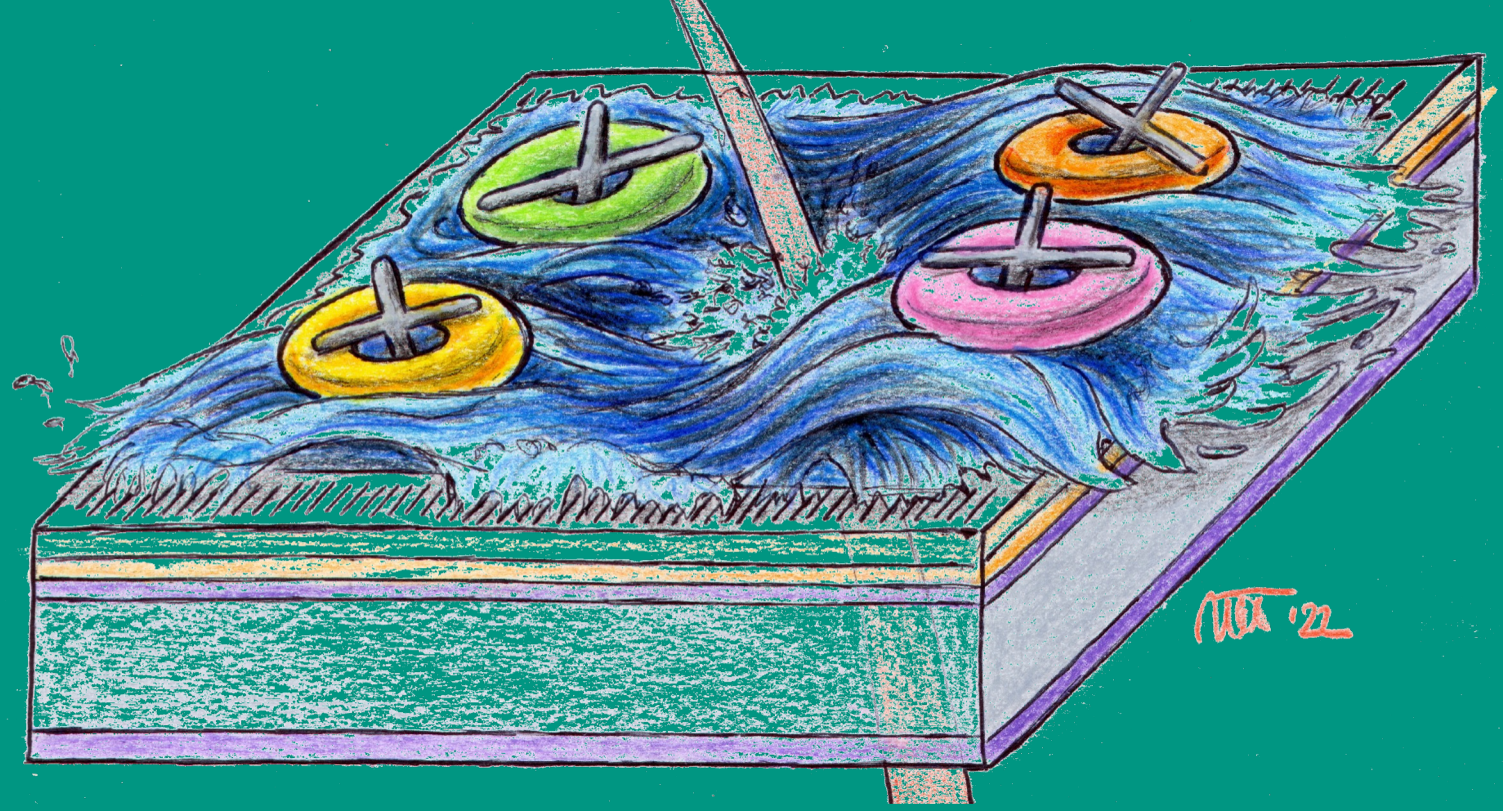


By Marta Tornago

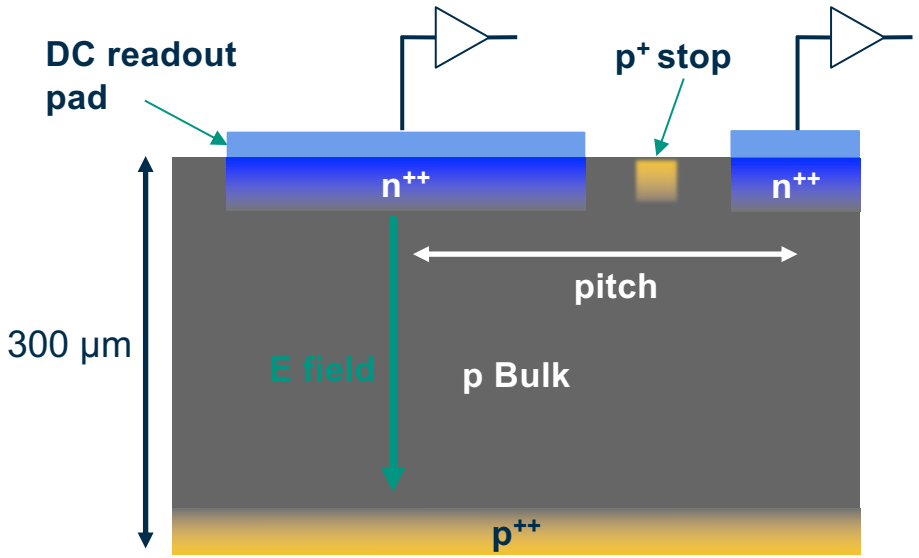
Irradiation and Charge Sharing Studies on Resistive Silicon Detectors for 4D Tracking

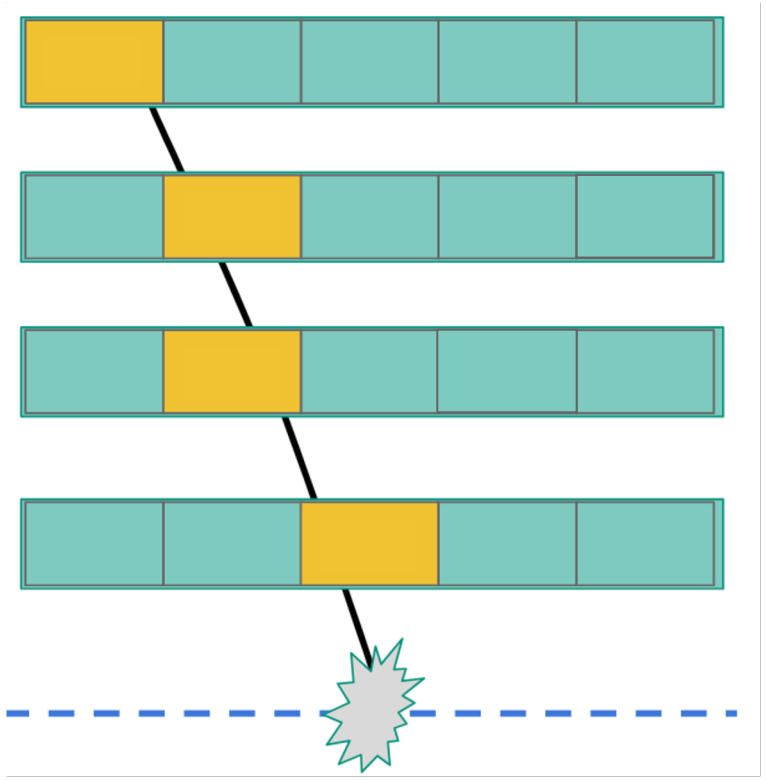
ETP Monday Meeting, 22. December 2025

Master's Thesis of **Ling Leander Grimm**

Silicon Tracking Detectors

- pn-junction with extra steps
- Passing particle excites charges ⇨ separated by E field
  ⇨ signal induced on readout electrodes



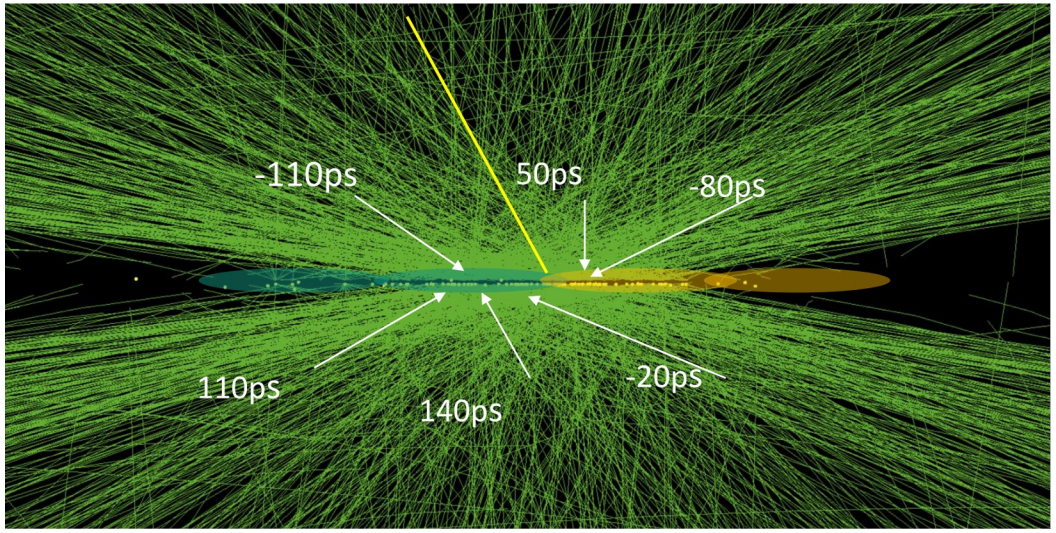


Hit position ⇨ Reconstructed track

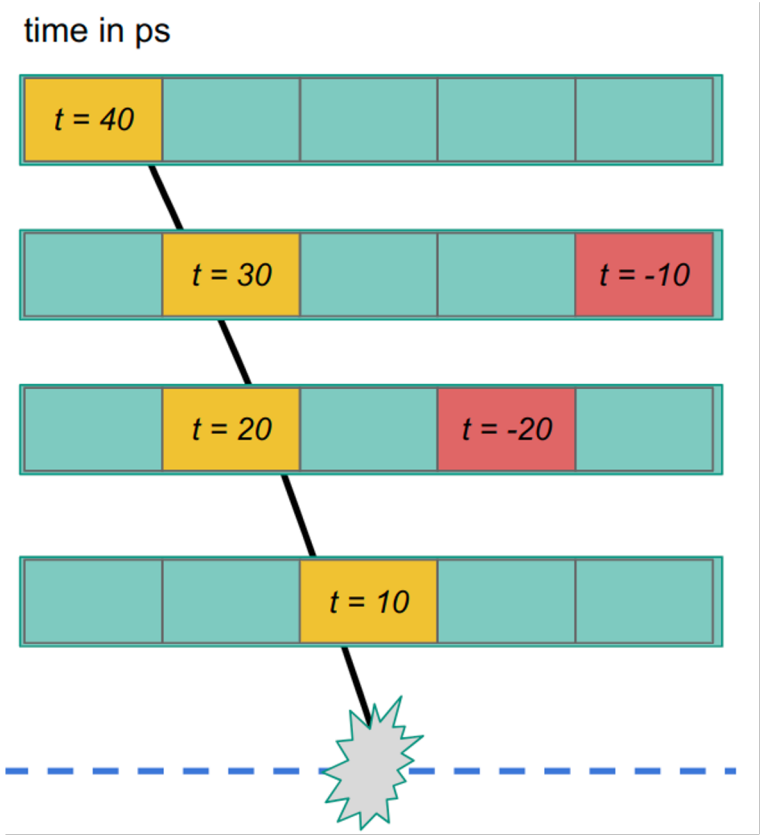
- Binary readout ⇨ resolution of $\frac{\text{pitch}}{\sqrt{12}} \sim 30\%\ \text{of pitch}$

3 Dimensions is not enough

- Timing opens new possibilities
  - Pile-up discrimination in future experiments e.g. HL-LHC, FCC-hh
  - Time-of-flight measurements for improved particle identification at lepton colliders e.g. FCC-ee, CEPC
  - “4D” tracking = 3D spatial + timing resolution



F. Hartmann



B. Regnery: VCI2025

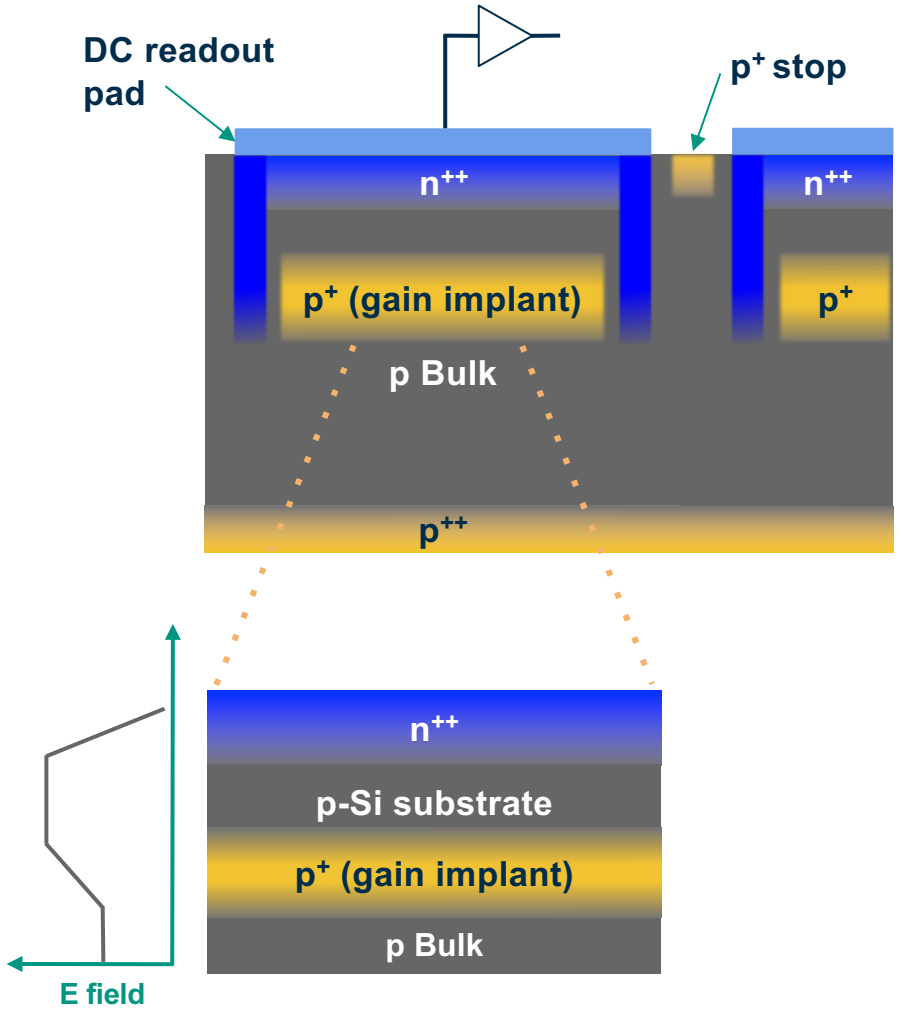
Low Gain Avalanche Diodes (LGADs)

- Gain implant creates high electric field ($\sim 300\ \mathrm{kV/cm}$)
- Charge multiplication with Gain $= N_{e,h}/N_{0:e,h} \approx 10 - 30$
  - Thinner sensors possible
  - High Signal-to-Noise ratio

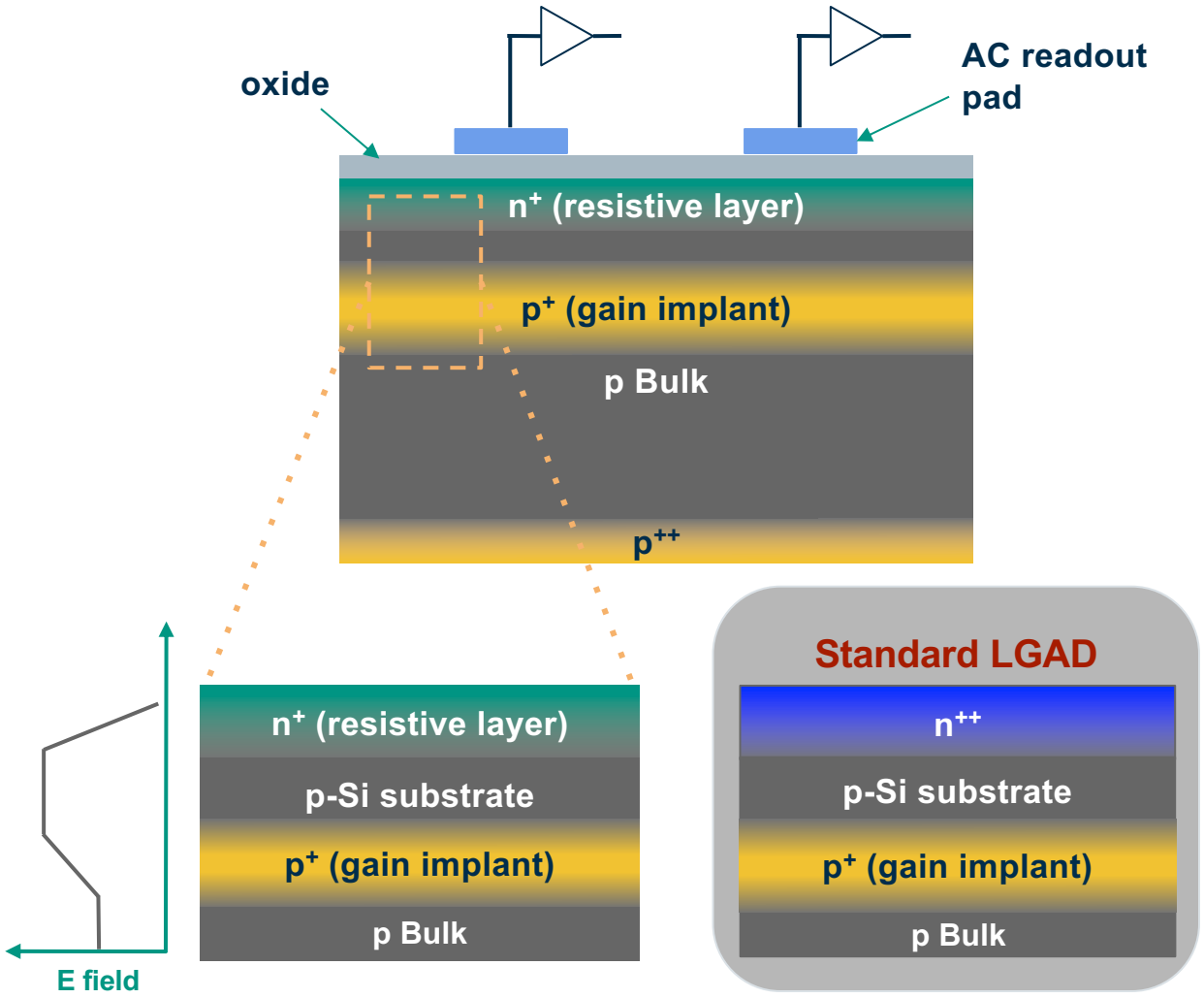
⇨ High timing resolution ($\sim 30\ \mathrm{ps}$)

- Granularity by segmenting gain and readout layer
  - Gaps in detector ($< 100\ \%$ fill factor)
  - Large readout pads

- Proven technology
  - used in ATLAS and CMS Phase II upgrades



Resistive Silicon Detectors (RSDs)



Combine LGADs with resistive readout layer

Redefinition of tracking: Multi-electrode readout

- Continuous gain layer
  - High temporal resolution
  - 100 % fill factor
- Resistive layer
  - High spatial resolution
  - Low number of readout channels

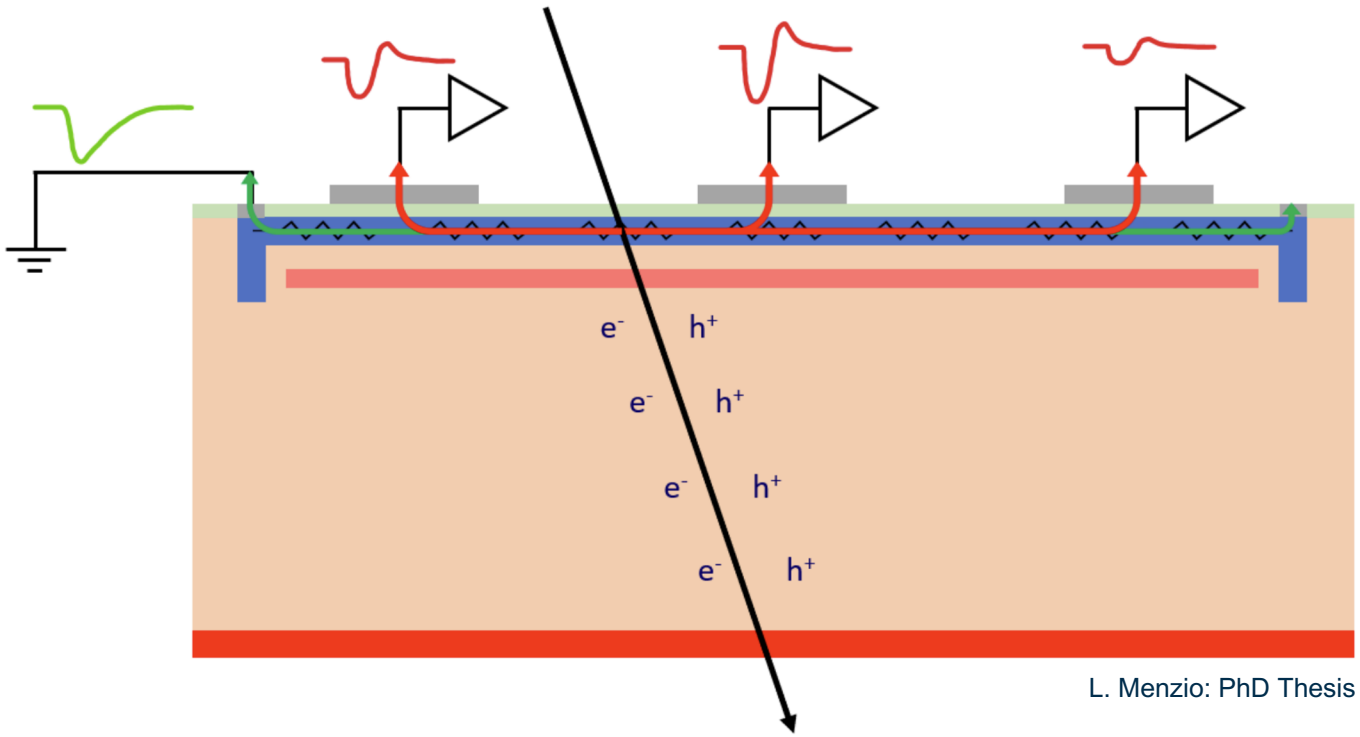
- Our sensors designed and produced by INFN Torino & FBK
  - Second RSD production
  - No irradiation hardening techniques used yet

Position Reconstruction by Charge Sharing

Redefinition of tracking: Multi-electrode readout

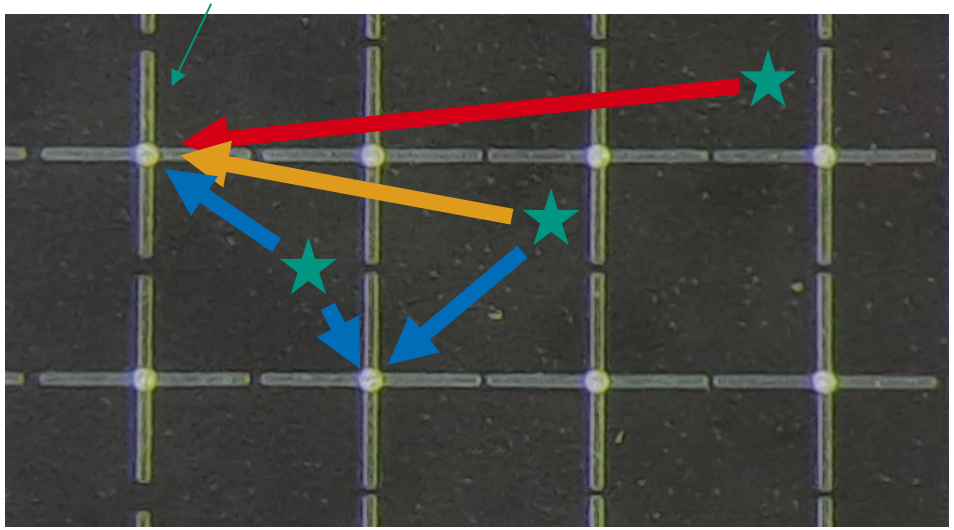
- Signal spread in resistive n^+ layer
- Signal on multiple electrodes used for position reconstruction

- To study:
  - **Influence of irradiation on the resistive layer**
  - **Test hybrid electrode geometries**



L. Menzio: PhD Thesis

Cross-shaped electrode

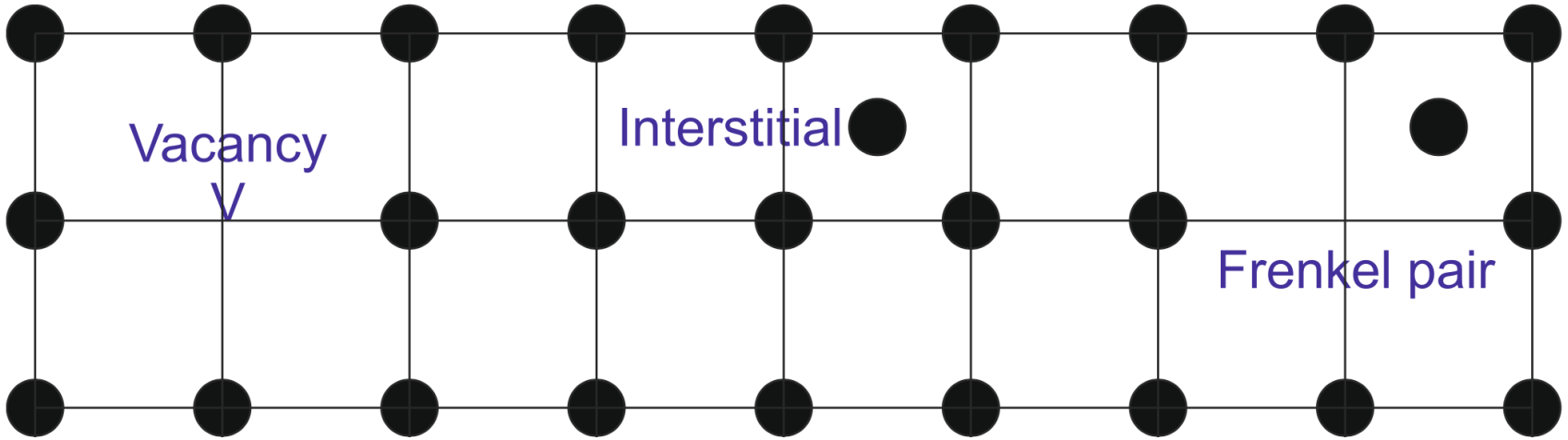


Precisely tuned n^+ layer required!

Radiation Damage in Silicon

- Particles passing through the detector can interact with lattice atoms
  - Change lattice structure

- LGAD's p^+ layer well studied
- RSD's n^+ not!



F. Hartmann: Evolution of Silicon Sensor Technology in Particle Physics

- **Donor and acceptor removal, and acceptor creation**
  - $N_{\mathrm{eff}} = N_{\mathrm{D}} e^{-c_{\mathrm{D}}\Phi_{\mathrm{eq}}} - N_{\mathrm{A}} e^{-c_{\mathrm{A}}\Phi_{\mathrm{eq}}} + b\Phi_{\mathrm{eq}}$

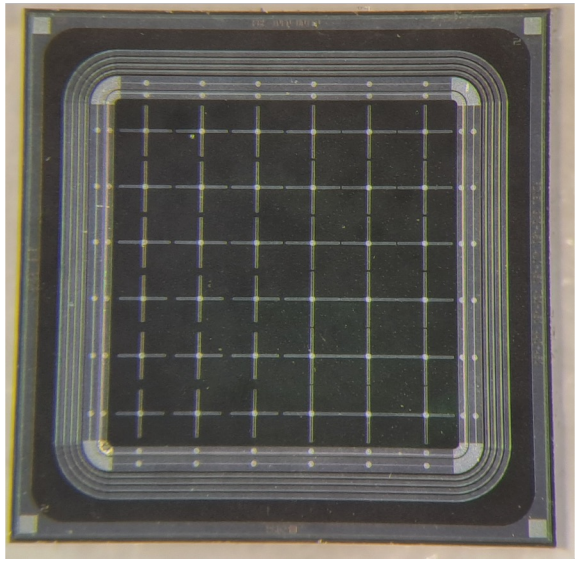
Irradiation Campaign

- Irradiation centers:
  - JSI TRIGA Reactor (neutrons)
  - KIT KAZ (23 MeV protons)
- 3 Wafers with varying n^+ layer doping concentration:

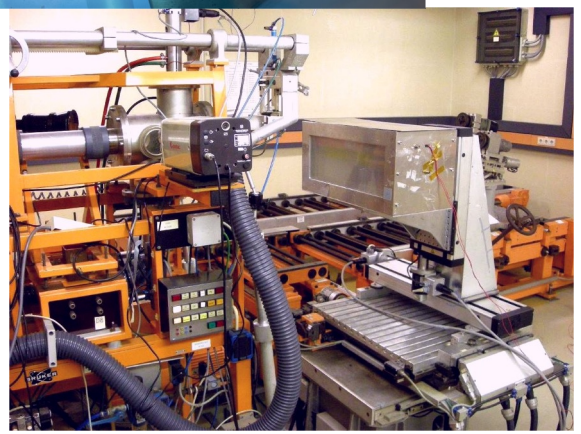
$$W_{low} < W_{mid} < W_{high}$$

Fluence (10^{15} cm^{-2})

JSI (neutrons) (nominal)	KIT (protons) (measured)
1.0	0.6
2.0	1.0
3.5	1.8
5.0 (only test structures)	2.8 (only test structures)



Neutron irradiation at JSI

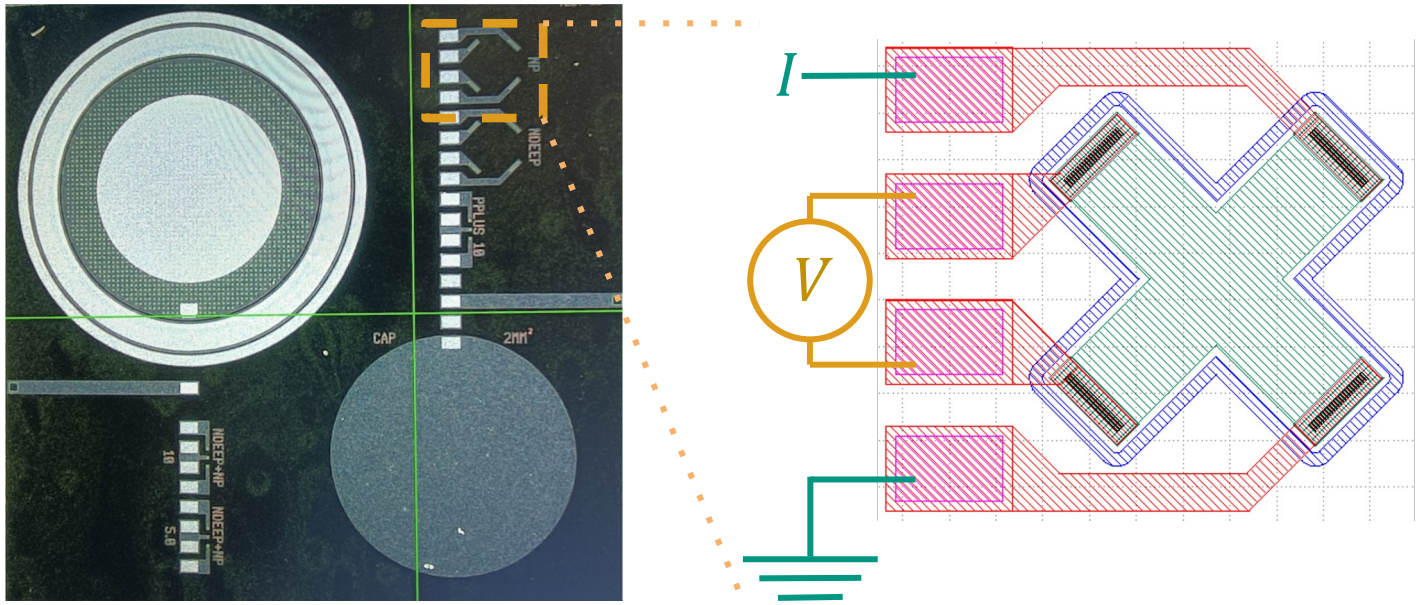


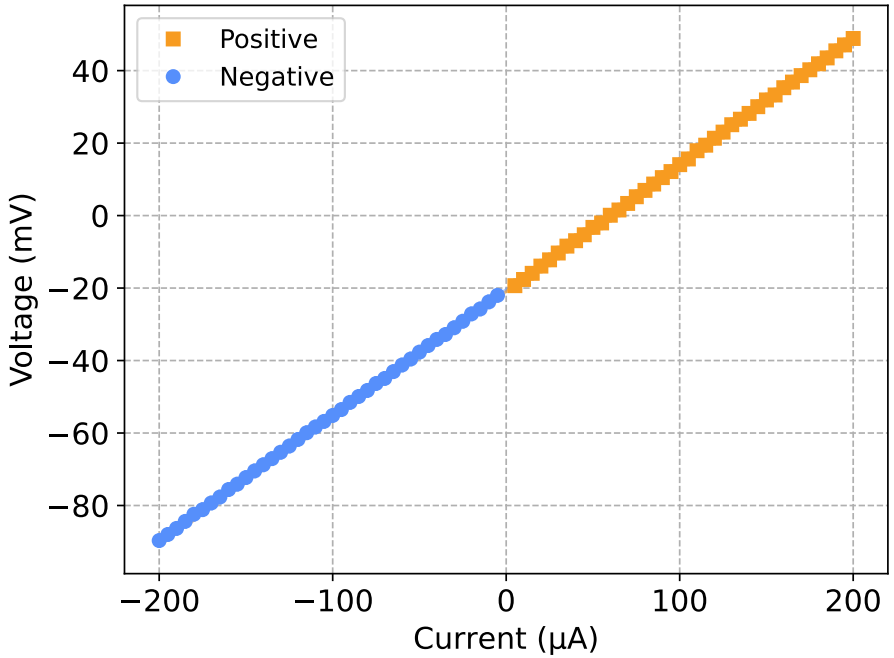
Proton irradiation at KIT

Obtaining the Sheet Conductance

- Sheet conductance σ_s from measurement of test structures (4-point resistivity measurement)
  - Apply current at two points
  - Measure voltage at remaining
  - Inverse slope of curve leads to sheet conductance

$$\sigma_s = \frac{1}{R_s} \propto N_D$$

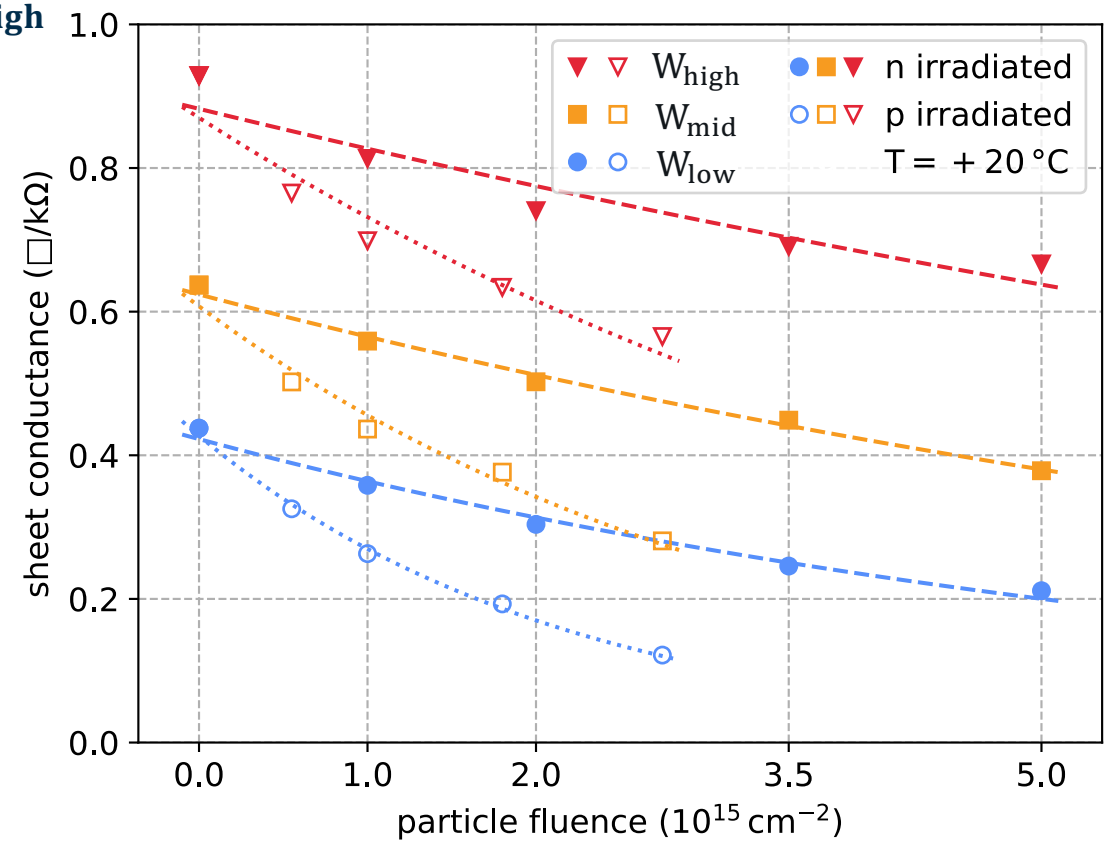




Estimating the Donor Removal Coefficient

- **Reminder:** n⁺ layer doping concentration $\mathbf{W_{low} < W_{mid} < W_{high}}$
- $\sigma_s \propto N_D \Rightarrow \sigma_s = Be^{-c_D\phi} \Rightarrow$ **donor removal coefficient c_D**
- Confirmation measurements done in Perugia
  - Remove bias from setup
- One of the first measurements of c_D for this doping range

		c_D (10^{16} cm^2)		
Irradiation	**Location**	$\mathbf{W_{low}}$	$\mathbf{W_{mid}}$	$\mathbf{W_{high}}$
Neutron	KIT	1.5 ± 0.2	1.0 ± 0.2	0.6 ± 0.2
	Perugia	1.6 ± 0.2	1.0 ± 0.2	0.7 ± 0.1
Proton	KIT	4.6 ± 0.4	2.9 ± 0.4	1.7 ± 0.3
	Perugia	4.7 ± 0.6	2.9 ± 0.4	1.7 ± 0.3

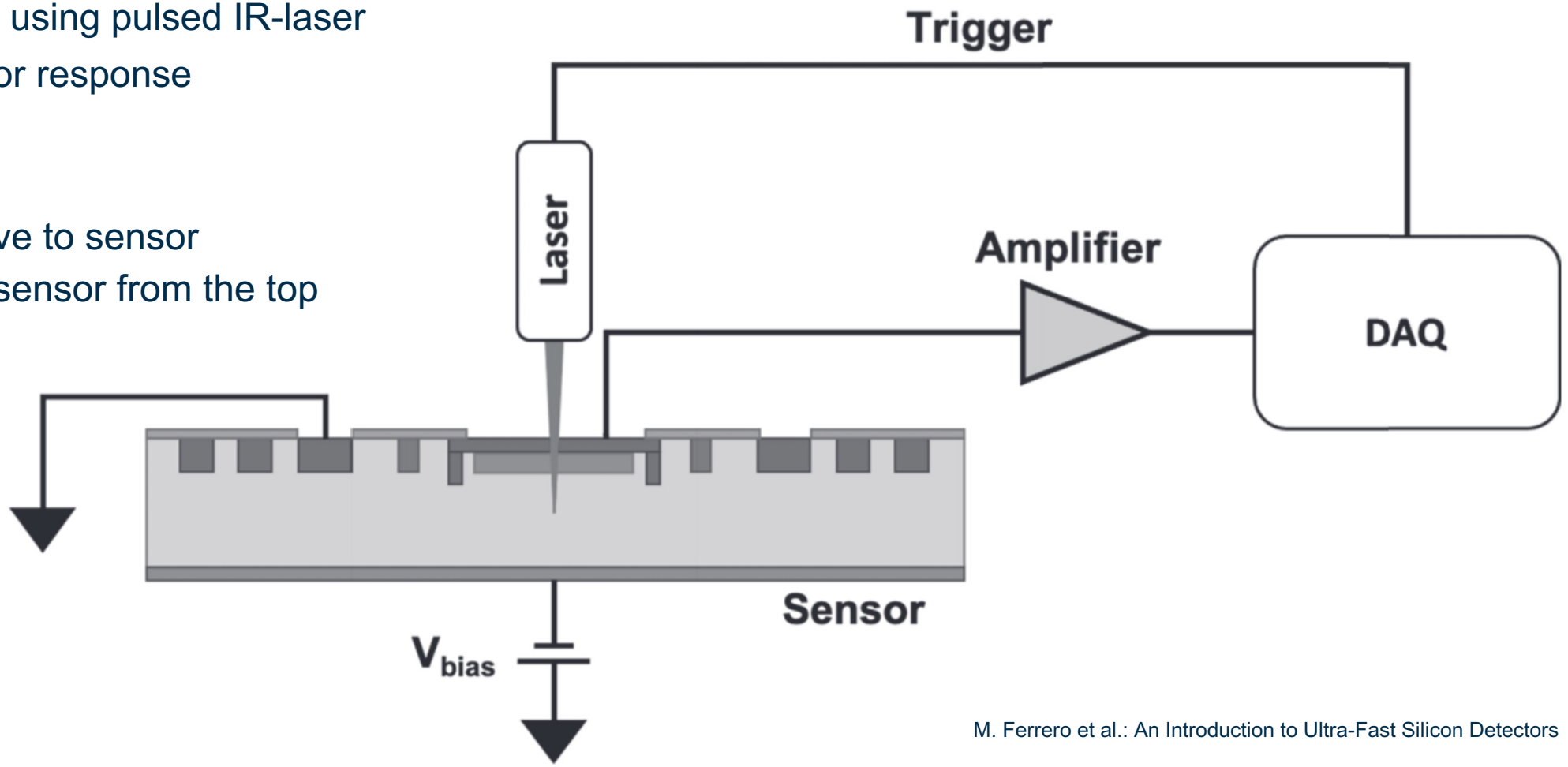


* Protons in measured fluence!

The Transient Current Technique (TCT)

- Mimic MIP passage using pulsed IR-laser
- Used to study sensor response

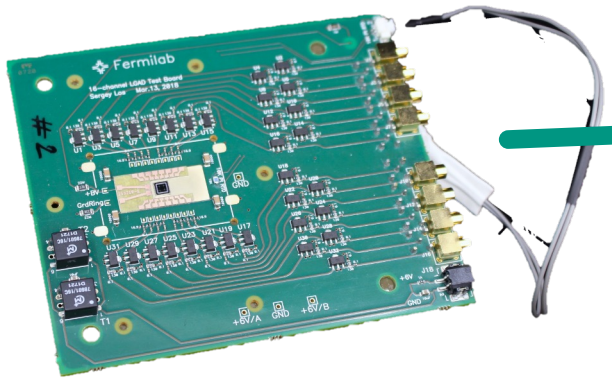
- Scanning Top-TCT:
  - Move laser relative to sensor
  - Laser shines on sensor from the top



M. Ferrero et al.: An Introduction to Ultra-Fast Silicon Detectors

The KIT TCT Setup

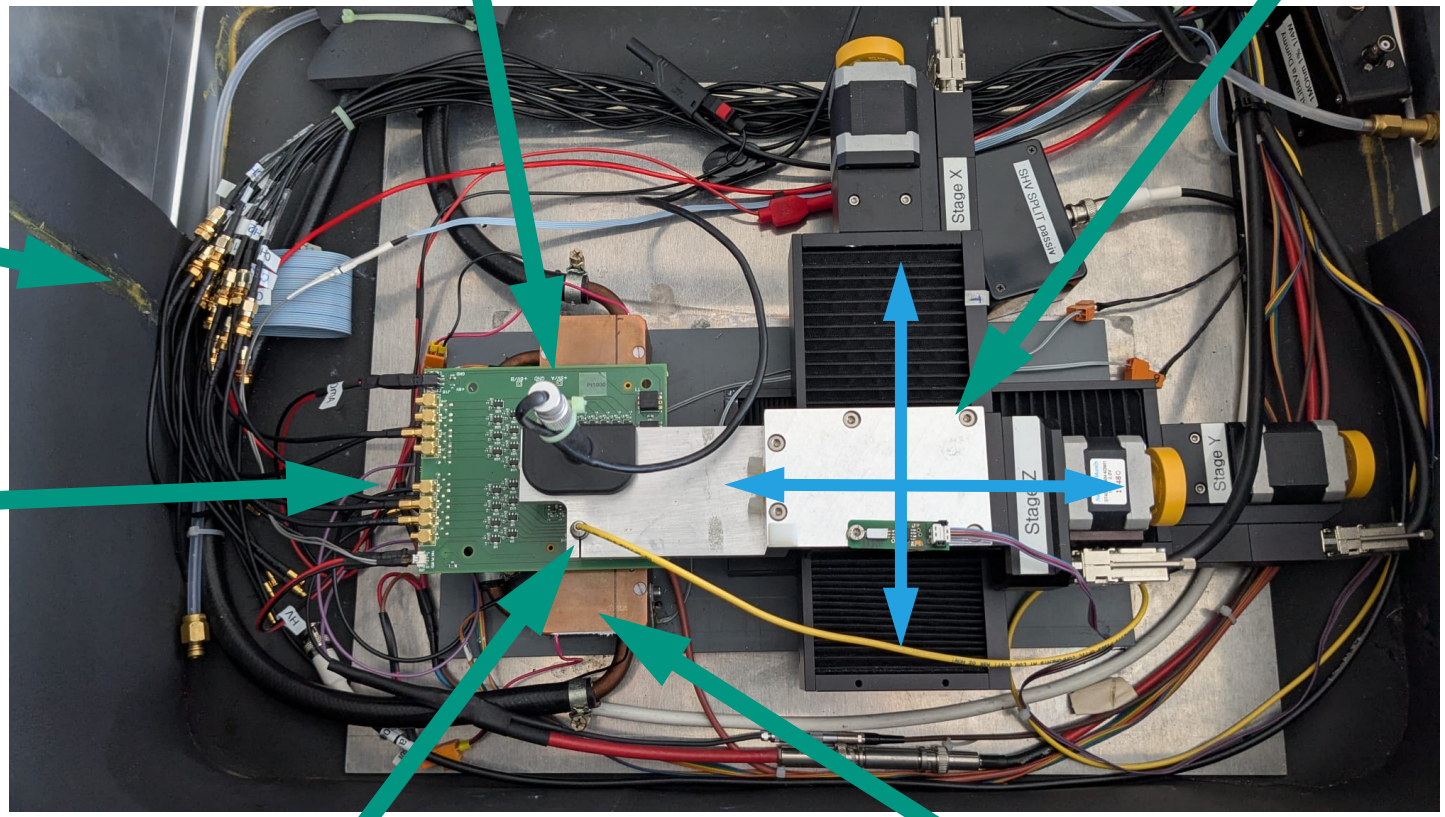
16 channel digitizer



Multichannel amplifier board

Camera for laser alignment

Movable stage in xyz-direction



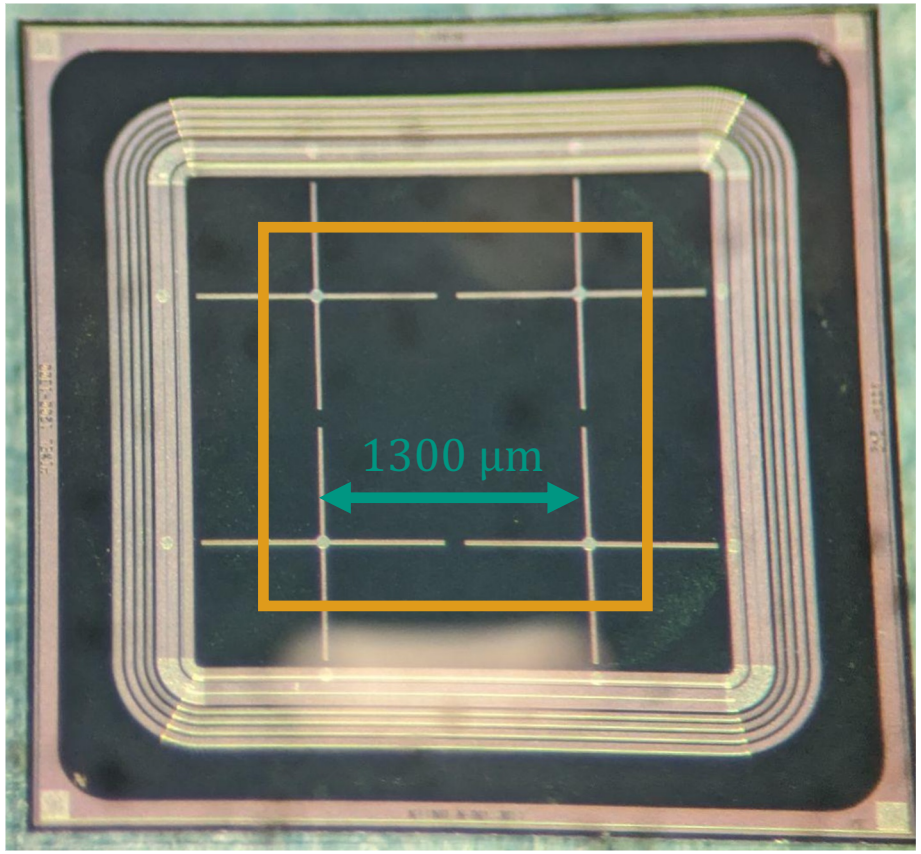
IR-Laser (1055 nm)

Cooling to -20 °C
for irradiated sensors

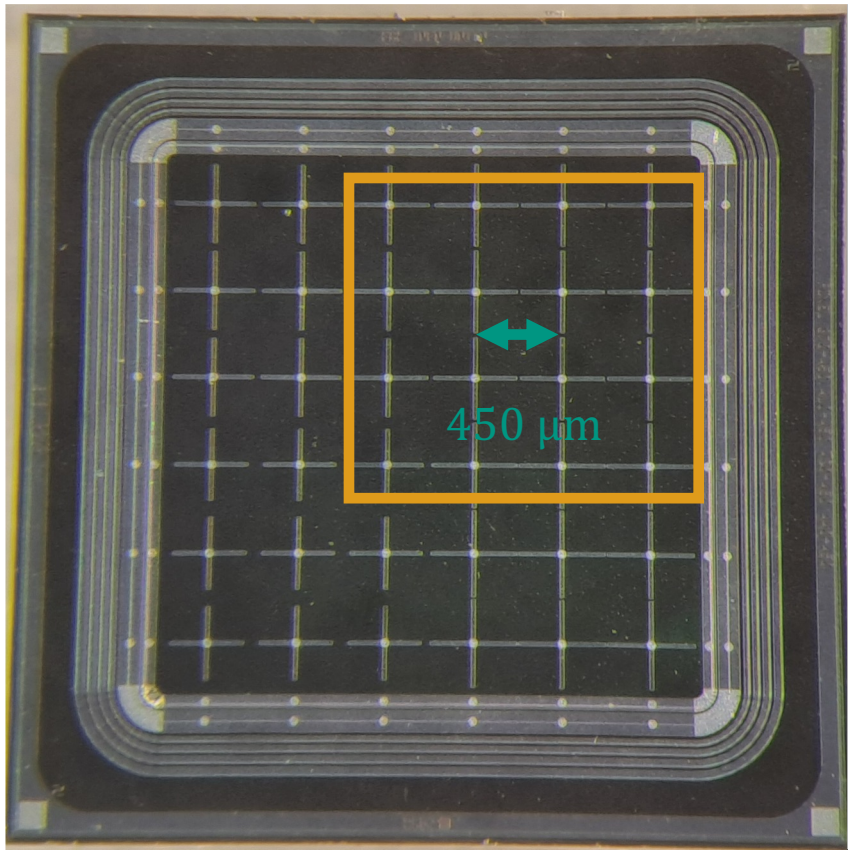
The Sensors

Cross-shaped electrodes shown to be great design for pixel applications

2x2 with 4 electrodes of W_{mid} and W_{high}

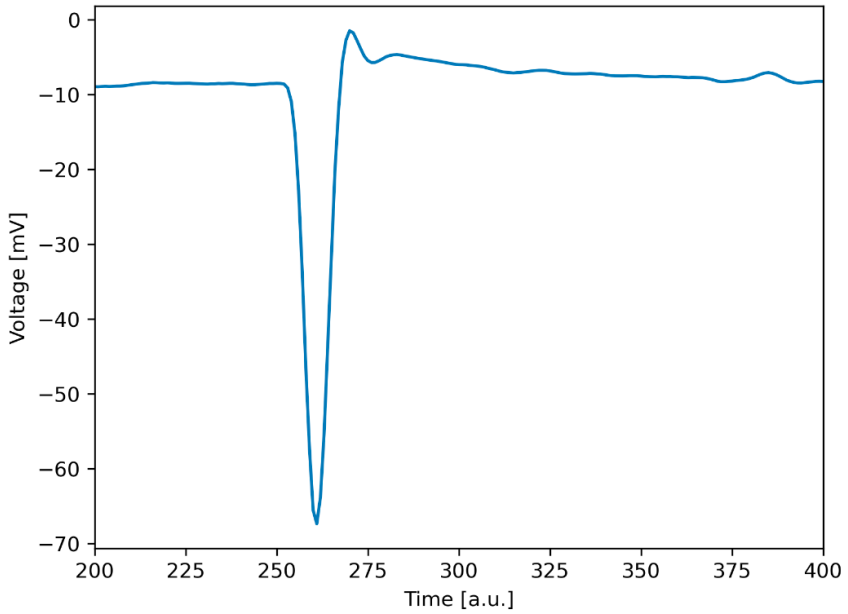


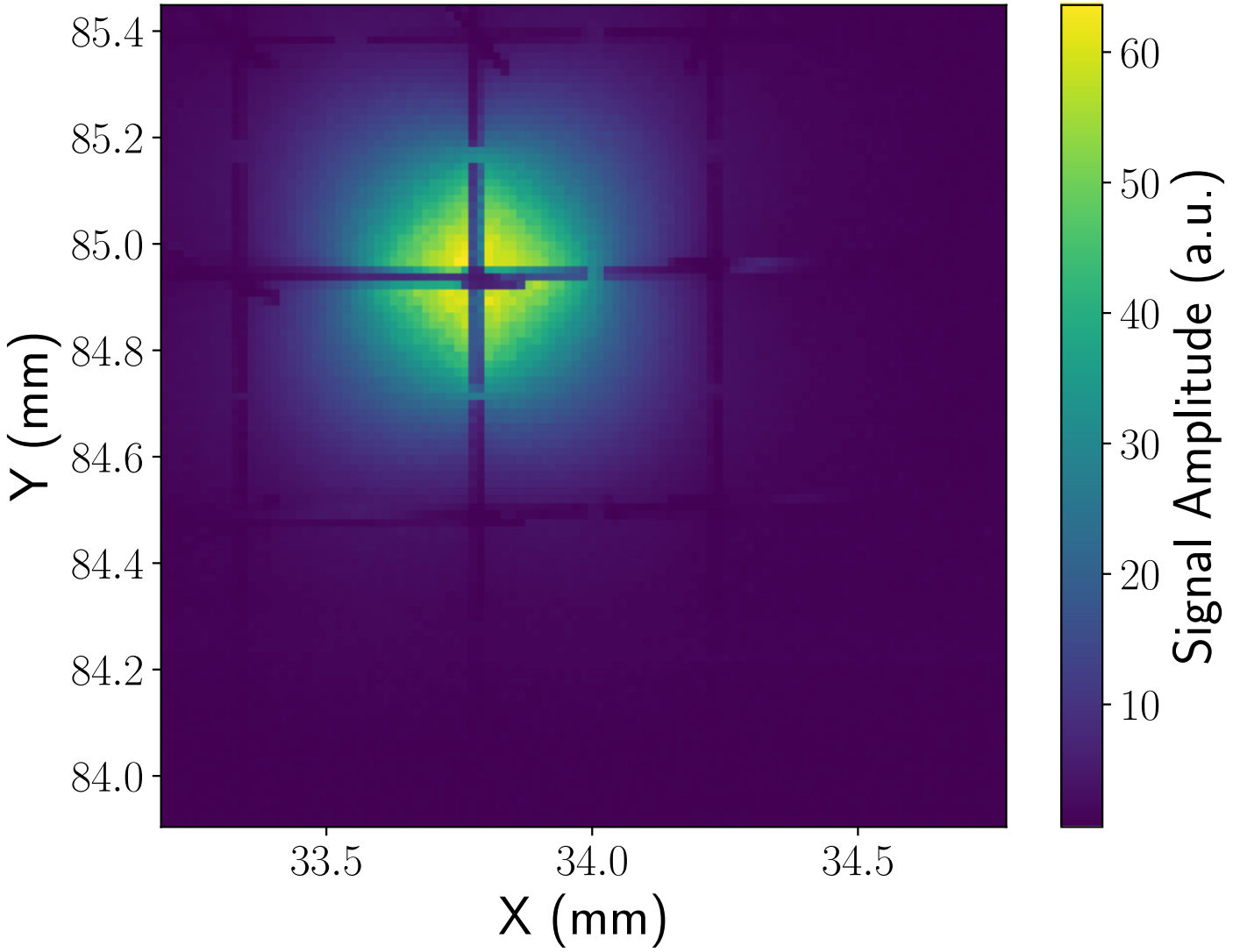
6x6 with 16 electrodes of W_{low} and W_{mid}



Scanning over the sensor

- Scan laser over sensor in 15 µm x 15 µm grid
- Monitor waveforms on AC-pads
  - Analyze signal amplitude
  - And signal area

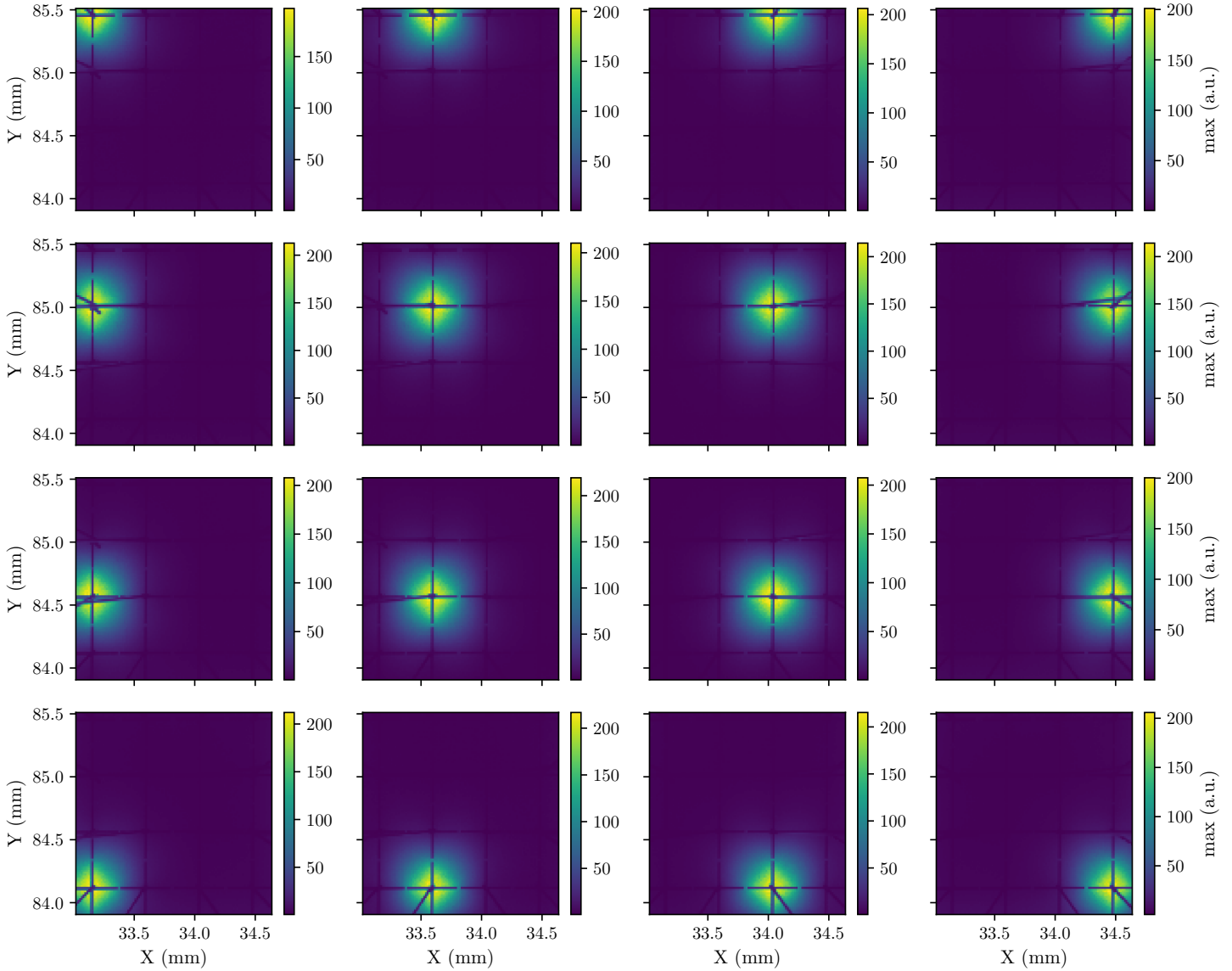




Scanning over 6x6 sensors

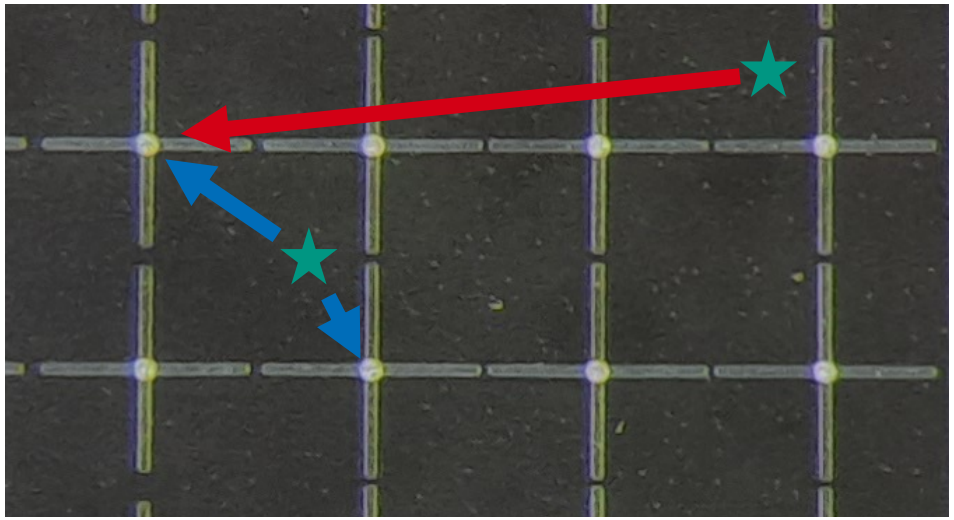
- Scan laser over sensor in 15 µm x 15 µm grid
- Monitor waveforms on AC-pads
  - Analyze signal amplitude
  - And signal area
- Readout of all 16 channels
- Repeat for different irradiations

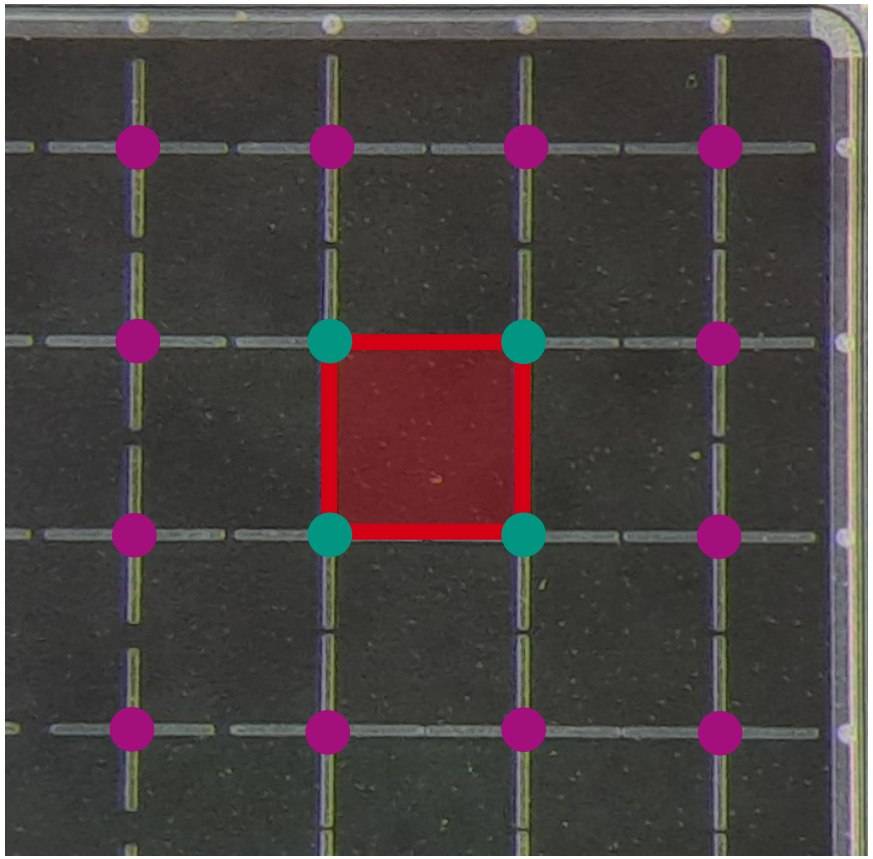
- Does the charge spread differently after irradiation?
- Quantify the spread using:
  - Leakage Ratio
  - Charge Spread Distance and Diagonal Signal



The Leakage Ratio

- How much of the signal is visible outside of a pixel?
- Does that change with irradiation?

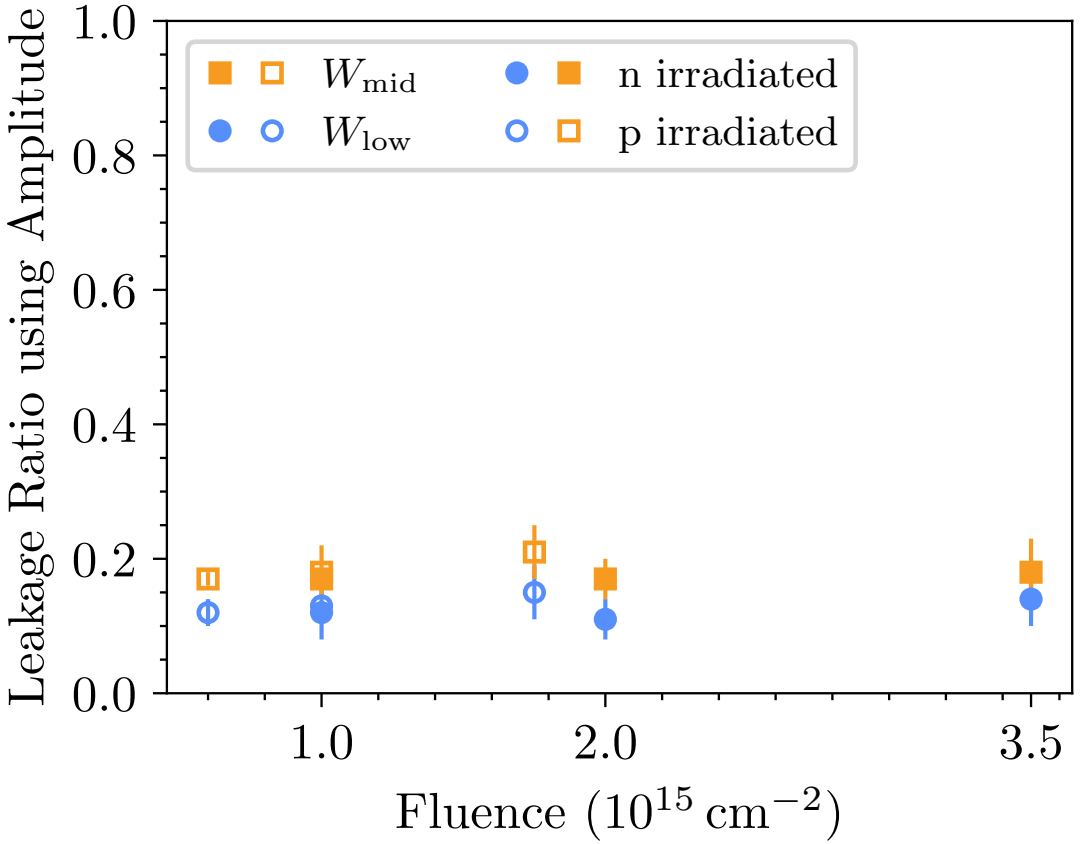


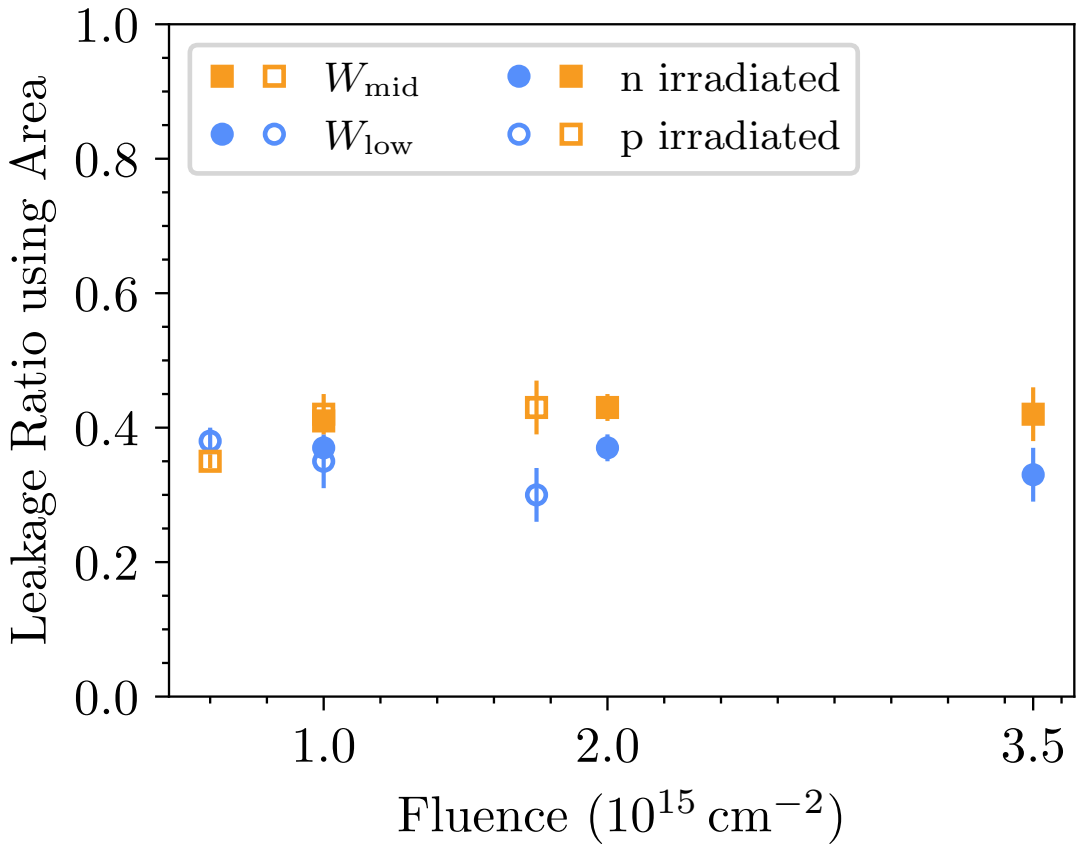


- For all electrodes: A = sum of signal inside pixel (red)
- Compare outer (purple) with all (purple + green) electrodes

$$\text{Leakage Ratio} = \frac{\text{Sum over A's of outer electrodes}}{\text{Sum over A's of all electrodes}}$$

The Leakage Ratio





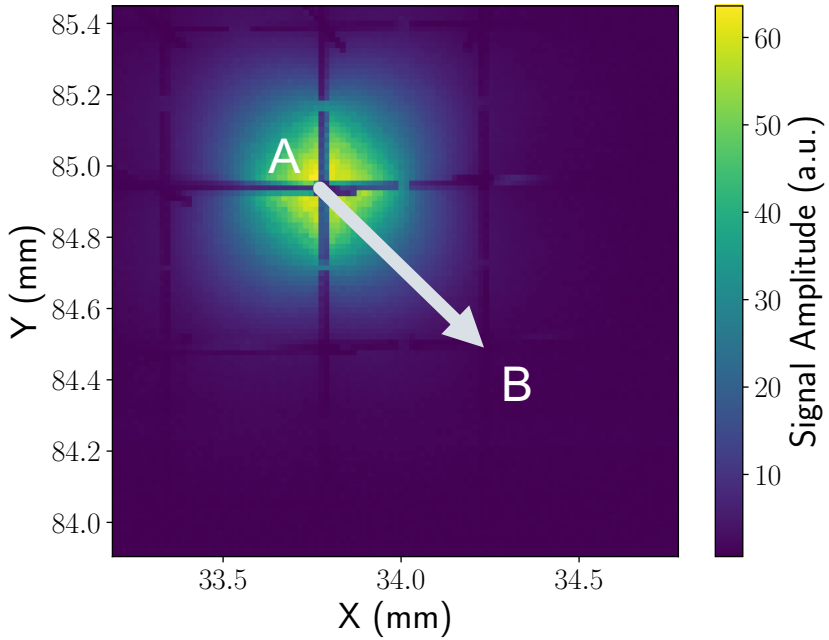
- Good signal containment in pixel

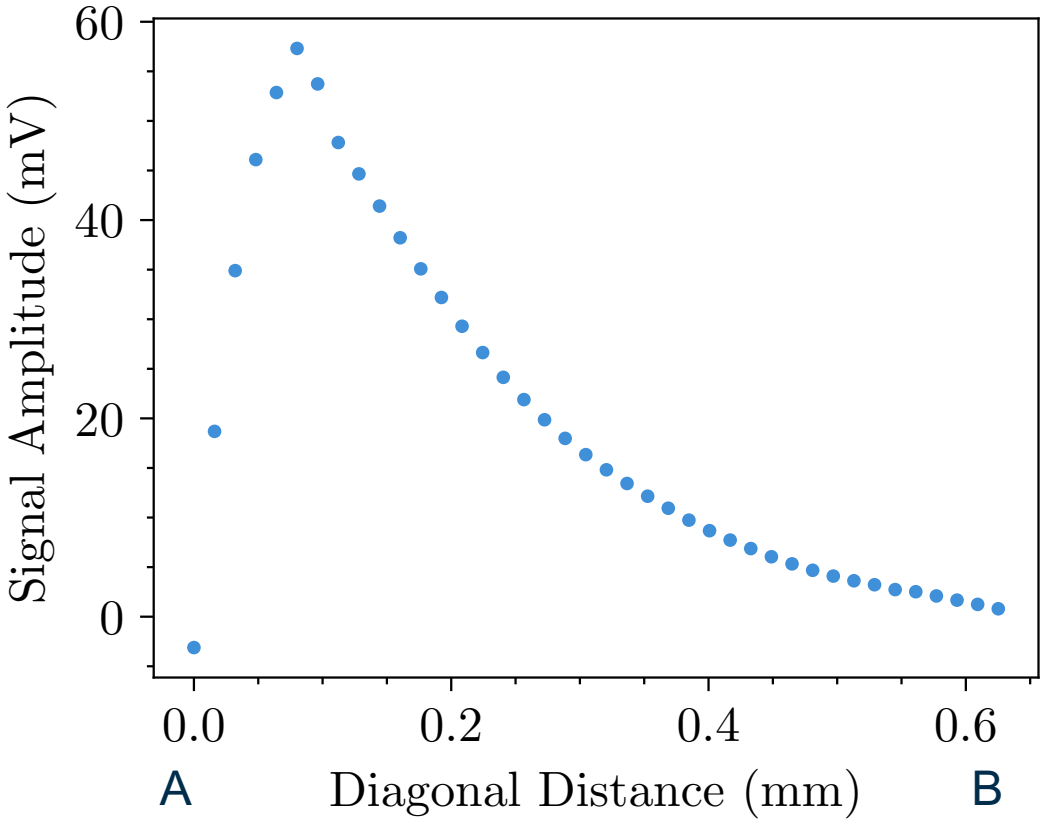
⇨ **Leakage not affected by irradiation**

Studying the Signal Spread

- Does the signal spread change with irradiation?

- Signal with increasing distance from electrode
- Find distance where signal drops by 85% = x_{15}



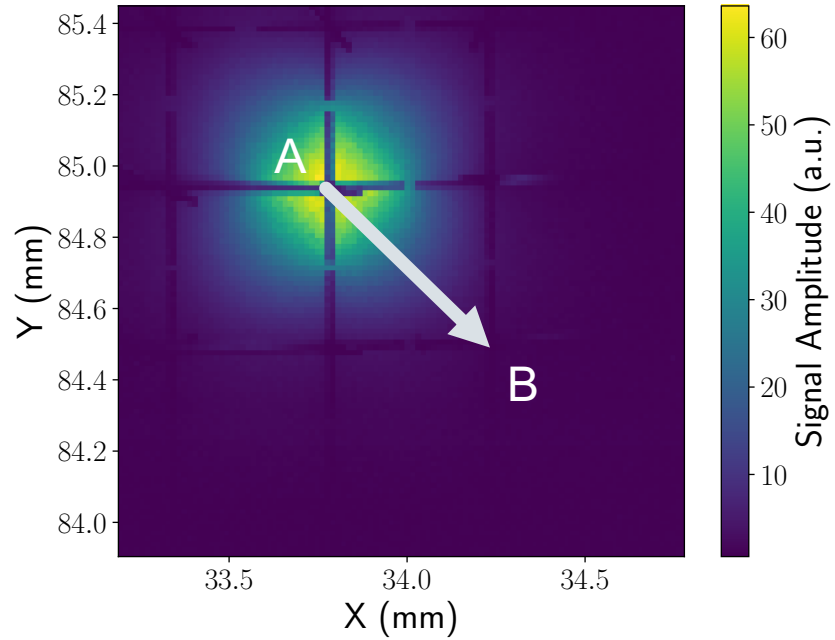


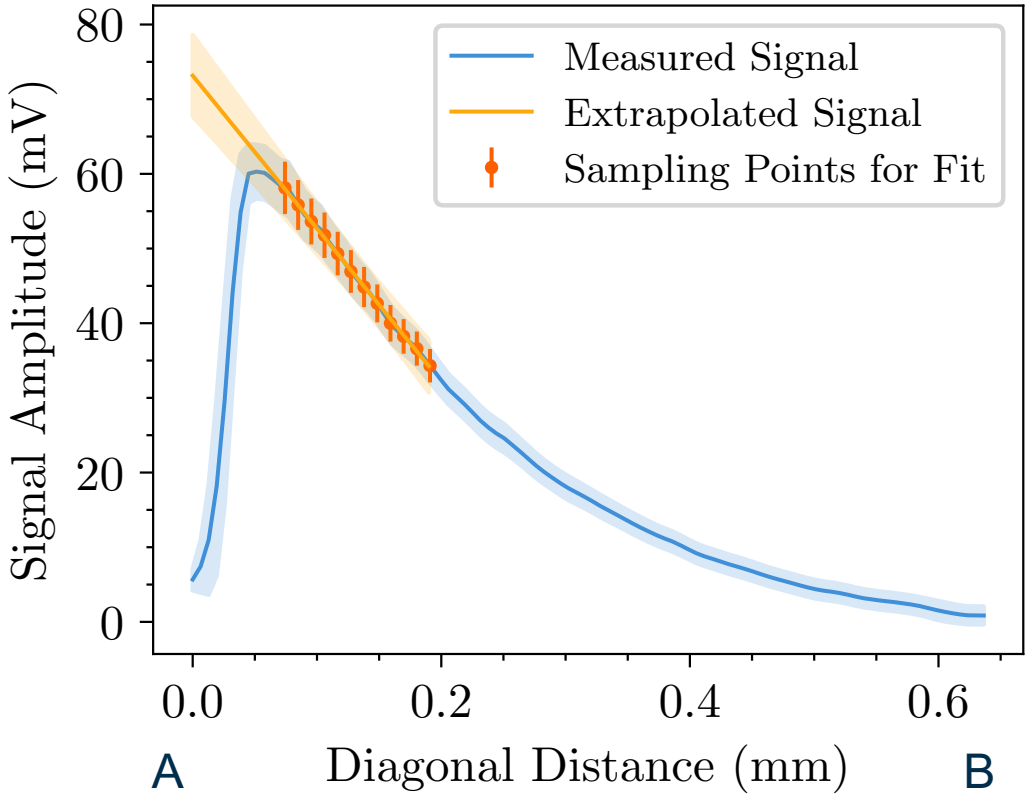
- But what is the maximum signal?
- Electrode and wire bonds block laser

The Diagonal Signal

- Does the signal spread change with irradiation?

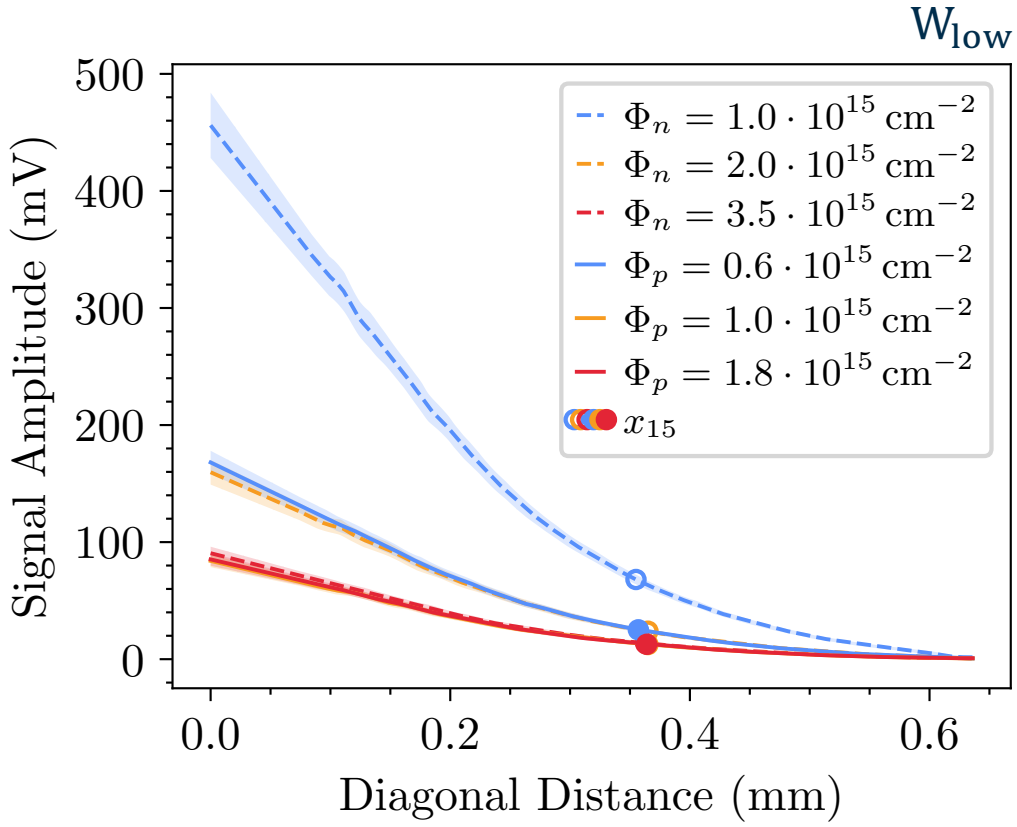
- Signal with increasing distance from electrode
- Find distance where signal drops by 85% = x_{15}

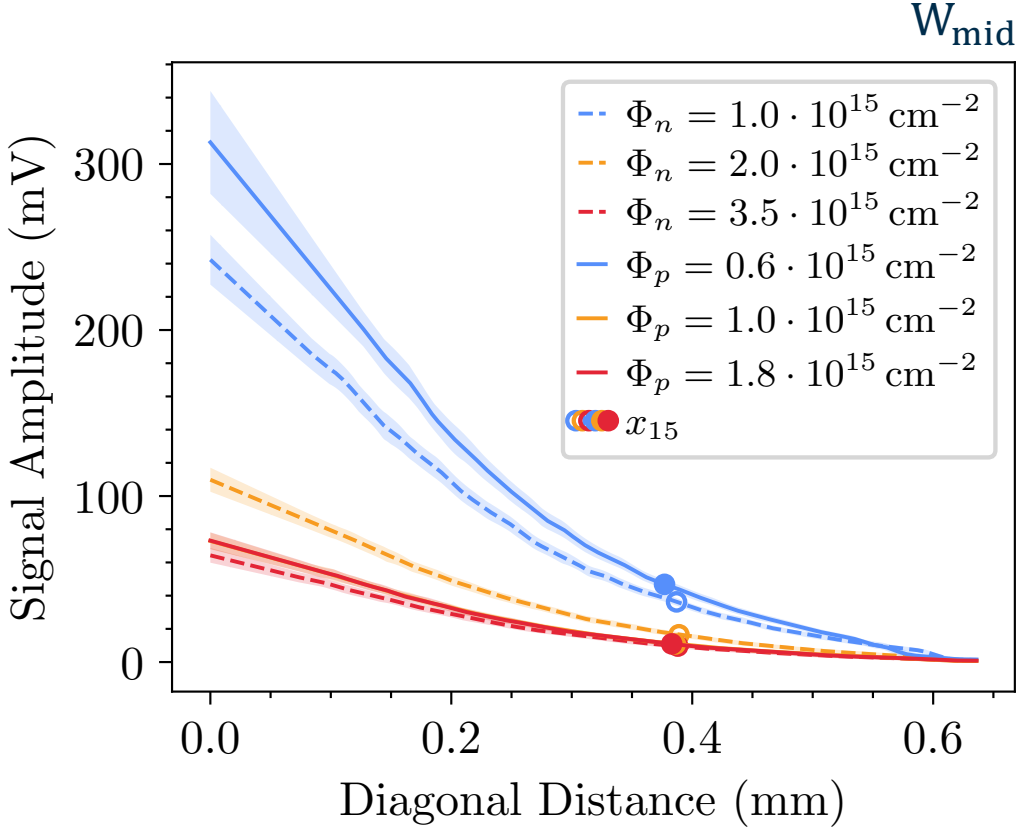




- Get the maximum using a fit in linear region to extrapolate in blocked region

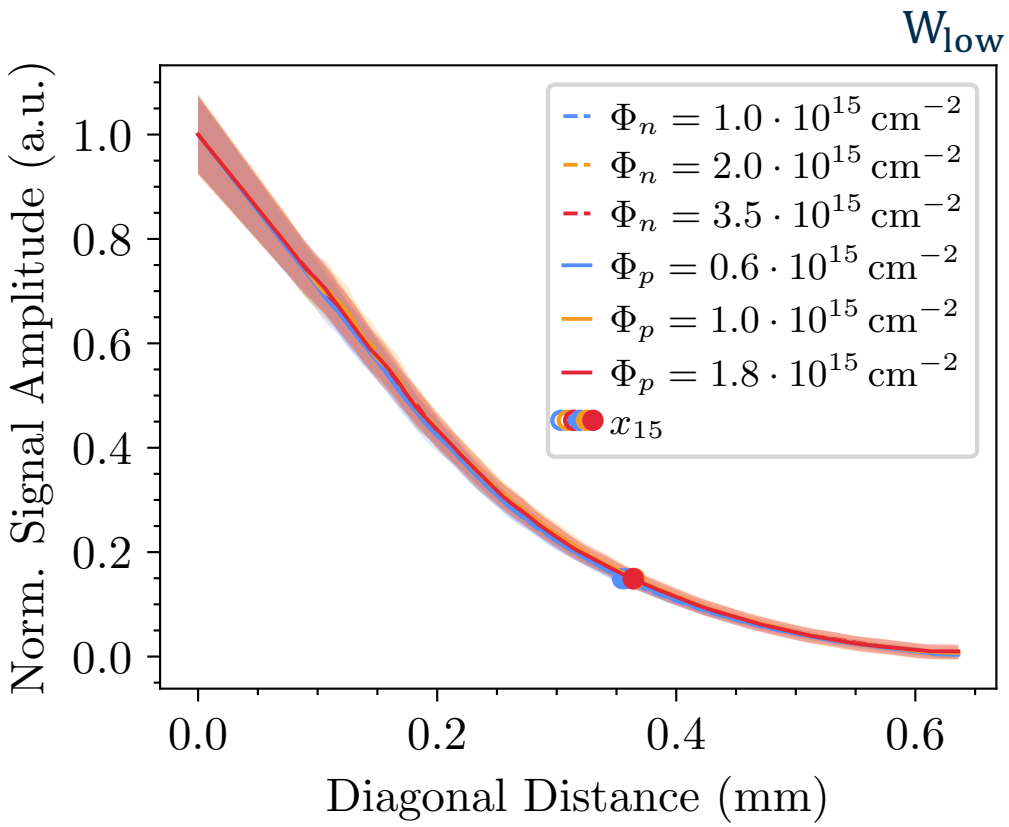
Signal Spread Results

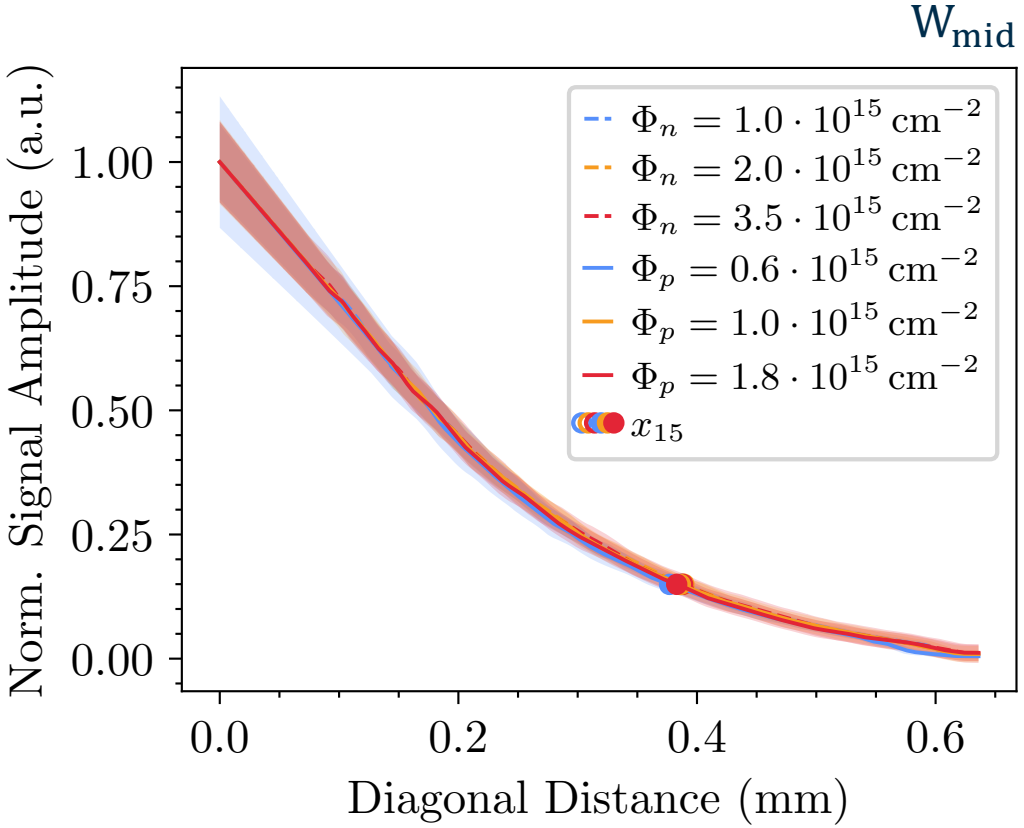




- Reduced internal gain due to irradiation
- x_{15} at similar distance

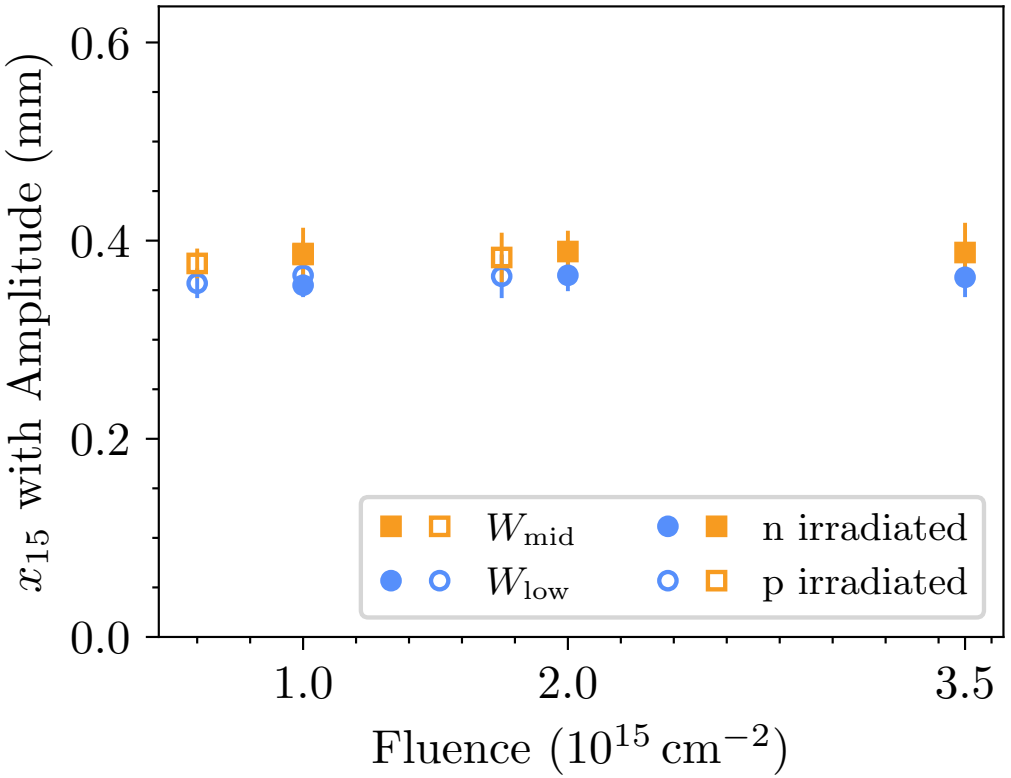
Signal Spread Results: Normalized

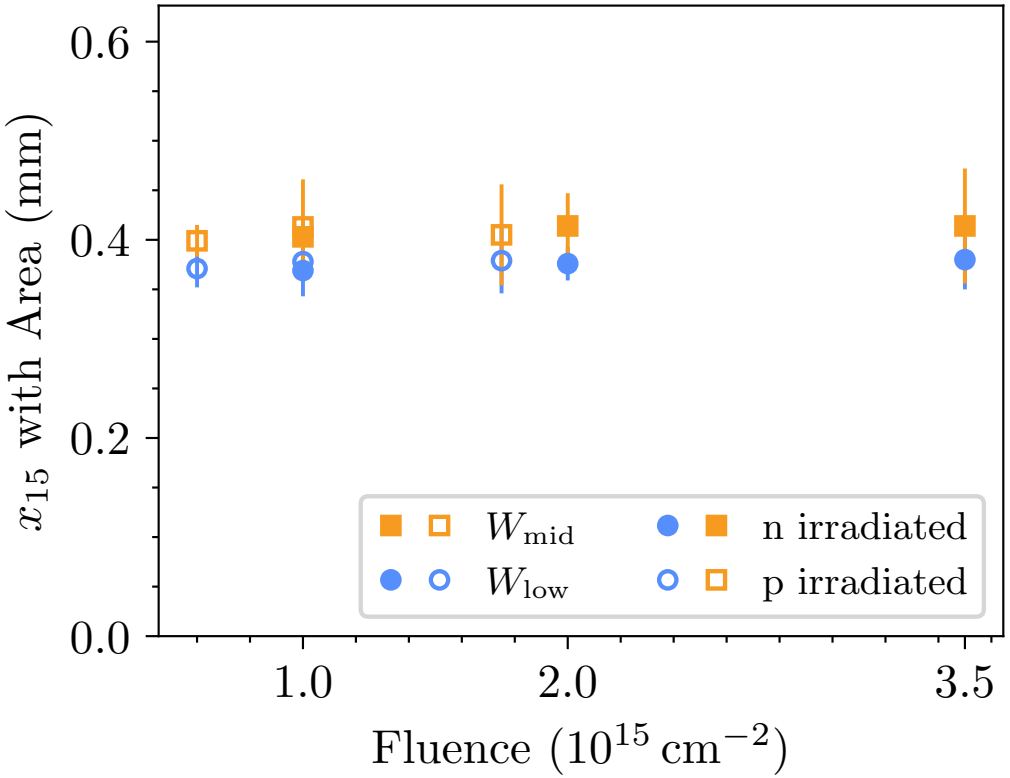




- x_{15} at similar distance
- Curves look identical

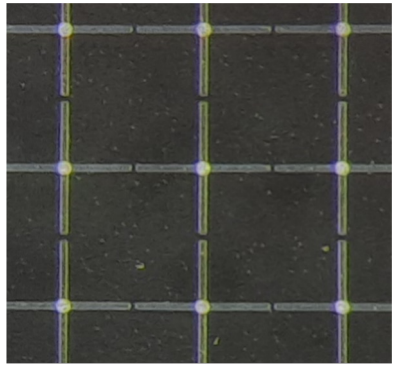
Charge Spread Distance





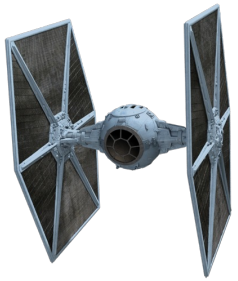
- Signal spreads further for higher doping = lower resistivity

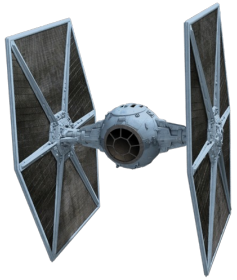
Change of topic

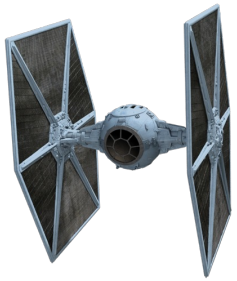
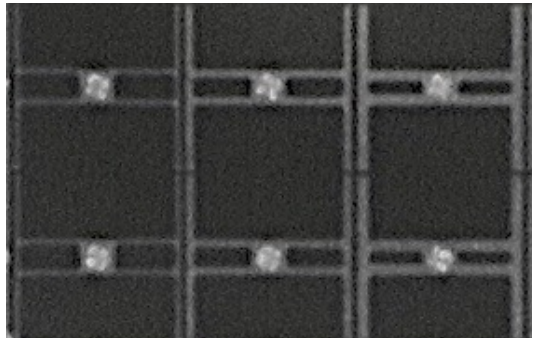


- No changes to signal spread with irradiation observed
  ⇨ **Signal spread not affected by irradiation**

- Crosses worked out fine for pixel applications
- Untested designs included in RSD2 production
- Study them for possible other applications
  ⇨ First measurements of hybrid (pixel and strip) RSD's

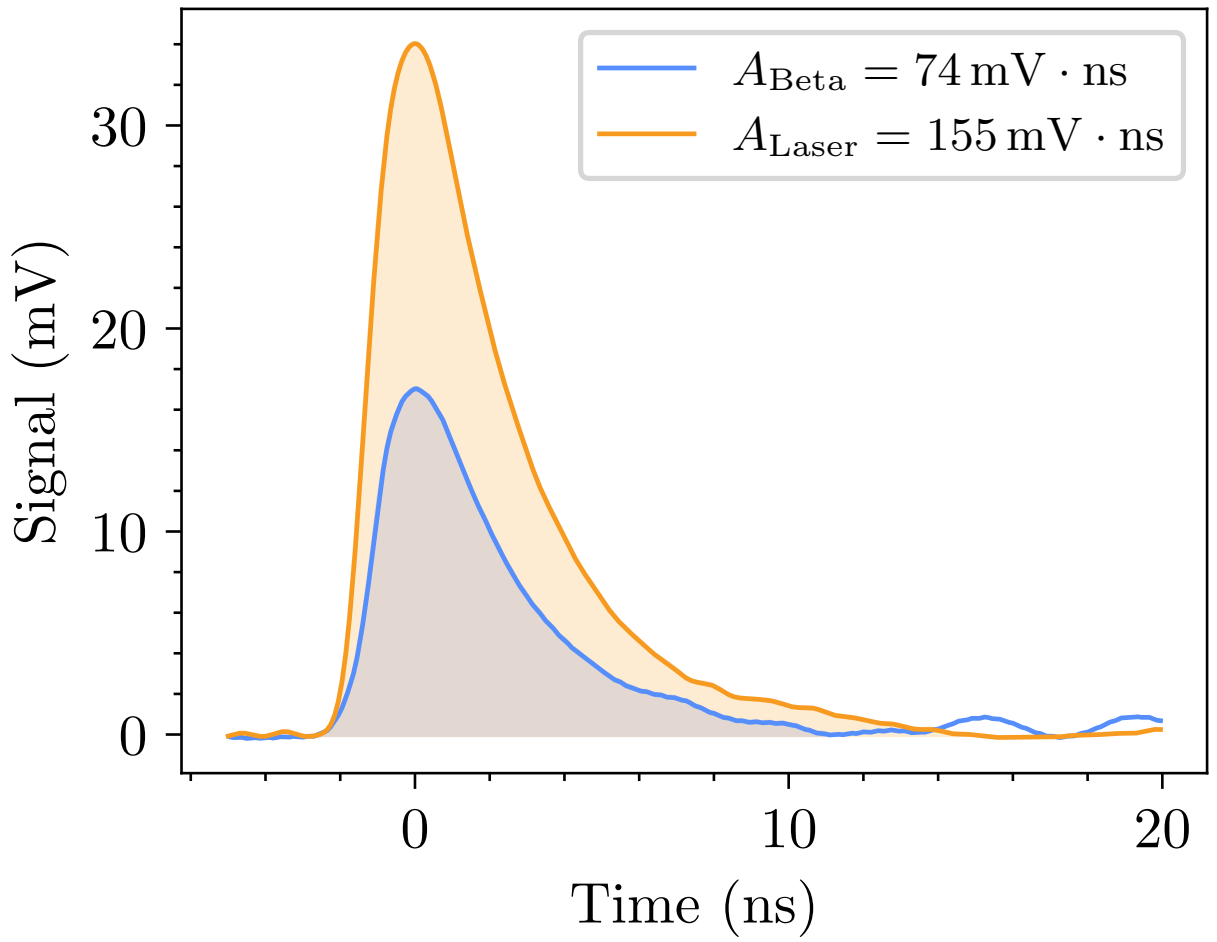
Mom, can we have  ?

No. There is  at home.

 at home: 

Calibrating the setup

- Calibrate laser intensity to 1-3 MIP using β-source
- Record 10000 events each
- Calculate area of average
- Performed on a sensor from W_{high} with 150 V bias

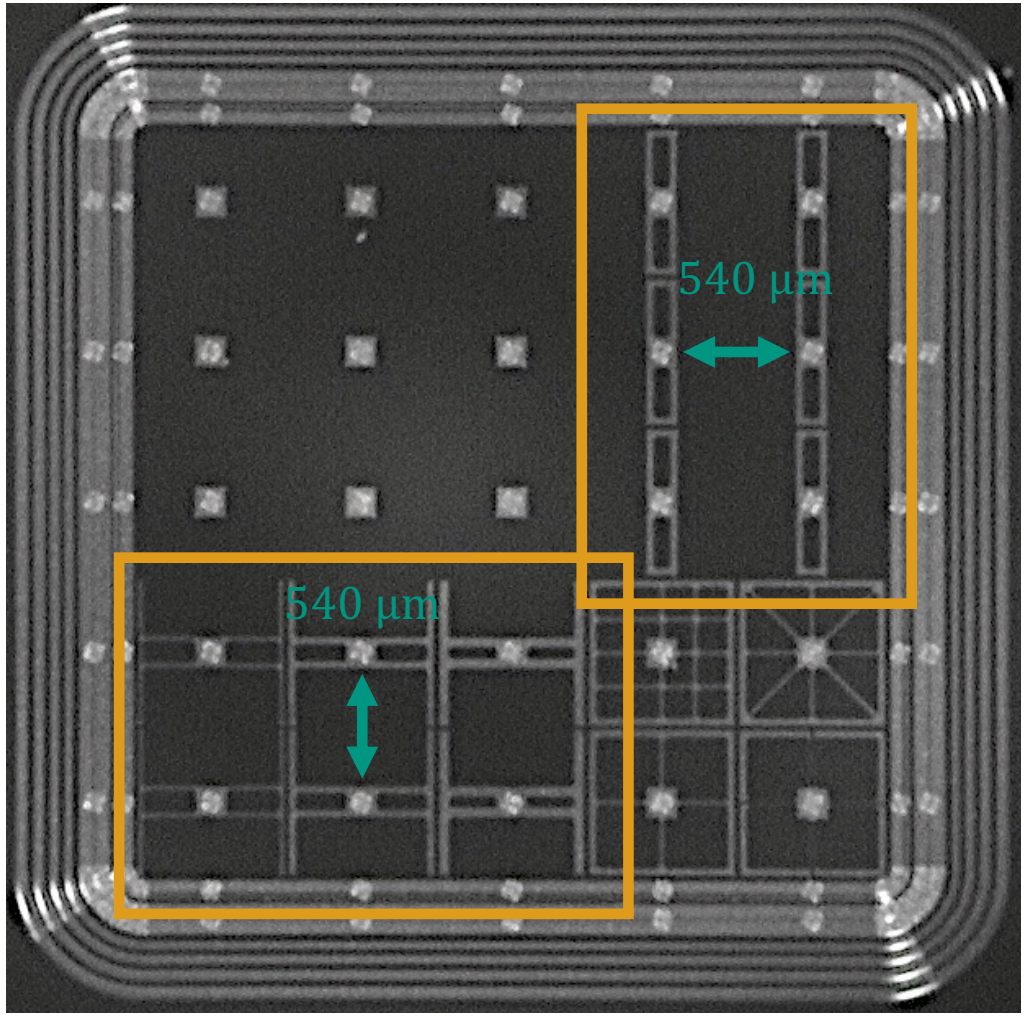


Spatial resolution of strip-like electrode shapes

- Two electrode shapes trying to emulate a strip-sensor
  - Bar-shape
  - H-shape

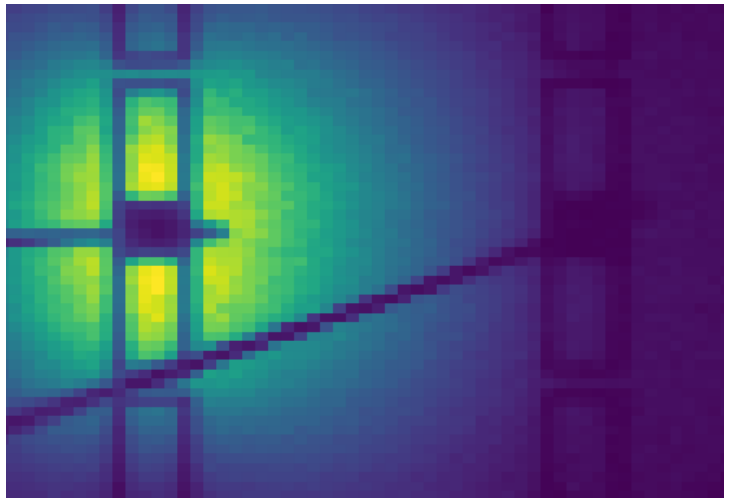
- Hybrid of pixel and strip-detector
- 1D resolution instead of 2D with pixels

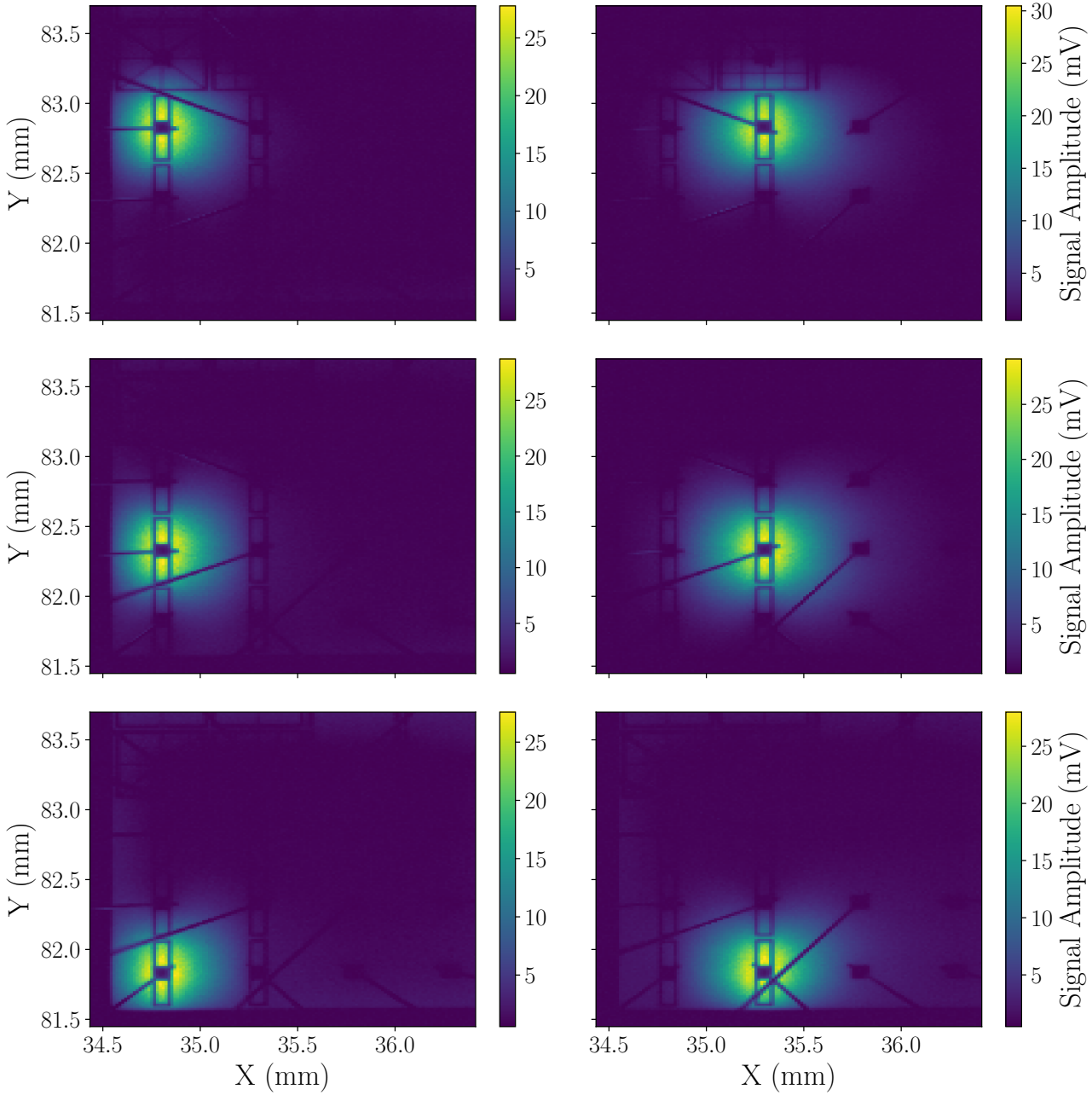
- Perform scans with the TCT
- Test reconstruction algorithms
  - Focus on 1D nature
- Estimate resolution



The bars

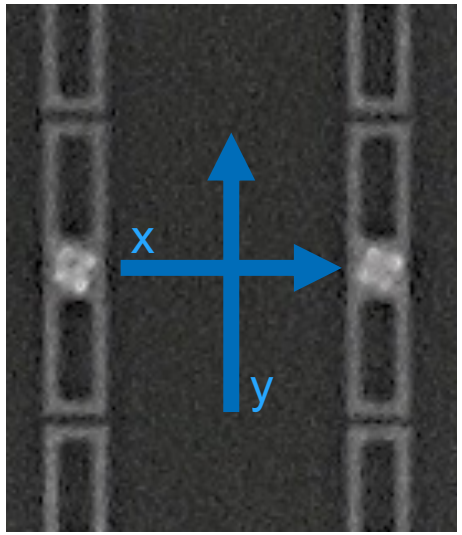
- Somewhat circular behavior
  ⇨ Y-dependent/not perfectly 1D
- Wire bonds block laser at some positions
  ⇨ Mask and remove



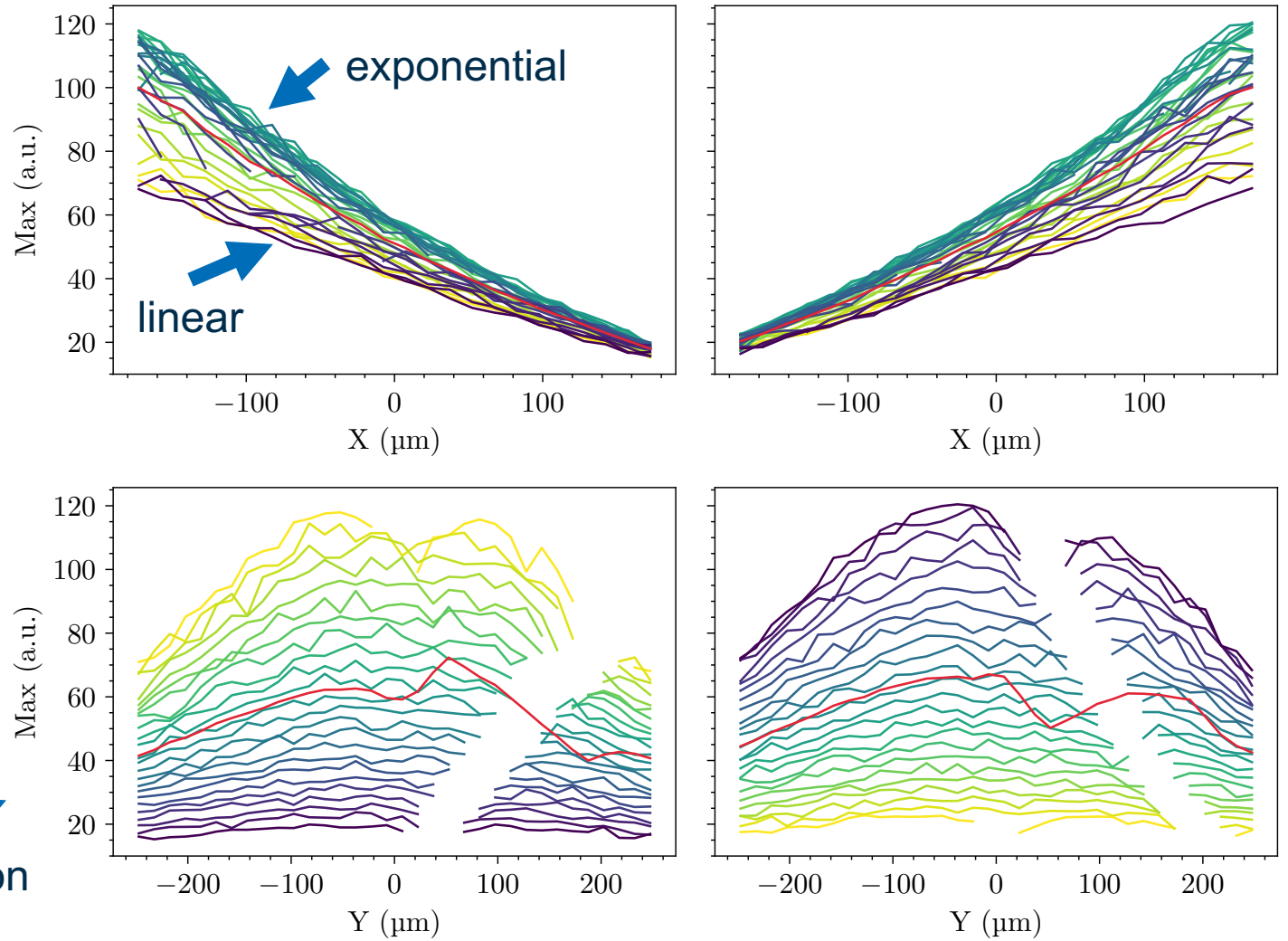


Looking at the signal from the side

- Middle pair of electrodes
- Masked out are wire bonds
- Color highlights different X or Y positions



Average in red

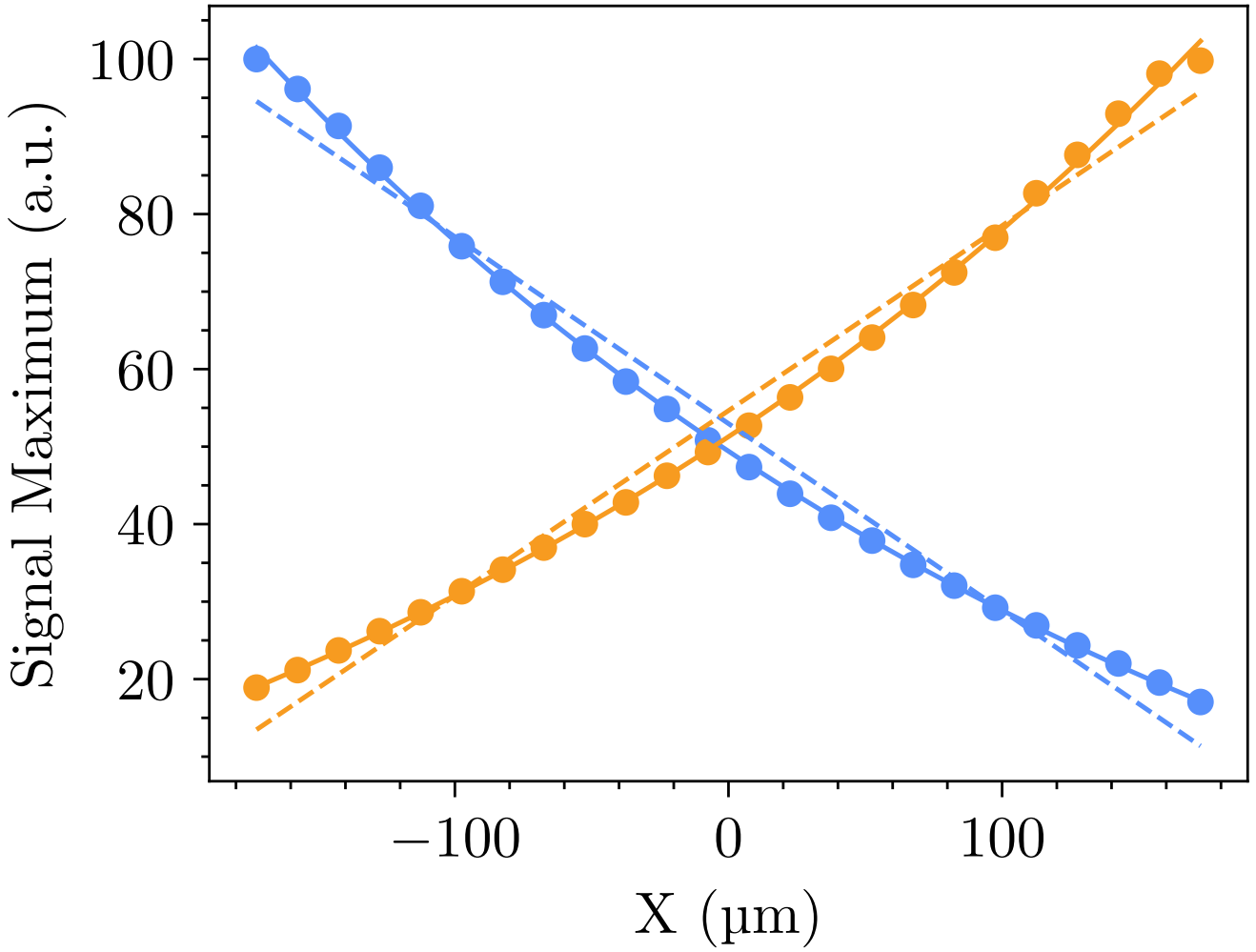


Dependence on X position

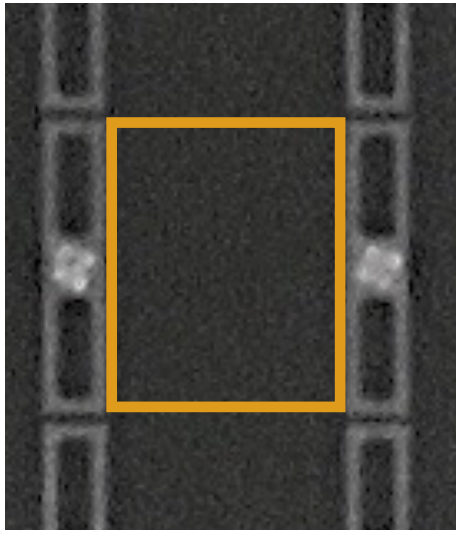
Finding the reconstruction parameters

- Test two 1D functions for reconstruction
  - Linear curve (dashed)
  - Exponential curve (solid)
- Fit both curves on average of all three pairs
  - Ignore Y axis

- Exponential follows the mean nicely
- Linear over-/underestimates the signal in the middle/outside

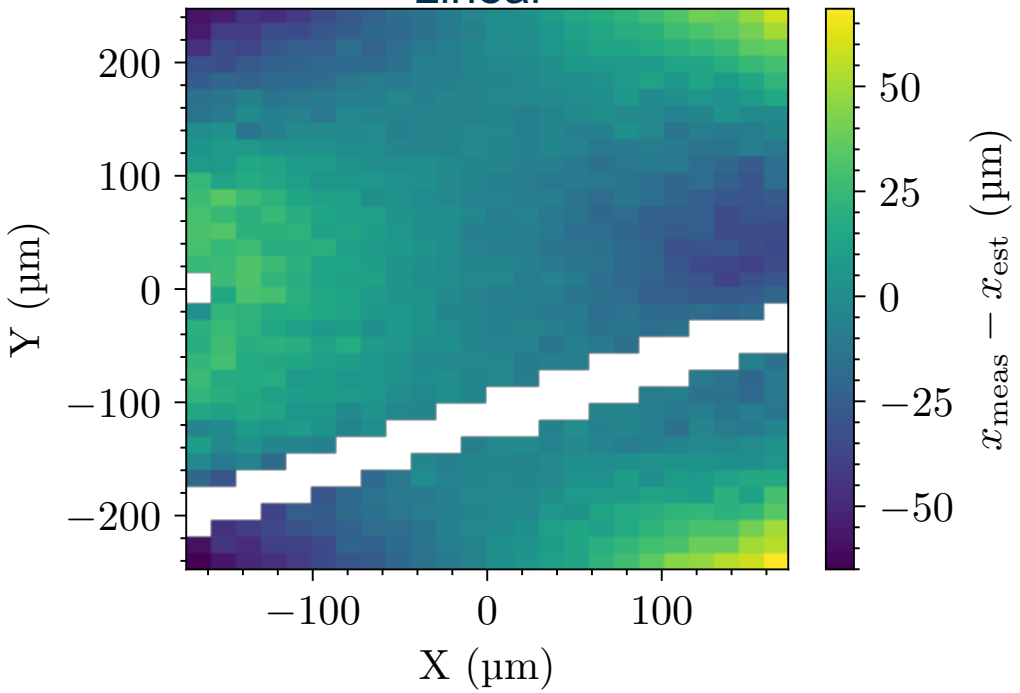


Reconstructing the hit position



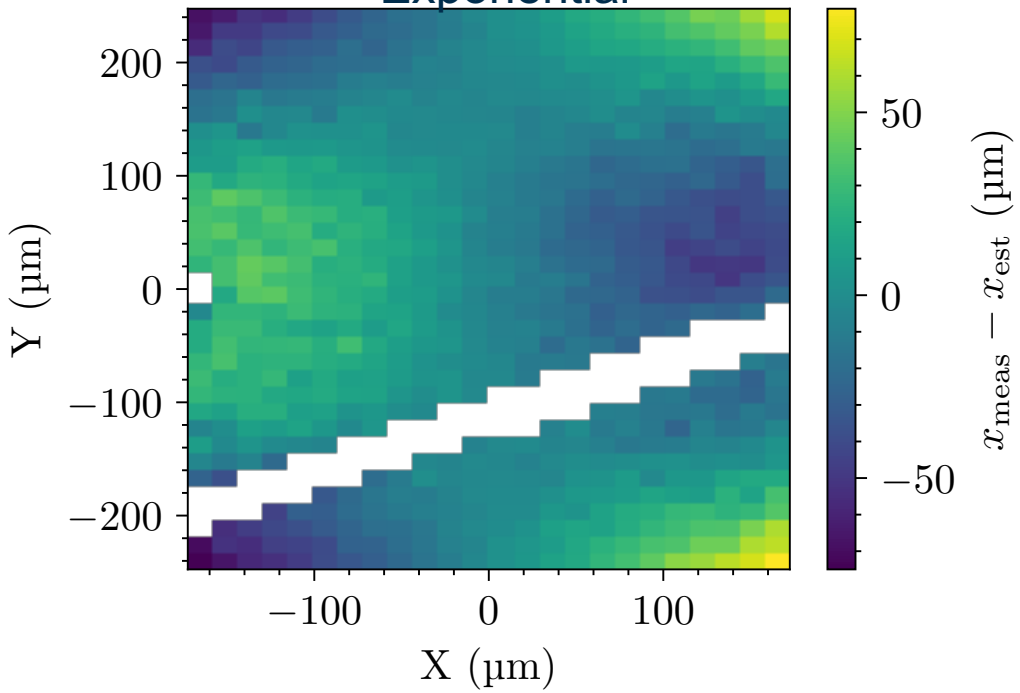
- Minimize for each pair of electrodes $\chi^2 = \sum_{i=\text{left,right}} \left(S_{\text{i,meas}} - S_{\text{i,est}}(x)\right)^2$
- Blue is reconstructed to the right, yellow to the left

Linear



Middle pair

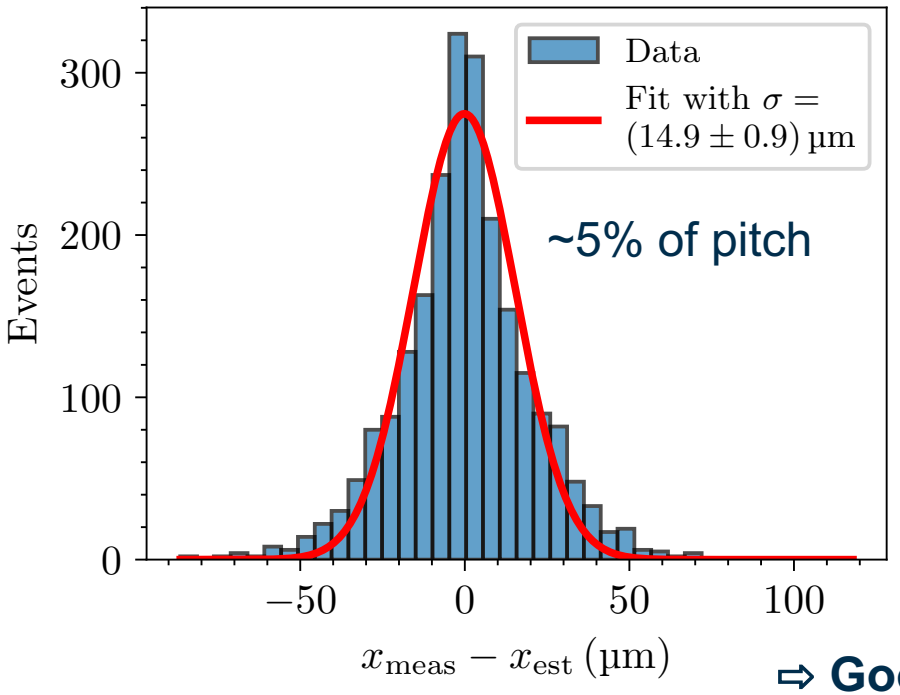
Exponential



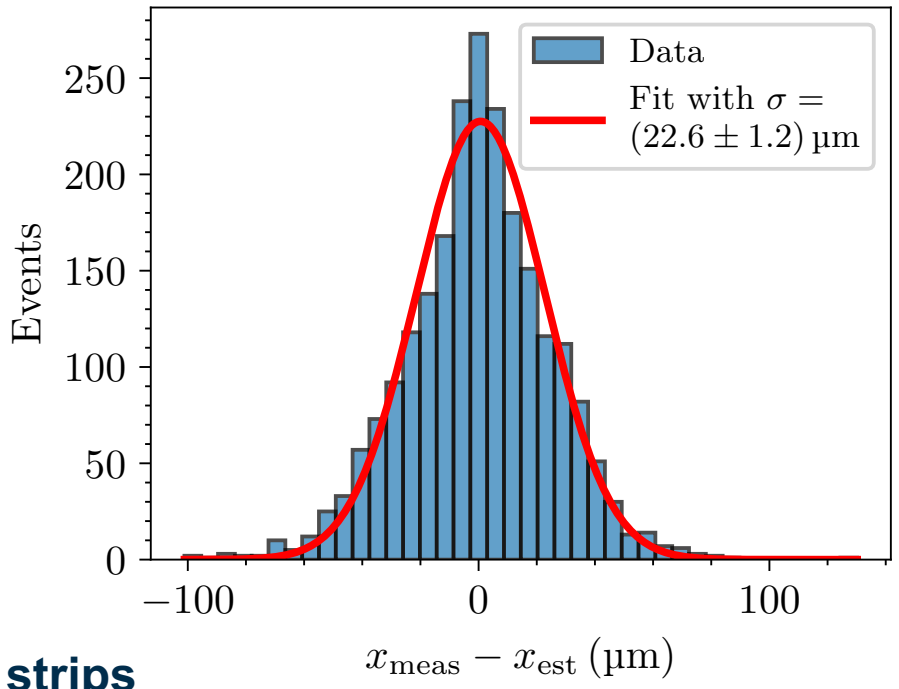
The resolution

- All three pairs of bars combined
- Gaussian fit in red

Linear



Exponential

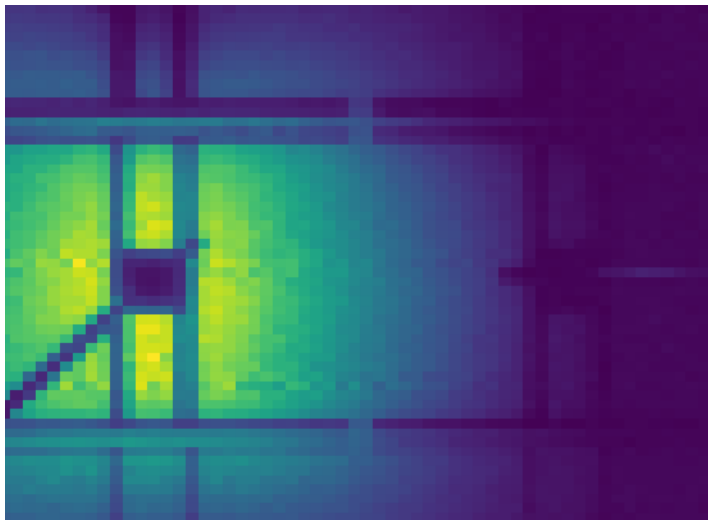


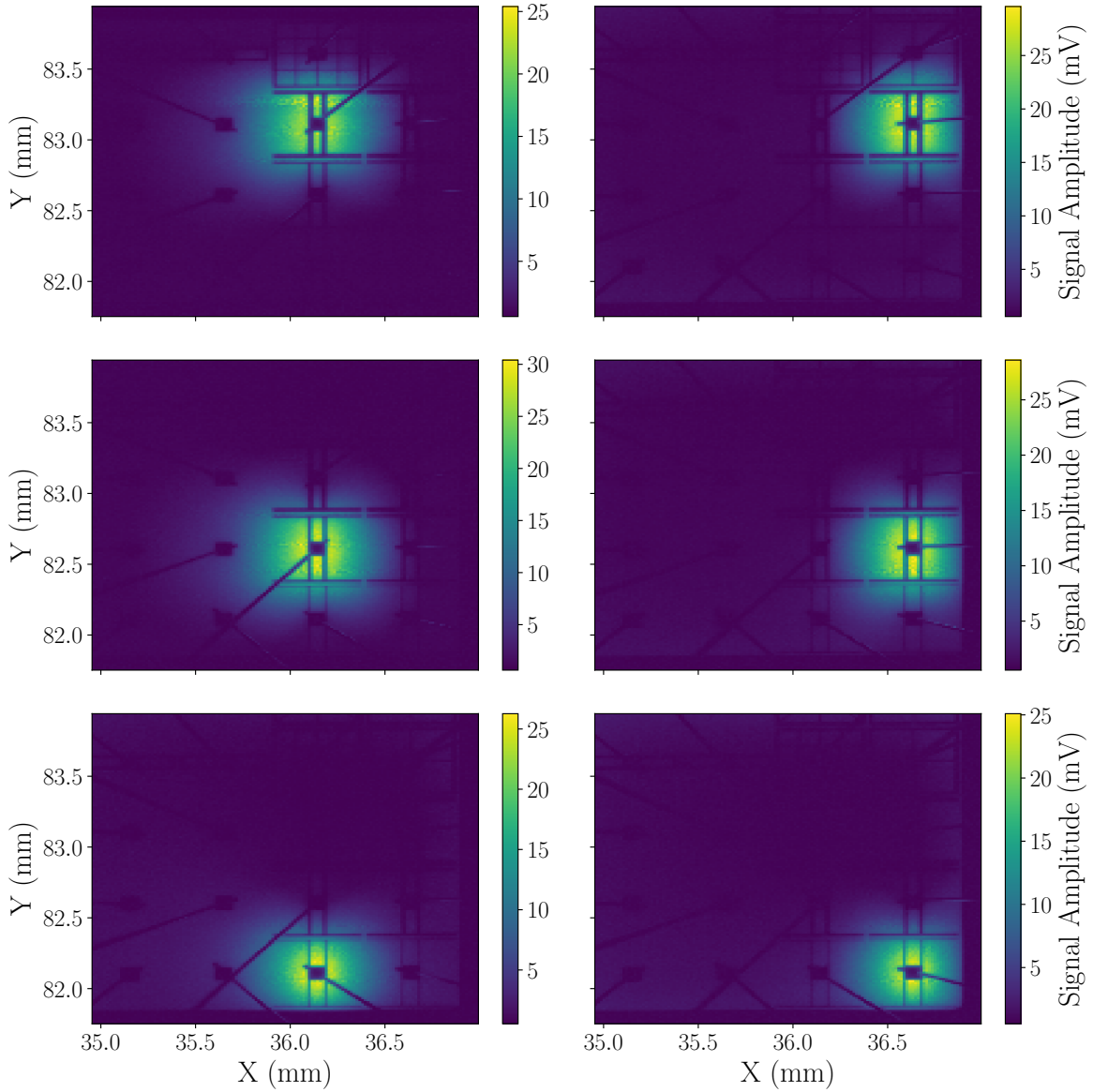
⇨ **Good attempt for strips**

The H-shaped electrodes

Time to shoot lasers at some TIE fighters!

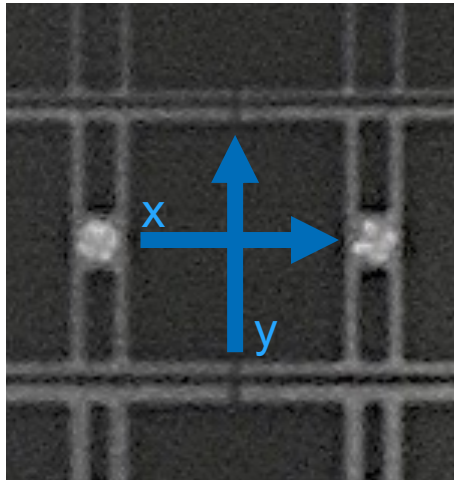
- Signal looks “boxy”
  ⇨ Better 1D behavior
- Wire bonds block laser at some positions
  ⇨ Mask and remove



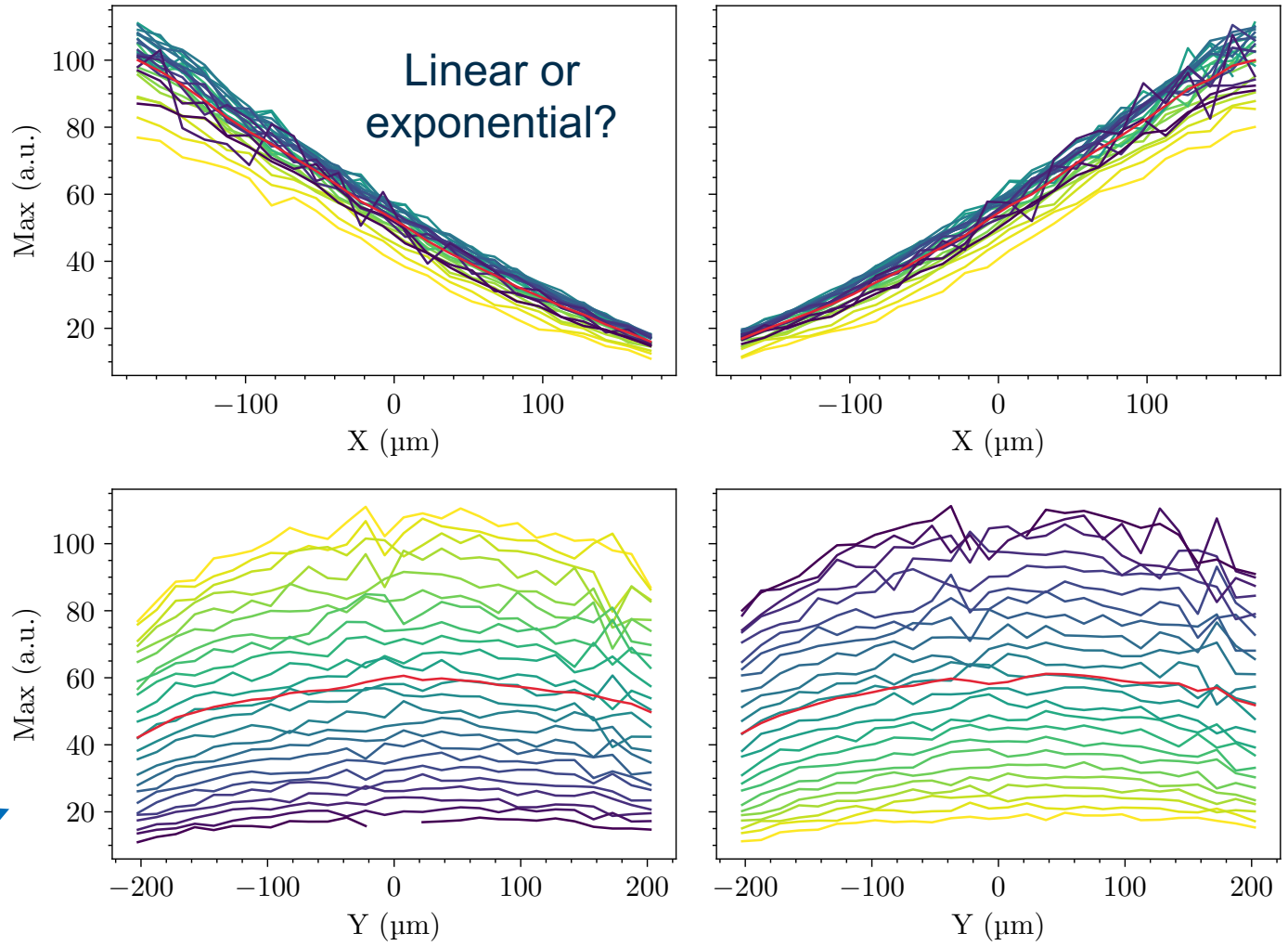


The signal from the side

- Middle pair of electrodes
- Masked out are wire bonds
- Color highlights different X or Y positions



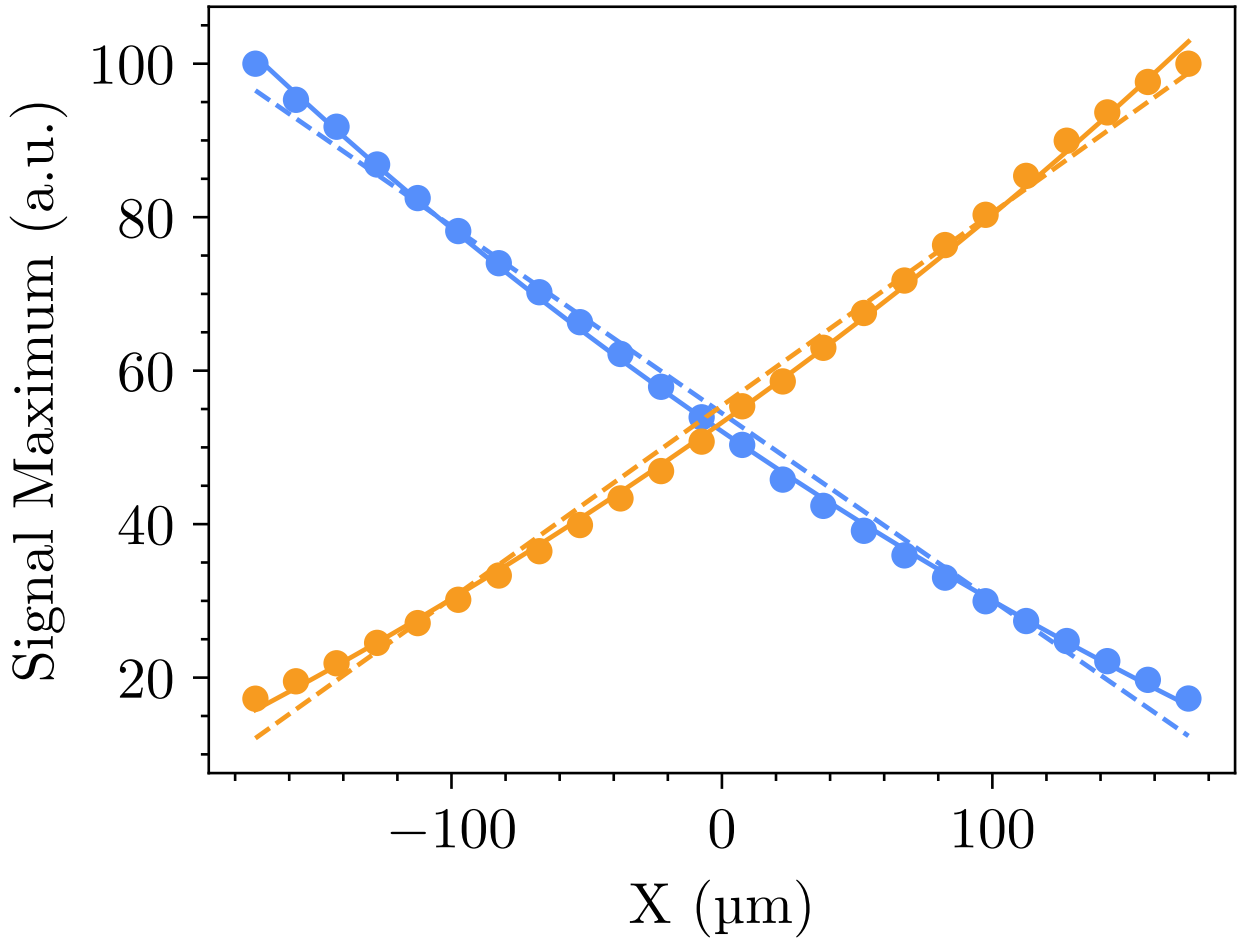
Average in red



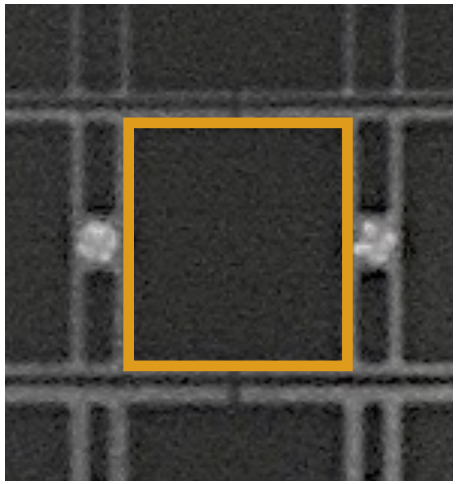
Fitting the reconstruction template

- Test two 1D functions for reconstruction
  - Linear curve (dashed)
  - Exponential curve (solid)
- Fit both curves on average of all three pairs
  - Ignore Y axis

- Exponential follows the mean nicely
- Linear slightly over-/underestimates the signal in the middle/outside

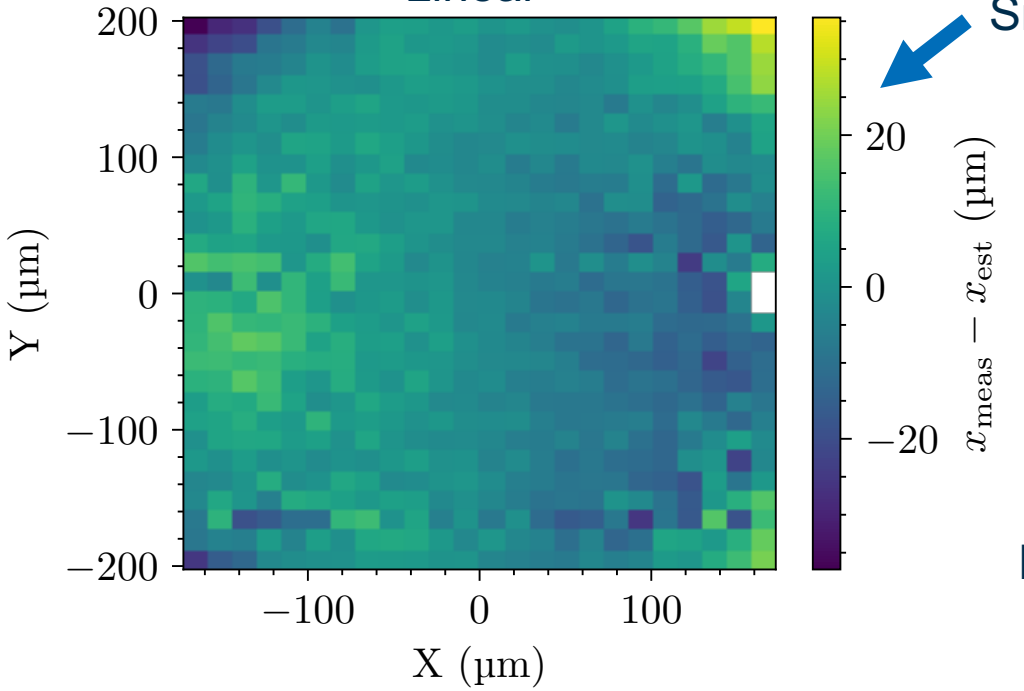


Reconstructing the hit position



- Minimize for each pair of electrodes $\chi^2 = \sum_{i=\text{left,right}} \left(S_{\text{i,meas}} - S_{\text{i,est}}(x)\right)^2$
- Blue is reconstructed to the right, yellow to the left

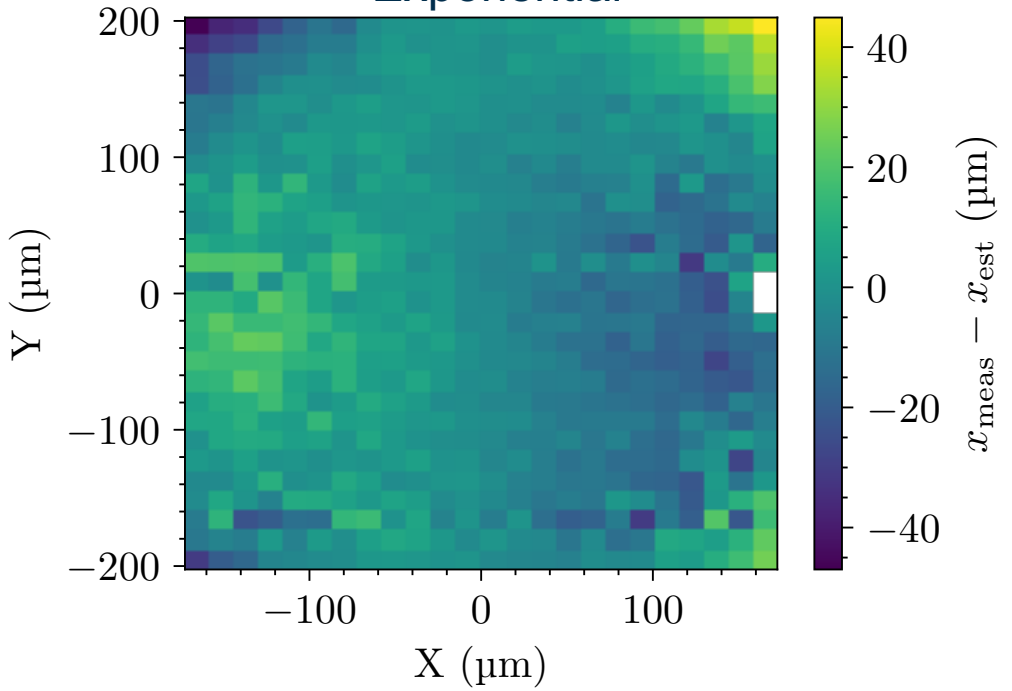
Linear



Small range

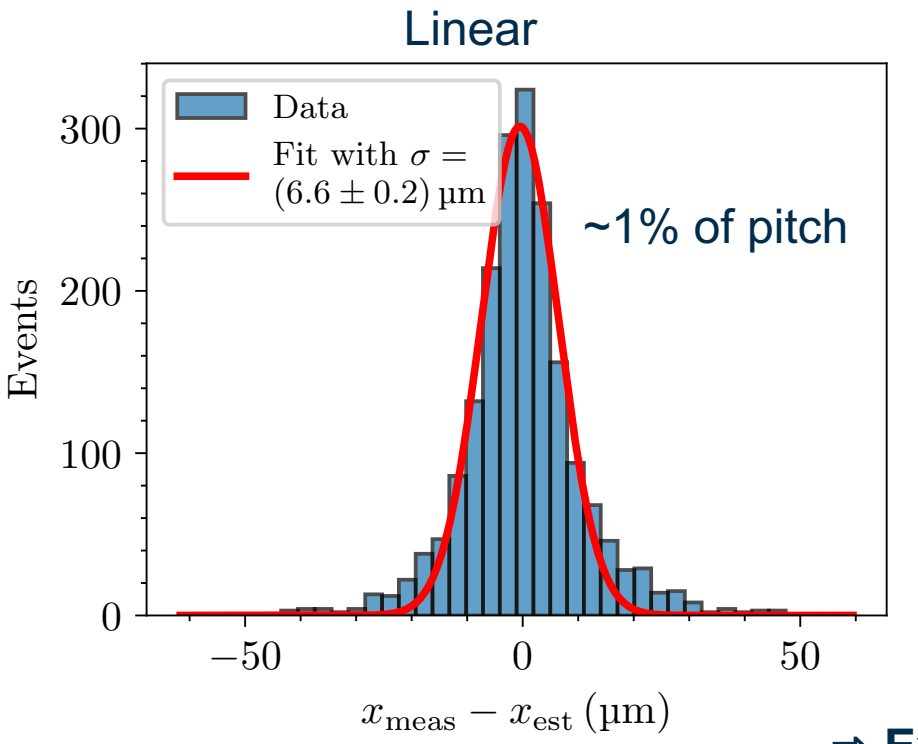
Middle pair

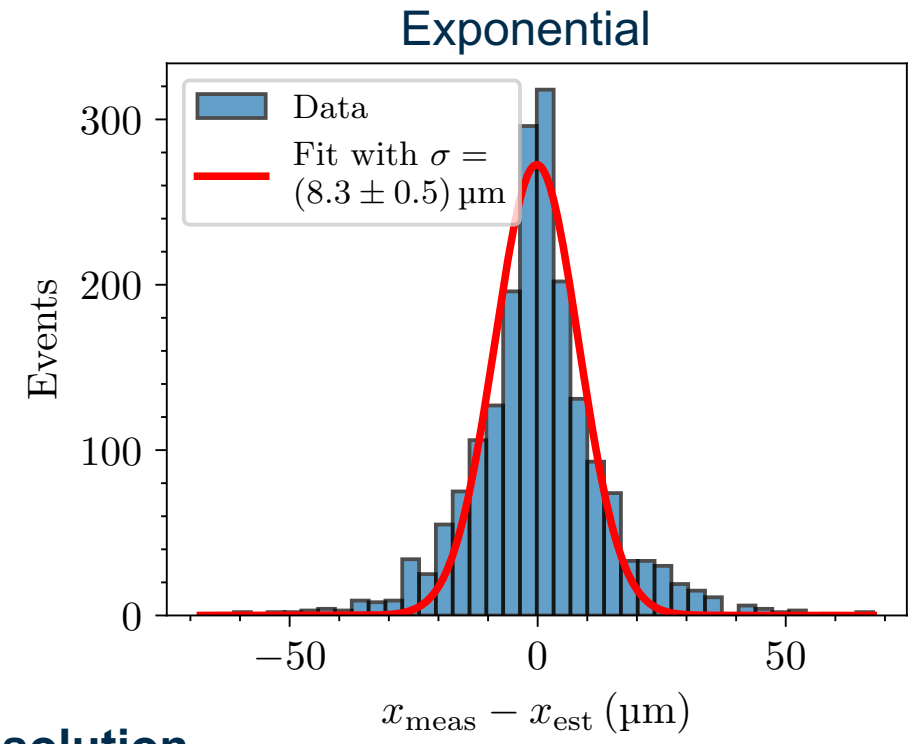
Exponential



The resolution

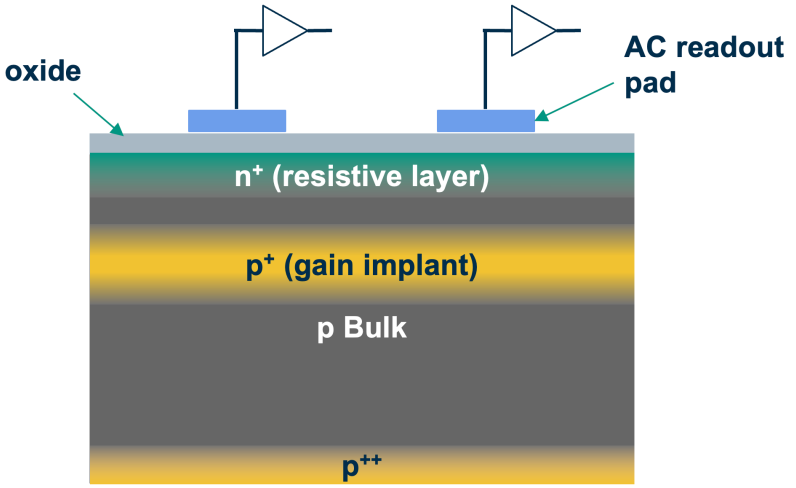
- All three pairs of H's combined
- Gaussian fit in red

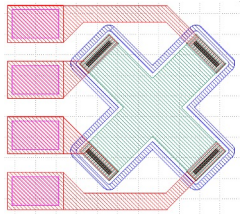




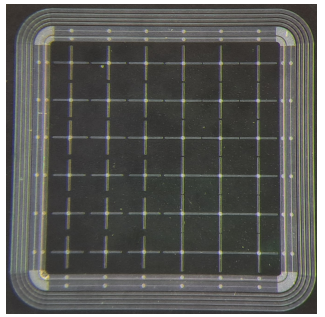
⇨ **Exceptional resolution**

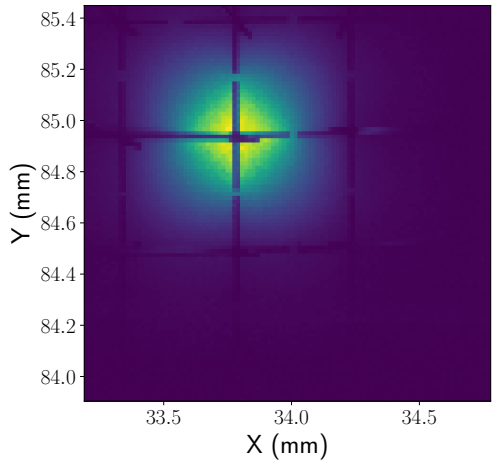
Summary



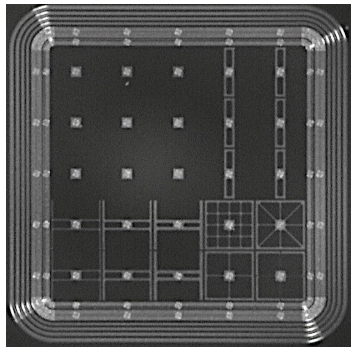


- RSDs as candidates for future tracking detectors
- Fundamental redefinition of how tracking works!
- Measured donor removal in RSDs
  - One of the first measurements for this range of n^+ doping concentration



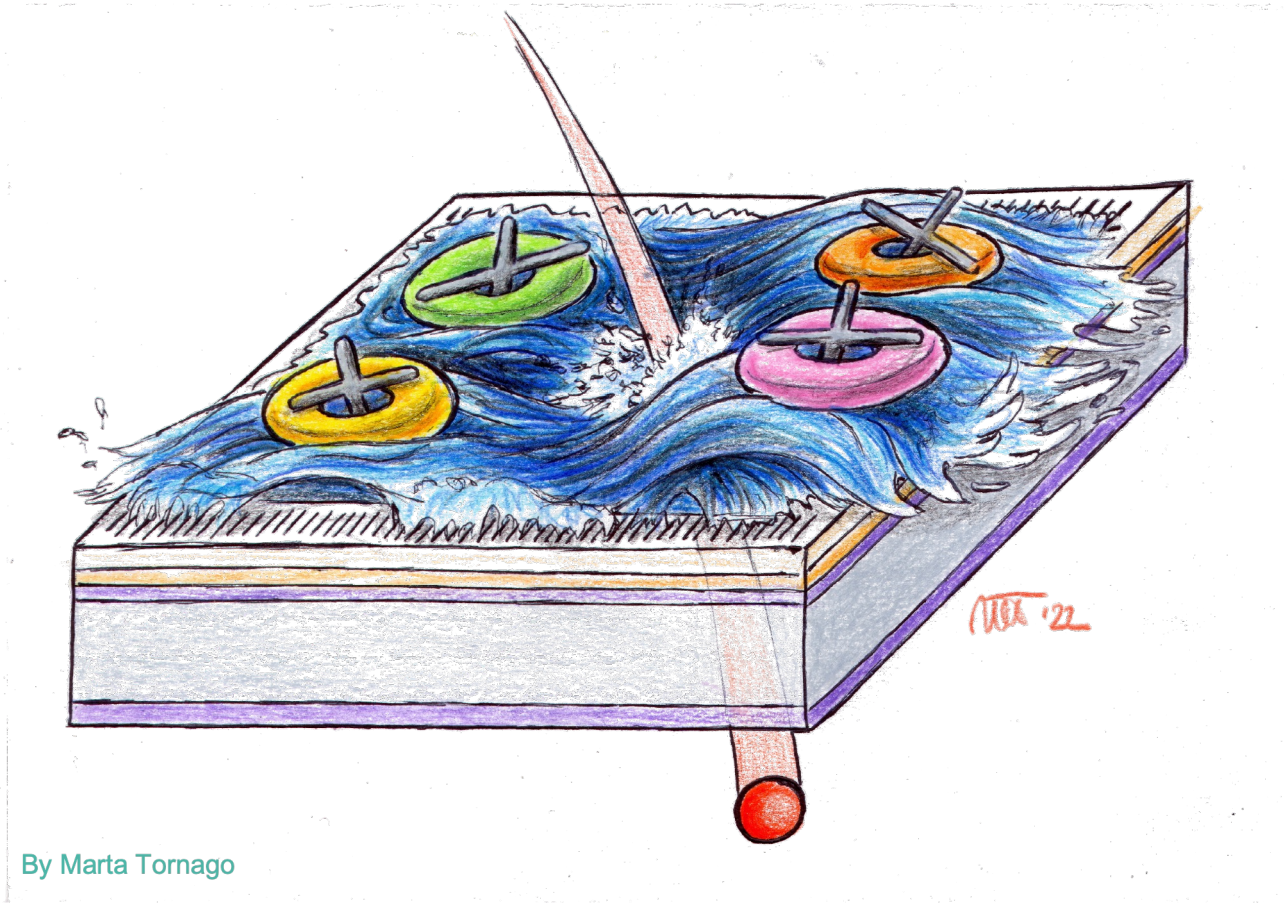


- Study on influence of irradiation on charge spread in TCT
  - Measured Leakage Ratio
  - Studied Diagonal Signal
  - ⇨ **Irradiation only has little influence on charge sharing in RSDs!**



- Spatial Resolution of strip-like electrode shapes
  - Investigated bar- and H-shapes
  - Reconstructed position using simple 1D fits to the mean signal
  - ⇨ **Resolution relative to pitch of 5% for bars and 1% for H's**
    MUCH better than 30%!

Backup



By Marta Tornago

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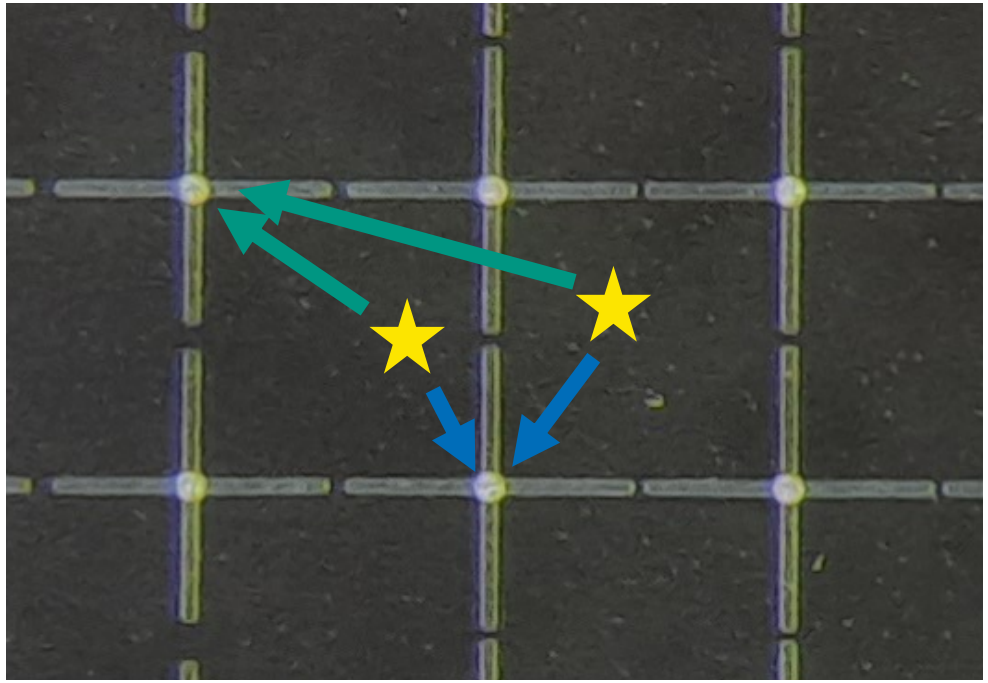
- European Union's Horizon Europe Research and Innovation programme Grant Agreement No 101057511 (EURO-LABS)
- Alexander von Humboldt Stiftung
- KCETA Ausschreibung Sachmittel
- INFN - Gruppo V RSD
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- RD50 Collaboration, CERN

The Problem with Multiple Particles

- Two particles passing at the same time
- Some electrodes have signal of both particles induced on them

⇨ Loss of sensitivity

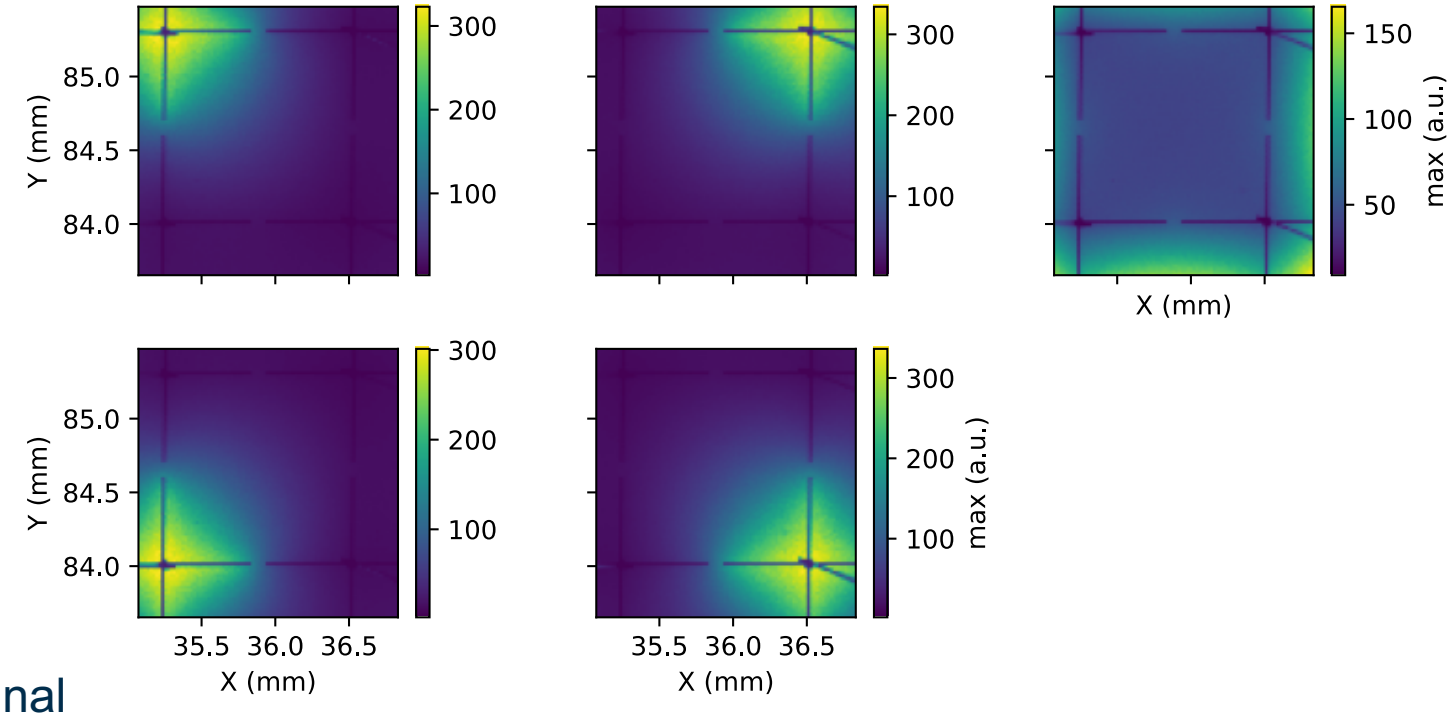


Scanning over 2x2 sensors

- Does the charge spread differently after irradiation?

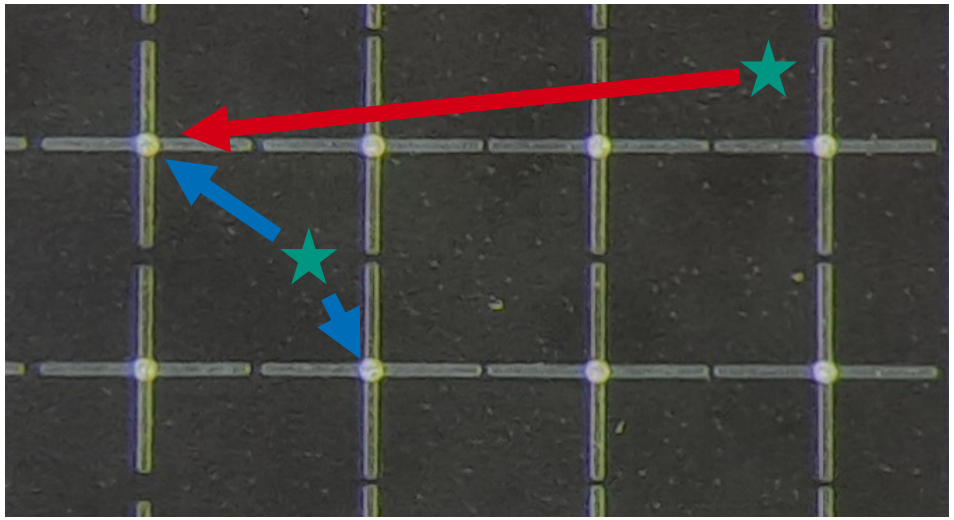
- Scan laser over sensor in $20\ \mu m \times 20\ \mu m$ grid
- Monitor waveforms on AC-pads
- Two metrics used:
  - Signal amplitude
  - Signal area
- Readout of all 16 channels

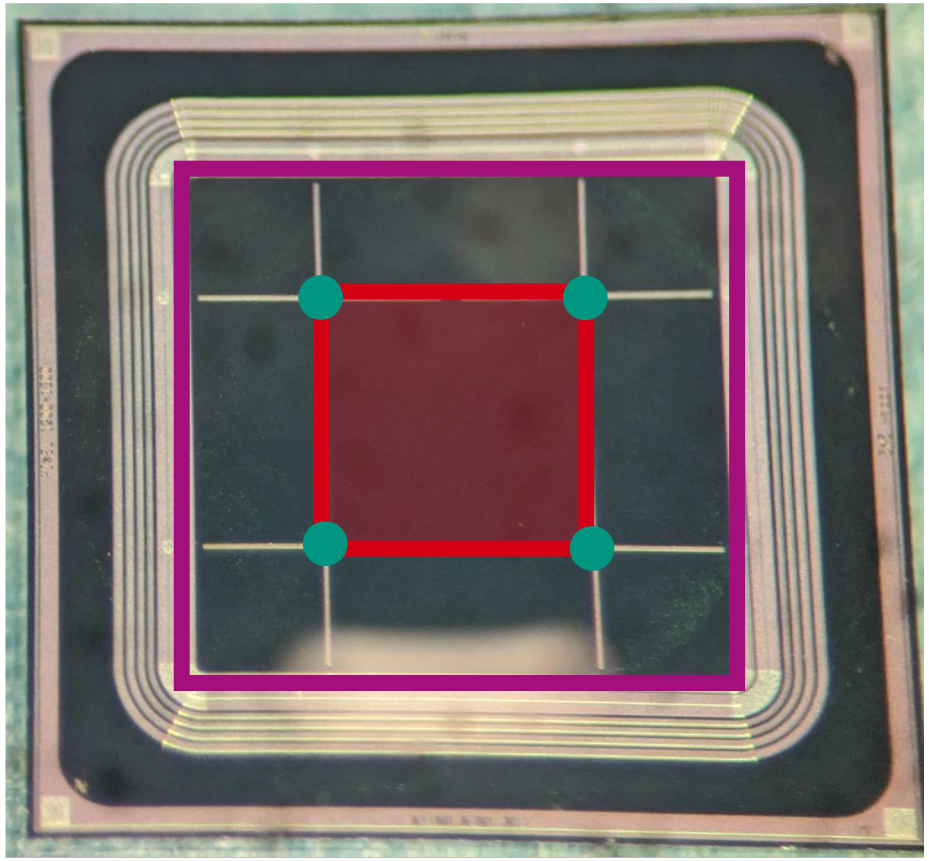
- Quantify the spread using:
  - Leakage Ratio
  - Charge Spread Distance and Diagonal Signal



The Leakage Ratio

- How much of the signal is visible outside of a pixel?
- Does that change with irradiation?

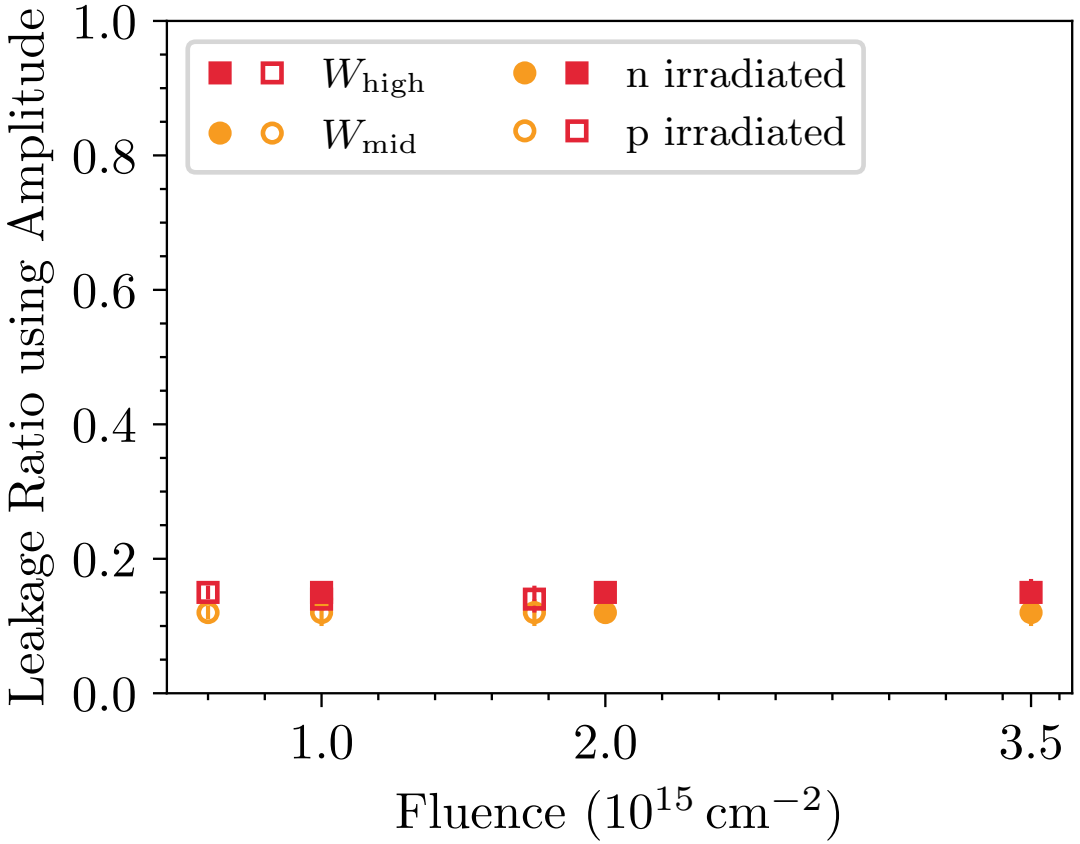


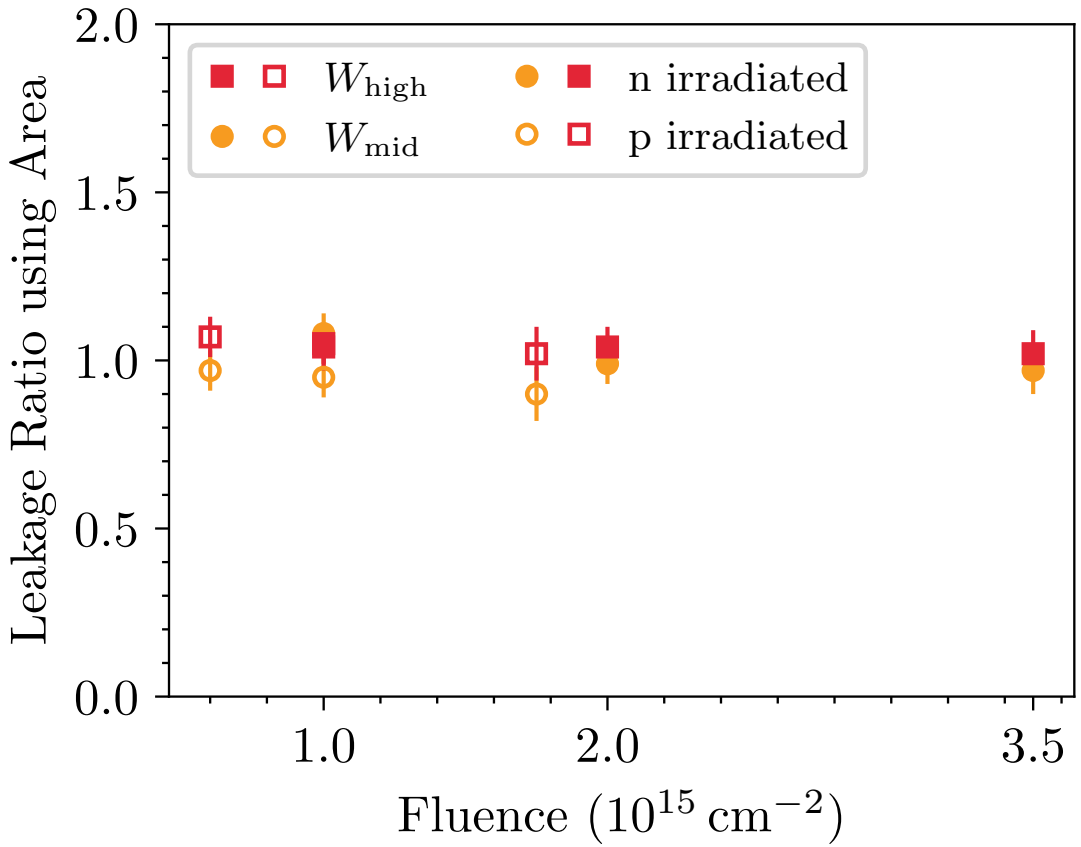


- For all electrodes: A = sum of signal inside pixel (red)
- Compare DC ring (purple) with 4 (green) electrodes

$$\text{Leakage Ratio} = \frac{\text{A of DC ring}}{\text{Sum over A's of 4 electrodes}}$$

The Leakage Ratio



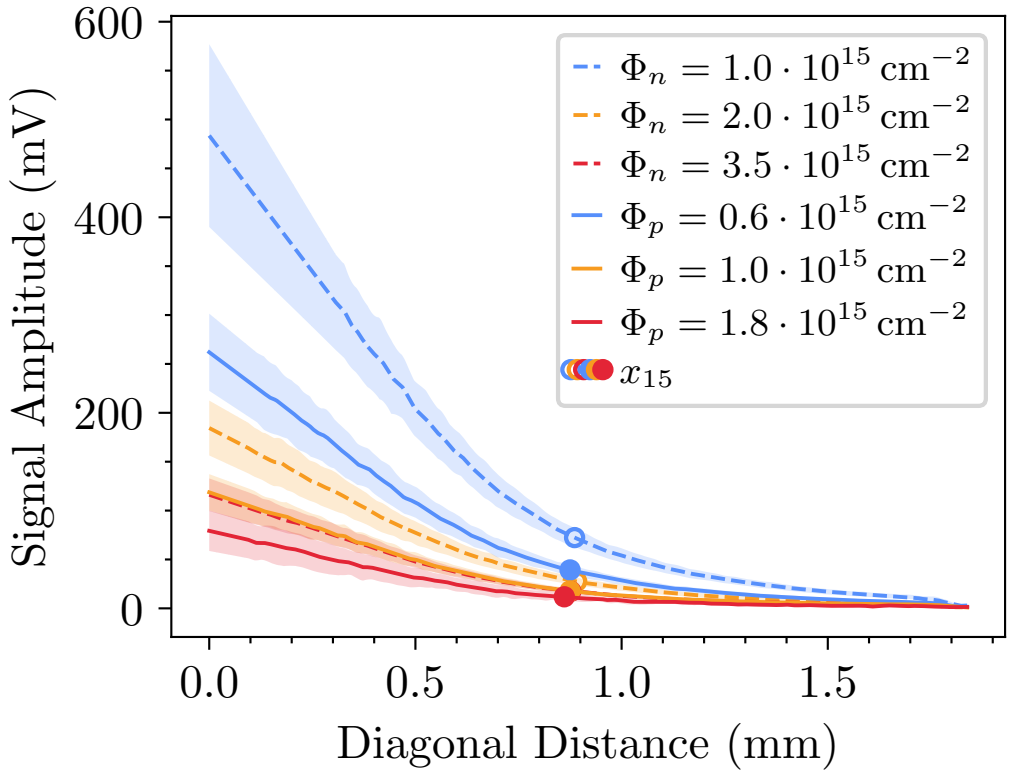


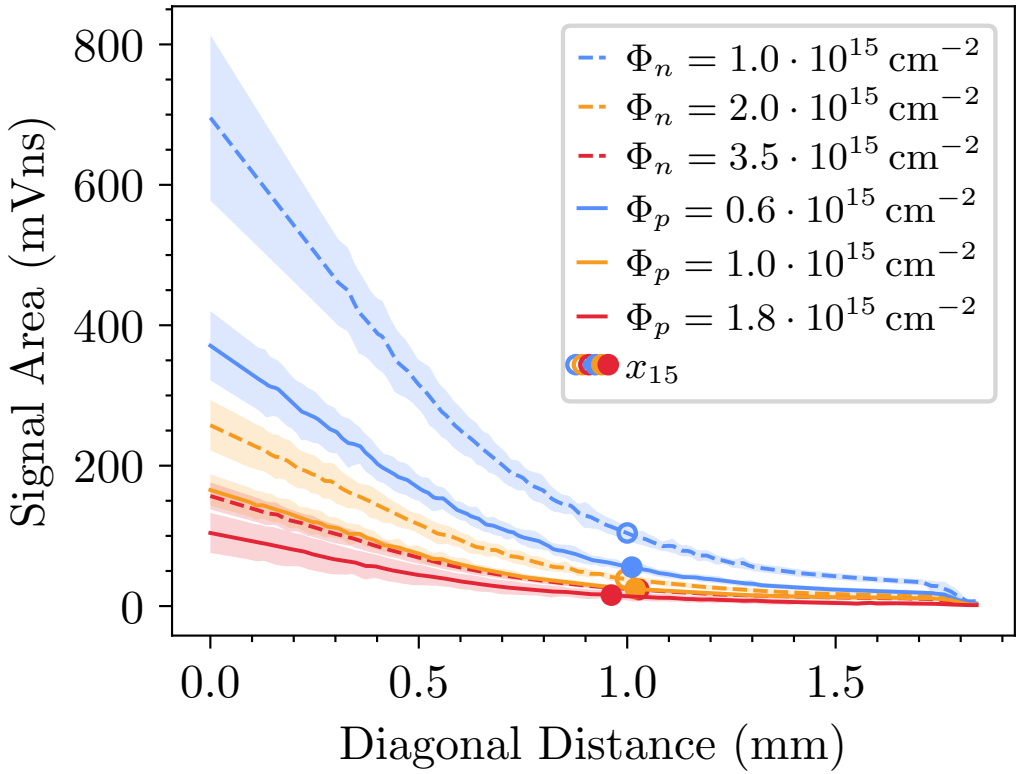
- Good signal containment in pixel
- All charge drifts to DC ring

⇨ **Leakage not affected by irradiation**

Signal Spread Results

W_{mid} here

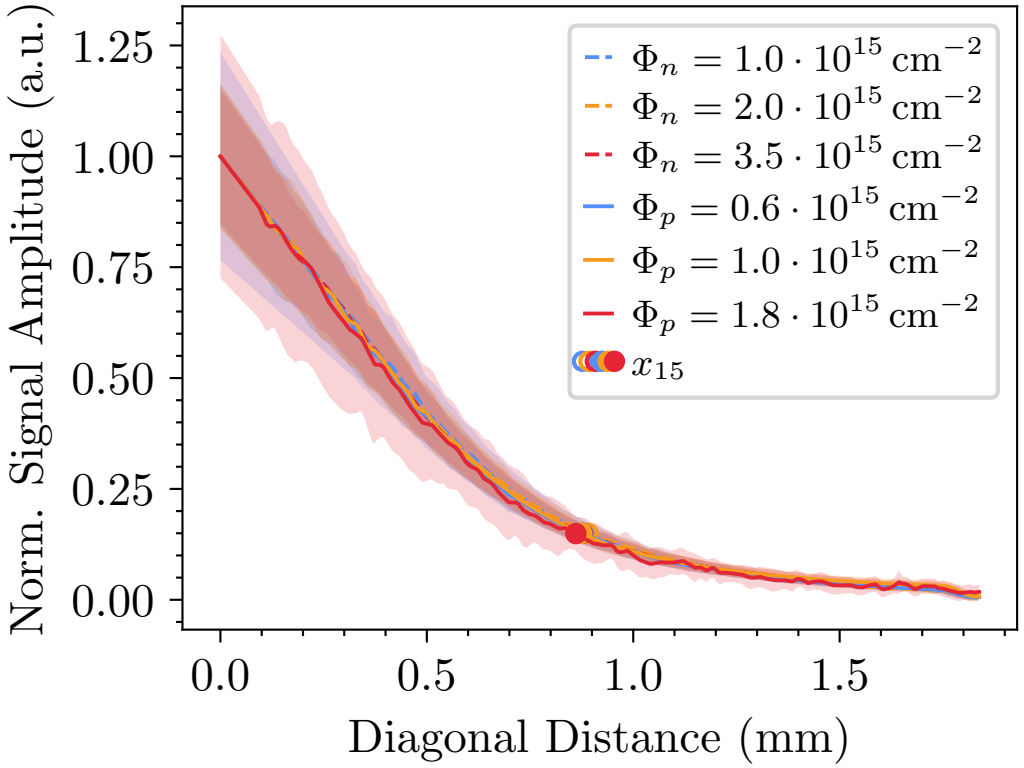


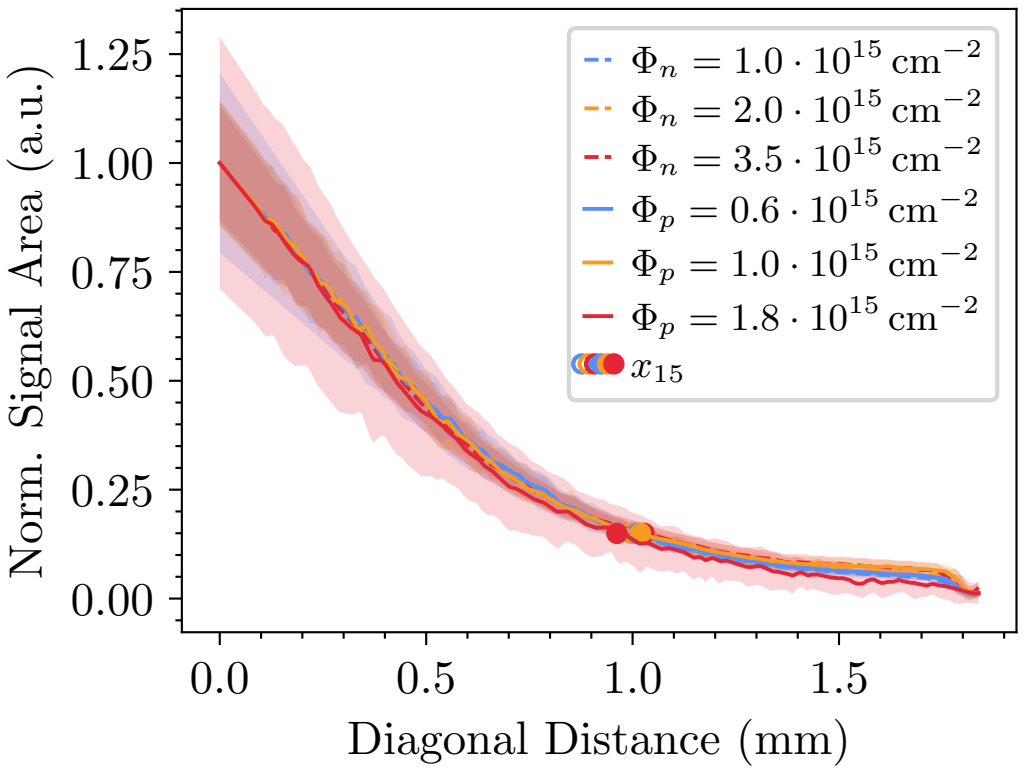


- Reduced internal gain due to irradiation
- x_{15} at similar distance

Signal Spread Results: Normalized

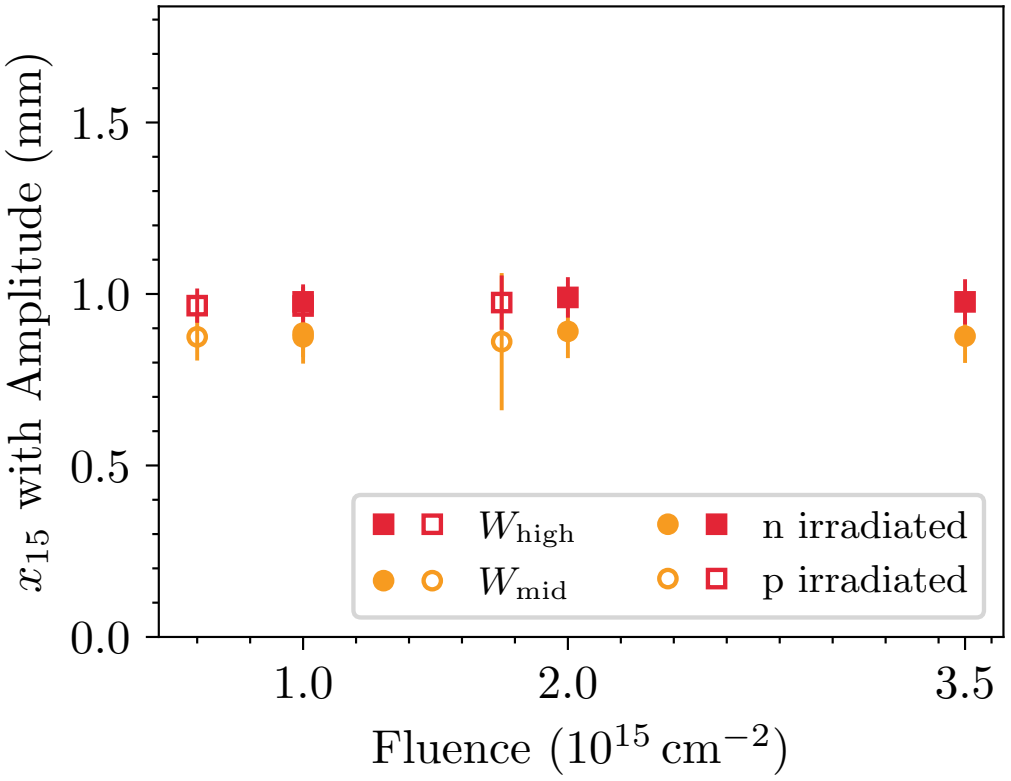
W_{mid} here

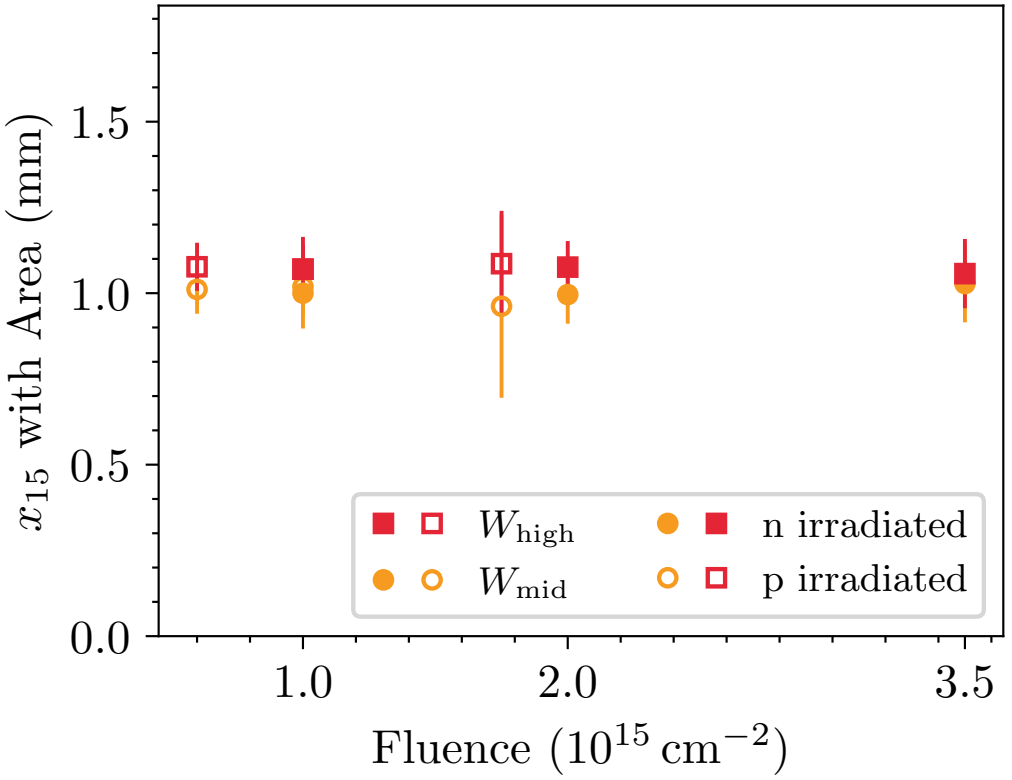




- x_{15} at similar distance
- Curves look identical

Charge Spread Distance





- Signal spreads further for higher doping = lower resistivity
- No change

⇨ **Signal spread not affected by irradiation**