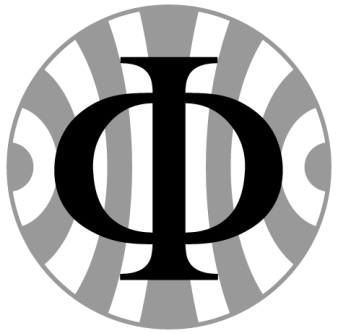
Charge Deposition and Collection in HV-MAPS



27.02.2023

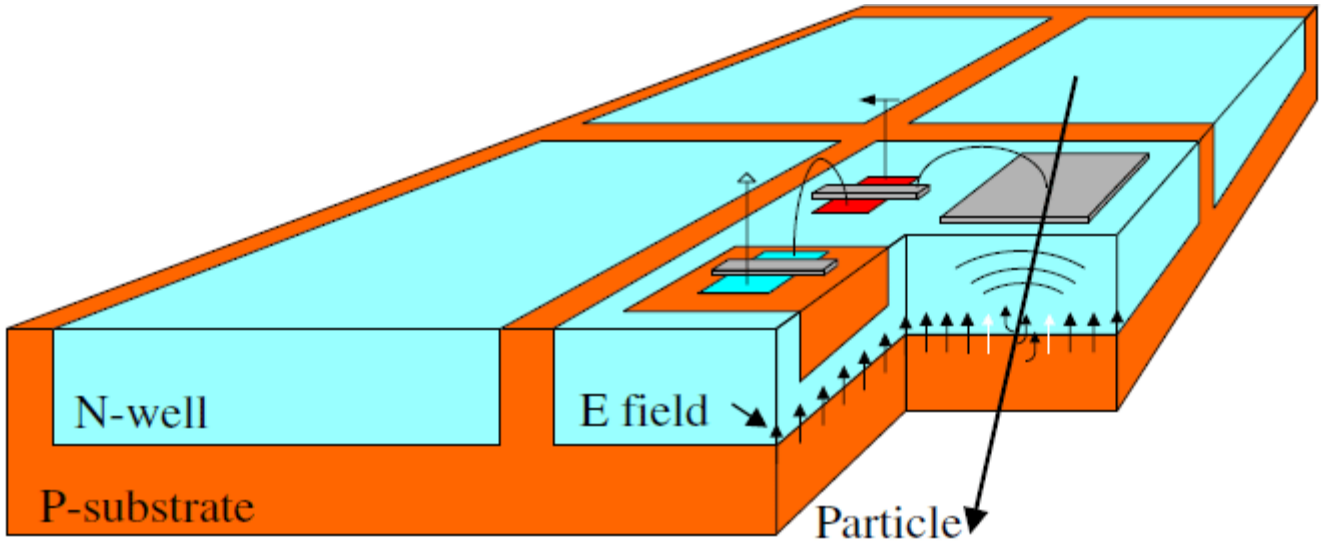
BMBF Verbund Meeting CMOS

Ruben Kolb

On Behalf of the HV-MAPS Collaboration Heidelberg

High Voltage - Monolithic Active Pixel Sensors (HV-MAPS)

- Monolithic: Readout and active volume on same chip



[I.Peric, P. Fischer et al., NIM A 582 (2007) 876]

Characteristics:

- Diode realised as deep n-well in p-substrate reversly biased up to -140 V

→ $w \propto \sqrt{\rho U}$

- Fast charge collection via drift in depleted volume

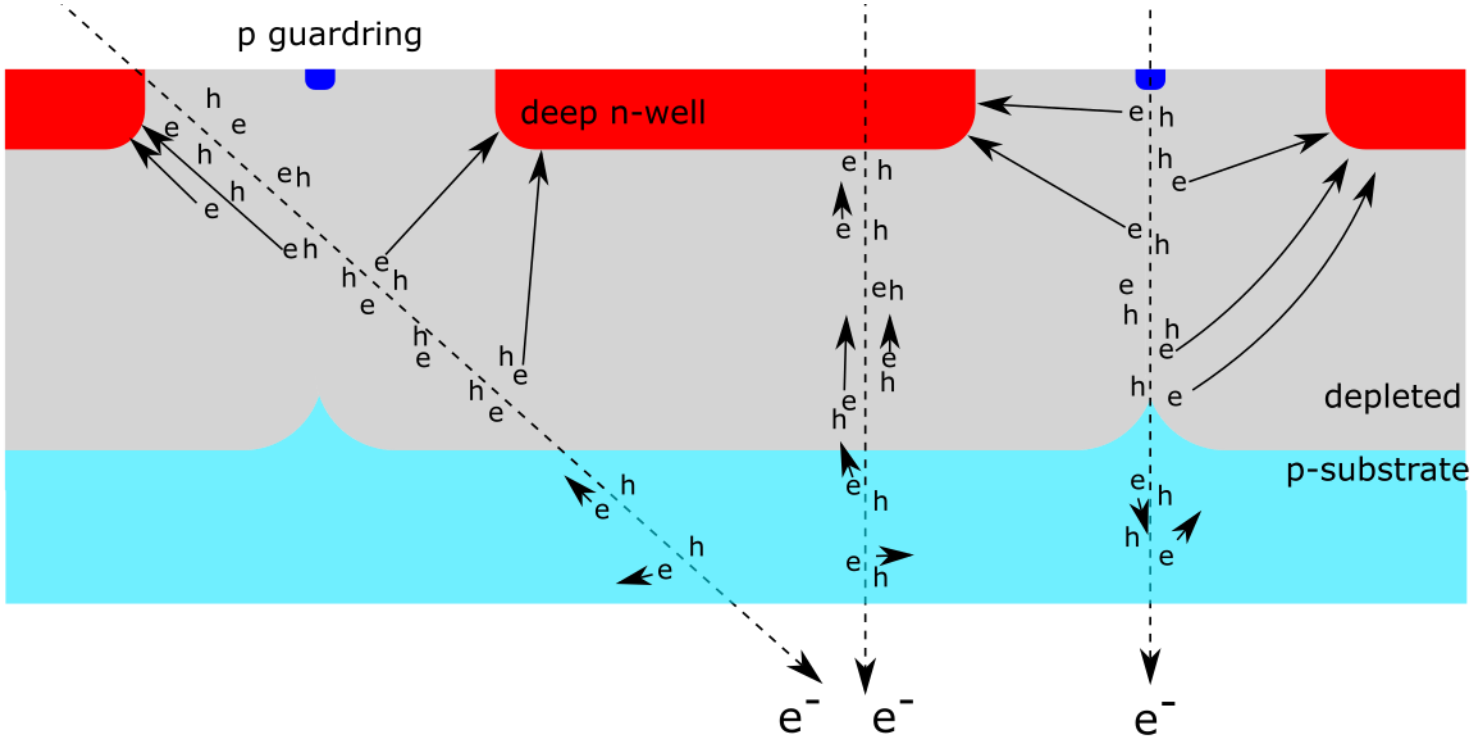
Charge Deposition and Collection in HV-MAPS

- Traversing particle creates e-h pairs
- Fast charge in depleted volume collected via drift
- Diffusion in non depleted volume
- $\sigma = \sqrt{2Dt}$

Time [ns]	Gaussian spread σ [µm]
500	62 ± 2.4
750	75 ± 3
1000	87 ± 3

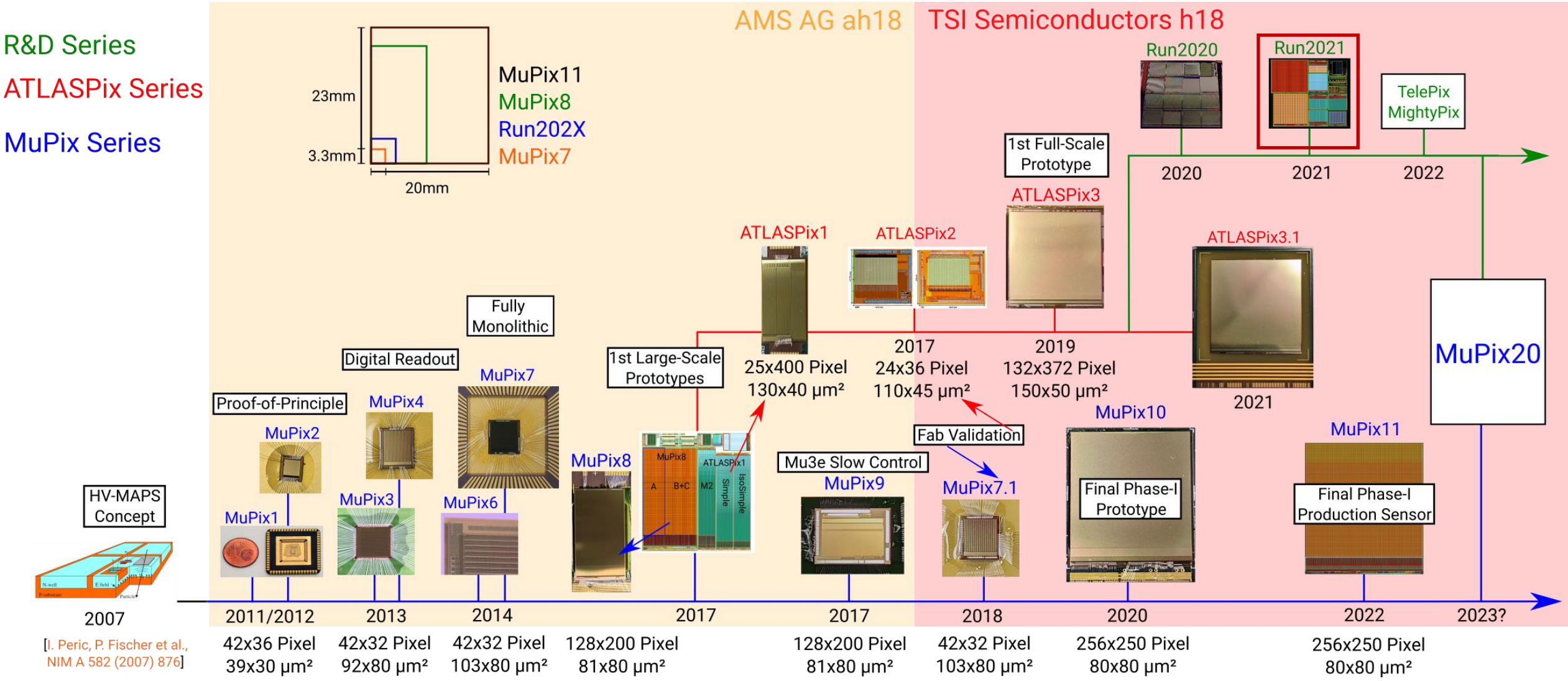
→How large is the contribution from diffusion?

[H. Augustin doi:10.11588/heidok.00030885, modified]



Fick's law: $\frac{\mathrm{d}Q}{\mathrm{d}x}(\vec{x},t) = \frac{1}{8(\pi Dt)^{\frac{3}{2}}} \int Q_0(\vec{x}) e^{-\frac{(\vec{x}-\vec{x}')^2}{4Dt}} \mathrm{d}\vec{x}$

HV-MAPS Roadmap

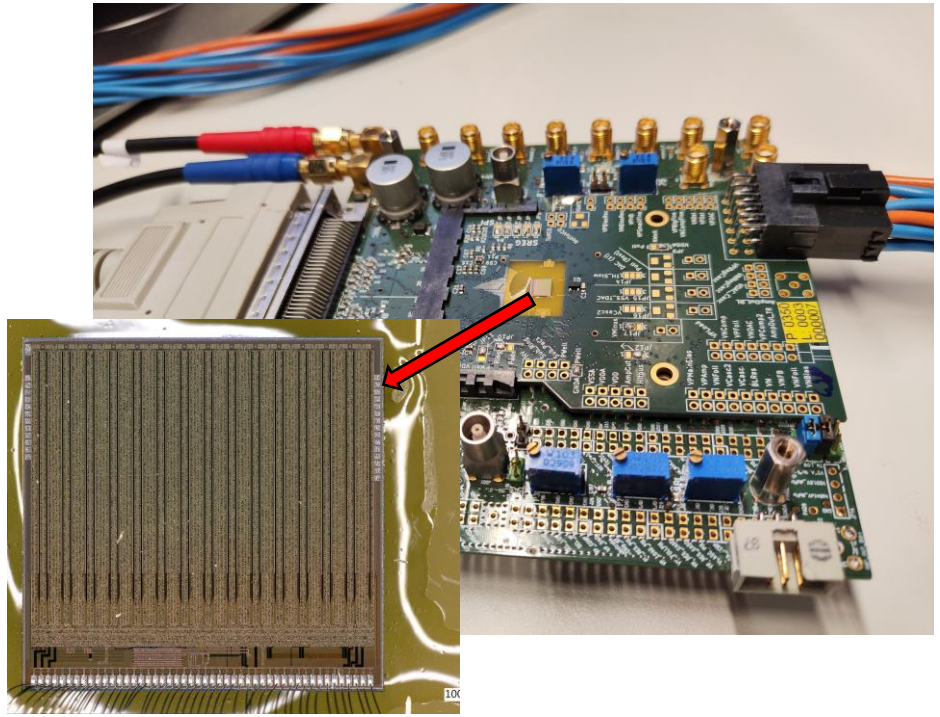


D. Immig, *MuPix10: An Unexpected Journey* (2022)

Run2021V2

- Small scale (5×5 mm²) R&D sensor
- In-pixel electronics contain amplifier and CMOS comparator

→Best possible sensor architecture

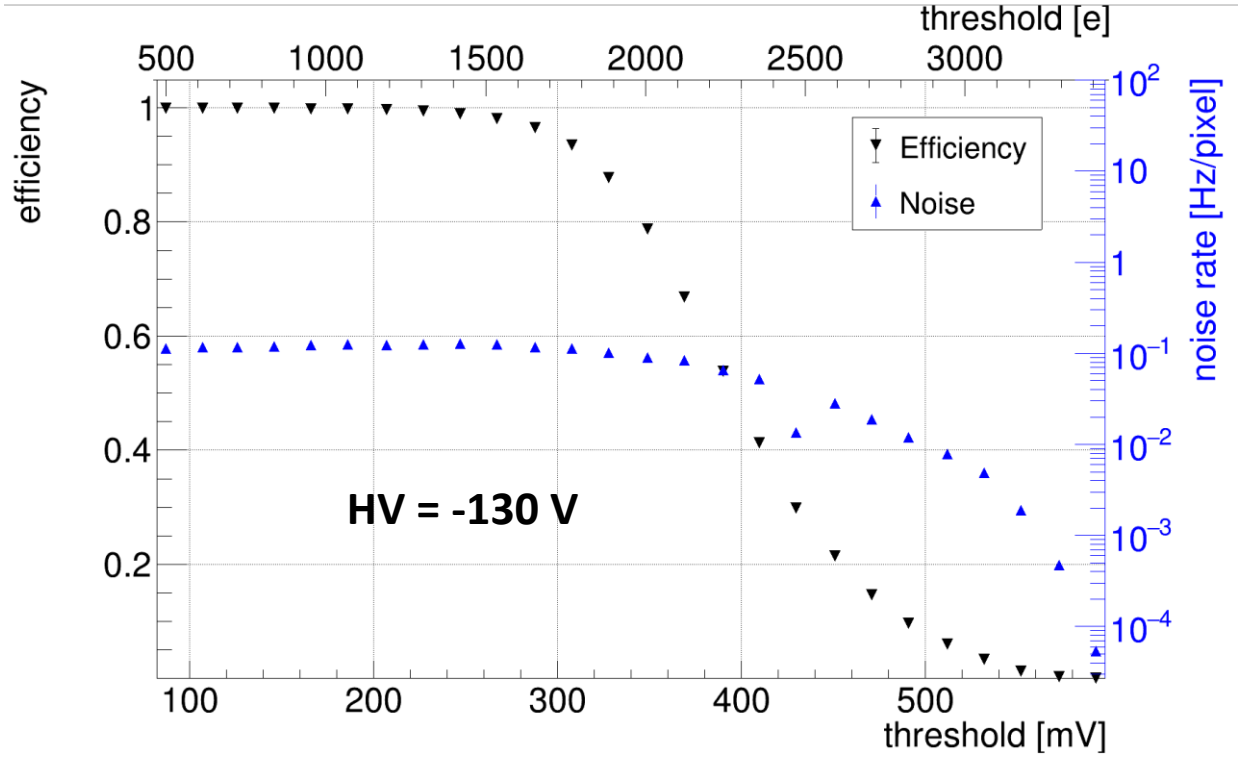


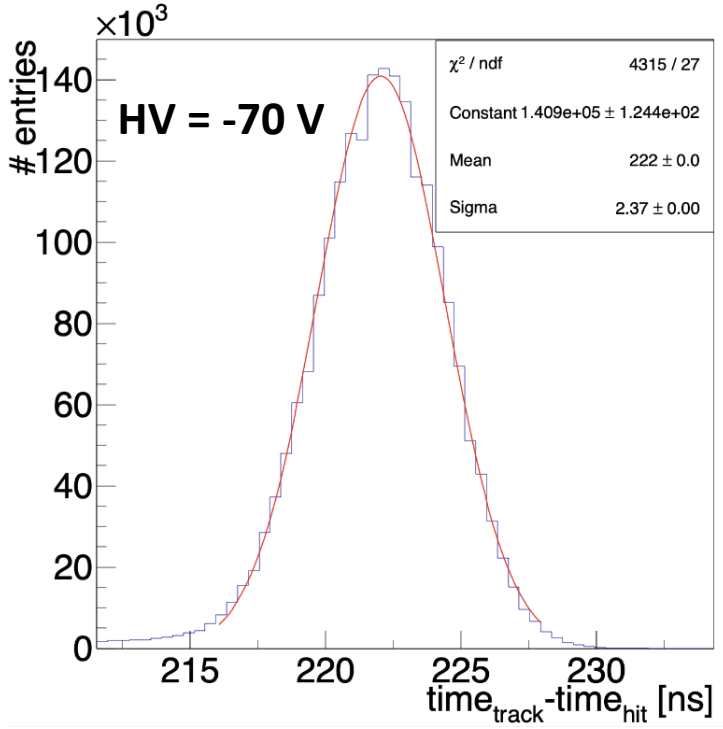
→Following results focus on:
d=50 µm, 100 µm, 600 µm; $\rho = 370\ \Omega\mathrm{cm}$

Substrate [Ωcm]	20, **370**, ~8000
Thickness [µm]	**50**, **100**, 300, **600**
Matrix [Pixel]	29x124
Pixel size[µm²]	165x25
Sensor size [mm²]	5x5

Prototype Performance: Efficiency and Time Resolution

- 100 µm, source: 4 GeV e^- beam
- Efficiency > 99%, average noise < 0.1 Hz/pixel
- With 8 ns binning and without corrections: $\sigma_t < 2.4$ ns

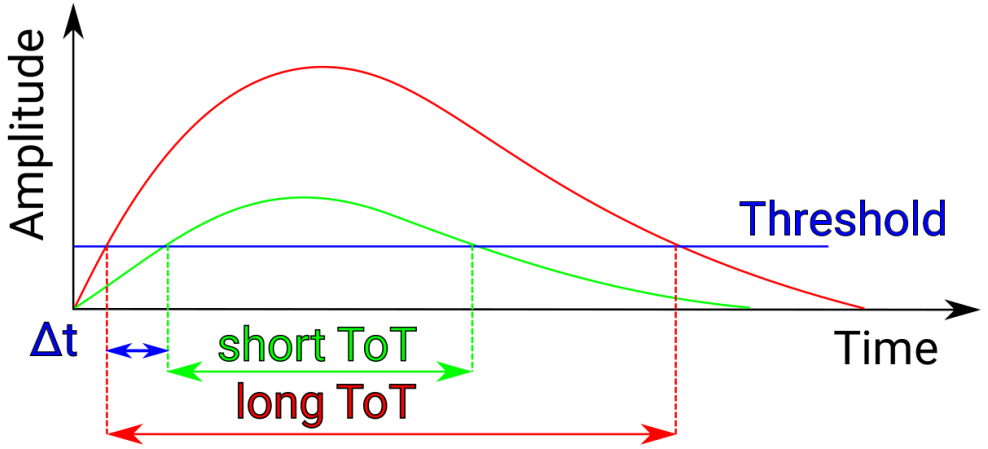




H. Augustin, arXiv:2212.10248

Measurement Setup

- Study charge collection by varying HV with various signal sources
- Compare ToT & Cluster size of DUTs at **same configuration** & **HV**

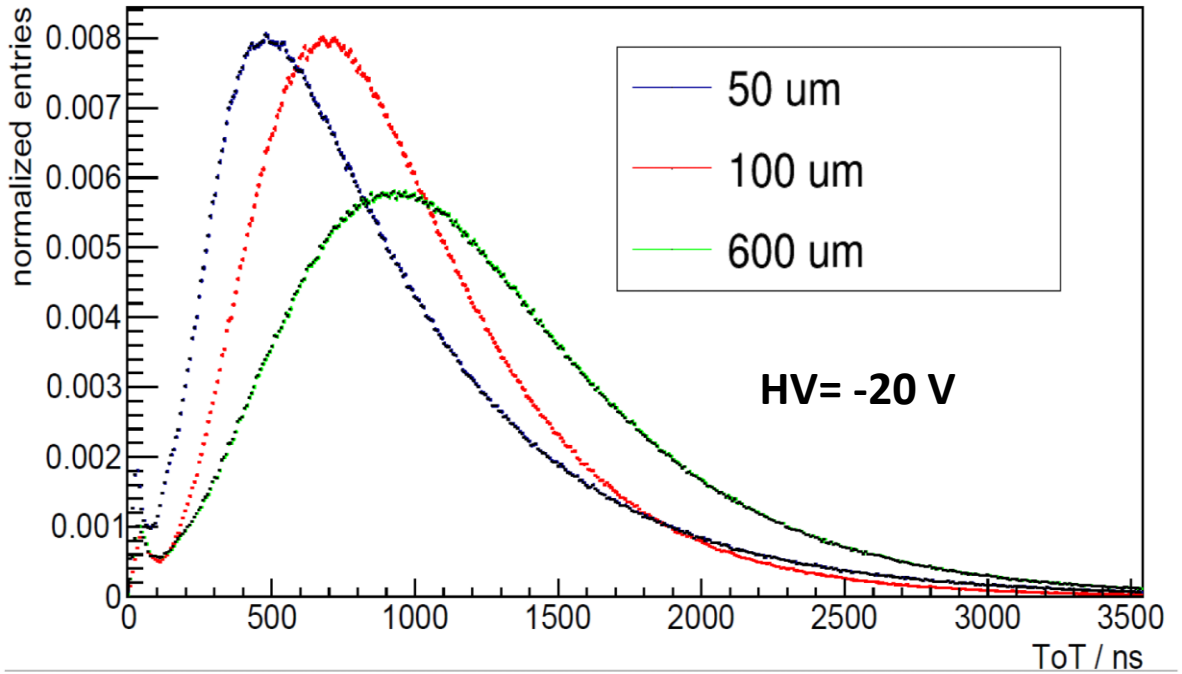


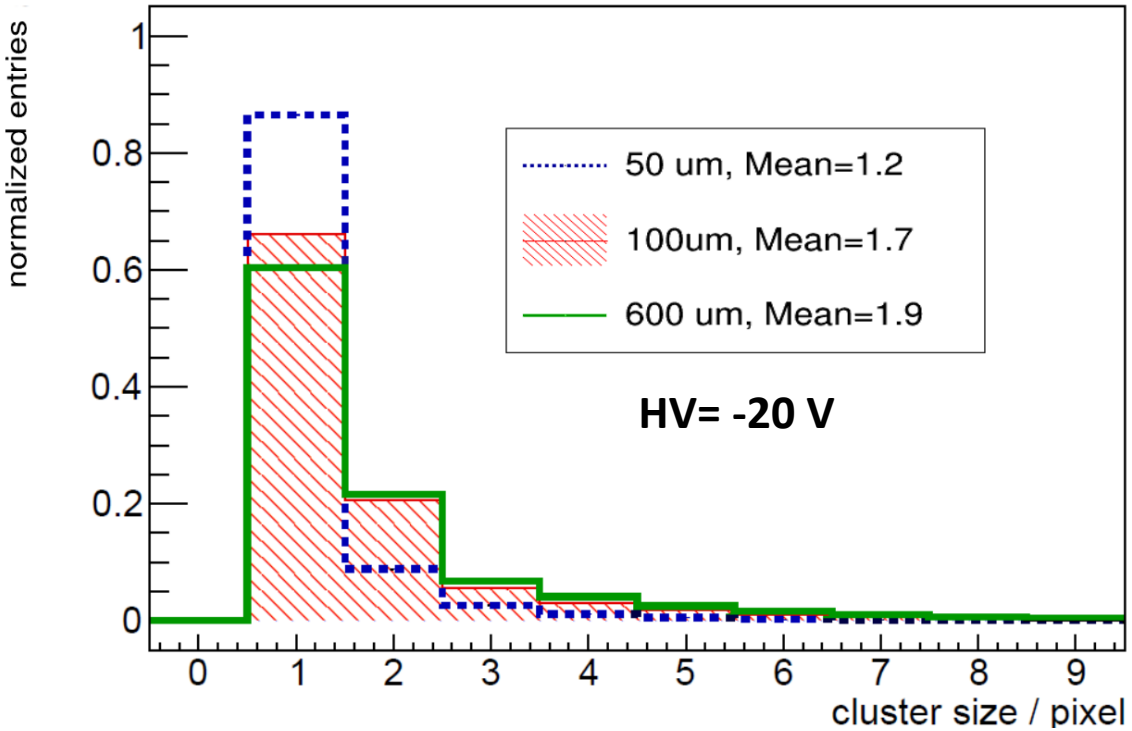
- $^{90}\mathrm{Sr}$: 2.28 MeV e^- source → continous spectrum
- $^{55}\mathrm{Fe}$: Monochromatic x-ray source 5.9 keV
- Testbeam@DESY: 4 GeV electrons

$$w \propto \sqrt{\rho U}$$

High Voltage [-V]	Approx. Depletion Depth (ρ= 370 Ωcm) [µm]
20	30
80	60
130	~75

Cluster Size and ToT Spectra of ^{90}Sr





- 50 µm sensor completly depleted

→No diffusive contribution to signal

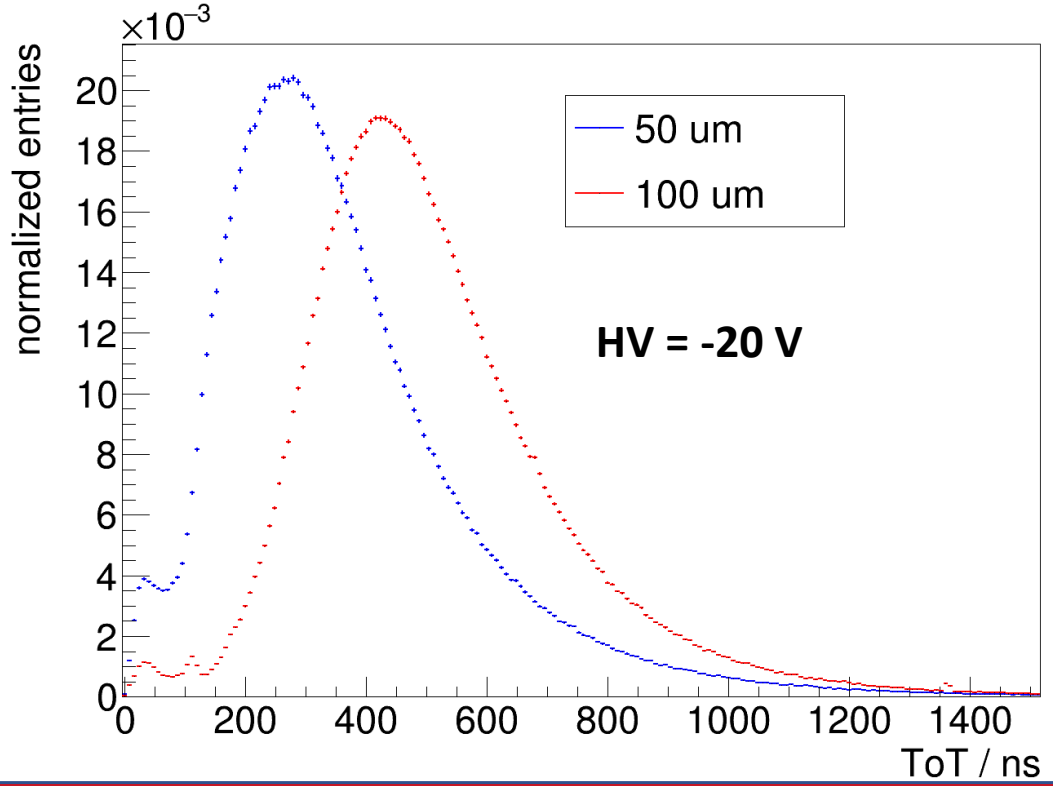
- Thicker chip → higher ToT, larger average cluster size

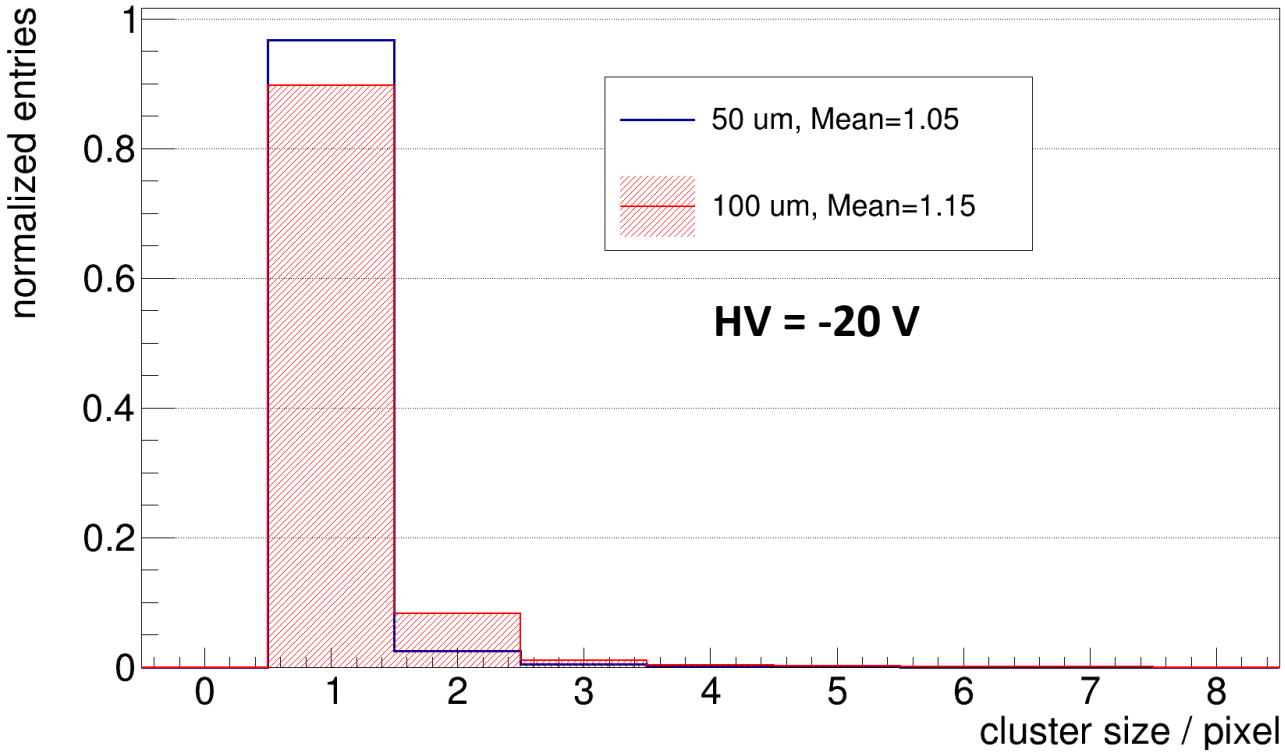
Chip Thickness	Depletion Depth[µm]	Undepleted Substrate [µm]
50	30	~0
100	30	50
600	30	550

Testbeam: Clustersize and TOT 50 µm vs 100 µm

- 4 GeV electron beam, both sensors at same configuration
- Higher ToT/ cluster size for 100 µm Chip

→Diffusion of charges into depleted volume



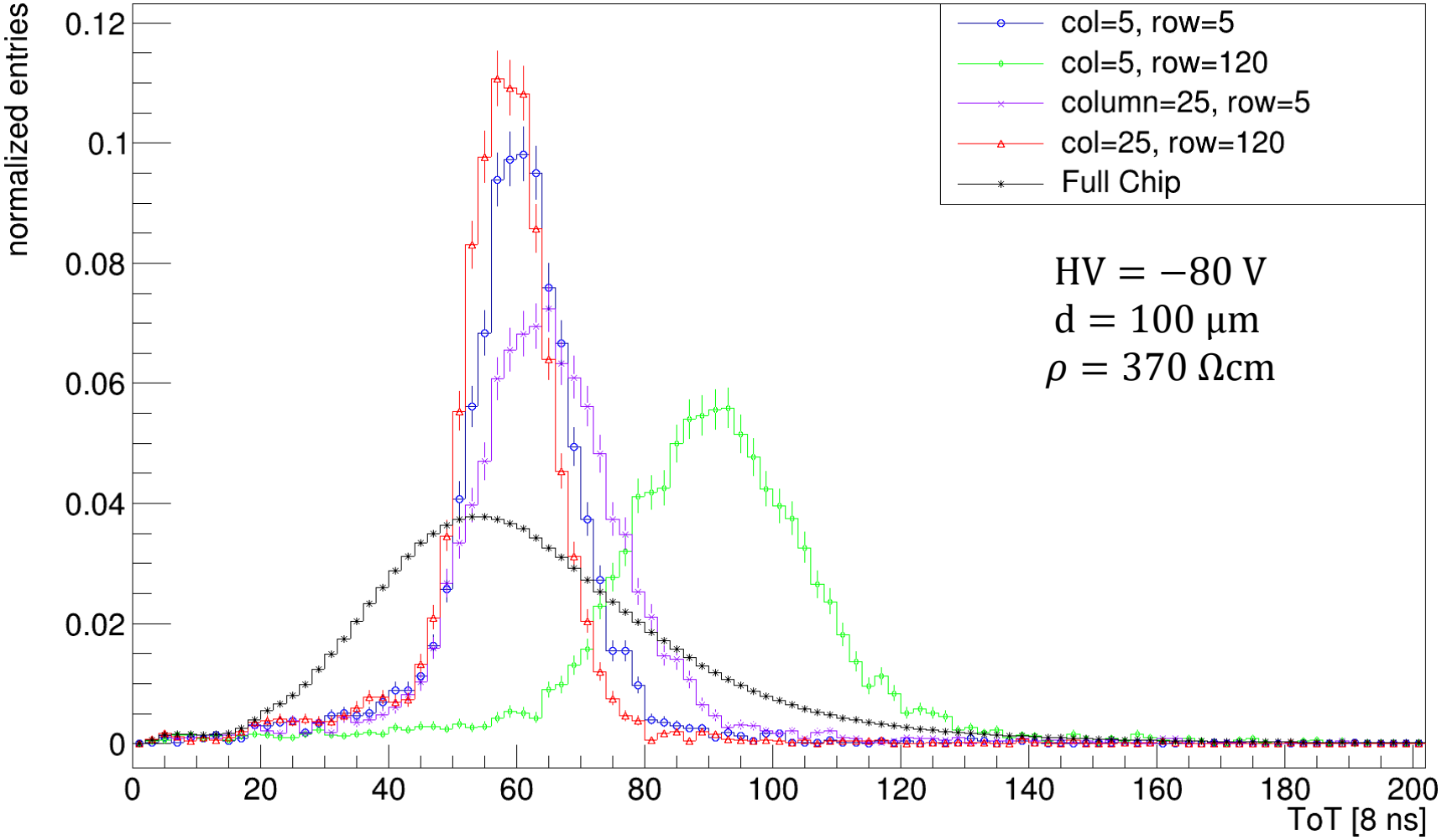


^{55}Fe Spectrum - Single Pixel vs Full Chip

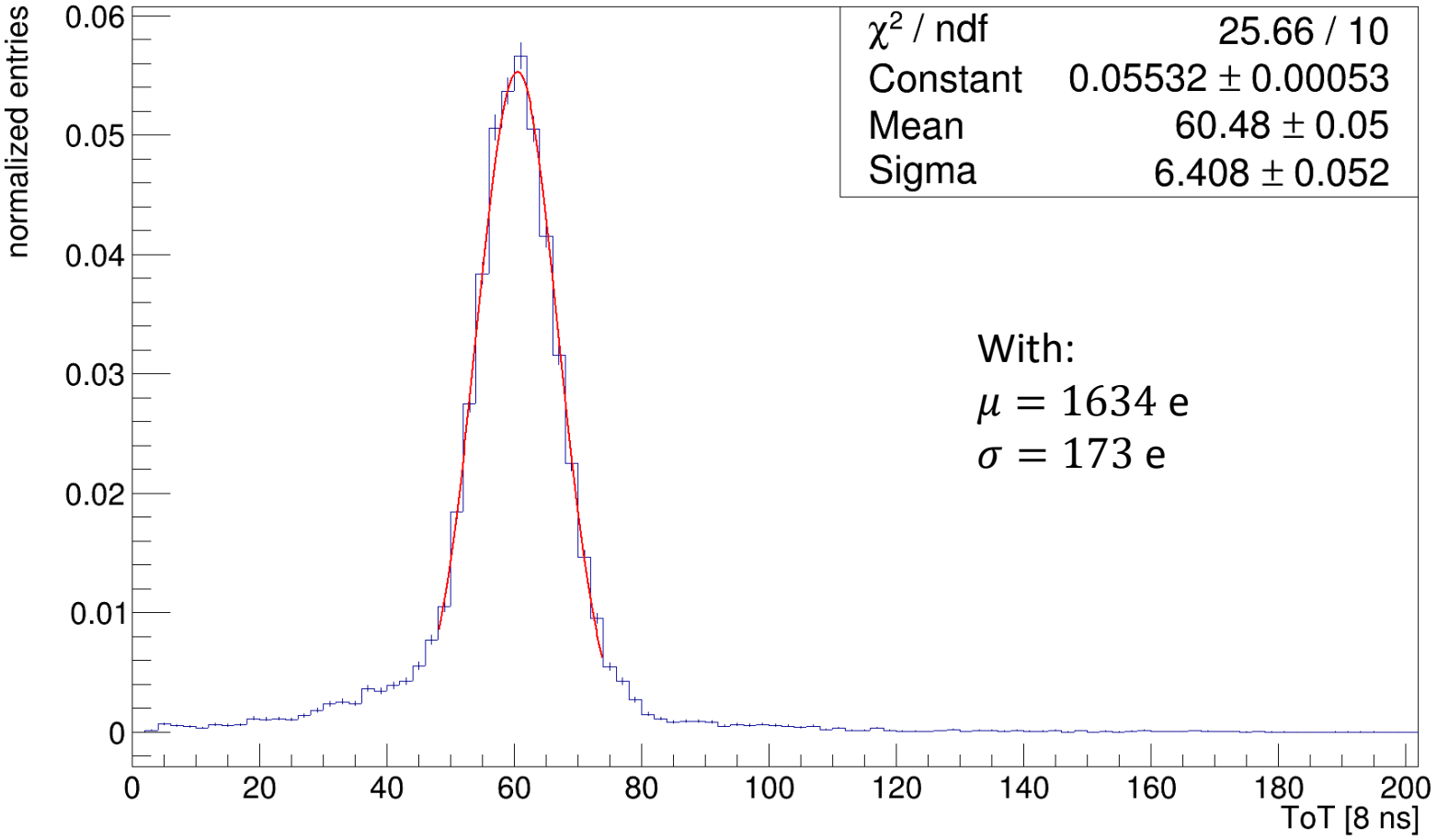
- ^{55}Fe : Monochromatic x-ray source 5.9 keV
- Full chip ToT vs (random) single pixels ToT

→Pixel response varies

→Calibration necessary



Energy Resolution



- Use $^{55}\mathrm{Fe}$ single pixel ToT
- Not considered: Charge sharing, second peak (6.5 keV)
- Assume linearity ToT to Energy
- $\frac{\sigma_E}{E} = 0.106$
- Energy resolution (FWHM):

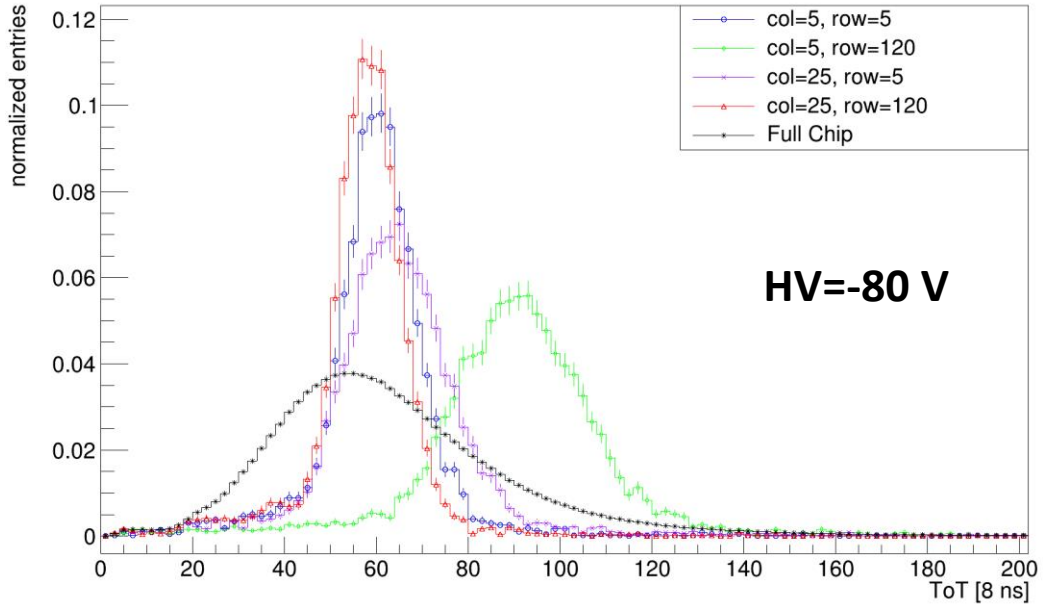
$$\frac{\Delta E}{E} = 0.250$$

Summary & Outlook

- ToT/ cluster size increases with thickness (testbeam & laboratory)

→Diffusion considerably increases signal and cluster size for small depletion depth

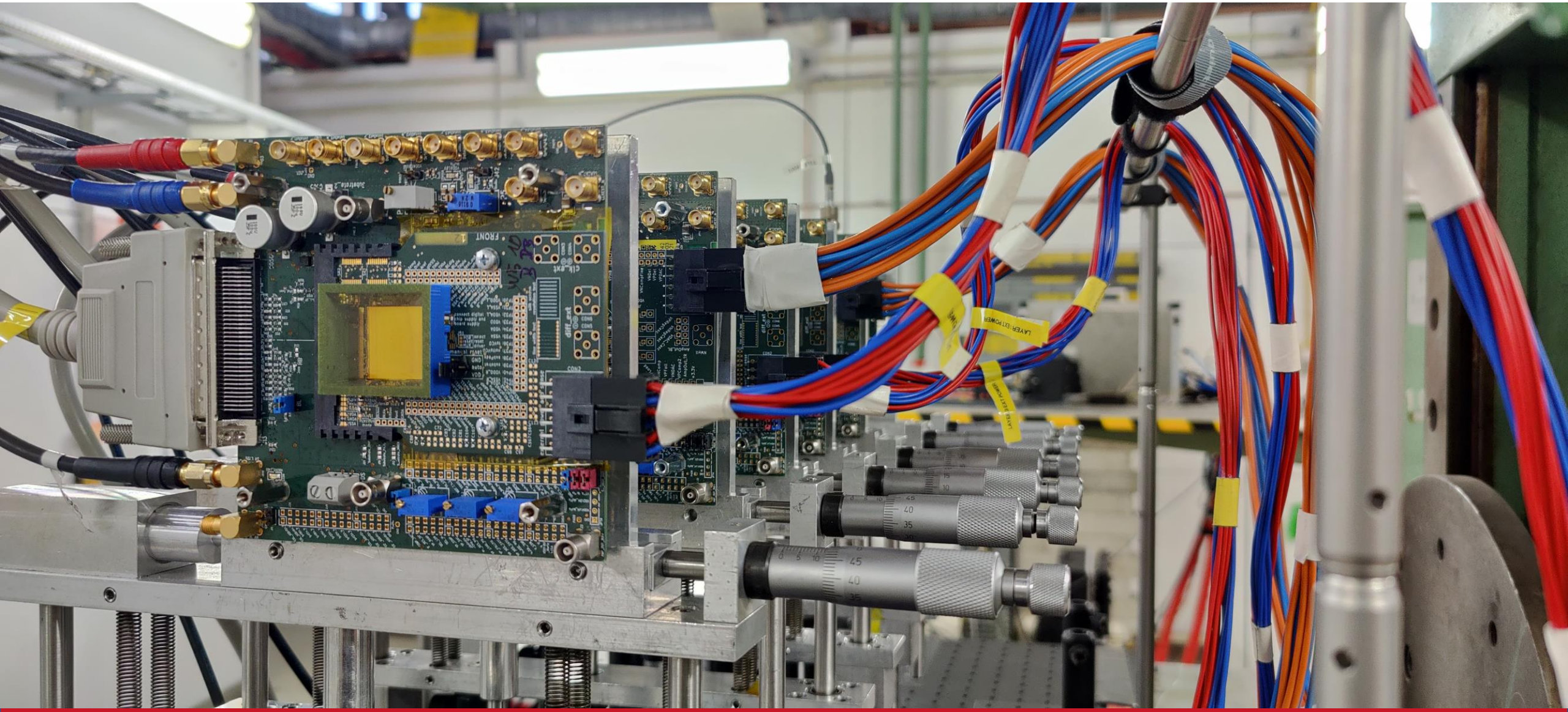
- Single Pixel: $\frac{\sigma_E}{E} = 0.106$ (at 5.9 keV)
- Pixel response varies → to compare two pixels calibration needed → $^{55}\mathrm{Fe}$



→Outlook: Compare calibrated sensors with different thicknesses

- Compare measurements with Allpix^2 simulation

Backup

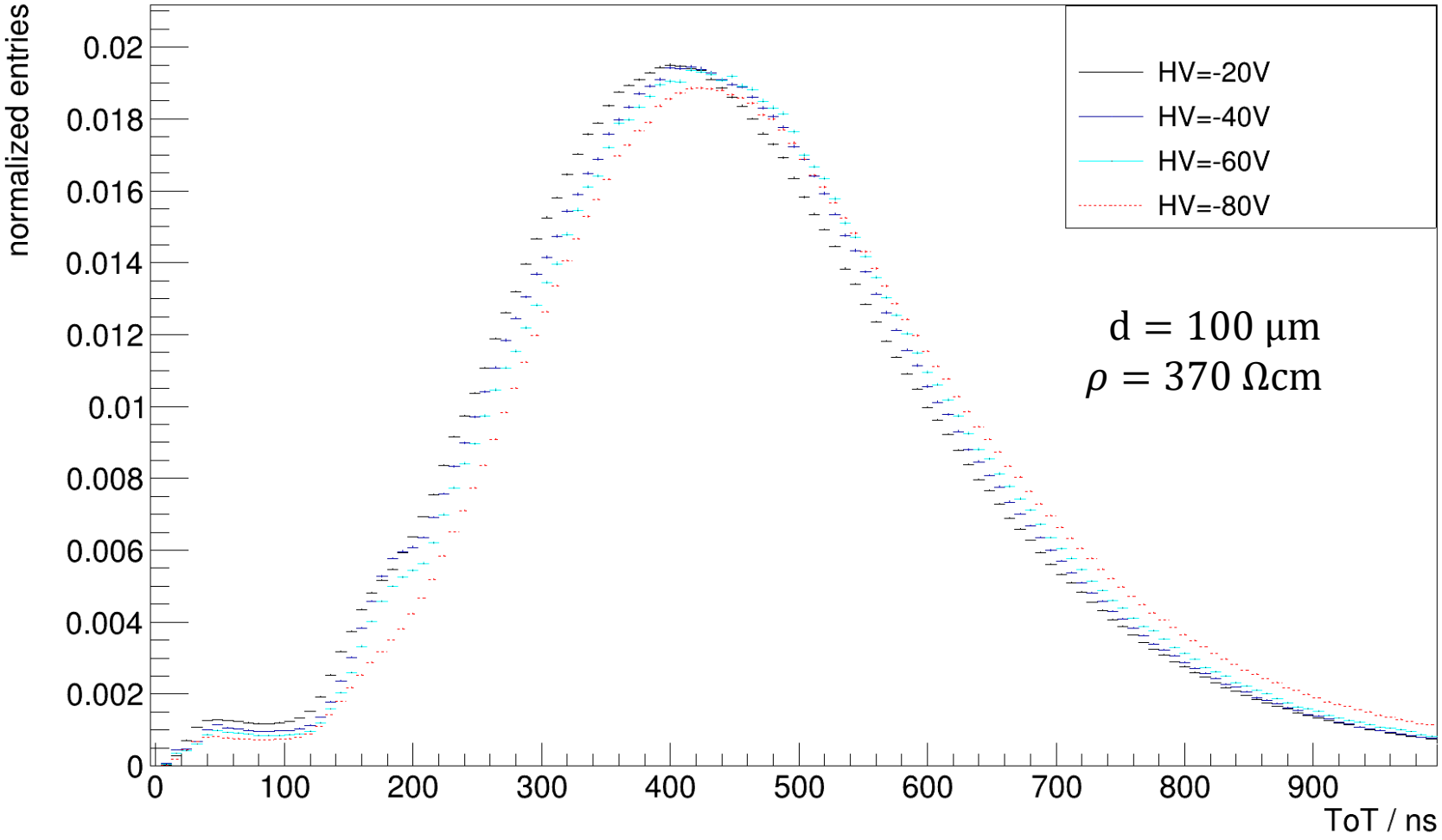


^{55}Fe Spectrum – HV Dependence

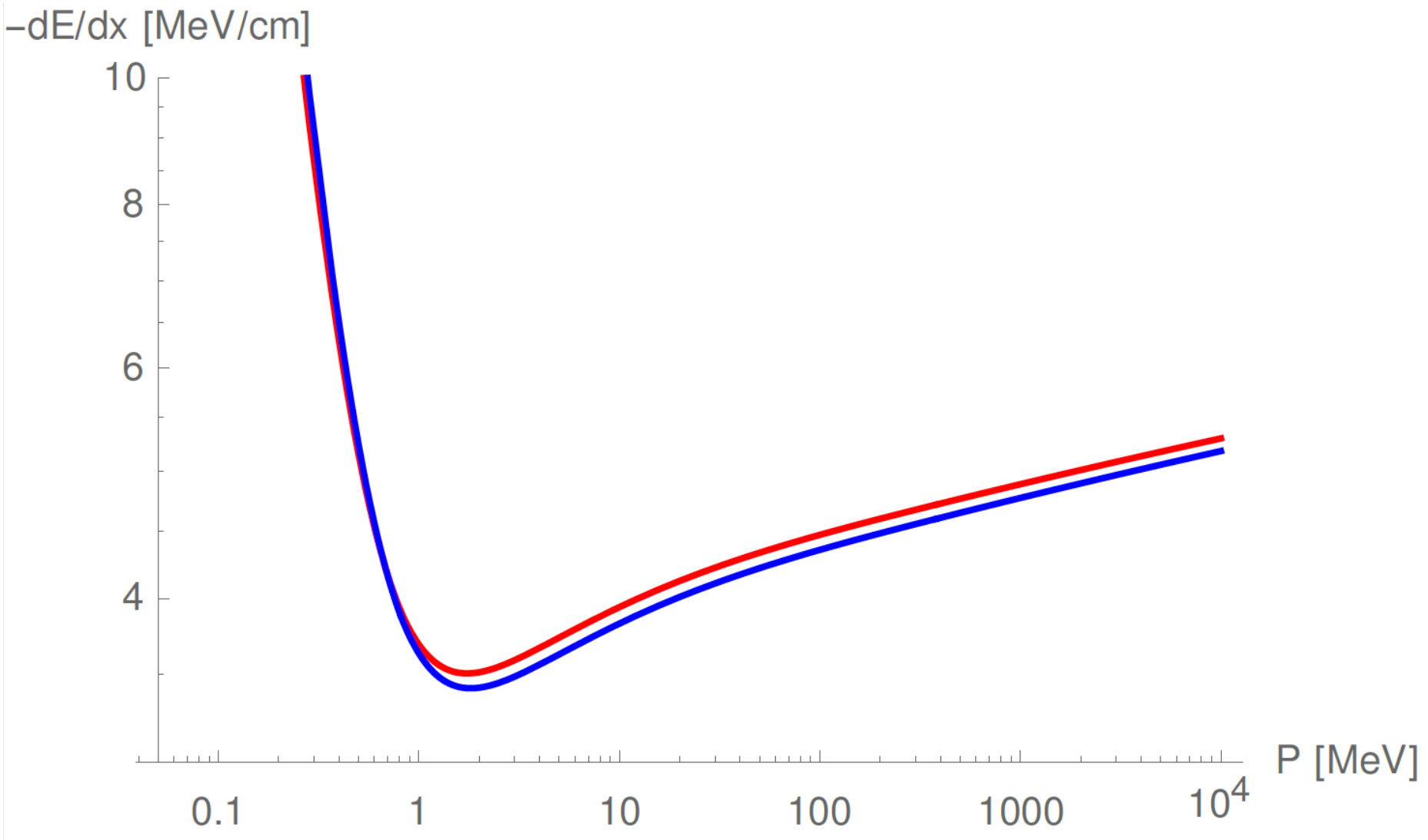
- ^{55}Fe signal in dependence of HV
- Only small shifts visible

→No large contribution by diffusion: 5.9 keV e^- is absorbed in depleted zone

- Difference in signal by decreasing pixel capacitance

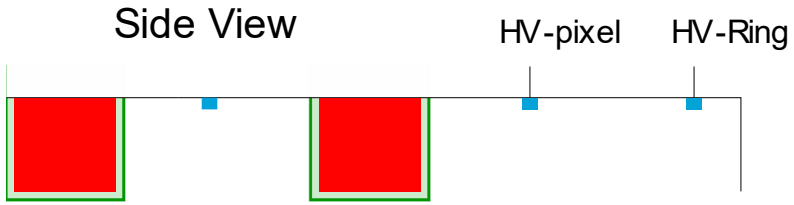


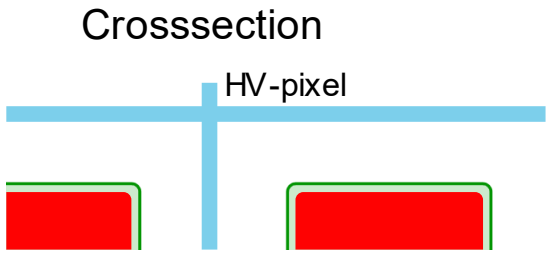
Berger Seltzer

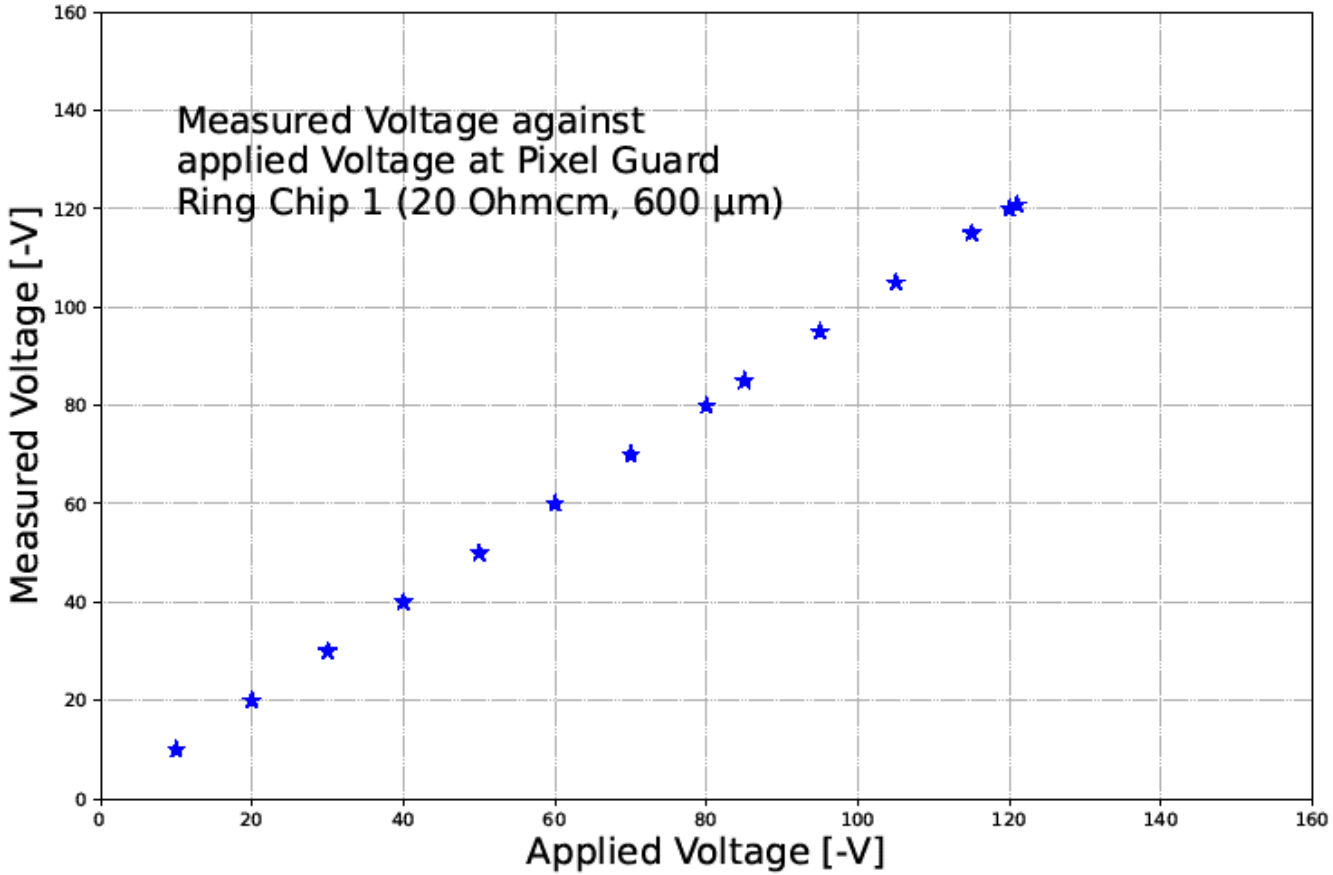


Voltage Measurements Run 2021 v2, $\rho = 20\ \Omega\mathrm{cm}$

- HV applied at Pixel Guard Ring, measured at Chip Guard Ring
- Voltage at Chip Guard Ring follows exactly

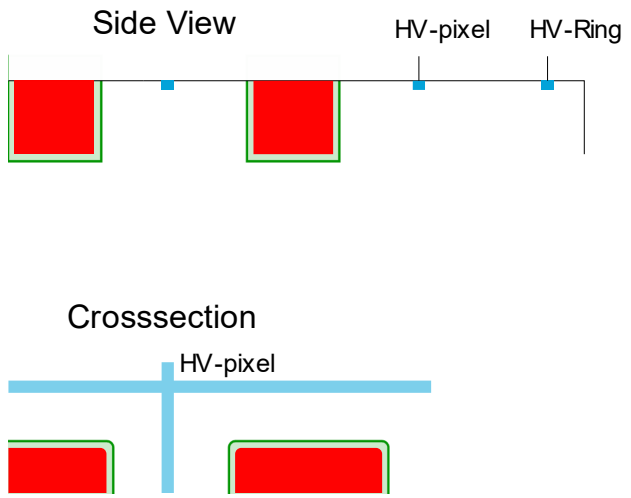


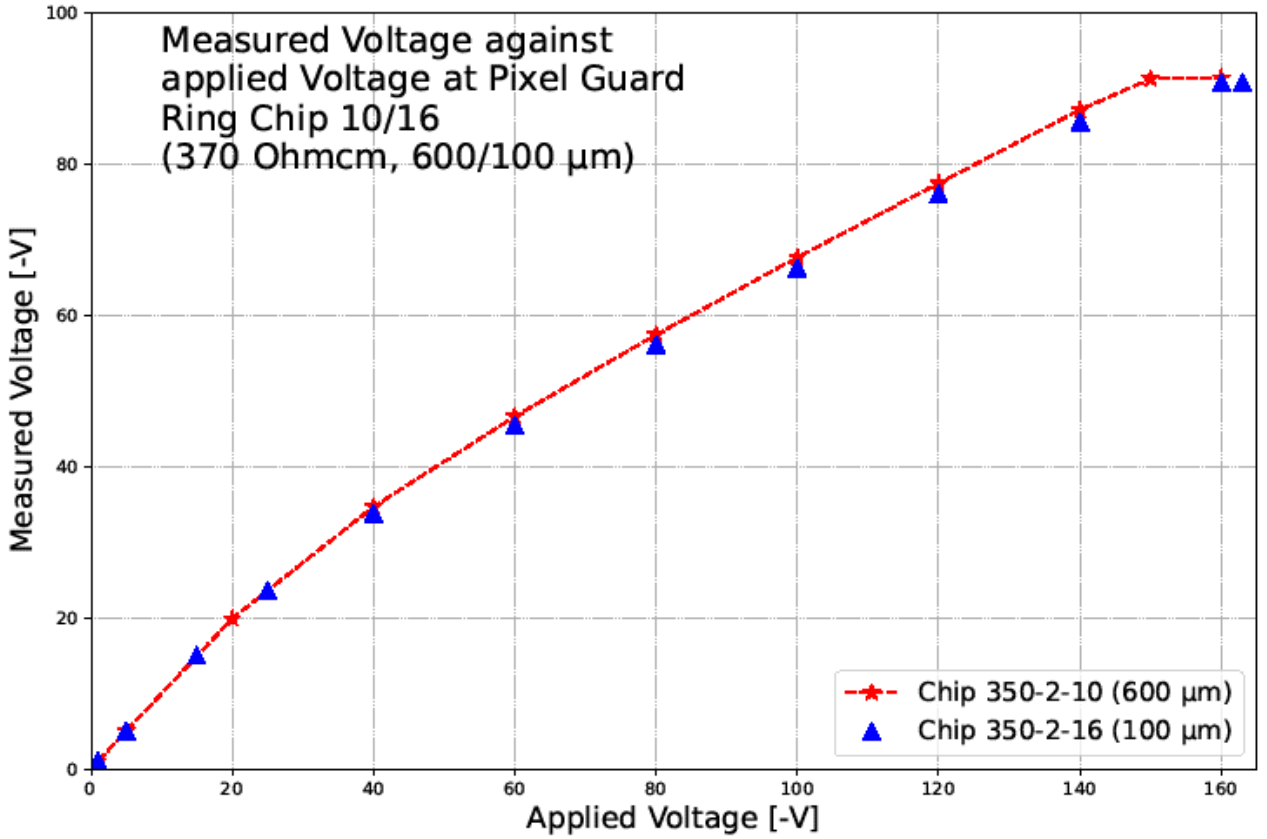




Voltage Measurements, $\rho = 370\ \Omega\mathrm{cm}$

- HV via Chip Guard Ring → Measured voltage at Pixel Guard Ring is lower
- At breakdown voltage ~ 91 V measured at Pixel Guard Ring





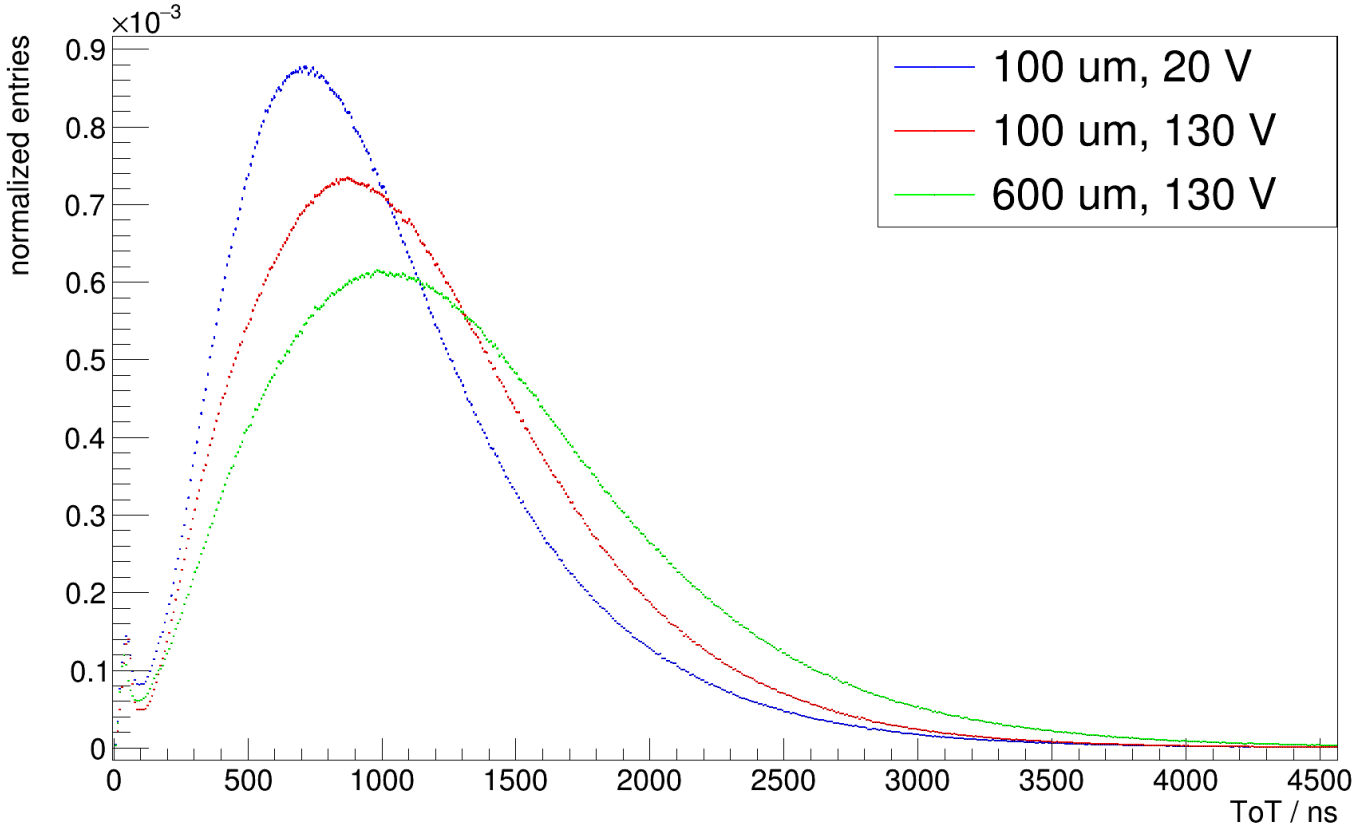
ToT Spectra of ^{90}Sr

- HV= -130 V: ~75 µm depletion depth

→Larger signal from drift

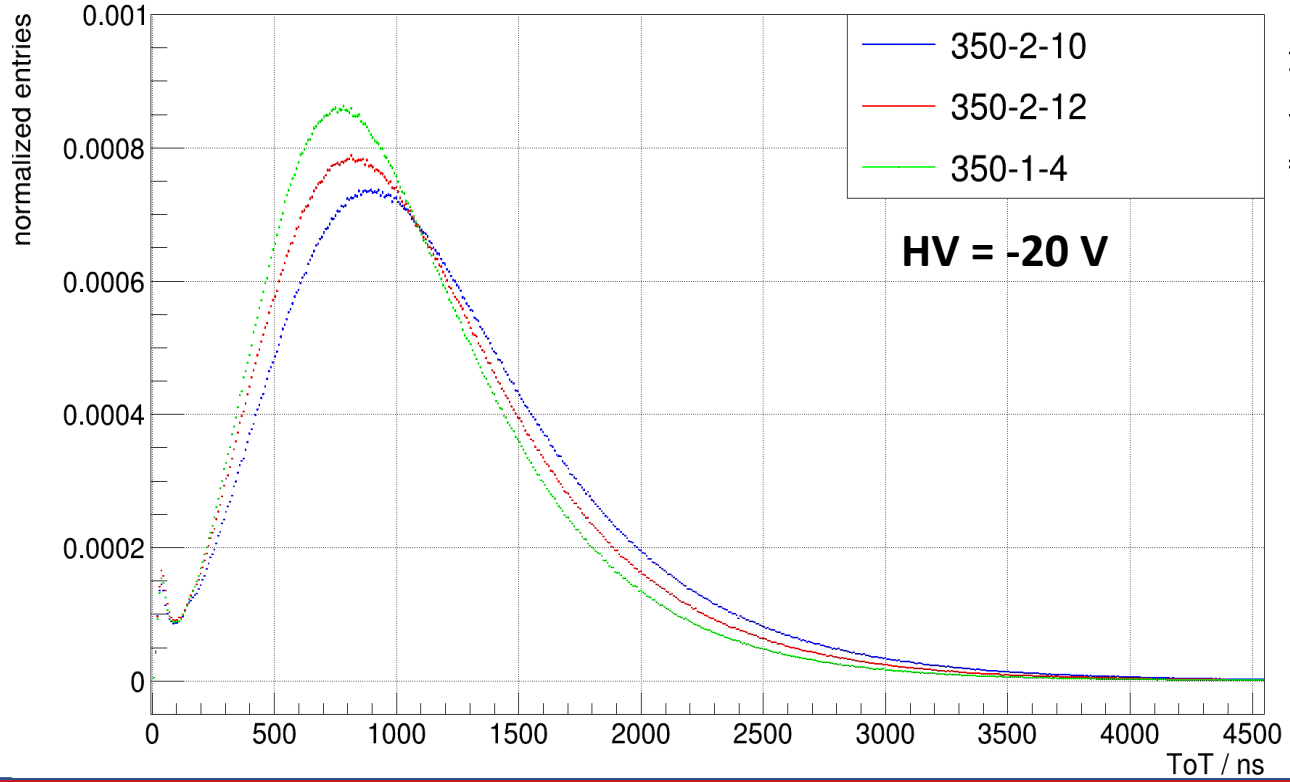
→Amplifier reaches saturation

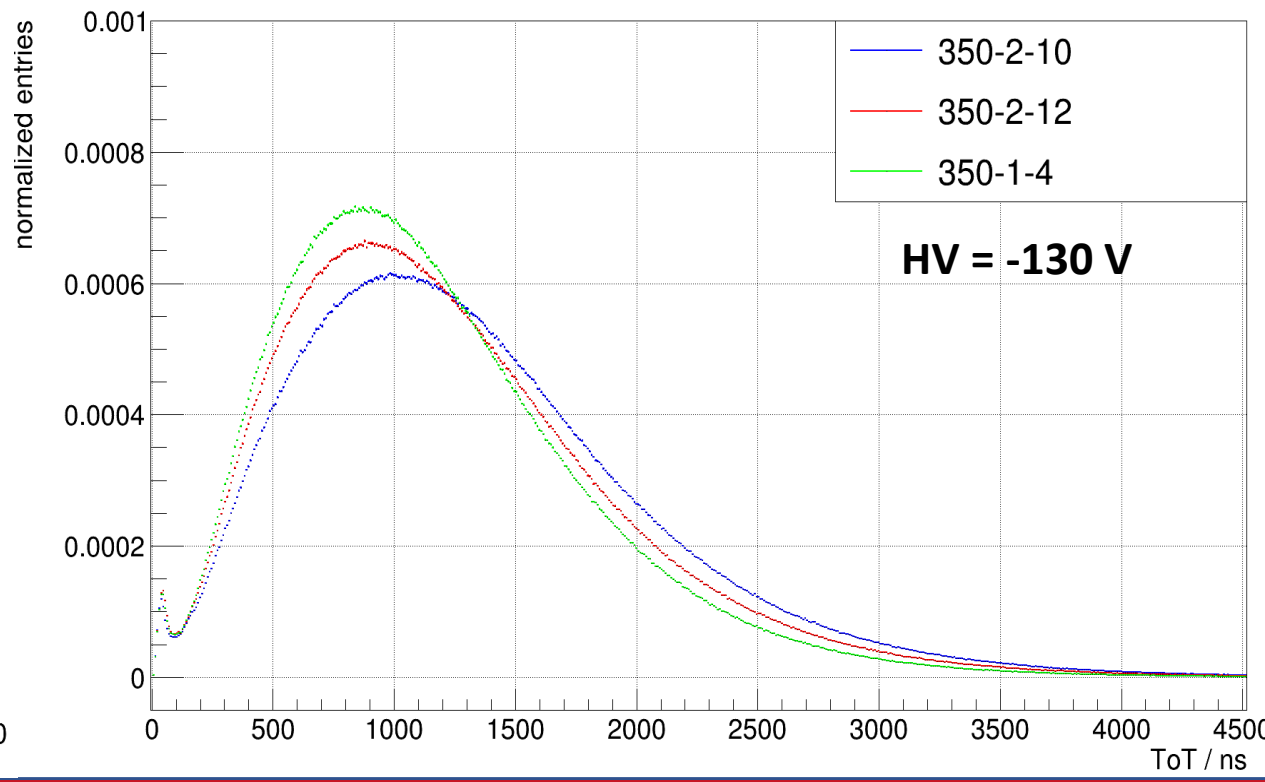
- Only small diffusive contribution to signal at HV = -130 V



Chip to Chip Comparison 600 µm

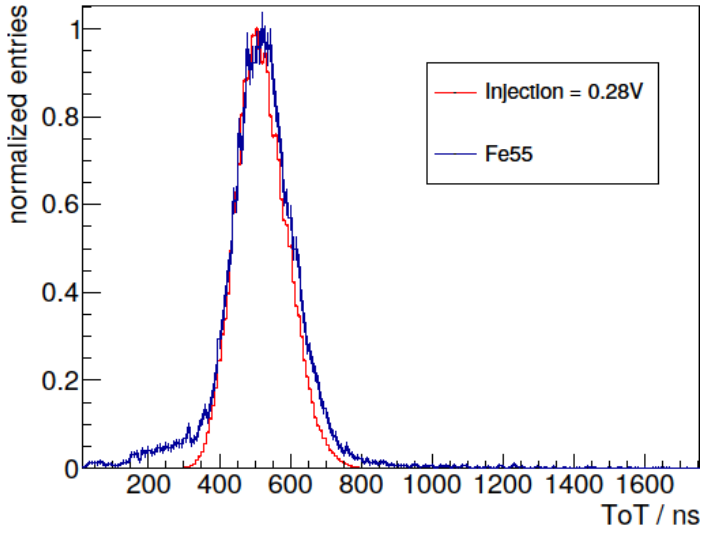
- All sensors on same settings

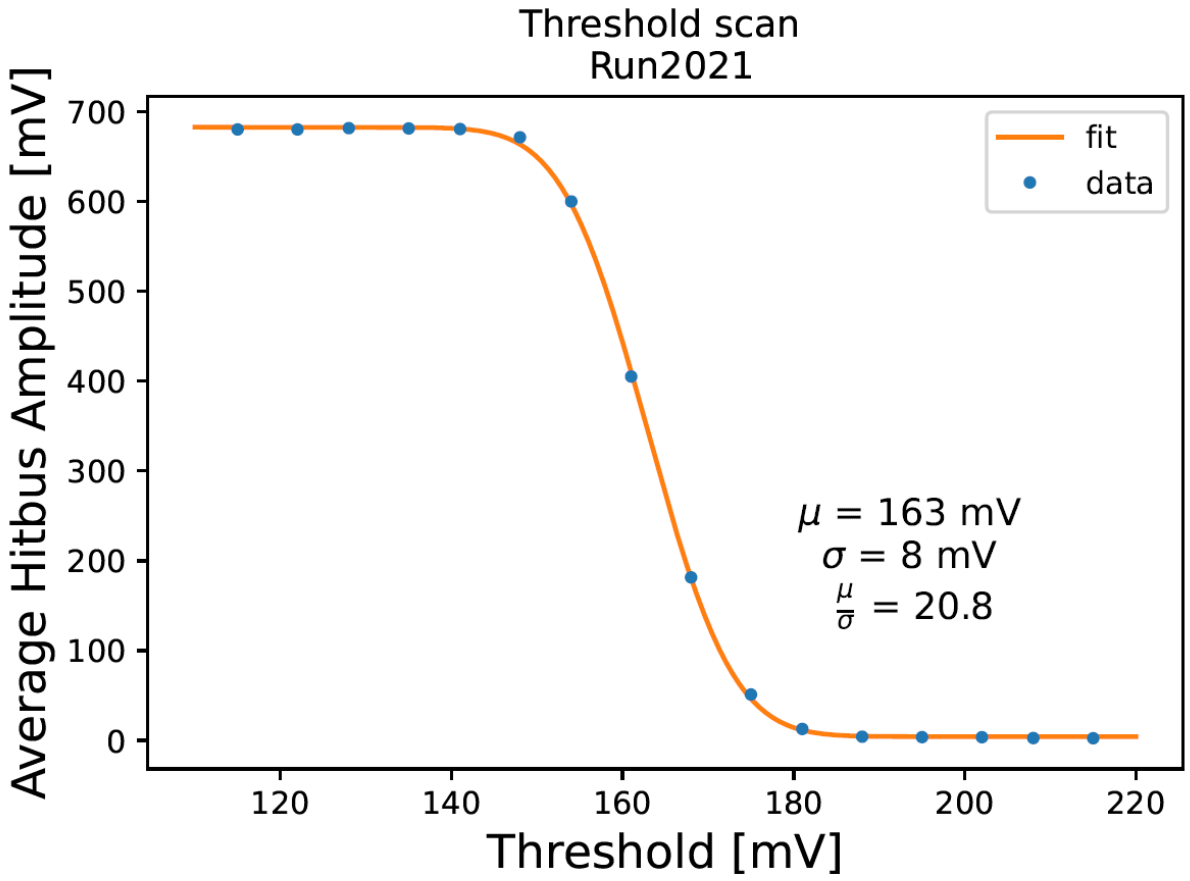




Injection Calibration to Fe55

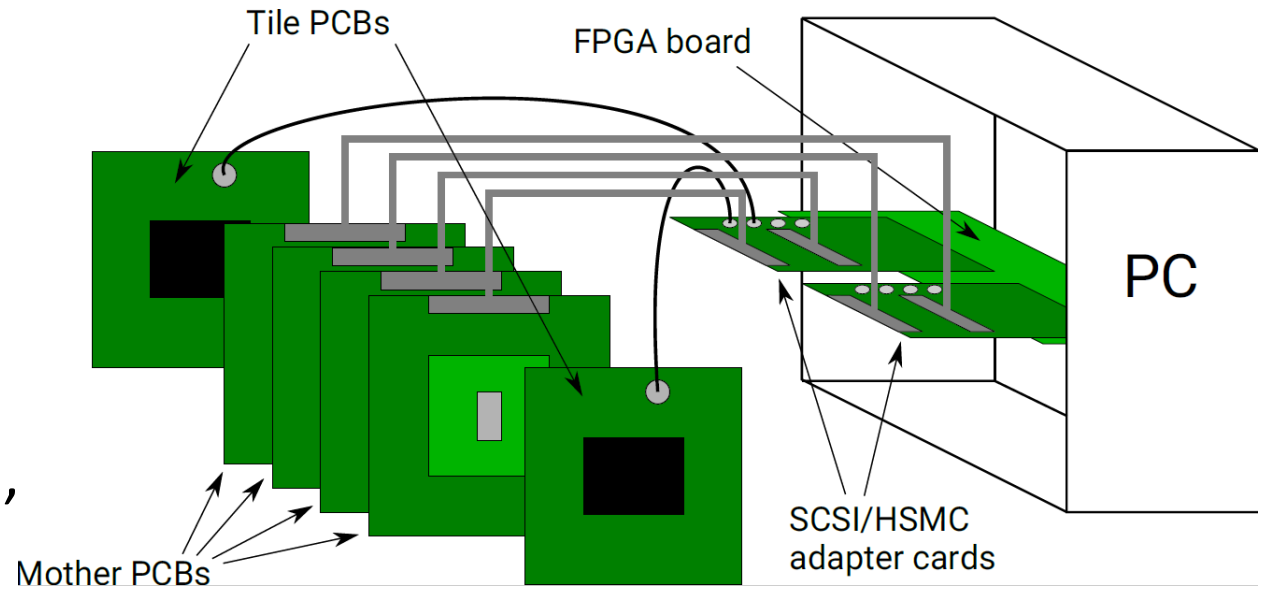
- 100 µm, $\rho = 370\ \Omega\mathrm{cm}$, HV = 125 V
- Fe55: 5.9 keV x-rays
- Injection Voltage = 0.28 V
- $\frac{\mu}{\sigma} = 20.8$

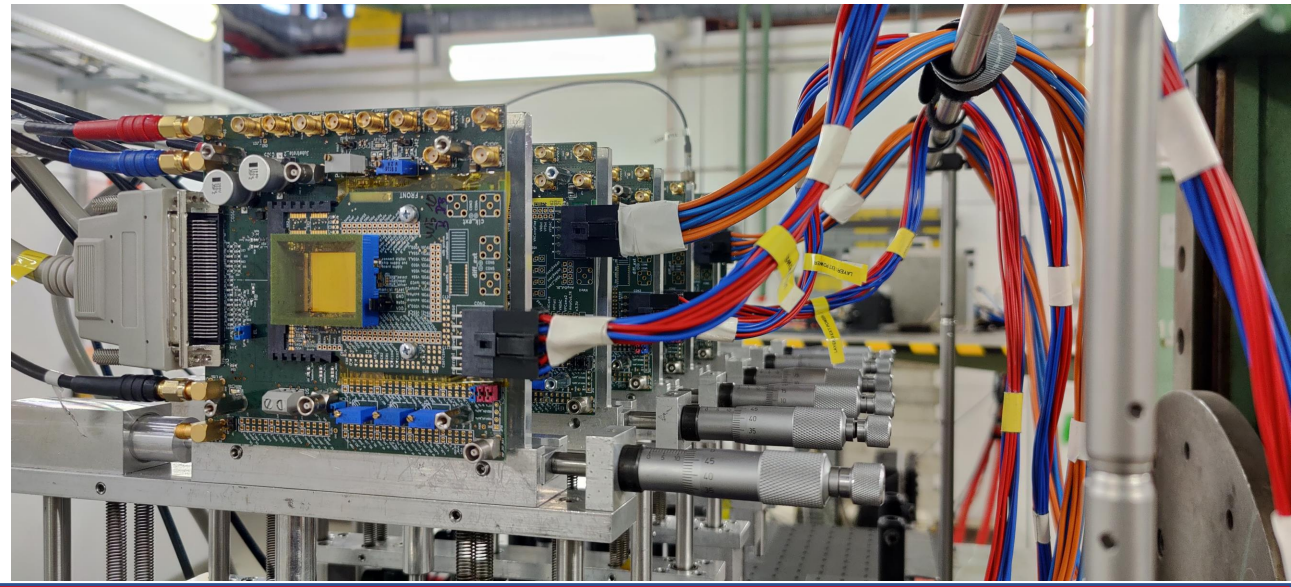




Desy Testbeam

- Telescope consisting of 3 reference Layers (MuPix11) + DUT
- DUT: Run 2021v2; 300 µm ($\rho = \sim 8000\ \Omega\mathrm{cm}$), **100 µm** and **50 µm** ($\rho = 370\ \Omega\mathrm{cm}$)
- Threshold scans and high statistic runs at different HVs
- Focus: Compare DUTs at same settings & HV





Power Consumption Run2021

	VDD	VDDA
Power consumption on default settings (measured)	90.18 mW	88.02 mW
Minimal power consumption:	1.44 mW	2.88 mW
Scaling with pixel #: Pixel, Periphery	0.35 µW/Pixel	16.9 µW/Pixel
Total Power Consumption	1.26 mW	60.84 mW
Power comsumption per active area	/	**410.15 mW/cm²**
Scaling with chip #: Link, Clock	88.92 mW/Chip	27.38 mW/Chip

- MuPix10: Power consumption per active area: ~200 mW/cm²
- Run2021 has half the pixel size