Direct Measurement of Optical Cross-talk in Silicon Photomultipliers Using Light Emission Microscopy

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Outline

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- Motivation
- Optical Cross-talk in SiPMs
- Light Emission Microscopy and Experimental Setup
- Direct Measurement of Cross-talk in a sample SiPM
- Summary and Outlook

Motivation

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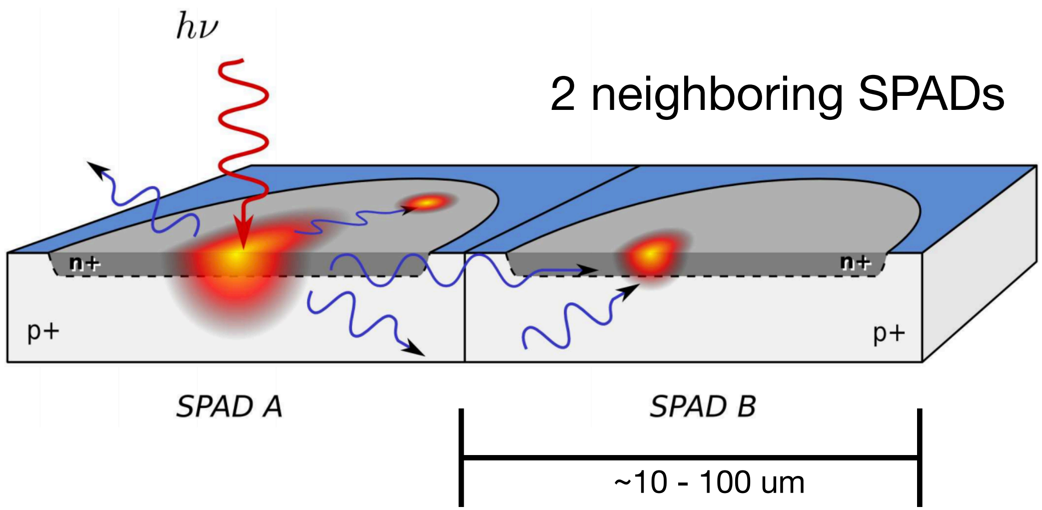
- Silicon Photomultipliers (SiPMs) are becoming ubiquitous in HEP and Astroparticle experiments, and in medical and industrial applications.

- One of the main limitations of SiPMs is light emission (~10^{-5} photon/electron[1]) during the avalanche process that causes optical cross-talk between neighboring cells.

- To achieve optimal device performance, optical cross-talk should be further studied and reduced as much as possible.

[1] R. Mirzoyan et al., NIM A 610 (2009) 98-100

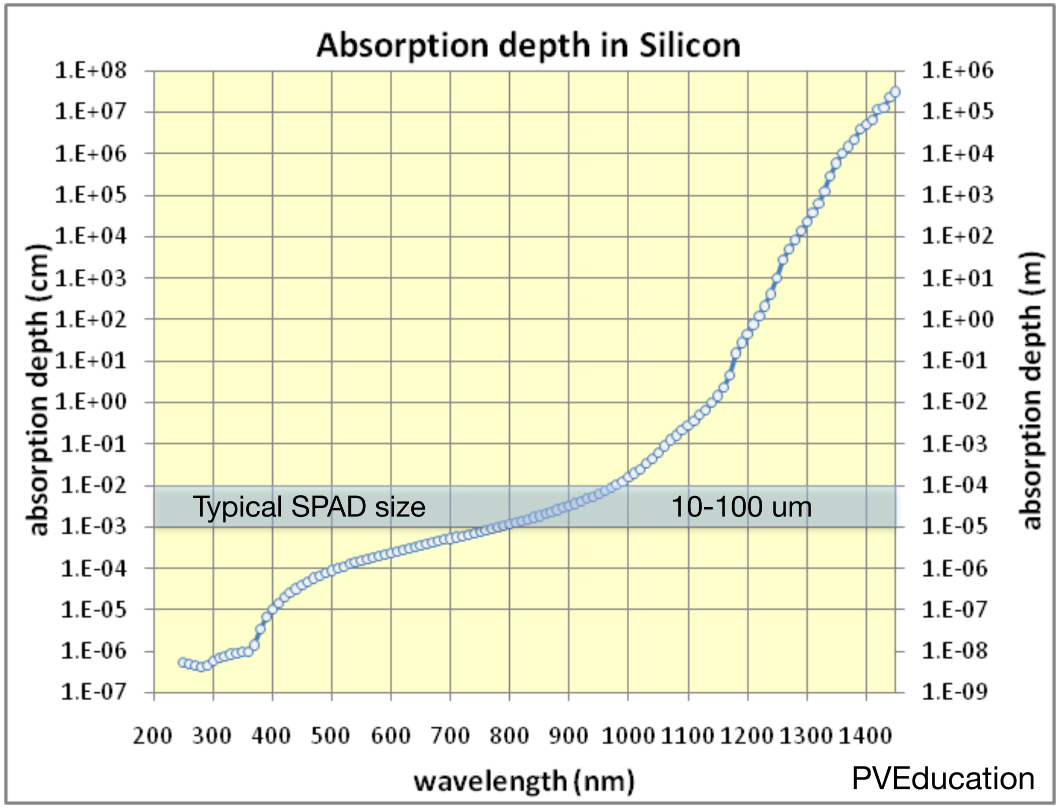
Optical Cross-talk in SiPMs



- Optical cross-talk
  - Probability for photons to trigger neighboring cells
  - Few 10s of photons emitted during primary avalanche
  - Results in artificial increase in signal
  - Contributes to excess noise factor
  - Can be significant and problematic in some applications

- Objective: to learn about cross-talk probability from light emission in SiPMs

Photon Absorption in Silicon



Strong wavelength dependence of photon absorption depth in silicon

Optical Cross-talk in SiPMs

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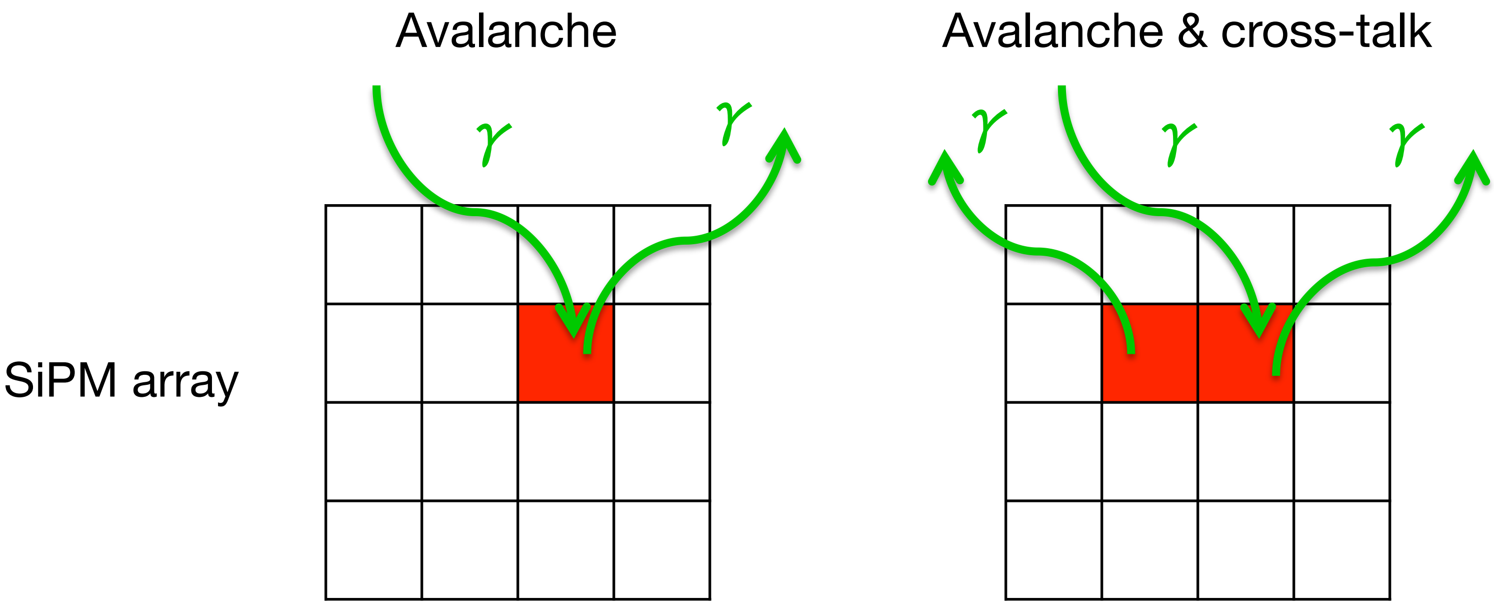
- How to measure cross-talk? By counting photons.



- Light emission microscopy (LEM) is a precise and powerful visual tool for directly measuring optical cross-talk.
- Useful to also observe defects in cells, morphology of the avalanche process, etc.

Light Emission Microscopy

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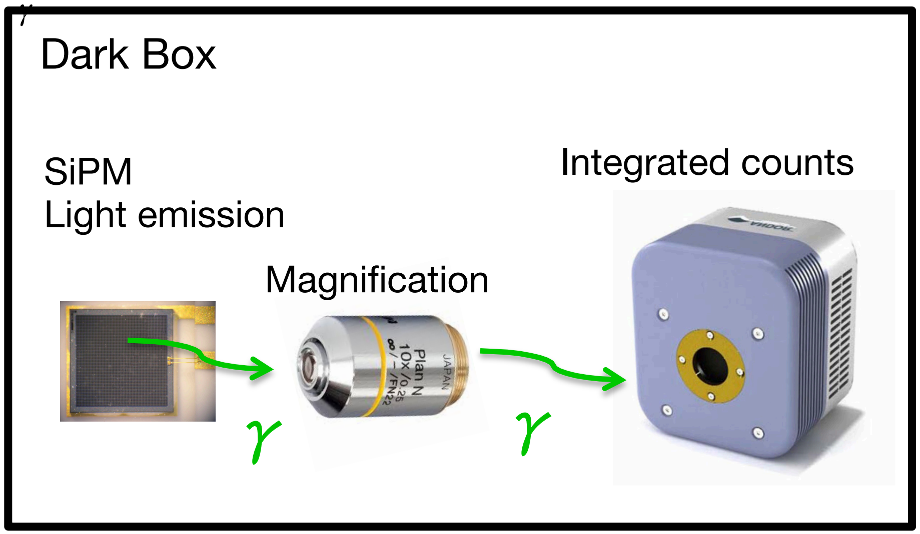
- LEM is a powerful root cause failure analysis technique for detecting low light levels otherwise not visible to an observer.
- Utilizes resolving power of an objective lens and a low-noise camera to detect weak light emission, e.g. from semiconductor devices such as SiPMs.



Direct Measurement of Cross-talk

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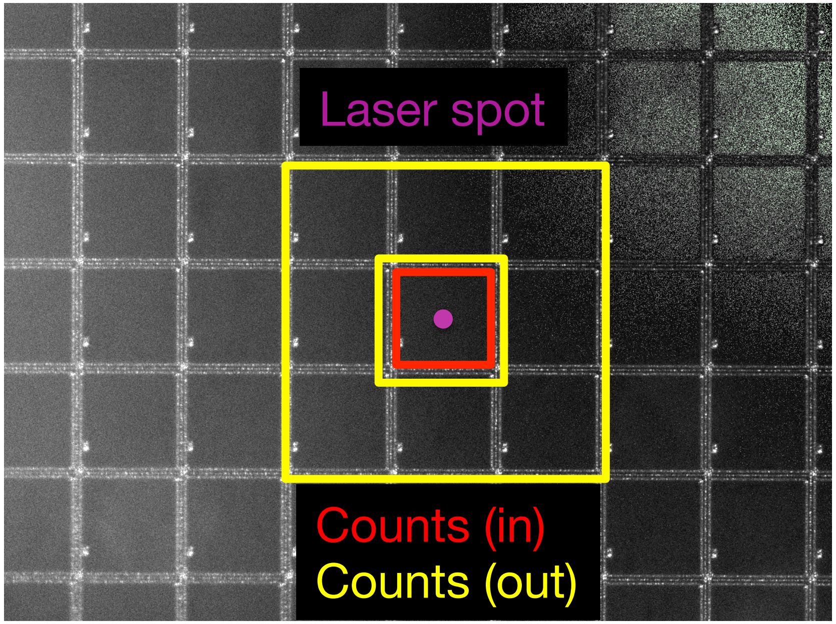
- Illuminate one SiPM cell with small laser spot (<< cell size).
- Observe photon emission from primary and secondary avalanche processes using a microscope and record with a low-noise CCD.
- Count photons emitted from the central cell where laser is fired and from neighboring cells at distance 1 cell-unit away.
- Assume the counts outside central cell are all cross-talk counts since the laser is focused well within the central cell.

SiPM Array

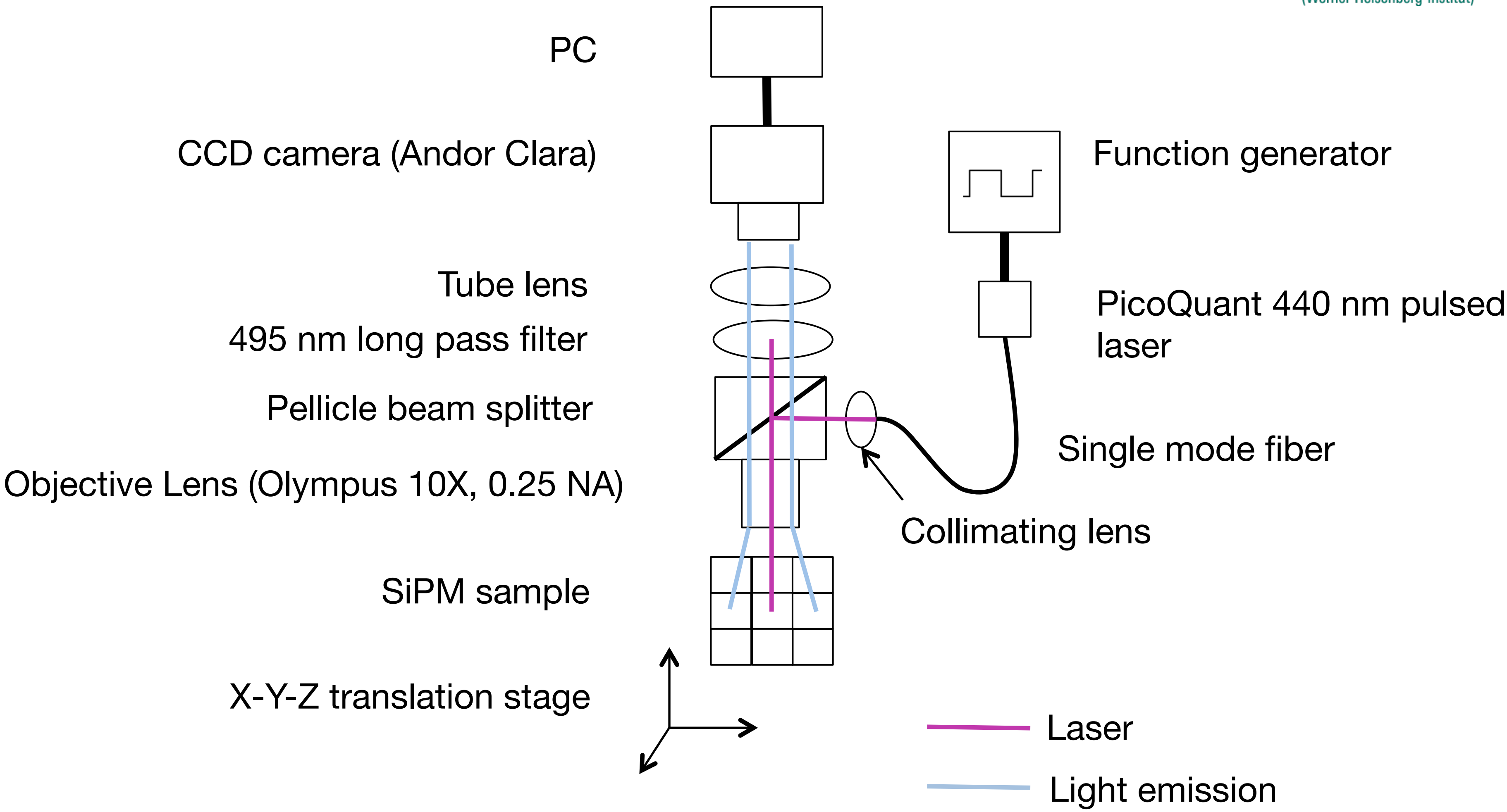


- Measure cross-talk

  Cross-talk = Counts (out) / Counts (in)

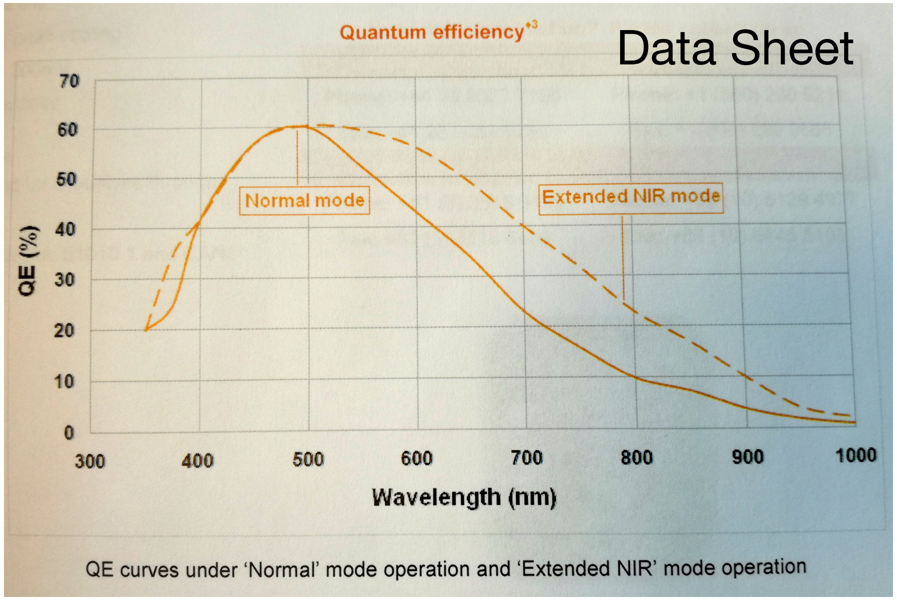
- Building upon previous work by M. Knötig, R. Mirzoyan, and Jürgen Hose at MPI

LEM Setup


PC
CCD camera (Andor Clara)
Tube lens
495 nm long pass filter
Pellicle beam splitter
Objective Lens (Olympus 10X, 0.25 NA)
SiPM sample
X-Y-Z translation stage
Function generator
PicoQuant 440 nm pulsed laser
Single mode fiber
Collimating lens
Laser
Light emission

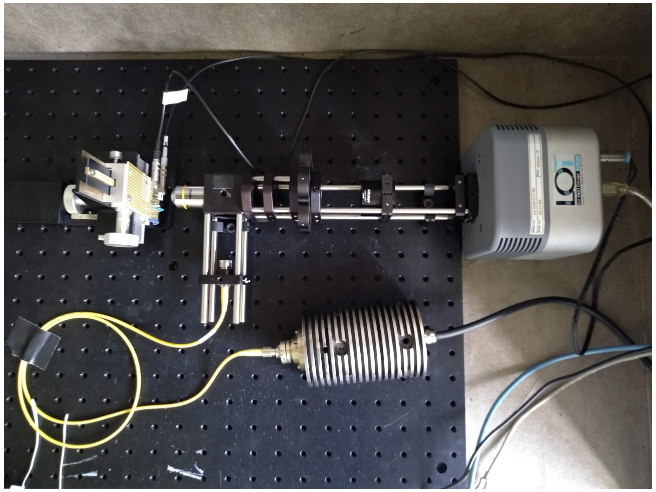
Andor Clara CCD Camera

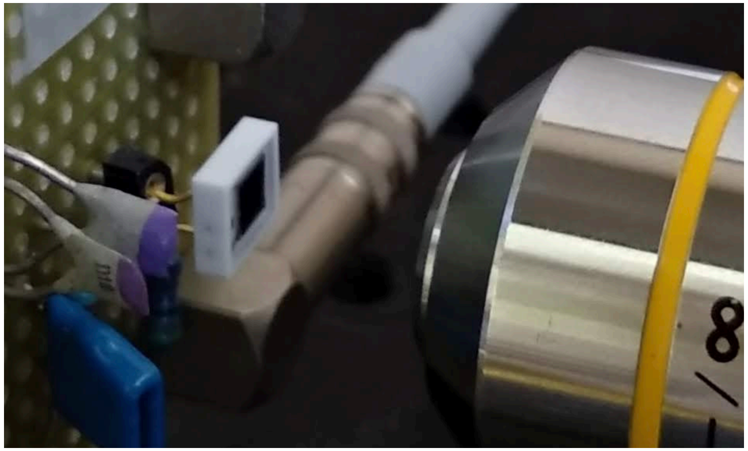
- 1392 x 1040 sensor
- 6.45 x 6.45 um^2 pixel size
- High QE
- NIR sensitive



- Cooled to -55C to reduce thermal noise
- Thermal noise: 1 e^-/hr
- Readout noise: 2.4 e^- @ 1 MHz

LEM Setup





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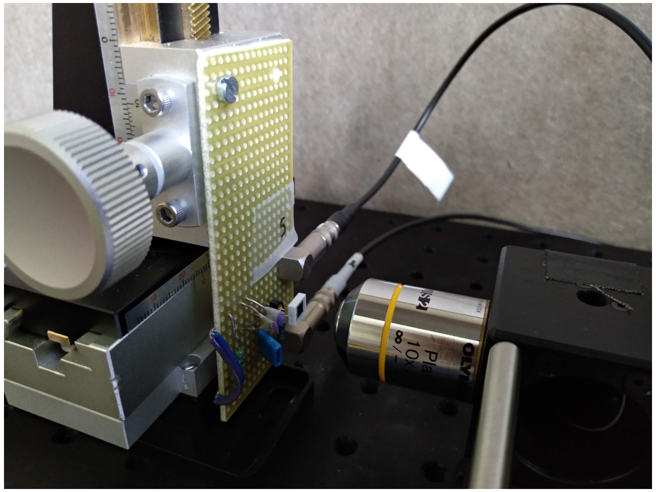

SiPM Sample

- Hamamatsu LCT4 single element
- Device size = 3 x 3 mm^2
- Cell size = 75 x 75 um^2
- Breakdown voltage = 51.10V
- Cross-talk measured as function of overvoltage

SiPM under 10X Magnification

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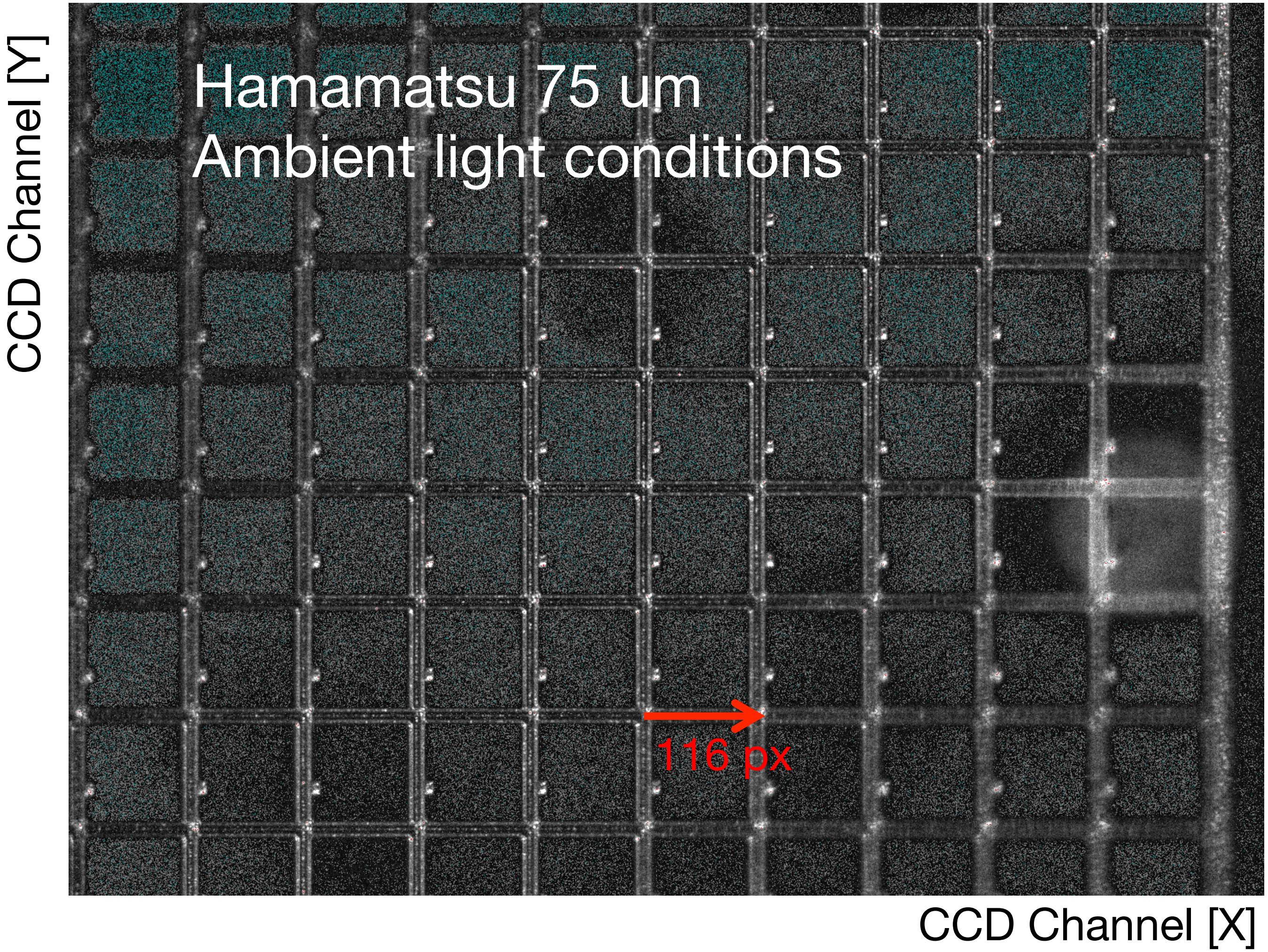


CCD Imaging Steps

Step 1: Dark image

Step 2: Background image with laser light only

- To account for any reflections off the surface of the SiPM

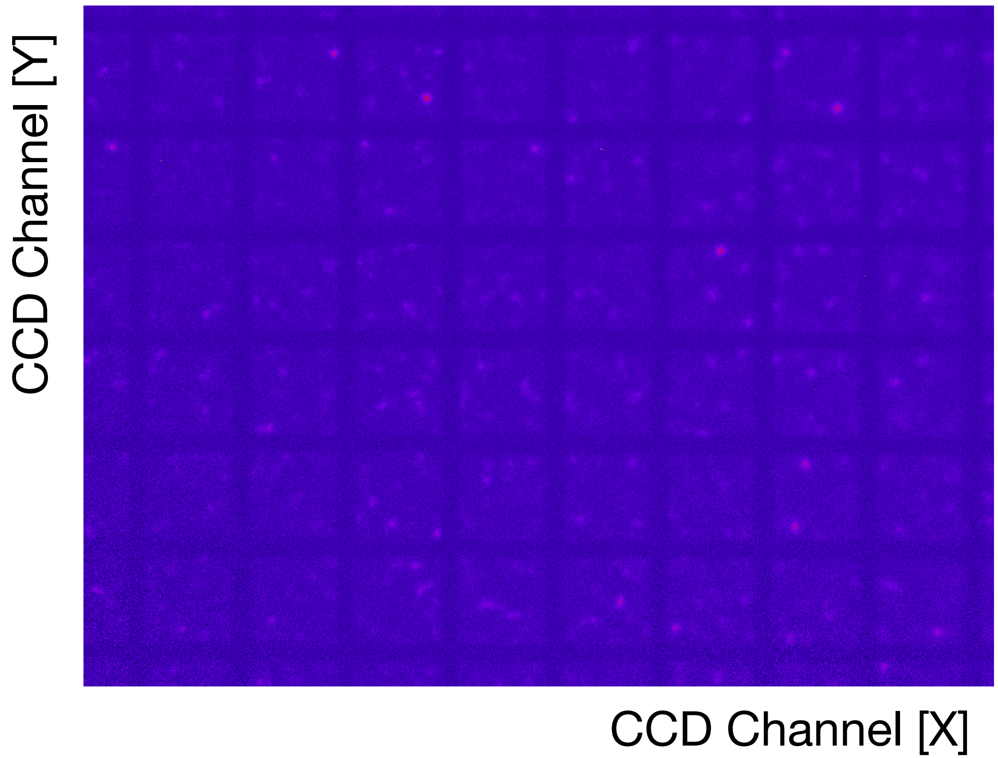
Step 3: Background image with bias voltage only applied to SiPM

- To account for any light emission from the powered device

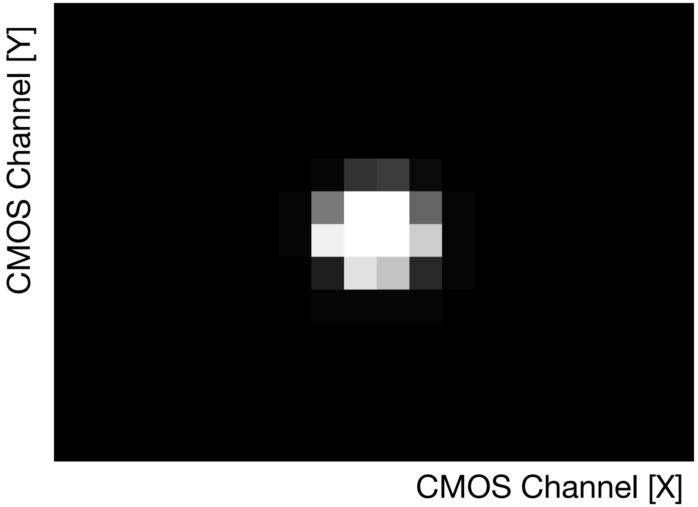
Step 4: Signal image with laser light and bias voltage applied to SiPM

Integration time for each step is 30 seconds

Emission from powered device

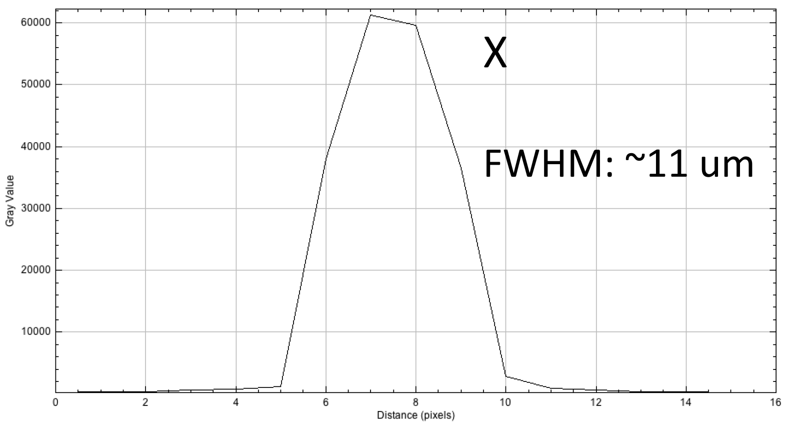


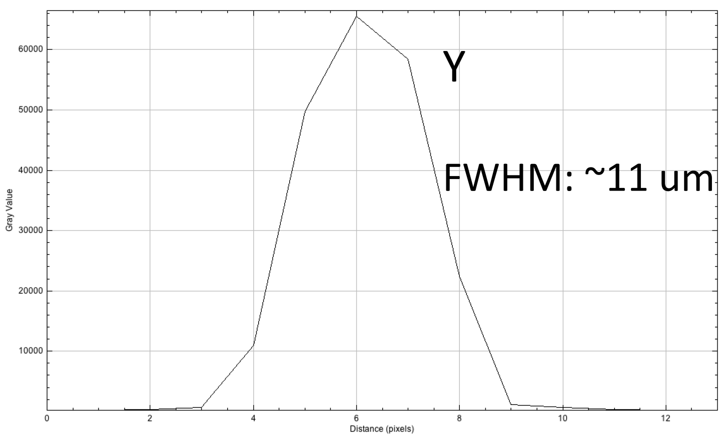
Beam Spot Profile



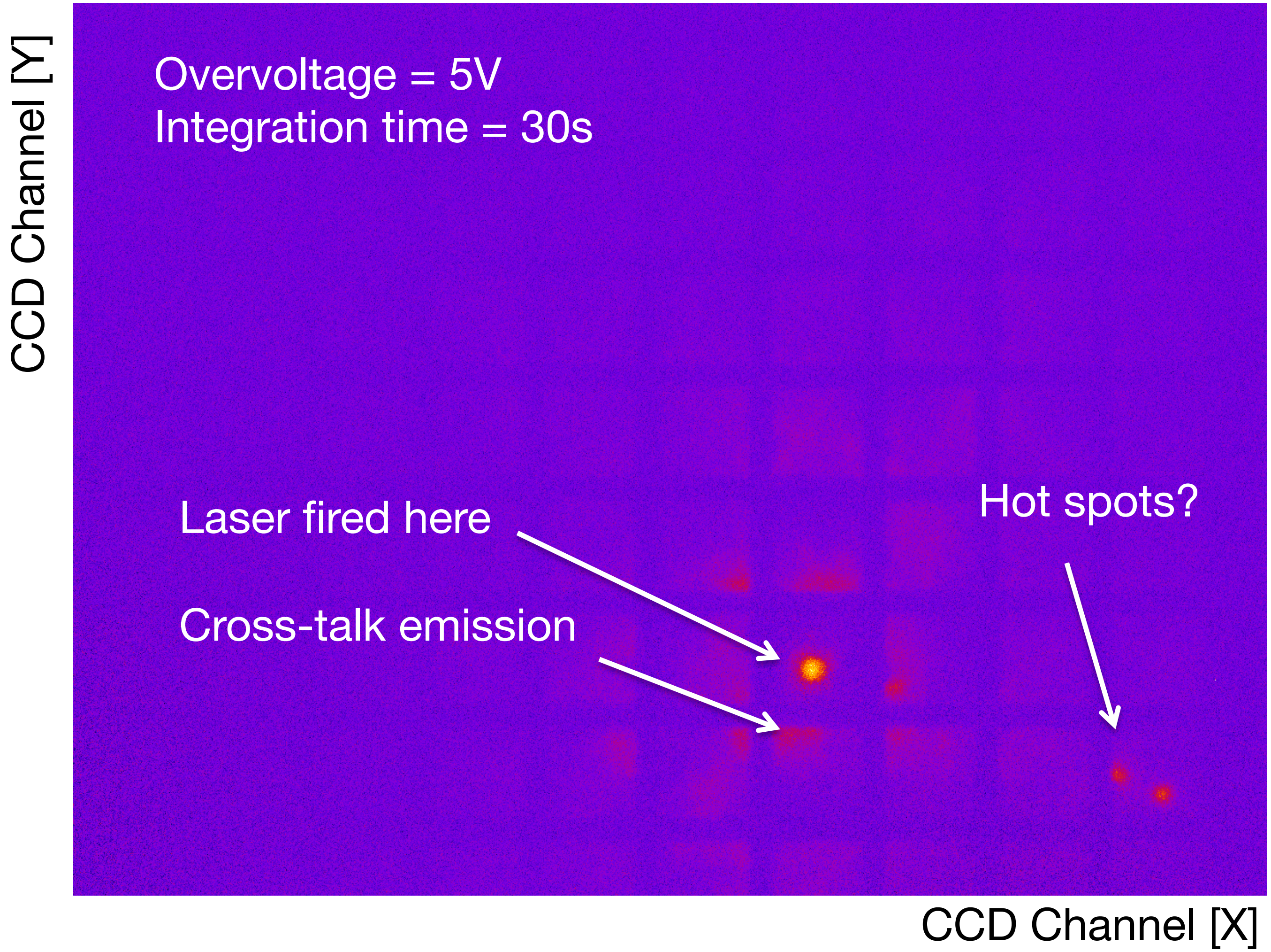
Measured with CMOS camera
1px = 3.8 um

Beam spot size << SiPM cell size





Observed Light Emission



Observed Light Emission

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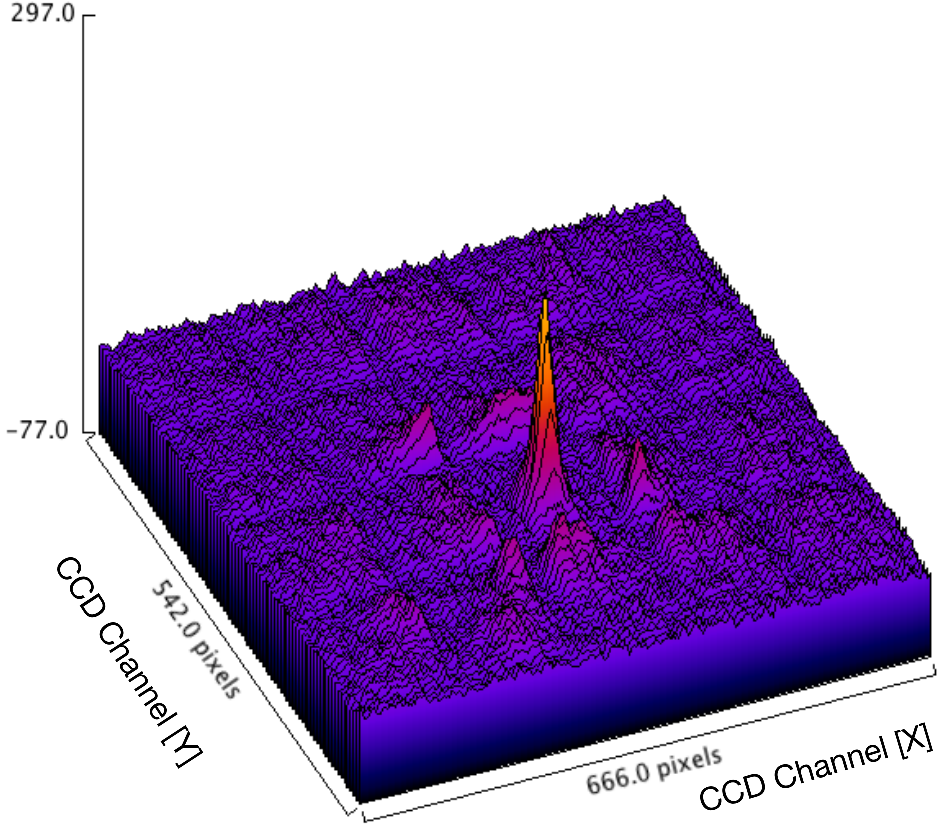
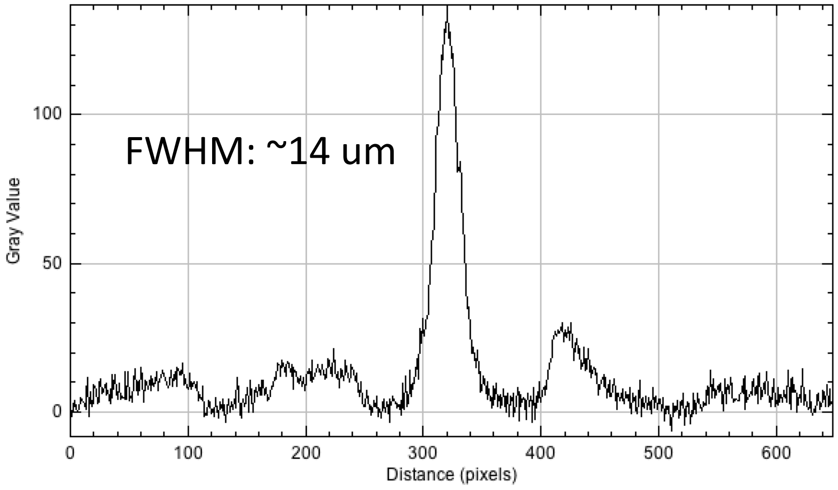
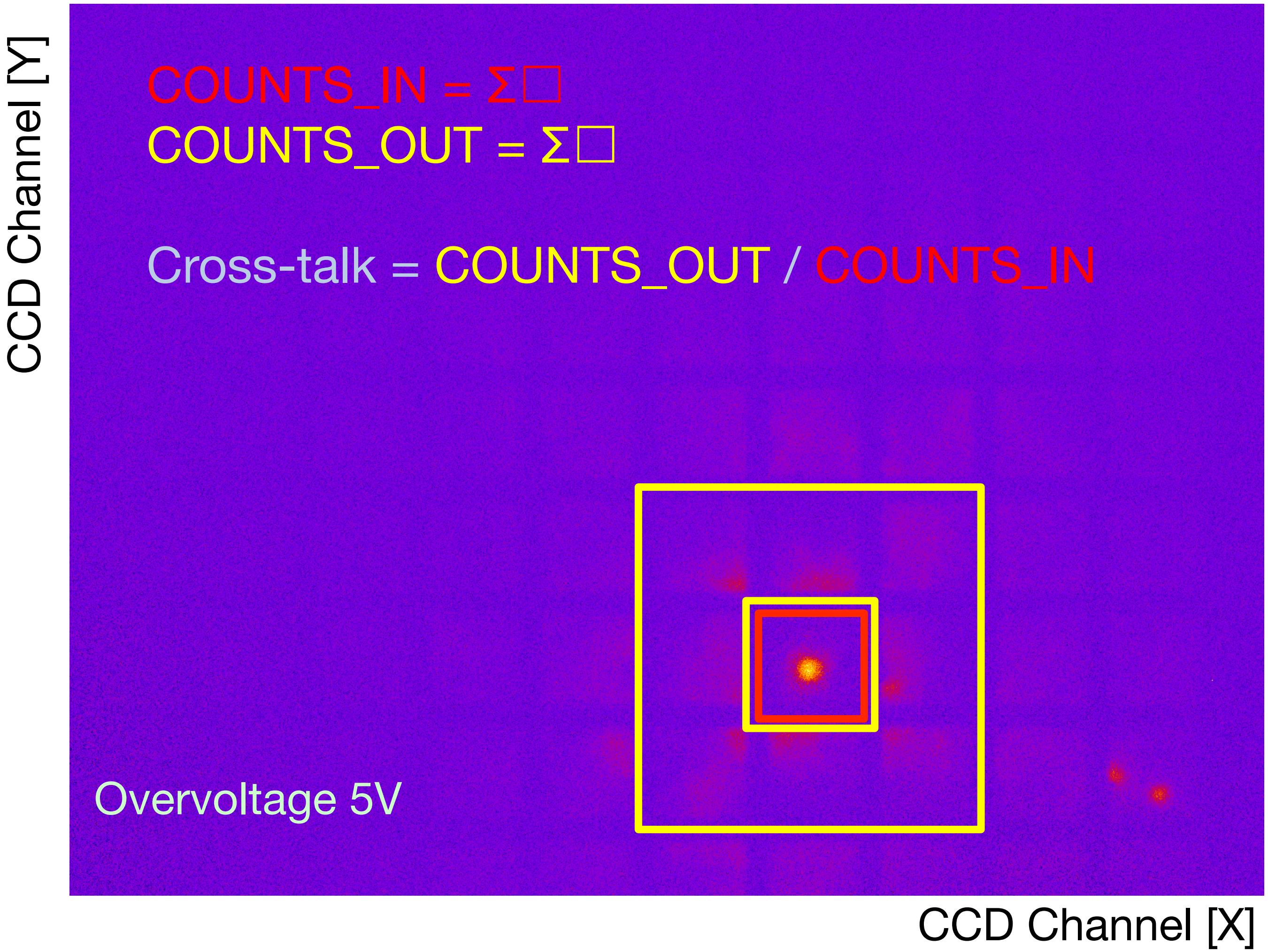
- The laser light is focused on a single cell.
- Emission is observed from the central cell and also neighboring cells.



Profile along x-axis

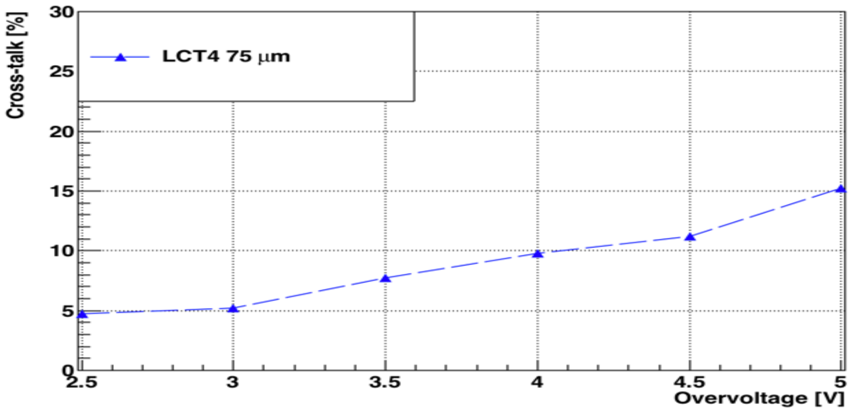


Direct Measurement of Cross-talk

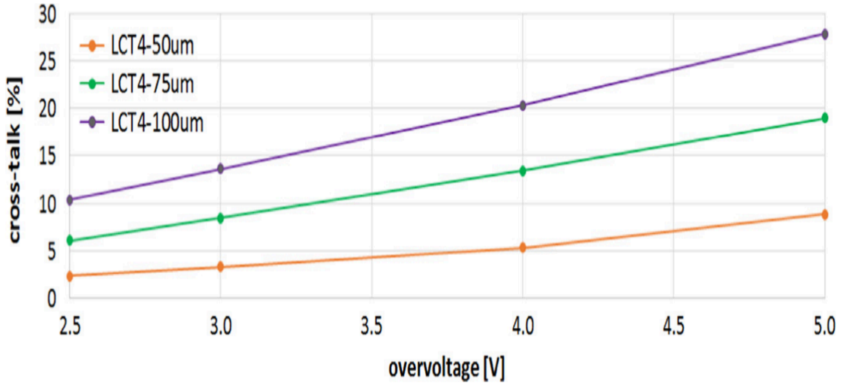


Optical Cross-talk vs. Overvoltage

LEM Method - Preliminary



Standard Method (i.e. theshhold)



[NIM A 806 (2016), 383-394]

Summary and Outlook

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- SiPMs are attractive photo-detectors for high-energy and astroparticle physics experiments, as well as medical and industrial applications.
  - Compact in size
  - Fast (few ns) response time
  - Low operating voltages compared to classical PMTs
  - Insensitive to magnetic fields
  - Photon detection efficiencies greater than 40%.
- Crucial for some applications to reduce/eliminate cross-talk between neighboring cells.
- Light emission microscopy is a powerful visual tool for measuring and understanding the physics behind optical cross-talk, as well as for observing device defects, avalanche morphology, etc.
- LEM method is the most precise measurement of cross-talk.
- Plans to measure cross-talk:
  - in new batches of SiPMs,
  - in cells > 1 unit distance away from center,
  - at different regions of the cell,
  - near the borders of the device,
  - using lasers of different wavelengths.

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the European Union's Horizon 2020 research
and innovation programme
under grant agreement no 713171

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SENSE

Ultimate
Low Light-Level
Sensor
Development

sense-pro.org

Consortium Members

UNIGE: A. Nagai, D. della Volpe, T. Montaruli

KIT: A. Haungs, K. Link

DESY: K. Henjes-Kunst

MPI: R. Mirzoyan, D. Strom

Backup

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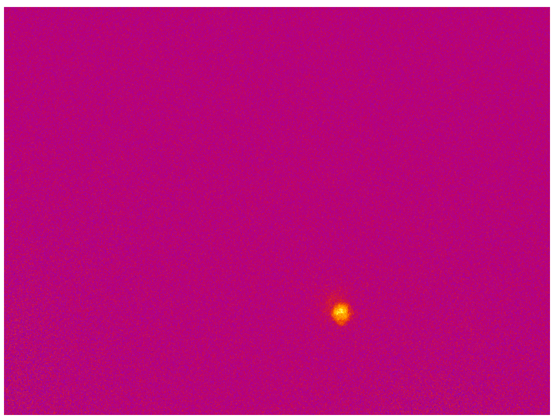
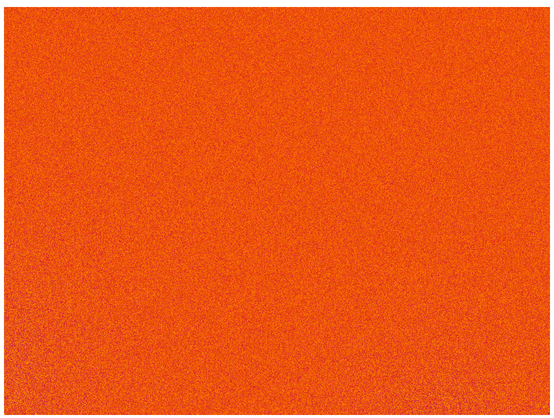
Hot Spot

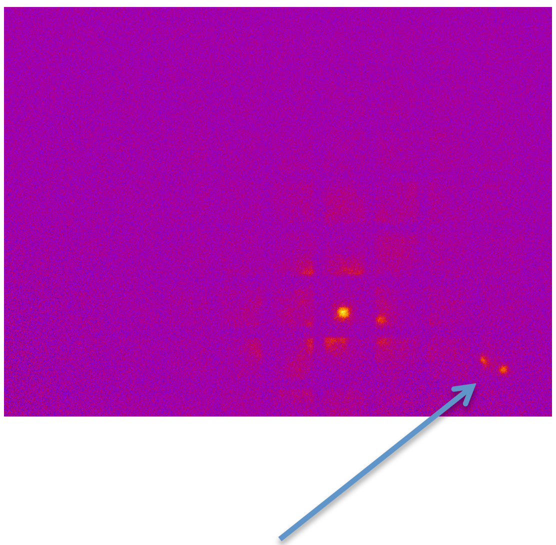
Bkg: Laser Only



Bkg: Bias Only

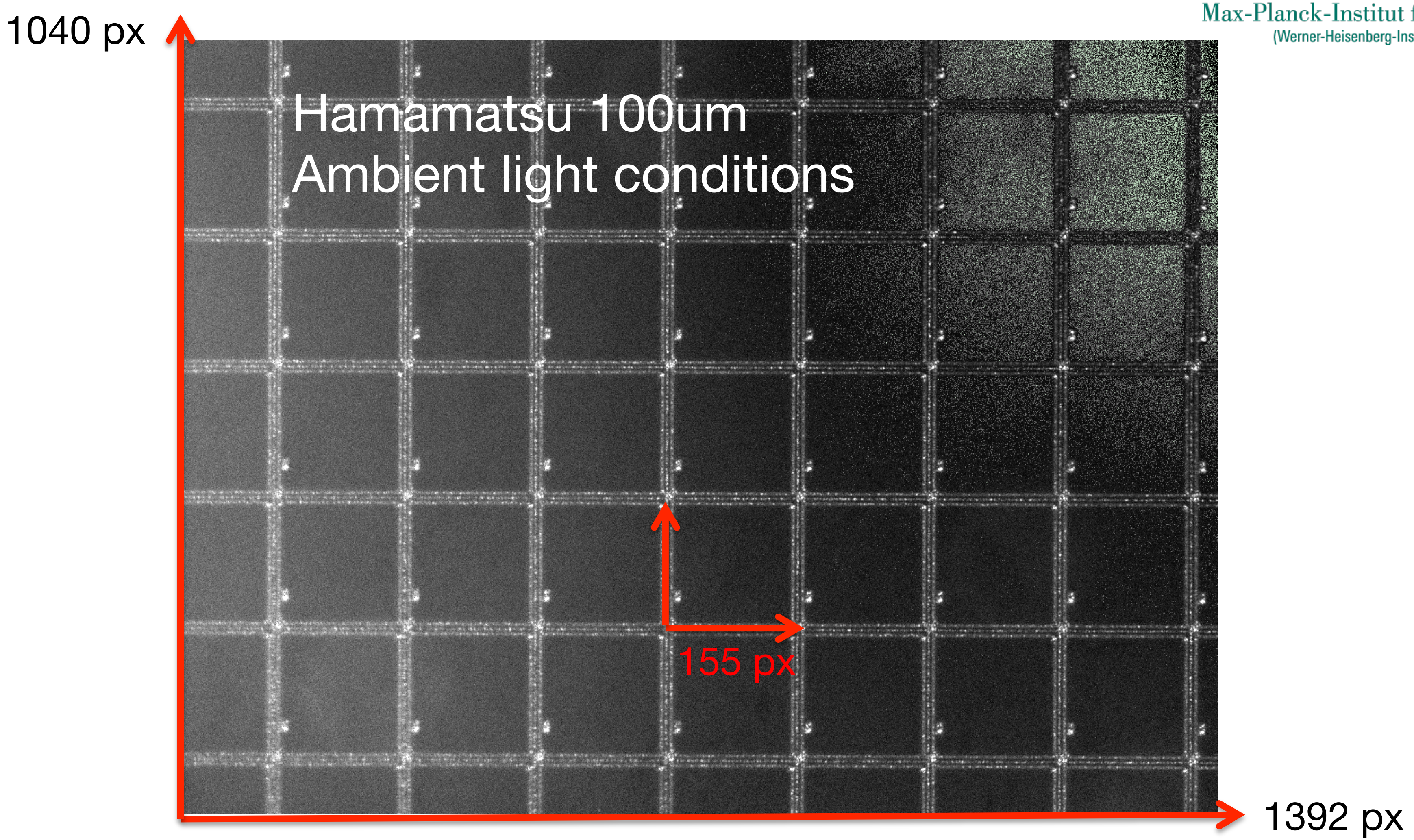


Signal



Emission observed in signal image only

SiPM under 10X Magnification



Silicon Photomultiplier (SiPM)

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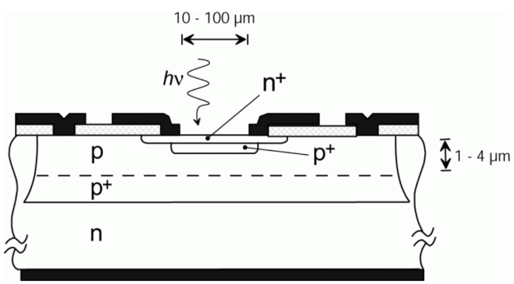
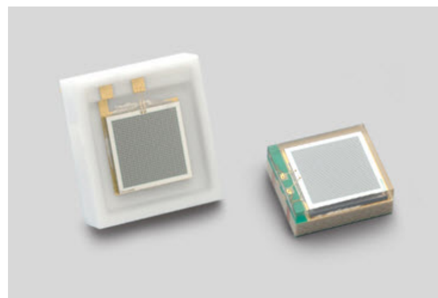
Solid-state single-photon-sensitive device
based on single-photon avalanche diode (SPAD)

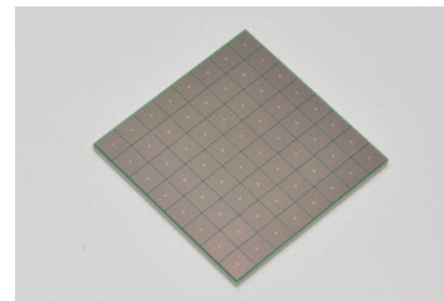
SPAD concept



Single element detector



Multi-element arrays



Advantages
Small cell sizes (10-100 um)
Nanosecond resolution
Low operating voltage
B-field insensitive
PDE greater than 40%
Large dynamic range

Disadvantages
High Dark Count Rates (wrt PMT)
Afterpulsing
Cross-talk

Low Intensity Background Rejection

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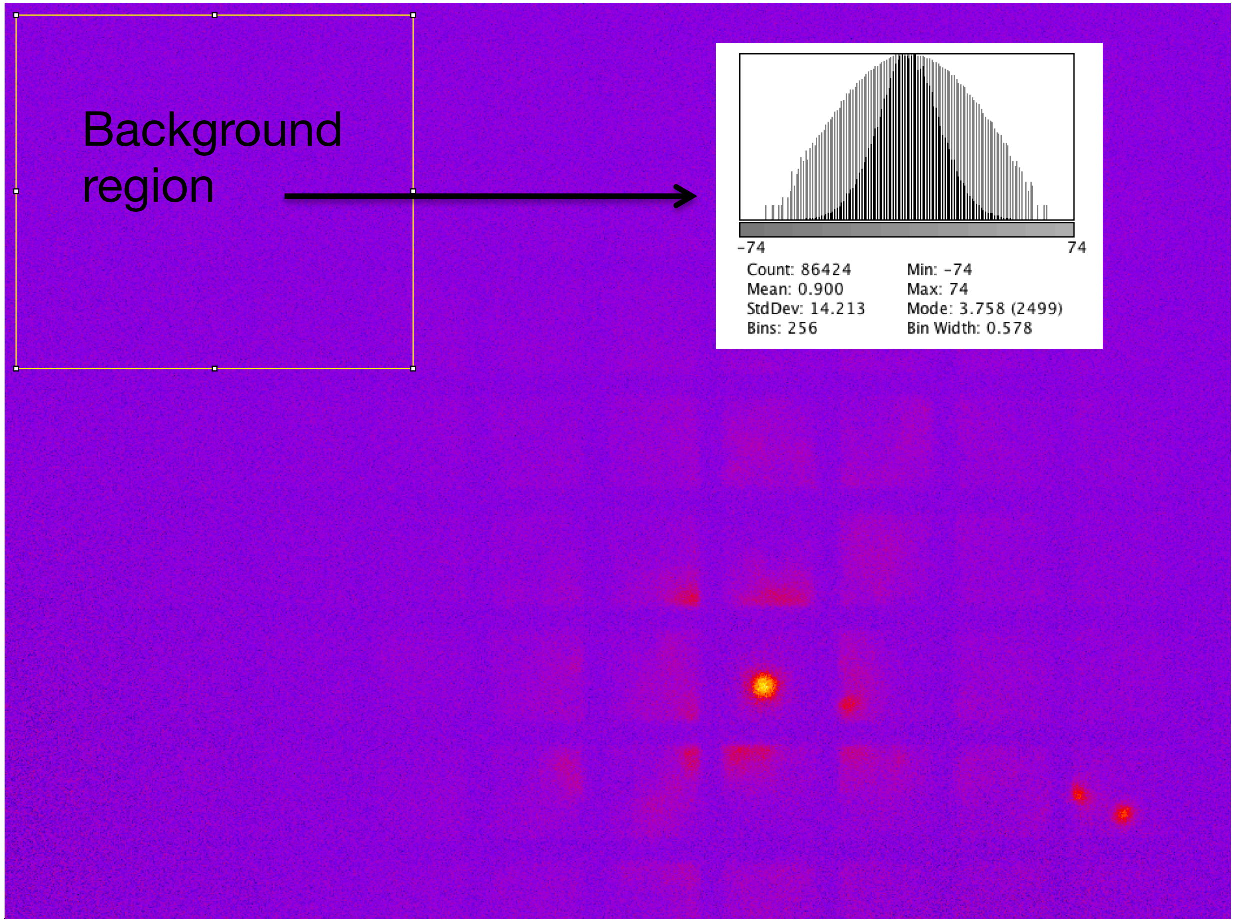

Low Intensity Background Rejection

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