Characterization of FBK TI-LGAD and pixelated BNL AC-LGAD with laser TCT and beam tests

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FBK TI-LGAD

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FONDAZIONE BRUNO KESSLER

BNL AC-LGADs

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- CERN: A. Rummler, V. Gkougkousis

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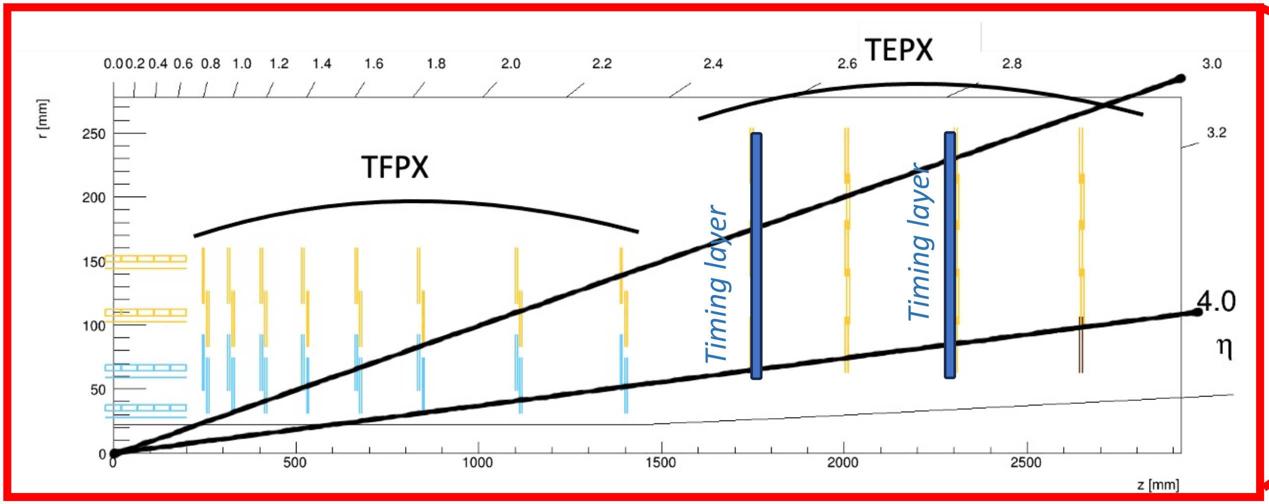
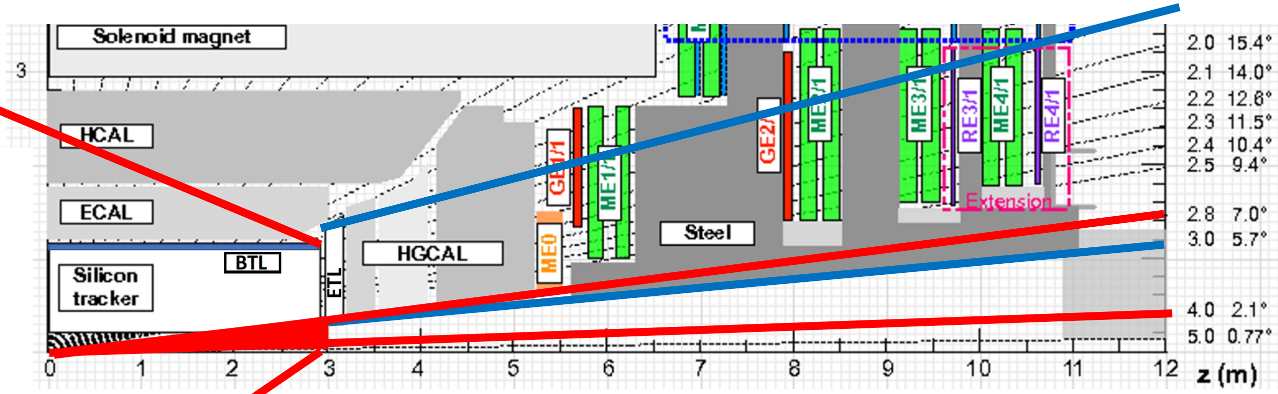
Timing detectors applications: HL-LHC and FCC-ee

Extension of CMS timing capabilities in the forward region, now ensured by ETL, to higher rapidity, will greatly improve detector performance

Options in TEPX for Phase-3:

- Replace one or two disks instrumenting them with **LGADs pixels**





CMS Phase-3 detector

Implement timing capabilities in the outermost silicon layers for the **Trackers in FCC-ee experiments** to enhance particle identification and help to reduce the systematic uncertainty on the measurement of the beam energy.

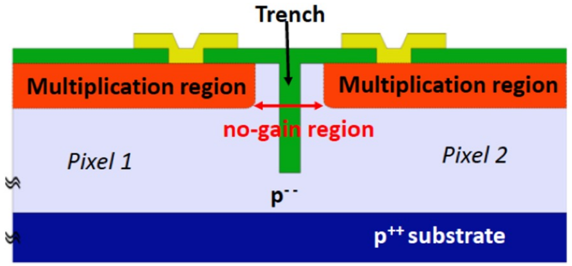
- **AC-LGAD pixels** to cover large surfaces **OR**
- **CMOS DMAPs** with enhanced timing capabilities

Technologies: path towards small pitch LGADs

- Different technologies to be explored to achieve small pitch LGADs necessary for 4D tracking; timing resolution ~ 30 ps achievable with all these technologies

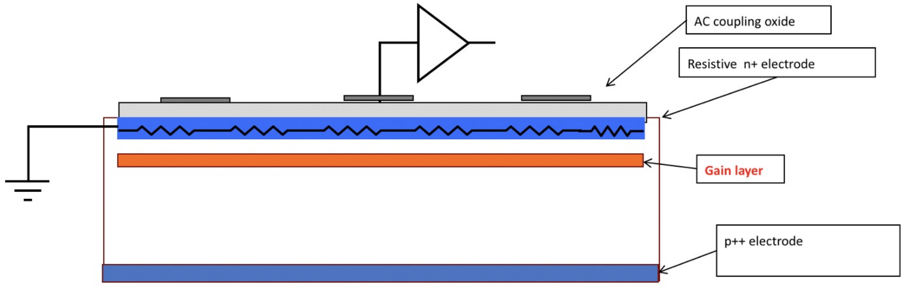
Trench-isolated LGADs (TI-LGAD)

- Sensor with small pitch and high fill factor



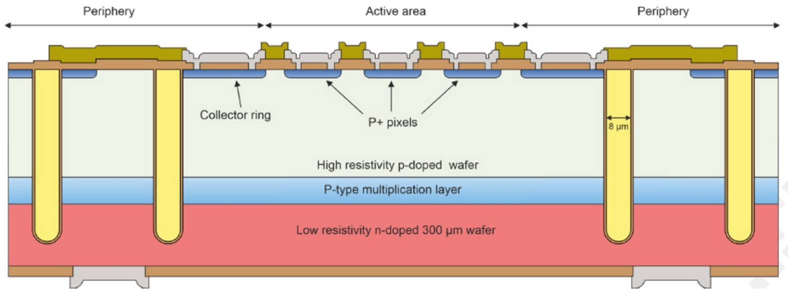
Resistive AC-Coupled Silicon Detectors (RSD), FBK and BNL

- AC-pad coupled to the resistive n+ layer via dielectric coupling
- Not segmented gain layer: 100% fill factor
- Good spatial resolution with relaxed pitch



Inverse LGAD (iLGAD):

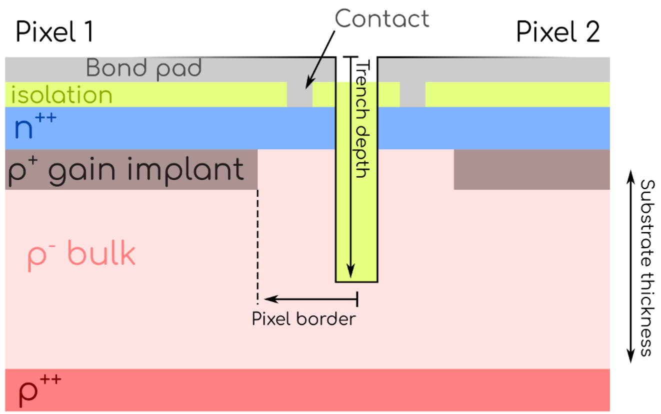
- multiplication region on the opposite side of the read-out electrodes

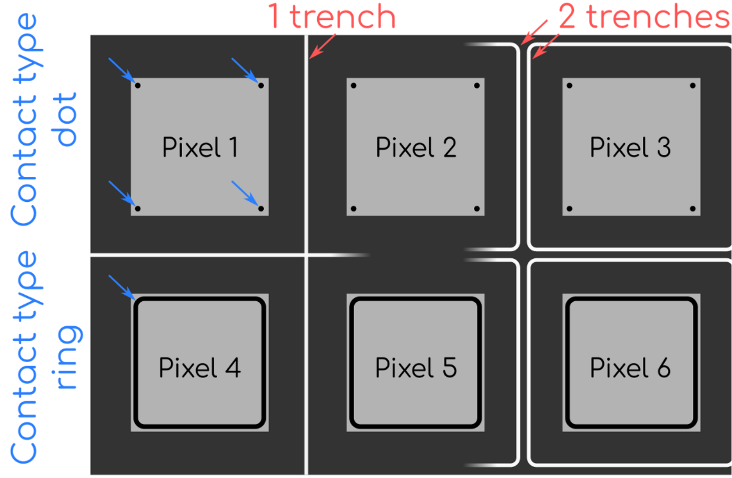


TI-LGAD – RD50 production at FBK

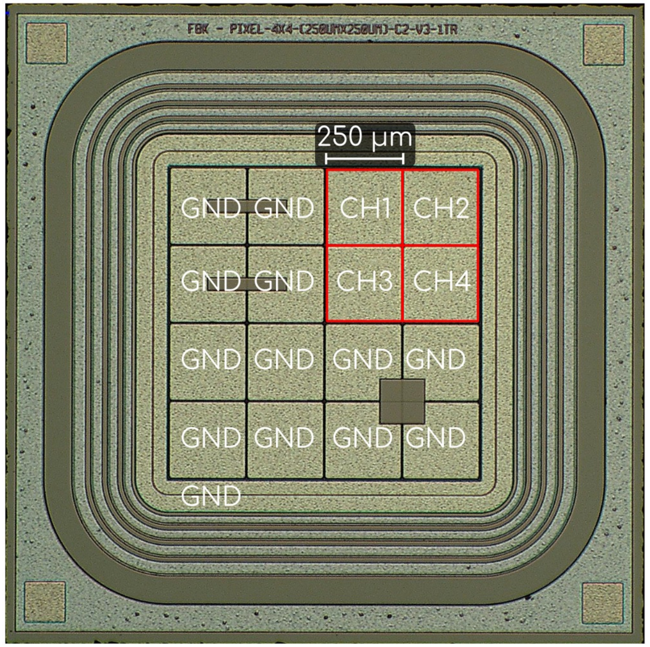
TI-LGAD FBK RD50 production:

- Trenches: 1 or 2.
- Contact type: “Ring” or “dot”.
- Pixel border: “V1” < “V2” < “V3” < “V4”.
- Trench depth: “D1” < “D2” < “D3”.





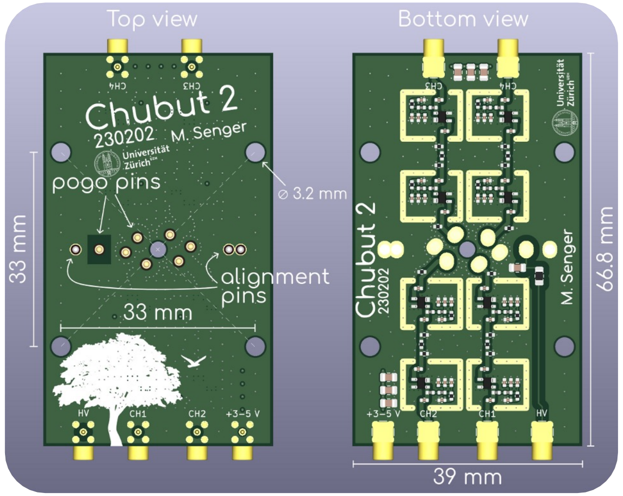
- All from FBK RD50 TI-LGAD production
- Same physical layout and connection →
- 8 DUTs, details in table below ↓

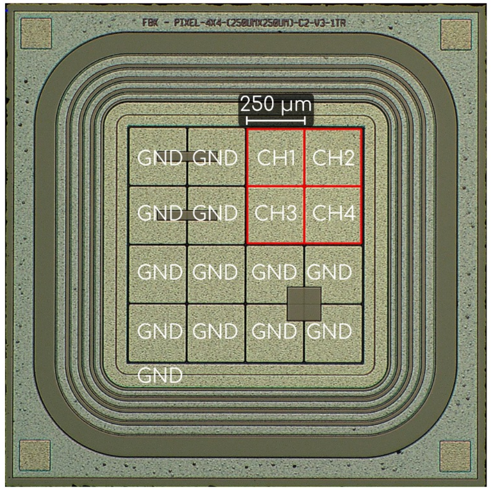


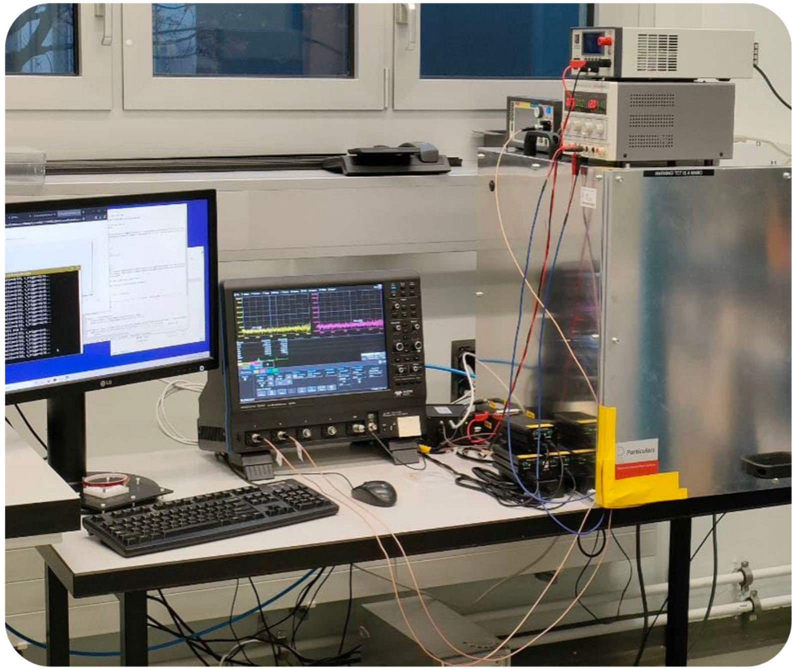
wafer	trench process	trench depth	trenches	pixel border	contact type	Fluence (neq/cm²)
16	P2	D3	1	V3	dot	0.0E+0
16	P2	D3	1	V3	ring	0.0E+0
16	P2	D3	1	V3	ring	0.0E+0
16	P2	D3	1	V2	ring	0.0E+0
16	P2	D3	1	V2	ring	1.0E+15
16	P2	D3	1	V2	ring	1.0E+15
7	P2	D2	1	V3	ring	1.0E+15
7	P2	D2	1	V3	ring	1.0E+15

Characterization of TI-LGADs with TCT

- Particulars Scanning TCT:
  - Infrared laser (1064 nm).
  - Laser spot Gaussian with σ ~ 9 μm.
  - ~1 μm spatial resolution.
  - Laser intensity set to match ≈ 1 MIP.
- Laser splitting+delay[1] introduced with optic fiber for timing measurements provides two pulses separated by 100 ns.
- Oscilloscope LeCroy 640Zi.
  - 3 GHz, 20 GS/s.
- Chubut 2 readout board[2], 4 channels with 2 amplification stages.

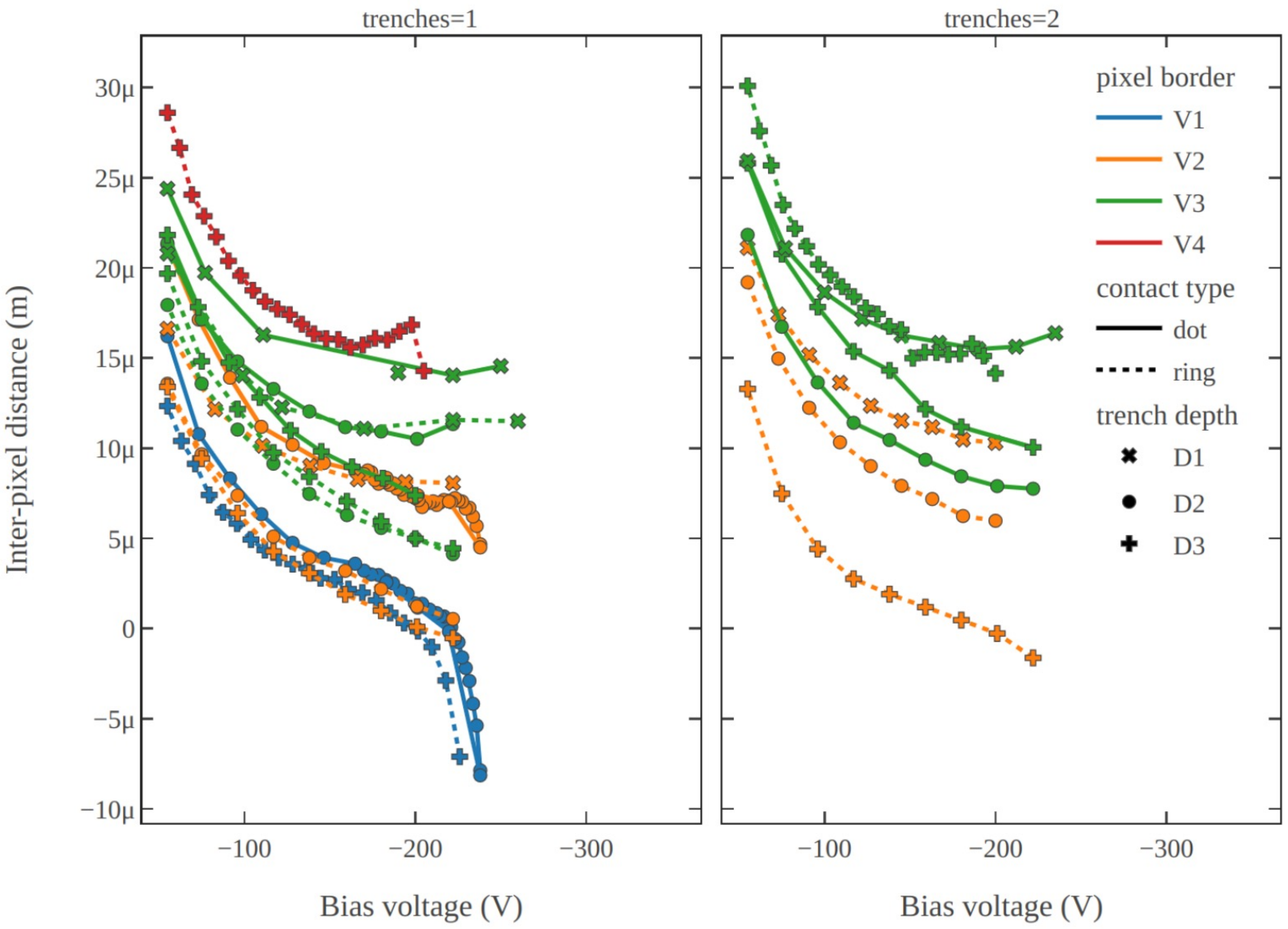


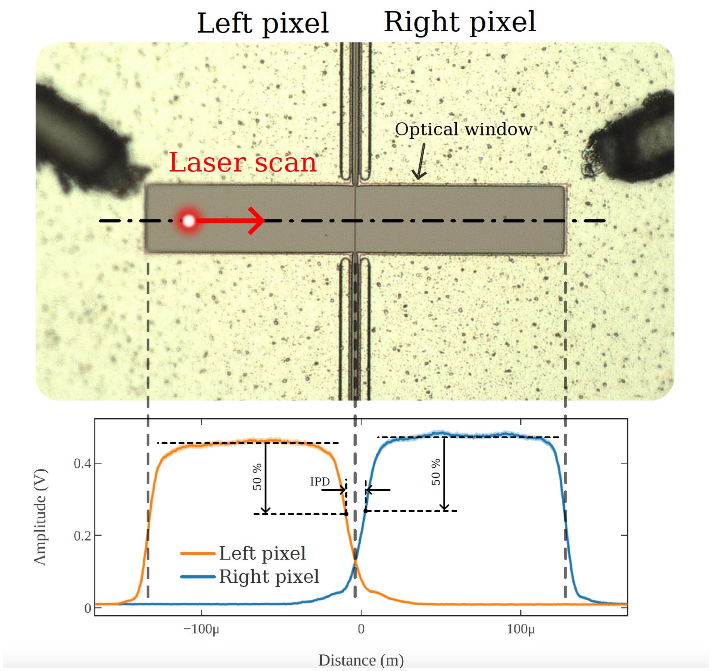




[1] https://msenger.web.cern.ch/laser-delay-system-for-the-scanning-tct/
[2] https://github.com/SengerM/Chubut_2

Inter-pixel distance measured with TCT



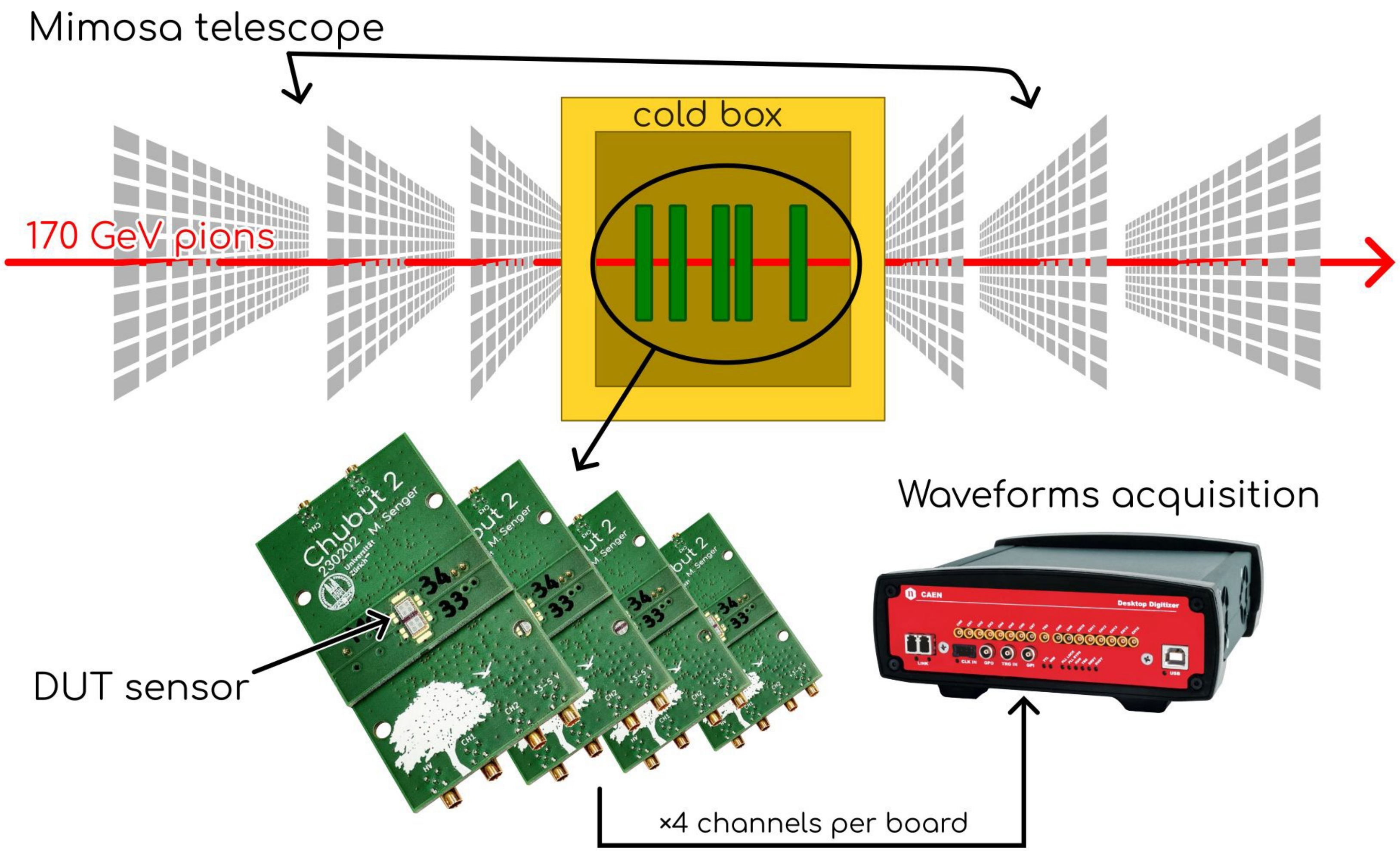


- The pixel border parameter has a strong influence on the value of the IPD

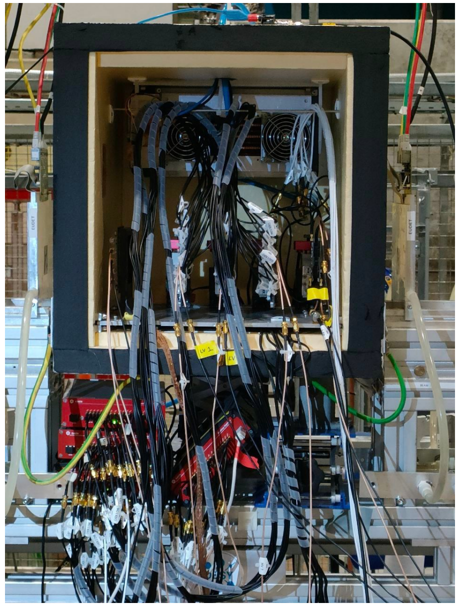
- Negative values of IPD:
  - additional charge multiplication in the region in close proximity with the trenches structure.
  - Structures become unstable in this regime

M. Senger et al, Characterization of timing and spacial resolution of novel TI-LGAD structures before and after irradiation, https://doi.org/10.1016/j.nima.2022.167030

AIDAinnova Test-beam



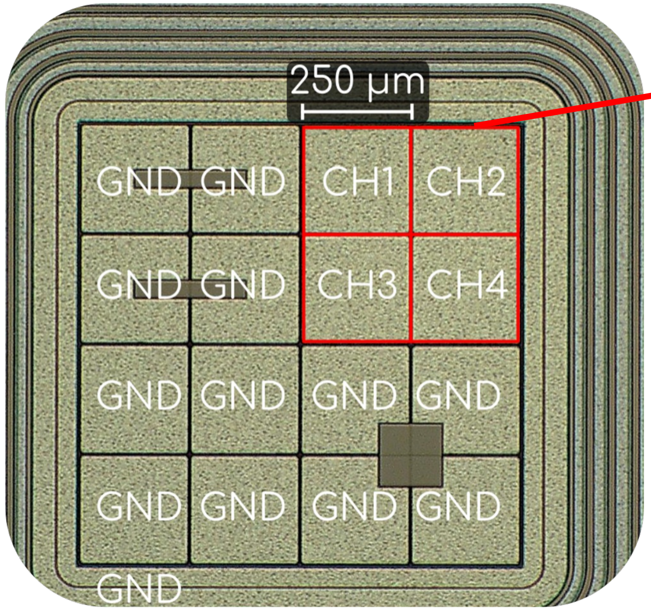
- CERN H6 beamline
  - (170 GeV pions)
  - Mimosa telescope
- Chubut 2, 4 channels readout board[1]
- CAEN DT5742 digitizer, 500 MHz @ 5 GS/s
- Cold box for irradiated DUTs, down to -12 °C

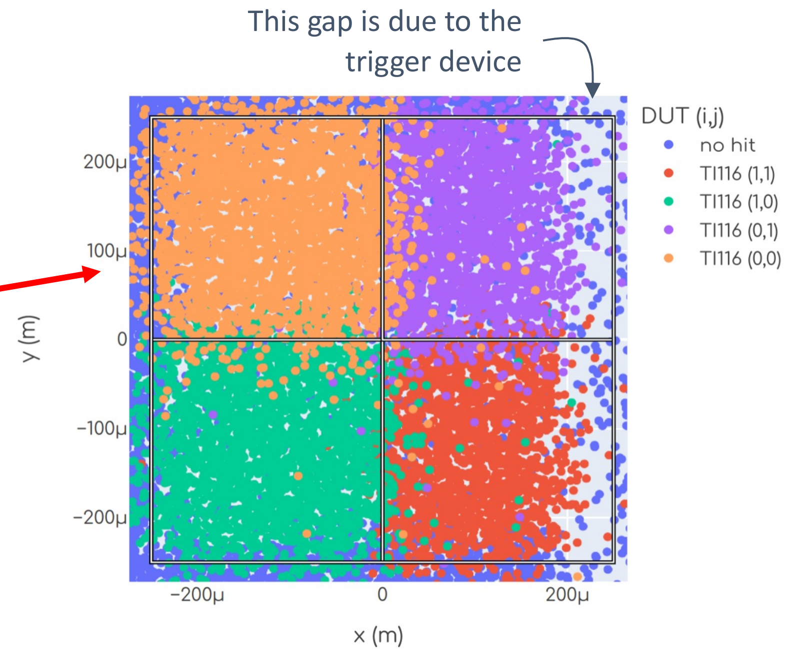


M. Senger et al., First characterization of TI-LGAD technology in a test beam setup, 43rd RD50 Workshop, CERN, Nov. 2023

Tracks and hits on DUTs

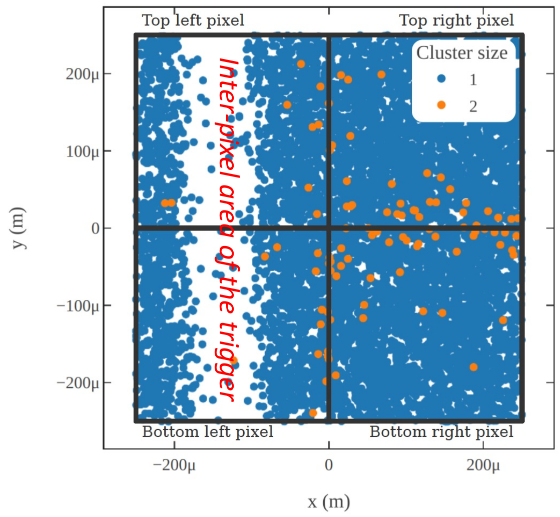
- Each dot is a track
- Colored according to which channel was hit
- Tracks reconstruction using Corryvreckan[1]

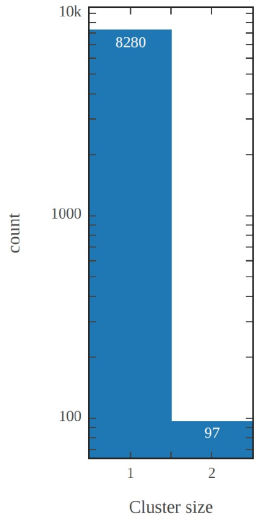




Only ~1 % of events share charge at perpendicular incidence, low value consistent with expectation, good isolation thanks to the trenches

Spatial resolution= digital resolution

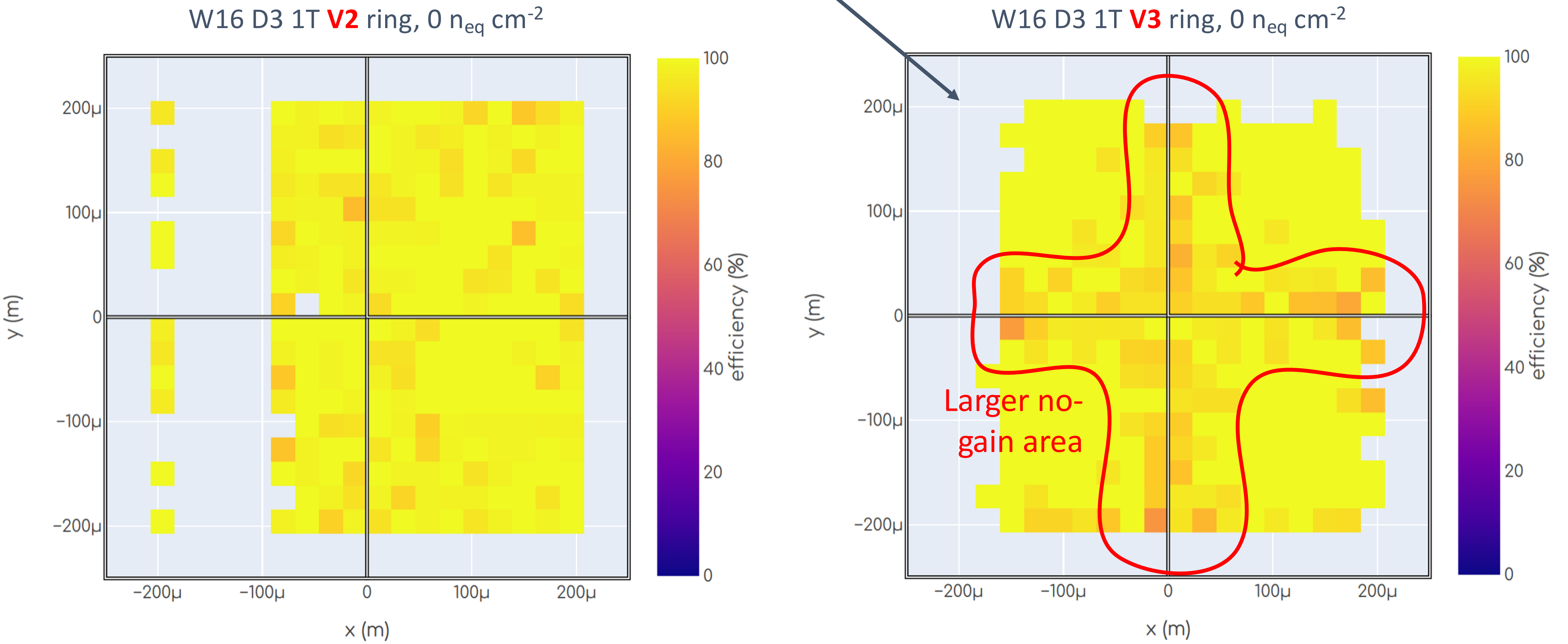




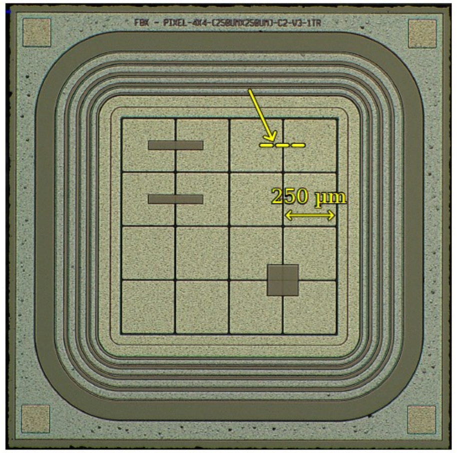
Efficiency vs position TI-LGAD

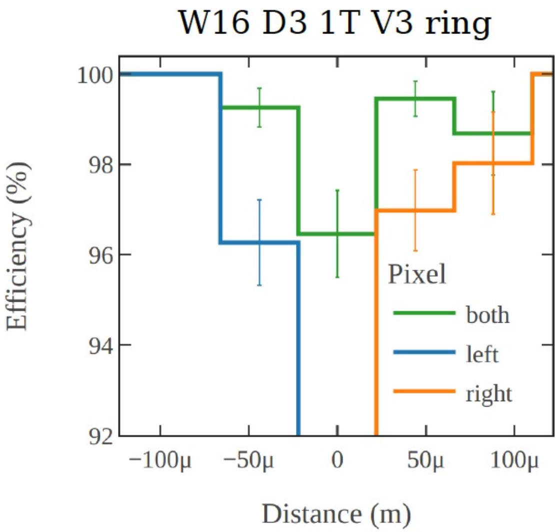
$$\text{Efficiency} = \frac{\text{Number of detected particles}}{\text{Number of particles that went through}}$$

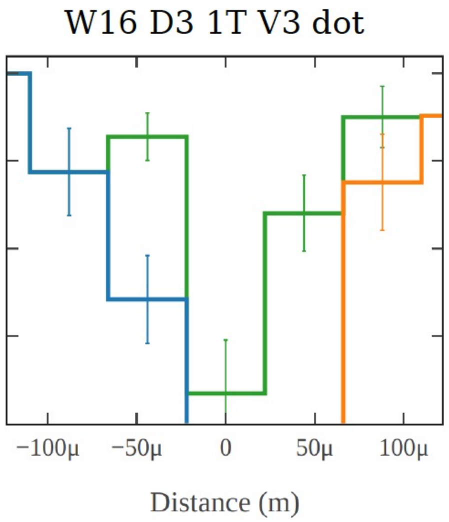
This DUT was measured as a control DUT, knowing it has a larger inter-pixel distance. Here we can see it ✅



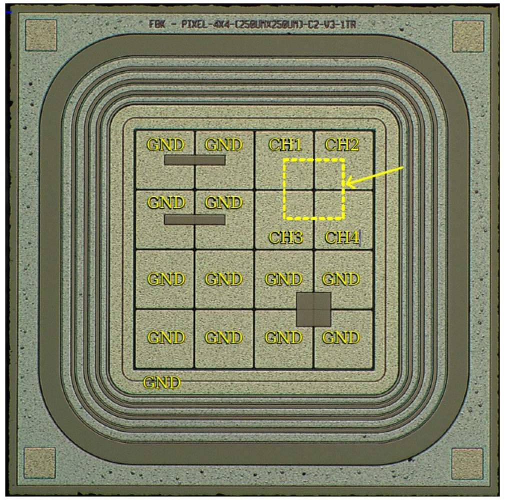
Efficiency overview

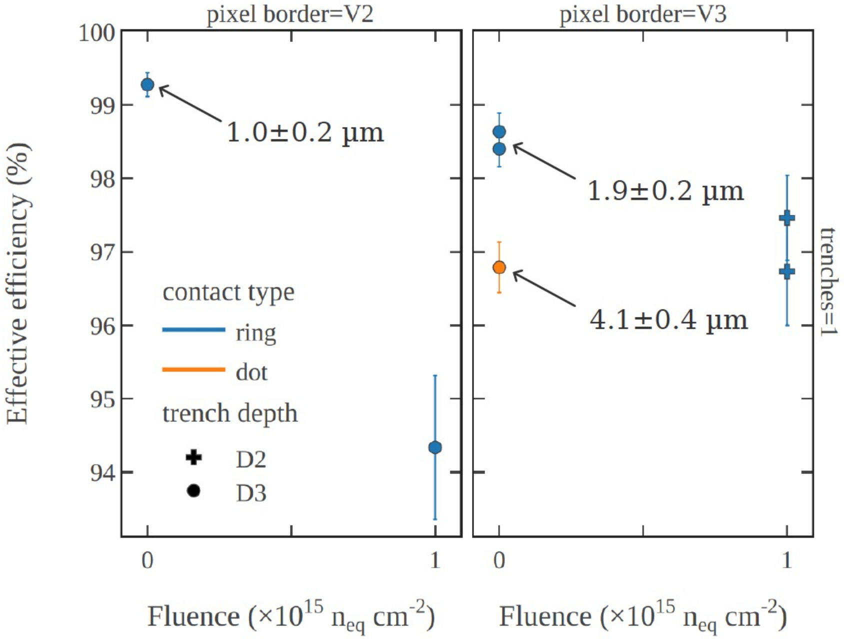






- Before irradiation, inefficiency is only due to inter-pixel distance
- Ordering of the process parameters in terms of efficiency is consistent with TCT studies
  - ”Ring” better than “dot”
  - V2 better than V3 before irr.





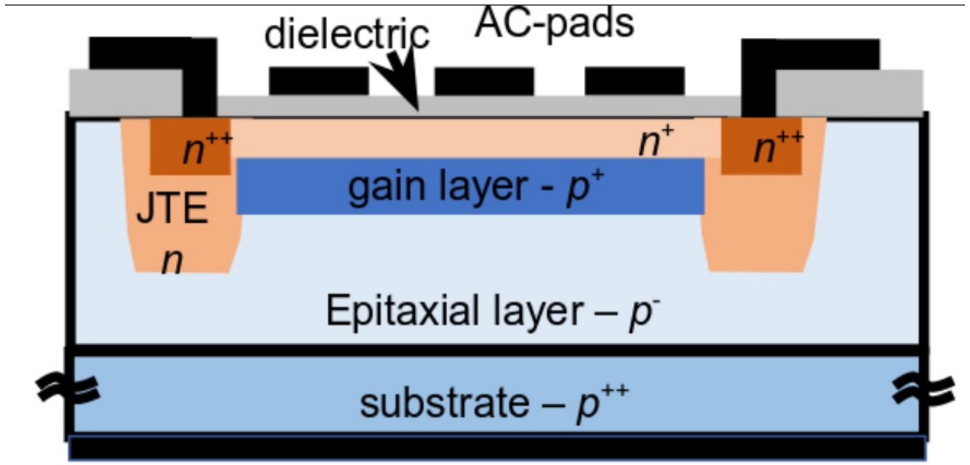
Assuming all inefficiency before irradiation is due to fill factor, we can estimate an “effective IPD”

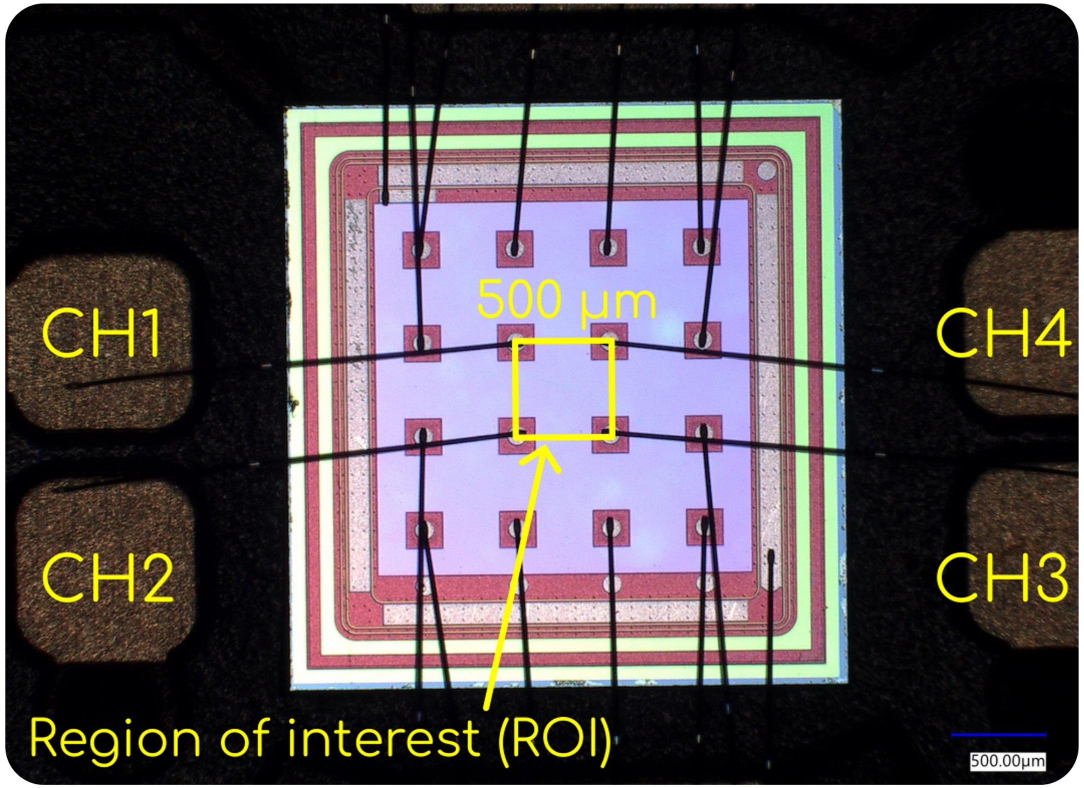
$$\text{Fill factor} = \frac{(\text{Pitch} - \text{IPD})^2}{\text{Pitch}^2}$$

- After irradiation, gain loss contributes to inefficiency, in the same way as for the standard LGAD technology

BNL AC-LGAD: characterized devices

- 2 identical devices manufactured at BNL
- Fabricated on 4” epitaxial wafers
- Active epi-thickness: 50 μm grown on top of 500 μm low-resistivity substrate
- Pad size: 200 μm, pitch: 500 μm
- 2×2 pads readout, unused pads to GND
- Not irradiated





Time reconstruction algorithms

Two methods tested with TCT:

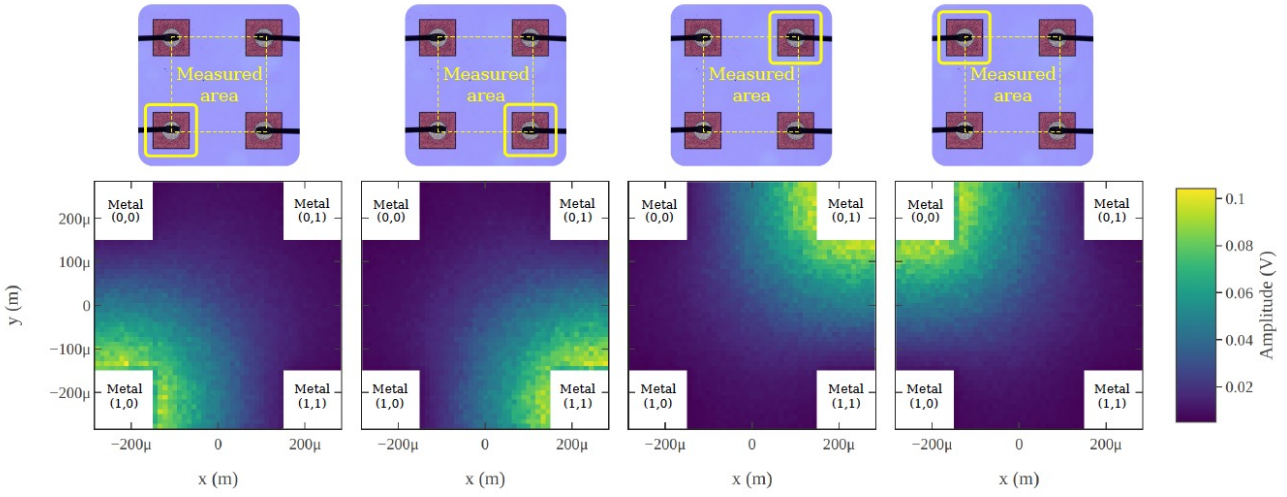
Single pad approach.

- The leading pad, i.e. the one with the largest amplitude, is selected. The time t is determined from the waveform from such pad as the one at which 50 % of the max amplitude is reached (CFD). This is repeated for every event at every position.

Weighted combination:

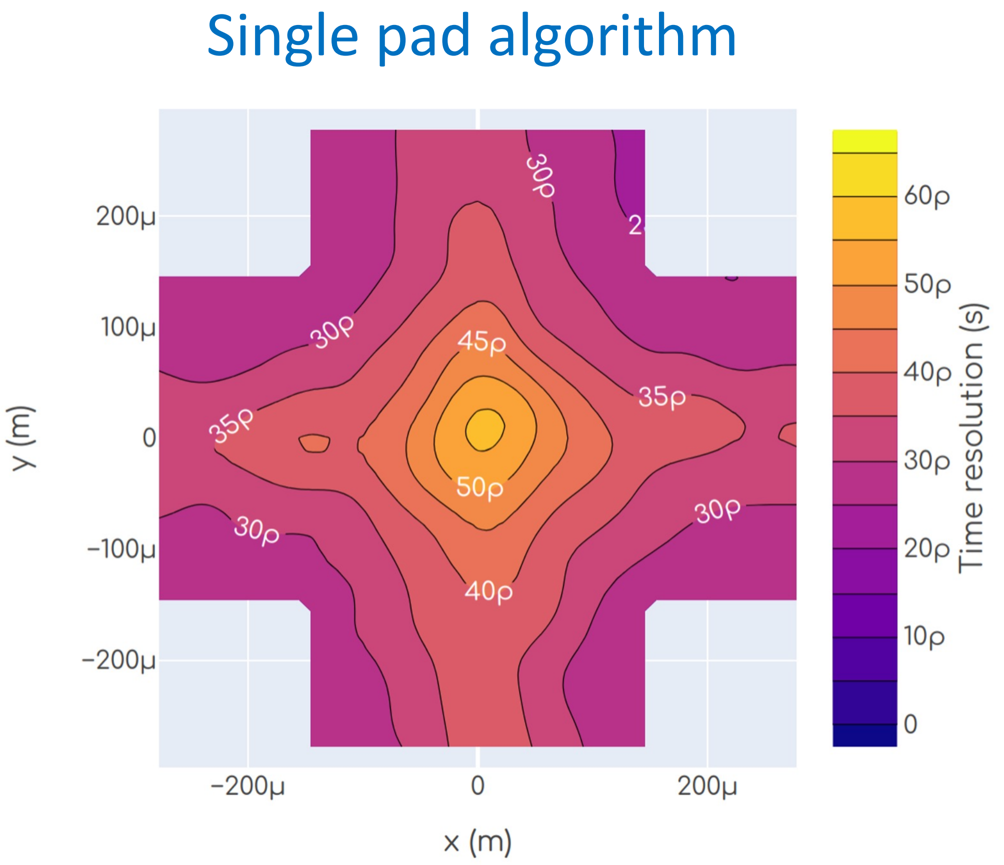
- Amplitude weighted average from several pads.
- No “hit position corrections”.

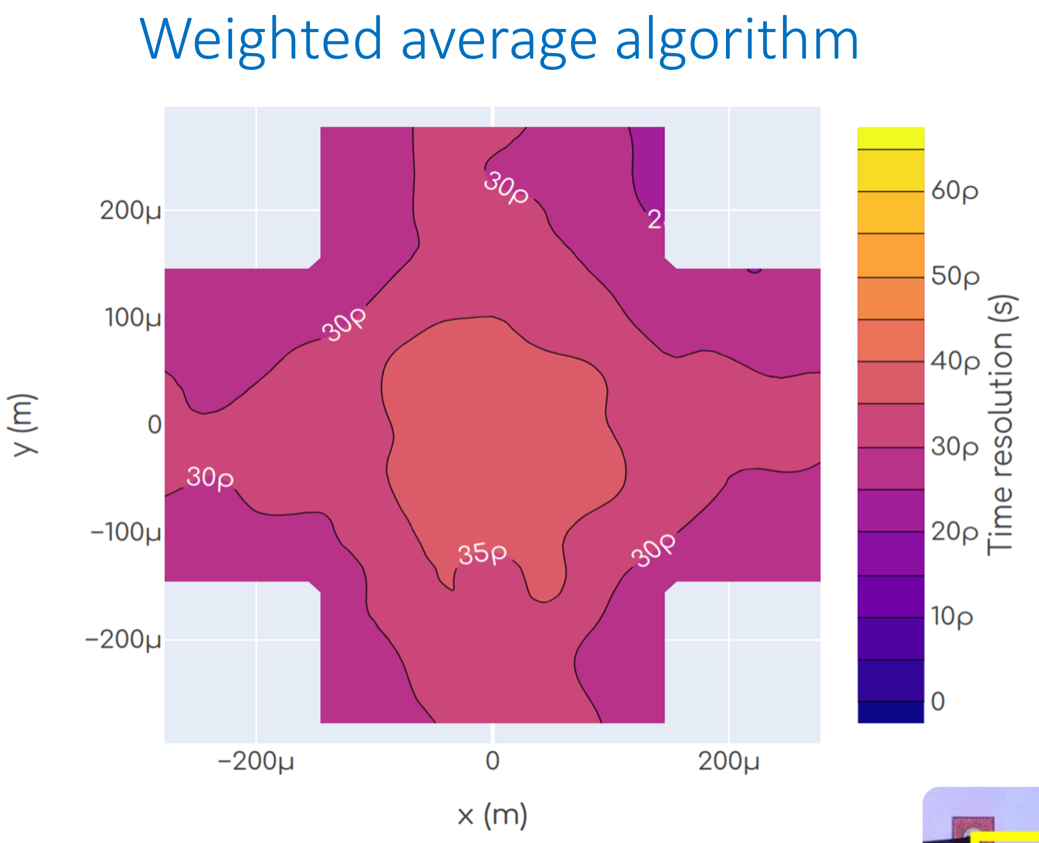
$$t_{\mathrm{reco}} = \frac{\sum_i a_i^2 t_i}{\sum_i a_i^2}$$

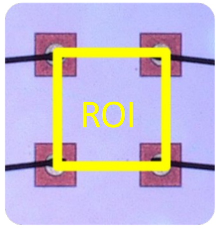


M. Senger et al., “2D pixelated BNL AC-LGADs: From laser TCT to Test Beam characterization”, *43rd RD50 Workshop, CERN, Nov. 2023*

BNL AC-LGADs: Time reconstruction results with TCT

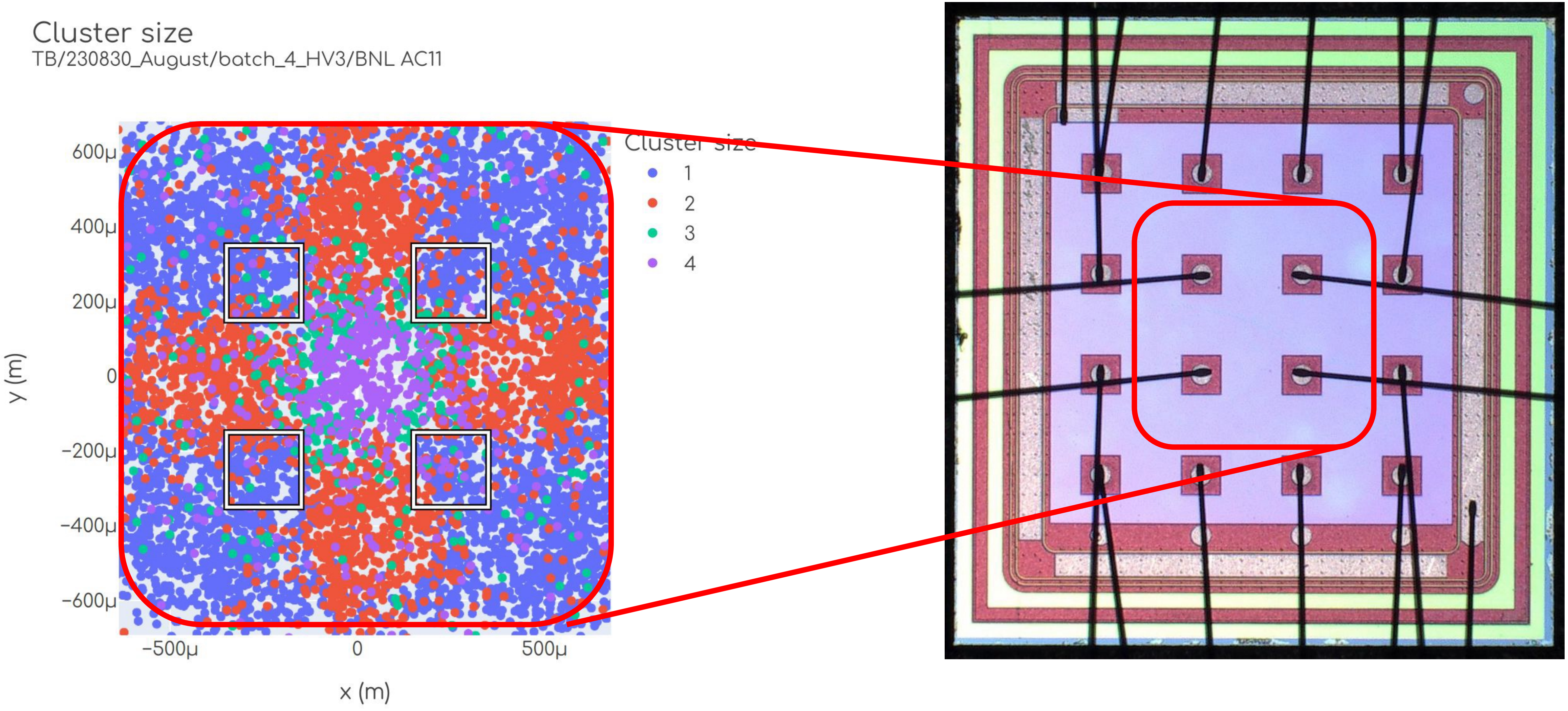






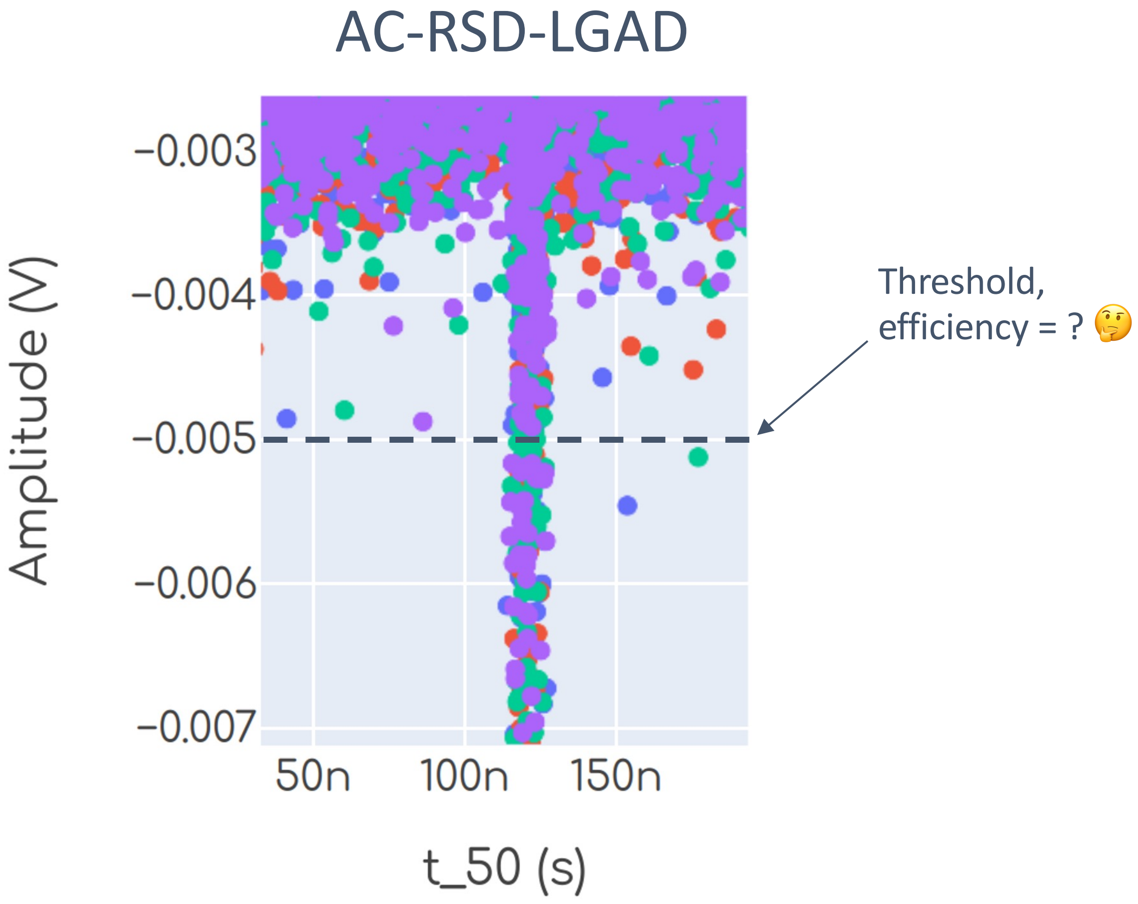
- TDCs from all pads have to be active all the time to get the desired time resolution, one TDC out of 4 is not enough.
- ⚠️ Laser TCT lacks of Landau fluctuations

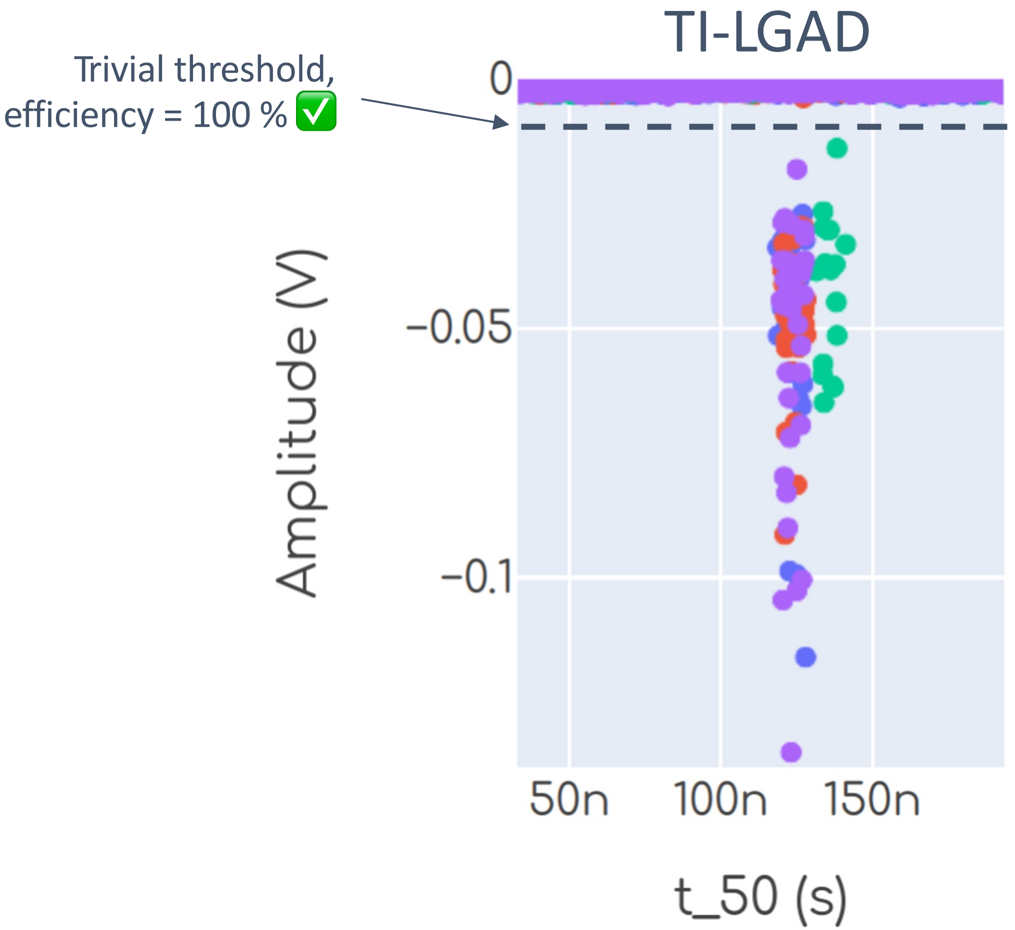
AIDAinnova TB: Charge sharing for BNL AC-LGADs



The downside of charge sharing

Definition of the threshold level not trivial anymore, as opposed to a “normal LGAD” such as e.g. a TI-LGAD:





Position reconstruction methods - BNL AC-LGAD

1. Charge imbalance formula: linear interpolation displays some deviations from the ideal result
2. DNN (neural network) using Amplitude Shared Fraction (ASF)

$$\begin{cases} x_{\text{reconstructed}} = \dfrac{\text{pitch}_x}{2} Q_{\text{imbalance } x} \\ y_{\text{reconstructed}} = \dfrac{\text{pitch}_y}{2} Q_{\text{imbalance } y} \end{cases}$$

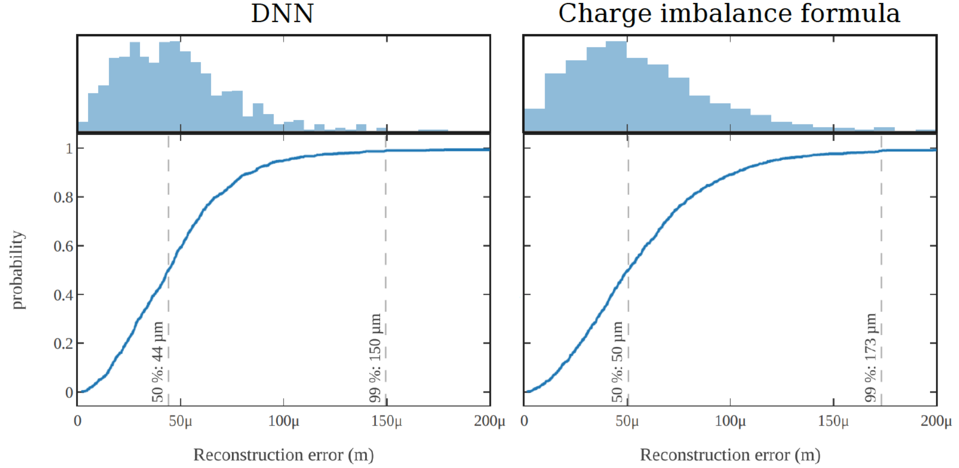
$$\begin{cases} Q_{\text{imbalance } x} = \dfrac{Q_{11} + Q_{01} - Q_{00} - Q_{10}}{\sum Q_{ij}} \\ Q_{\text{imbalance } y} = \dfrac{Q_{00} + Q_{01} - Q_{11} - Q_{10}}{\sum Q_{ij}} \end{cases}$$

$$\text{ASF}_i = \frac{A_i}{\sum_j A_j}$$

$$\text{reconstruction error} = \sqrt{\sum_{\text{coord} \in \{x,y\}} (\text{reconstructed}_{\text{coord}} - \text{telescope}_{\text{coord}})^2}$$

	Median	99 %
DNN	44 μm	150 μm
Charge imbalance formula	50 μm	173 μm
500×500 μm² SBRP*	204 μm	330 μm

Cumulative distribution function of the reconstruction error



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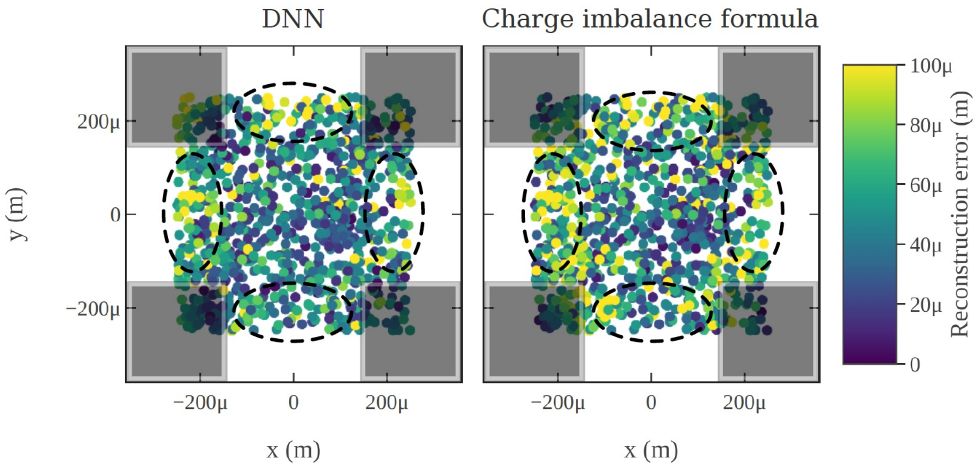
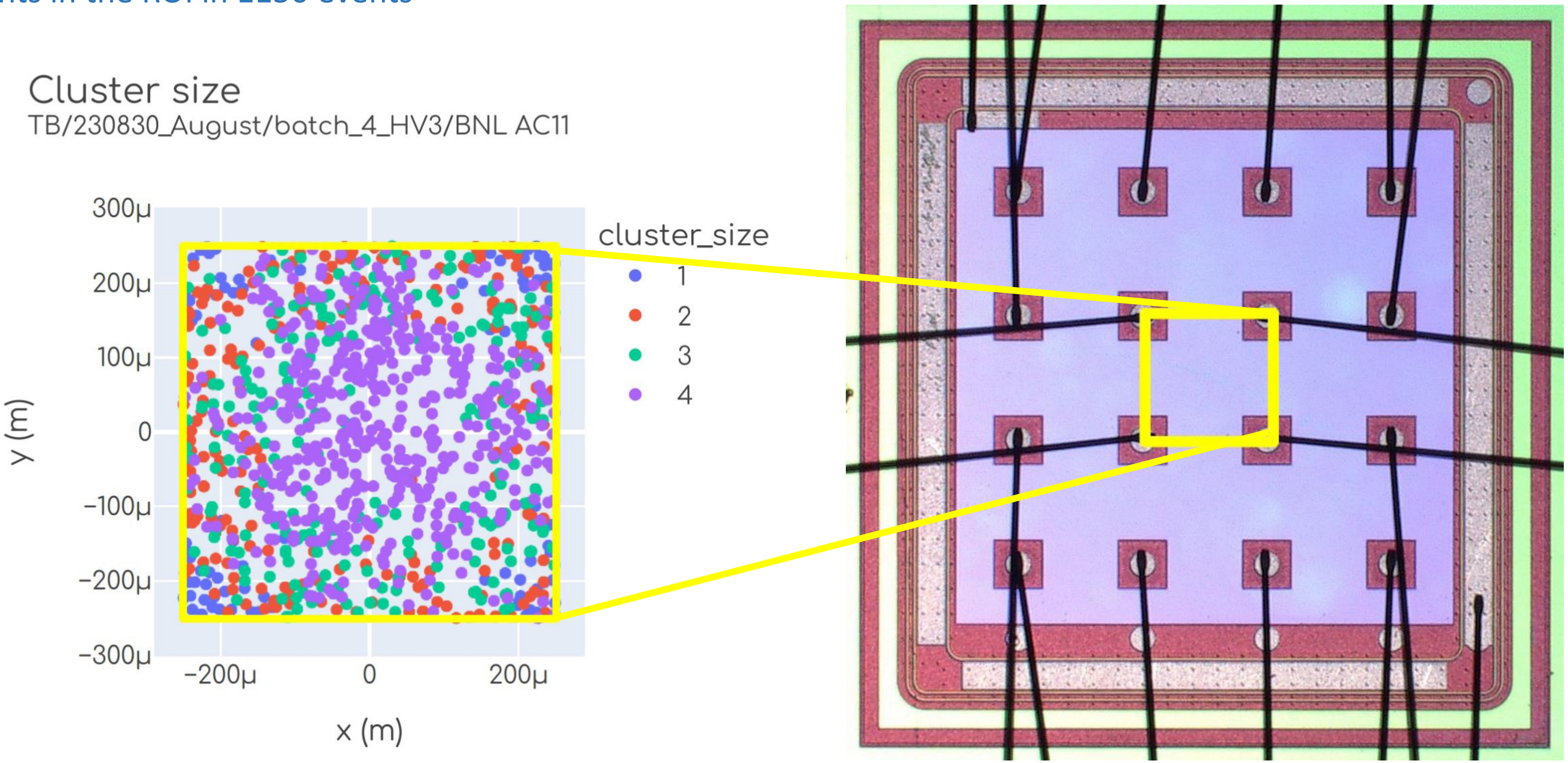


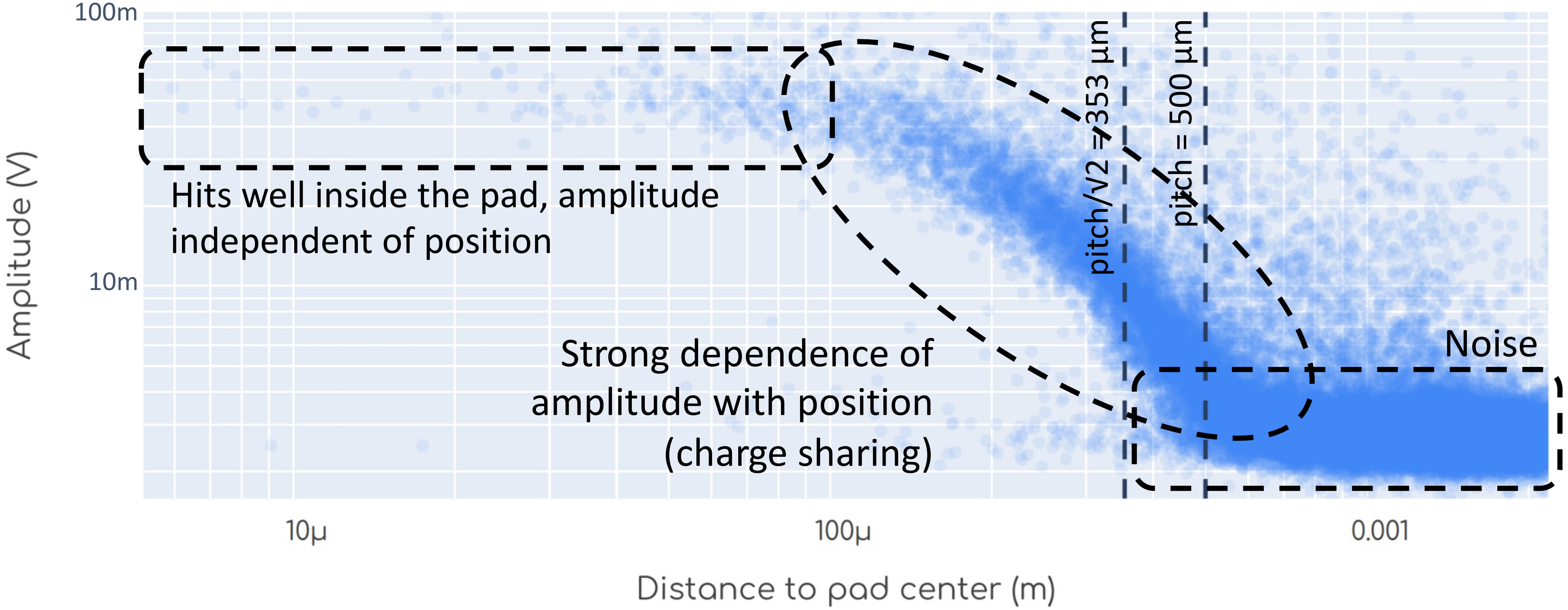
Efficiency for BNL AC-LGADs

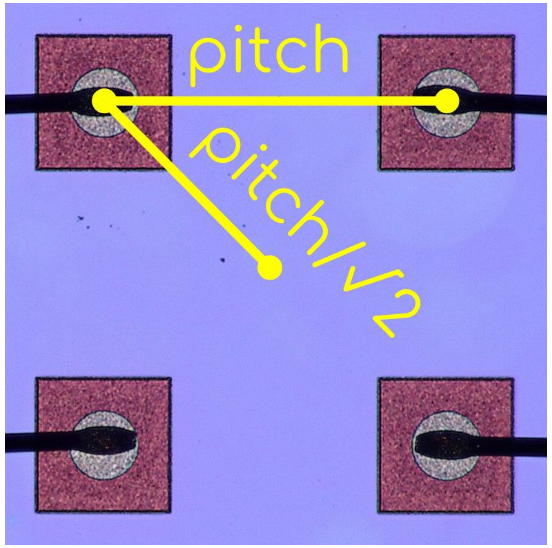
- Measured efficiency 100%
- Zero undetected events in the ROI in 1150 events



How much gain loss we can afford?

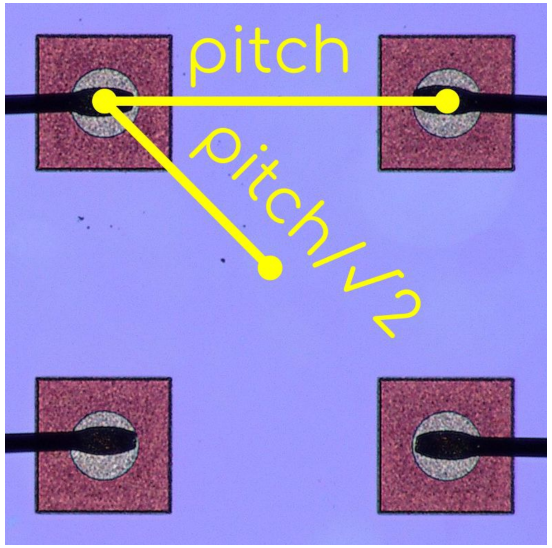
- Study of the amplitude as a function of the distance to the pad center in TB data
- Three different regimes are recognizable

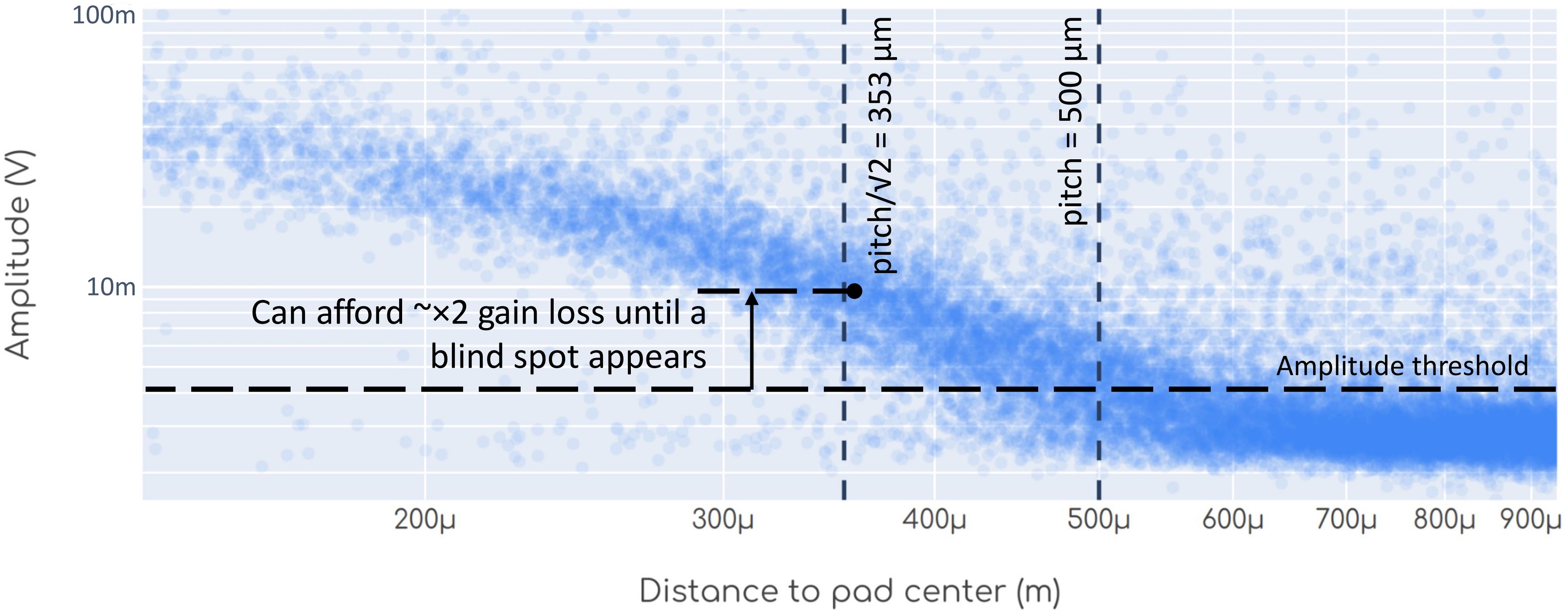




How much gain loss we can afford?

- Study of the amplitude as a function of the distance to the pad center in TB data
- Three different regimes are recognizable
- As long as the amplitude at the epicenter of the pads is higher than the noise, we can expect 100 % efficiency in all the surface, i.e. 100 % fill factor.

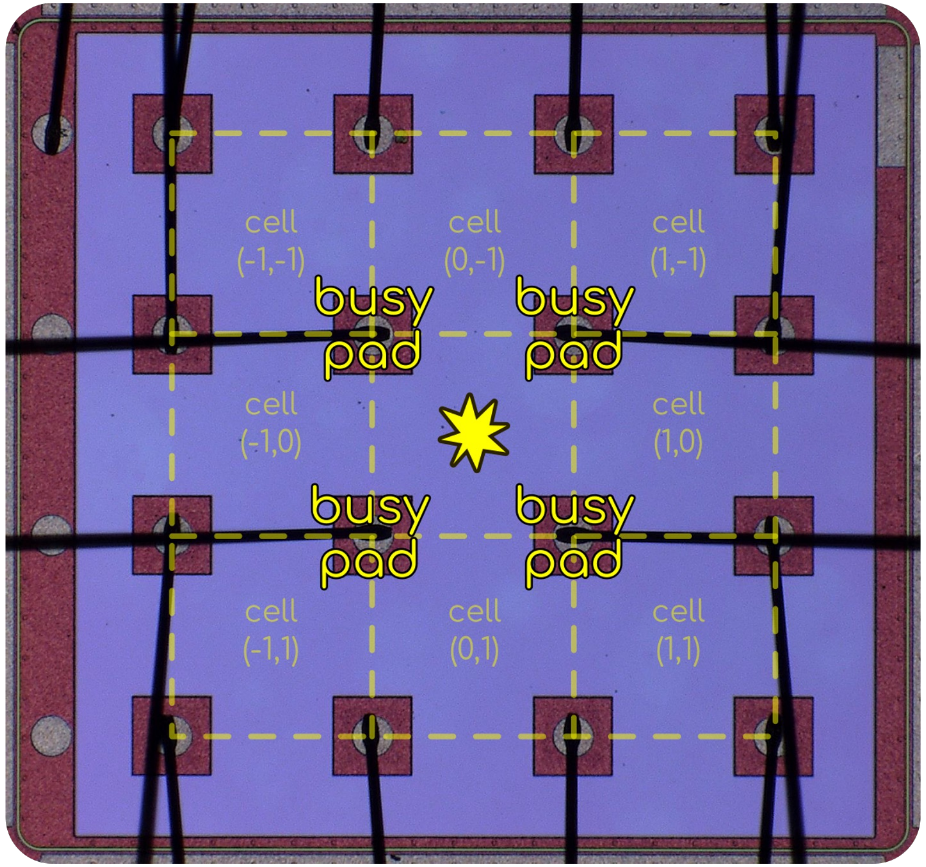




- This assumption has to be confirmed with a campaign on AC-LGAD irradiated devices

Maximum occupancy allowed by sensor technology

- TI-LGAD
  - Calculate it as a normal binary readout pixel
  - Small pixel sizes feasible by sensor technology itself (e.g. 50×50 μm²)
- AC-LGAD
  - Because of the charge sharing, neighboring cells must be free of hit for it to work (see cartoon)
  - For square cells: Factor of 9 worse than binary readout pixel with same pitch
  - For other cell shapes, this factor can improve*

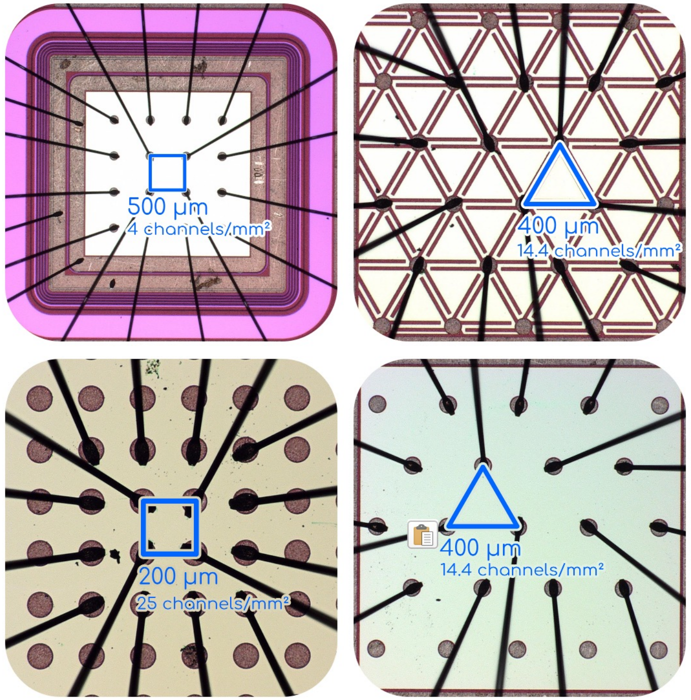


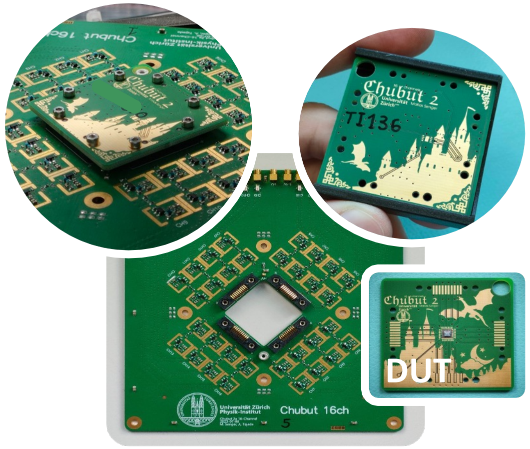
Future plans

- FBK AIDAinnova TI-LGAD production is presently being tested at the AIDAinnova TB in DESY
  - Addition of carbon co-implantation for enhanced radiation hardness: structures irradiated at 1e15, 1.5e15, 2.5e15
  - Interconnect TI-LGAD sensors to Timespot, Picopix and Timepix4 chips

  → *See presentation of A. Bisht in this workshop*

- BNL AC-LGAD is presently being tested at the AIDAinnova TB in DESY
  - New geometries: square and triangular pad arrays
  - Varying pitch between 200 and 500 μm
  - Some of these samples already irradiated, to be mounted on 16 channel boards





Chubut board, 16 channels with carrier board

Additional material

<table>
<tr><th>Wafer n.</th><th>Sub</th><th>Trench Depth</th><th>PGAIN</th><th>Diff</th><th>Trench isolation</th><th>note</th></tr>
<tr><td>1</td><td rowspan="18">45um</td><td rowspan="10">medium</td><td rowspan="2">D2</td><td rowspan="2">HD</td><td rowspan="5">v1 (W5,W7 from HD0 batch)</td><td>out</td></tr>
<tr><td>2</td><td></td></tr>
<tr><td>3</td><td rowspan="2">D1</td><td rowspan="2">LD</td><td>out</td></tr>
<tr><td>4</td><td></td></tr>
<tr><td>5</td><td>D3</td><td rowspan="14">HD</td><td></td></tr>
<tr><td>6</td><td rowspan="13">D2</td><td rowspan="3">v2</td><td>broken</td></tr>
<tr><td>7</td><td>out</td></tr>
<tr><td>8</td><td></td></tr>
<tr><td>9</td><td rowspan="2">v3 (W9 from HD0 batch)</td><td>out</td></tr>
<tr><td>10</td><td></td></tr>
<tr><td>11</td><td rowspan="4">shallow</td><td rowspan="2">v1</td><td>out</td></tr>
<tr><td>12</td><td></td></tr>
<tr><td>13</td><td>v2</td><td></td></tr>
<tr><td>14</td><td>v3</td><td></td></tr>
<tr><td>15</td><td rowspan="4">deep</td><td>v1</td><td></td></tr>
<tr><td>16</td><td rowspan="2">v2</td><td>out</td></tr>
<tr><td>17</td><td></td></tr>
<tr><td>18</td><td>v3</td><td></td></tr>
</table>

V1 ~ 1 µm
V2 ~ 3 µm
V3 ~ 4 µm
V4 ~ 5 µm