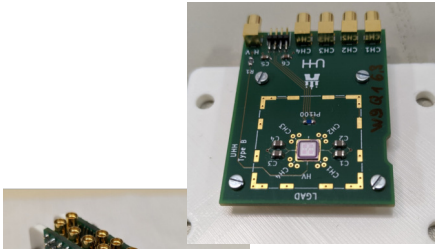
- A pixel 3 in front of B pixel 2
- C pixel 3 in front of A pixel 2
- C pixel 3 in front of B pixel 2

Data

Trigger on 40mV thresholds for signals within ± 2 ns coincidence window

Tested at the testbeam:

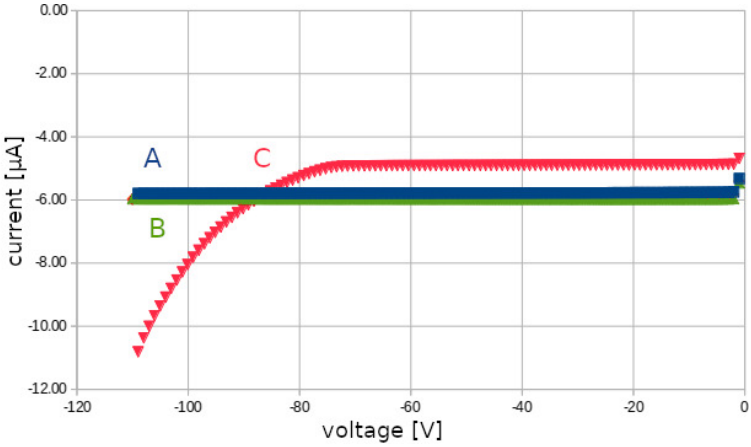
- A: W1 Q2 1,5
- B: W3 Q1 5,4 (“the new one“)
- C: W9 Q1 2,4 (high current already in lab)



Combinations at the testbeam:

- A pixel 3 in front of B pixel 2
- C pixel 3 in front of A pixel 2
- C pixel 3 in front of B pixel 2

IV-Curves



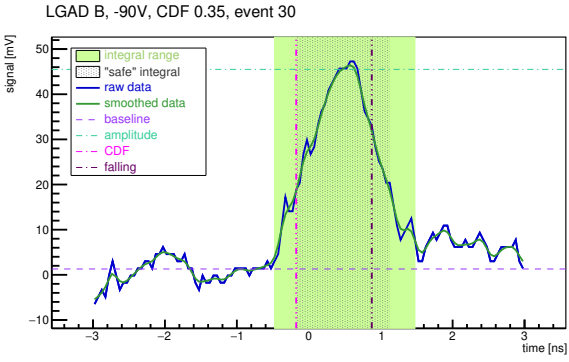
Decide to measure only up to 110 V, plus a few lower voltages

Analysis - raw waveforms

First strategy:
Smooth waveform “a bit“,

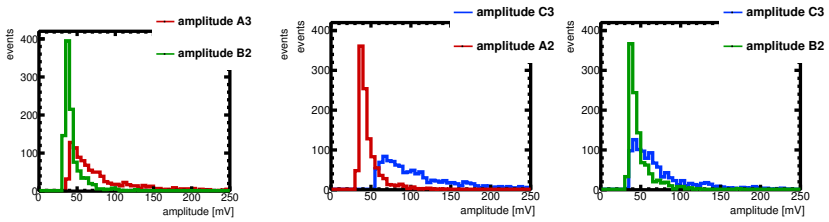
Subtract baseline,

Apply constant-fraction discrimination (CDF) to define pulse starting time for each raw waveform

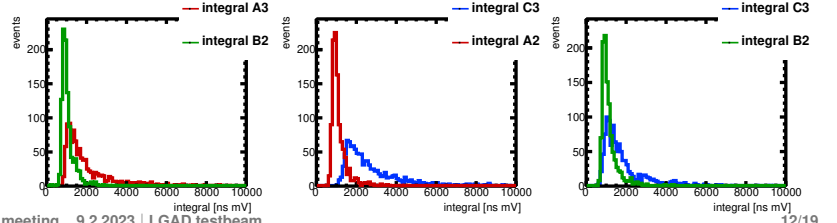


Collected charge

Amplitude (CDF 35%, bias -90V)



Integral (CDF 35%, bias -90V)



Always lower in second LGAD?

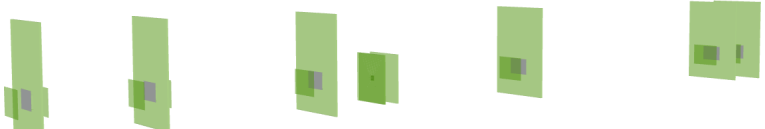
Allpix^2 simulation

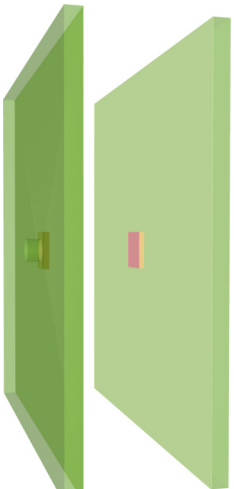
Implement setup in Allpix^2

[doi:10.1016/j.nima.2018.06.020, arXiv:1806.05813]

Geometry:

- 45 um active thickness
- 540 um support wafer (Si)
- 1.6 mm thick PCB
- 2 mm cutout below LGAD
- z-positions as measured at the testbeam



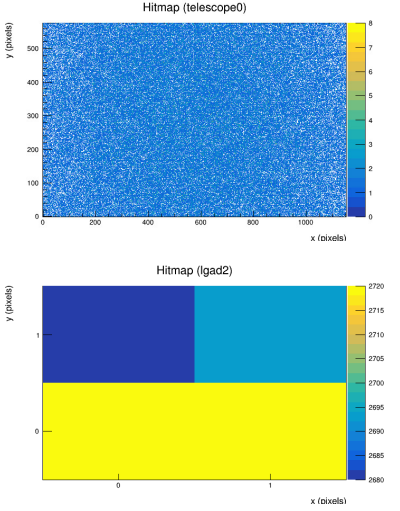


Geometry check: event rate

Allpix^2 with 5 mm diameter beam, starting 4 m out:
Compared to all events with hit in first telescope layer, the number of events in LGAD-2 pixel 0 is $\sim$0.9%

With 1kHz trigger rate for 20x10 scintillators:
Expect hit rate per LGAD of 10Hz
$\rightarrow \sim$2 minutes for 1100 events

IF all of them are above threshold

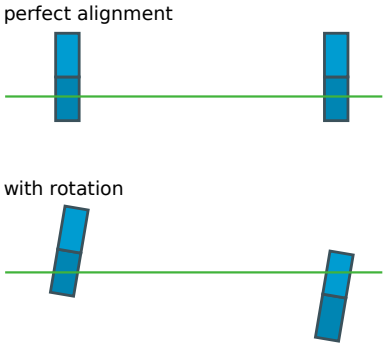


Event rate: reality

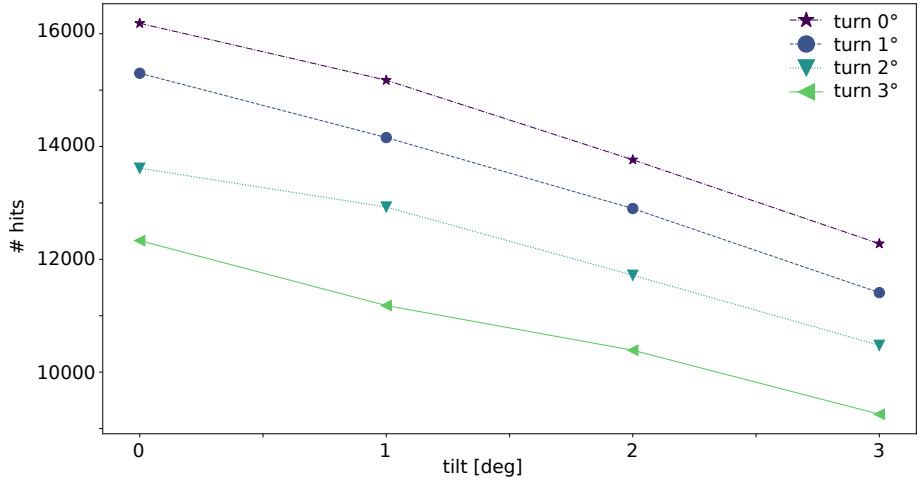
bias voltage	file name	telescope run	run duration
-110V	C3-and-B2_BWFULL_1100_mult_2022-12-10_12-19-08.Wfm.bin	101574	7 min
-100V	C3-and-B2_BWFULL_1100_mult_2022-12-10_11-41-00.Wfm.bin	101571	12 min
-90V	C3-and-B2_BWFULL_1100_mult_2022-12-10_11-54-56.Wfm.bin	101572	22 min
-80V	C3-and-B2_BWFULL_1100_mult_2022-12-10_12-32-44.Wfm.bin	101575	43 min
-70V	C3-and-B2_BWFULL_1100_mult_2022-12-10_13-22-12.Wfm.bin	101576	73 min

Higher bias voltage:
$\rightarrow$ Higher gain
$\rightarrow$ Higher amplitudes
$\rightarrow$ More events above threshold

Also: very sensitive to mis-alignments



Simulation: hit rate vs rotation



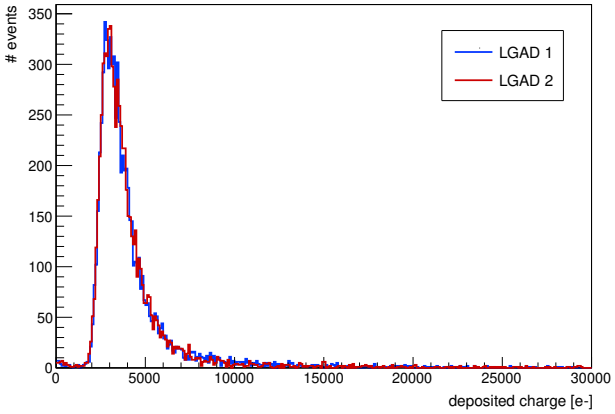
Simulation: charge deposit

Looking at deposited charge:
Same charge for both LGADs
(which makes sense for 2.8 GeV beam)

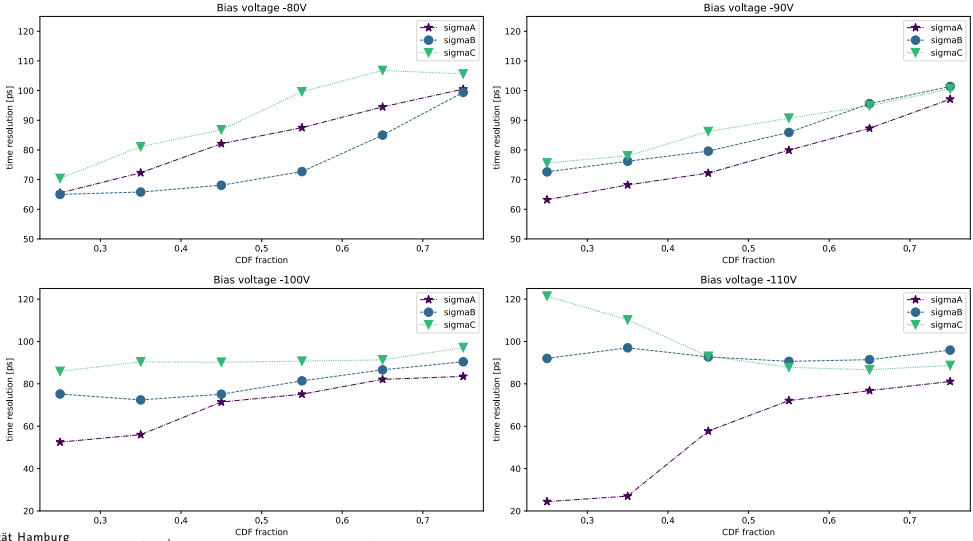
Does not match effect seen in data ☹

→ need to keep thinking about this...

Until then:
calculate time resolution anyway



Results: Time res vs bias



Summary & Outlook

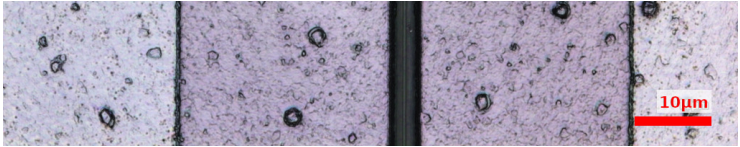
- Test beams: tool for detector development
- TB infrastructure: beam telesopes
  $\rightarrow$ goal: beam telescope timing layer
- Long term: 55 µm pitch structures with readout chip
- Current status: first test structures
- Setup of LGAD characterisation tools in progress
- First test in electron beam:
  Learned a lot about the setup,
  Many open questions
  $\rightarrow$ **Nice to-do-list for the future**

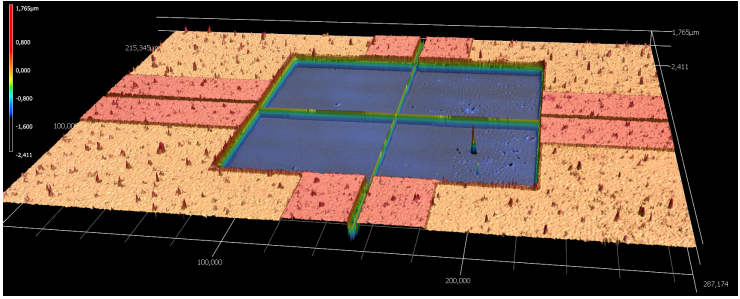
[CERN-EX-66954B / Teo Zirinis / kindpng.com]

Backup Slides

First LGAD samples (2)

Close look at the samples:





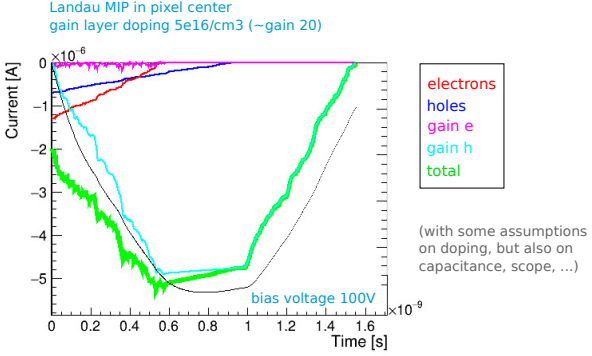
thickness 584±2 µm

Risetime

What time scale of the signal can we expect?

At saturated drift velocity, drift time for 45 µm: electrons ∼450 ps, holes ∼750 ps

Example (rough guess) from Weightfield 2 simulation
[http://personalpages.to.infn.it/∼ *cartigli / Weightfield2*]



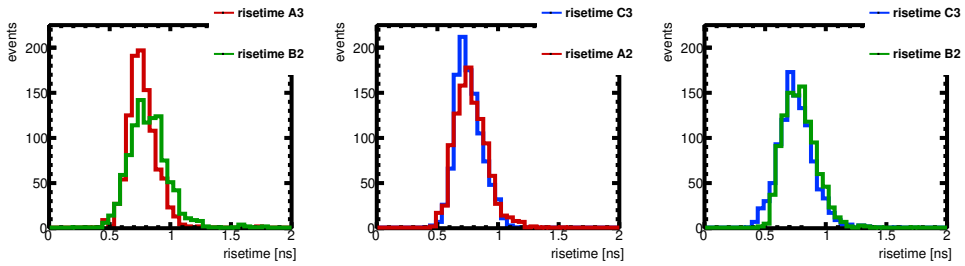
(with some assumptions on doping, but also on capacitance, scope, ...)

Measured risetime

"10-90" risetime

Note: this includes possible amplifier effects

Risetimes (CDF 35%, bias -90V)

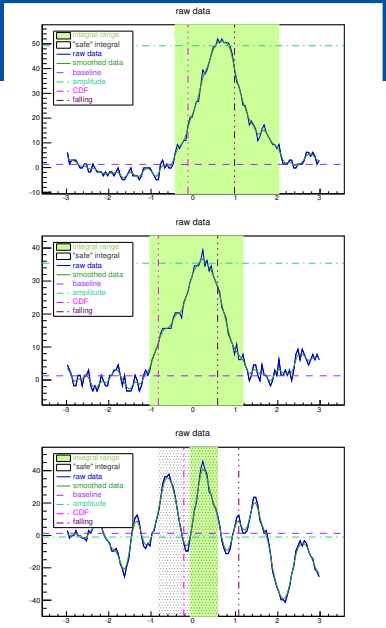


Similar risetimes for all samples, order of magnitude makes sense

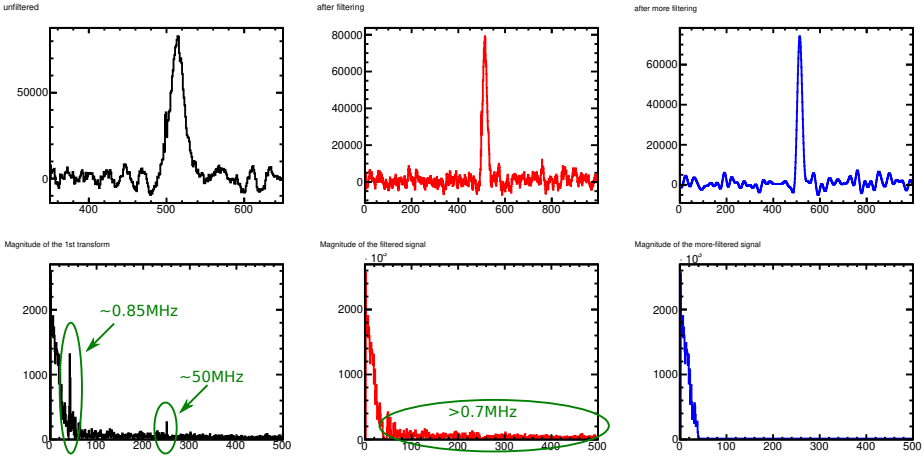
Open questions

- Data quality: remove “bad“ waveforms?
- Reduce noise (“ringing“)?
- Why signal so low in downstream LGAD?
- Gain at these voltages? ($\rightarrow$ Laser)
- Time resolution for same setup with Sr-90 source?

$\rightarrow$ To-Do list for the lab ☺

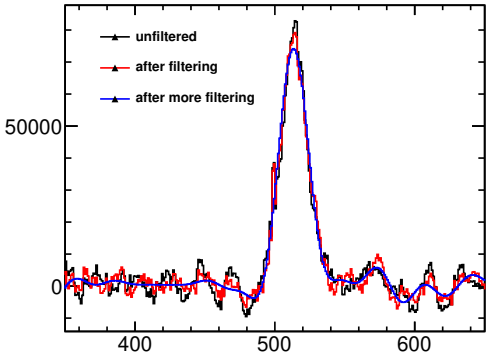


FFT to filter noise?



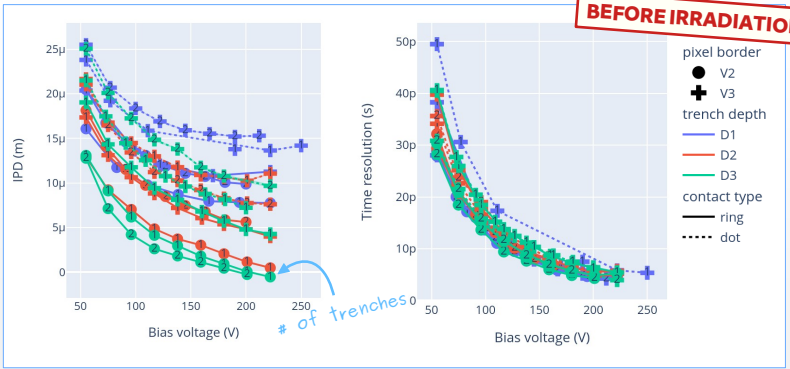
Not perfect. Also: Sadly, not all wave forms have such “clear“ noise ...

FFT to filter noise?



Not perfect. Also: Sadly, not all wave forms have such “clear“ noise ...

Interpixel distance and time resolution



- Border V2 is always better.
- Deeper trenches are better.
- Contact type "ring" is better.

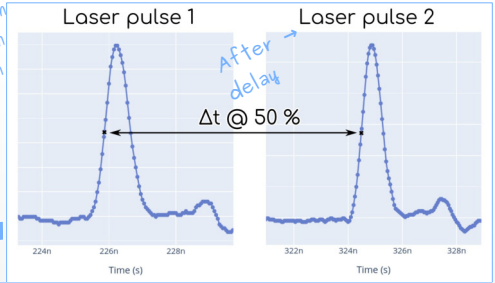
- Time resolution does not seem to depend systematically on these design parameters.

Time resolution

Example from a random scan

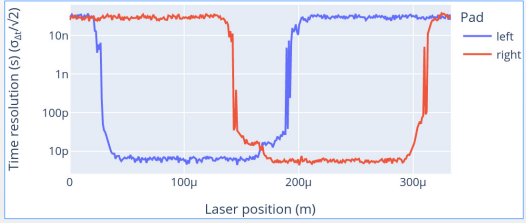
- Modified TCT setup with optic fiber delay line.
- Constant fraction discriminator.
- Time resolution vs laser position.

$$Time\ resolution = \frac{\sigma_{\Delta t}}{\sqrt{2}}$$

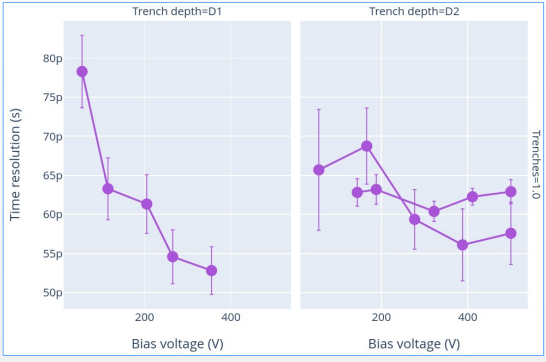


- Within window (laser in silicon):
  - ~ 10 ps ✔

  Outside window (laser in metal):
  - > 10 ns because the software is measuring noise ✔



Time resolution with beta source

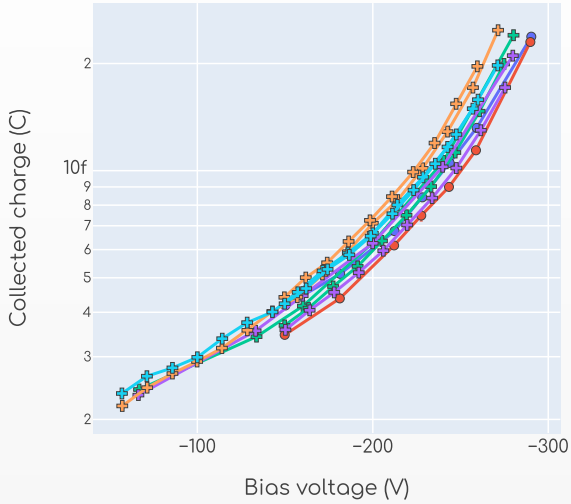


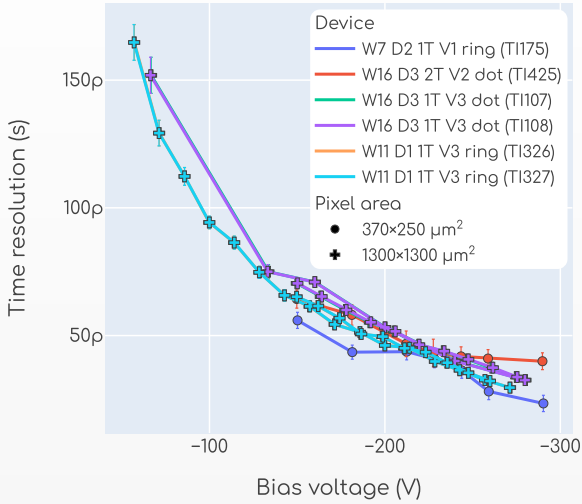
- Time resolution of same devices in TCT setup: 35-50 ps @ 500 V.

Test beam results

T = Room T (September)

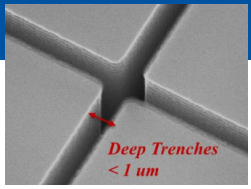
Same data from previous slide but as function of bias voltage.





Cividec C2-HV

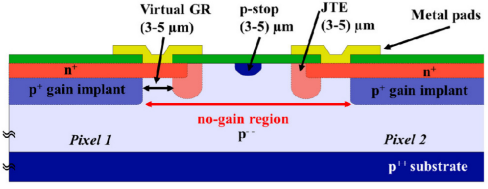
TI-LGAD



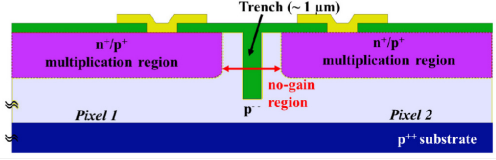
Trench isolation:

- Barrier structures replaced by trenches to isolate the pixels
- Filled with SiO2, Si3N4, Polysilicon
- Typical trench width $< 1\,\mu m$, much smaller than conventional segmentation
  $\rightarrow$ smaller no-gain region
  $\mathcal{O}(\approx 4\,\mu m$ to $7\,\mu m)$

a) Standard segmentation

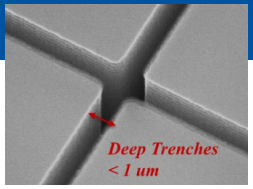


b) Trench-isolated LGAD



[doi: 10.1109/LED.2020.2991351]

TI-LGAD



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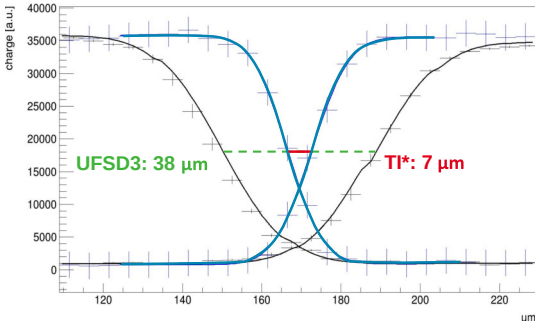
  $\mathcal{O}(\approx 4\,\mu m$ to $7\,\mu m)$

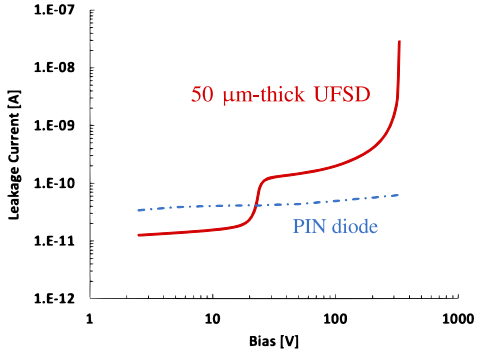
Comparison of FBK productions: UFSD3 vs Trench-Isolated



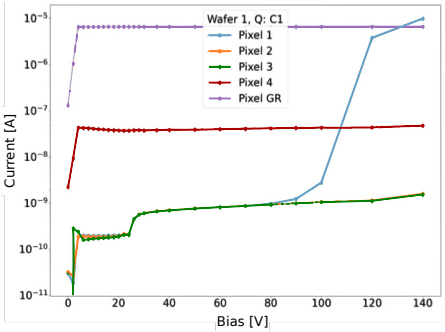
[F. Siviero, 35th RD50 workshop, Nov 2019]

Current-Voltage measurement

IV-curves (textbook and reality)



[M. Ferrero, R. Arcidiacono, M. Mandurrino, V. Sola, N. Cartiglia, 2021 "An Introduction to Ultra-Fast Silicon Detectors", ISBN 9780367646295]



FBK measurement with automatic probe (before dicing)