Detailed Bench Investigations and Comparison of 4 low-light Cameras: EMCCD, 2 x scientific CMOS, and Image Intensifier

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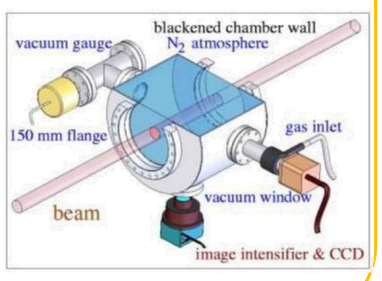
Introduction

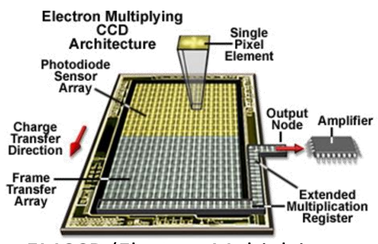
- Low-light cameras are used in beam diagnostics for profile measurements, e.g. in beam induced fluorescence (BIF), OTR and Scintillation Screens
- Characterization of:
  - **EMCCD** camera **ProEM:+512B, Teledyne Princeton Instruments**
  - **sCMOS** camera **pco.edg4.2bi, PCO**
  - **sCMOS** camera **Kinetix 22, Teledyne Photometrics** (same sCMOS sensor)
  - **ICCD: Image Intensifier** (**ProxiVision**) plus regular CMOS camera (Basler)
- Pulsed LEDs with different light pulse durations (0.05 - 8ms)
- Different wavelengths (500 nm -385 nm)

Schematic of a BIF monitor

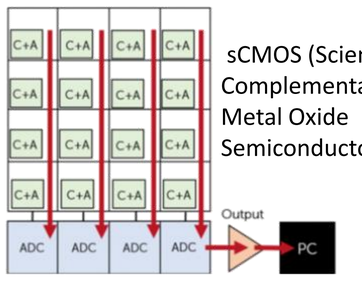


Three Types of Cameras

EMCCD ProEM:+ 512B, Teledyne	**sCMOS** pco.edge 4.2bi, PCO	**sCOMS** Kinetix 22, Teledyne Photo	**Image Intensifier + CMOS** ProxiVision design
Pixels: 512 x 512, 16 µm Full frame mode Different em-gains (1, 10, 100, 1000)	2400 x 2400, 6.5 µm Noise-filter possible (median filter) Only rolling shutter (!)	2048 x 2048, 6.5 µm Offers 4 acquisition modes: e.g, 'Sub-Electron Mode': 2 rows simultaneous sample & measuring each pixel 8 times. Only rolling shutter (!)	Photocathode: S20 UV-enh. Double MCP for single photons detection Relay lens coupling to CMOS Pixel 1200 x 1920, 5.9 µm



EMCCD (Electron Multiplying Charge Coupled Device) [1]



sCMOS (Scientific Complementary Metal Oxide Semiconductor) [2]

Image Intensifier with Relay Lens

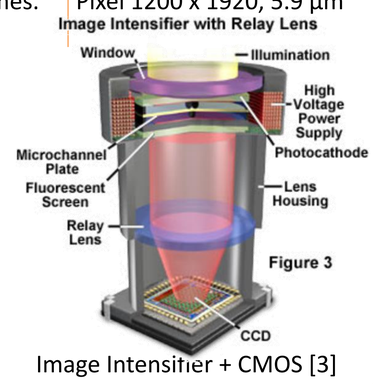
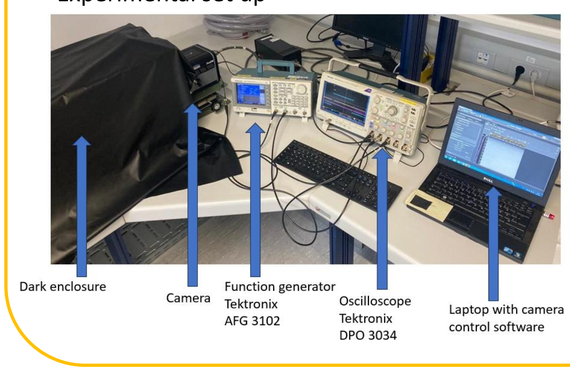


Image Intensifier + CMOS [3]

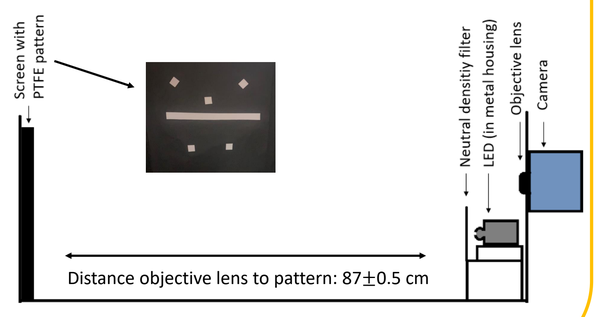
Experimental Set-up

- Experimental set-up contains: dark enclosure, camera, function generator, oscilloscope and laptop
- Cameras are mounted onto a wall of the dark enclosure
- Inside of dark enclosure: LED installed in metal housing, neutral density filter (transmission 27-31 %)
- Target pattern is made of PTFE (reflectance ≈ 92 %)
- Walls of dark enclosure are coated with blackened aluminium foil (reflectance ≤ 5 %)
- Objective lens: f= 16 mm (FL-CC1614-2M; RICOH)
- Variation of LED light duration for fluence variation (typically 0.5 to 8 ms)

Experimental set up



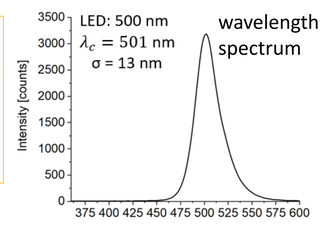
Schematic of the inside of the dark enclosure

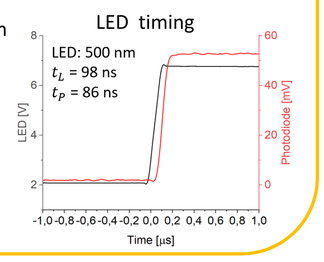


LEDs´ Characterization: Example for λ = 500 nm

- Pulsed LEDs as light source for linear variation of photon number (fluence)
- LEDs´ characterization by spectrometer for wavelength, photodiode + trans-impedance amp. for linearity

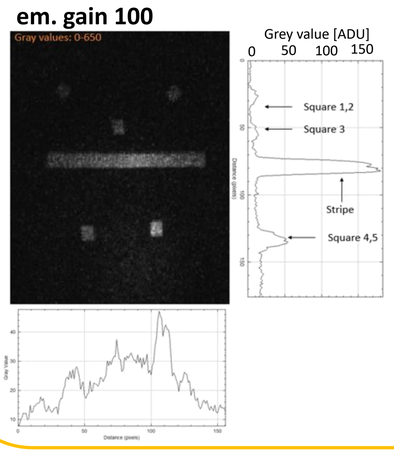
LEDs´ Parameters:
Wavelength [nm]: 500; 470; 430; 400; 390; 385
Light pulse [ms]: 0.5; 1; 2; 4; 8
Leading edge [ns]: 100
Trailing edge [µs]: 1



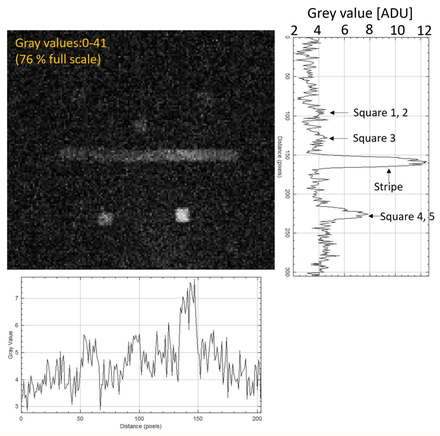


Projections of a ROI for a 0.5 ms Light Pulse for λ = 500 nm

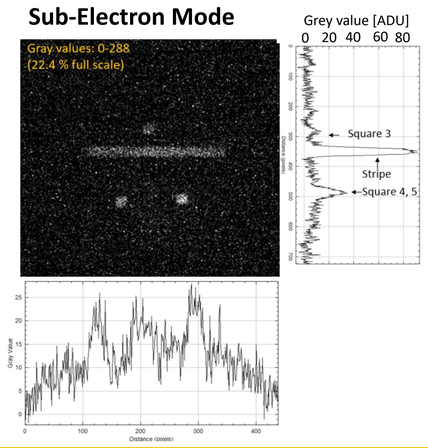
EMCCD
em. gain 100



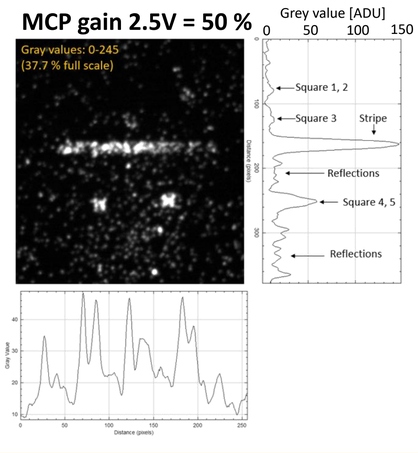
sCMOS pco.edge 4.2bi

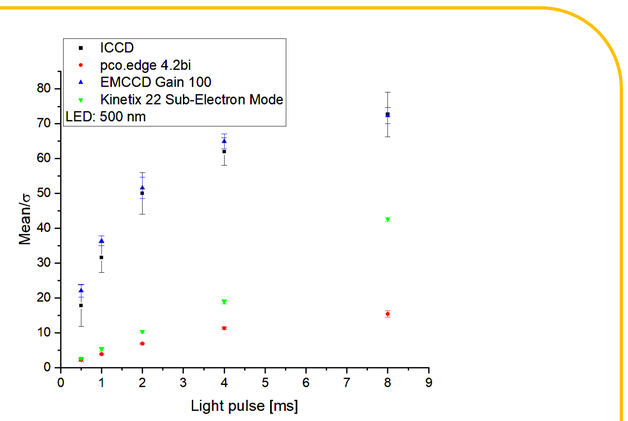


sCMOS Kinetix 22
Sub-Electron Mode



ICCD
MCP gain 2.5V = 50 %

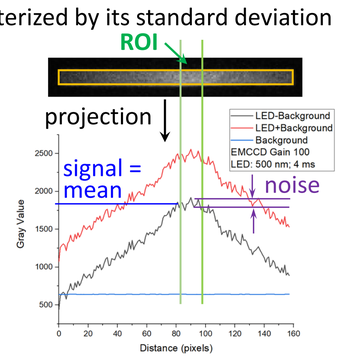




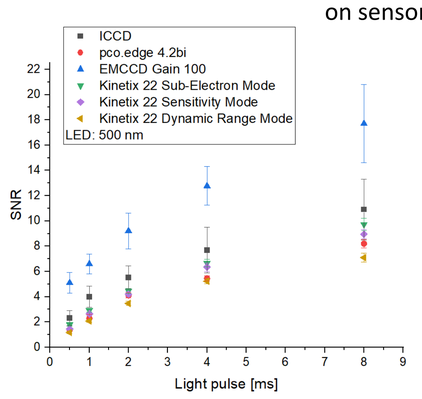
Ratio of the mean height of the horizontal projection of the stripe and σ determined in a „dark " image ROI as function of llight pulse duration.

Signal-to-Noise Ratio Evaluation

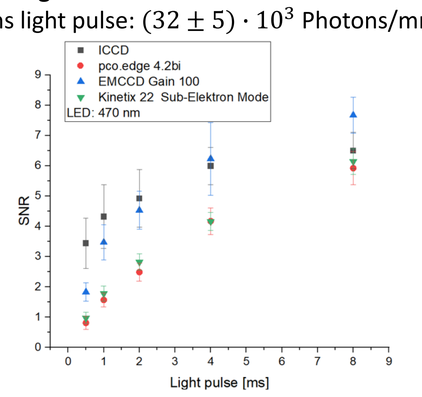
Signal determination: Homogeneously illuminated ROI characterized by the mean value
Noise determination: Fluctuations of the signal characterized by its standard deviation



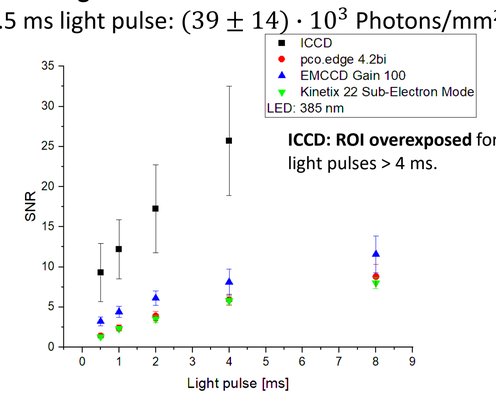
Wavelength λ = 500 nm:
0.5 ms light pulse: $(54 \pm 9) \cdot 10^3$ Photons/mm² on sensor plane



Wavelength λ = 470 nm:
0.5 ms light pulse: $(32 \pm 5) \cdot 10^3$ Photons/mm²



Wavelength λ = 385 nm:
0.5 ms light pulse: $(39 \pm 14) \cdot 10^3$ Photons/mm²



ICCD: ROI overexposed for light pulses > 4 ms.

Results EMCCD (em-gain 100) versus **ICCD:**
- λ= 500 nm: **EMCCD** 2 times **ICCD** sensitivity
- λ= 470 nm: **EMCCD** equals **ICCD**
- λ= 385 nm: **EMCCD** 0.5 times **ICCD**

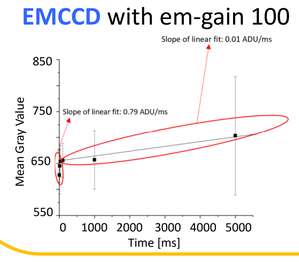
Reason: Wavelength-dependent quantum efficiency

Results for pco.edge 4.2bi & Kinetix 22:
- **EMCCD** (em-gain 100) ≈ 3 times **sCMOS** sensitivity
- **pco.edge 4.2bi & Kinetix 22** (Sub-Electron Mode) have almost equal sensitivity ⇒ special software modes not advantages for given slight duration

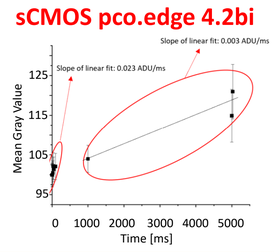
Background (Dark Count) Measurements

- **EMCCD** & **sCMOS** cameras: cooled sensor and constant temperature; non-linear increase of dark counts as a function of the exposure time
- **ICCD:** field emission from photo-cathode (450±60 photons/ms/cm²) ⇒ neglectable for pulsed operation

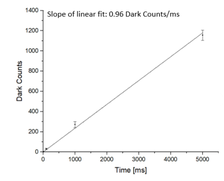
EMCCD with em-gain 100



sCMOS pco.edge 4.2bi

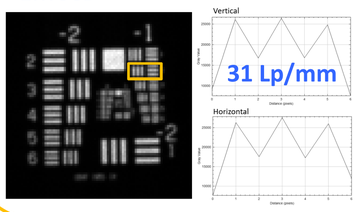


ICCD
Dark counts from photo-cathode

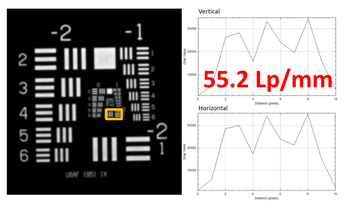


Spatial Resolution at Sensor Plane

EMCCD



sCMOS pco.edge 4.2bi



ICCD

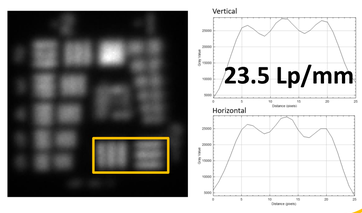
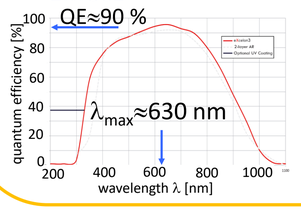


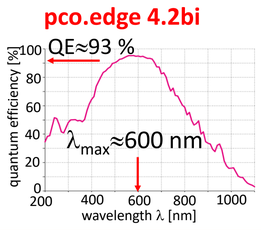
Photo-cathode Sensitivity (from Manufacturer)

- Different wavelength dependence expected and experimentally confirmed

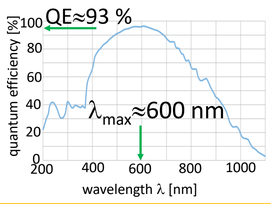
EMCCD



pco.edge 4.2bi



Kinetix 22



ICCD

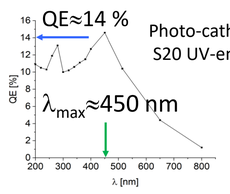


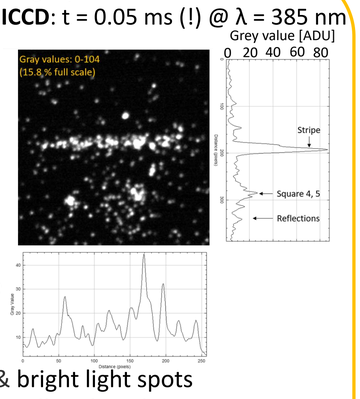
Photo-cathode: S20 UV-enhanced

Interpretation & Conclusion

Set-up low-light camera characterization:
- **sCMOS:** have the best spatial resolution
- Pulsed LEDs as light source
- Characterization for wavelength-dependent sensitivity
- Signal-to-noise ratio in a homogeneous illuminated ROI: Highest for **EMCCD** (λ ≈ 500 nm) or **ICCD** (λ ≤ 400 nm).
- **sCMOS:** SNR depends on wavelength & acquisition mode but comparable for both types
- **sCMOS** & **EMCCD**: projection from 0.5 ms light pulse duration are visible
- **sCMOS:** Rolling shutter readout has to be considered for the acquisition
- **ICCD**: a 0.05 ms light pulse is sufficient for a horizontal projection ⇒ best suited for single photon detection due to very **low dark counts** & bright light spots
- Future improvement by using a homogeneously illuminated pattern by an Ulbrecht sphere

⇒ **Quantitative comparison is difficult ⇒ best suited camera depends strongly on application:** **ICCD** for single photons; **EMCCD** almost same sensitivity (!), but some noise, **sCMOS** for more light.

Single photon detection:
ICCD: t = 0.05 ms (!) @ λ = 385 nm



References

Further reading: Leonie Bauer, 'Characterization of low-light Cameras for Beam Diagnostics, Master Thesis University Frankfurt 2024
R. Hampf, A. Ulrich, J. Wieser, 'Evaluation of CCD cameras for beam profile monitoring with high intensity particle beams traversing gases', EPJ Techn Instrum (2020) 7: 5 https://doi.org/10.1140/epjti/s40485-020-00057-0
[1] www.princetoninstruments.com/products/proem-family/pro-em
[2] www.excelitas.com/de/product/pcoedge-42-bi-usb-scmos-camera , www.photometrics.com/products/kinetix-family/kinetix22
[3] www.exosens.com/company-about-exosens/photonis-germany-gmbh