Crosstalk Characterization of a Digital SiPM in 150 nm CMOS Imaging Technology

DESY Summer School Program project, hosted by the DESY ATLAS group

Ono Feyens

Supervised by Finn King and Gianpiero Vignola

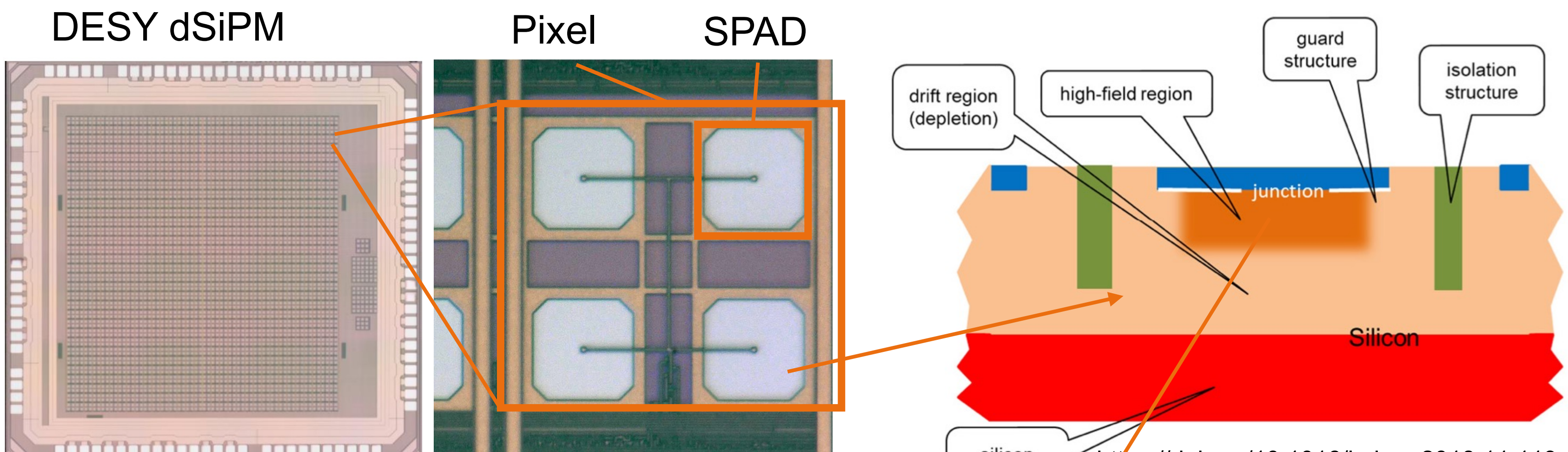
5/09/2024

HELMHOLTZ

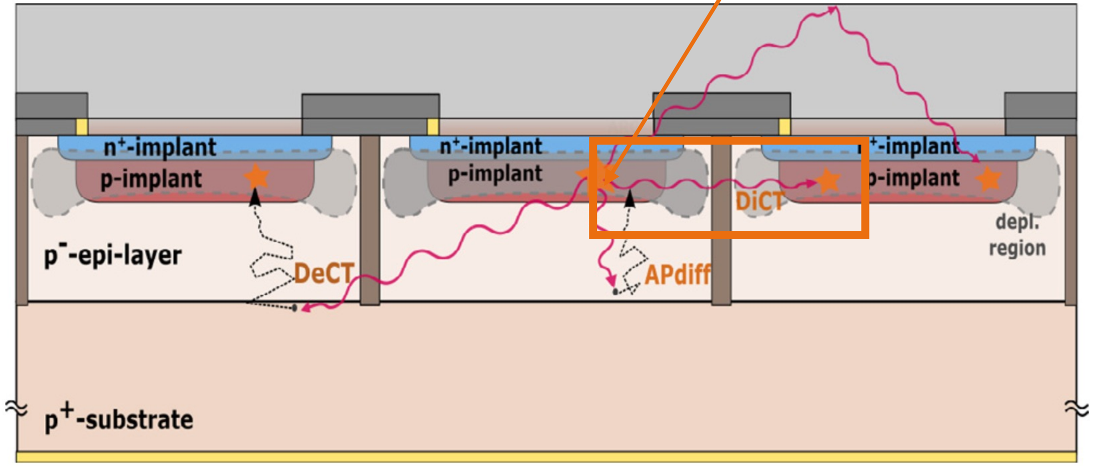
Introduction

dSiPMs and optical crosstalk

- **SiPM** (silicon photomultiplier): solid-state PMT
  - Single-photon sensitivity
  - Timing resolution, compact, insensitive to magnetic field
  - Digital → spatial information
- **Future** HEP experiments (readout scintillating fibers, 4D tracker)
- Pixel → 4 SPADs (single photon avalanche diodes), operated in Geiger-mode → **avalanche multiplication**
- **Secondary photons** created in avalanche process → **optical crosstalk (CT)**



https://doi.org/10.1016/j.nima.2018.11.119

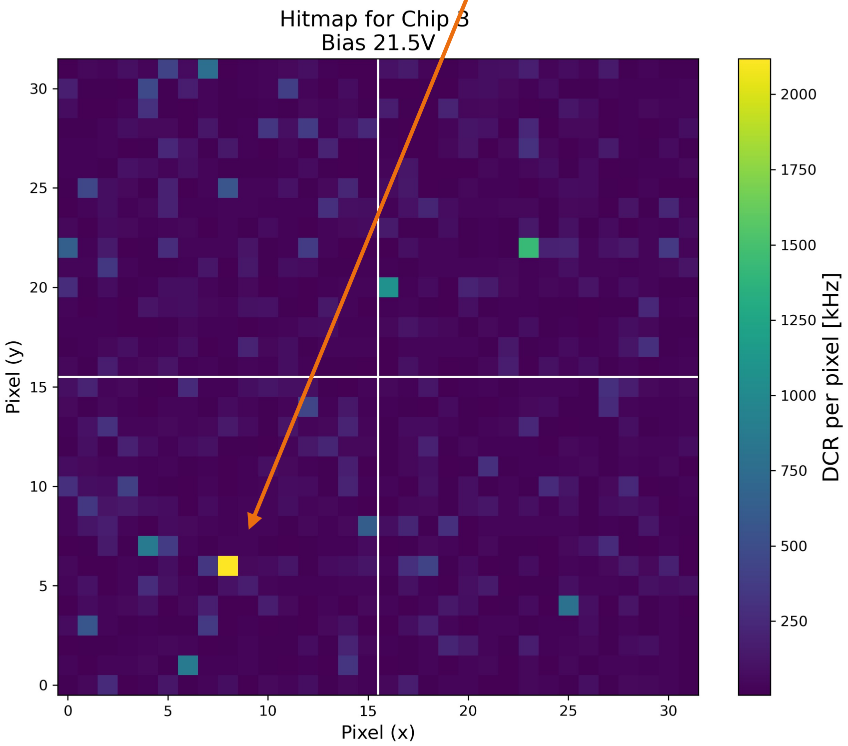


https://doi.org/10.1016/j.nima.2018.11.119

Sensor data

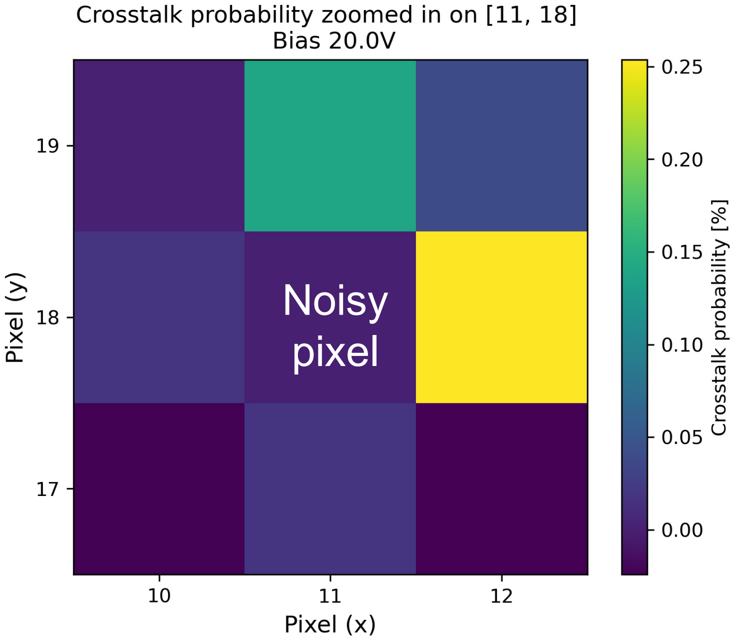
Detection of noisy pixels and determination of the crosstalk probability

- Senor data: in which pixel was a photon detected
- Hitmap in dark conditions → dark count rate (DCR) → detection of **noisy pixels**



- Determination of the **crosstalk probability**

1. Unmask only single pixel
2. Unmask central pixel and 1 neighbor
3. Additional dark count due to crosstalk



Camera data

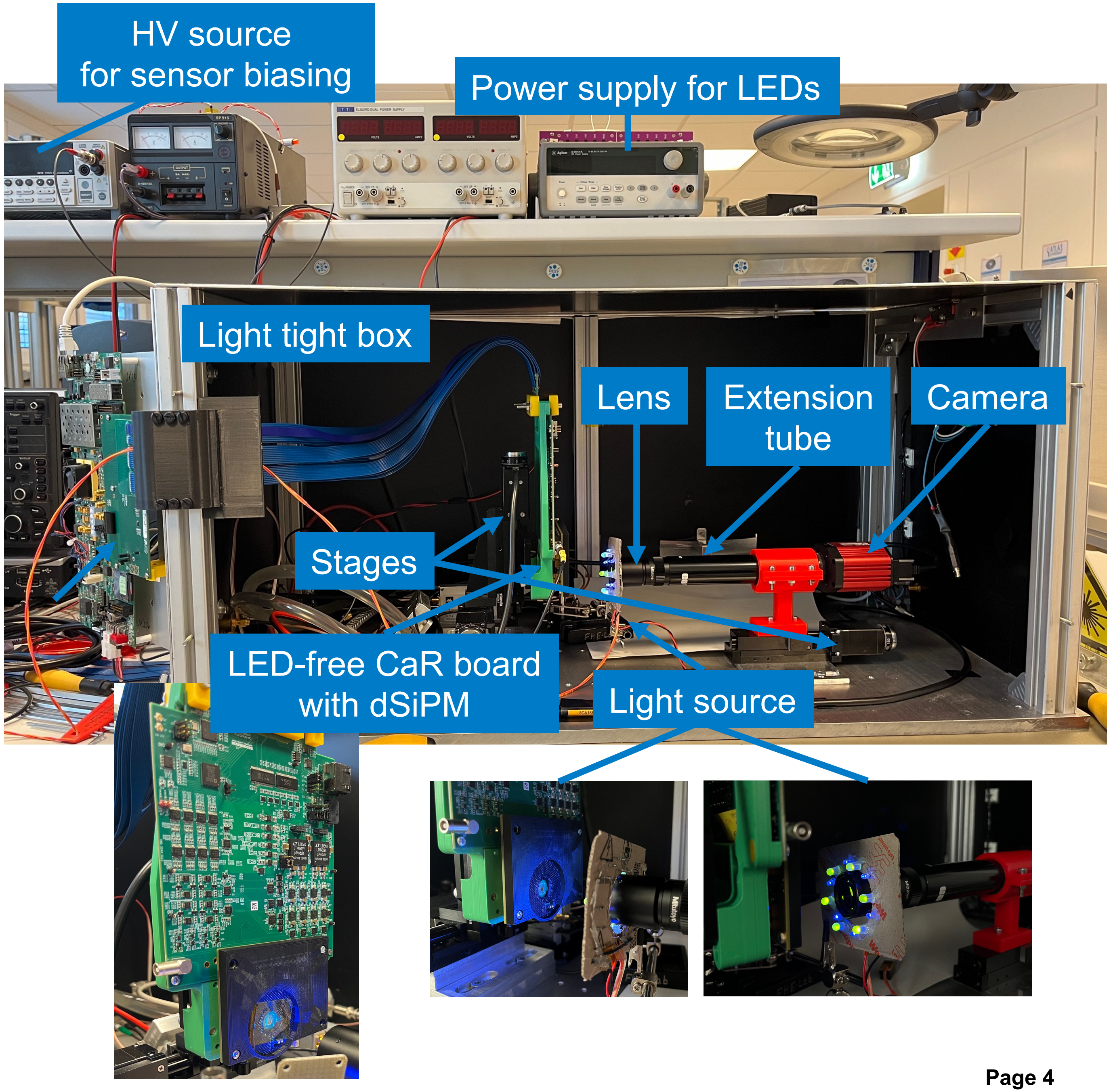
Brightness and location of secondary photons

- **NIR** (near infrared) CMOS **camera** from Thorlabs → longer wavelengths → look deeper

https://www.thorlabs.com/thorproduct.cfm?partnumber=CS135MUN

- What we are looking for:
  - Location source of secondary photons (identify noisy SPAD)
  - Identify defect in SPAD

- Experimental setup

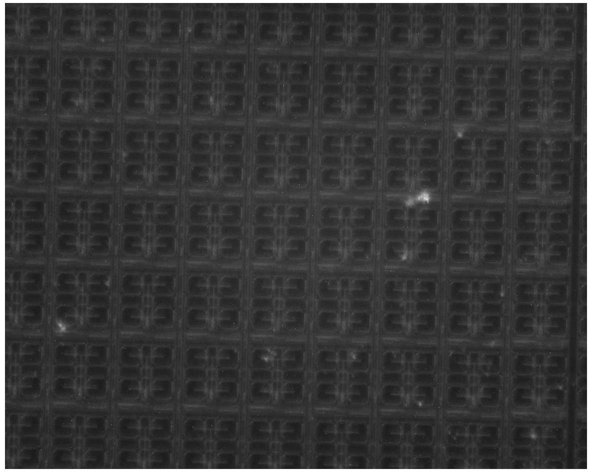


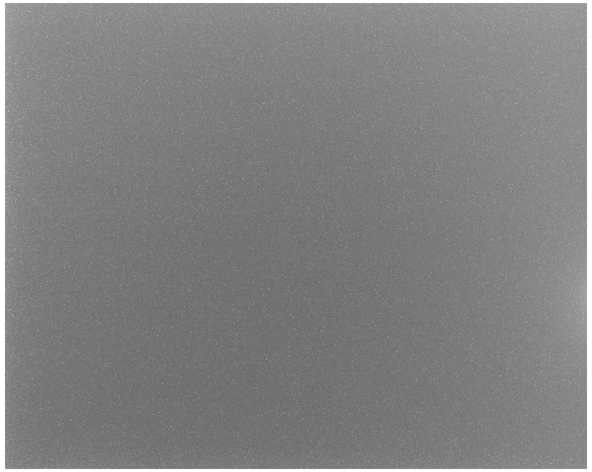
Camera data

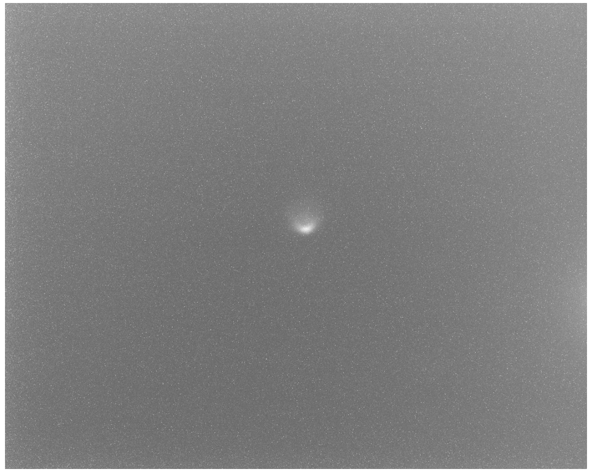
Data taking and processing

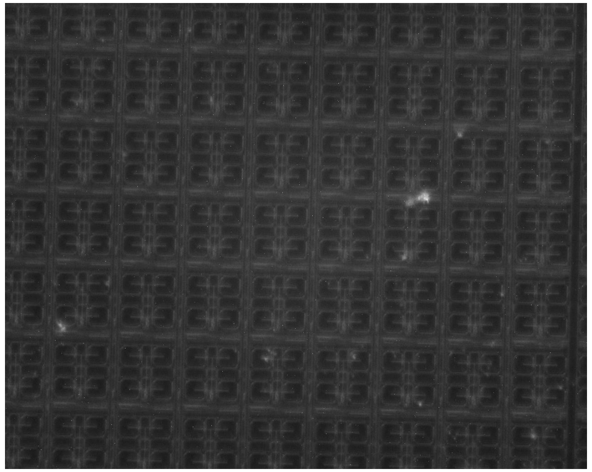
x repetitions, wait 5s in between

REF	DARK	LIGHT	REF
LEDs on, 1500 ms, HV off	LEDs off, 17500 ms, HV off	LEDs off, 17500 ms, HV on	LEDs on, 1500 ms, HV off
To determine location of the emission	Thermal and electronic noise of the camera	Secondary photons	Check for stable setup









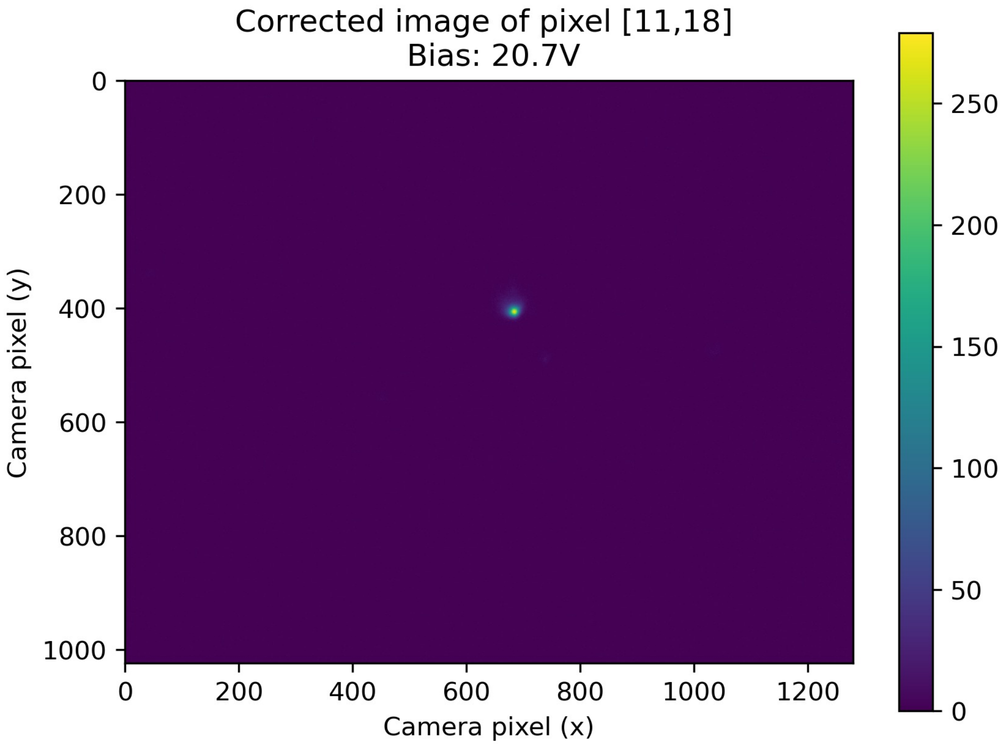
→ Automatized: LabVIEW

→ Remotely controlable: TeamViewer

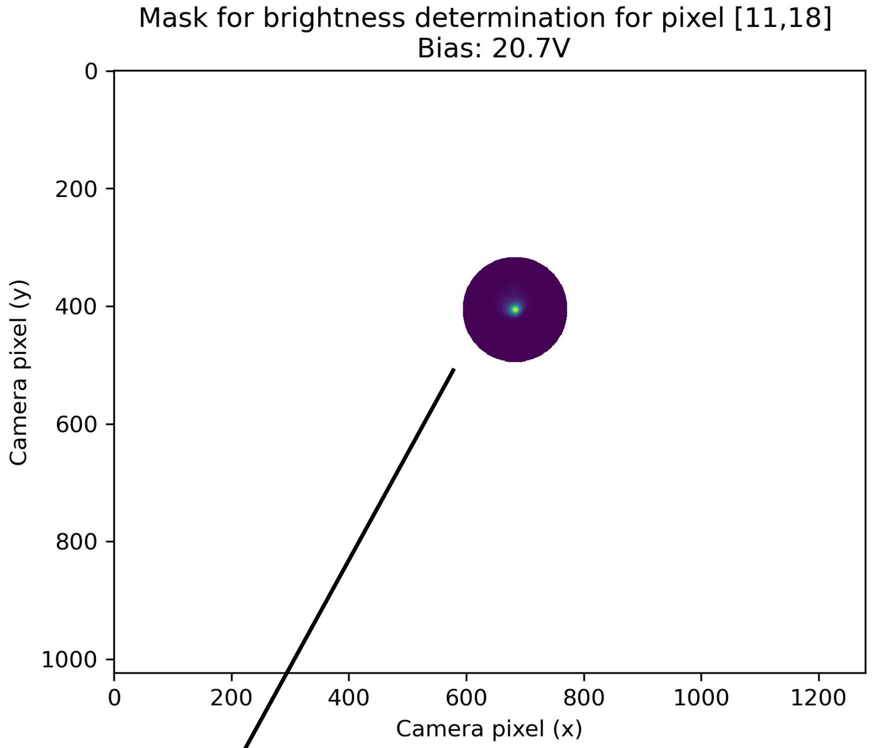
Camera data

Data taking and processing

Corrected image = mean(lights) – mean(darks)



Brightness

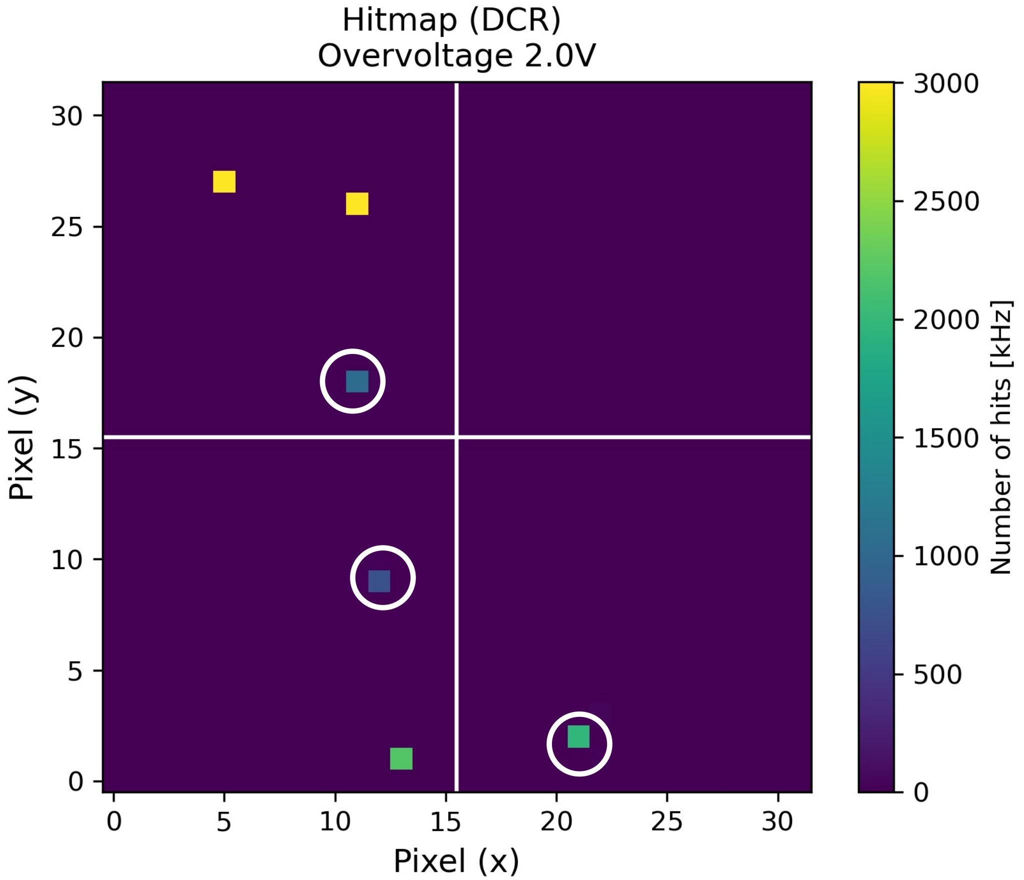


Integrate values in this area
→ brightness value

Results

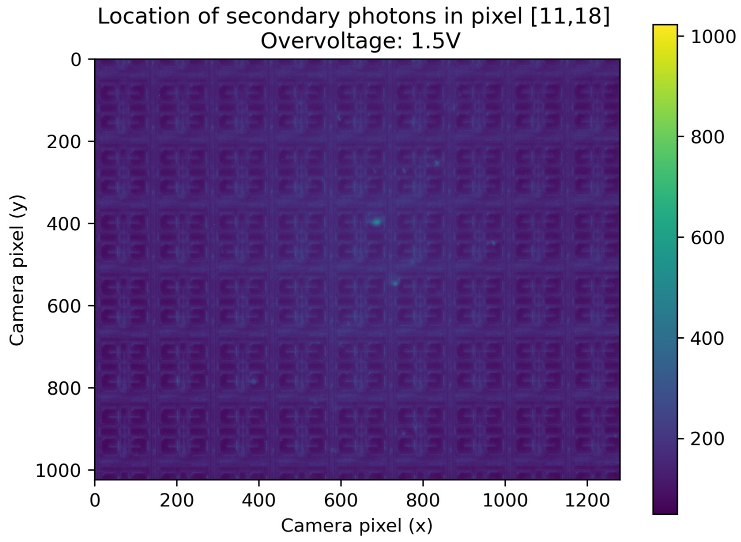
The DUT

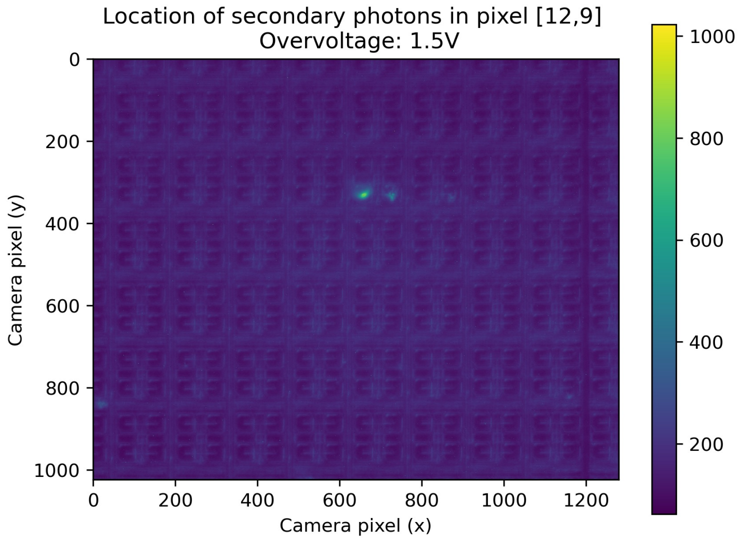
- Chip 1: 6 noisy pixels
  → looked at 3 [11,18], [12,9], [21,2]
- Camera and sensor settings:
  - Exposure time: 17500 ms / 1500 ms
  - Reperitions: 7
  - Delay time: 5 s
  - HV: 20.7 V – 22.2 V in steps of 0.25 V
    → Overvoltage (OV) = bias – breakdown voltage

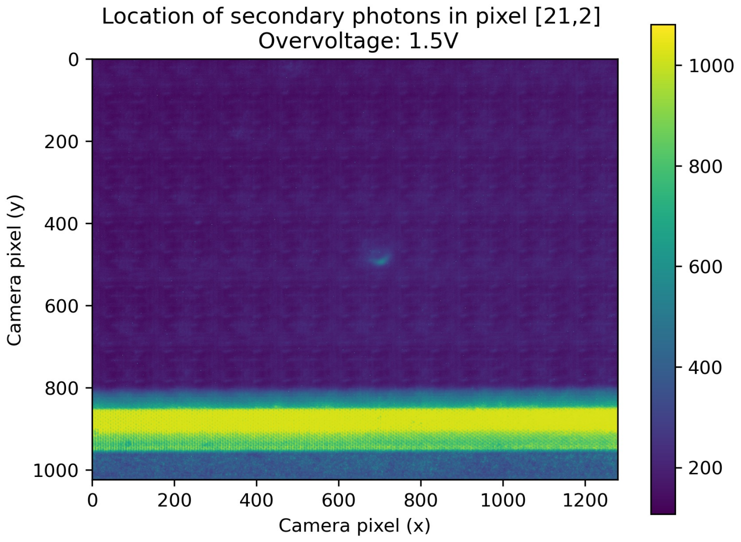


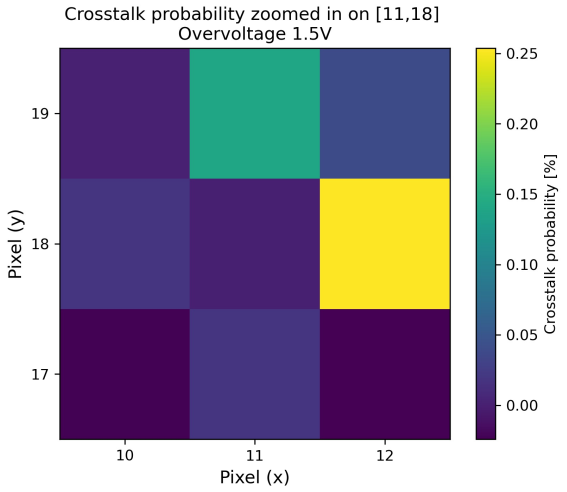
Results

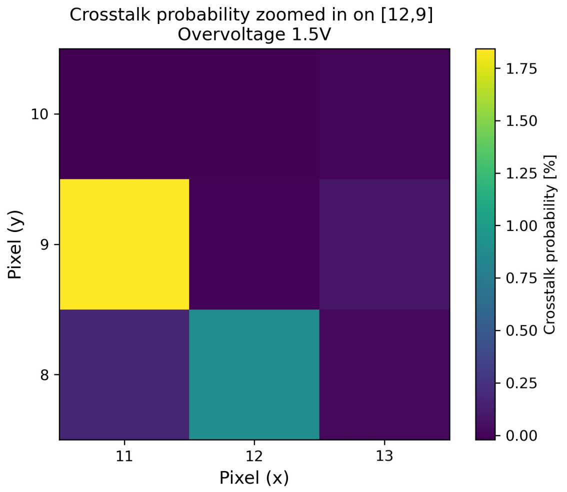
Identifying the noisy SPAD

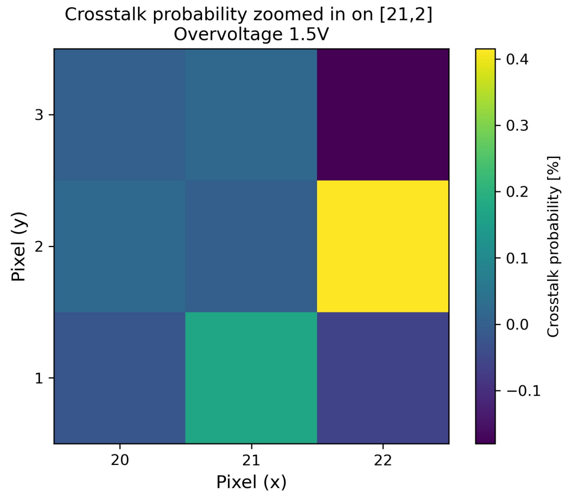






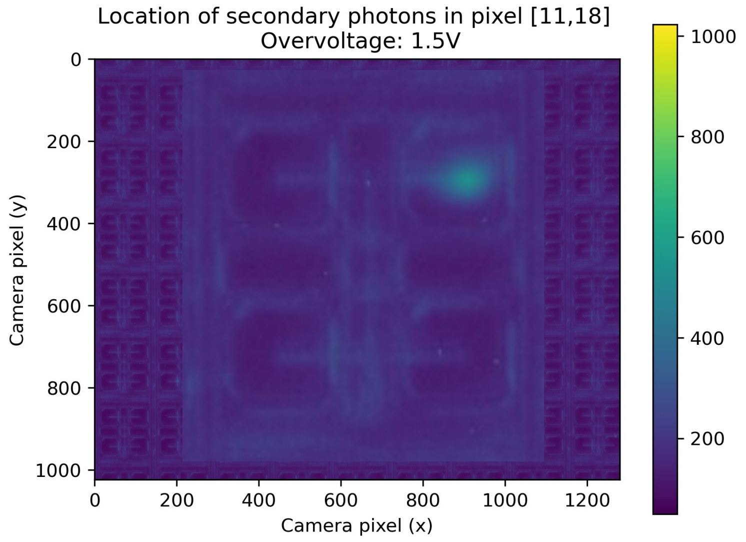


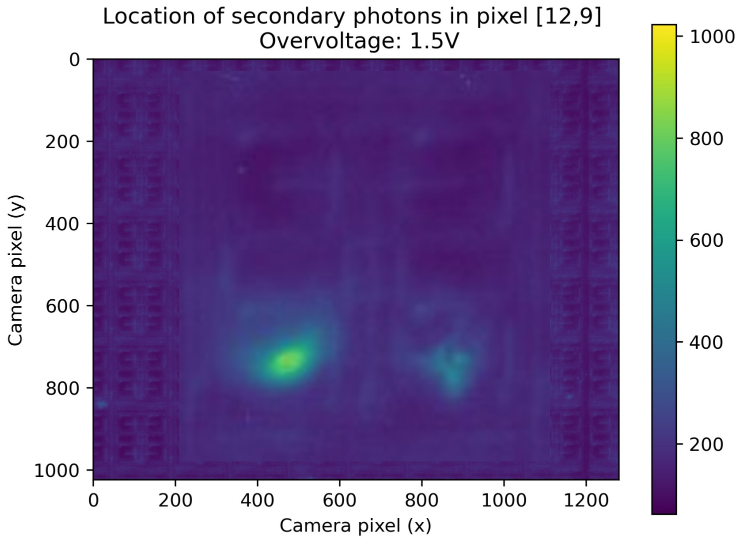


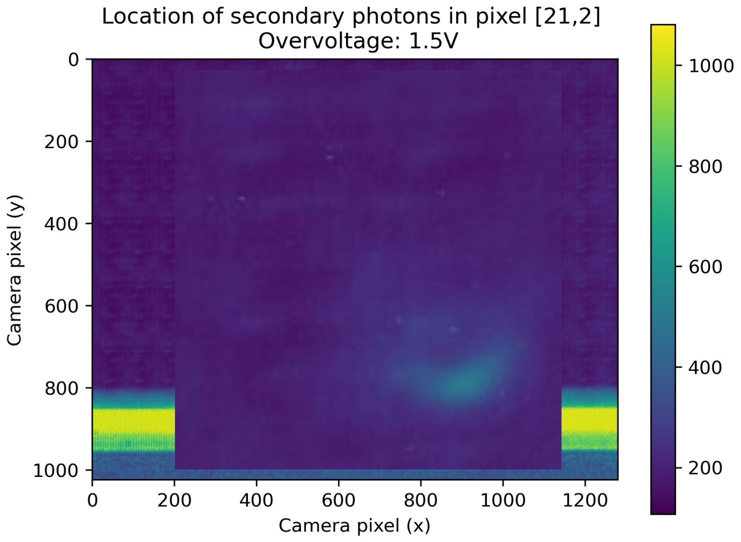


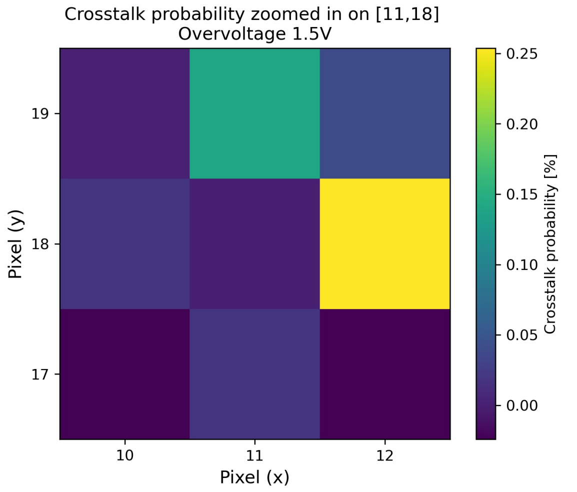
Results

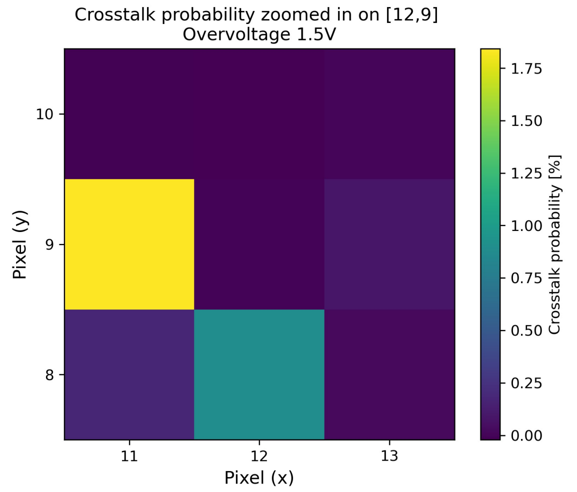
Idefining the noisy SPAD

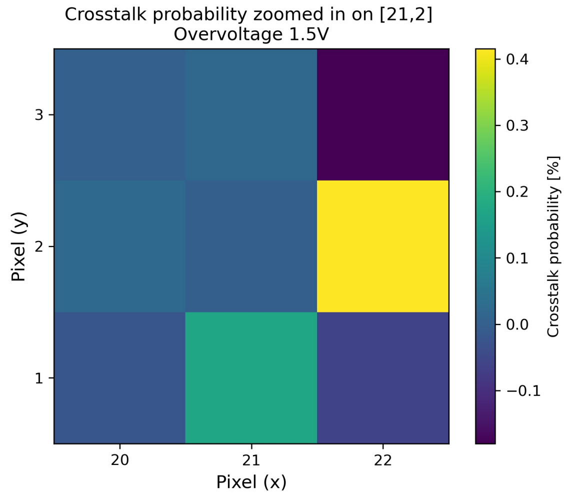






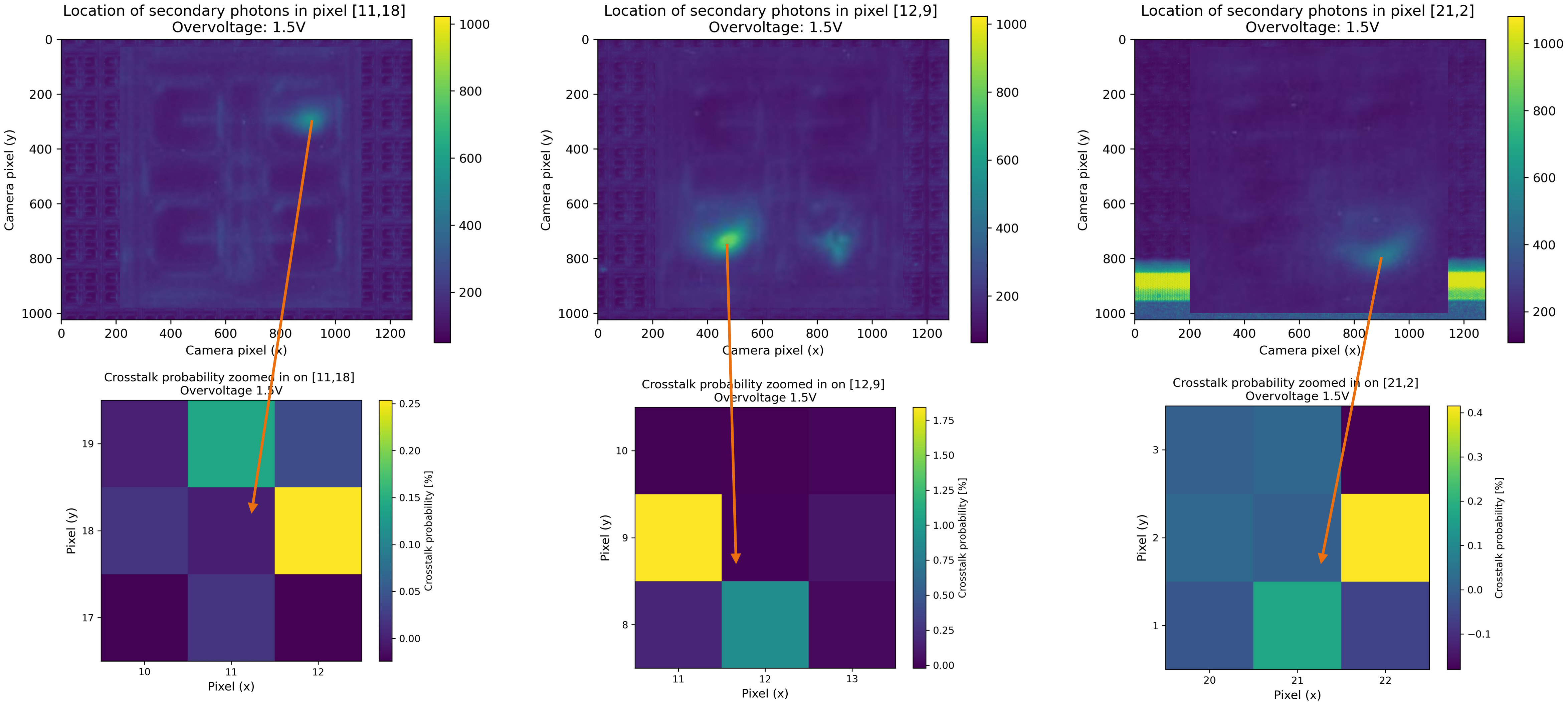






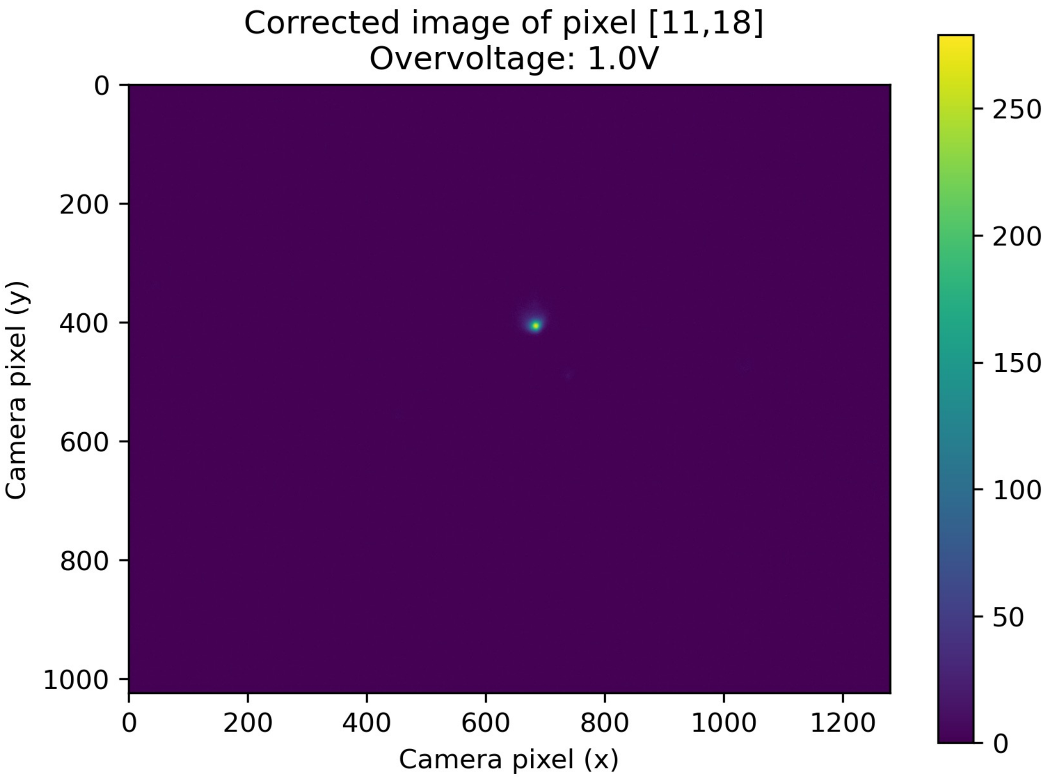
Results

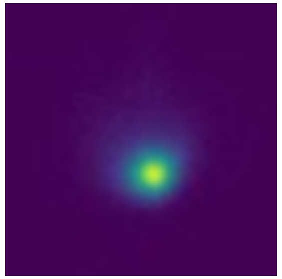
Idefining the noisy SPAD



Results

Shape of secondary photons → location of defect within the SPAD

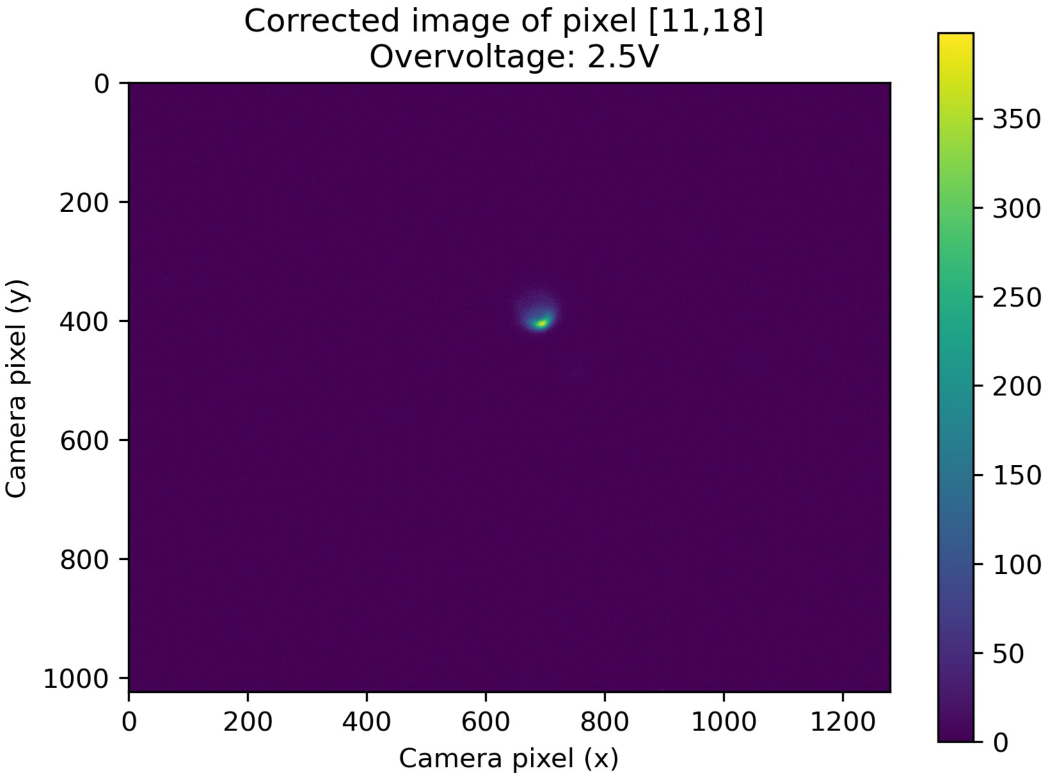


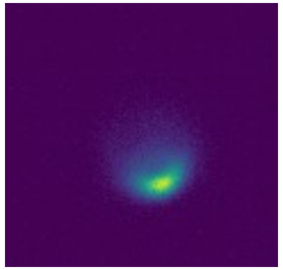


Sort of a droplet shape, but seen in all measurements
→ probaby **just a camera effect**

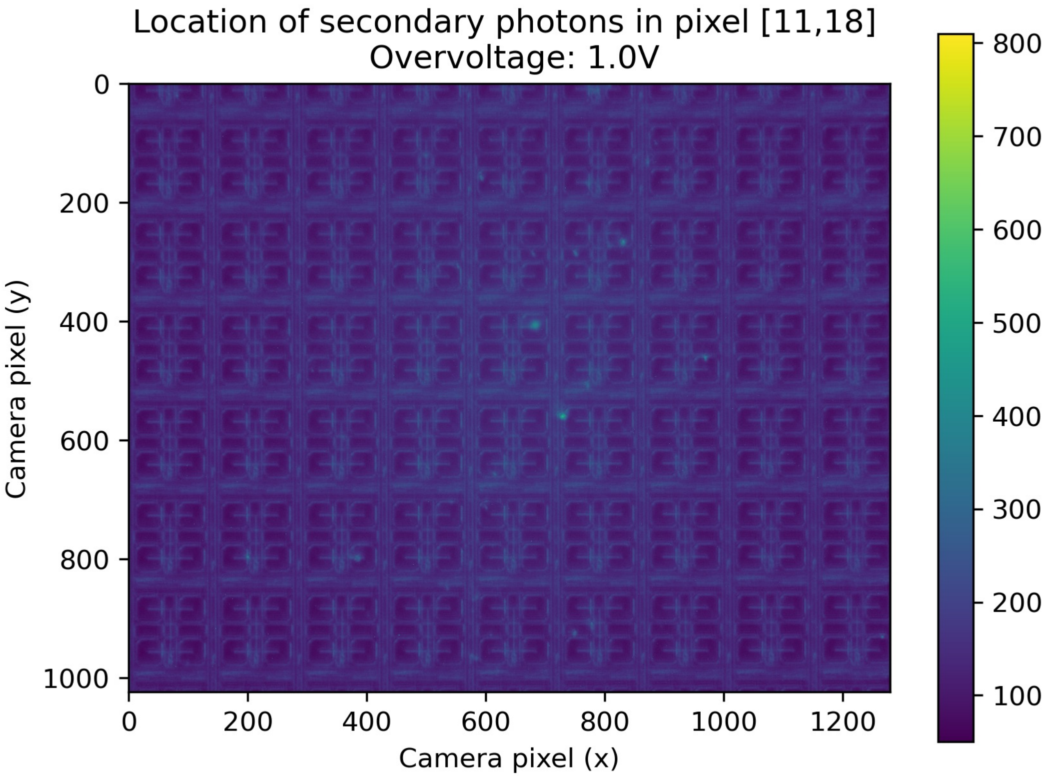
Results

Shape of secondary photons → location of defect within the SPAD





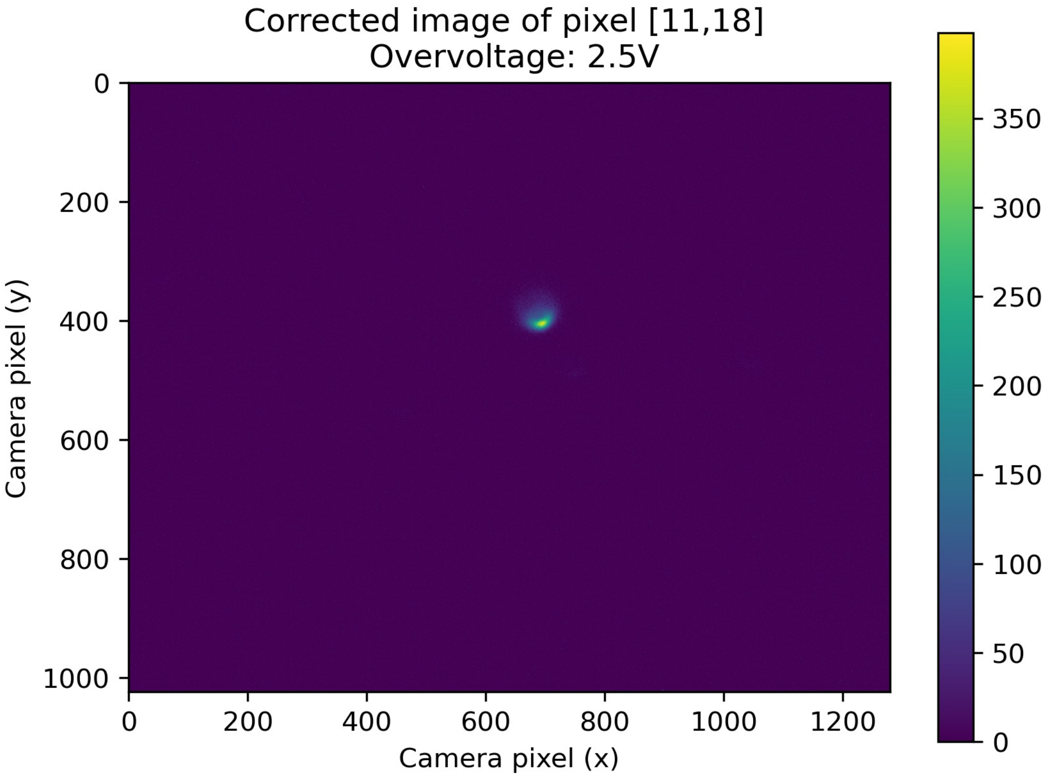
U-shape, often seen at higher overvoltages, after a lot of measurements

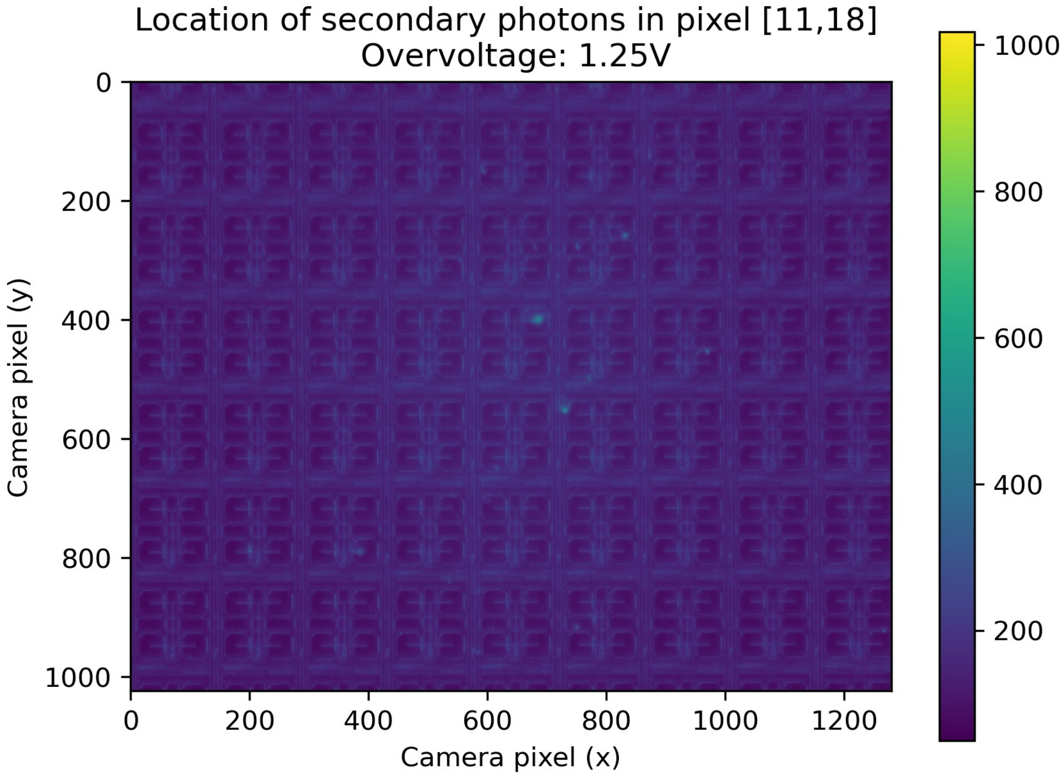


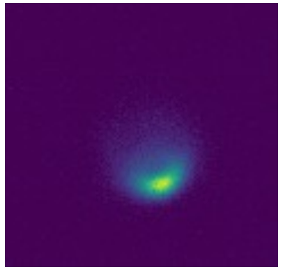
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





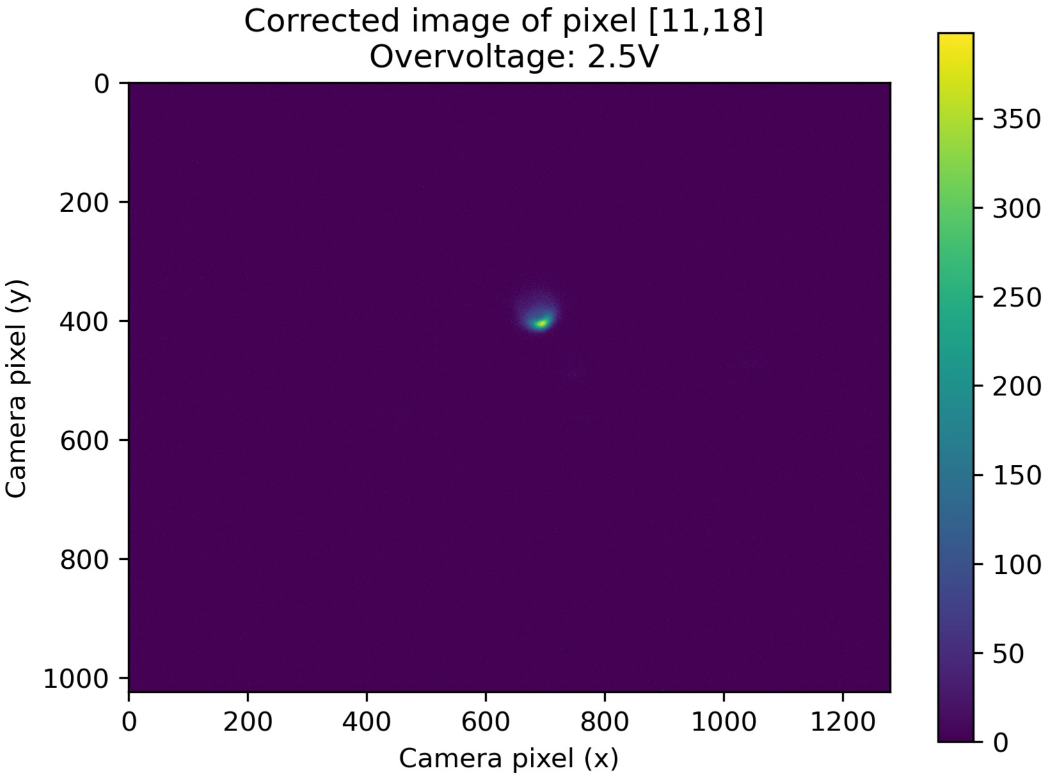


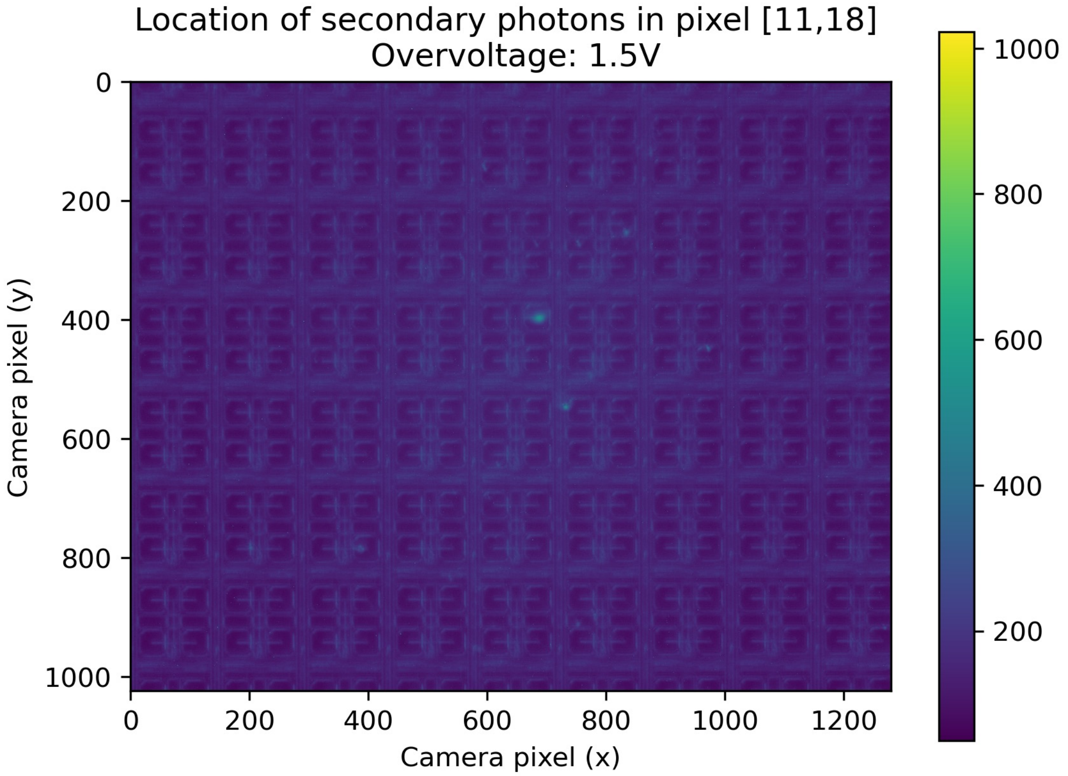
U-shape, often seen at higher overvoltages, after a lot of measurements

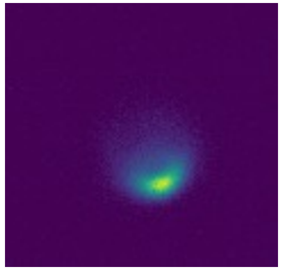
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





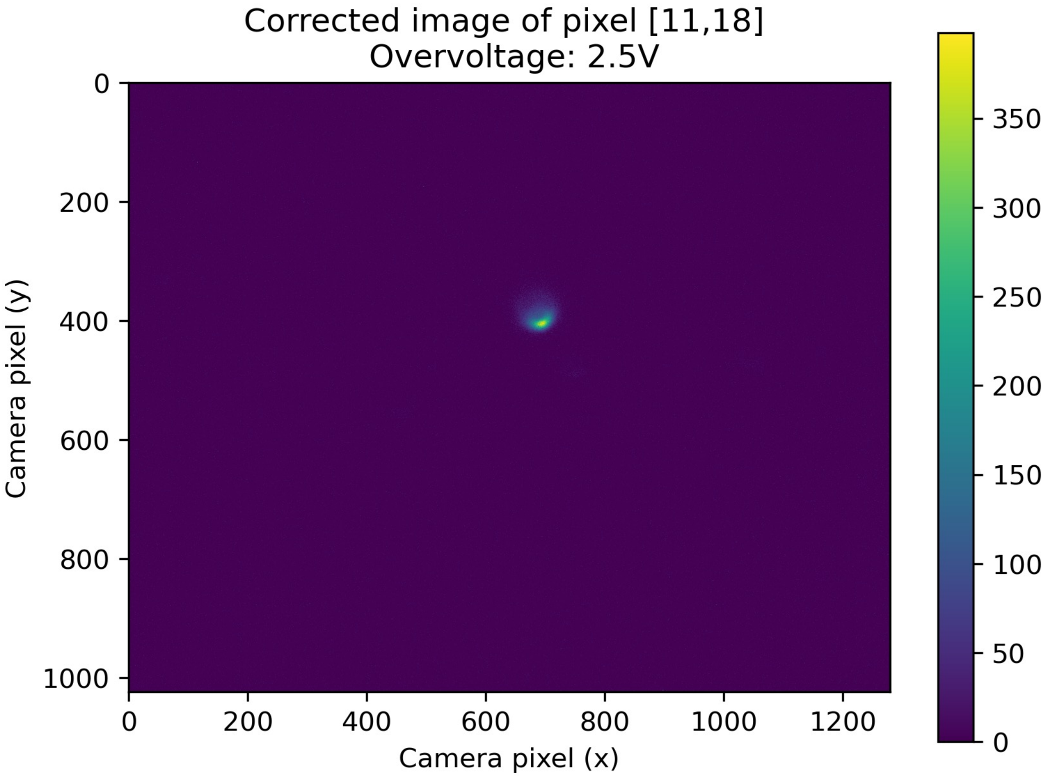


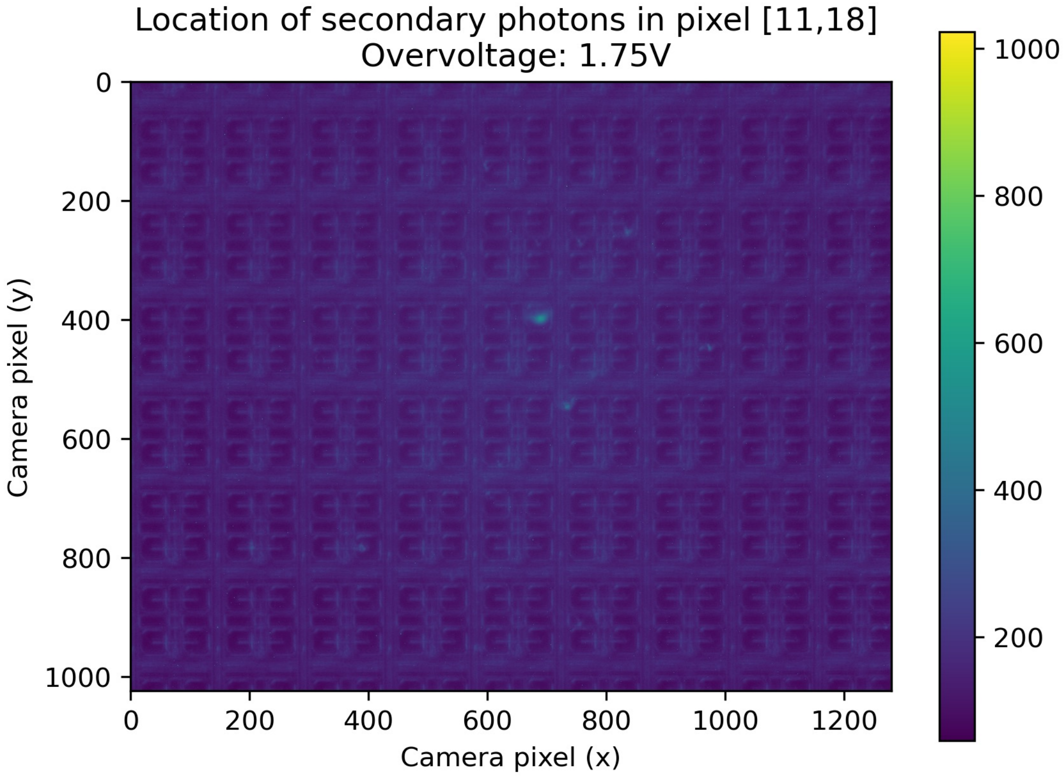
U-shape, often seen at higher overvoltages, after a lot of measurements

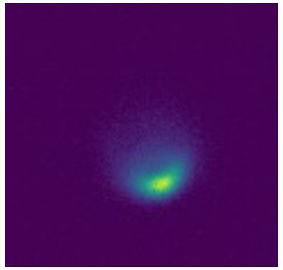
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





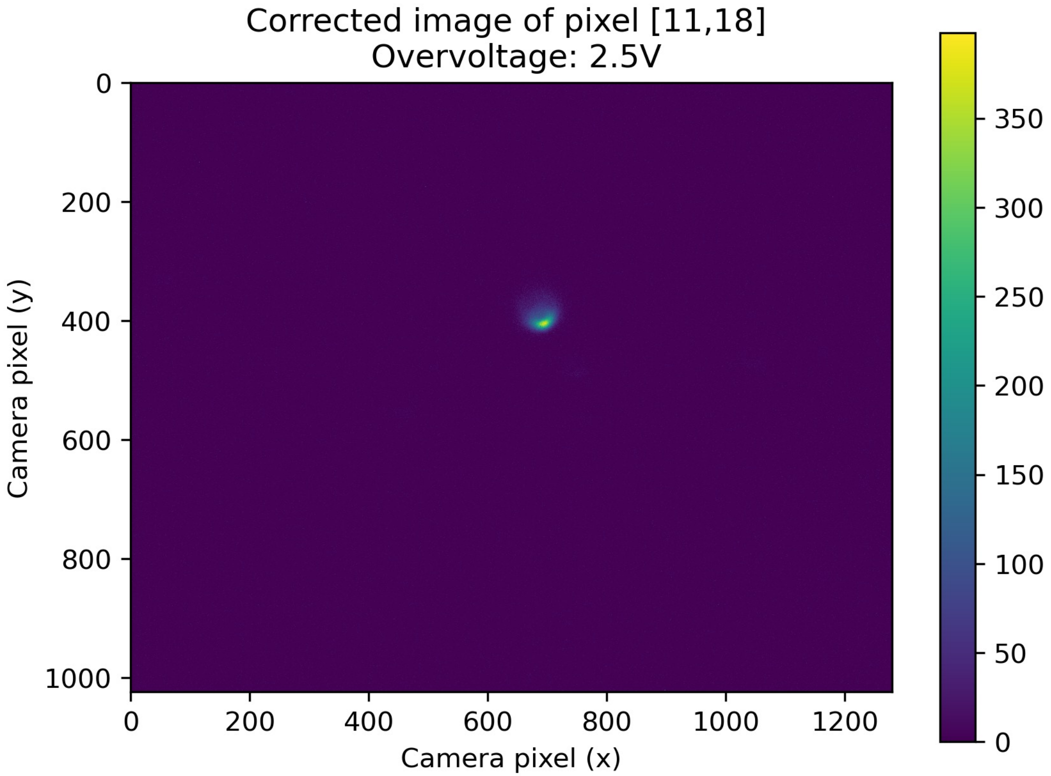


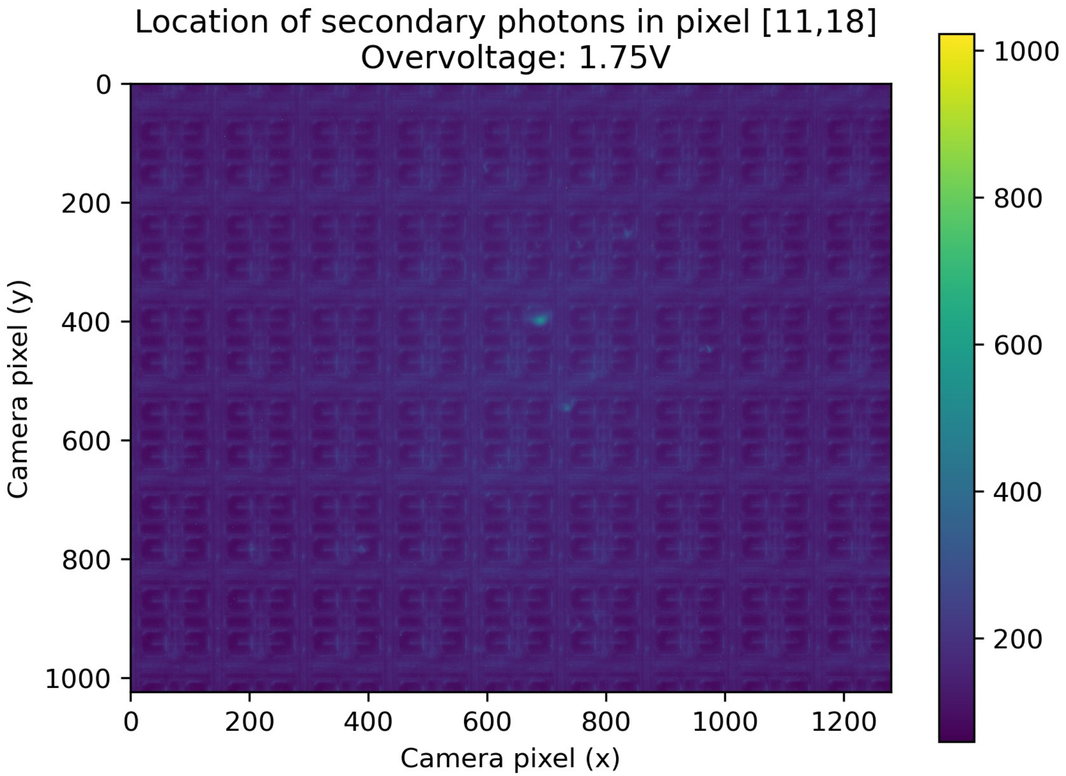
U-shape, often seen at higher overvoltages, after a lot of measurements

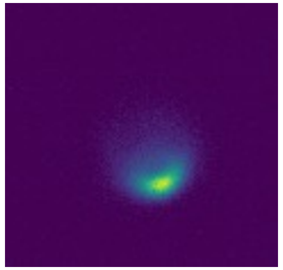
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





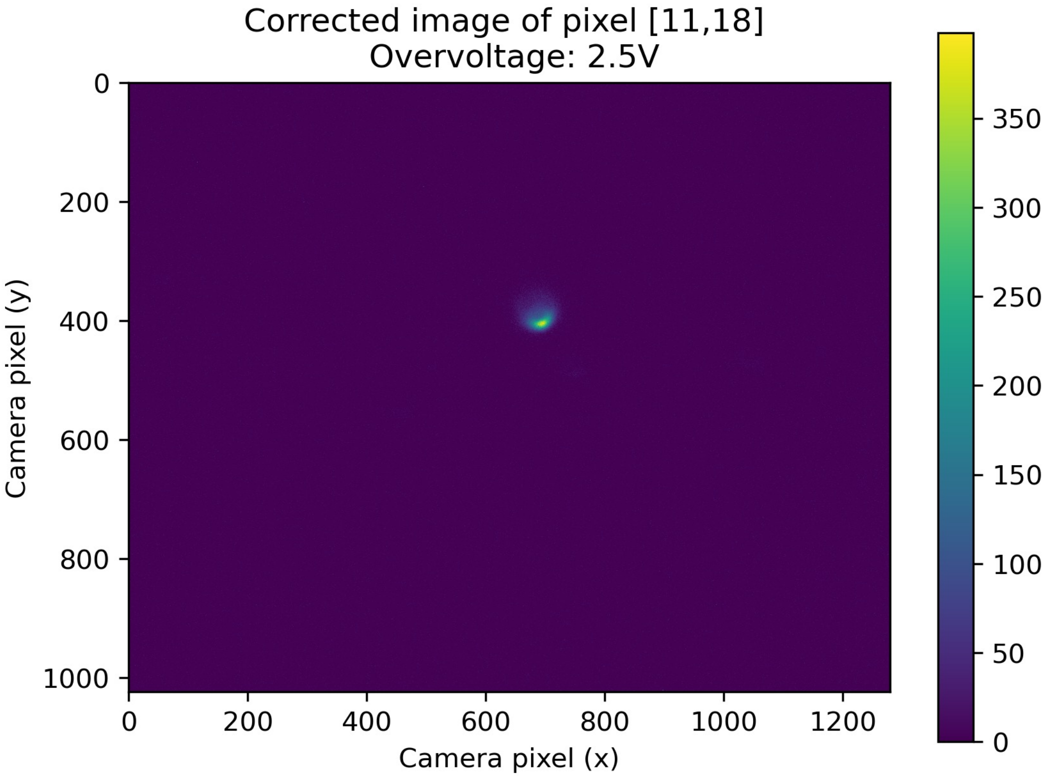


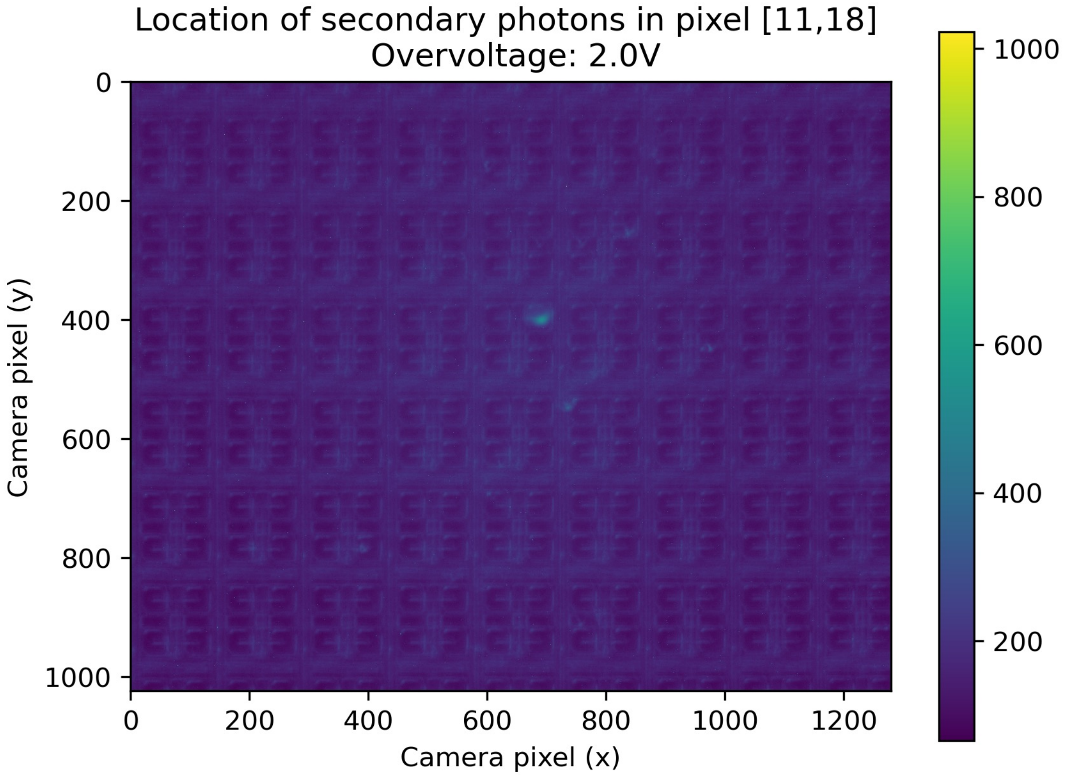
U-shape, often seen at higher overvoltages, after a lot of measurements

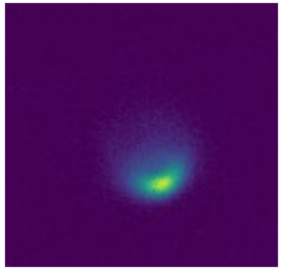
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





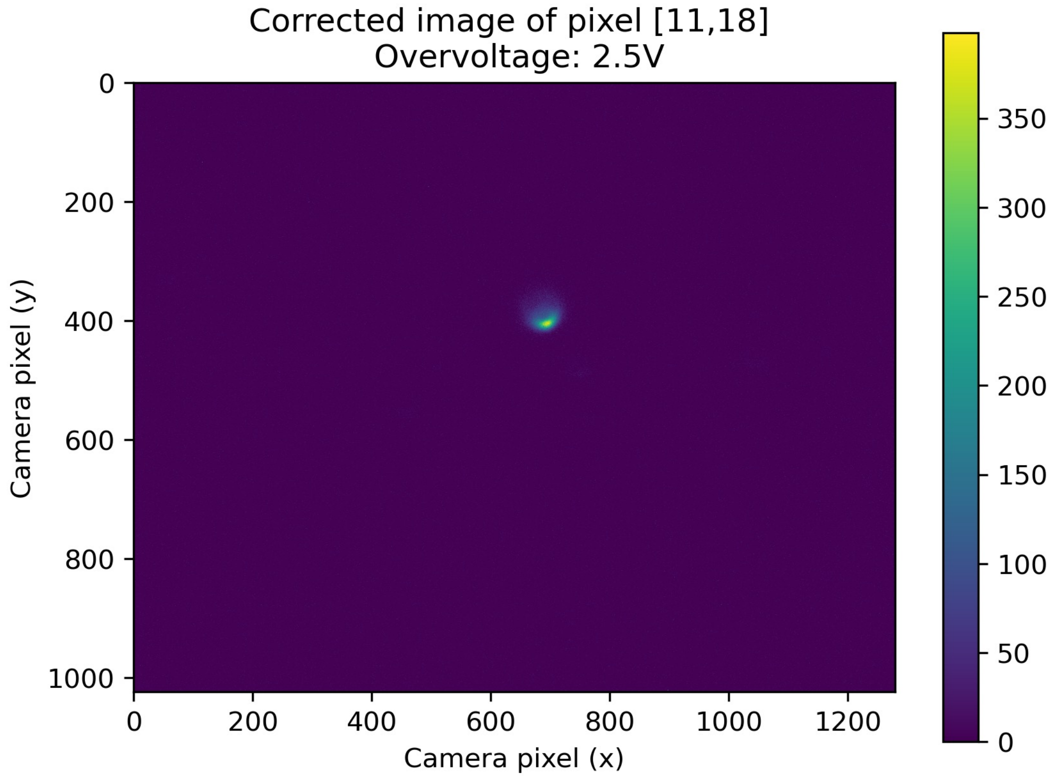


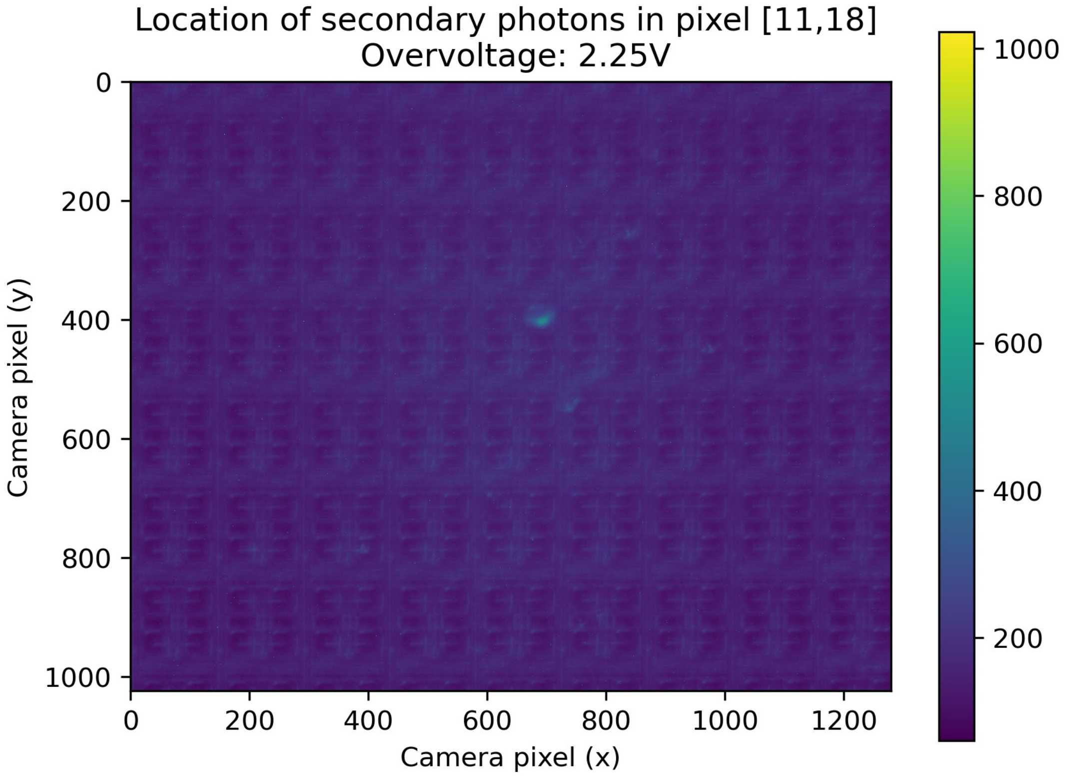
U-shape, often seen at higher overvoltages, after a lot of measurements

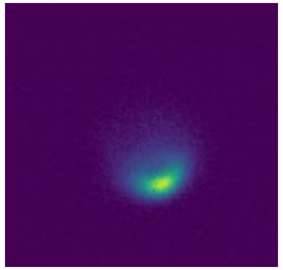
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





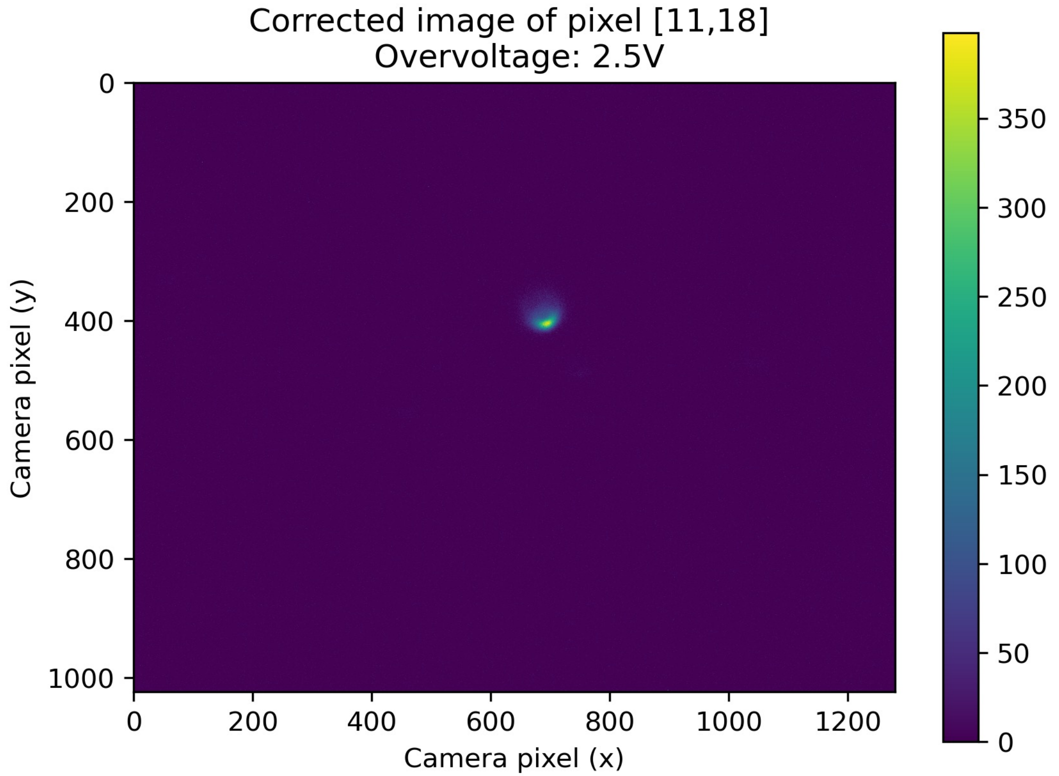


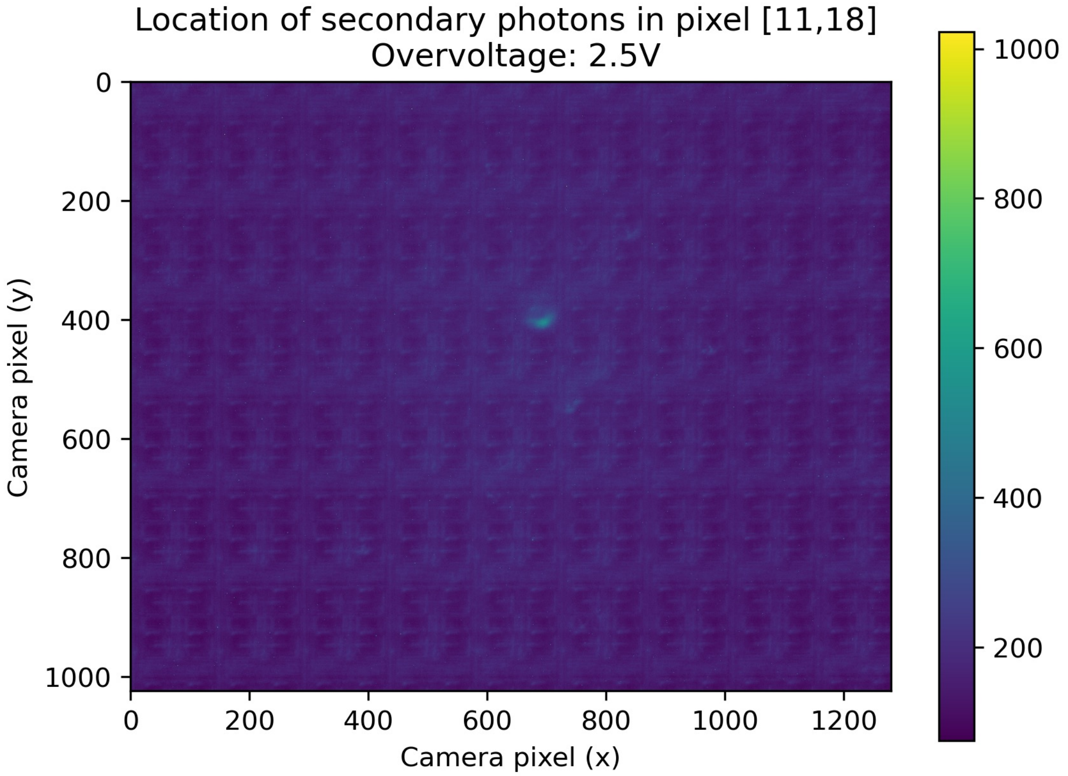
U-shape, often seen at higher overvoltages, after a lot of measurements

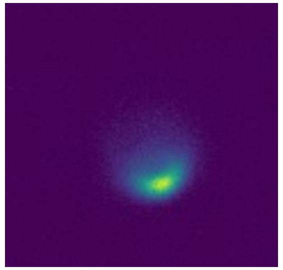
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

Shape of secondary photons → location of defect within the SPAD





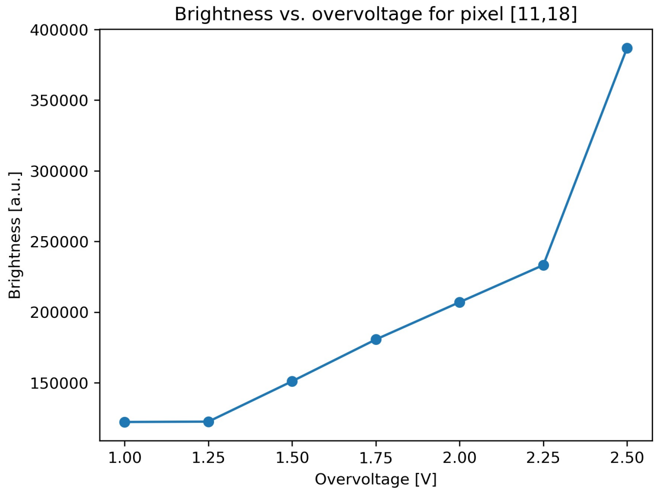


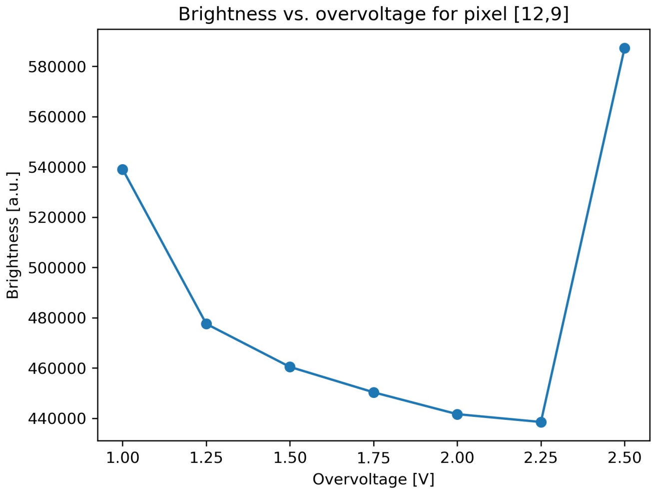
U-shape, often seen at higher overvoltages, after a lot of measurements

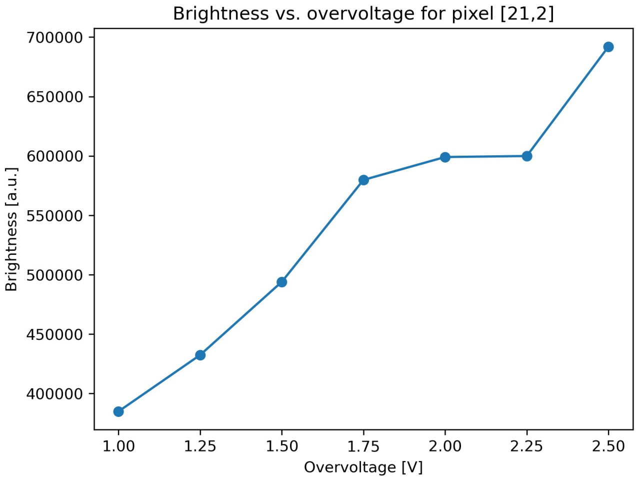
Not only does the emission shape changes, also the refence image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extention of materials

Results

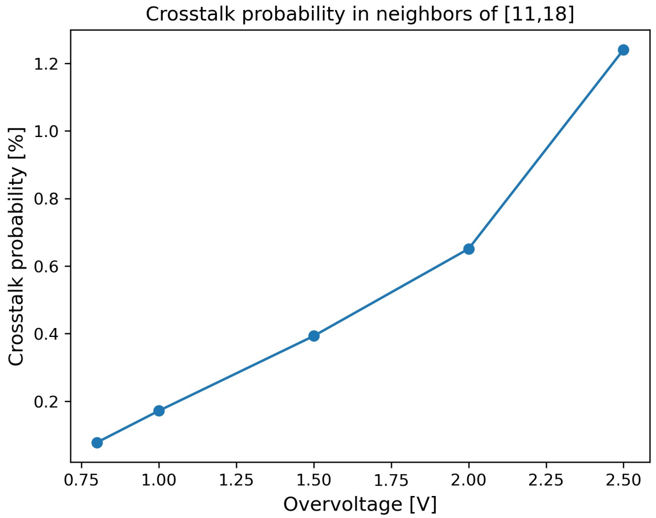
Quantitative data

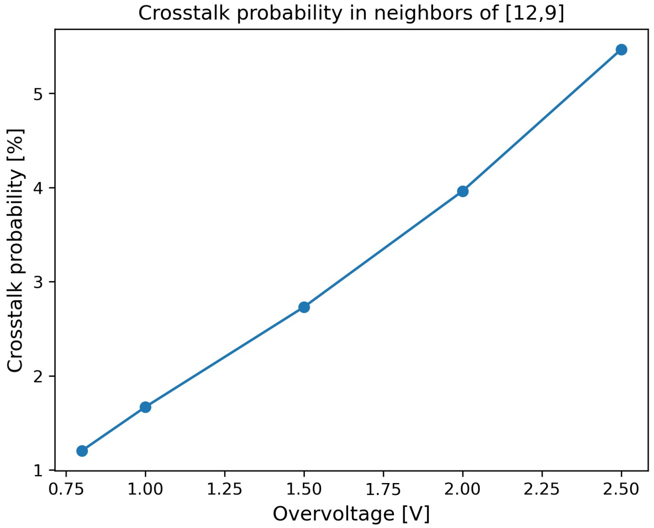


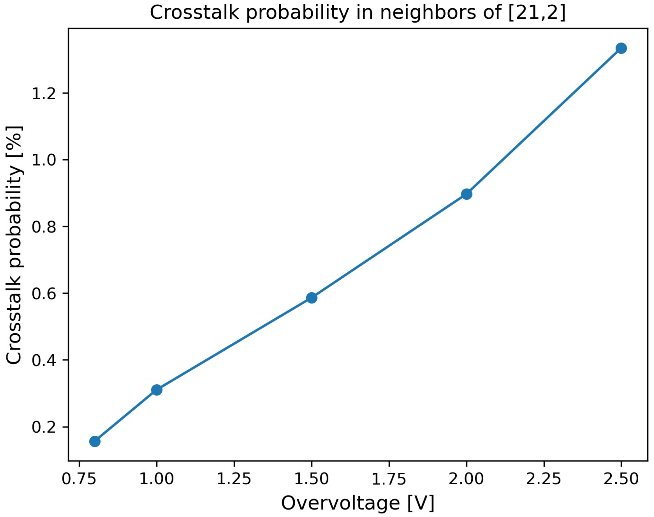




[11,18], [21,2]: Quantitative data confirms correlation between brightness (amount of secondary photons) and CT

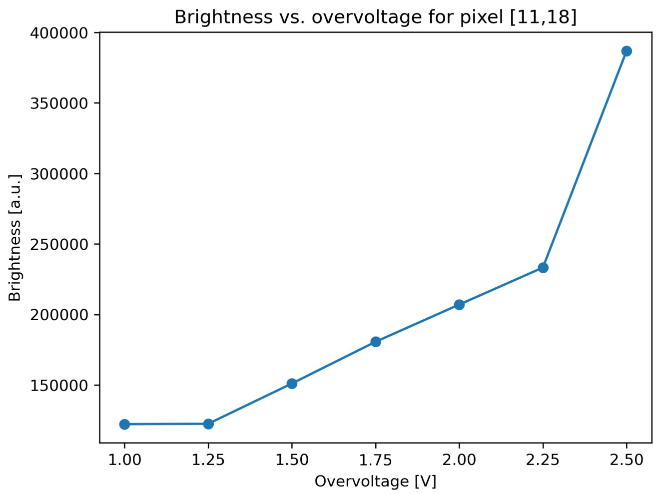


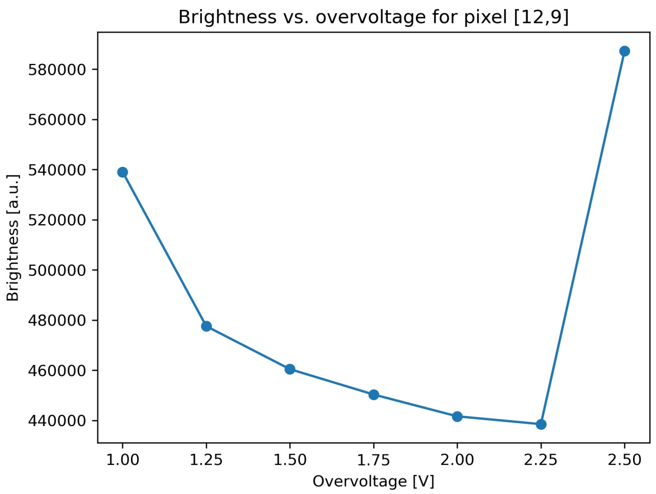


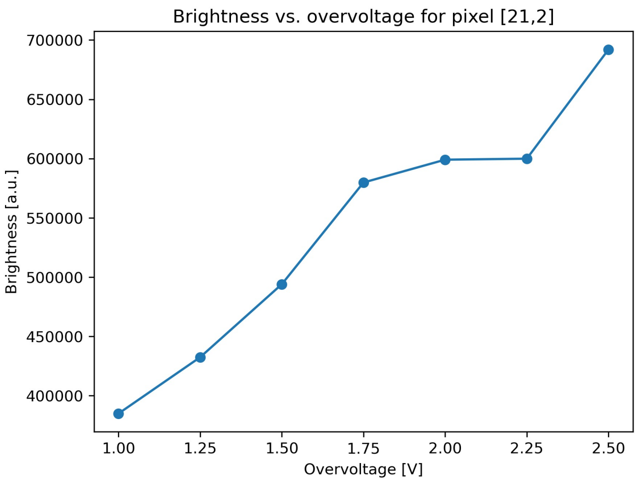


Results

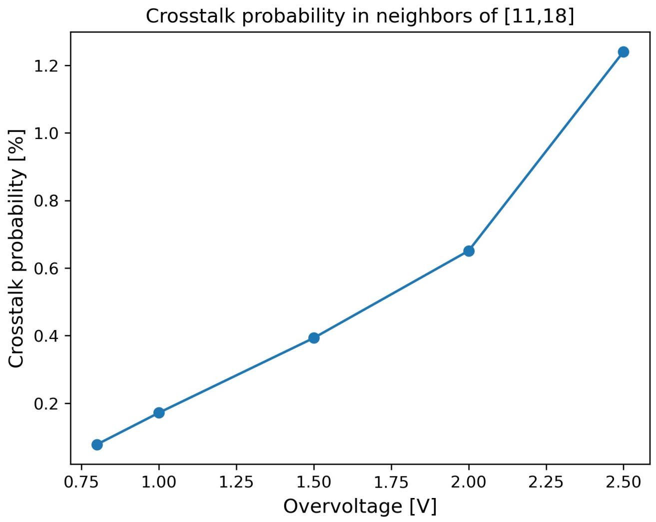
Quantitative data

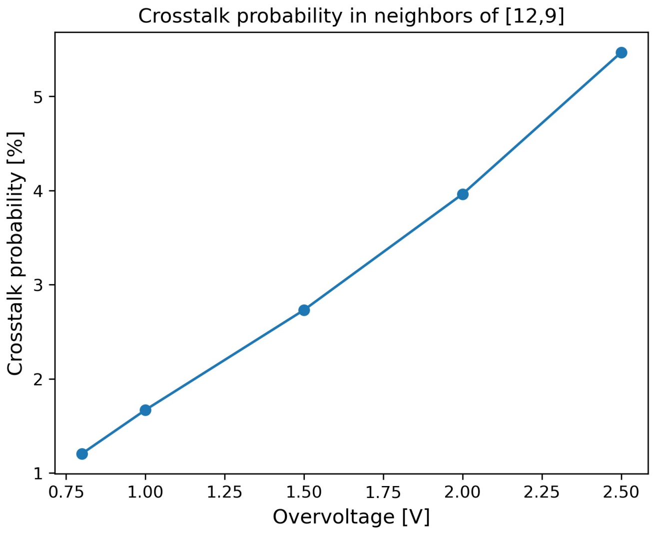


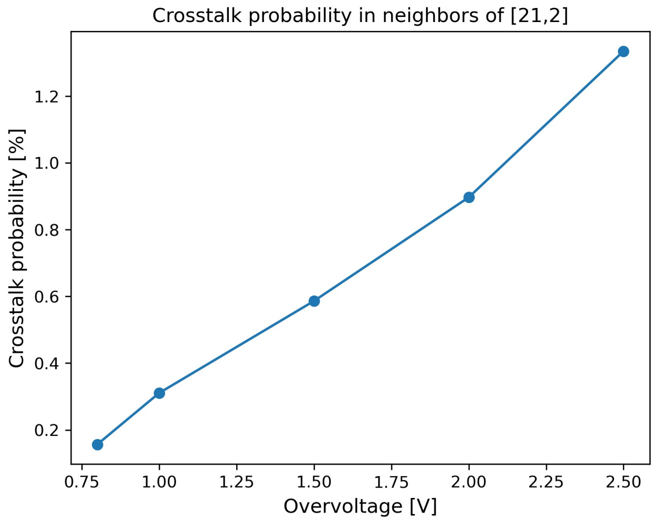




[12,9]: Decrease in brightness due to overcorrection → SPAD is too noisy, delay time should be increased



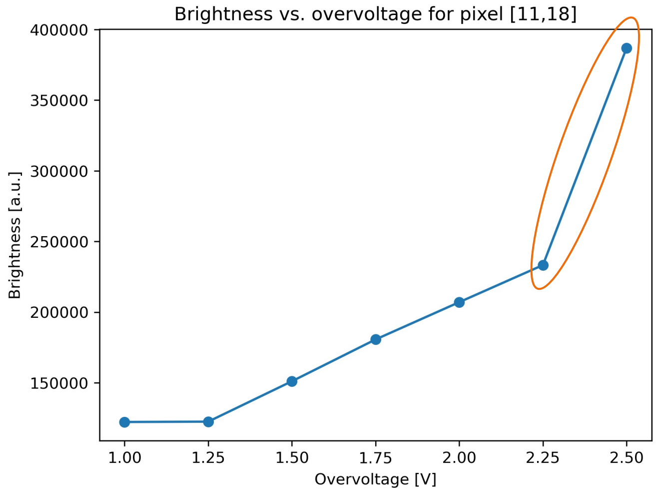


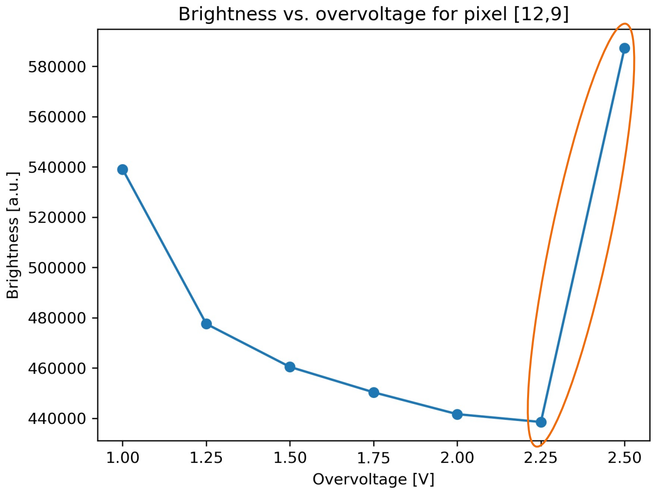


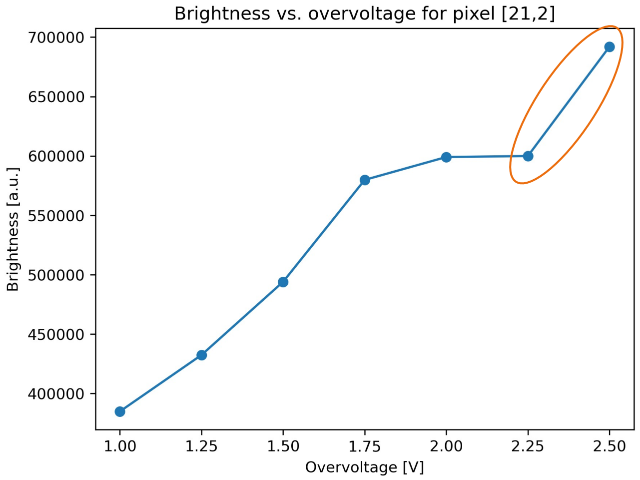
CT also only qualitatively correct

Results

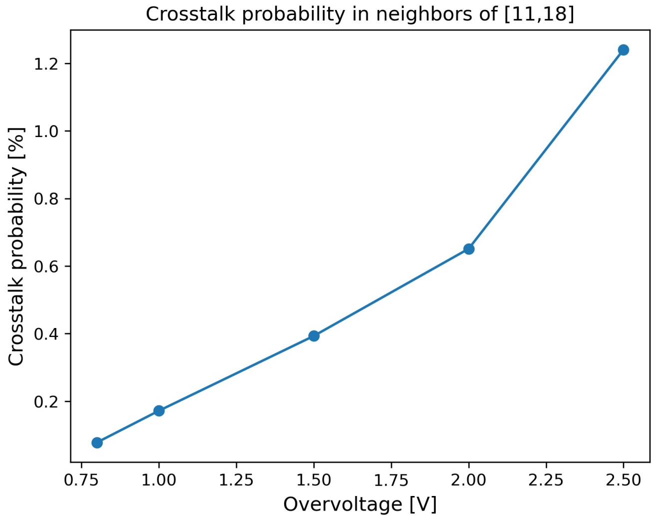
Quantitative data

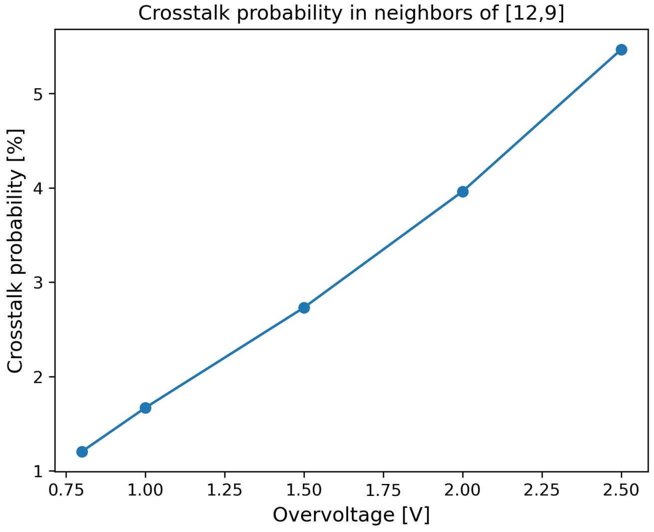


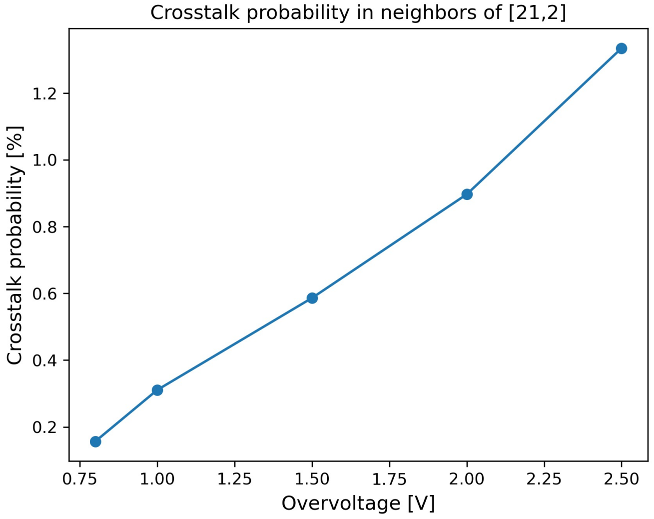




Sudden increase in brightness at higher OV → no explanation yet, should ckeck what is going on at even higher OVs







Conclusion and outlook

- The new NIR camera is well suited to detect the secondary photons
- We can determine the noisy SPAD in the pixel by looking at the CT probabilities to neighbors
- Quantitative data confirms correlatoin between brightness and CT

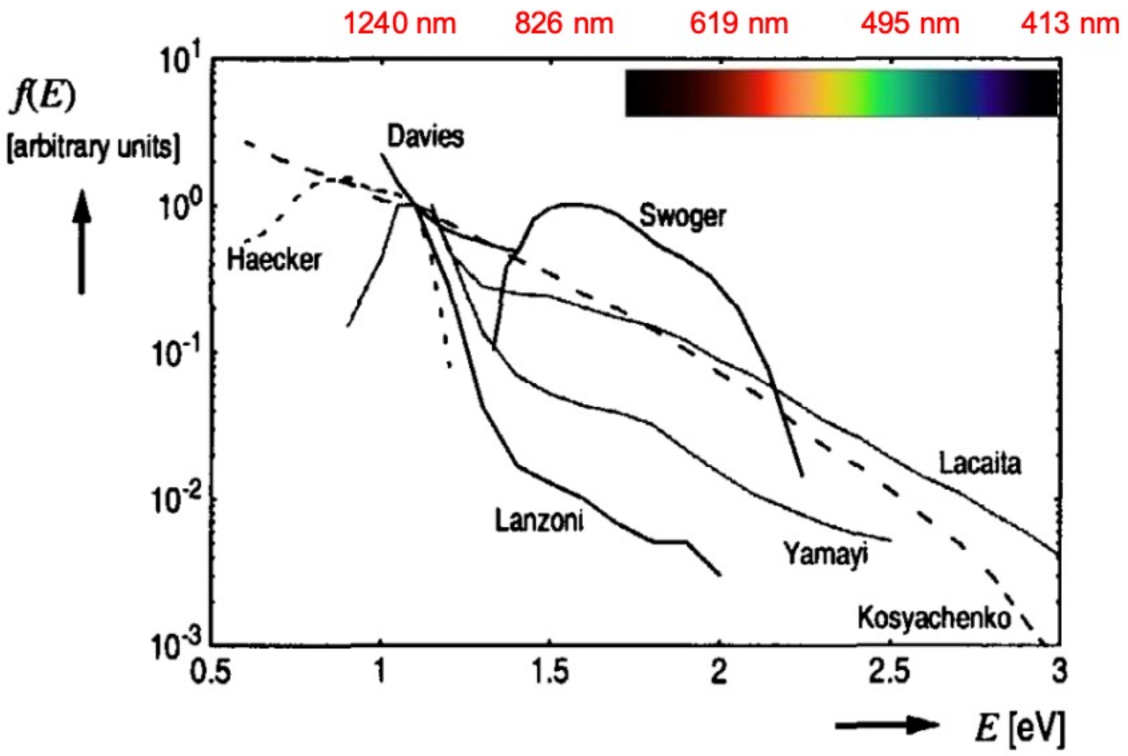
- A lot of systematics, not yet all under control (heating → lose focus?)
- Have to watch out for very noisy SPADs (both in CT calculation and emission measurements)
- What is going on at high OVs?

- What happens at even higher OVs?
- Investigate systematics
- Investigate characteristics of the camera

Thank you! Questions?

Back-up slides

Secondary photon emission in avalanche process



@ Gianpiero for conversion into wavelengths

https://repository.tudelft.nl/file/File_1833dbea-790d-4846-aeff-41b19ad2dd69?preview=1 W.J Kindt PhD thesis: Geiger Mode Avalanche Photodiode Arrays

Definition of the crosstalk probability

$$p_c = \frac{N_c}{N},$$

$$p_n = \frac{N_n}{N}.$$

$$p_{c\wedge n} = \frac{N_{c\wedge n}}{N}$$

$$p_x = \frac{p_{c\wedge n} - p_c p_n}{p_c(1 - p_n)};$$

The NIR camera

CS135MUN - Kiralux 1.3 MP NIR-Enhanced CMOS Camera, USB 3.0 Interface

Zoom

Part Number: CS135MUN -Ask a technical question

Package Weight: 0.73 kg / EACH

Available: 7-10 Days

RoHS: RoHS Exempt

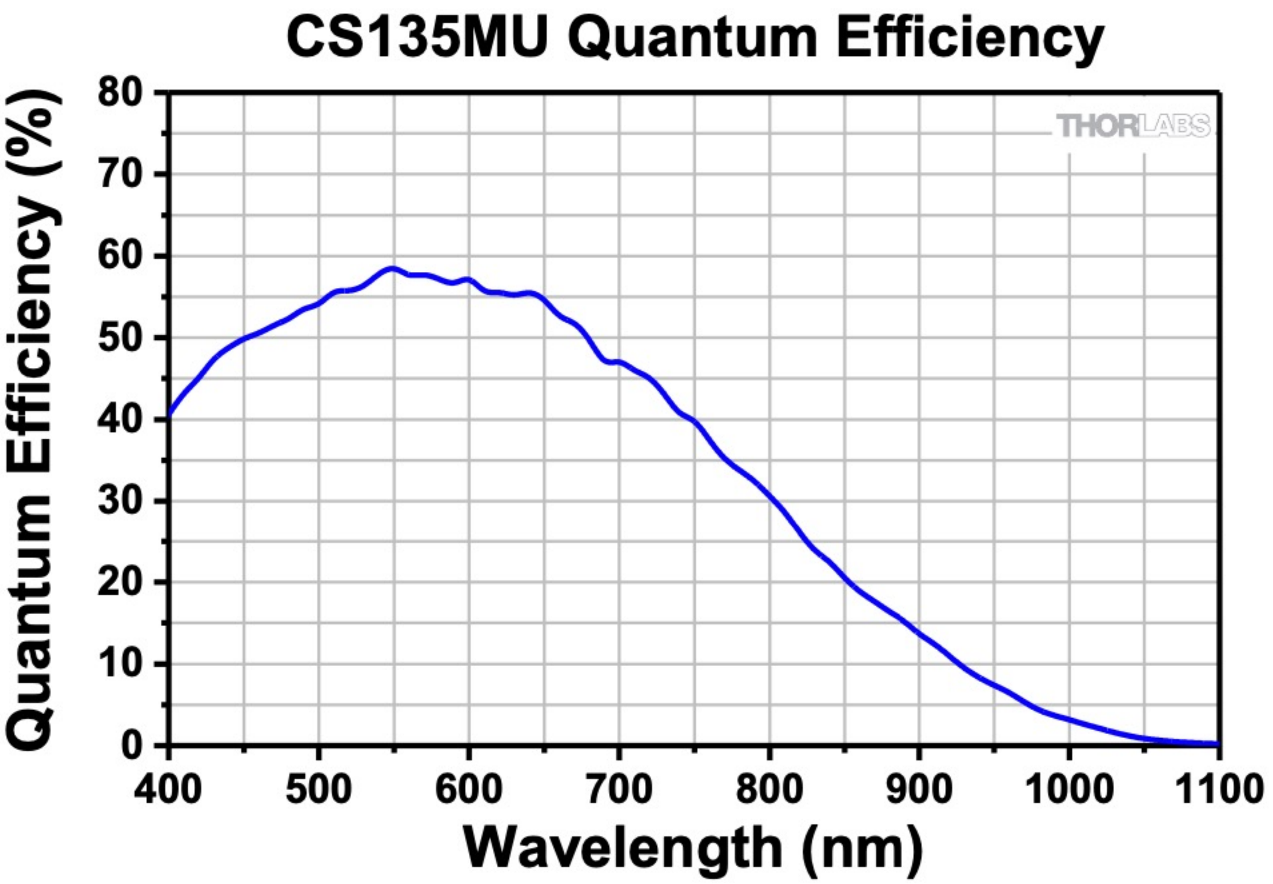
Price: 1.728,51 €

Add To Cart: Qty : 1

Add To Cart

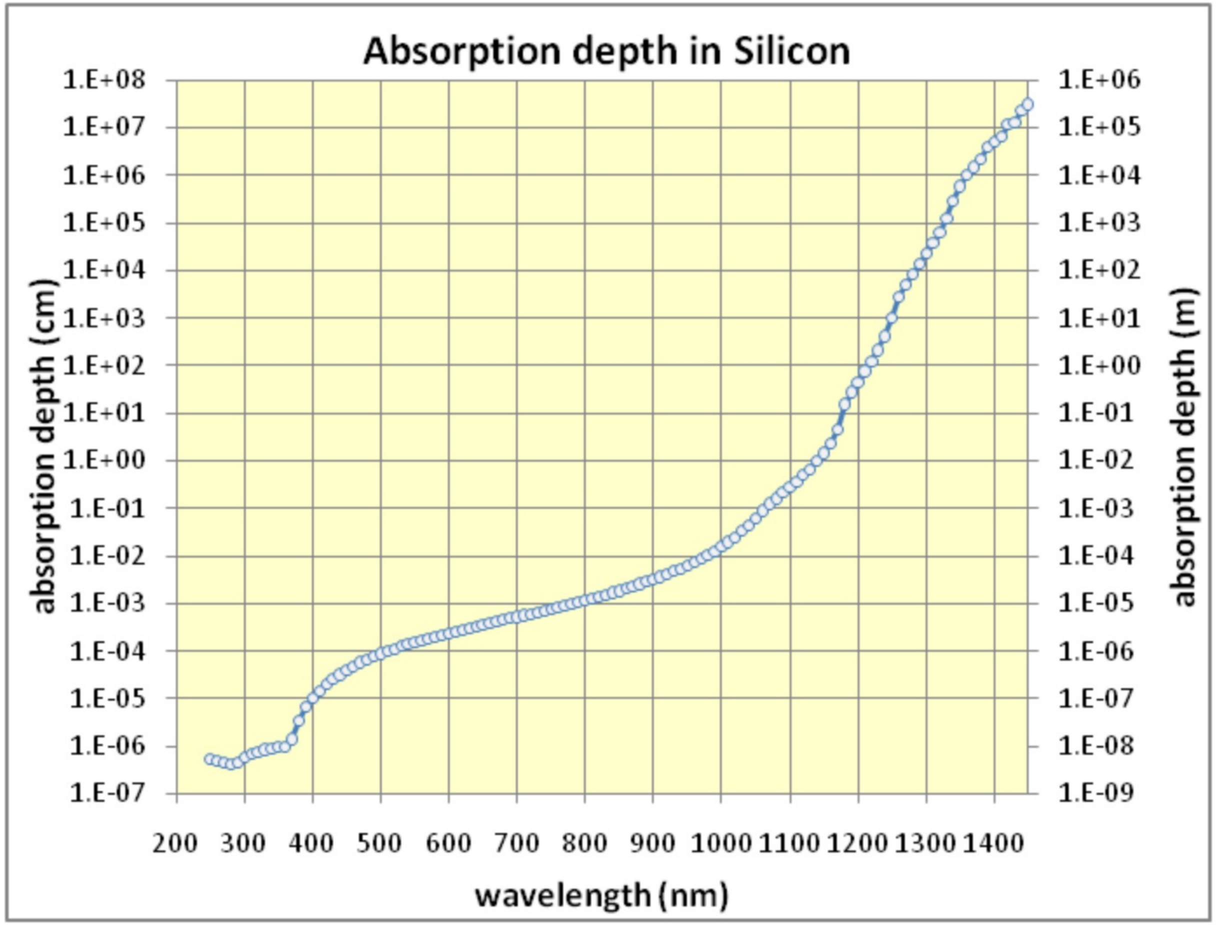
Release Date: 27.03.2020

Item #	CS135MU	CS135CU	CS135MUN
Sensor Type	Monochrome CMOS	Color CMOS	NIR-Enhanced CMOS
Effective Number of Pixels	1280 x 1024 (H x V)		
Imaging Area	6.144 mm x 4.915 mm (H x V)		
Pixel Size	4.8 µm x 4.8 µm		
Optical Format[a]	1/2" (7.76 mm Diagonal)		
Max Frame Rate	165.5 fps (Full Sensor)		
ADC[b] Resolution	10 Bits		
Sensor Shutter Type	Global		
Read Noise	<7.0 e^- RMS		
Full Well Capacity	≥10 000 e^-		
Exposure Time	0.100 ms to 59269 ms in 0.001 ms Increments		
Vertical and Horizontal Digital Binning[c]	1 x 1 to 5 x 5		
Region of Interest (ROI)	16 x 2 Pixels[d] to 1280 x 1024 Pixels, Rectangular		
Dynamic Range	>60 dB		



https://www.thorlabs.com/thorproduct.cfm?partnumber=CS135MUN

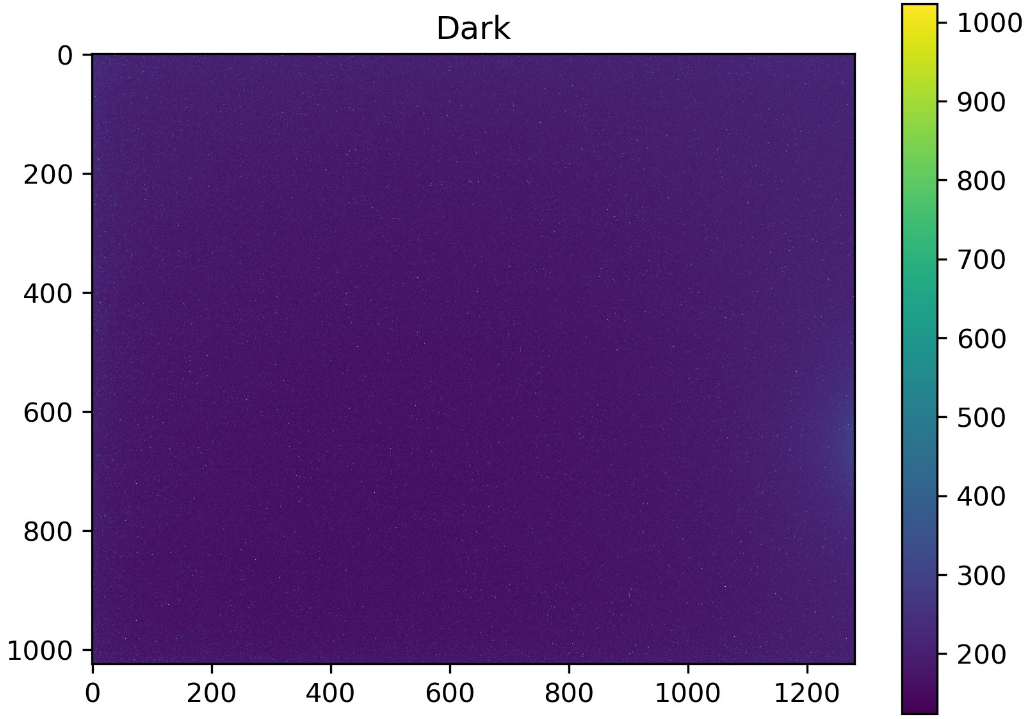
Absorption depth of photons in silicon

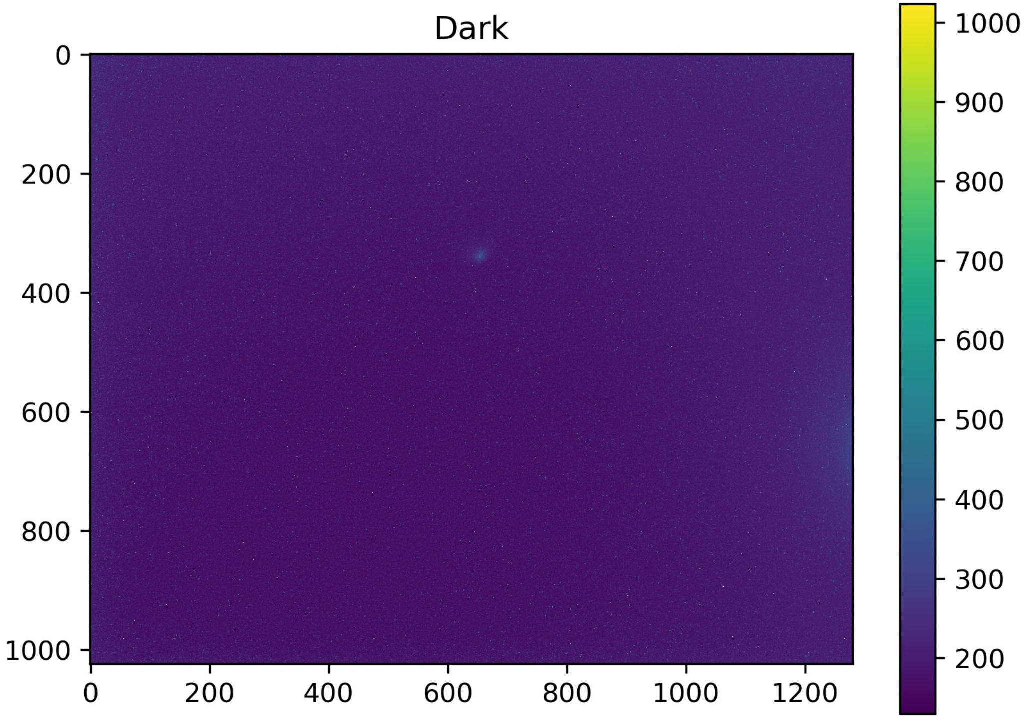


https://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon

Overcorrection problem with too noisy SPADs (see pix [21,9])

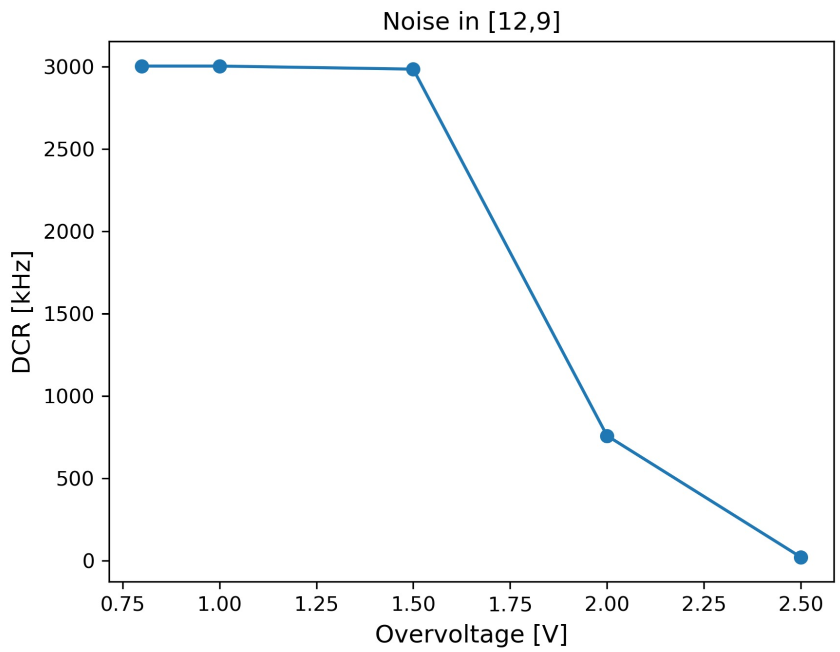
- Difference between firt and second dark frame
  - First only camera effects
  - Second still some afterglow → overcorrecting



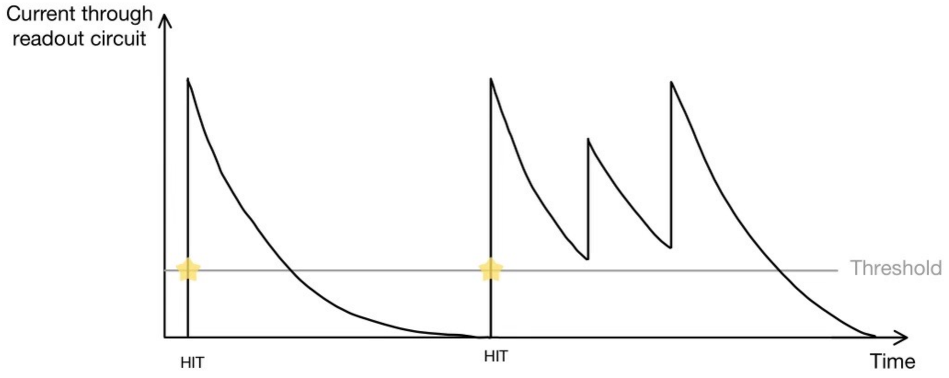


Too noisy pixels (see pix [21,9]) → problem in DCs & CT

- CT calculation assumes only one hit per frame
- If too noisy → multiple hits per frame, but only measure when current crosses a certain threshold, if it just stays above (as the case is for multiple hits happening fast after eachother) this is counted as one hit → DCR decreases and CT probability is overestimated in too noisy pixels



- Schematic illustration of saturation effects in SPADs



Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Ono Feyens
DESY ATLAS group
ono.feyens@desy.be