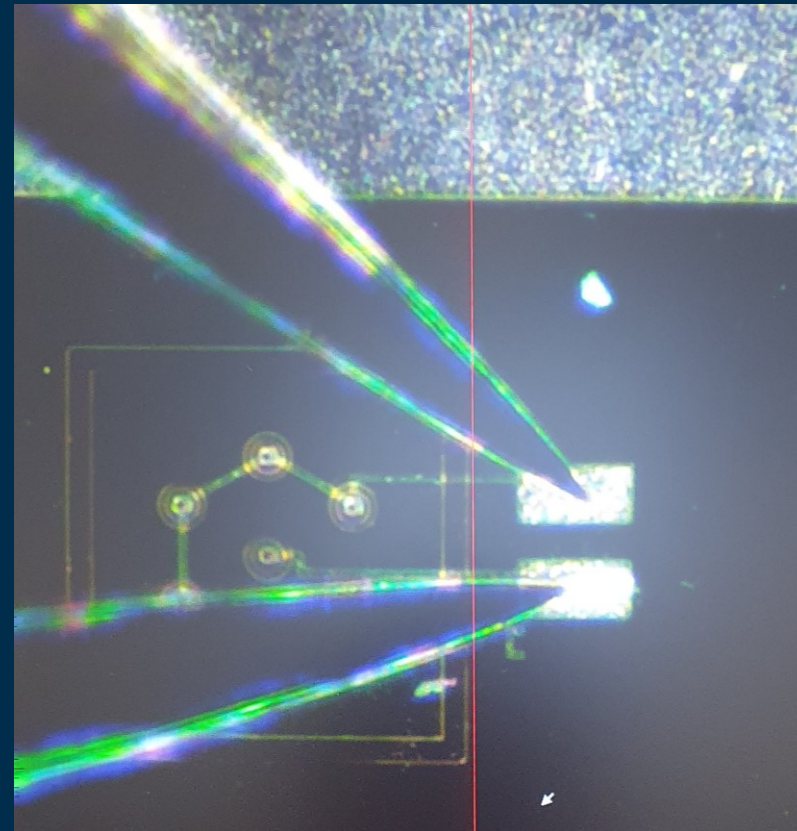
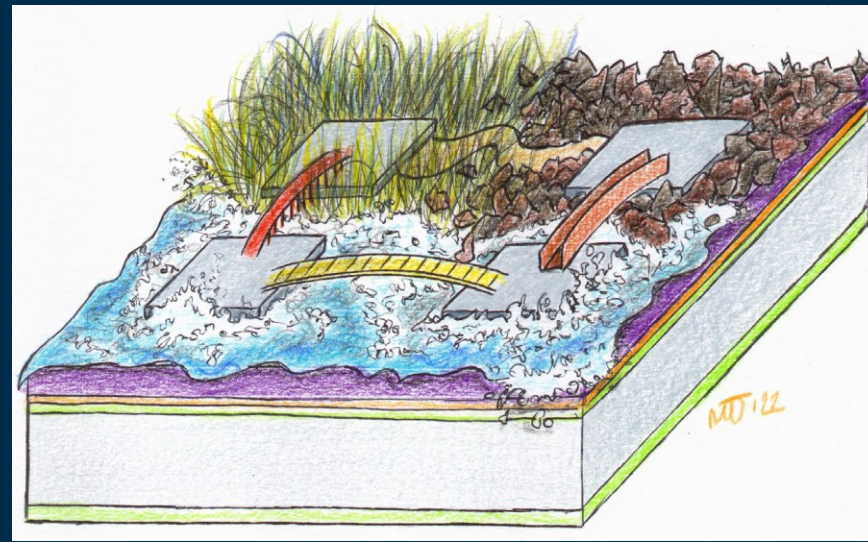


Time to Track – Characterization, TCT Measurements, and Test Beam Studies of Columnar 3D Sensors and Resistive Silicon Detectors

Lorena Hahn

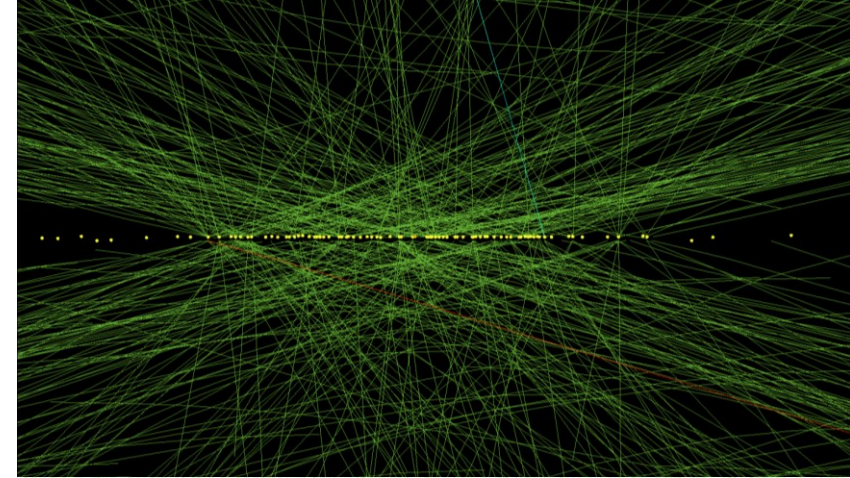
ETP Monday Meeting, 21.09.2026



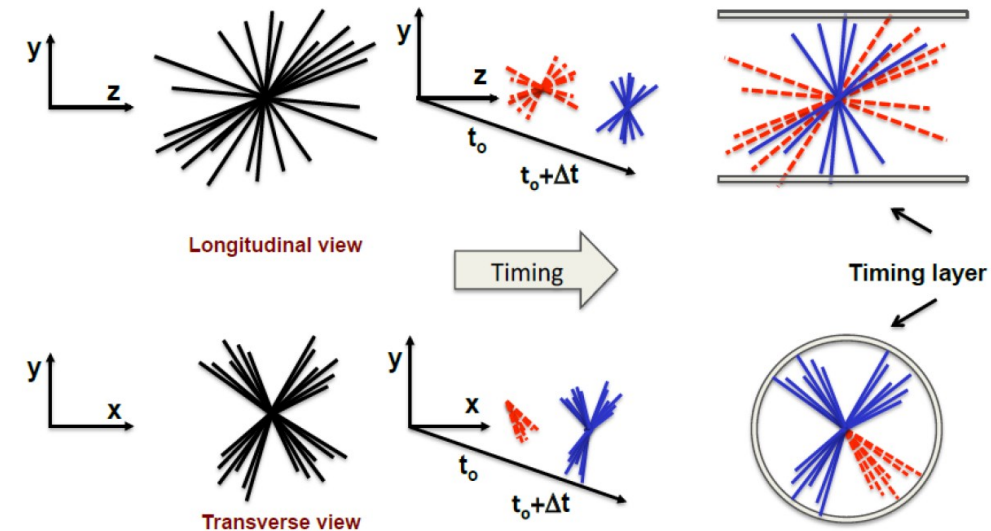
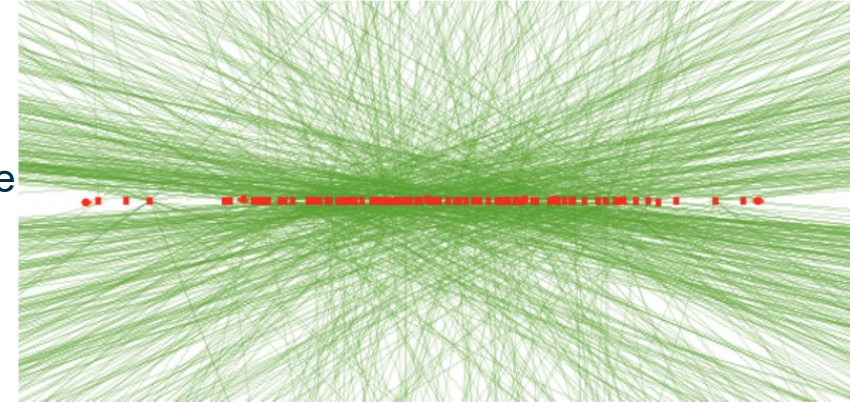
Time To Track

- High luminosity Large Hadron Collider (**HL-LHC**), Future Circular Collider (**FCC**) **challenge current technology**
 - Higher luminosity → high pile up
 - High fluences → high radiation hardness needed
- **Adding timing!**
 - Hadron collider: vertex reconstruction, pile-up discrimination
 - Lepton collider: particle identification through time of flight
 - Already used for HL-LHC, US electron ion collider

Pile up 2012



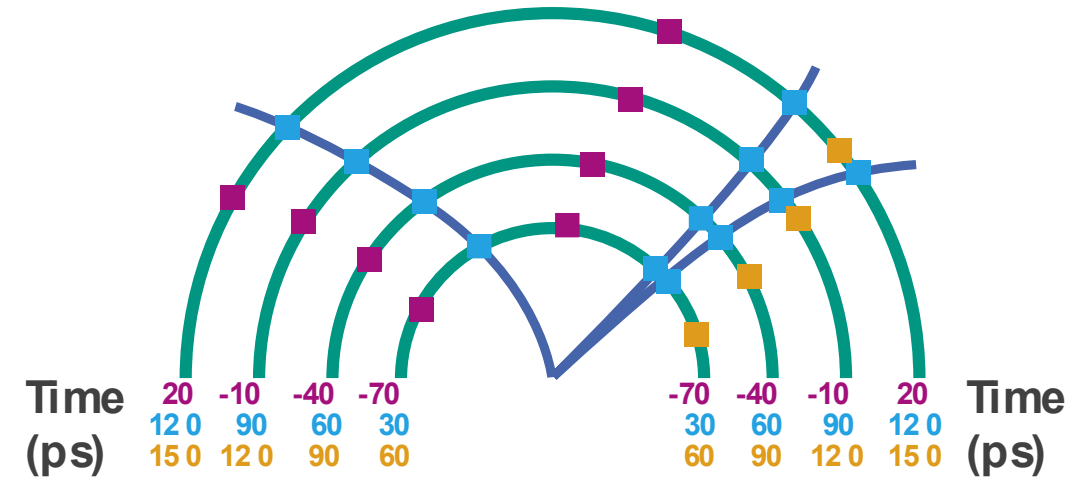
Estimated pile up HL-LHC



Time To *Track* – 4D Tracking

But why stopping at one timing layer?

- Adding time stamps for each layer
→ information in **3** spatial coordinates + **1** in time
- Transforms tracking fundamentally
- Reduces track finding combinatorics



Temporal Resolution

- Determined by signal slew rate + electronic noise
 - Reducible by increasing Signal-to-Noise Ratio (SNR)
- RSD lever

- Originate from readout electronics
- Reducible through ASICs and correction algorithms

$$\sigma_{\text{Time}} \approx \underbrace{\sigma_{\text{SpatialFluctuation}}^2}_{\text{Statistical fluctuations in charge deposition process}} + \overbrace{\sigma_{\text{Jitter}}^2}^{\text{Determined by signal slew rate + electronic noise}} + \underbrace{\sigma_{\text{Distortion}}^2}_{\text{Inhomogeneities in electric + weighting field}} + \overbrace{\sigma_{\text{TDC}}^2 + \sigma_{\text{TimeWalk}}^2}^{\text{Originate from readout electronics}}$$

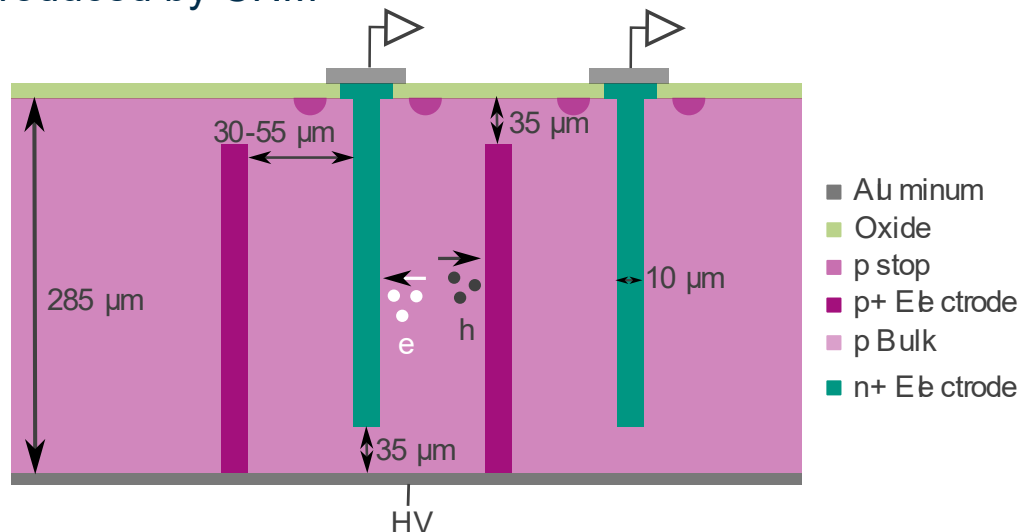
- Statistical fluctuations in charge deposition process
 - Relevant for Time of Arrival
 - Better for thinner sensors
- 3D + RSD lever

- Inhomogeneities in electric + weighting field
- 3D lever

Silicon Candidates for 4D Tracking

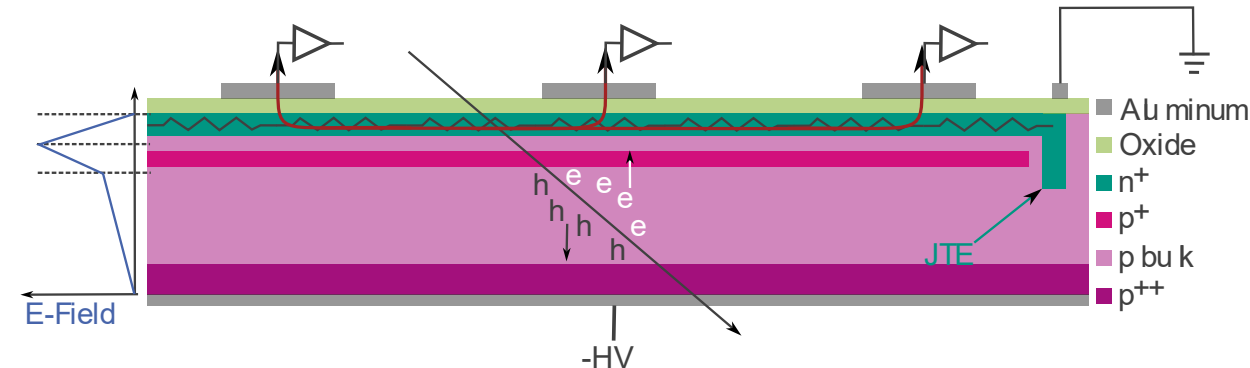
3D Silicon Sensors

- 3D **pillars** etched into p-doped bulk
- **Short drift path**
 - less prone to trapping → very radiation hard
 - good timing properties
- Pixelated → good spatial resolution possible
- Non-homogeneous fields
- Complicated production
- High noise
- Produced by CNM



Resistive Silicon Detector (RSD)

- **Based on Low Gain Avalanche Diode (LGAD) concept:**
 - Silicon sensor with **gain** implant → high electric field → charge multiplication → **thin sensors** with **high SNR**
- **Continuous** n-type **resistive layer** → lateral signal propagation → **charge sharing** across multiple electrodes
- Very good timing and spatial resolution
- 100 % fill factor
- Less radiation hard
- Produced by FBK

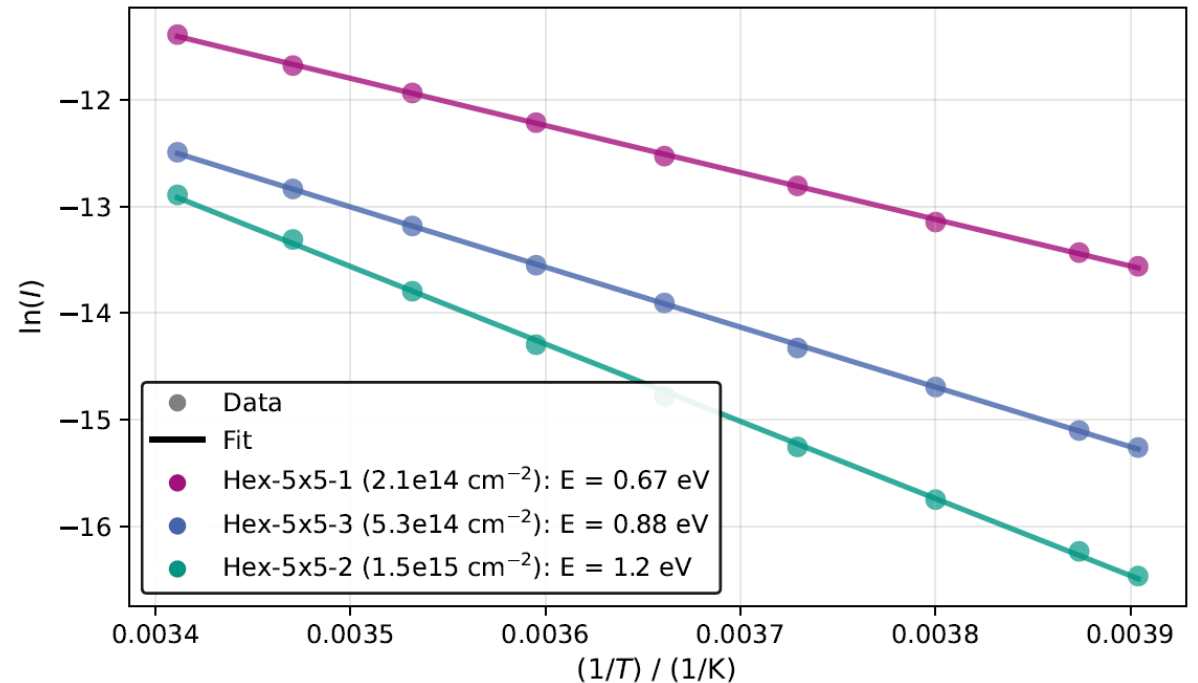
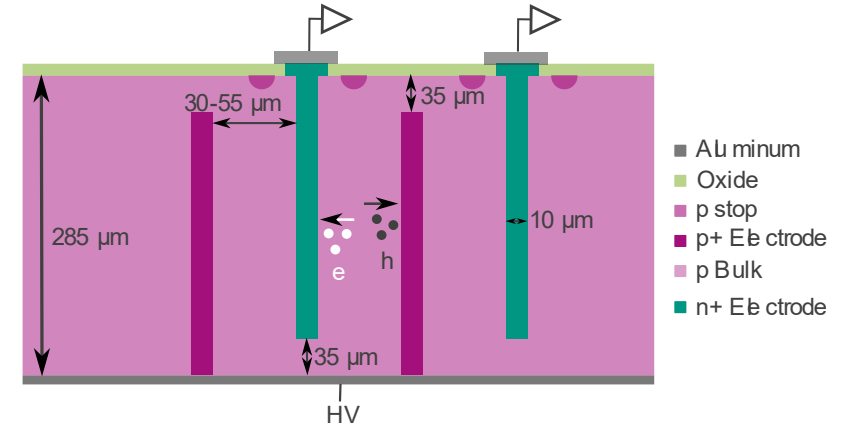


Characterizing 3D Silicon Sensors Temperature Dependent Behavior

- Measuring **leakage current** in dependence of bias voltage and **temperature**
- Expected current behavior:

$$I(T) \sim T^2 \cdot e^{-\frac{E}{2k_B T}}$$

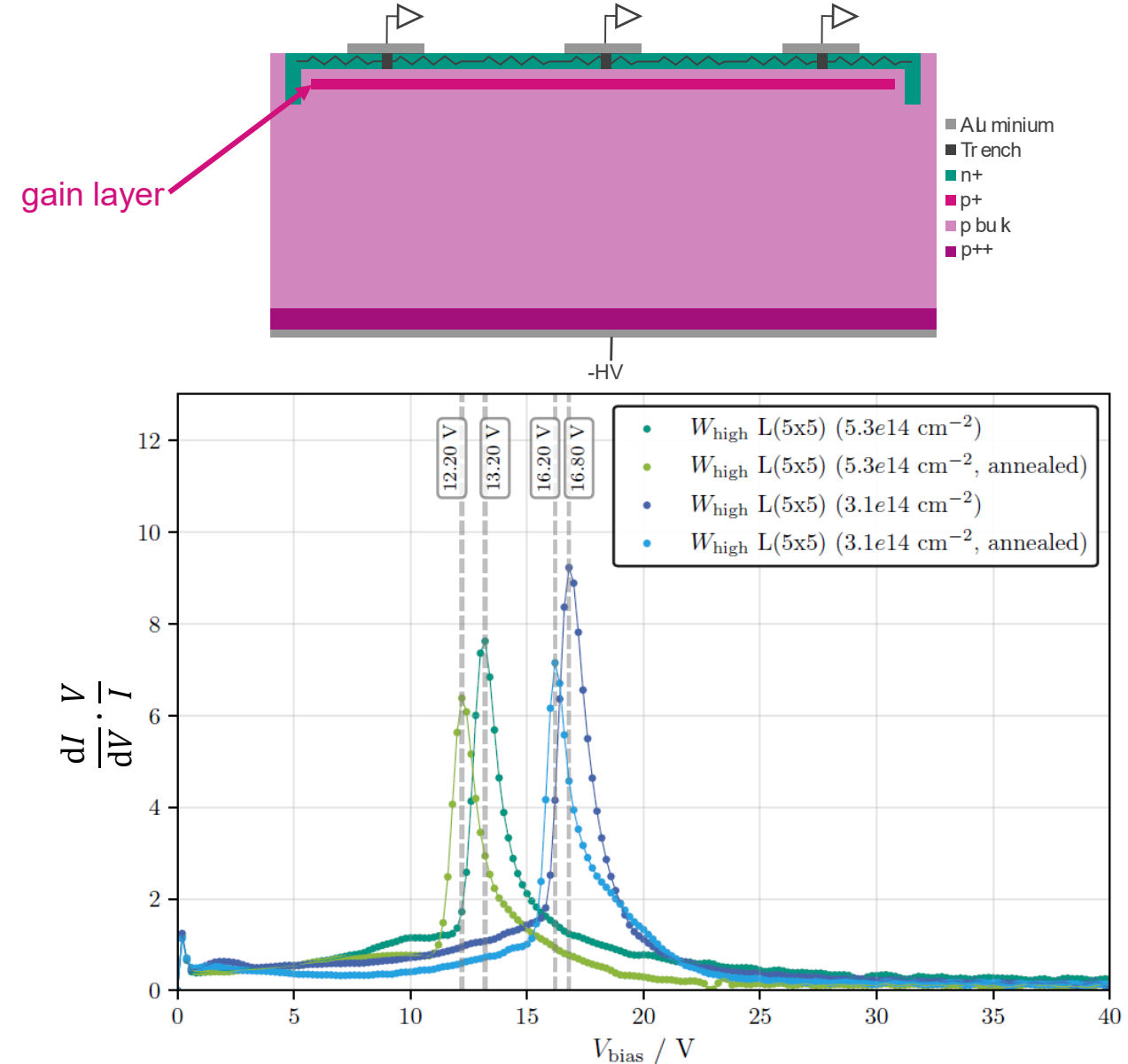
- Extract E from slope
- For bulk-dominated leakage current **$E \approx 1.21 \text{ eV}$ expected**
- Radiation damage increases bulk-generated contribution → high-field effects not dominant anymore



Characterizing RSD Acceptor Removal

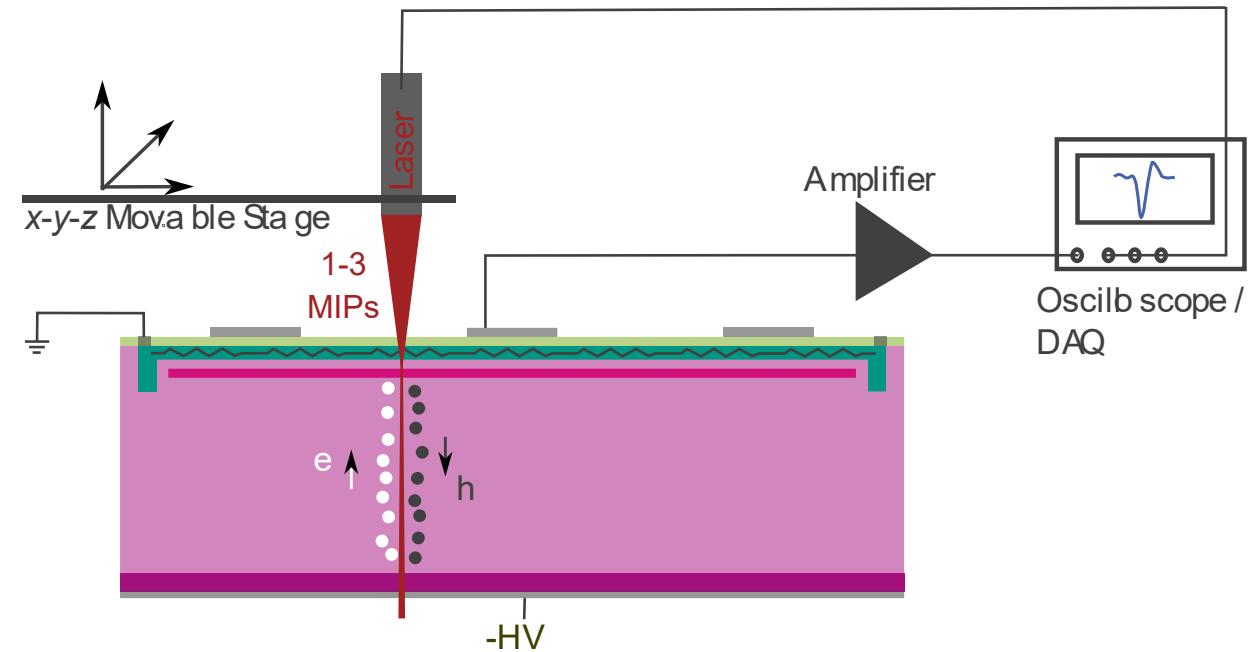
- Way to **evaluate radiation tolerance** of RSD
- Radiation-induced removal of acceptor states
→ modifies effective doping of gain layer
→ changes depletion behavior
- Gain layer depletion voltages changes with

$$\frac{V_{GL}(\phi)}{V_{GL}(0)} \propto e^{-c_A \phi}$$
 with acceptor removal coefficient c_A
- One method to extract V_{GL} :
 - Derivative of leakage current over bias voltage
 - Voltage at maximum = V_{GL}
- Fitting exponential decay to $V_{GL}(\phi)/V_{GL}(0)$
 → $c_A = (1.20 \pm 0.02) \cdot 10^{-15} \text{ cm}^2$
 ⇒ **consistent with literature for conventional LGADs**
- Measurements conducted by N. Müller

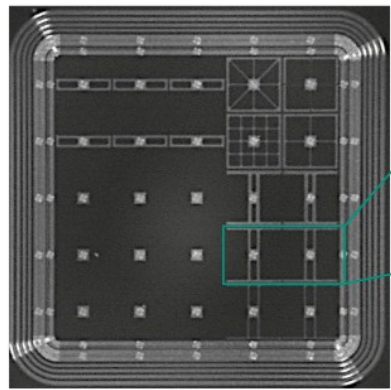


Transient Current Technique (TCT)

- Measure **position-dependent** sensor **response**
→ access to:
 - Charge transport + collection properties
 - Electric field distributions
 - Temporal + **spatial resolutions**
 - Radiation induced effects
- Movable **pulsed** infrared **laser**
- **Photoelectric effect** → laser photons create **electron-hole pairs** → **induce signal**
- Focused within Silicon bulk
- Intensity adjusted to MIP-like charge deposition

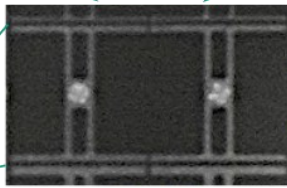


RSD in TCT – Spatial Resolution Tie Fighter



Tie Fighter
electrode layout

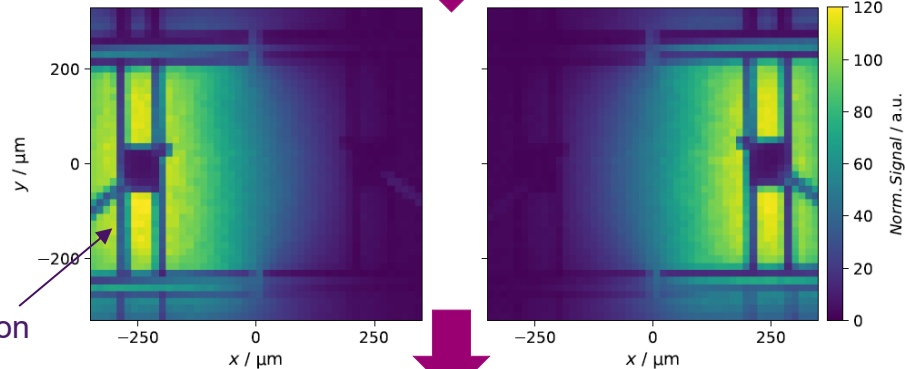
500 μm



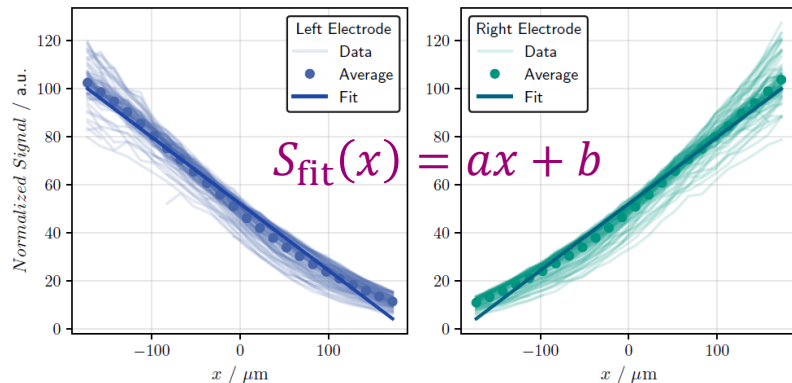
Binary Resolution,
Homogenous Signal

Signal Sharing
high resolution

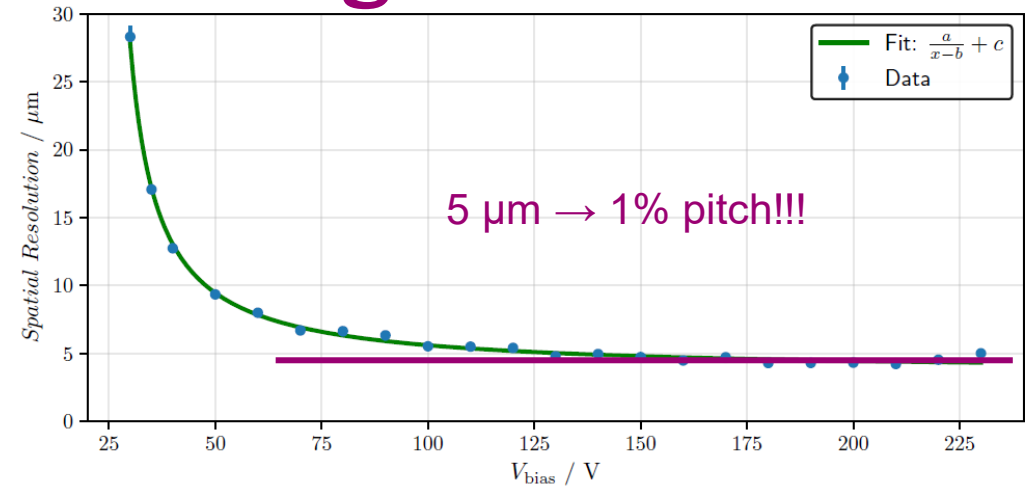
TCT scan



projection + linear decrease

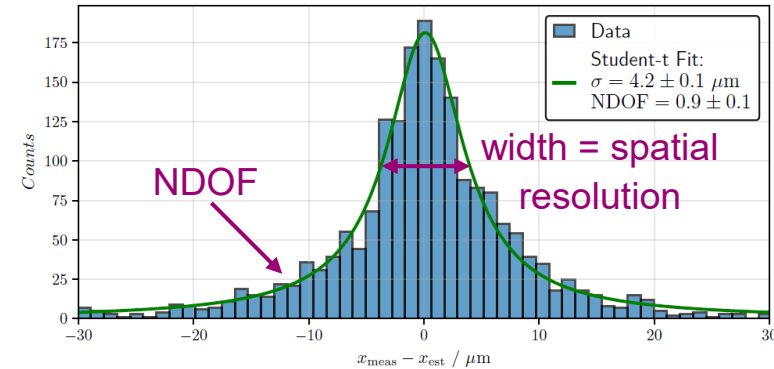


$$S_{\text{fit}}(x) = ax + b$$



5 μm → 1% pitch!!!

repeat for several bias points



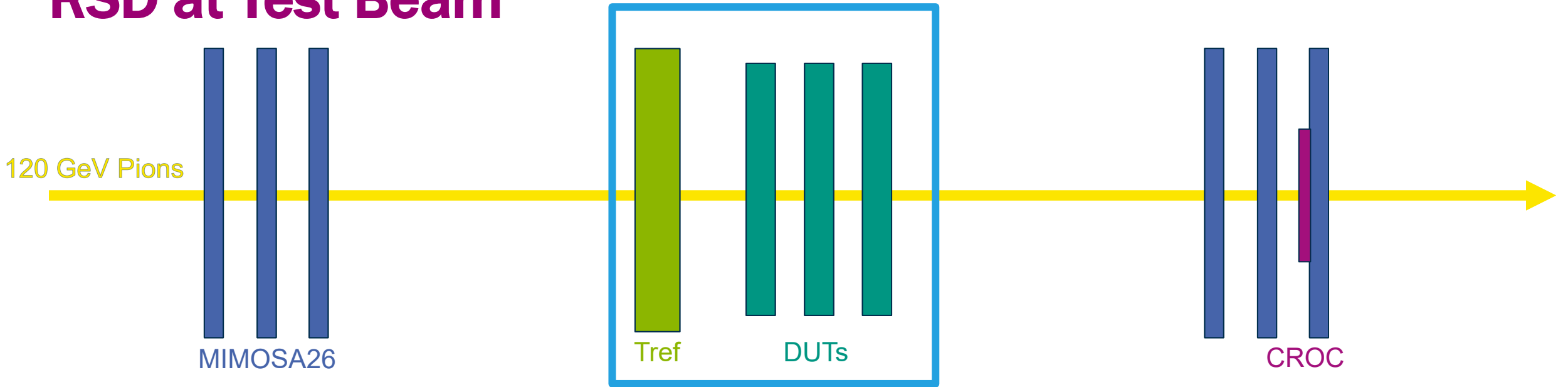
compare reconstructed x_{est} to
laser position x_{meas}

fit Student-t

Reconstruct hit with χ^2 -Minimizer

$$\chi^2(x) = (S_{\text{meas, left}} - S_{\text{fit, left}}(x))^2 + (S_{\text{meas, right}} - S_{\text{fit, right}}(x))^2$$

RSD at Test Beam



Setup

- 3 days in DRD3 test beam in October 2025
- 120 GeV Protons / Pions @ SPS
- 5 working MIMOSA planes for tracking information (EUNET telescope) + CROC: pixelated sensor + CROC-ASIC → used for ROI selection
- 3 RSDs as Devices Under Test (DUTs) at the same time

Aim

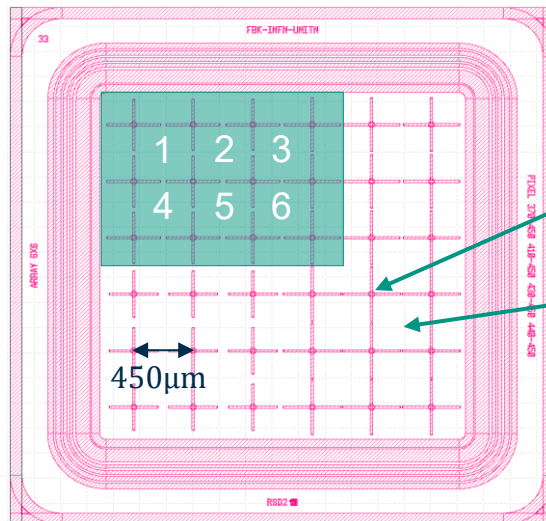
- Comparison of AC- and DC-coupled RSDs **under same conditions** and on **same type of readout board**
- Verification / development of alignment and reconstruction methods

RSD at Test Beam

Devices Under Test (DUTs)

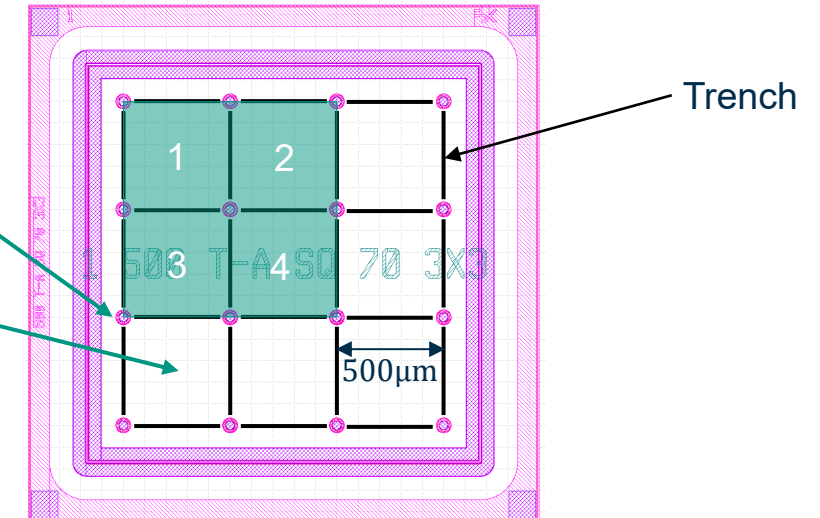
1 x AC-Coupled RSDs (RSD2)

- Pitch: 450 μm
- Signal containment strategy: cross-shaped electrodes
- Spatial resolution (TCT studies): 3-4 % of pitch (through **charge sharing**)
- Temporal resolution (TCT studies): O(40 ps)
- 2nd plane
- On **FNAL board**



2 x DC-coupled RSDs (DC-RSD1)

- Pitch: 500 μm
- Signal containment strategy: trenches + circular electrodes
- Spatial resolution (TCT studies): 3-4 % of pitch (through **charge sharing**)
- Temporal resolution (TCT studies): O(40 ps)
- 1st and 3rd plane
- On **FNAL board**



(Readout) Electrodes

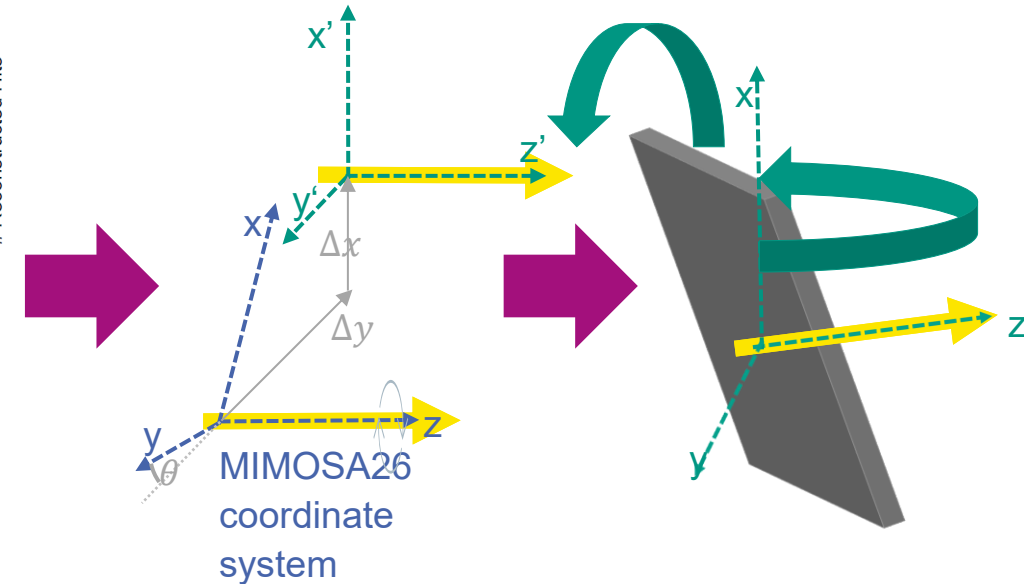
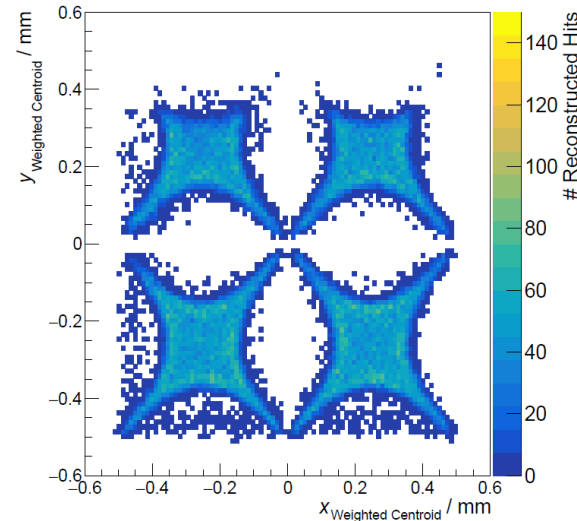
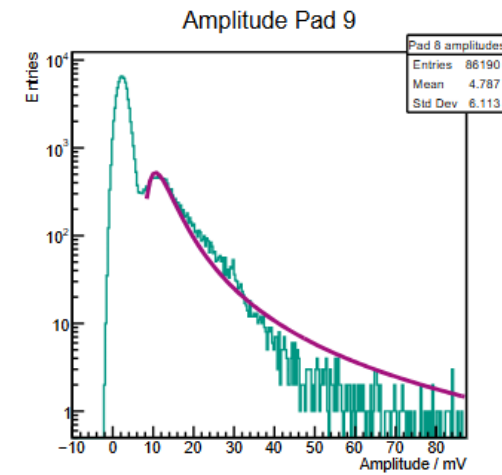
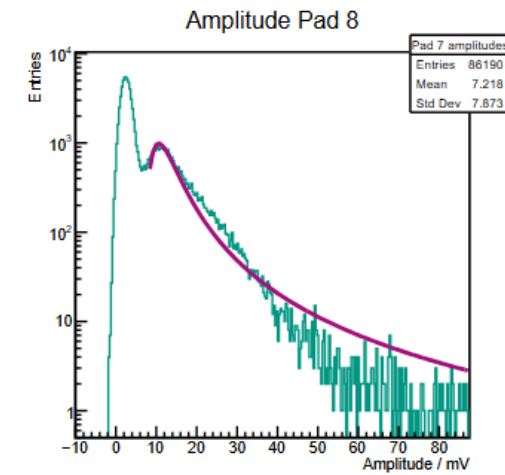
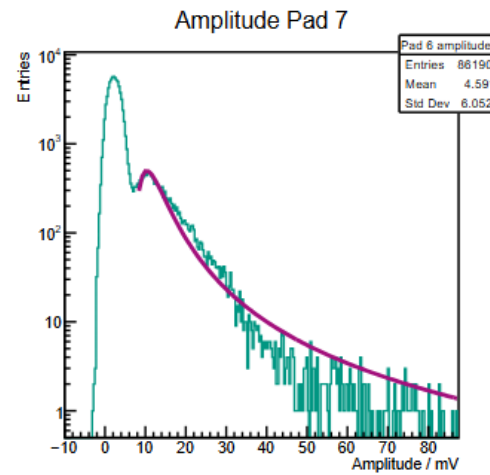
Pixel

* Pictures not to scale

RSD at Test Beam

How-To: Analyze RSDs

1. Equalize amplitudes of all channels
2. Find hit pixel
3. Reconstruct hit
4. Align sensor with respect to the telescope frame
→ translation + rotation around **beam axis**
5. Find correct position along **beam axis**
6. Extract rotations around other two axes

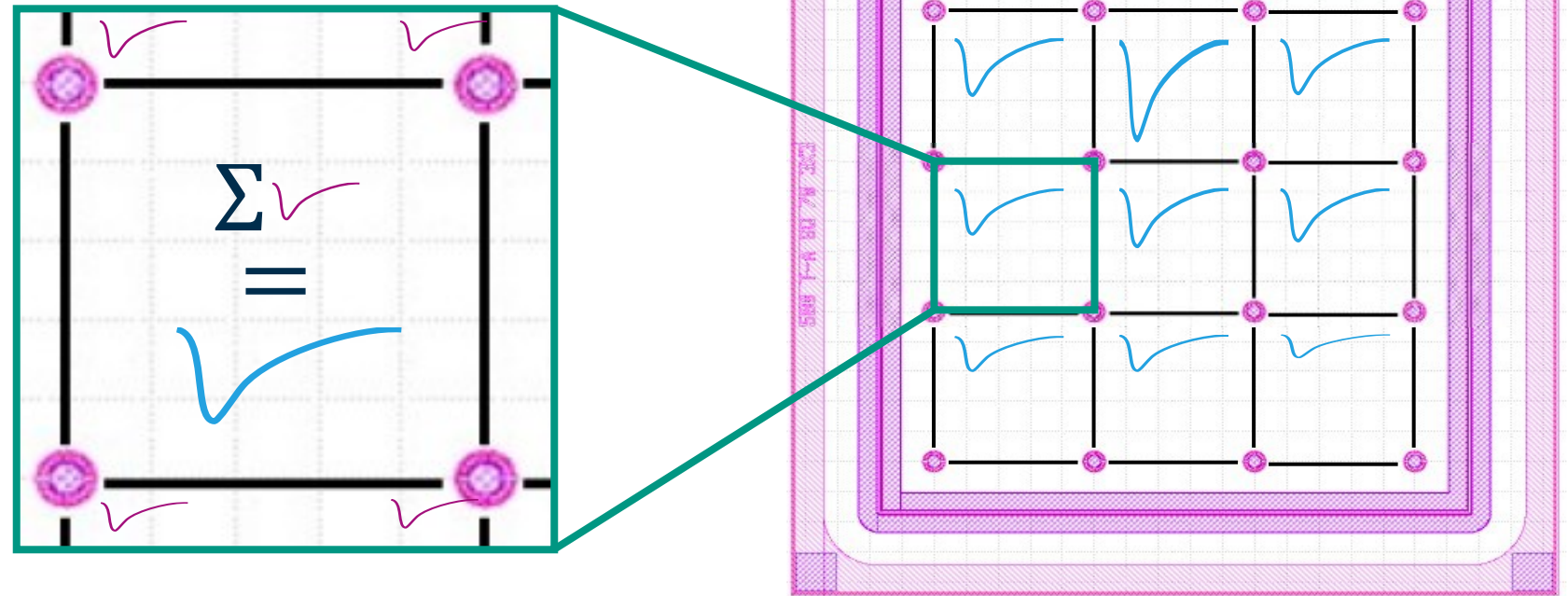


RSD at Test Beam

Lost in Charge Sharing – Finding the Hit Pixel

Hit Pixel = Pixel with highest A_{tot}

- Readout of all waveforms of all electrodes
- Extract max. Amplitude A
- For each pixel: $A_{\text{tot}} = \sum_{i=1}^4 A_i$
- Hit pixel = $\max(A_{\text{tot}})$

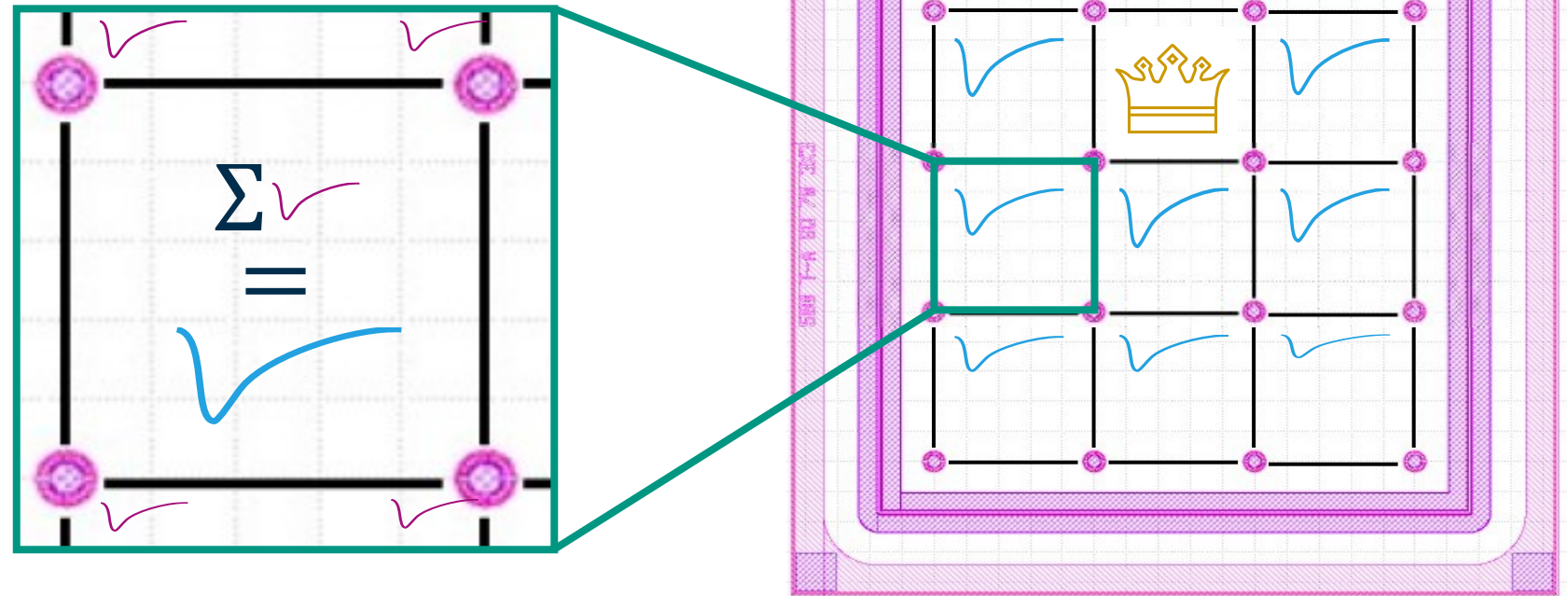


RSD at Test Beam

Lost in Charge Sharing – Finding the Hit Pixel

Hit Pixel = Pixel with highest A_{tot}

- Readout of all waveforms of all electrodes
 - Extract max. Amplitude A
 - For each pixel: $A_{\text{tot}} = \sum_{i=1}^4 A_i$
- 👑 Hit pixel = $\max(A_{\text{tot}})$



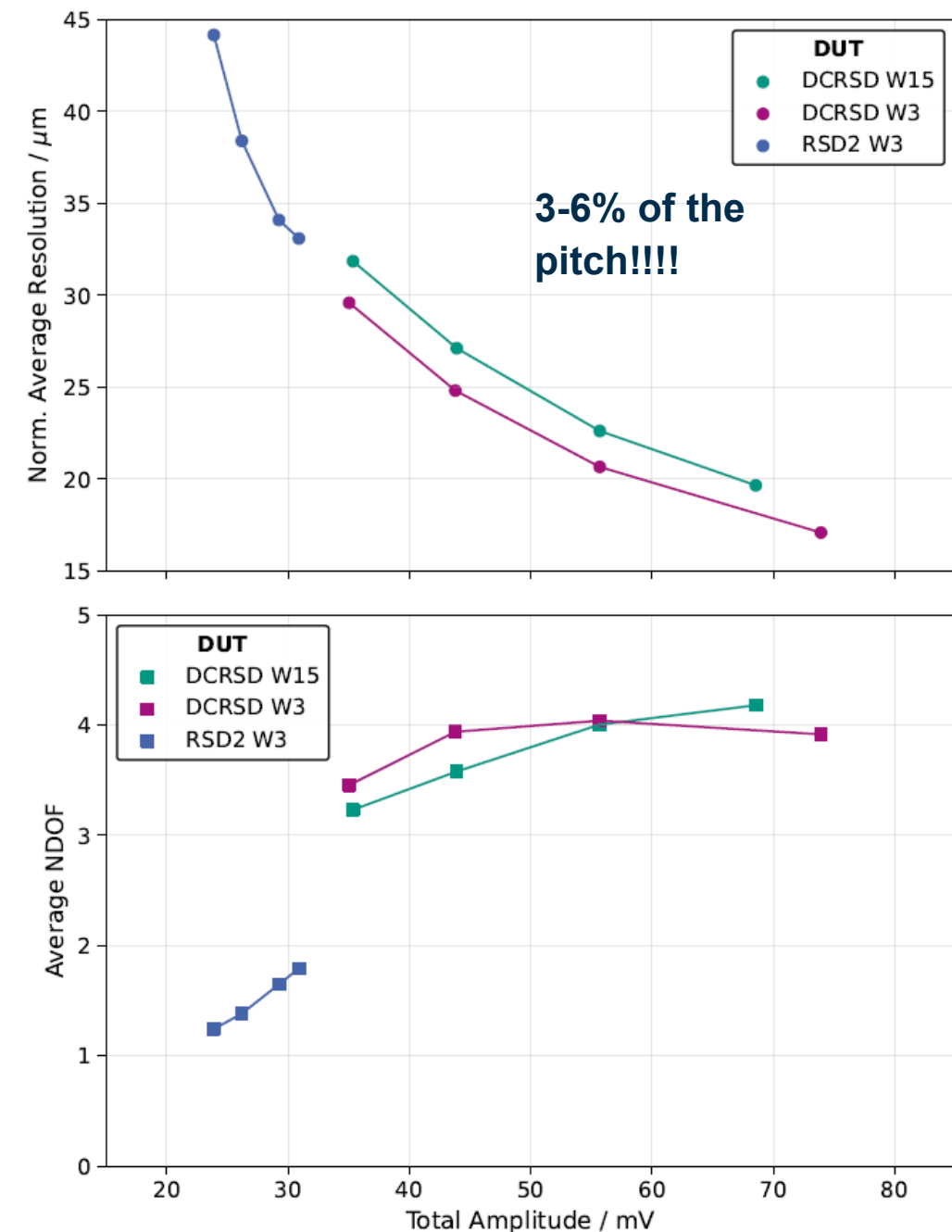
RSD at Test Beam Spatial Resolutions

Spatial resolution through fitting a Student-t distribution on the residuals $x_{\text{RSD}} - x_{\text{EUDT}}$

Resistivity of RSD2 $\approx$ DC-RSD W3

Resistivity of DC-RSD W15 lower

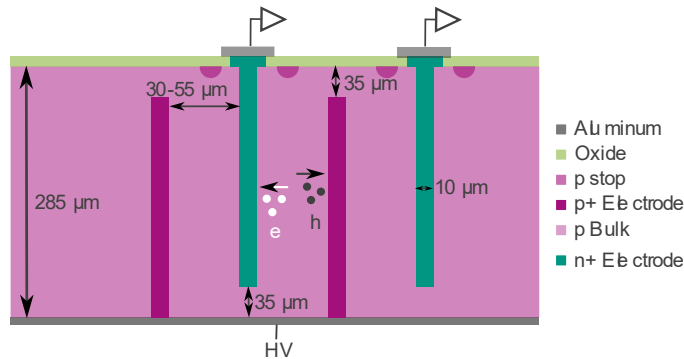
- Width of Student-t = spatial resolution
 - Difference in pitch $\rightarrow$ rescale to 500 μm pitch $\Rightarrow$ normalized resolution
 - Higher resistivity $\rightarrow$ better end point resolutions
 - Worse resolution of RSD2 might be due to FNAL board being less suited for AC-coupled version
- Degrees of Freedom (NDOF) of Student-t = uniformity of performance
 - High NDOF $\triangleq$ Gaussian distribution



Summary

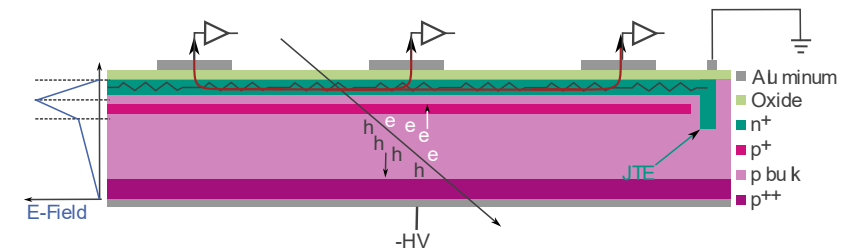
3D Silicon Sensors

- Extensive electrical analysis before and after irradiation
- High-field effects that eventually get dominated by bulk-generated leakage current after irradiation
→ sensors remain functionable, but require careful operation

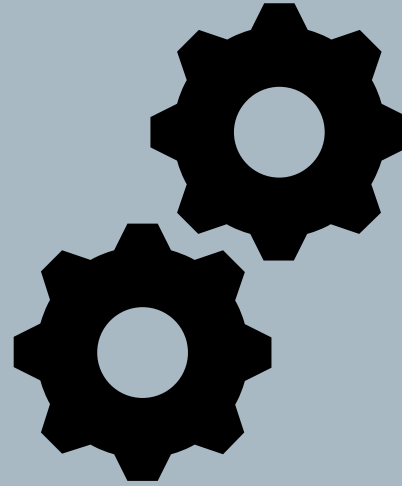


Resistive Silicon Sensors

- Electrical characterization of first DC-RSD production with extraction of **acceptor removal** coefficient **consistent with literature** for LGADs (together with N. Müller)
- Spatial resolution of novel hybrid **strip-pixel AC-RSD** using the TCT → **5 μm = 1% of the pitch!**
- Test beam to compare AC- and DC-coupled RSDs
→ complete reconstruction chain including calibration and alignment
→ **spatial resolutions of 6% and 3% of the pitch** for the best reconstruction technique

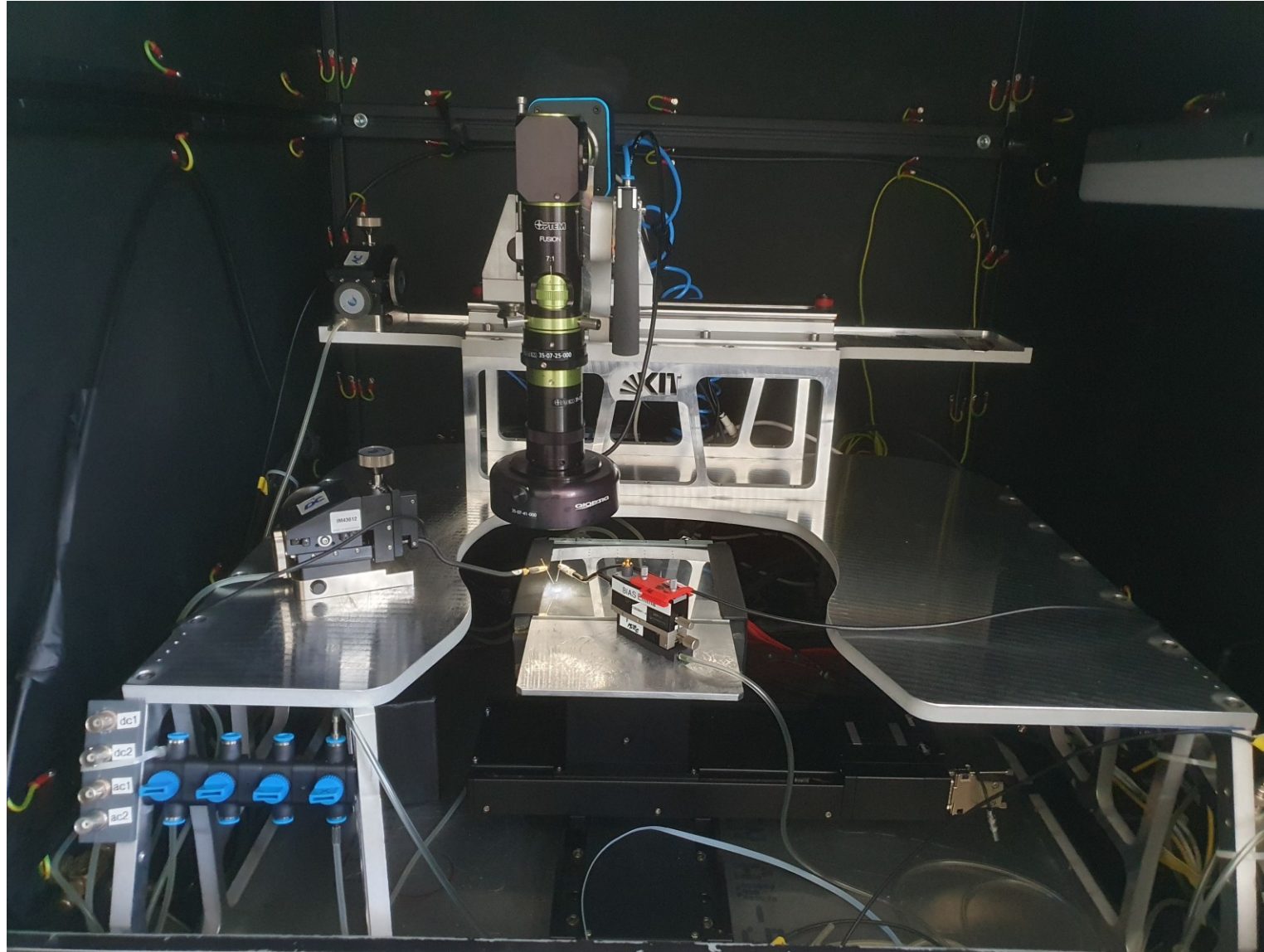




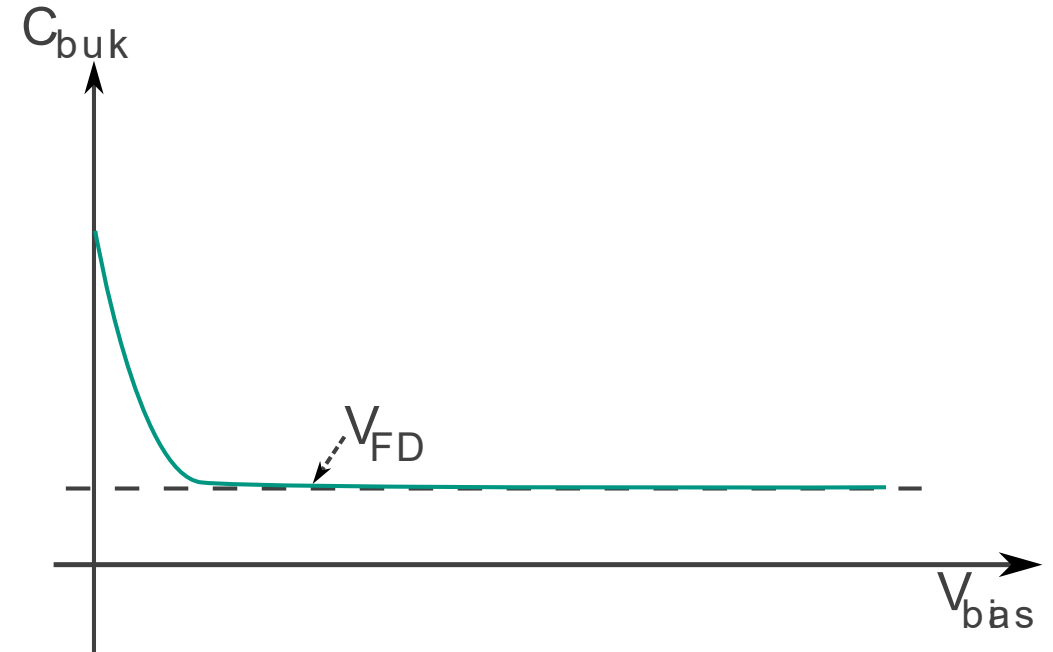
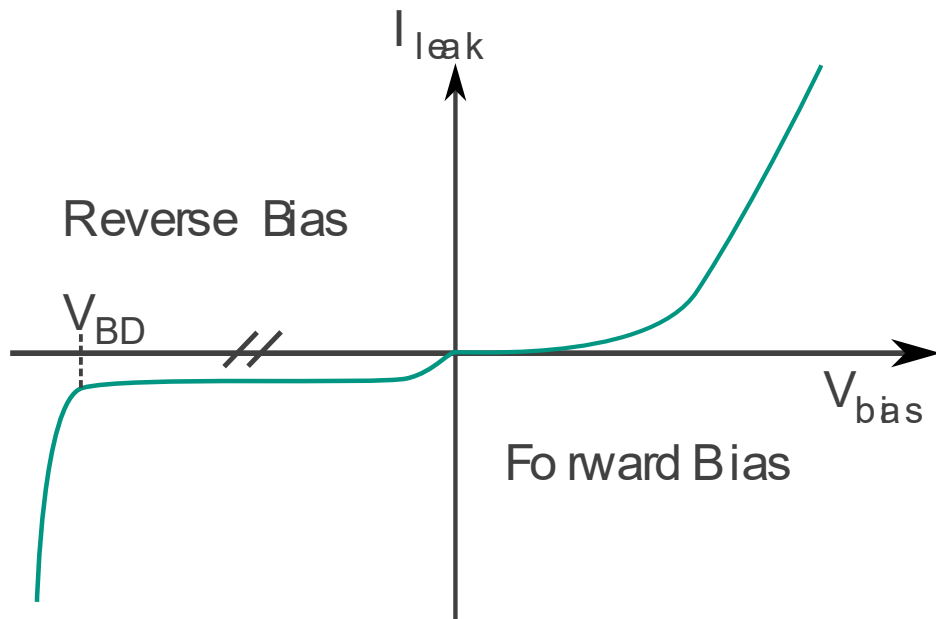


Test Setups

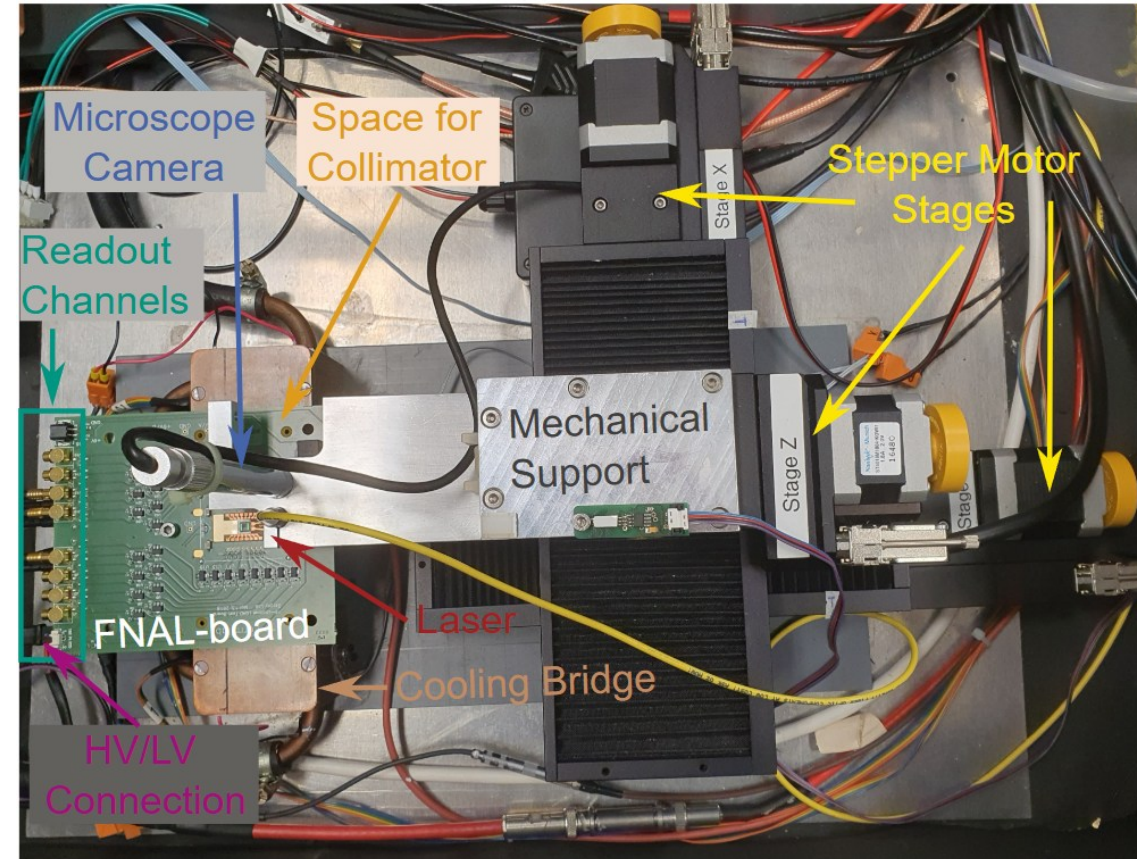
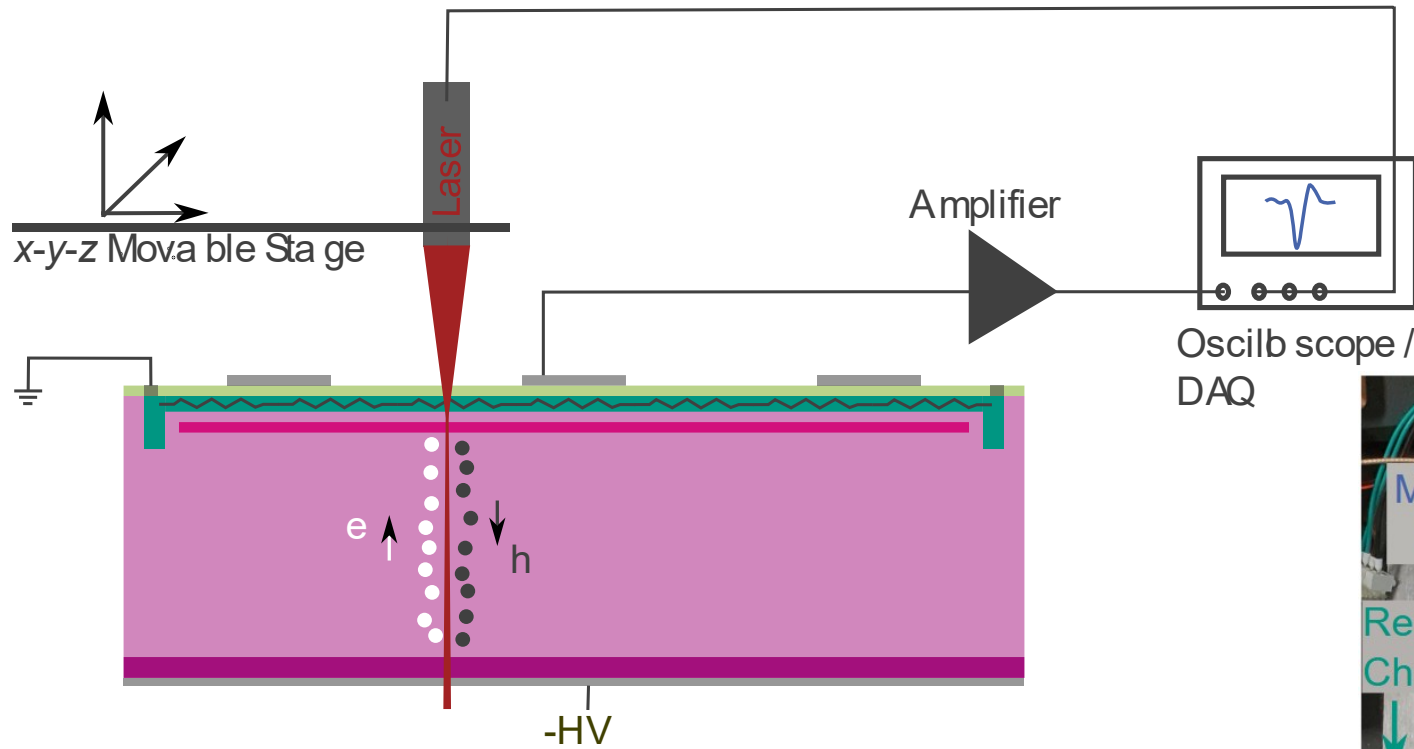
Probe Station



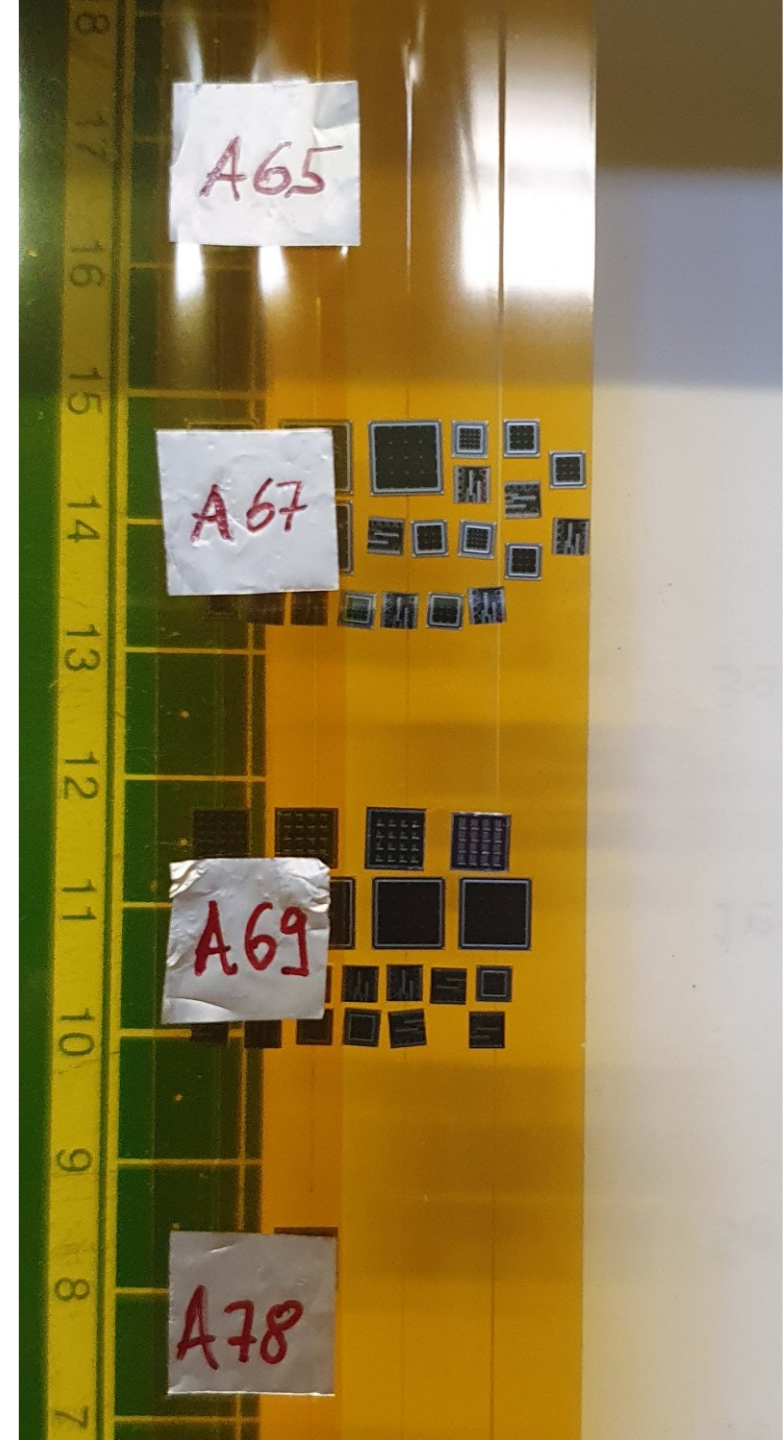
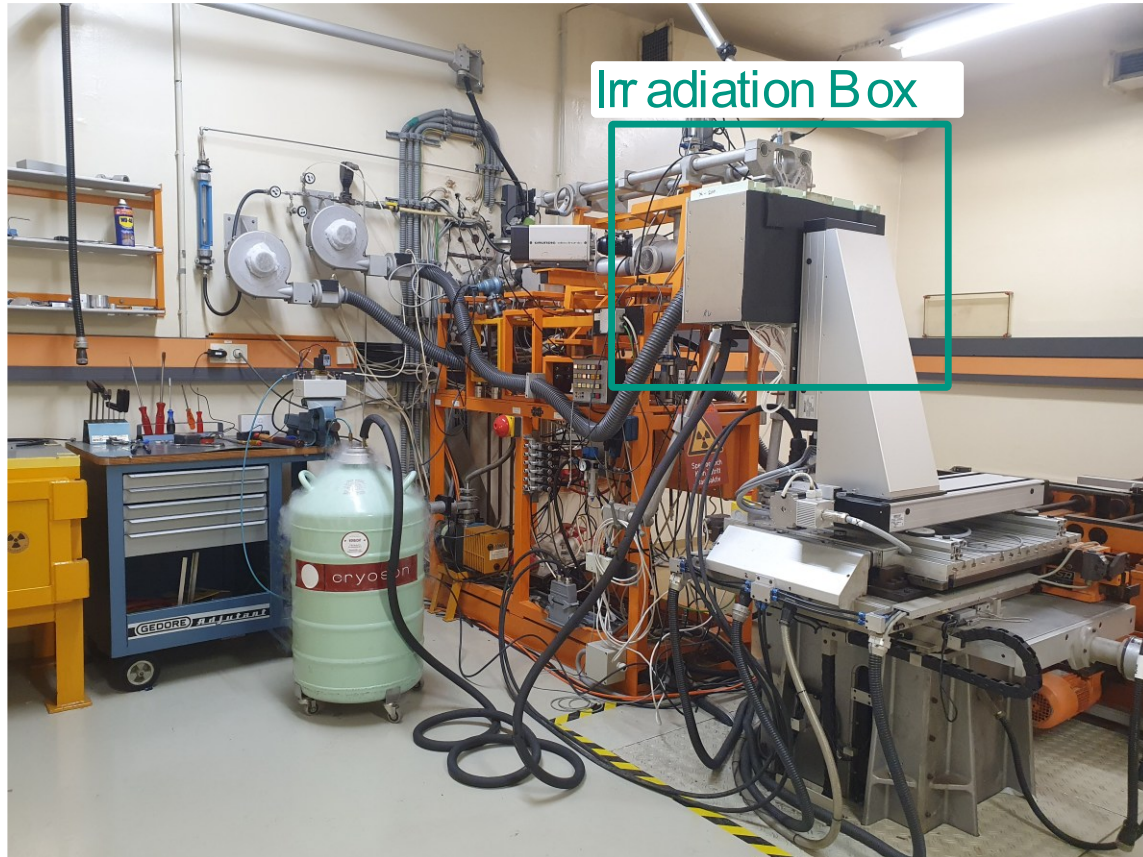
Probe Station – Electrical Characterization of a Diode

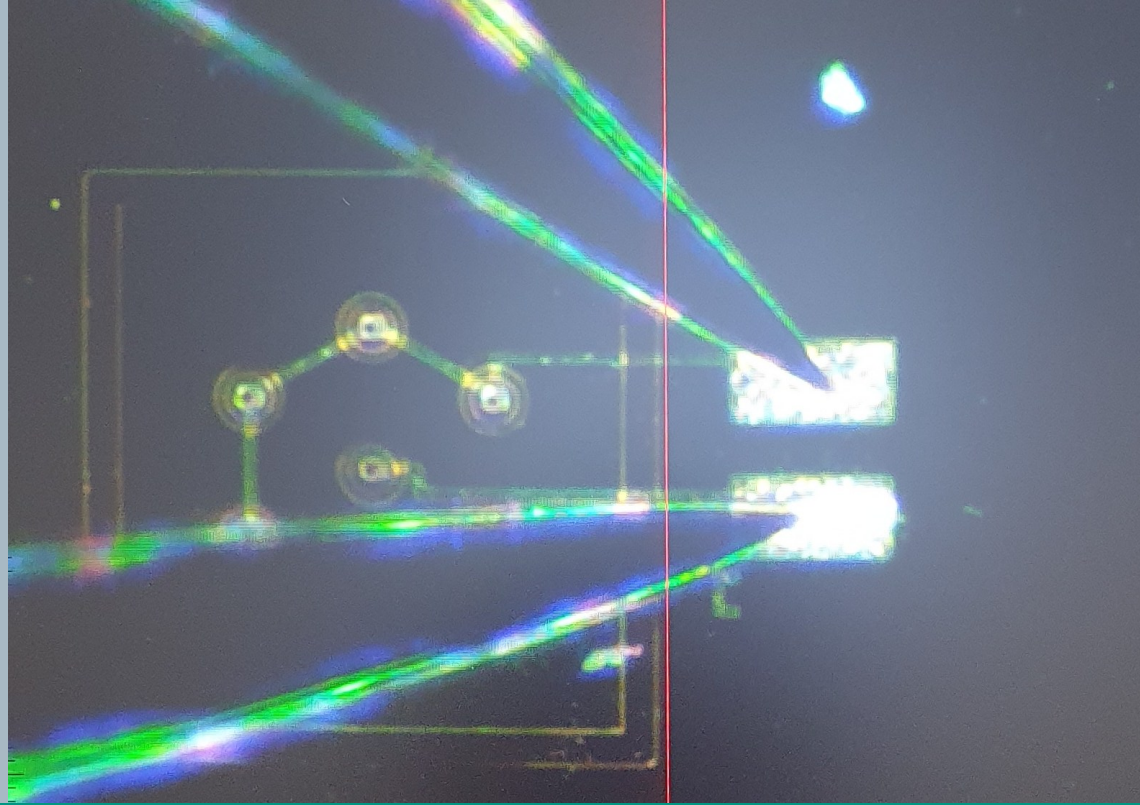


Transient Current Technique



Irradiation at KAZ

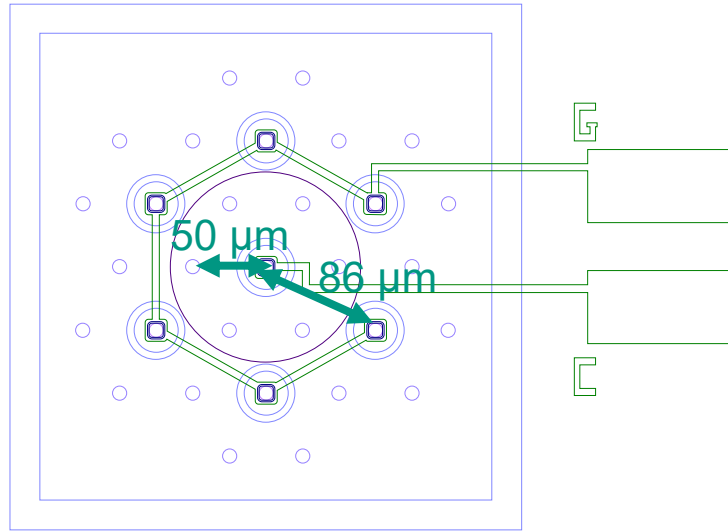




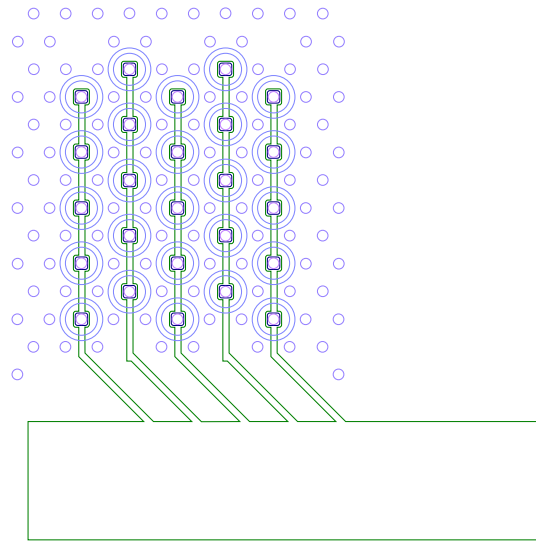
Columnar 3D Silicon Sensors

Pixel Layouts

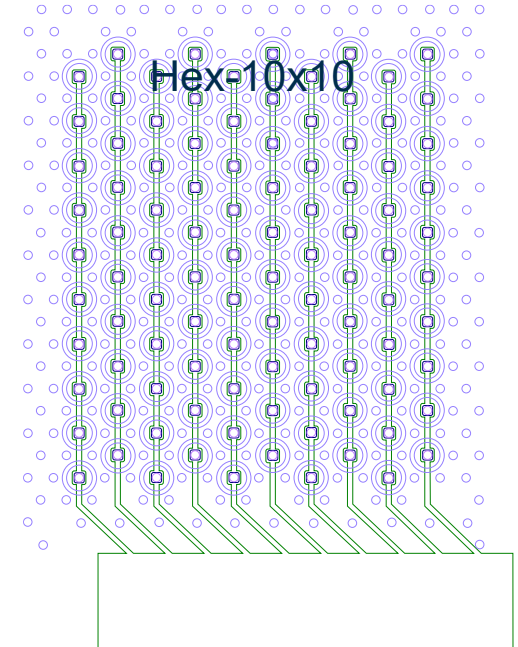
Hex-1



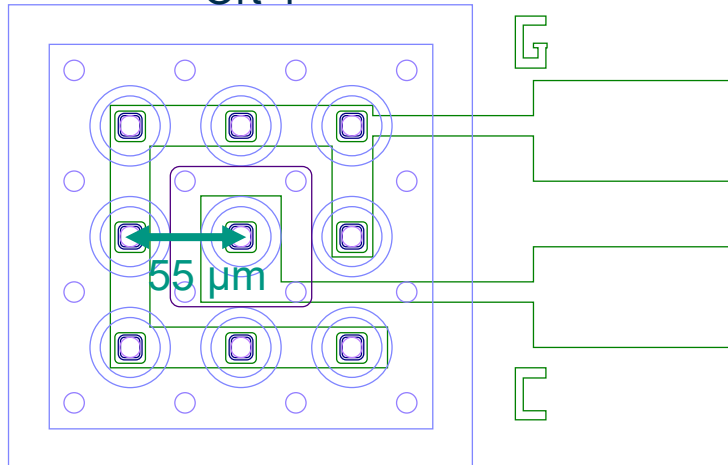
Hex-5x5



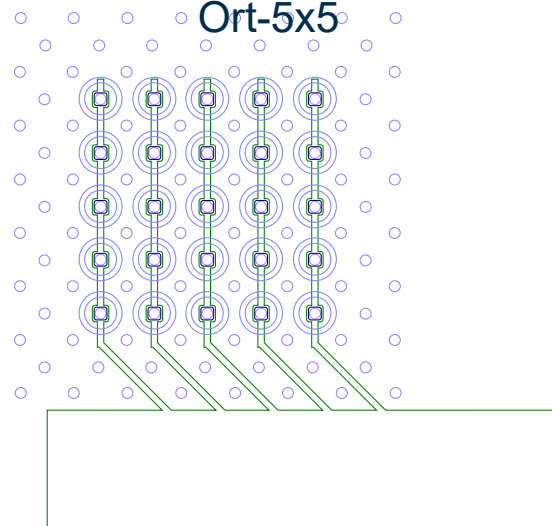
Hex-10x10



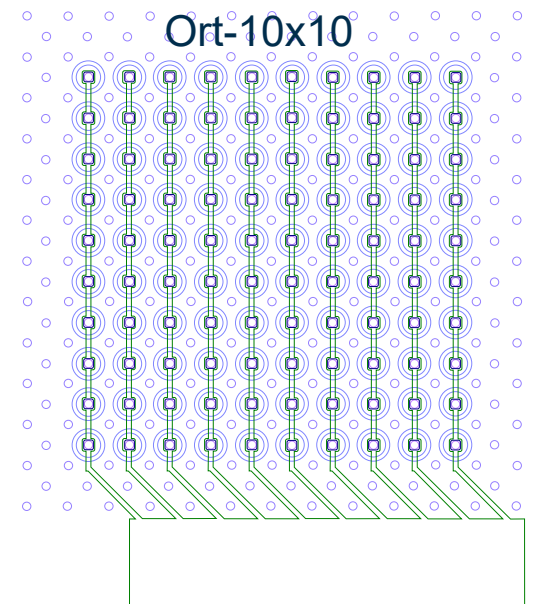
Ort-1



Ort-5x5



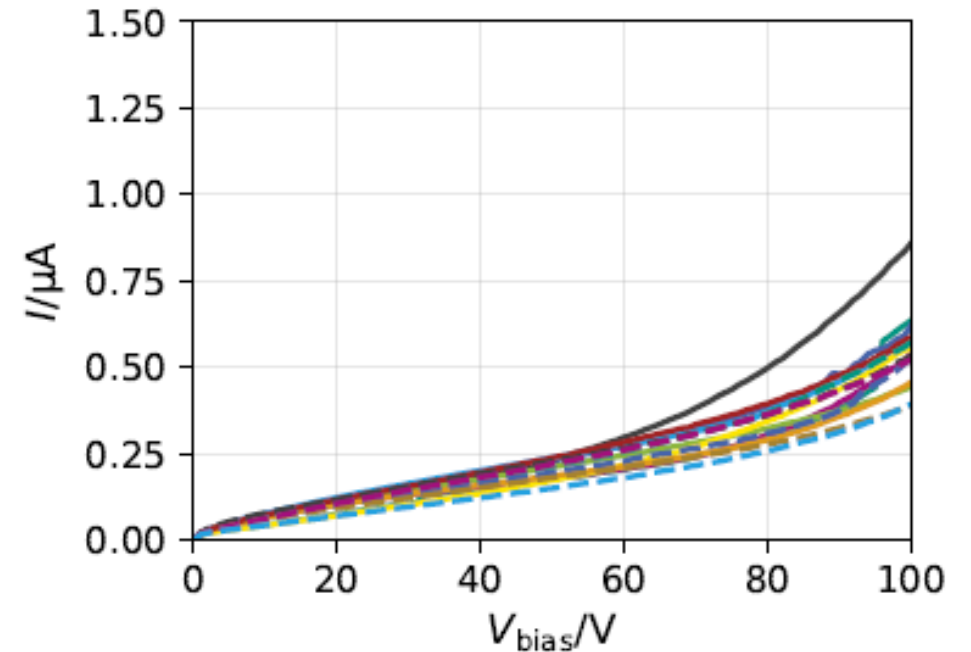
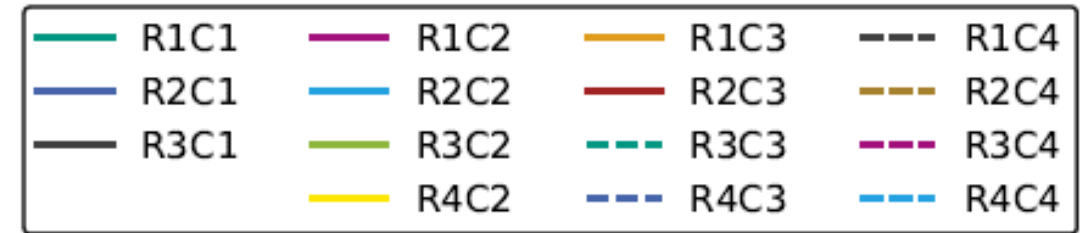
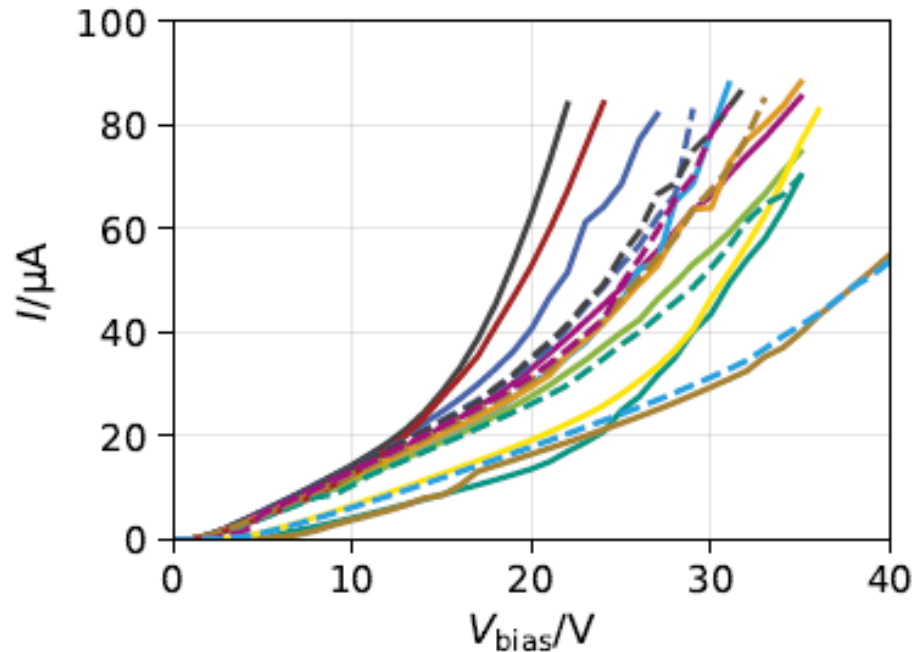
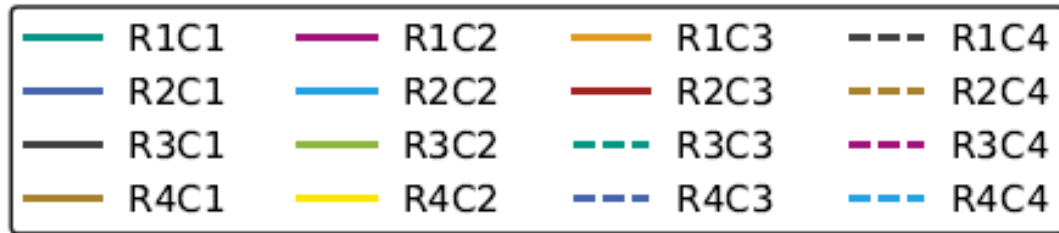
Ort-10x10



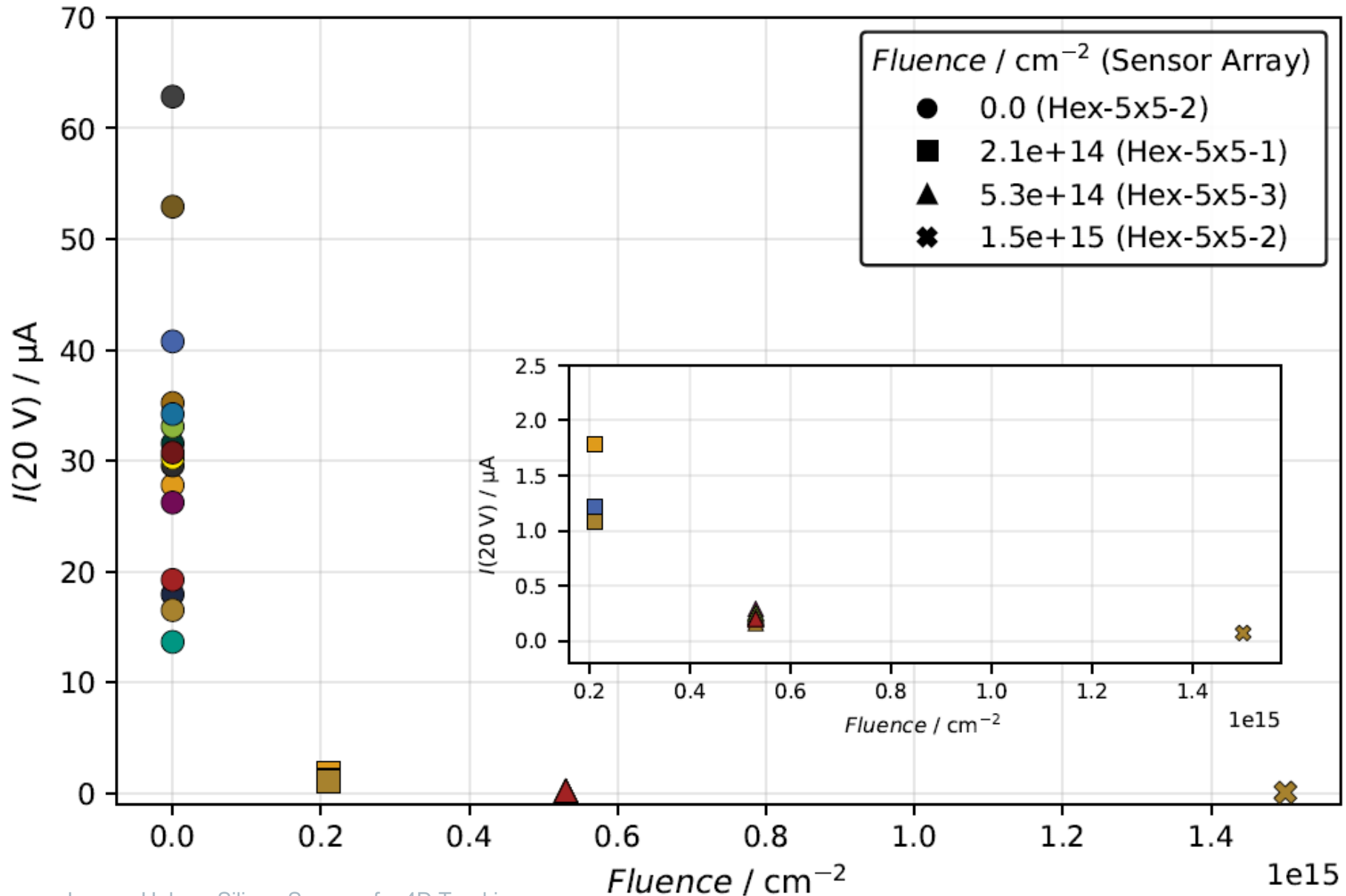
Irradiation Campaign

Measured Proton Fluence / cm^{-2}	Irradiated Arrays
2.1×10^{14}	Hex-1-3, Hex-5x5-1, Ort-5x5-1, Hex-10x10-2
5.3×10^{14}	Hex-1-4, Hex-5x5-3, Ort-5x5-2, Hex-10x10-3
1.5×10^{15}	Hex-1-2, Hex-5x5-2, Hex-10x10-1

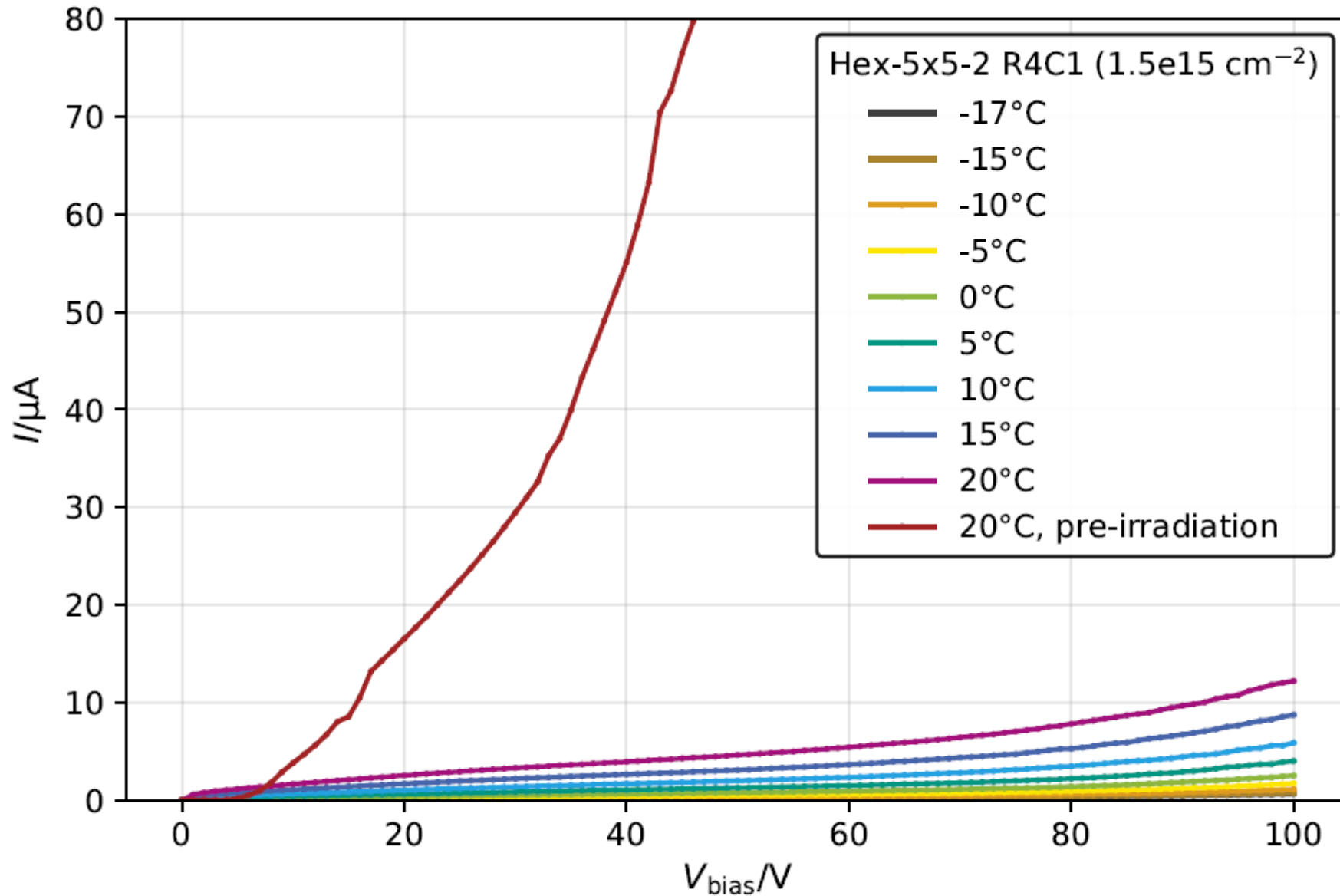
Leakage Current vs. Bias Voltage Hex-5x5-2



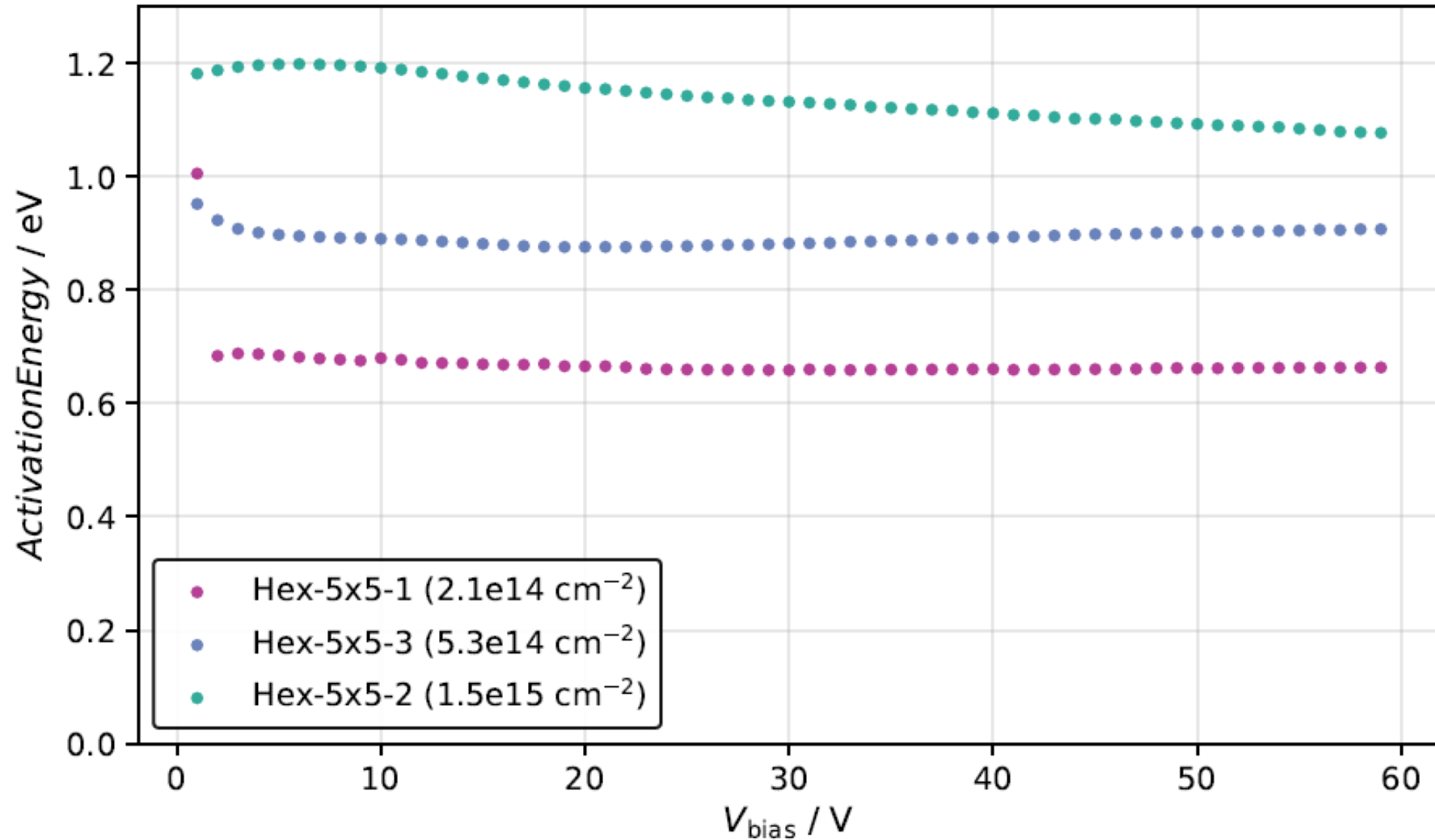
Leakage Current vs. Fluence Hex-5x5



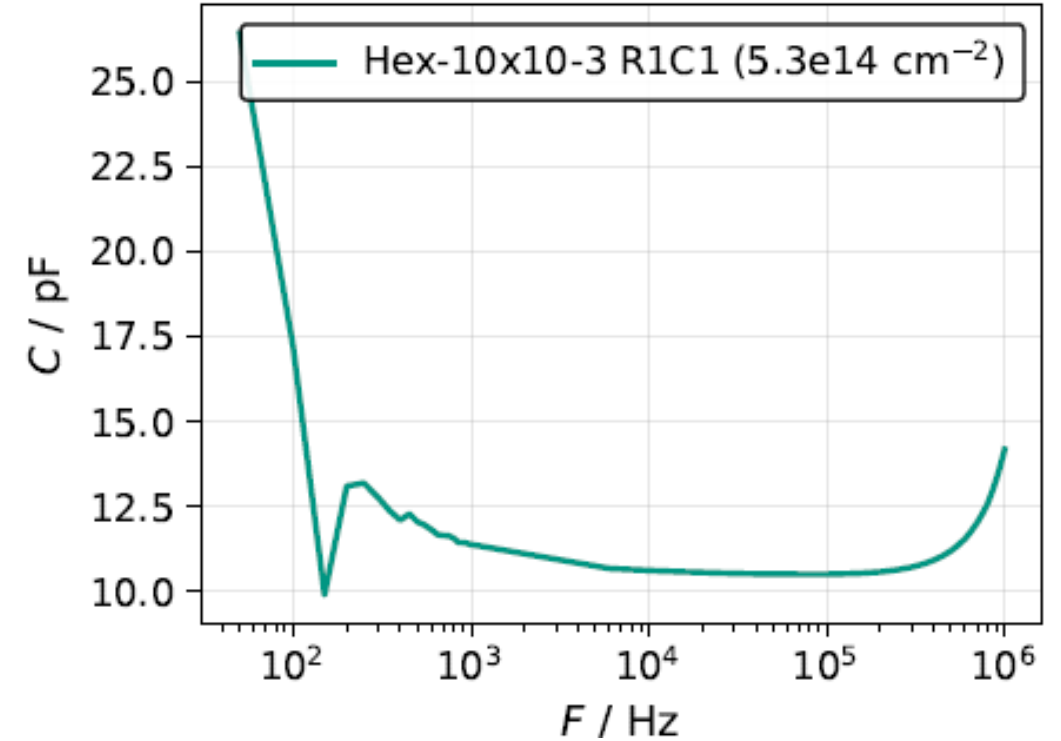
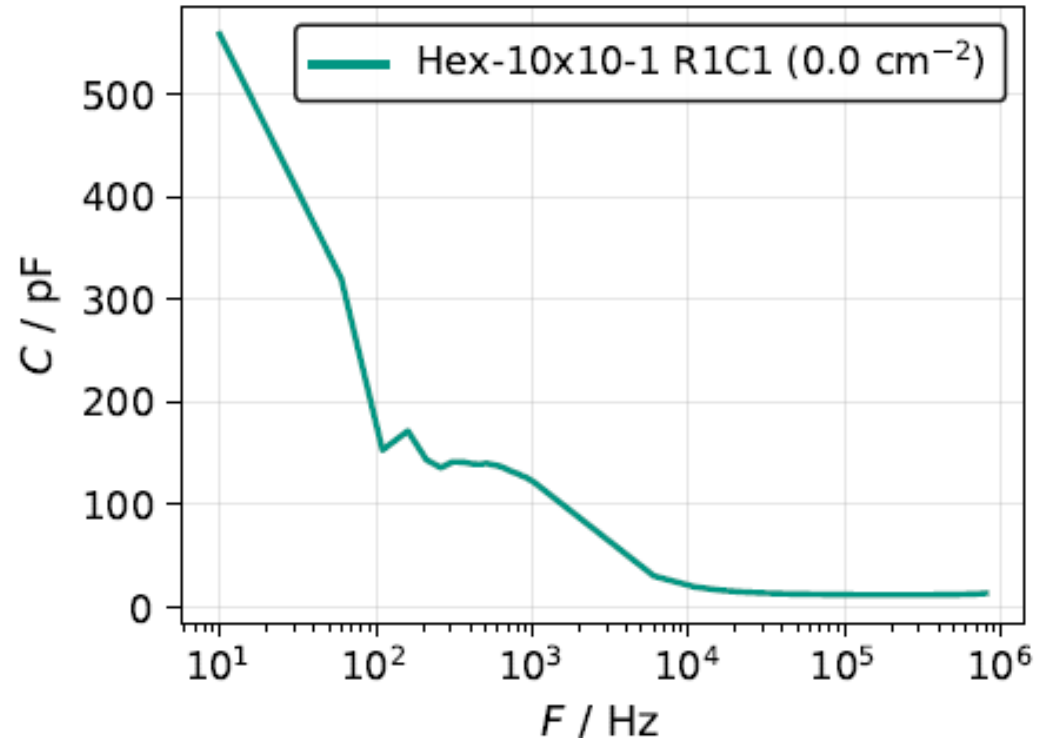
Temperature Dependent Leakage Current



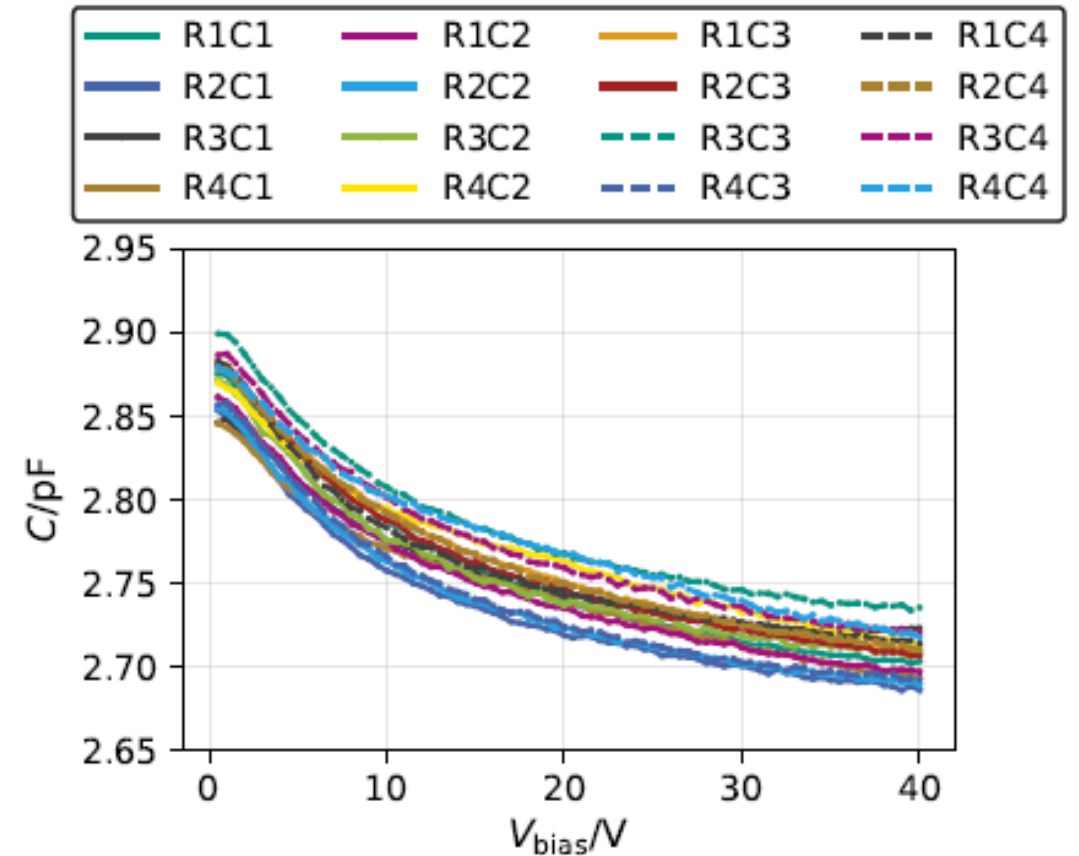
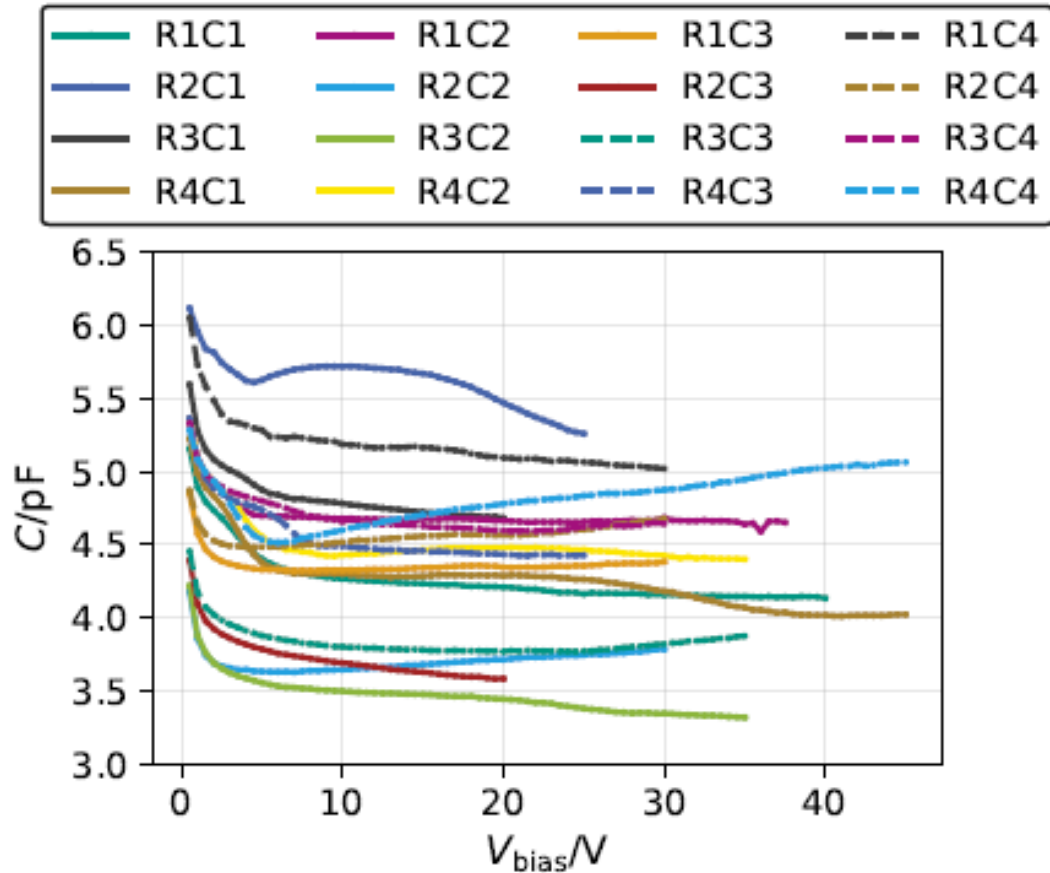
Activation Energy vs. Bias Voltage



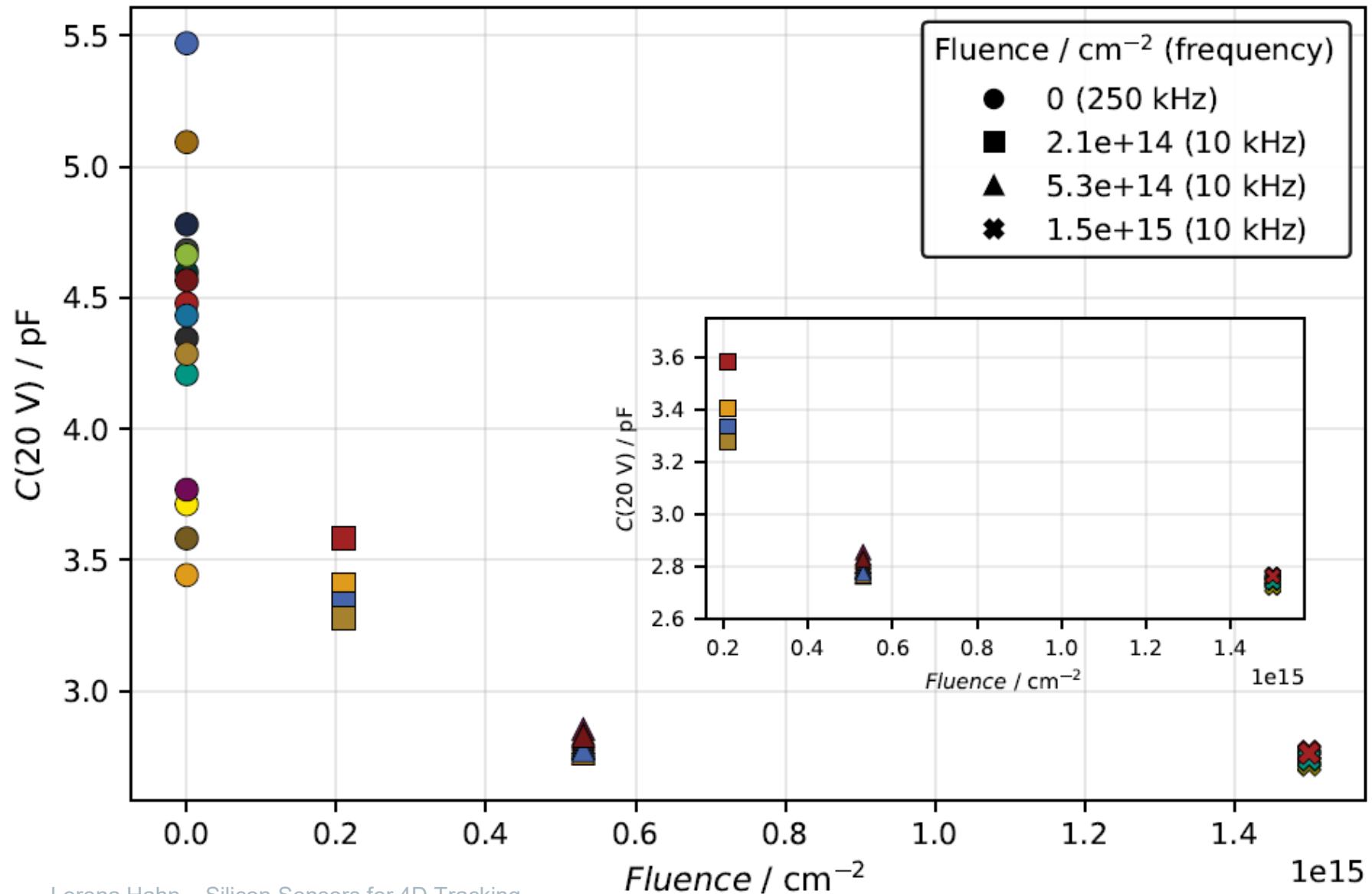
Capacity vs. Frequency Hex-10x10

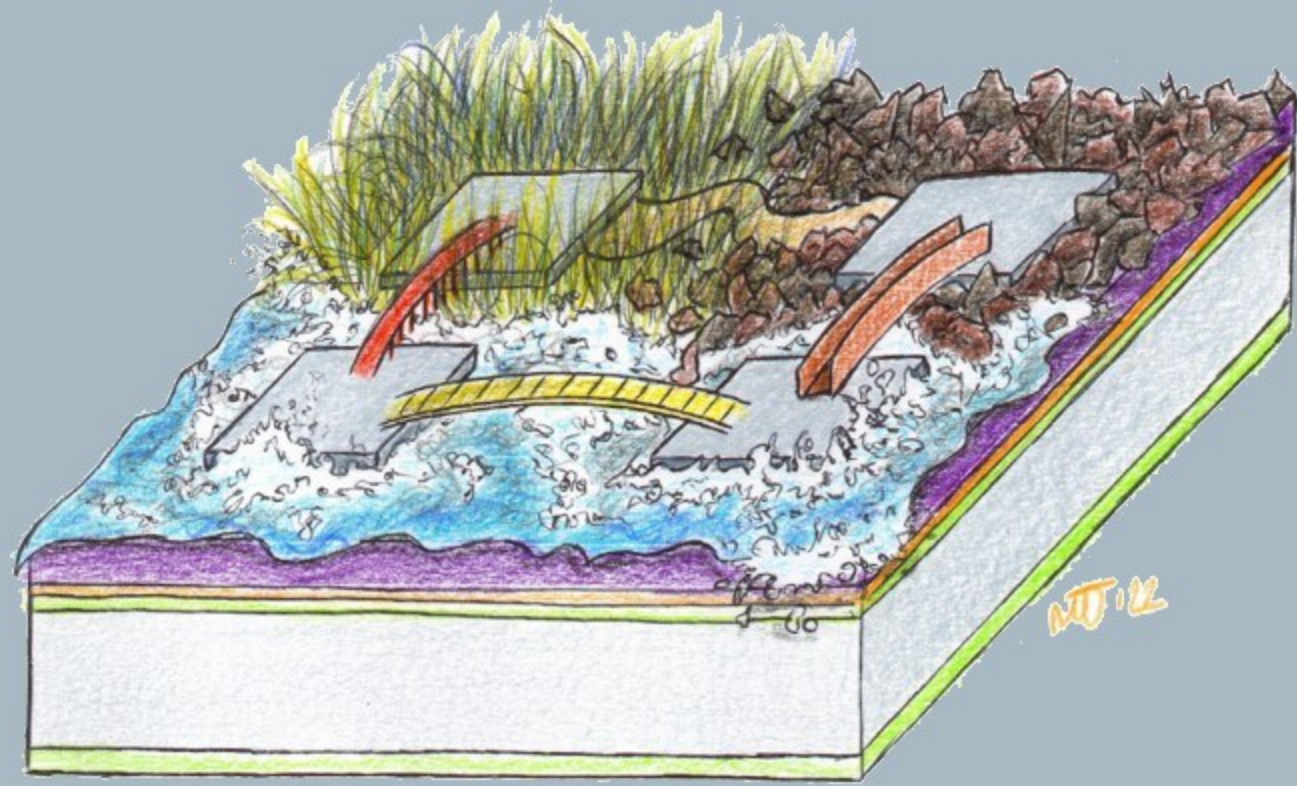


Capacity vs. Bias Voltage Hex-5x5-2



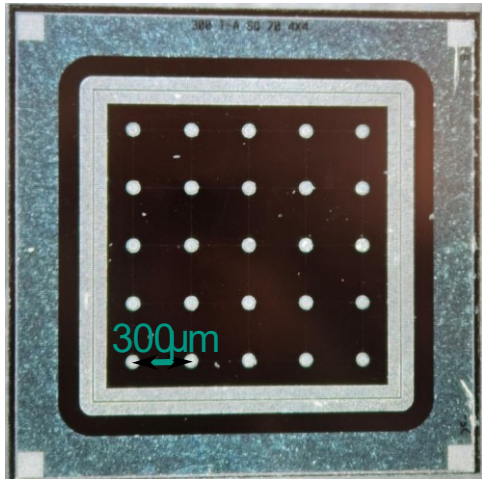
Capacity vs. Fluence Hex-5x5



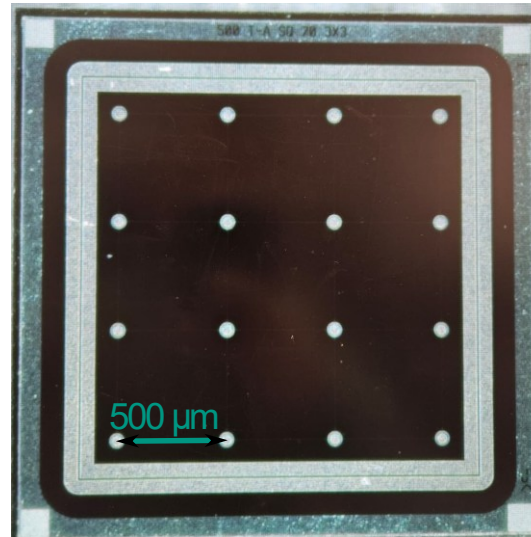


Electrical Characterization Resistive Silicon Detectors

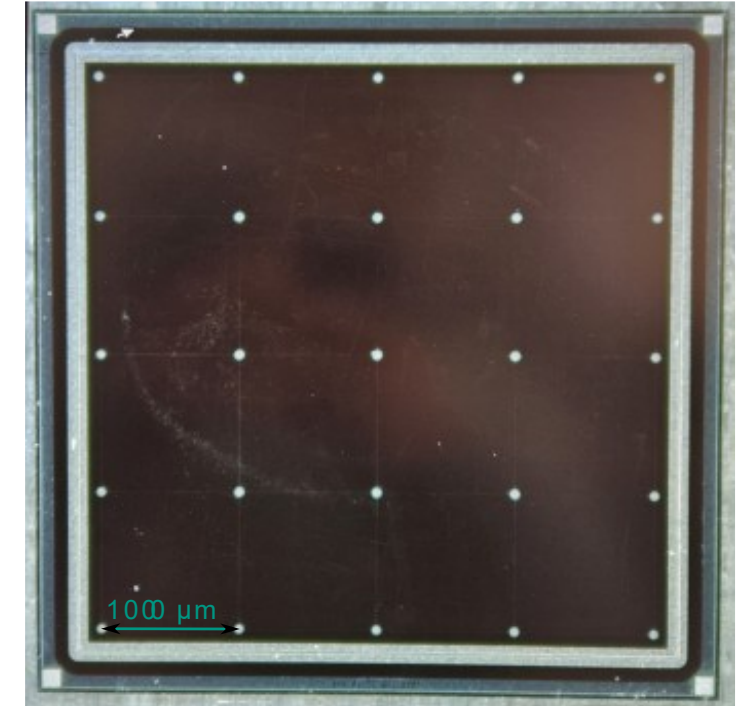
Investigated DC-RSD Layouts



S(5x5)



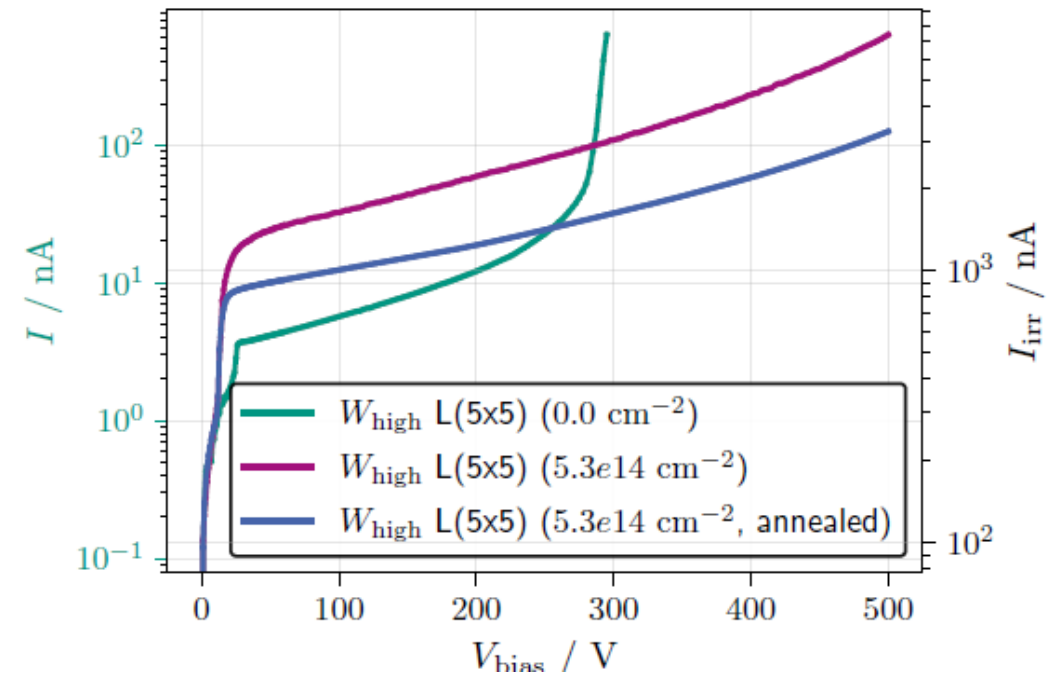
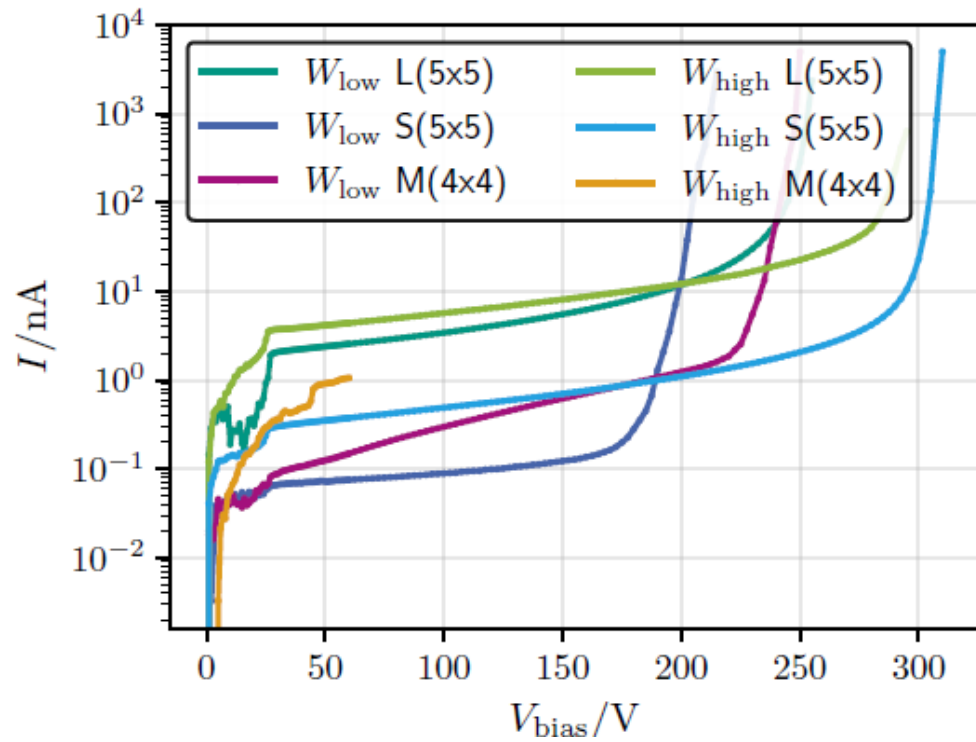
M(4x4)



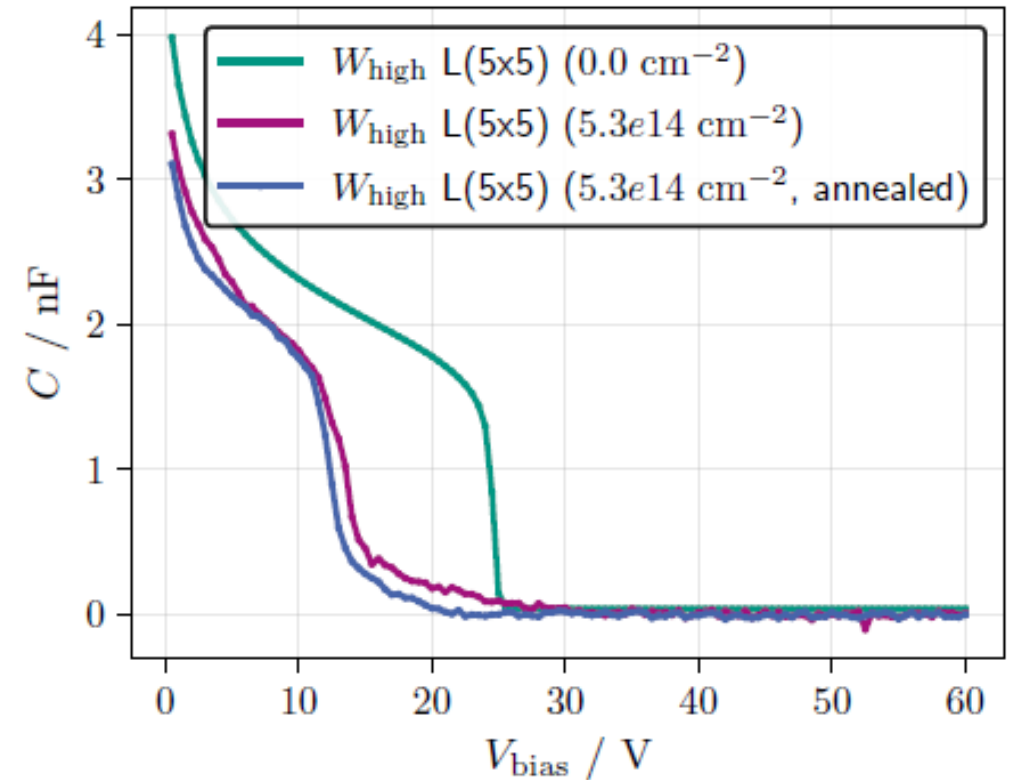
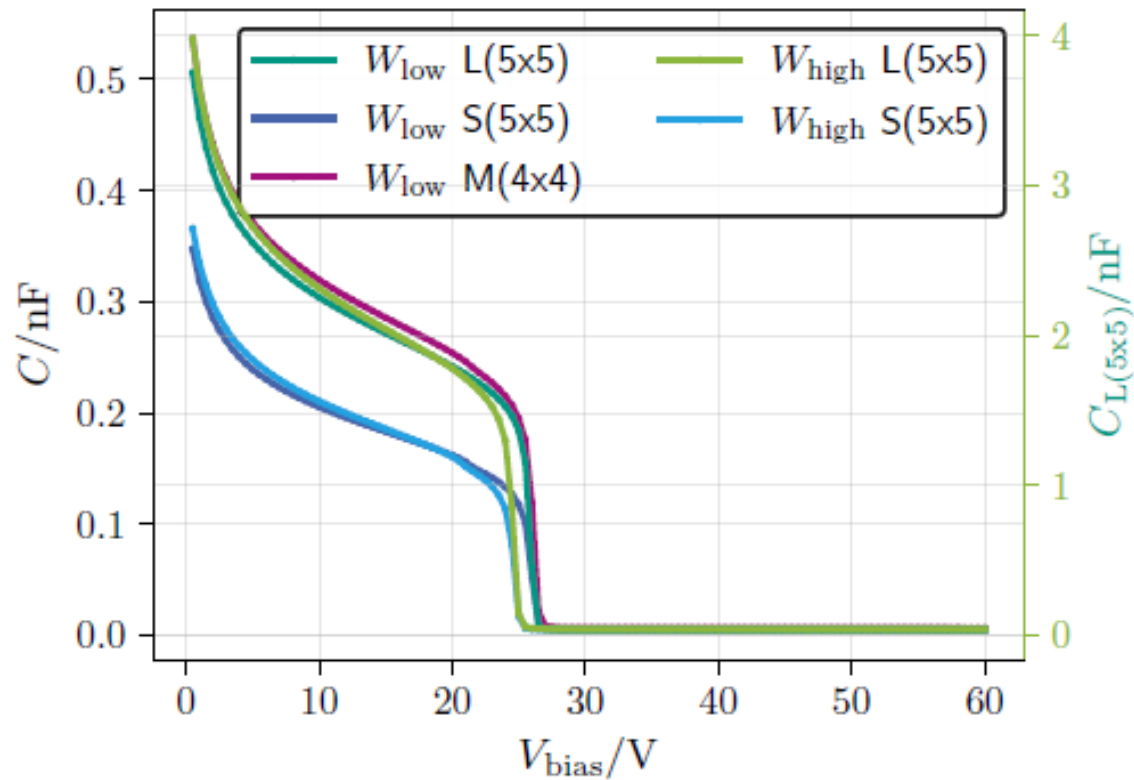
L(5x5)

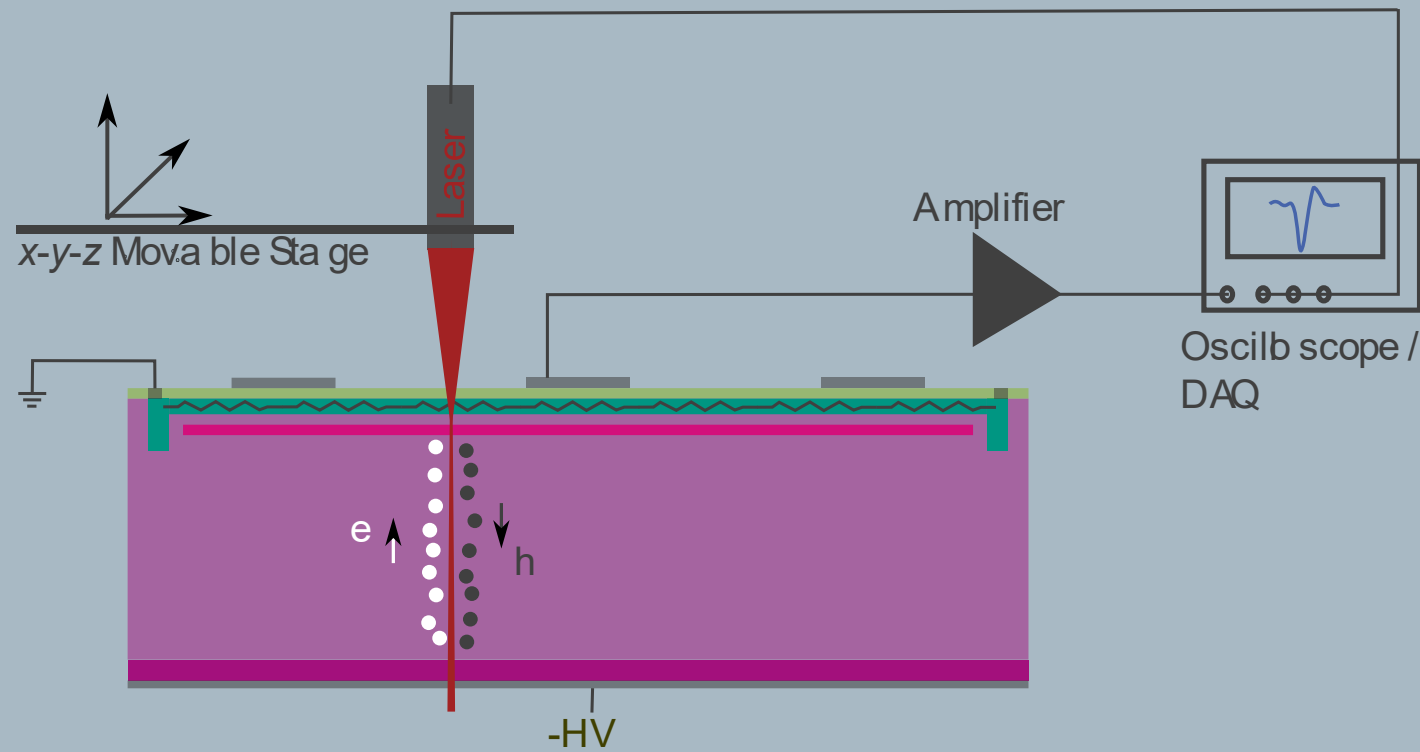
* Pictures not to scale

Leakage Current vs. Bias Voltage



Capacitance vs. Bias Voltage

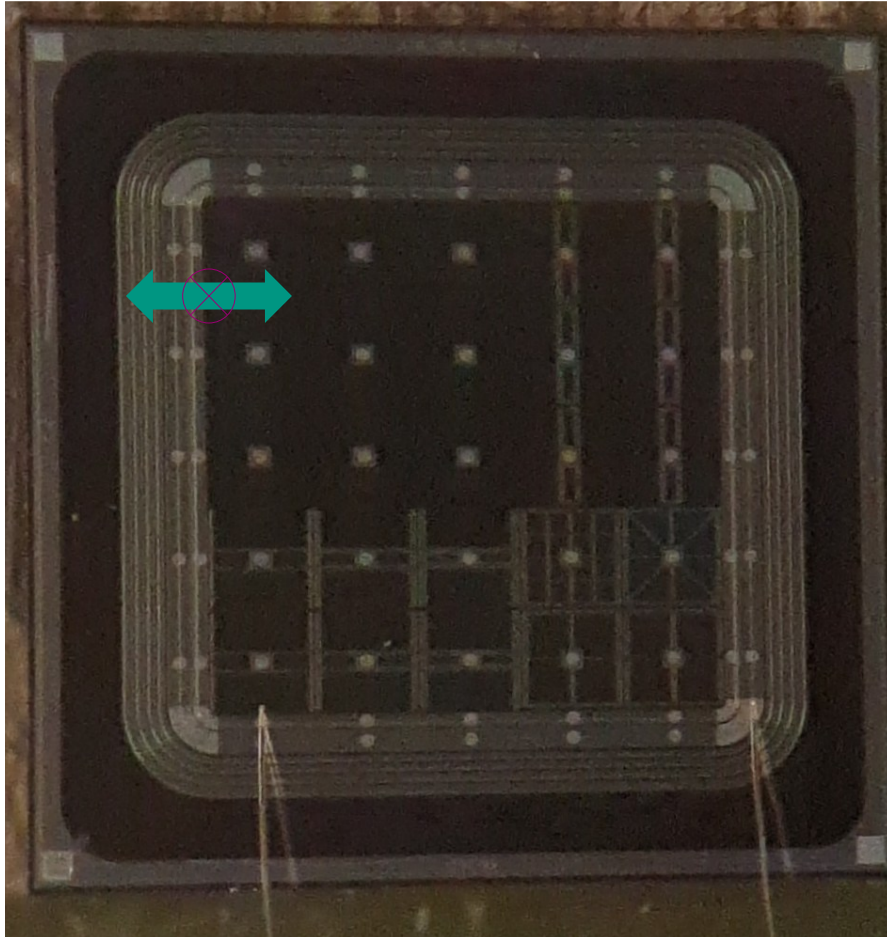




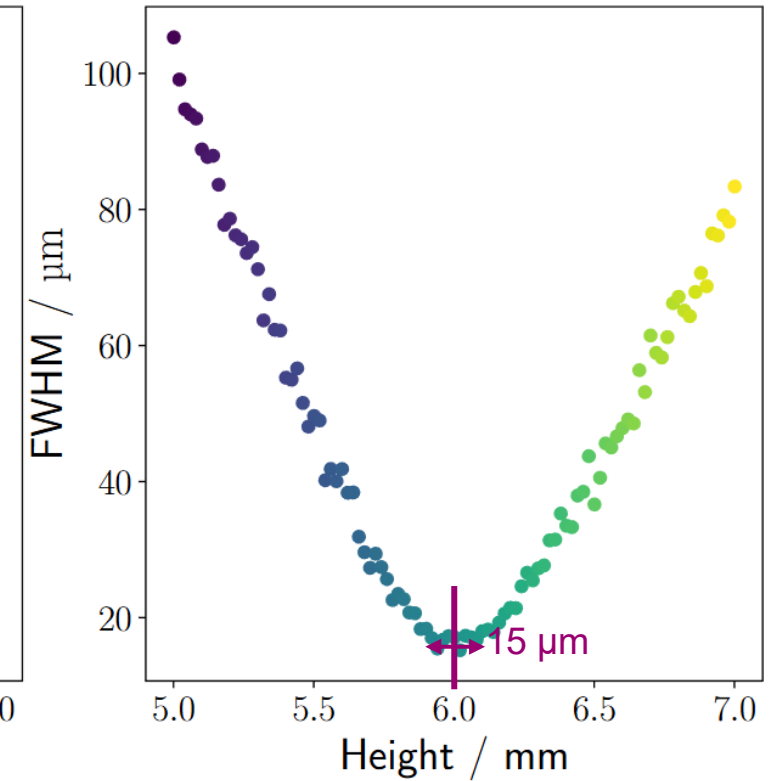
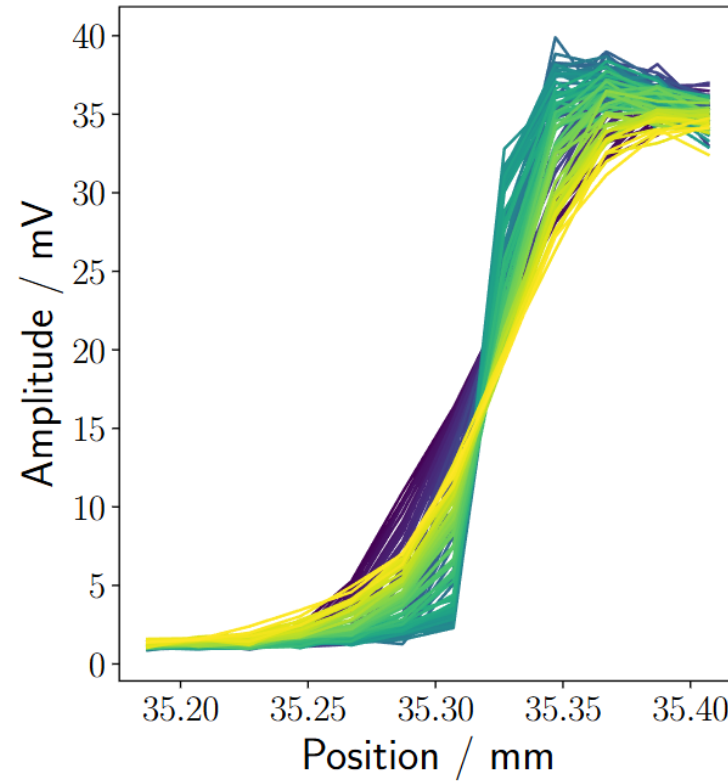
Calibrating the TCT

Laser Focusing

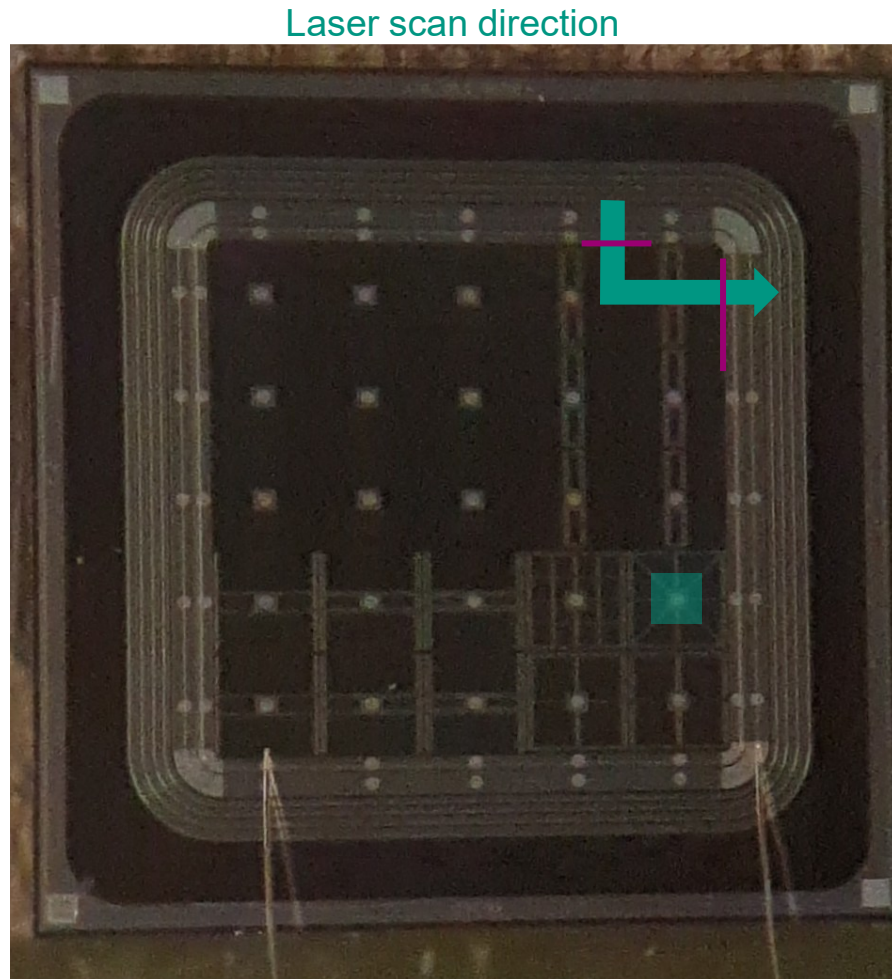
Laser scan direction



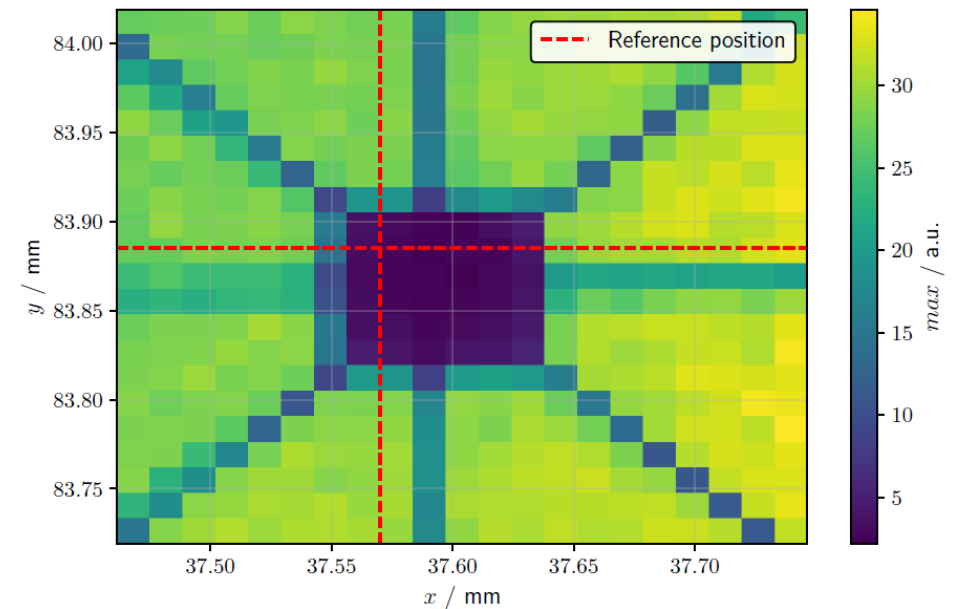
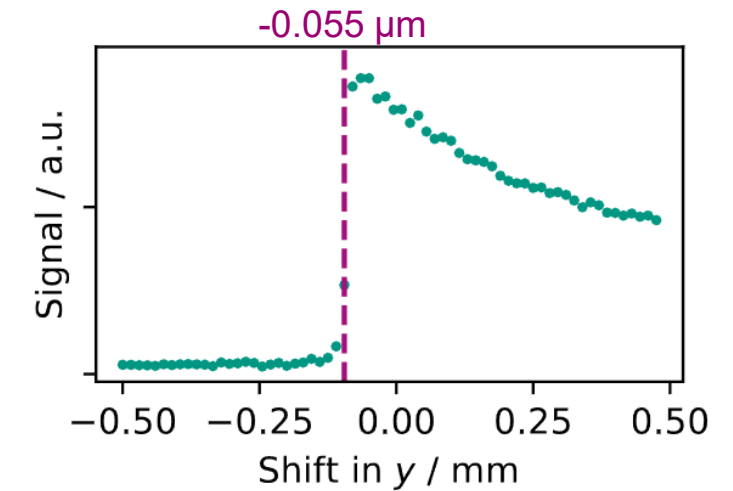
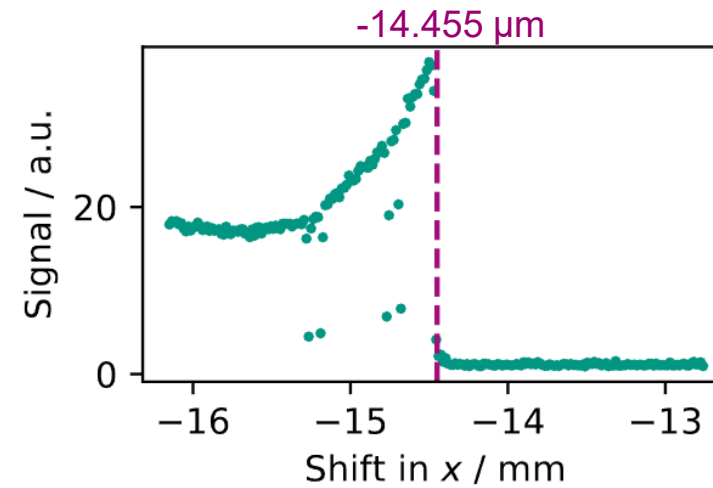
@ 150 V reverse bias

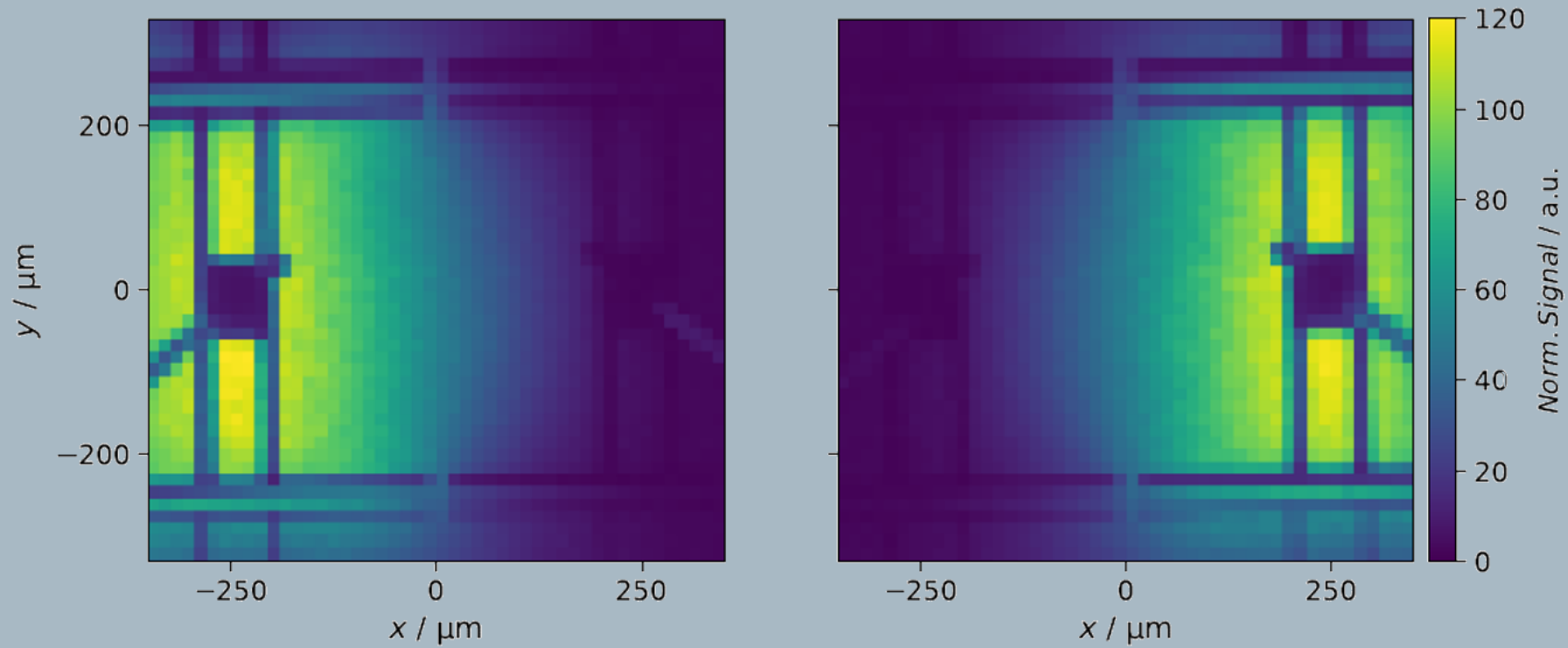


Camera-Laser Offset Calibration



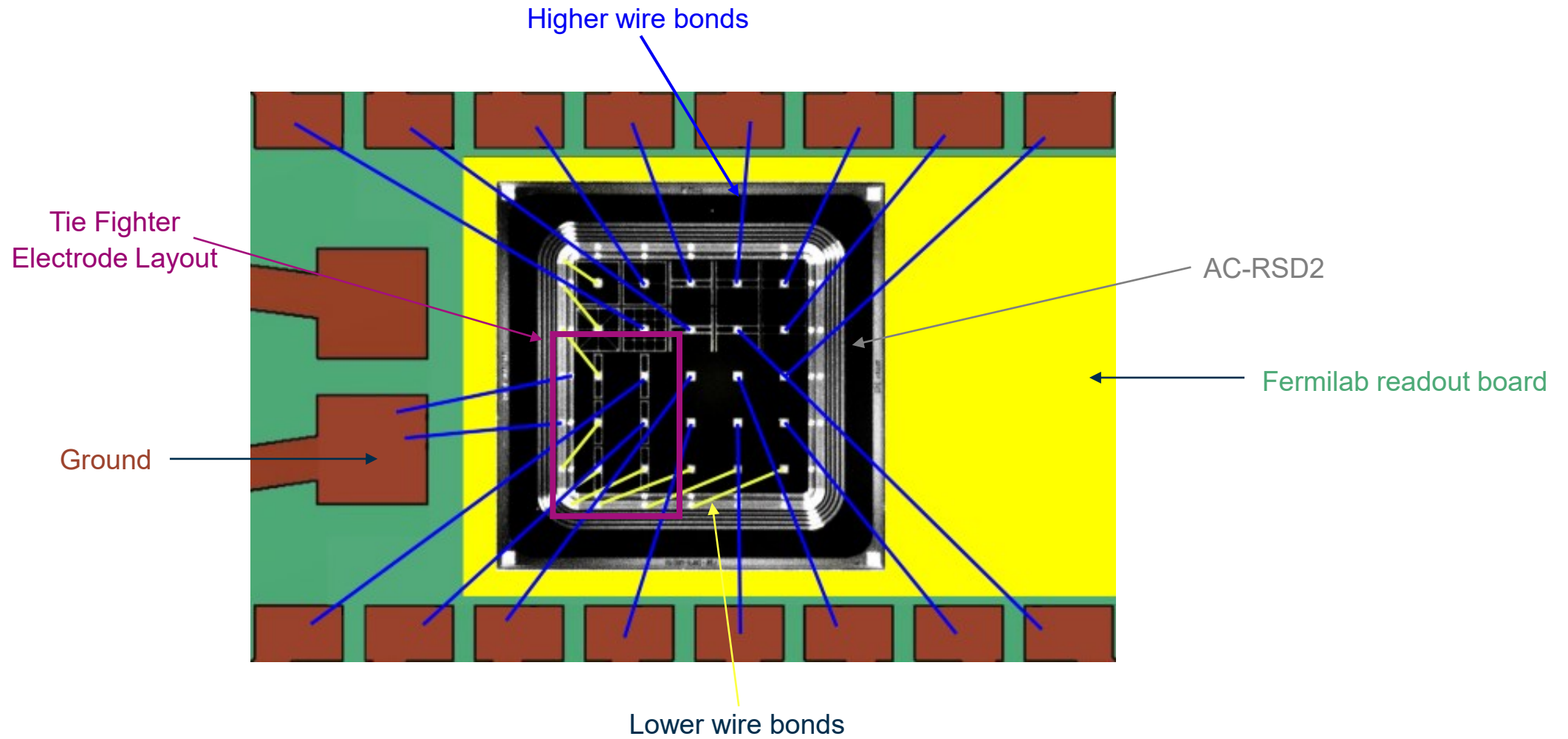
@ 150 V reverse bias

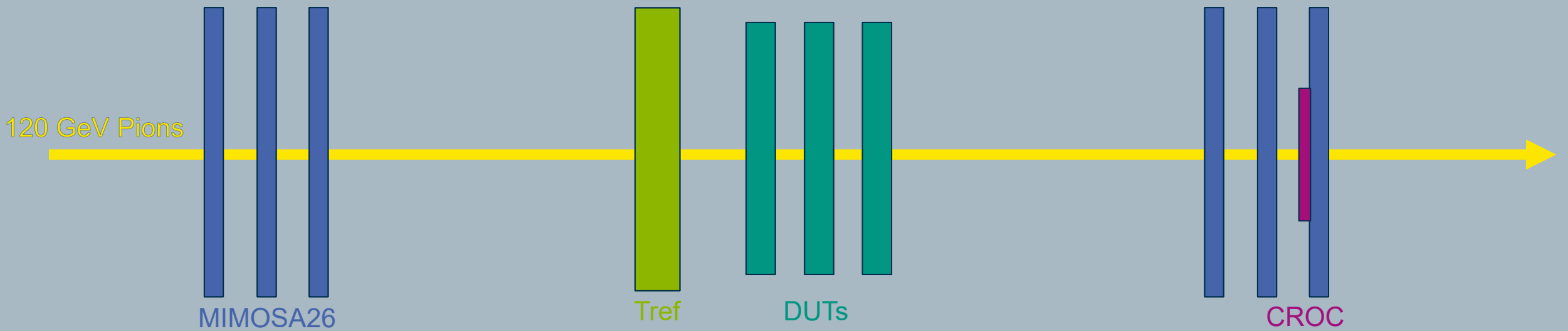




Spatial Resolution of Tie Fighter RSD Layout

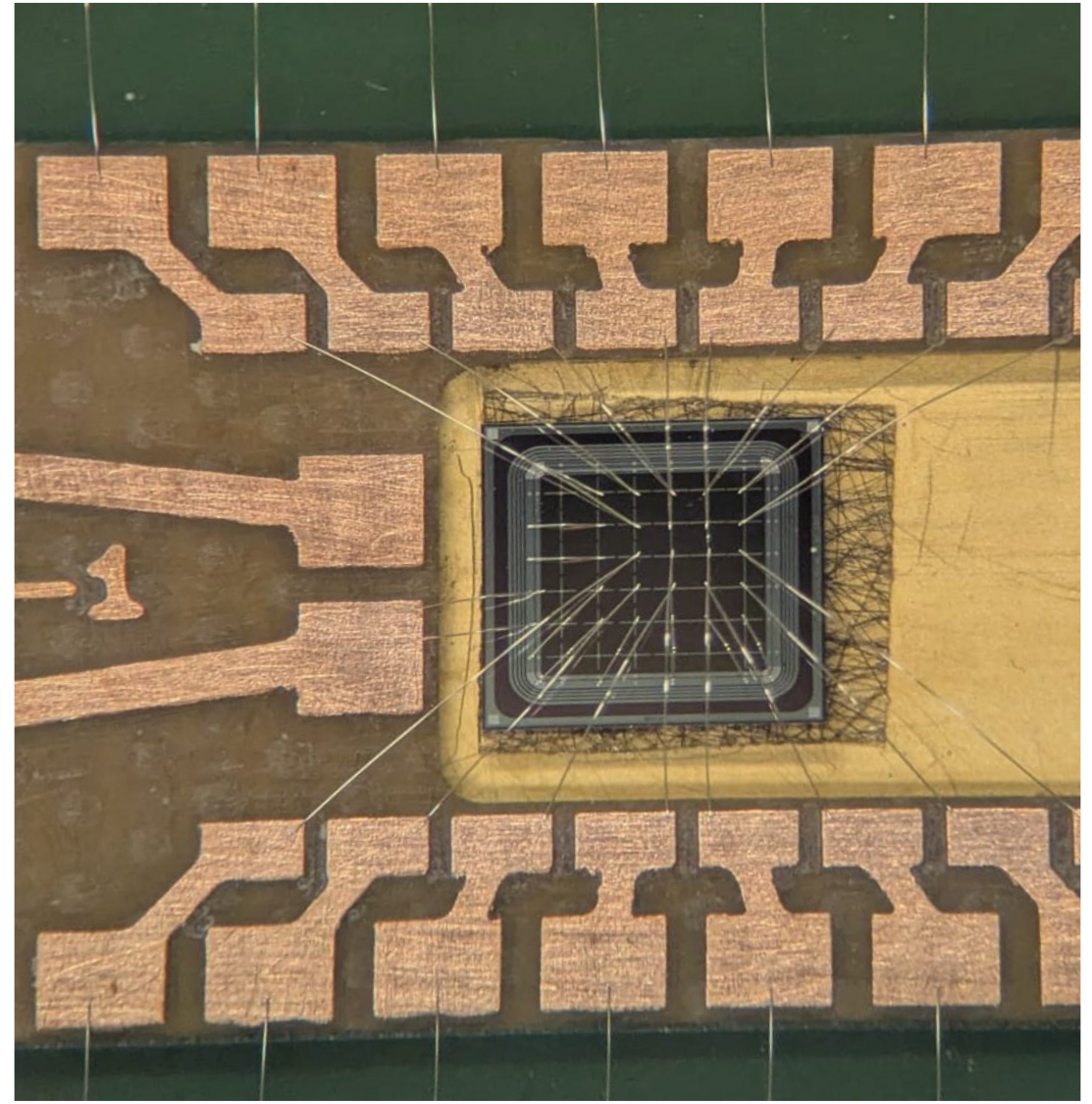
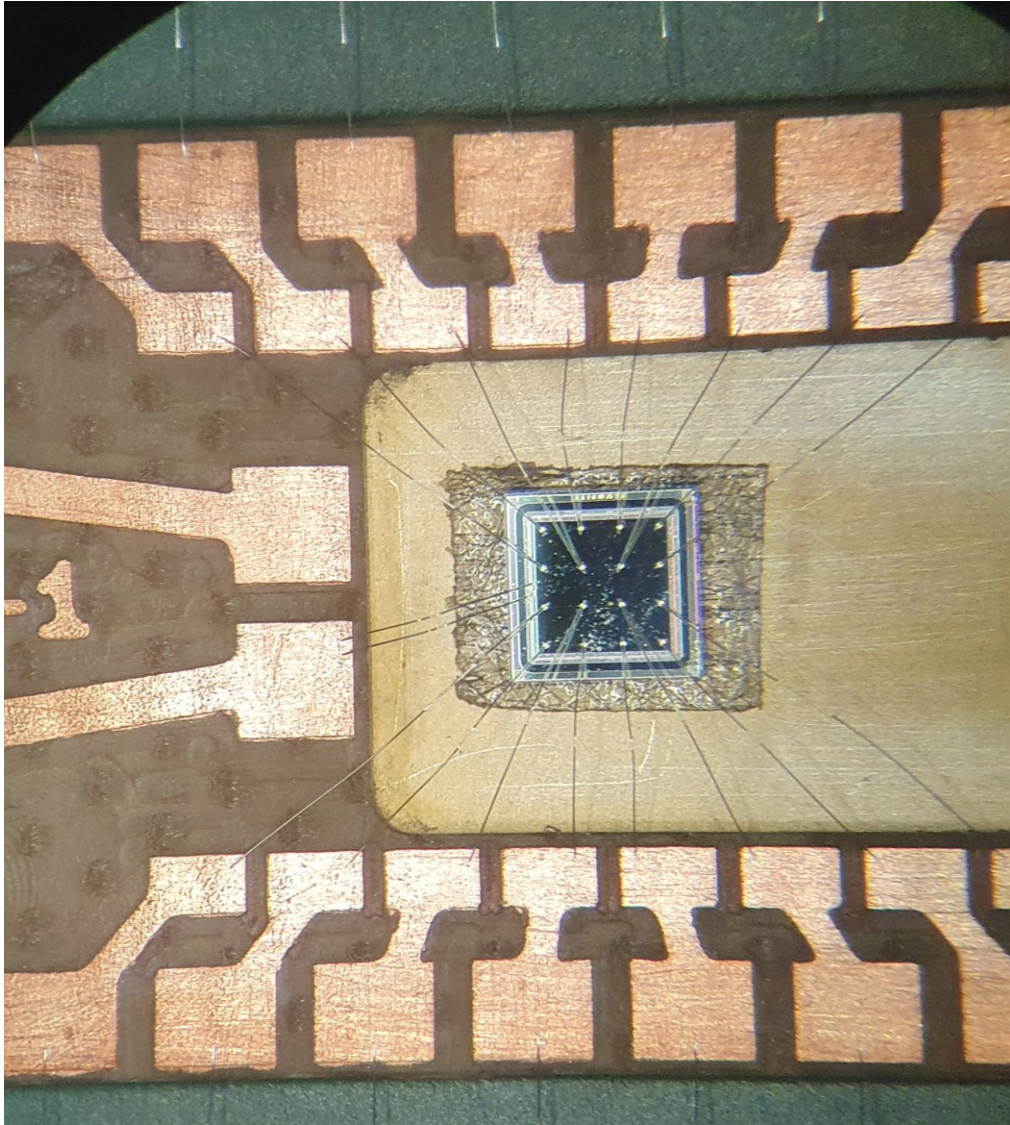
Bonding Scheme



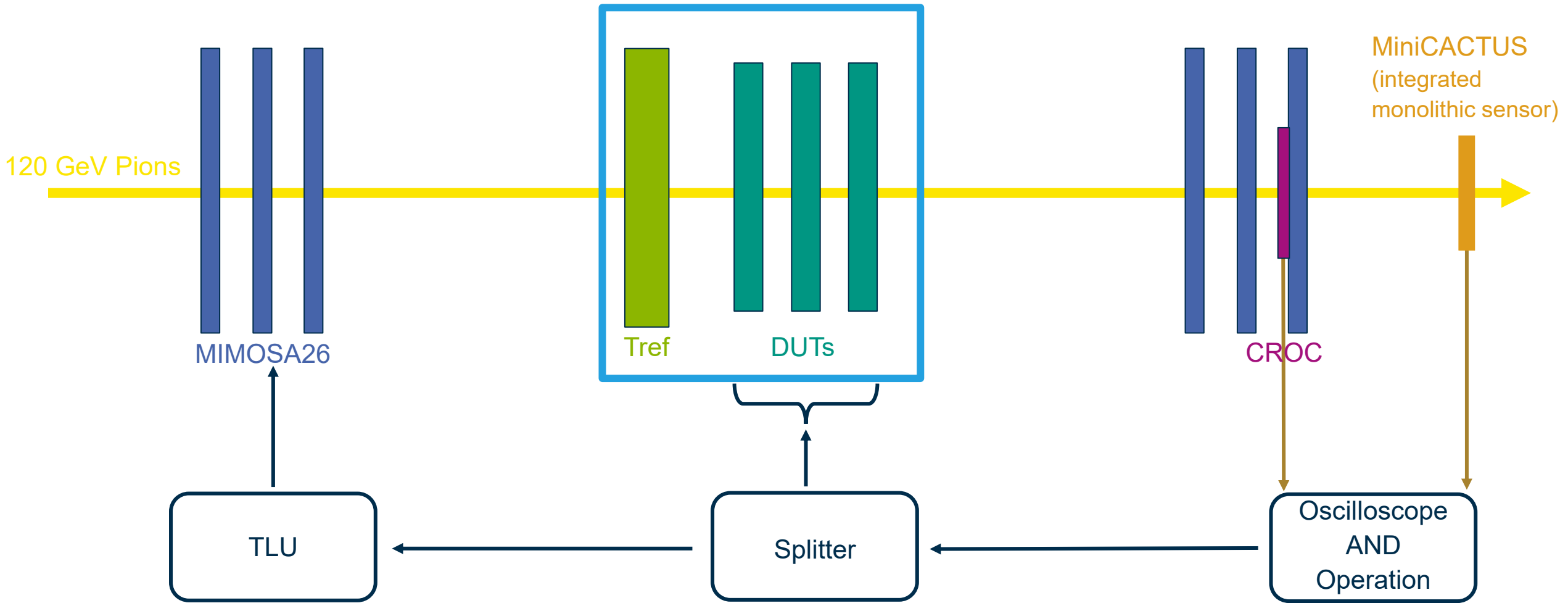


RSD Test Beam October 2025

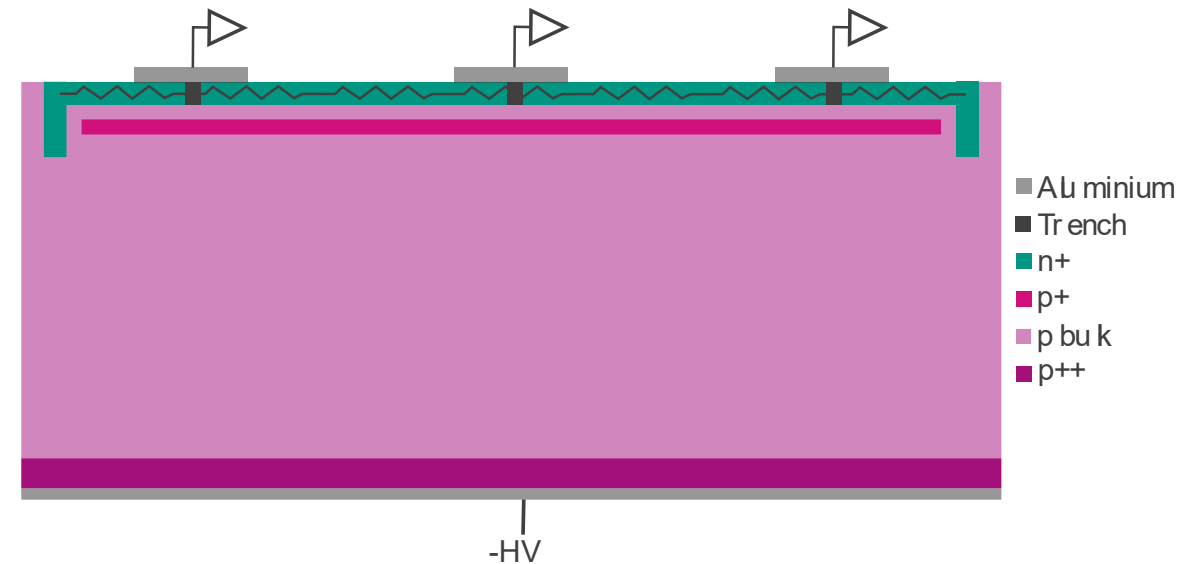
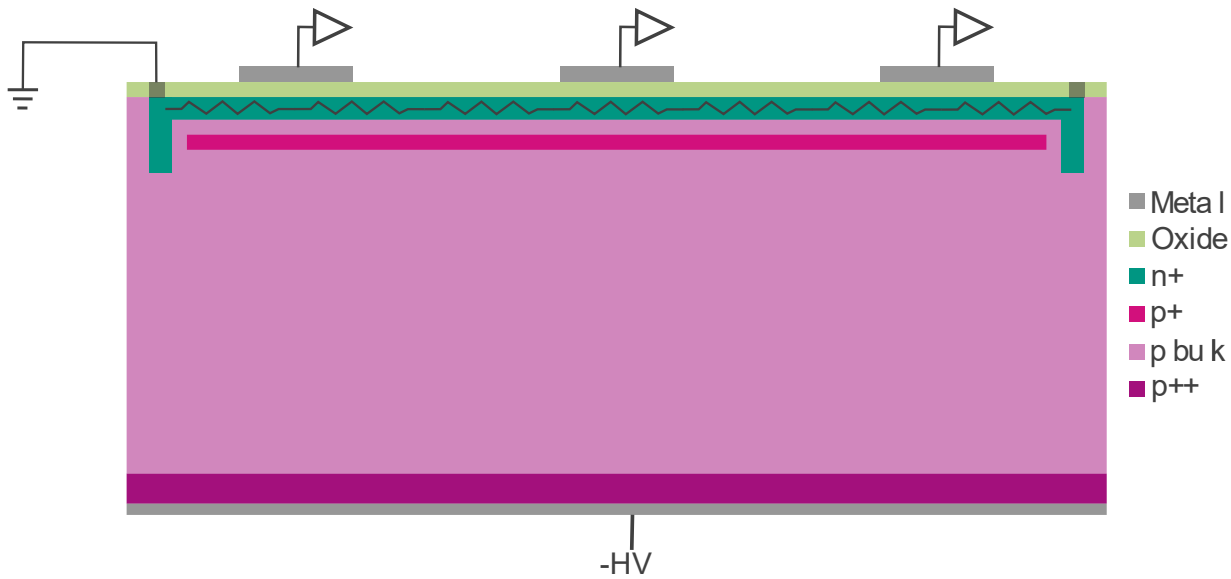
RSDs Bonded on FNAL Board



Setup



AC- vs DC-RSD Cross Section

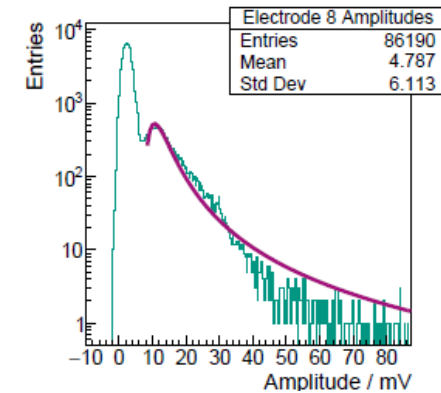
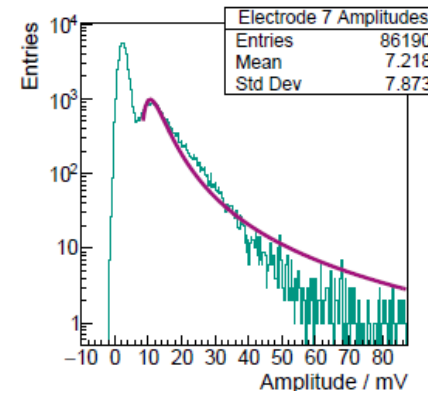
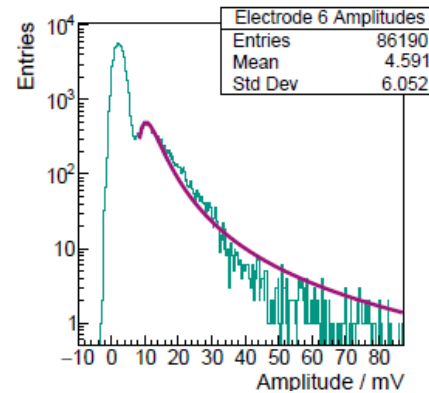
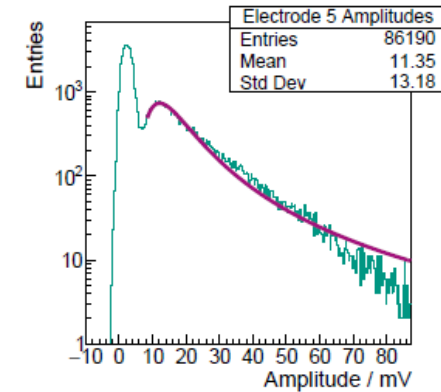
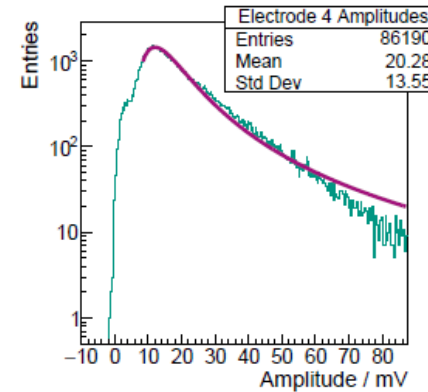
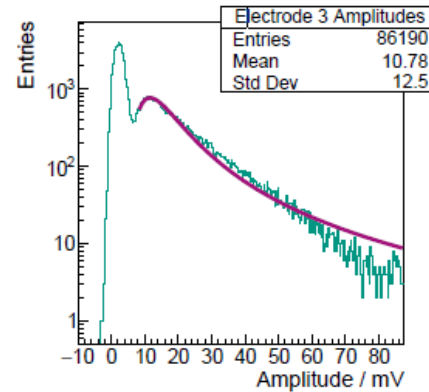
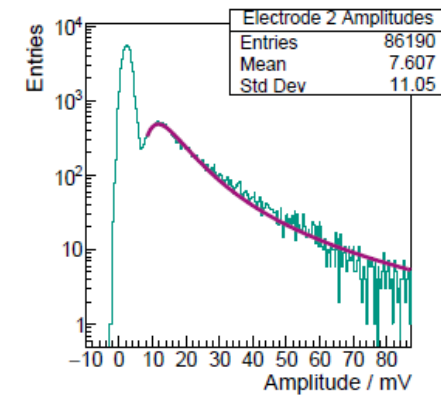
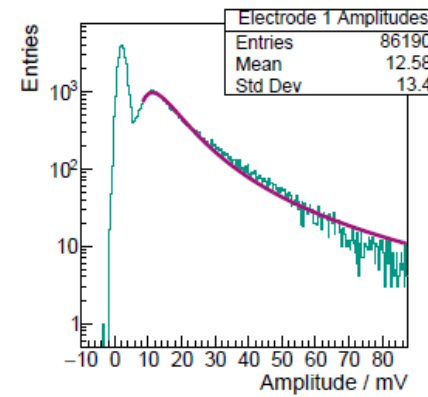
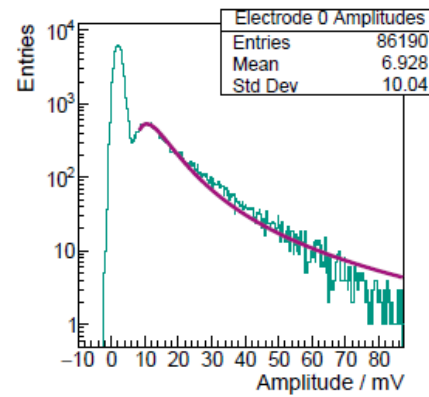


Amplitude Calibration

Equalizing amplitudes of all channels

- FNAL channel amplification can vary → **normalization**
- Histogram amplitudes per channel
- Fit Landau distribution
- Scan over all fitted functions, find the largest MPV and normalize with respect to that

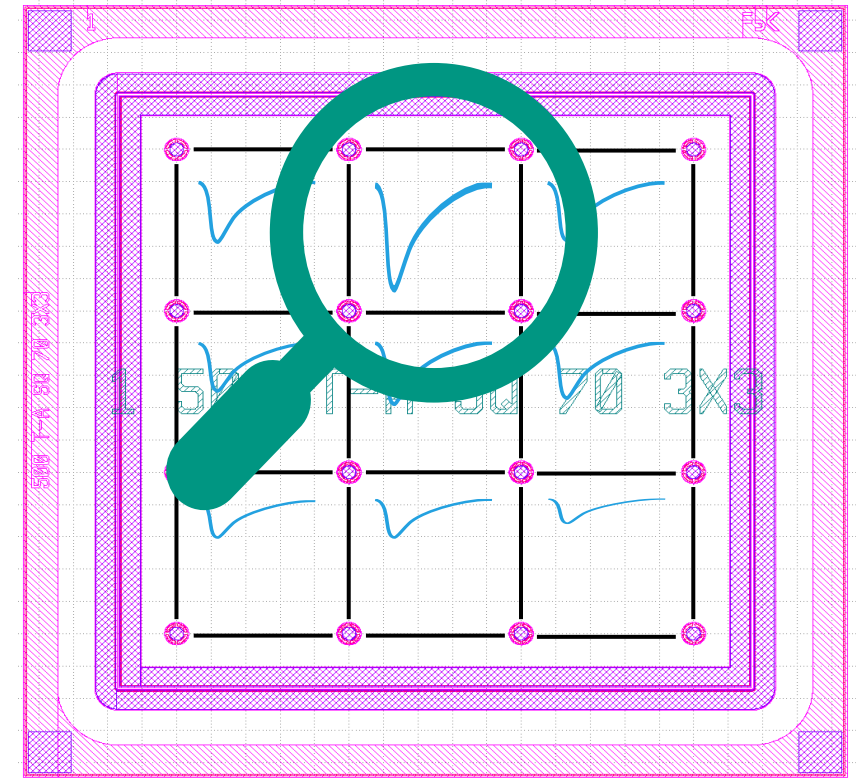
$$\text{CalibrationFactor} = \frac{p_{\max}}{p_i}$$



Lost in Charge Sharing – Template Approach

Position reconstruction by using a template

1. Identify Hit Pixel ($\max(A_{\text{tot}})$)
2. Generate 4 look-up tables inside a pixel at the best signal-to-noise datapoint == template
 - Describes how signal is split between the 4 electrodes in x and y
 - Uses ratio A_i/A_{tot}
3. Reconstructed position = closest match to 4 templates determined by χ^2 -minimizer



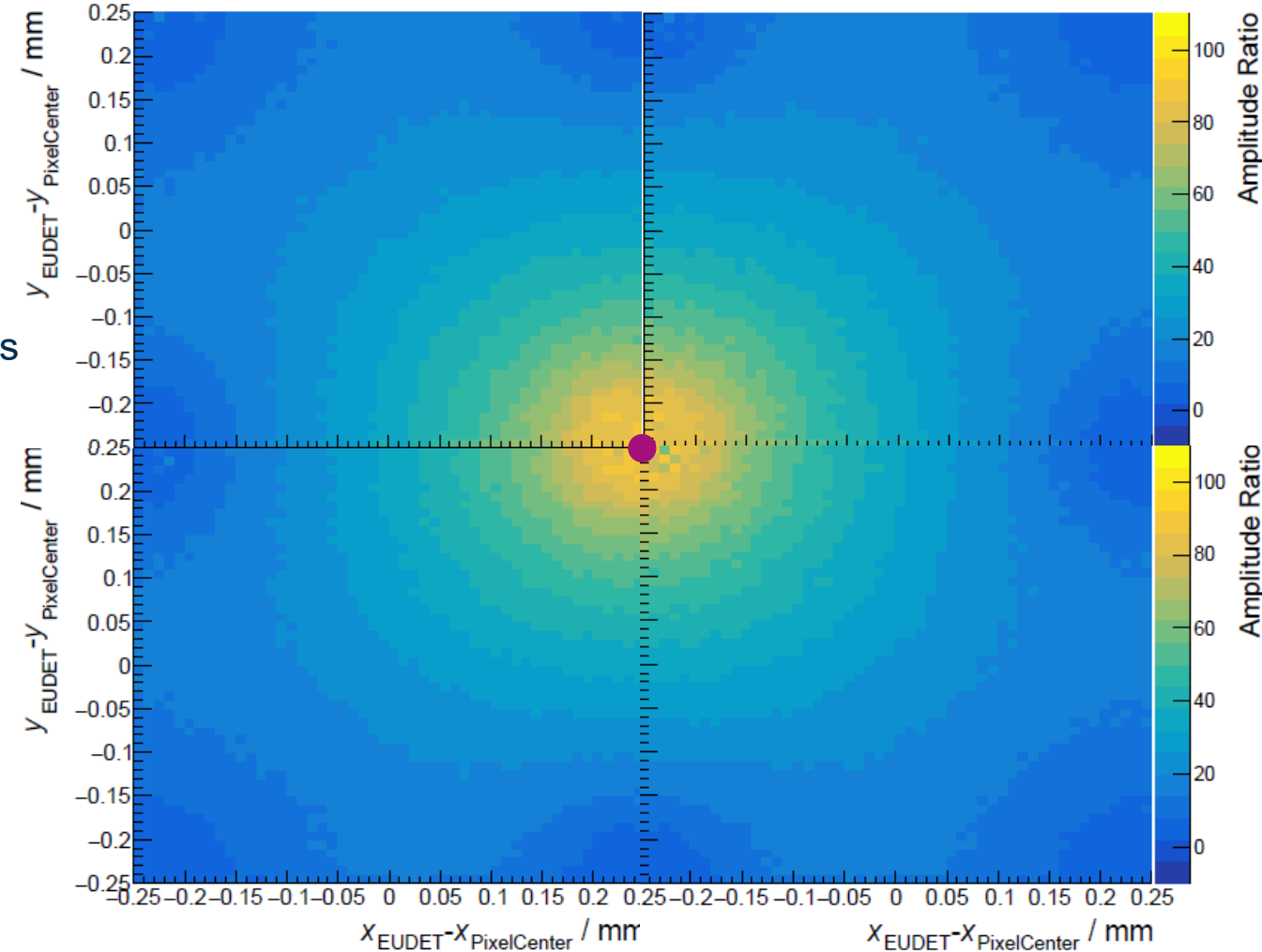
First done by Nicolò Cartiglia

Lost in Charge Sharing – Template Approach

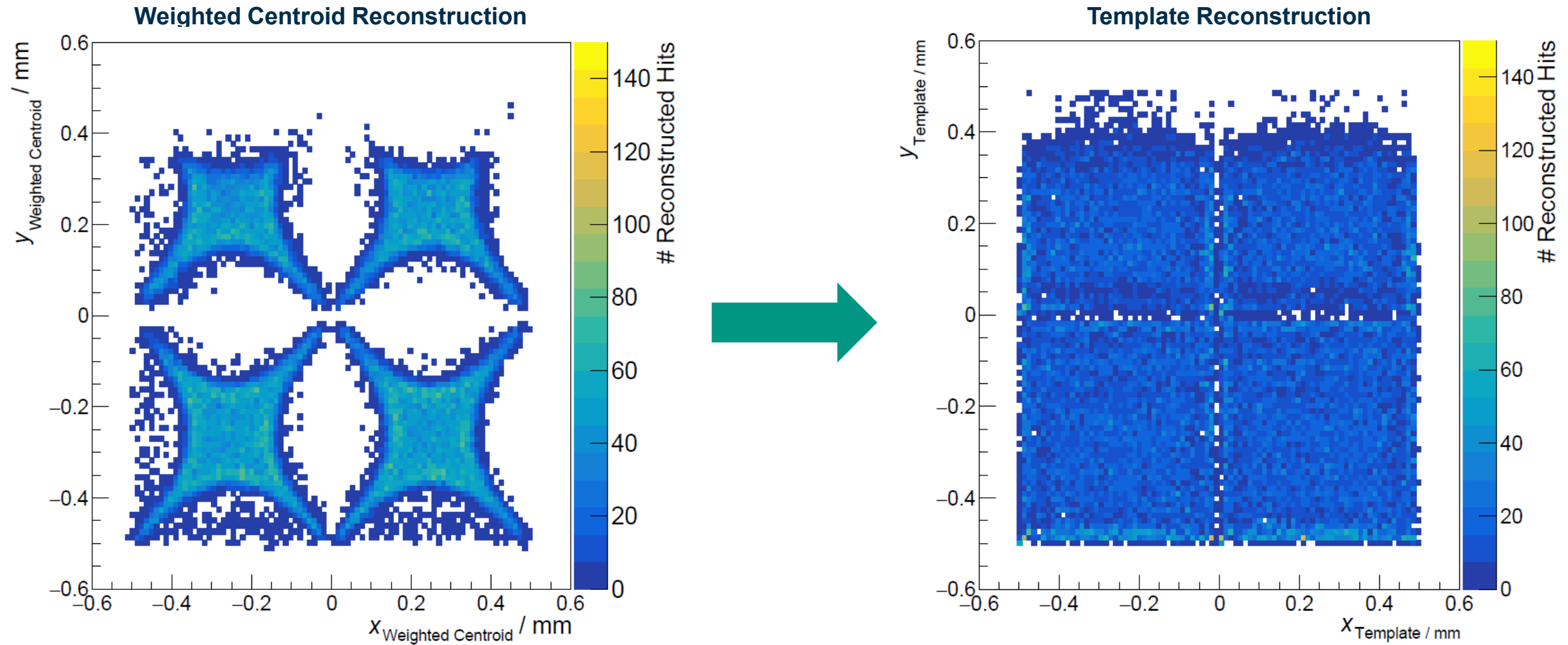
Position reconstruction by using a template

1. Identify Hit Pixel ($\max(A_{\text{tot}})$)
2. Generate 4 look-up tables inside a pixel at the best signal-to-noise datapoint == template
 - Describes how signal is split between the 4 electrodes in x and y
 - Uses ratio A_i/A_{tot}
3. Reconstructed position = closest match to 4 templates determined by χ^2 -minimizer

First done by Nicolò Cartiglia



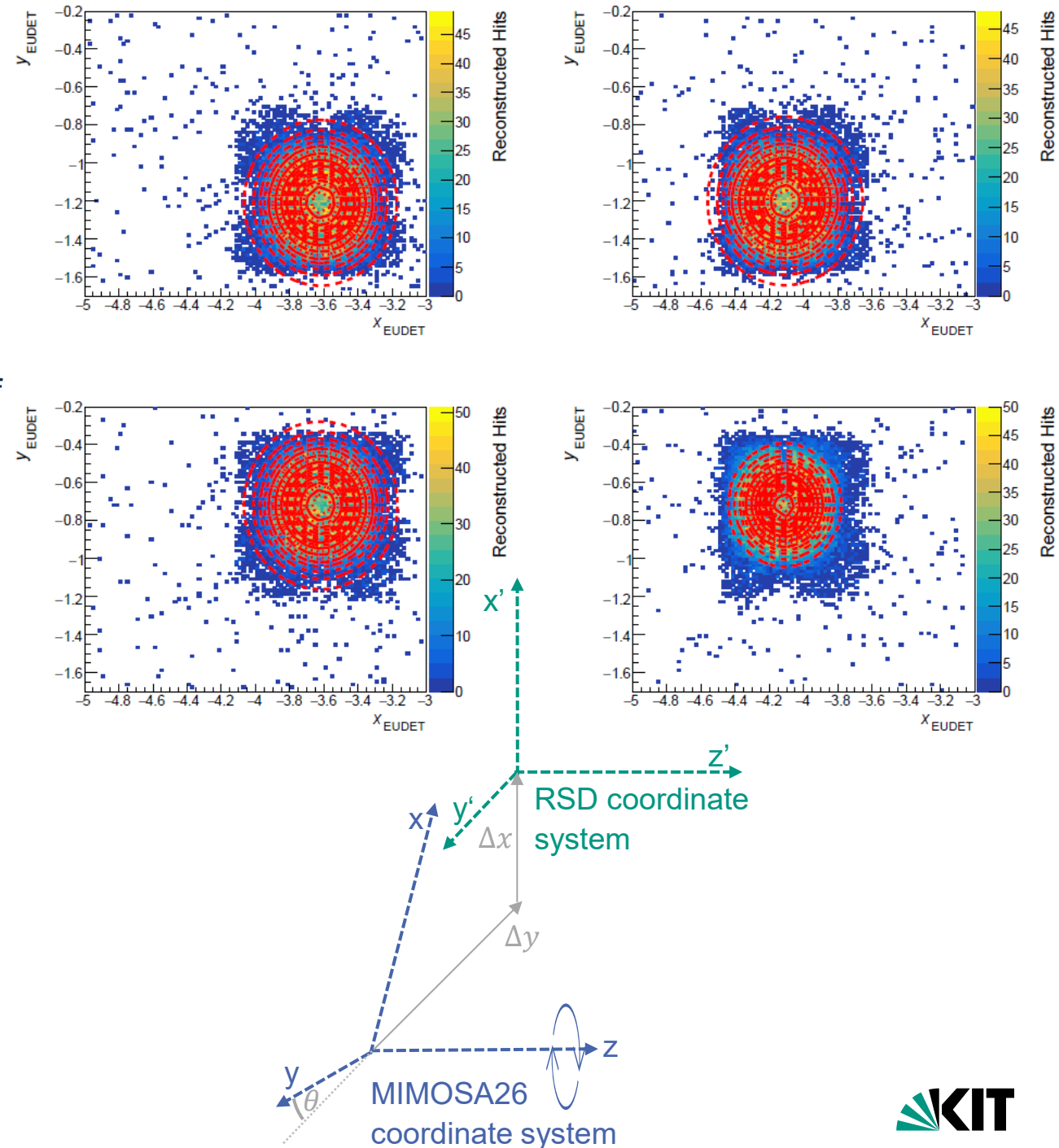
Reconstructed Positions – Unbalance vs. Template



Offset and Rotation

Transforming MIMOSA into RSD coordinate system by finding rotational angle θ + two translations Δx and Δy

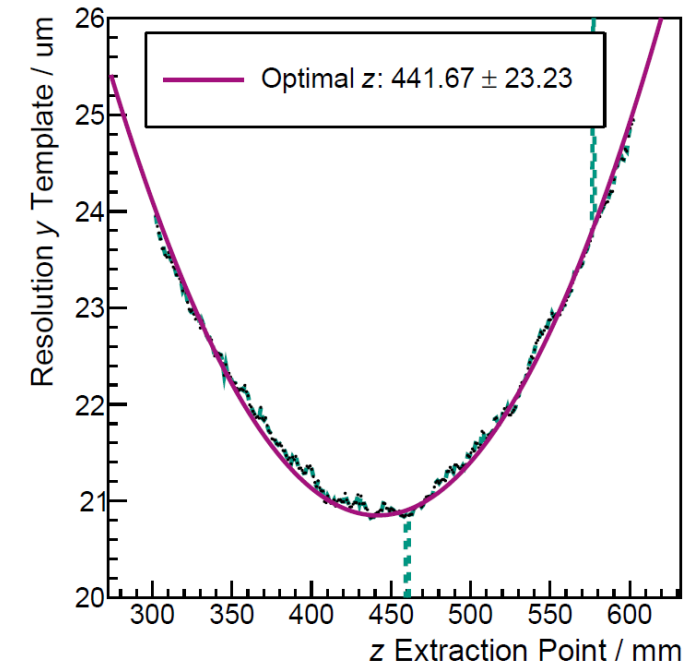
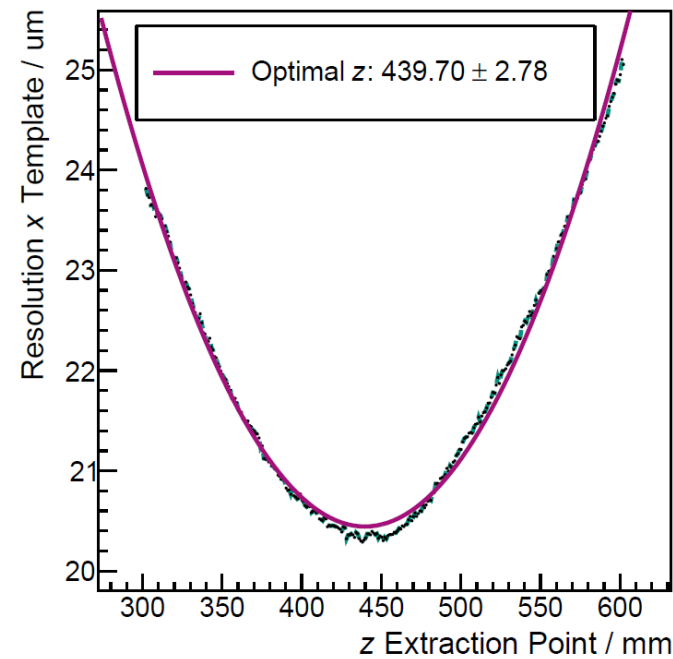
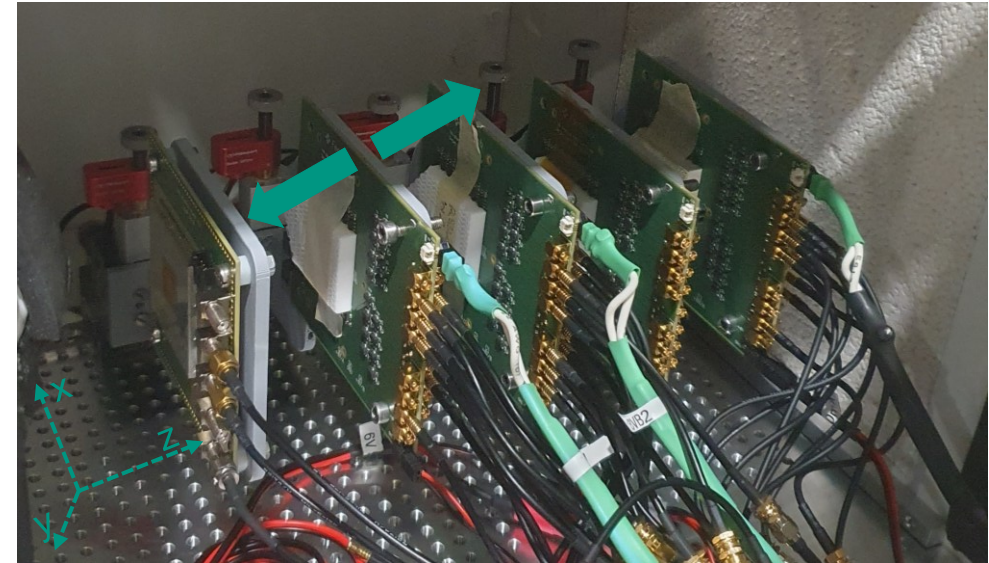
1. Finding x,y centers of the electrodes in the MIMOSA frame
 - Read x,y for chosen pixel electrodes in 2D histogram (if amplitude > threshold)
 - Fit a Gaussian with *ROOT.TF2* function *xygaus* → centers in x,y and σ_x, σ_y
2. Transform from MIMOSA to RSD frame
 - Input: ideal positions (RSD frame), real centers of step 1. (MIMOSA frame)
 - Rotation and translation:
 - $$P' = \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} + \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} * P$$
 - Weighted least squares with weights $w_i = \frac{1}{\sigma_{x,i}^2 + \sigma_{y,i}^2}$
 - Scipy minimization with BFGS and weighted least squares → $\theta, \Delta x, \Delta y$



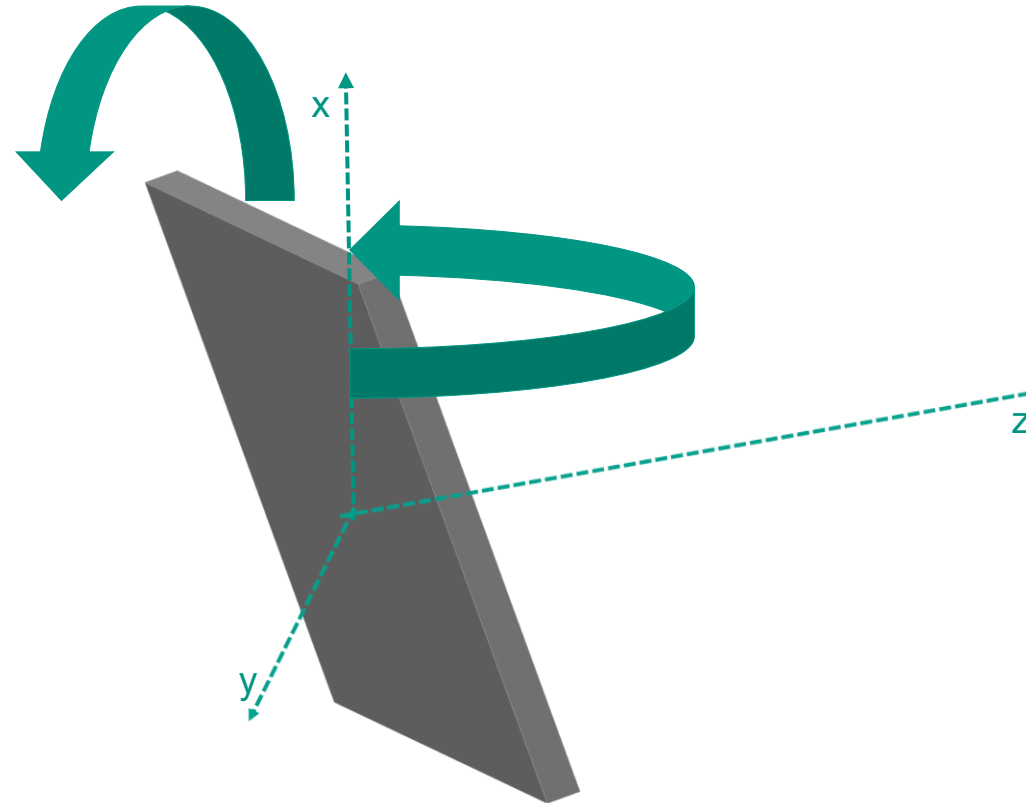
z-Sweep

Finding right positions in z

- Positions in z only measured roughly
- Need to find the correct z value
- Build 3D track through 1st and 2nd plane
- For each plane:
 - Move along z and respective calculate x, y
 - Determine spatial resolution for every point→ z with best resolution is the actual position



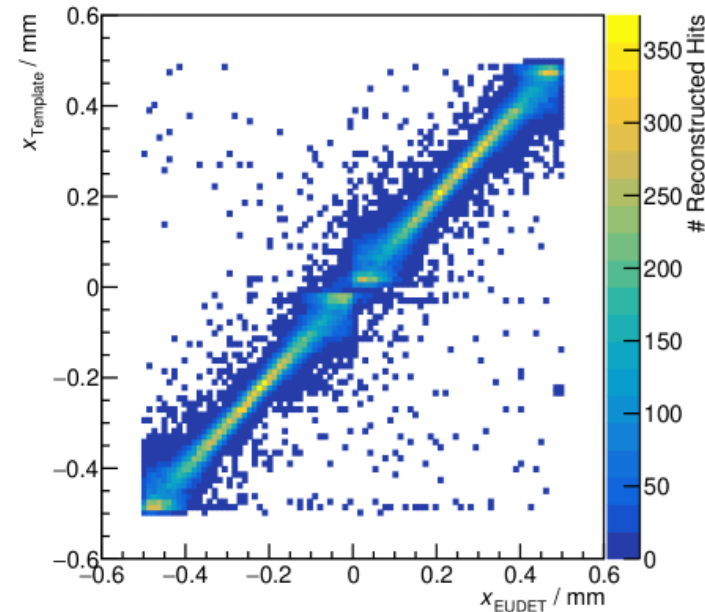
Tilt Correction



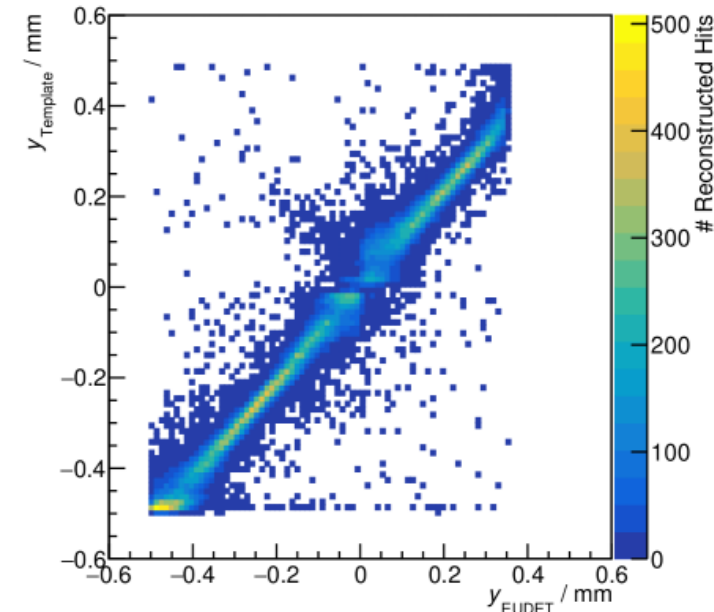
Tilt Correction

Rotation around x and y

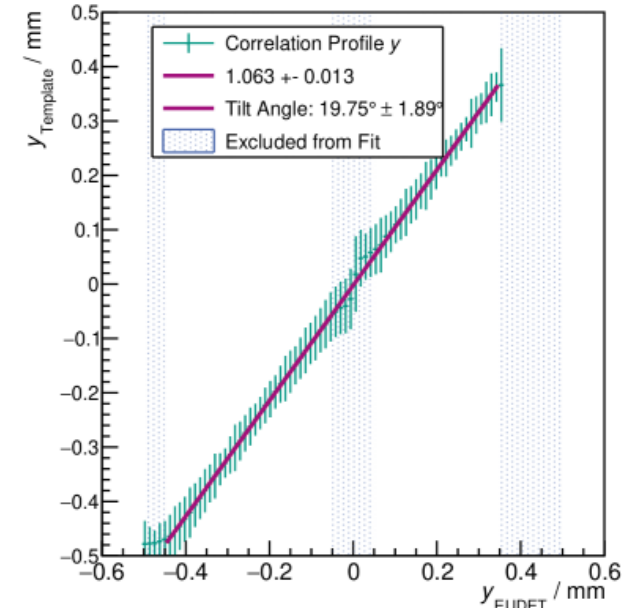
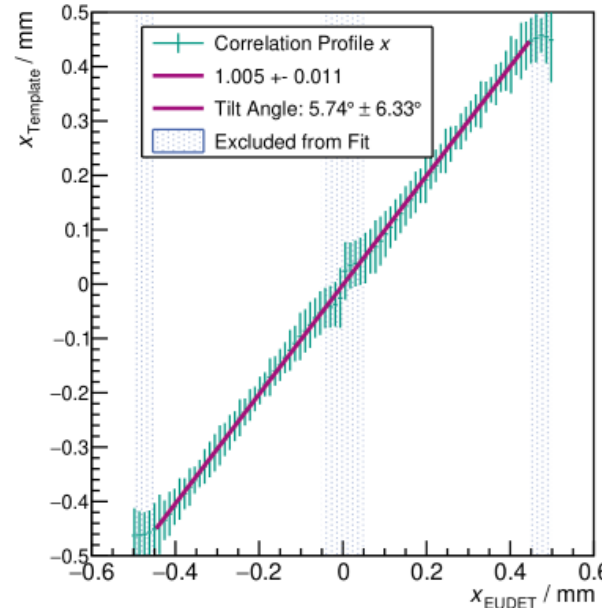
- Tilt / rotation corrected based on correlation plots
- Exclude problematic regions (middle, edges)
- Fit line on correlation plot $x_{\text{RSD}} = p_0 x_{\text{MIMOSA}} + p_1$
- For perfect alignment: $p_0 = 1$ and $p_1 = 0$
- Tilt angle $\varphi = \arccos \frac{1}{p_0}$



Correlation x Template



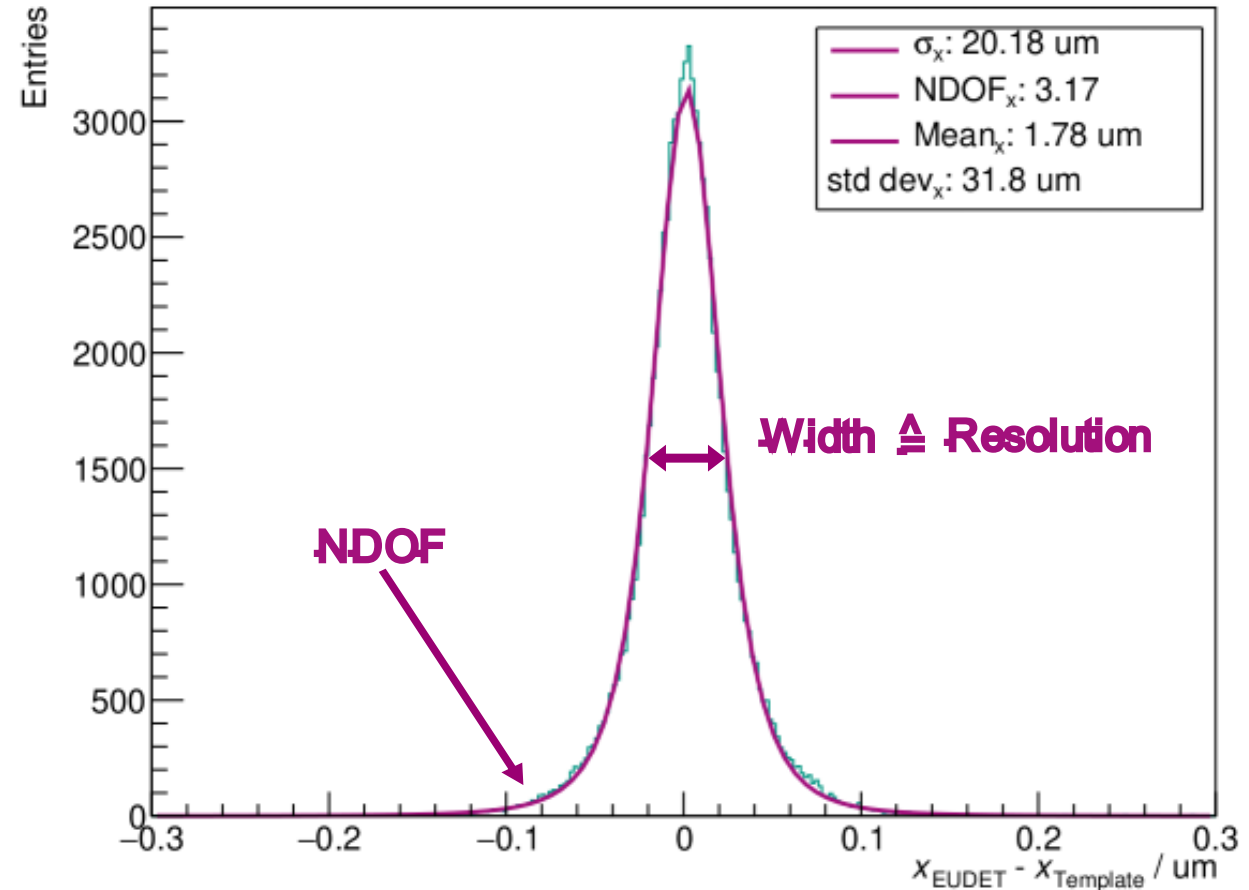
Correlation y Template



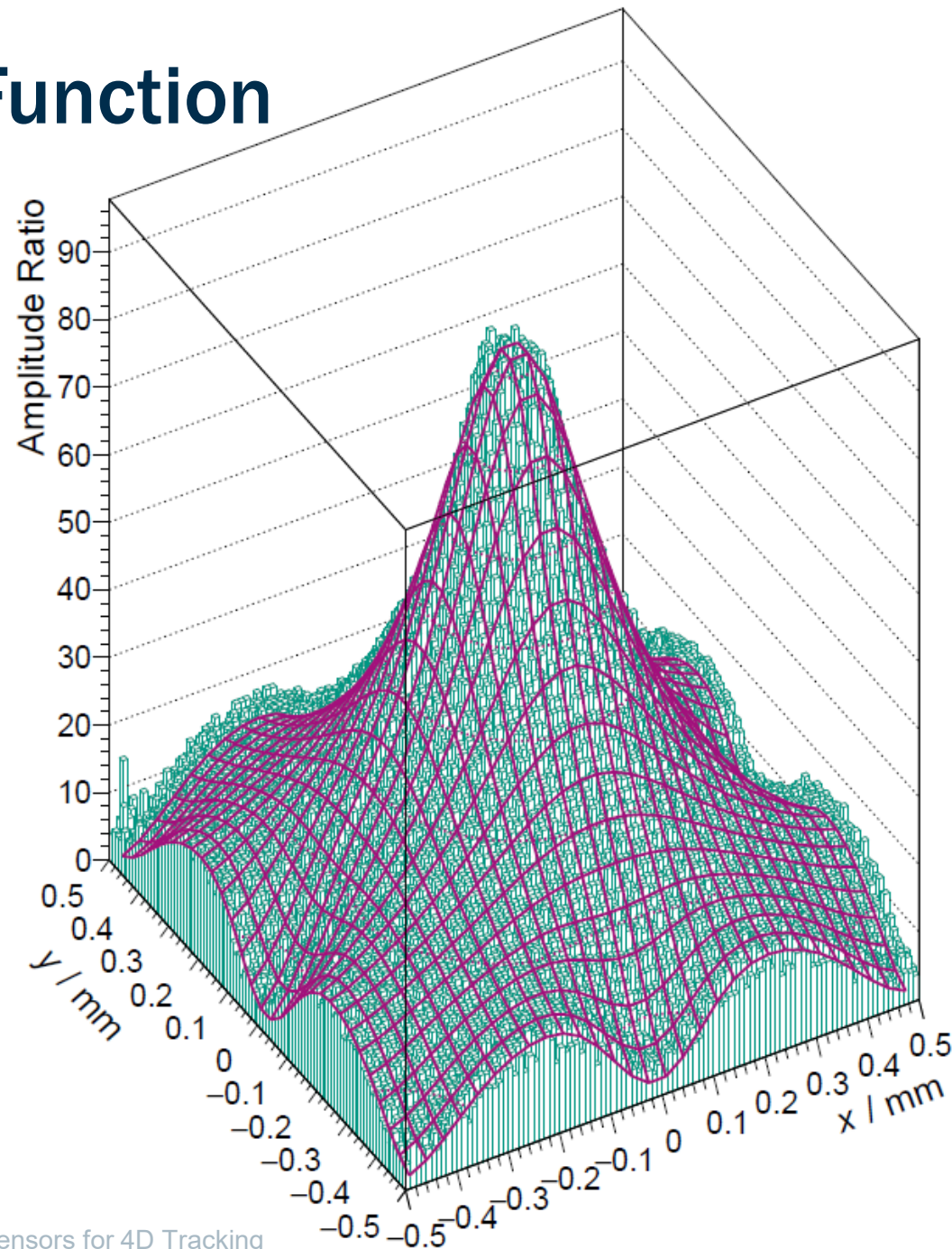
Spatial Resolutions

Spatial resolution through fitting a Student-t distribution on the residuals $x_{\text{RSD}} - x_{\text{MIMOSA}}$

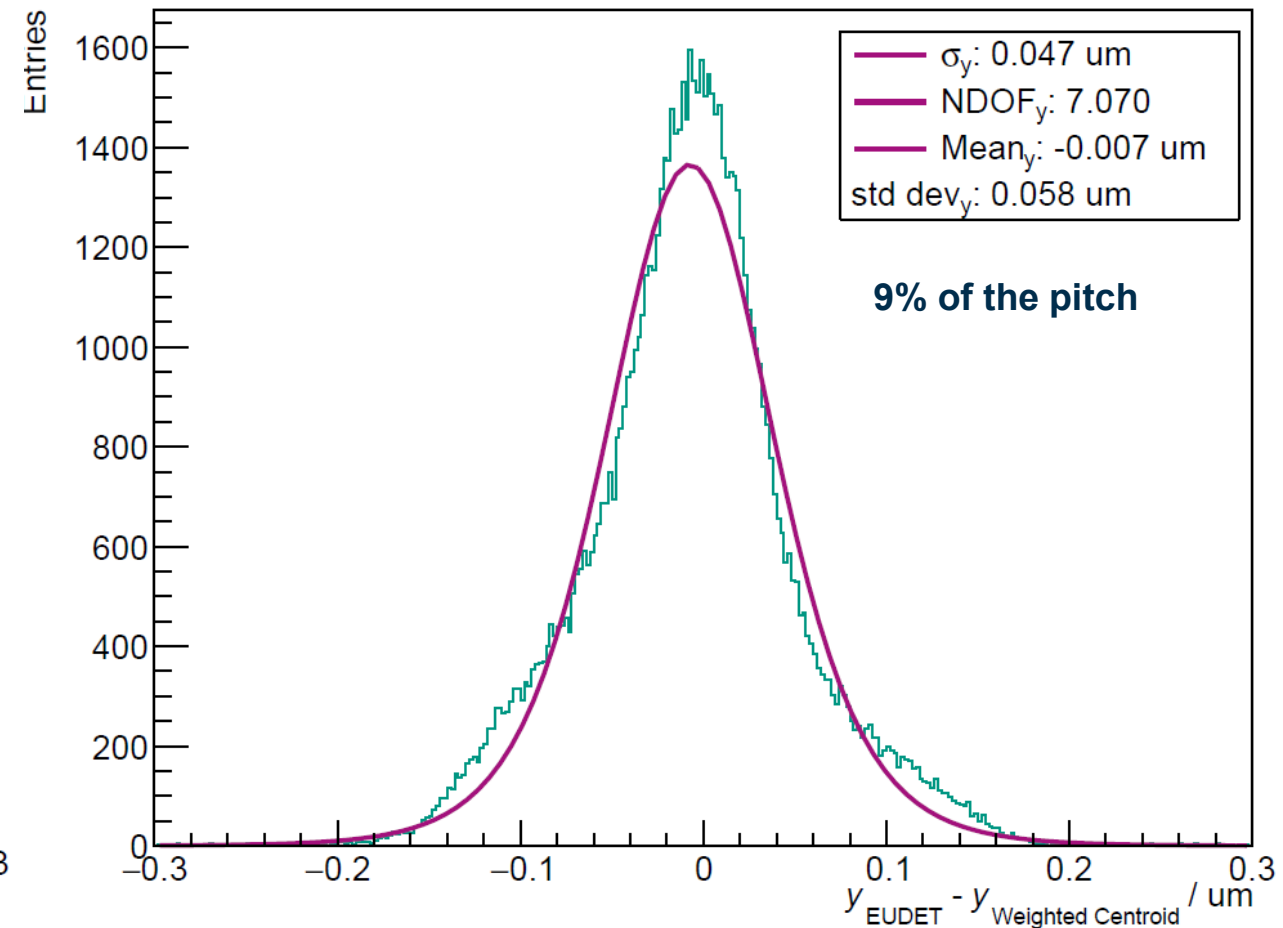
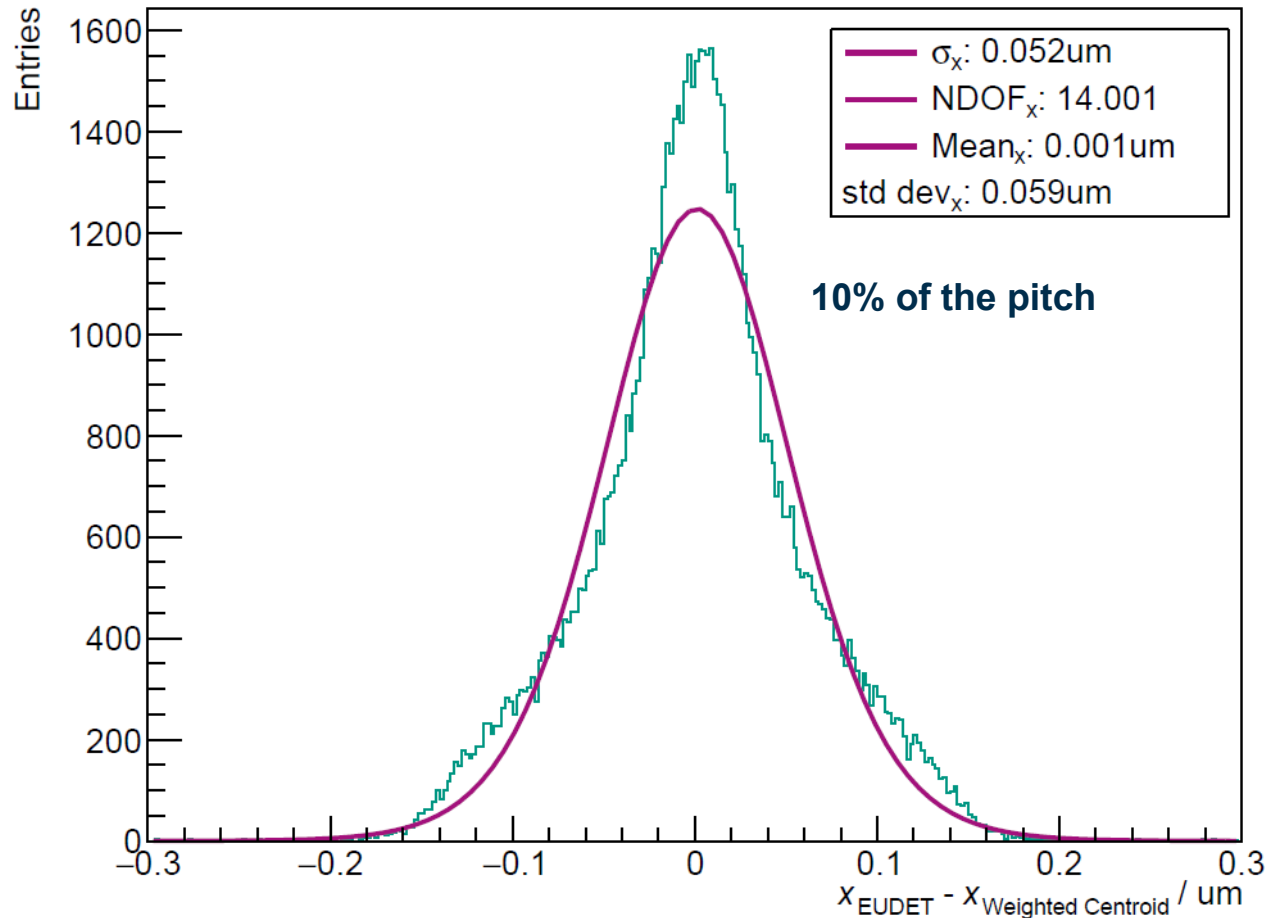
- Student-t very useful to compare how heavy distribution tails contribute
- Width of Student-t = spatial resolution
- Degrees of Freedom (NDOF) of Student-t = uniformity of performance
 - High NDOF $\triangleq$ Gaussian distribution



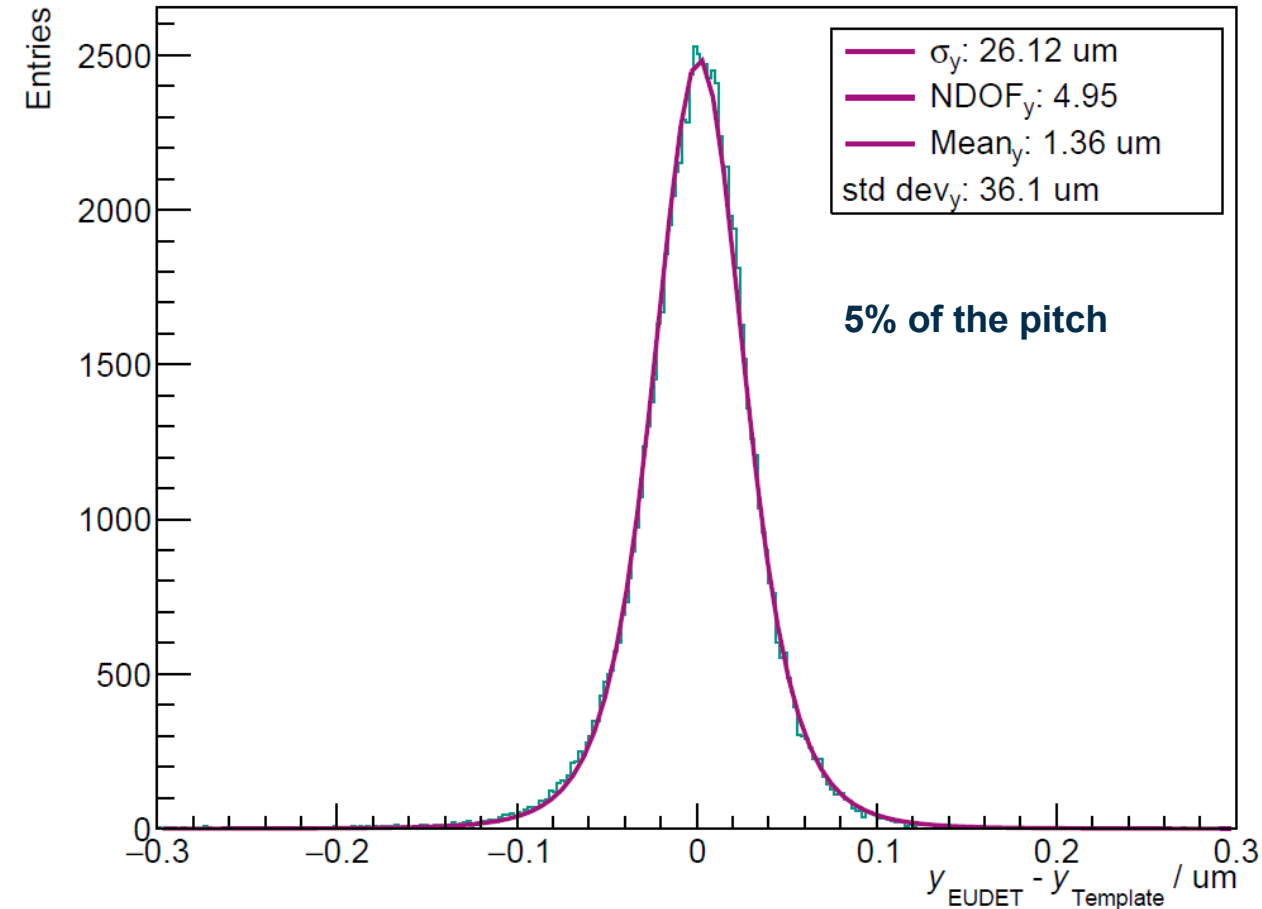
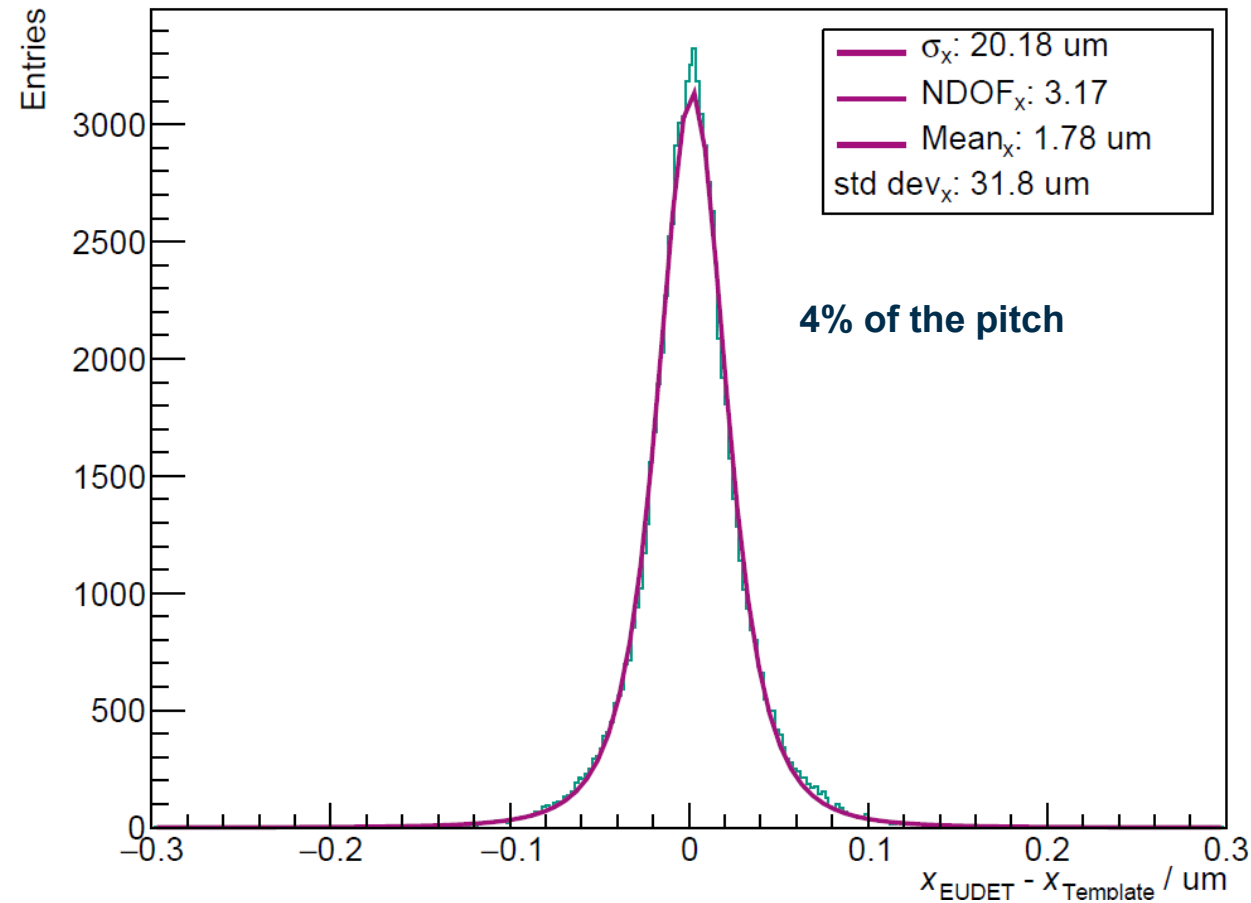
Fitted Template Function



Resolution Weighted Centroid Approach (Unbalance)



Resolution Template Approach



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- RD50 common project RD50-2020-01
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