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Electron detection

Armand Béché

12th May 2025

Quantitative Electron Microscopy 2025

11th – 23th May 2025

6th Edition

Port-Barcarès

Review and News of Quantitative TEM techniques

Overview

- How to detect electrons?
  - Scintillator
  - Direct detection

- Basic mathematical notions
  - Signal to noise ratio
  - Gain, dark reference and detector linearity
  - MTF and DQE

- CCD and DED

- Potential aberrations and distortions

How to detect electrons? Scintillator

- Electrons are first converted into photons before an eventual amplification step

- Applications: TEM viewing screen, HAADF detector, Secondary Electrons detector, CCD and CMOS camera’s

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How to detect electrons? Scintillator

- Scintillator types depend on photon detection
  - PMT: Blue/UV
  - CCD: Green M
- Efficiency depends on
  - Energy
  - Thickness
- Lowest decay time for fastest detection

	CRY 19	YAG:Ce	YAP:Ce	LuAG:Ce	CRY 18	LuAG:Pr	LuAP:Ce	BGO
Density	7.1 g/cm^3	4.57 g/cm^3	5.37 g/cm^3	6.73 g/cm^3	4.5 g/cm^3	6.73 g/cm^3	8.34 g/cm^3	7.13 g/cm^3
Hardness by Mohs	-	8.5	8.6	8.5	5.8	8.5	-	5
Index of refraction	1.81	1.82	1.95	1.84	1.79	1.84	-	2.15
Melting point	2100°C	1970°C	1875°C	2020°C	1980°C	2043°C	1960 °C	1050 °C
Crystal structure	monoclinic	cubic	rhombic	cubic	monoclinic	cubic	-	cubic
Hygroscopic	NO	NO	NO	NO	NO	NO	NO	NO
Wavelength of max. emission	420 nm	550 nm	370 nm	535 nm	425 nm	310 nm	365 nm	480 nm
Decay constant	41 ns	70 ns	25 ns	70 ns	45 ns	20 ns	18 ns	300 ns
Afterglow	-	<0.005 % at 6 ms	<0.005 % at 6 ms	-	-	-	-	<0.005% at 6 ms
Radiation length for 511 keV	2.1 cm	3.5 cm	2.7 cm	1.3 cm	2.74 cm	1.3 cm	-	1.1 cm
Photon yield at 300 K (27°C) x10^3 Photons/MeV	24	30	25	25	30	15-18	11	8-10
Integrated light output compared to NaI:Tl	75 % NaI:Tl	40 % NaI:Tl	70 % NaI:Tl	20 % NaI:Tl	80 % NaI:Tl	66 % NaI:Tl	-	15-20 % NaI:Tl

https://www.crytur.cz/materials/cry-19/

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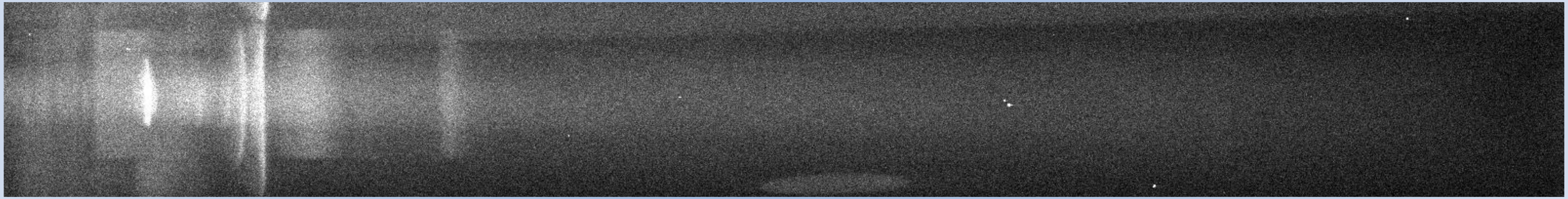
How to detect electrons? Scintillator

- Limitations:
  - Point spread function: photon emission comes from a larger source than the electron input position.
  - Afterglow due to scintillation decay.



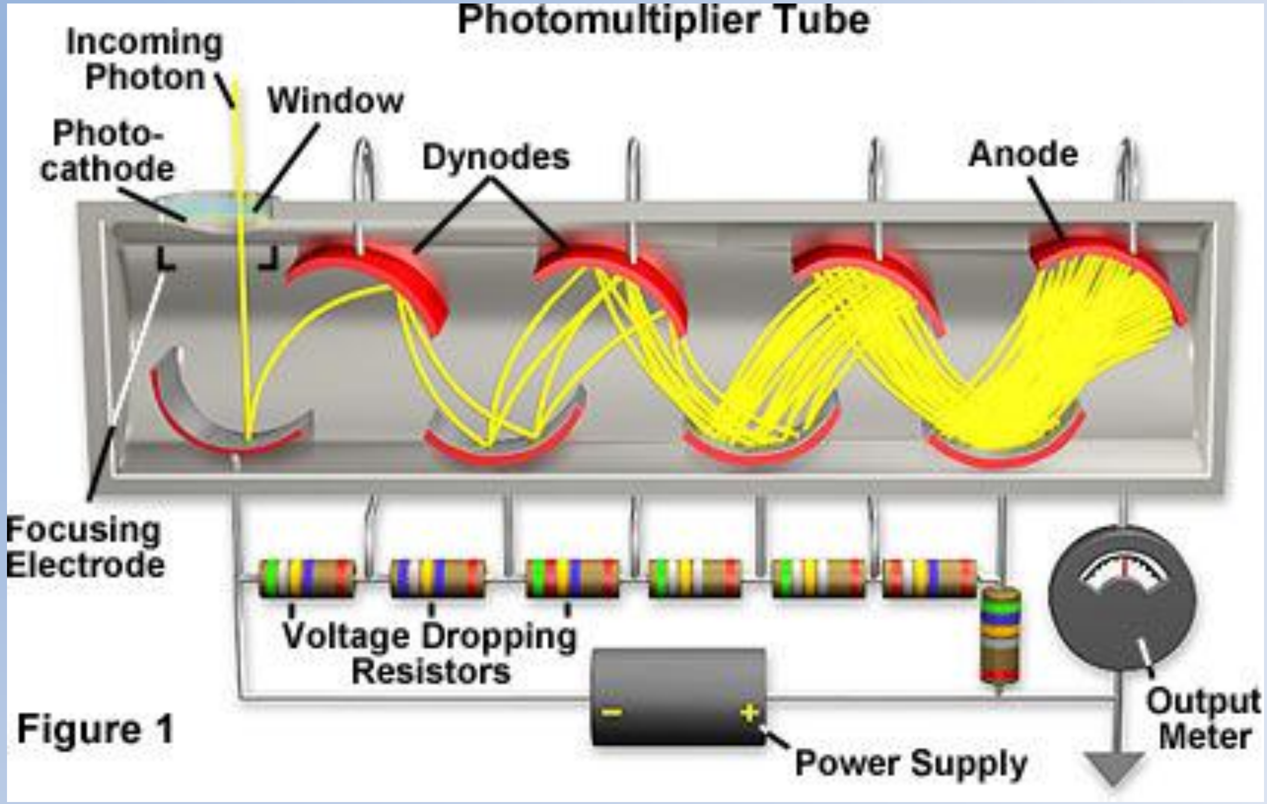
EELS camera
100s exposition
Microscope shutdown for 24 h

Nion UltraSTEM200
Camera EMCCD Princeton ProEM+
-70°C

Courtesy of Marcel Tencé, LPS, France

How to detect electrons? Scintillator

- Scintillators can be coupled to photomultiplier (PMT) tubes to increase signal intensity.
- Used in STEM, cathodoluminescence (CL)
- Needs high voltage (1-2 kV)



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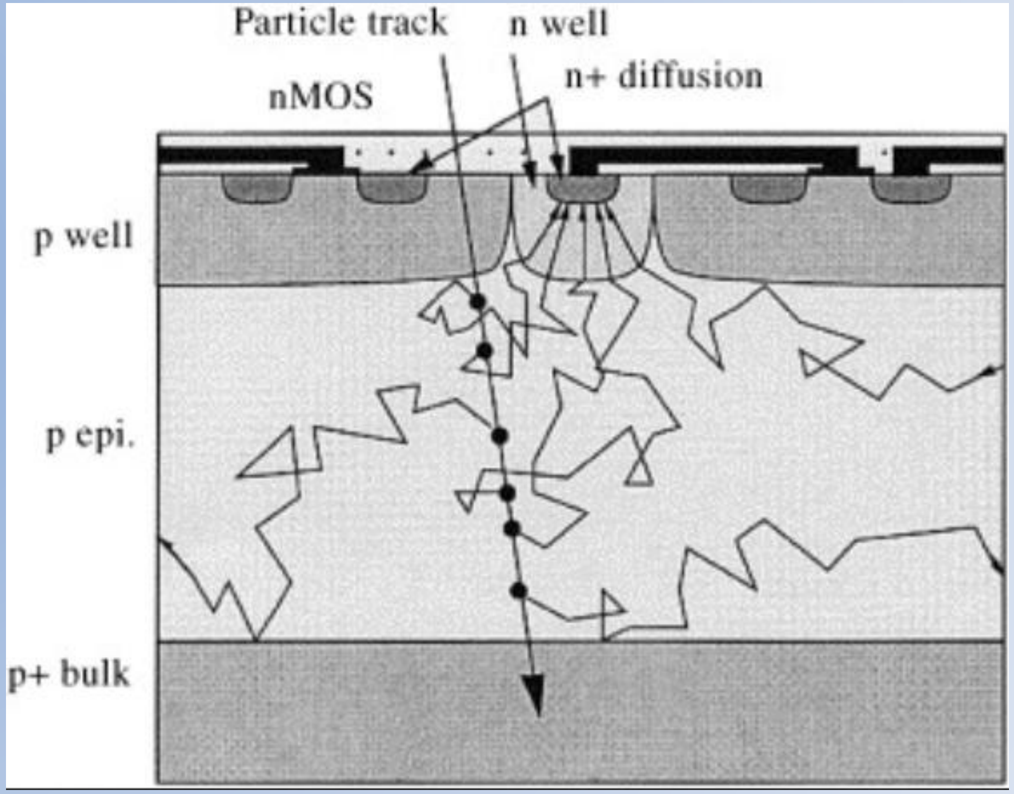
How to detect electrons? Direct detection

- Incident electrons create a cascade of ionization events (electron/hole pairs) separated and detected thanks to a PN diode

- Electronic placed near the active part

- Applications: STEM detectors, Direct Electron Detectors

- Limitations:
    - Either large pixels (but beam hard)
    - Or beam sensitive camera (but small pixels)



Milazzo A-C. et al., Ultramicroscopy 104.2 (2005) 152-159.

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Overview

- How to detect electrons?
  - Scintillator
  - Direct detection
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Basic mathematical notions – SNR

- Signal: What needs to be measured

- Noise:

  - Expected variations on the measured signal
    - Poisson (or shot) noise: $\sqrt{N}$
    - Gain variations

  - Extra unwanted signal
    - Dark current
    - Signal background
    - Other events (X-Ray…)

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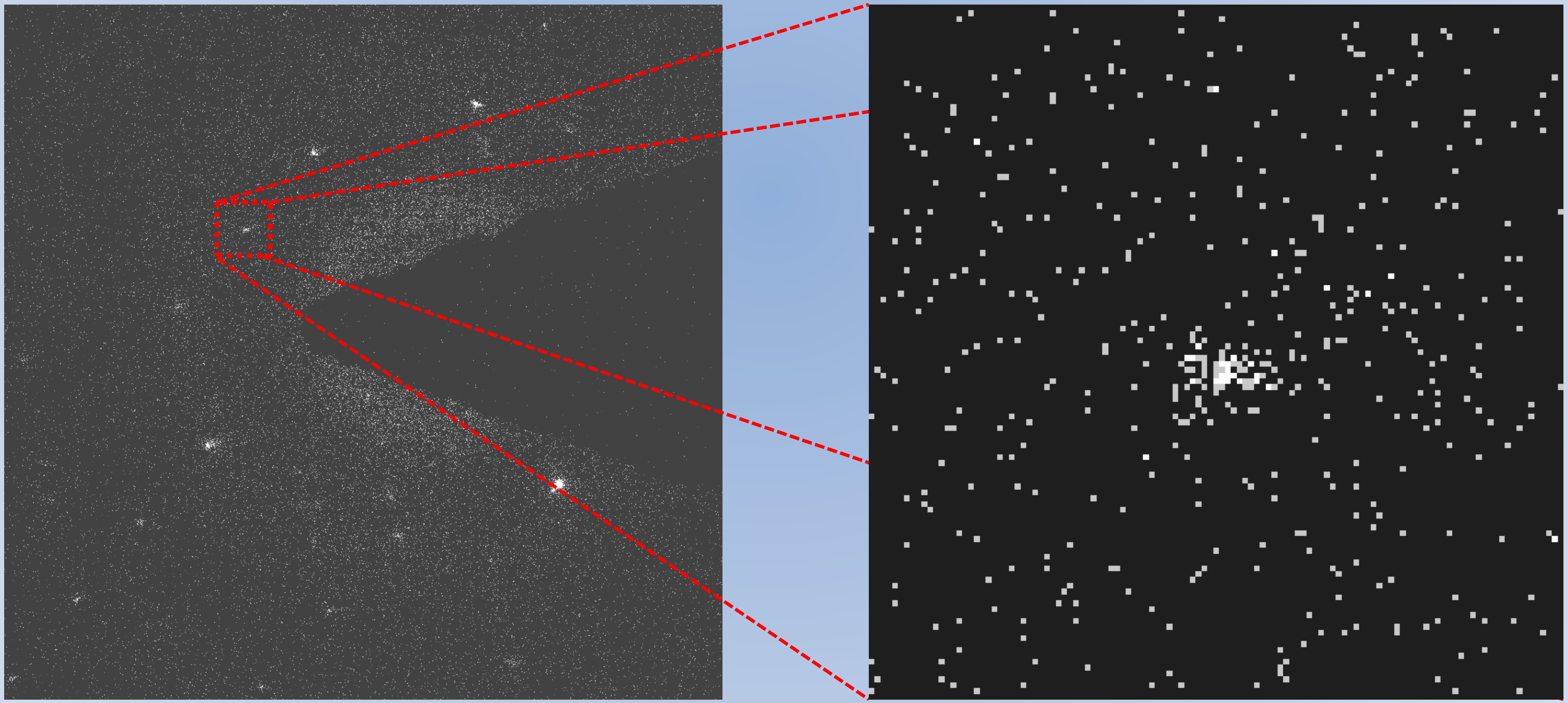
Basic mathematical notions – SNR

- Poisson noise

Comes from low statistic on the signal and results in lack of details



Diffraction pattern of a MOF 74 on a K2 Camera at 300 kV (courtesy from Matthias Quintelier, EMAT)

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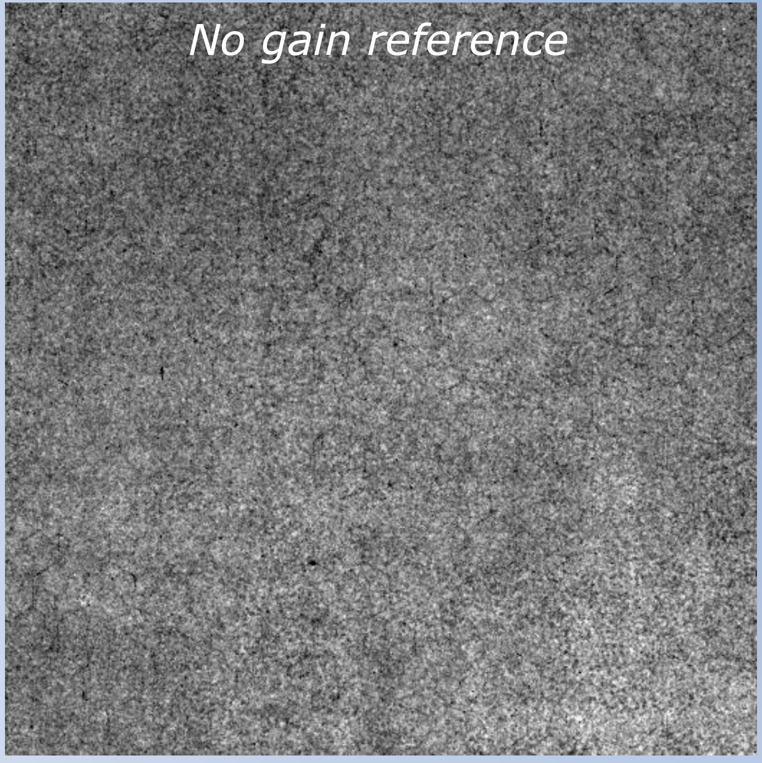
Basic mathematical notions – SNR

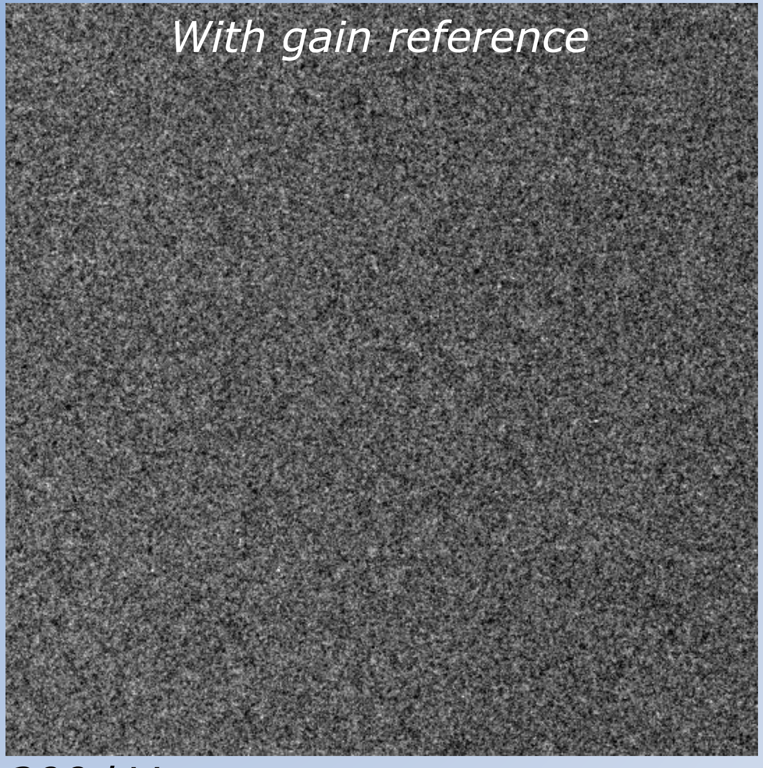
- Gain reference

  To compensate for inhomogeneous response of the detector and optical fiber array

No gain reference



With gain reference



US1000 CCD at 300 kV

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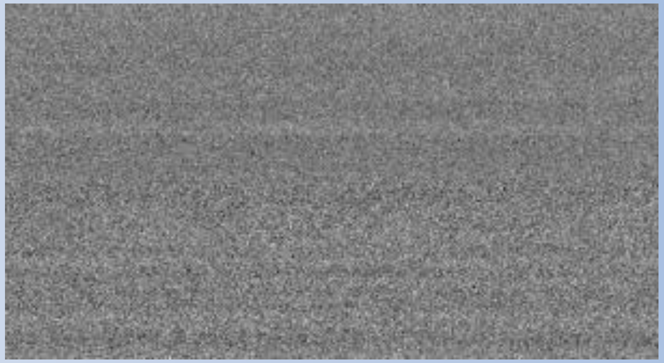
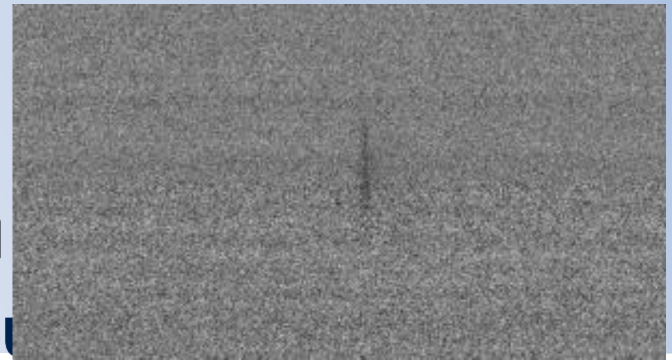
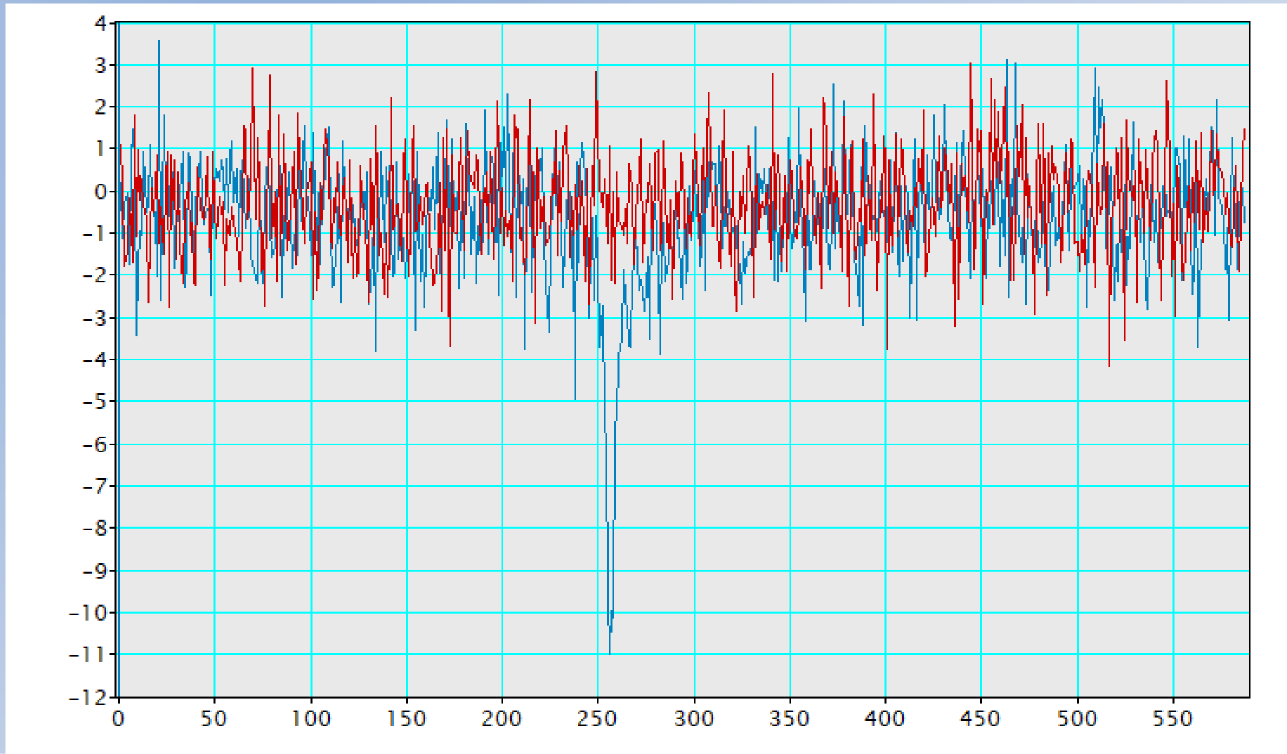
Basic mathematical notions – SNR

- Dark current

  Issued from thermal noise in the read-out electronic
  Strongly reduced at low temperature (cooling down of sensor)
  Correction helps removing time variable artefact (phosphorus decay time…)







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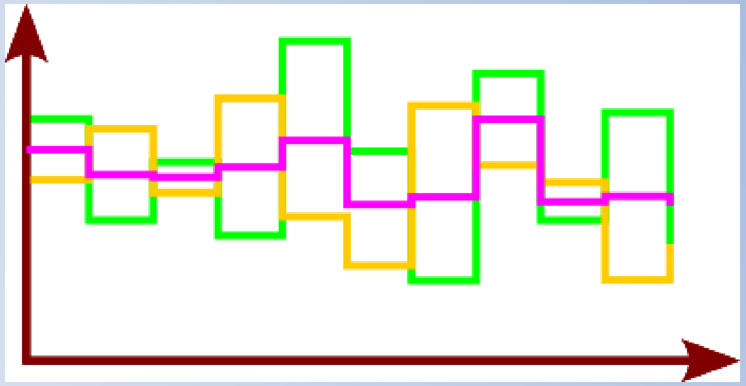
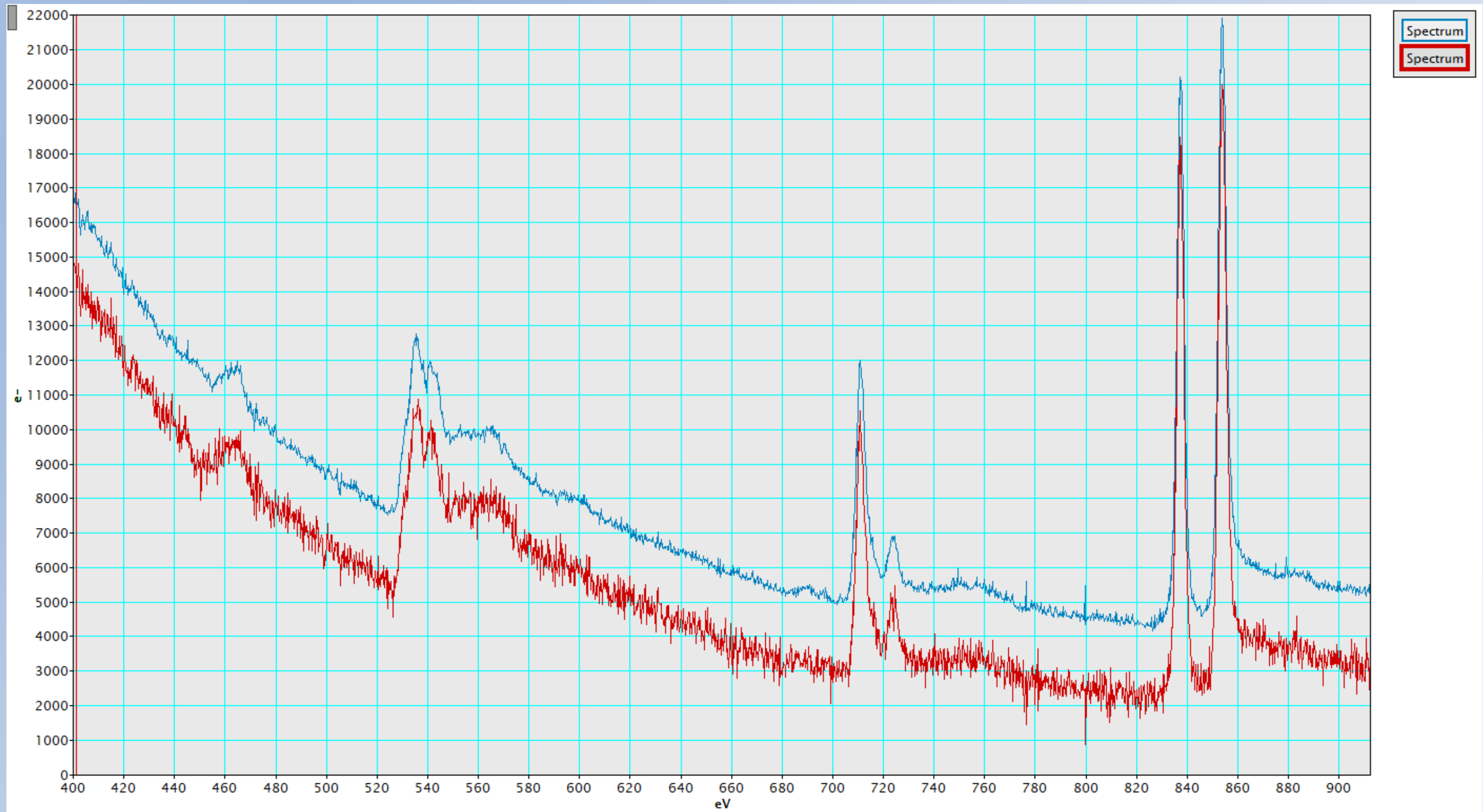
Basic mathematical notions – SNR

- Dark current

For multiple acquisitions (typical for EELS Maps), multiple gain references are necessary





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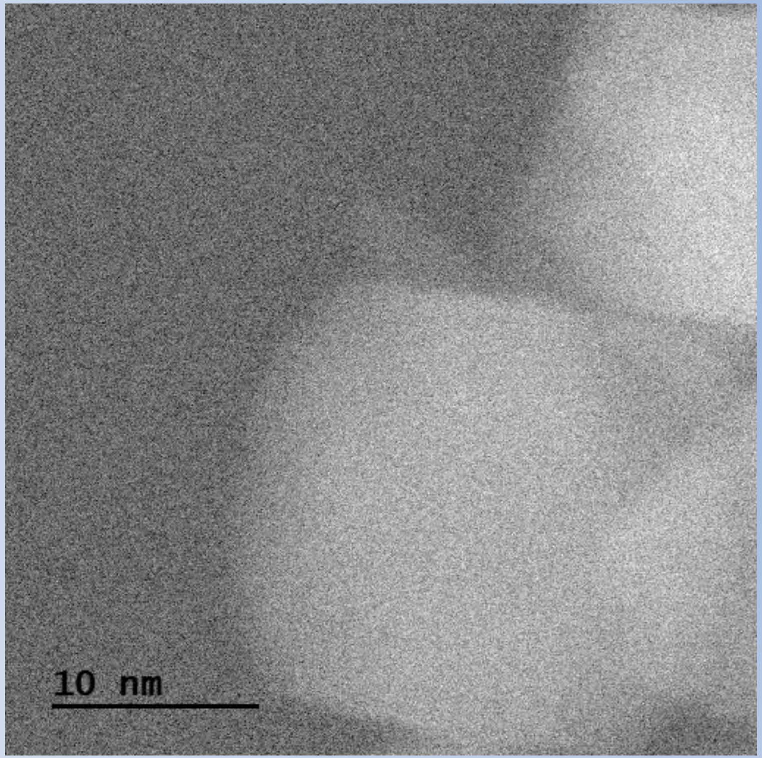
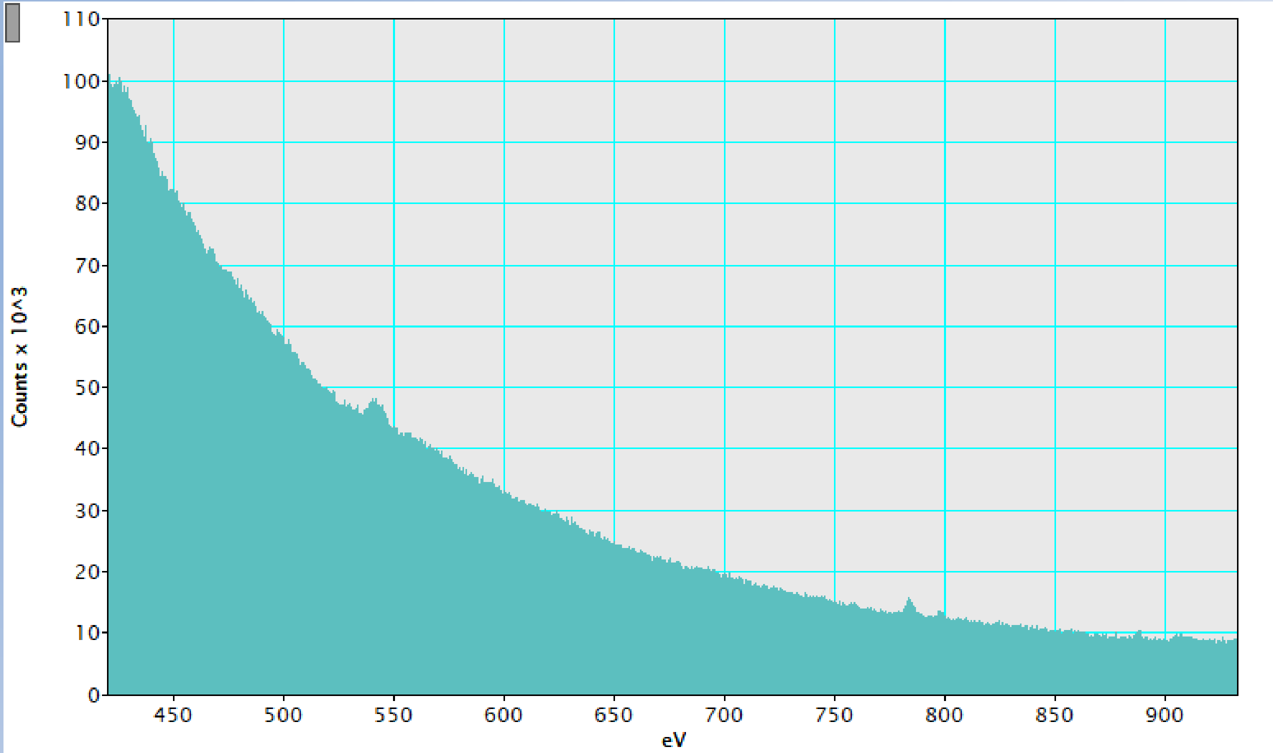
Basic mathematical notions – SNR

- Signal background

  EELS background, Support background…



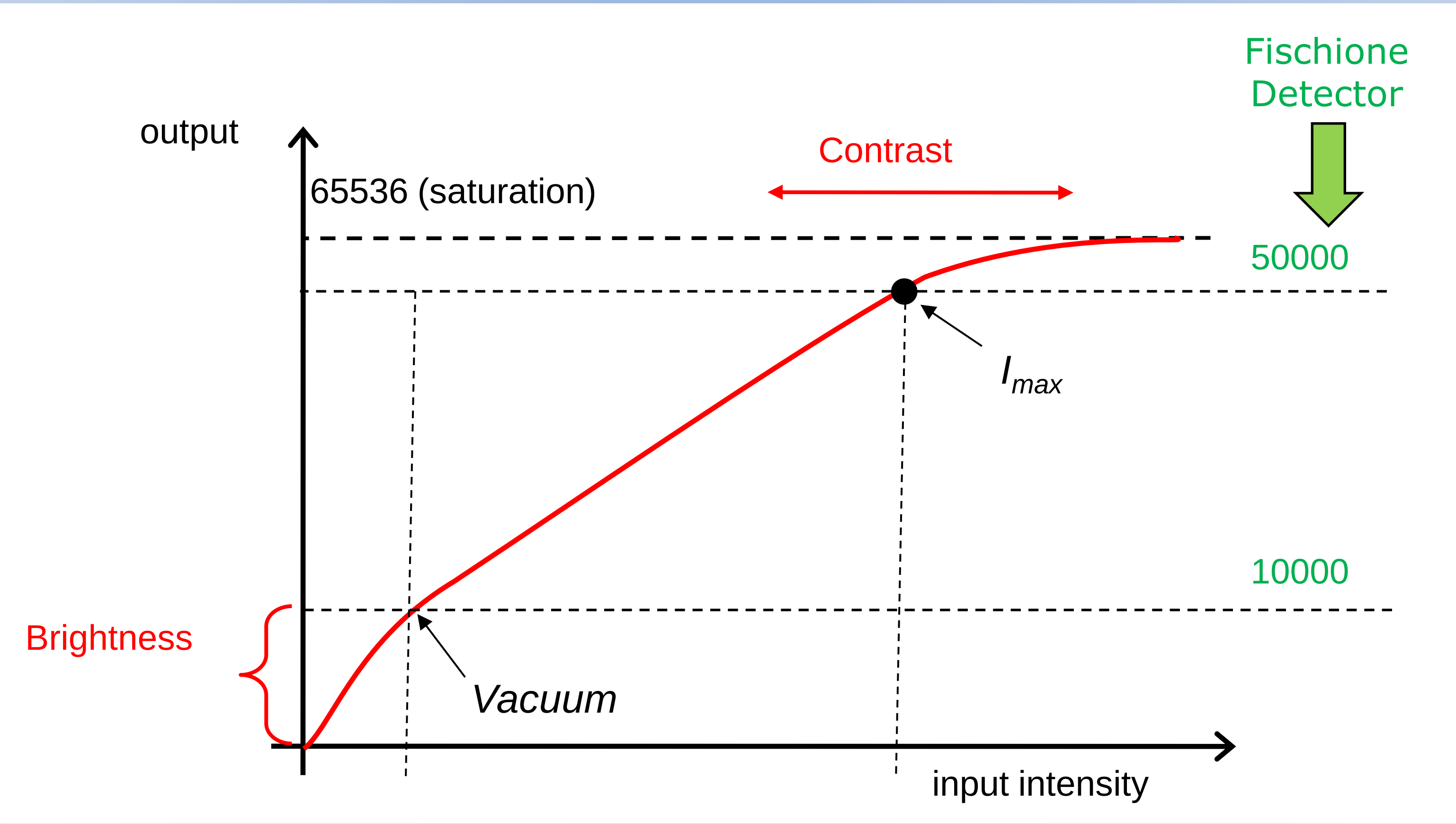


CoO particles at the surface of CeO_3 in gaseous environment (T. Altantzis, A. Béché)

Basic mathematical notions – SNR

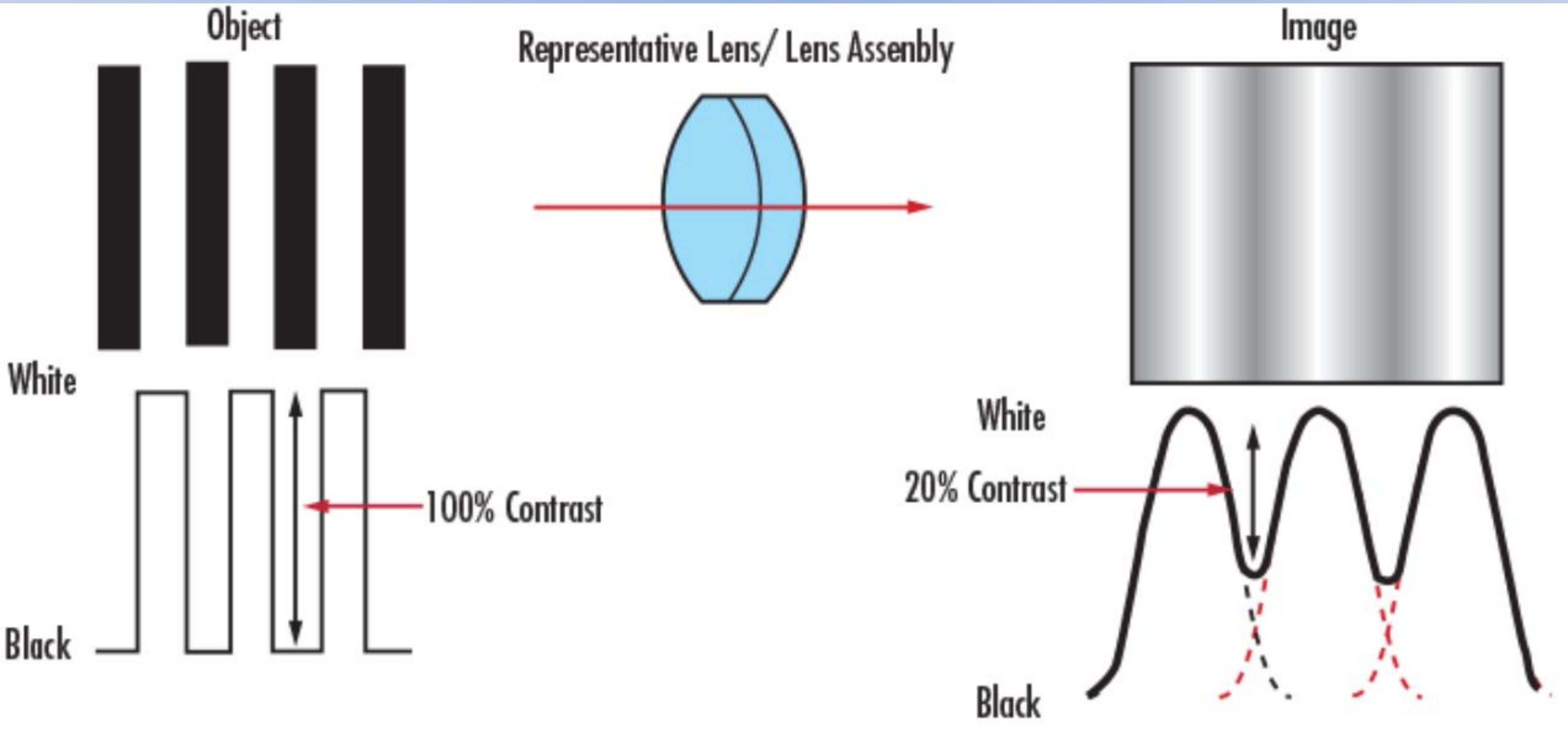
- Detector linearity

Response of the detector/electronic only linear in a certain range



Basic mathematical notions – MTF/DQE

- The MTF (Modulation Transfer Function) describes how an object is imaged by an optic system.
  → How properly high frequencies are sampled by the sensor



https://www.edmundoptics.eu/knowledge-center/application-notes/optics/introduction-to-modulation-transfer-function/

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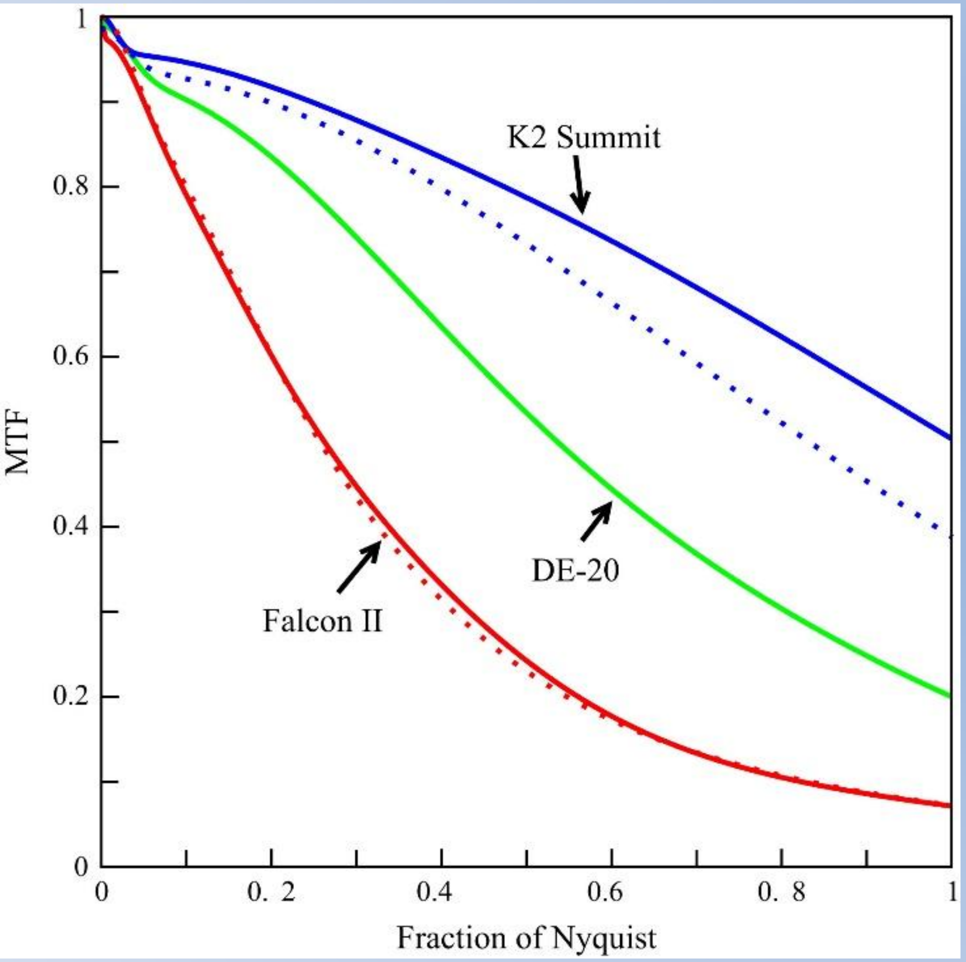
Basic mathematical notions – MTF/DQE

- Typical MTF of direct electron detector



Nyquist frequency corresponds to the highest frequency in a line of pixel

→ Period of 2 pixels

McMullan G. et al., Ultramicroscopy 147 (2014) 156-163

Basic mathematical notions – MTF/DQE

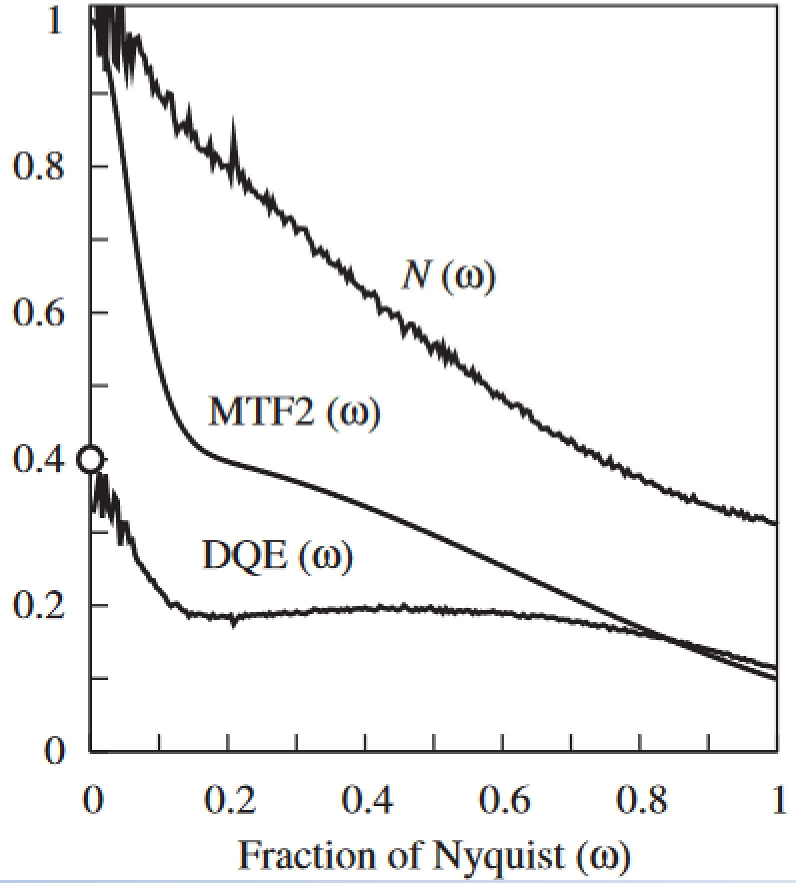
- DQE (Detective Quantum Efficiency): Ratio of squared output to squared input SNR's

$$\mathrm{DQE} = (S/N)^2_{\mathrm{out}}/(S/N)^2_{\mathrm{in}}$$

$$\mathrm{DQE}(\omega) = \mathrm{DQE}(0)\,\frac{\mathrm{MTF}^2(\omega)}{\mathcal{N}(\omega)}$$

Fraction of Nyquist

Normalized noise power spectrum



McMullan G. et al., Ultramicroscopy 109-9 (2009) 1126-1143

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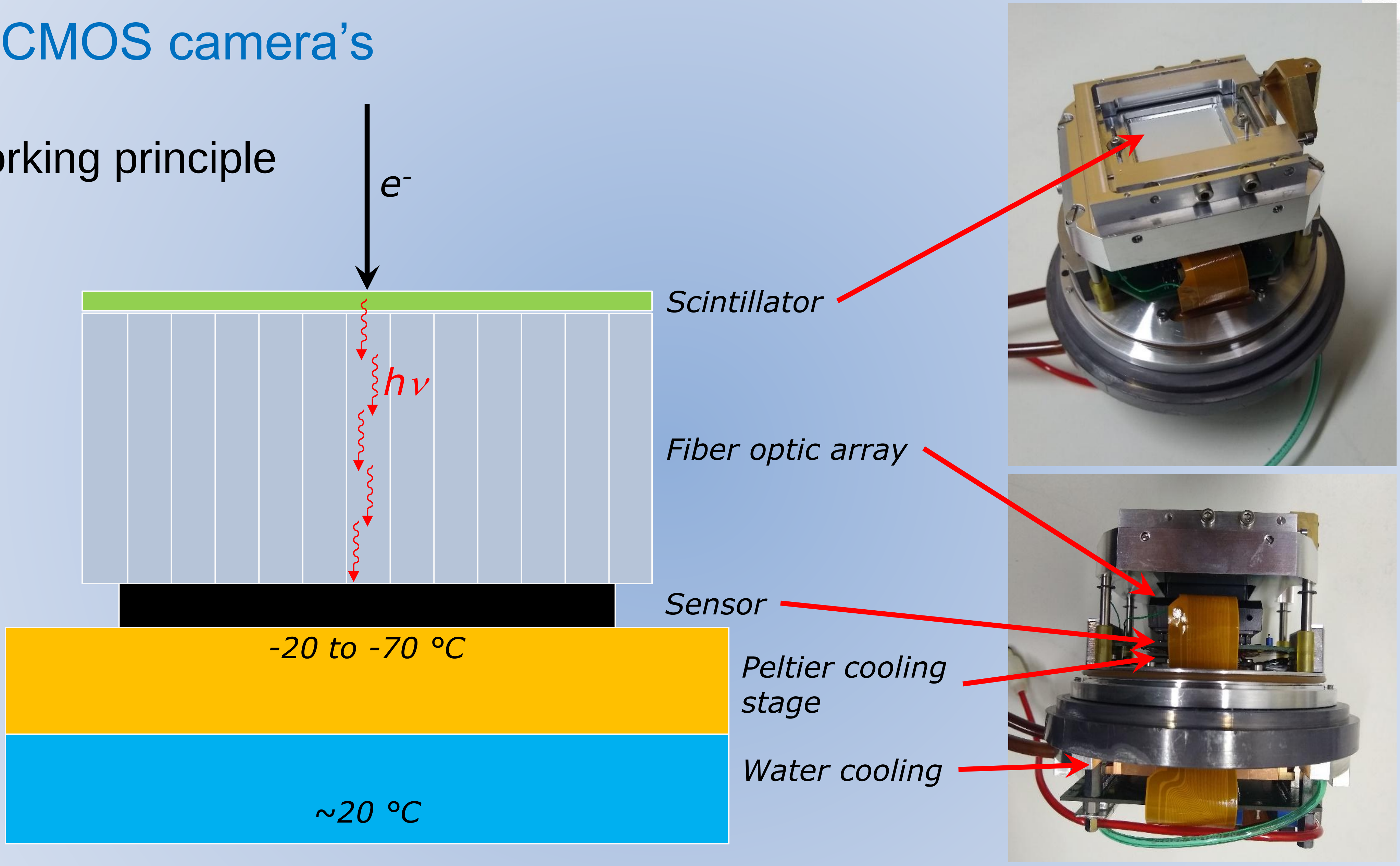
CCD/CMOS camera’s

- Working principle



Post GIF Gatan US1000 CCD

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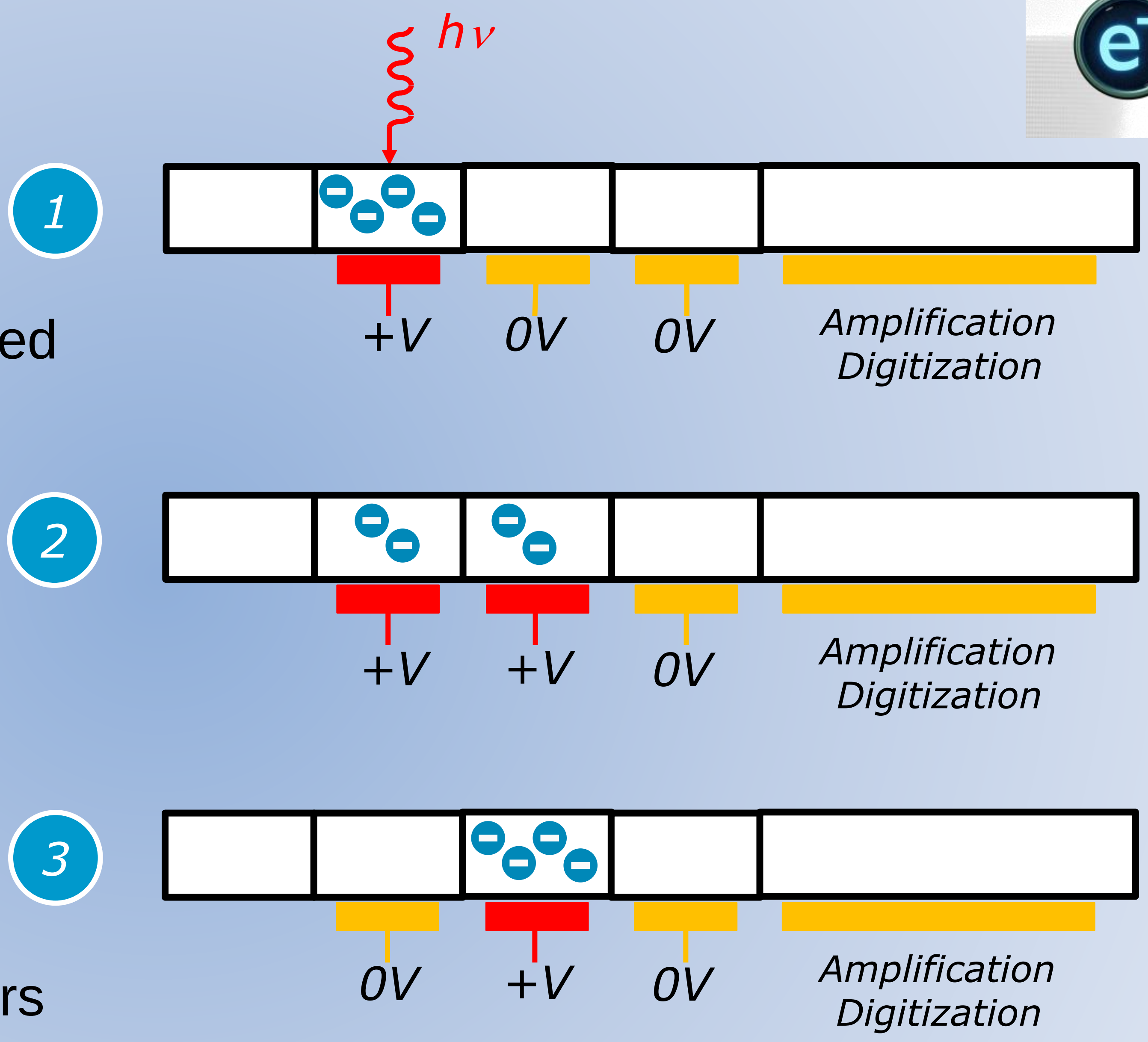
CCD/CMOS camera's

- Read-out principle
  - Pixels are defined by p-doped metal oxide capacitors
  - Charges are moved from pixel to pixel along a line
  - Signal is amplified and digitized at the end of each line
  - In CMOS sensors, capacitors are replaced by transistors



CCD/CMOS camera’s

- Difference CCD/CMOS camera’s
  - CMOS camera’s are less sensitive to blooming effect (leaking out of signal from adjacent pixels)
  - CCD camera’s have typically less read-out noise (but that starts now to level off)
  - CMOS camera’s can use rolling shutter mode (one line is read while the other one are still in exposition mode), eliminating the need of blanking the beam during read-out time

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CCD/CMOS camera’s

- Saturation/Beam sensitivity
  - Most digitizing parts have a 16 bit ADC (Analog to Digital Converter)
  - This offers 65,535 gray level
  - Above this value, the signal is no longer registered and reaches a maximum
  - Too intense electron beams (typically above saturation) can irremediably damage the scintillator

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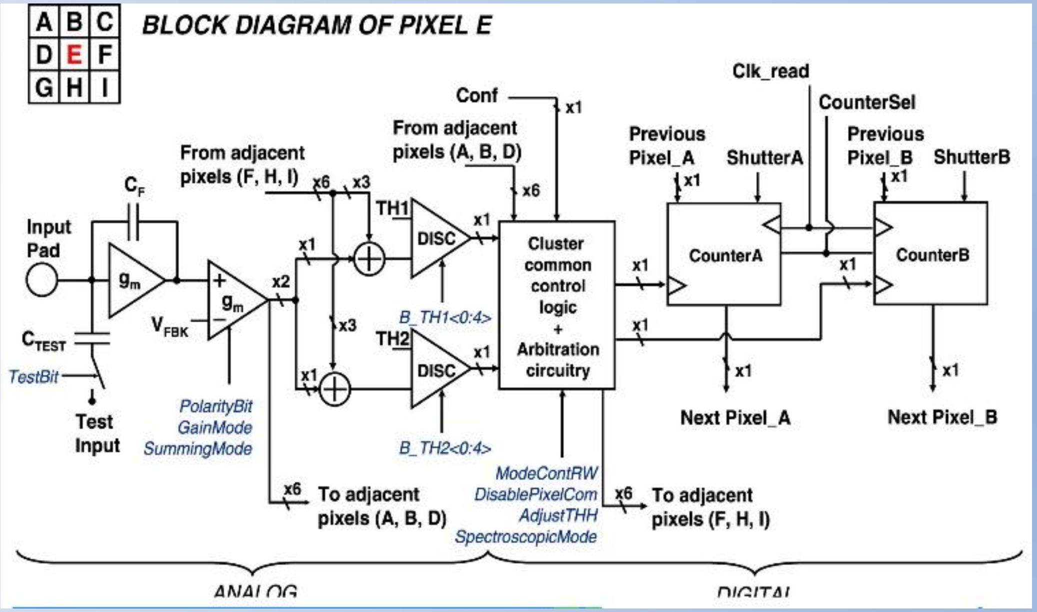
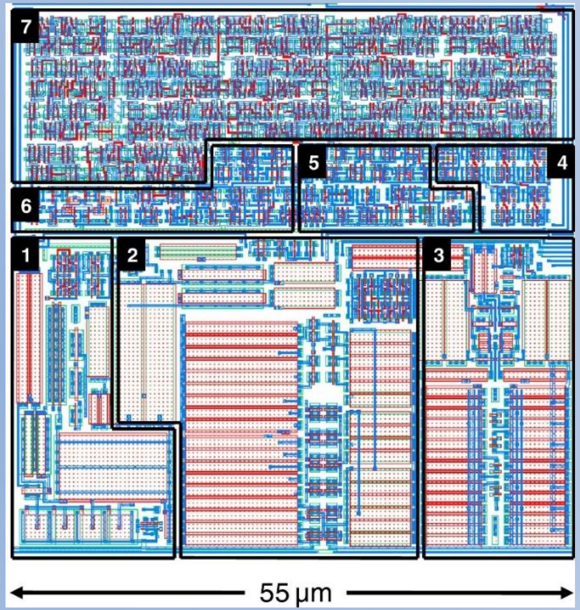
Direct Electron Detectors

- Readout electronic right below each pixel (1600 transistors/pixel for the Medipix³)





Ballabriga, R., et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 633 (2011): S15-S18.

- Two different types of detectors
  - Thin sensors
  - Thick sensors

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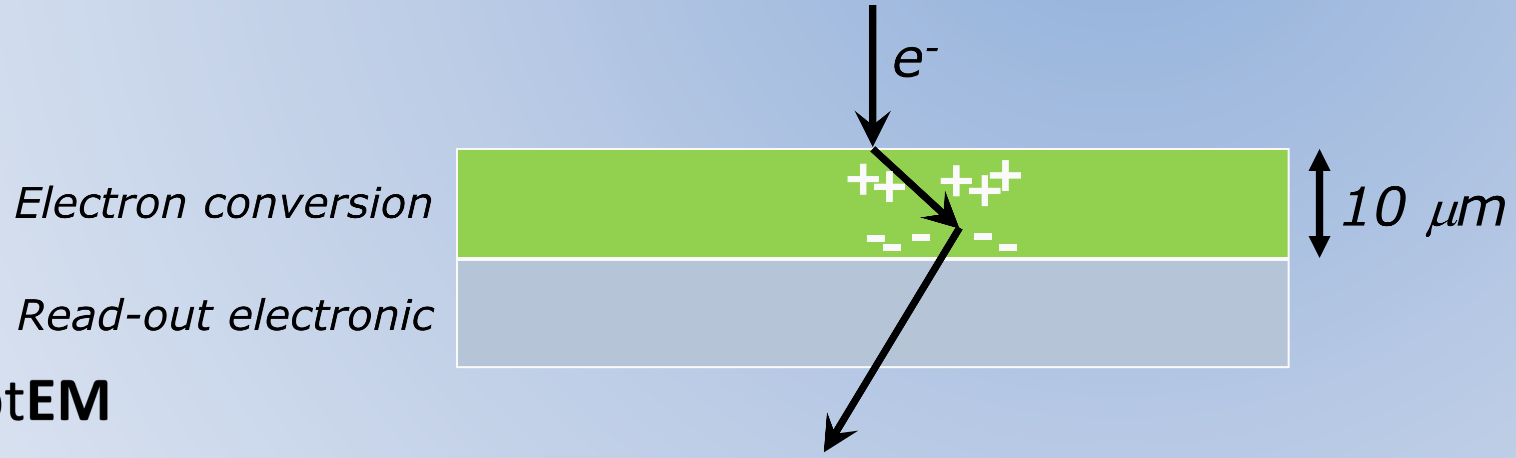
Direct Electron Detectors

- Thin sensors (DE16/Apollo, K3, Falcon…)

    - Small pixel size (5 to 14 μm)
    - Large pixels array (4k x 4k or more)
    - Fast read-out time (100 to 1500 frames/s)
    - Quickly saturates (10's to 100's e^-/pixel max)
    - Electron beam sensitive (10^9 total e^-/pixel max)
    - Most efficient at high voltage (200/300 kV)



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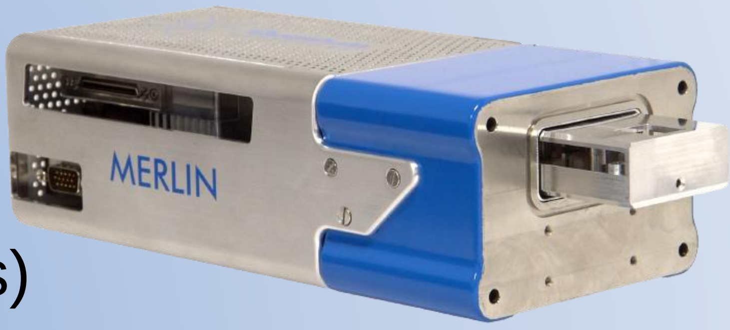
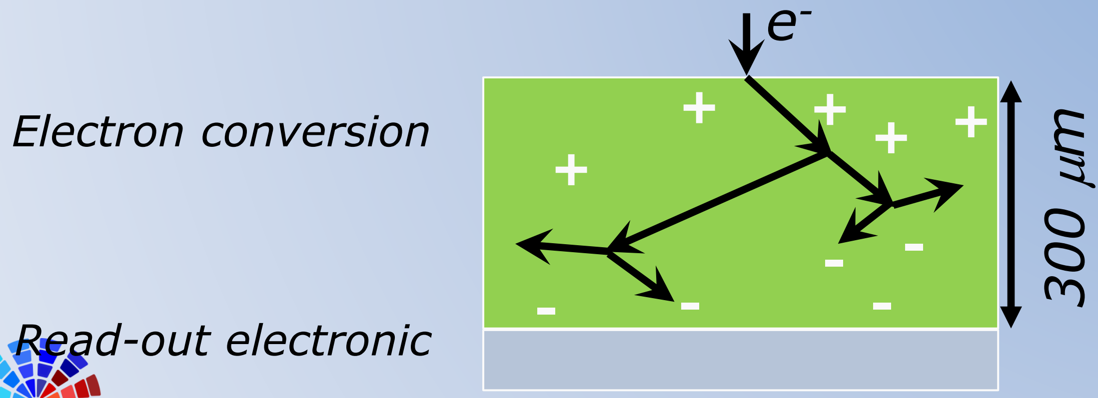
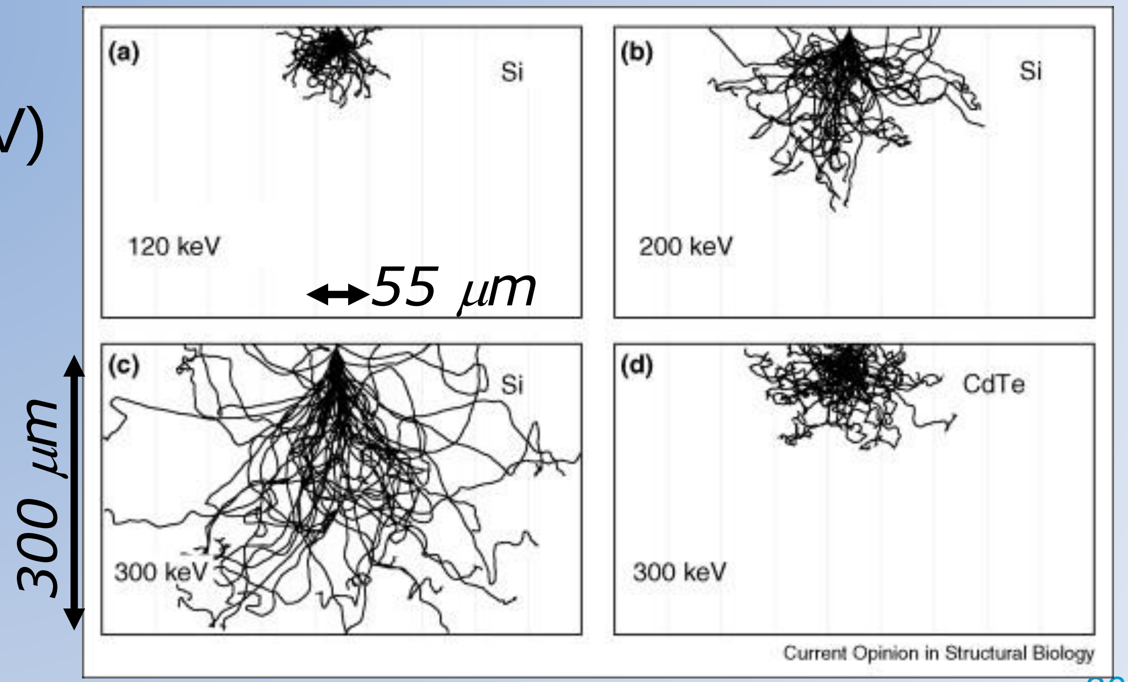
Direct Electron Detectors

- Thick sensor (Medipix, Stela, Arina…)
    - Large pixel size (55 to 120 μm)
    - Small pixel array (128x128 to 512x512)
    - Very fast readout time (1,200 to 120,000 frames/s)
    - Hard to saturate
    - Beam hard
    - Most efficient at low voltages (60/80 kV)







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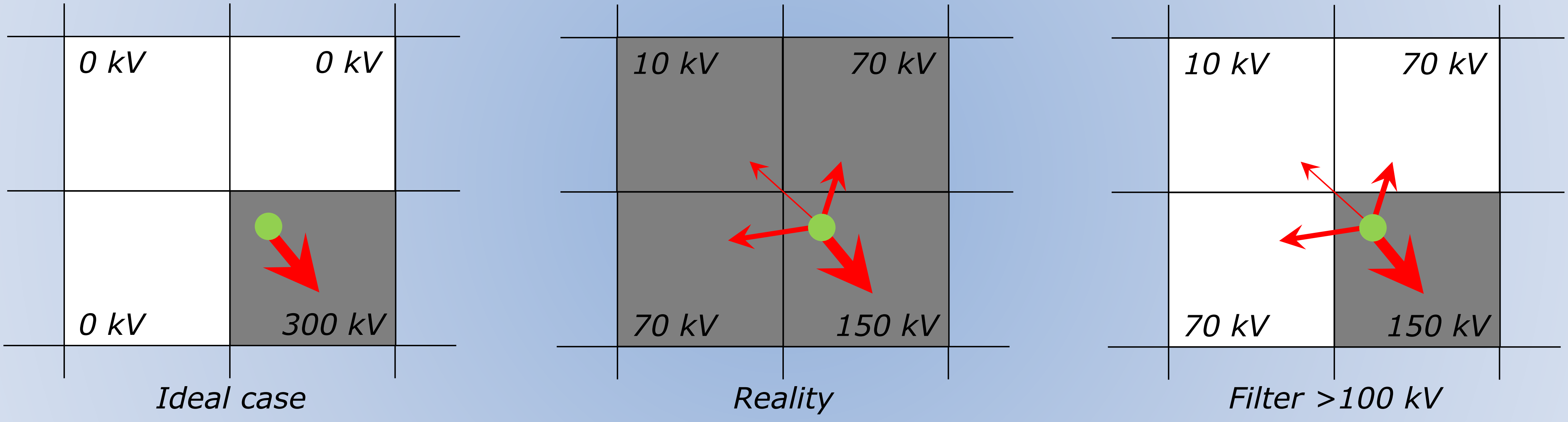
Faruqi and Henderson, Current opinion in structural biology 17.5 (2007) 549-555

Direct Electron Detectors

- Notion of threshold:



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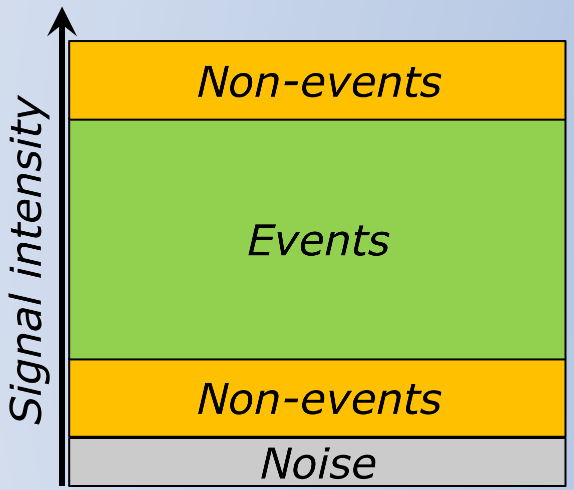
Direct Electron Detectors

- Notion of threshold:



- Signal measured by each pixel are locally pre-treated
- Can be filtered by energy (directly linked to signal intensity)
- Allow limiting the amount of cross-talk between pixel
- Could lead to lack of detection

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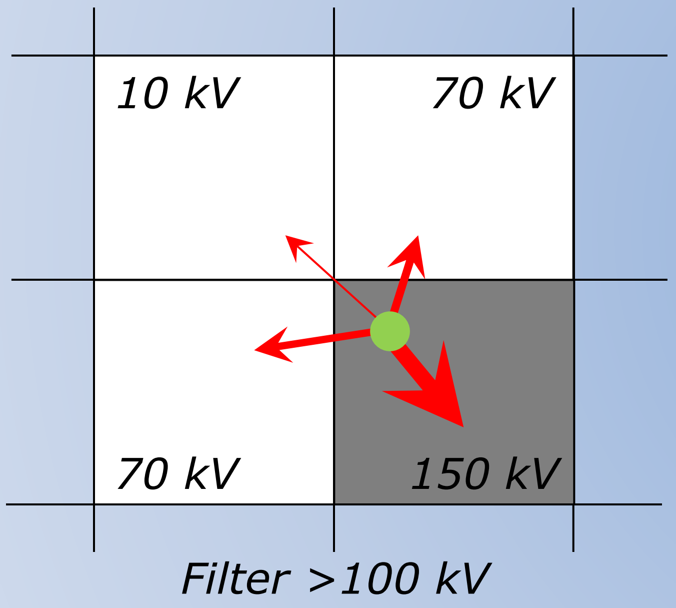
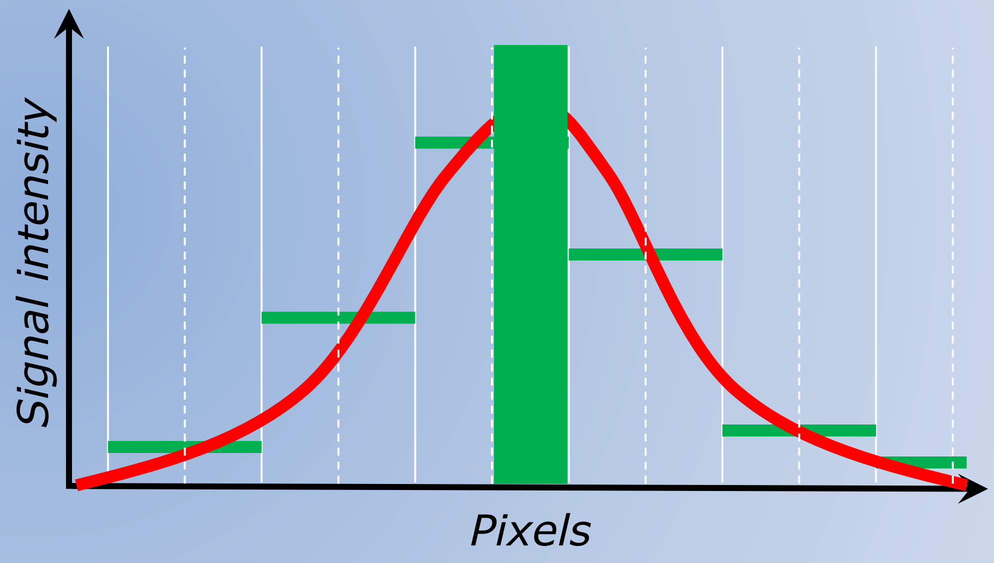
Direct Electron Detectors

- Super resolution:





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Direct Electron Detectors

- Maximum speed and data rate

  - K3: 5760 x 4096 sensor running at 150 fps, image coded on 16 bits

    56 Gbits/s = 6,6 Gb/s
    Fills a 1 Tb space in 152 s

  - Medipix 3: 256 x 256 running at 1200 fps, image coded on 16 bit

    1,2 Gbits/s = 157 Mb/s
    Requires 32 Gb of space for one 4D STEM map of 512 x 512

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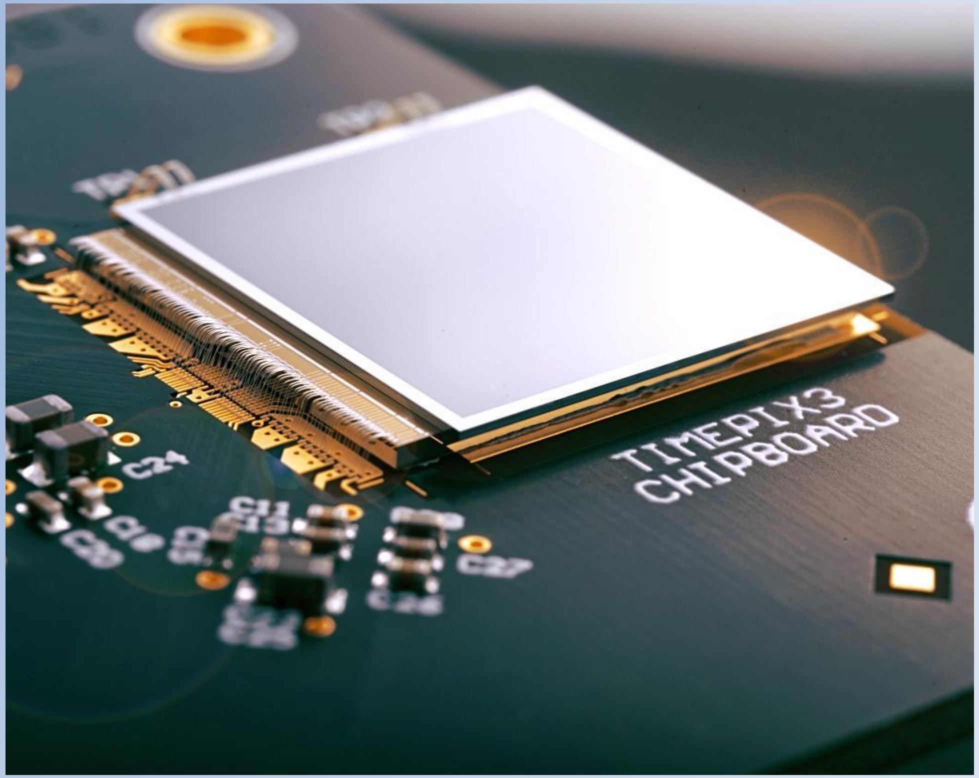
Direct Electron Detectors

- TimePix: Detector with event-based read-out
- Event driven detector providing position, energy and time of arrival (resolution of ~1.6 ns) of each detected event
- Basically no speed limit
- Maximum data stream of 40 million counts/s equal to a beam current of maximum 6 pA
- Designed for low dose imaging



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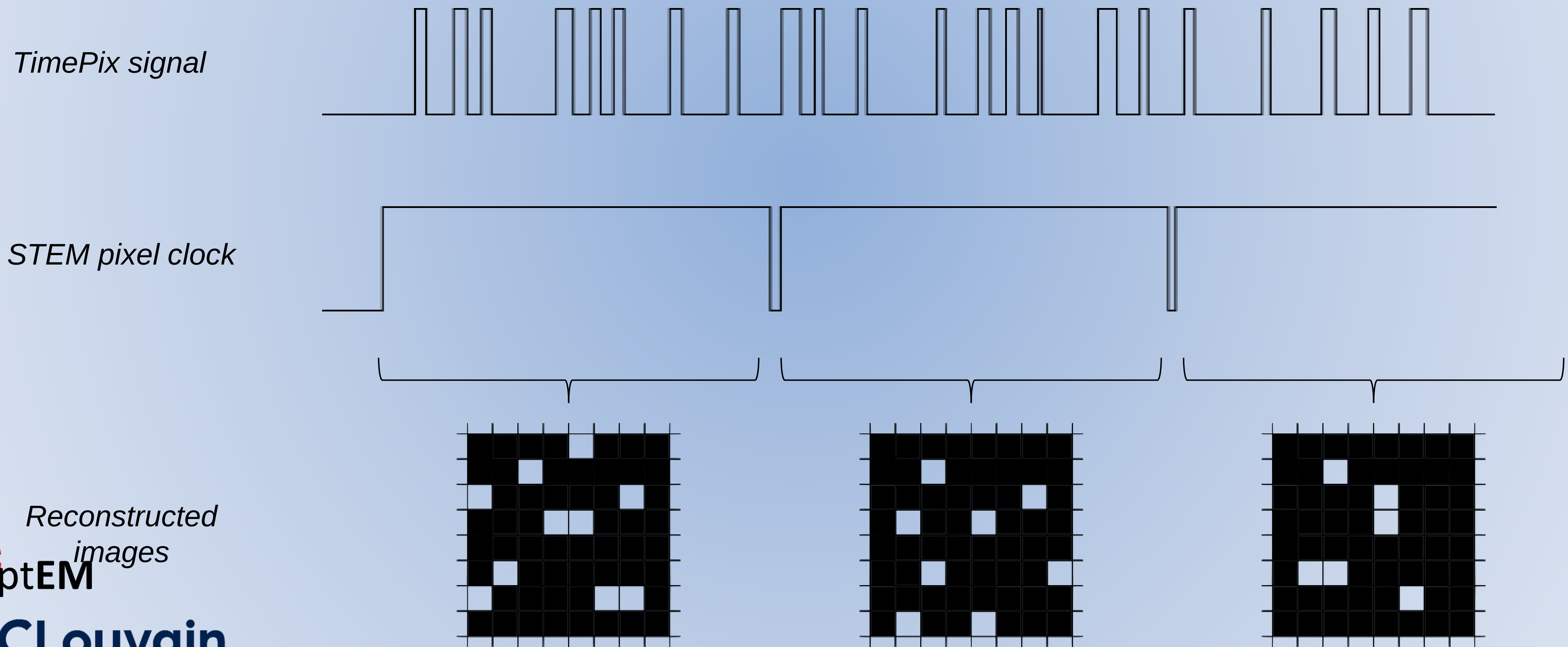
Direct Electron Detectors

- Images are reconstructed from the stream of data thanks to the synchronization with the scan engine



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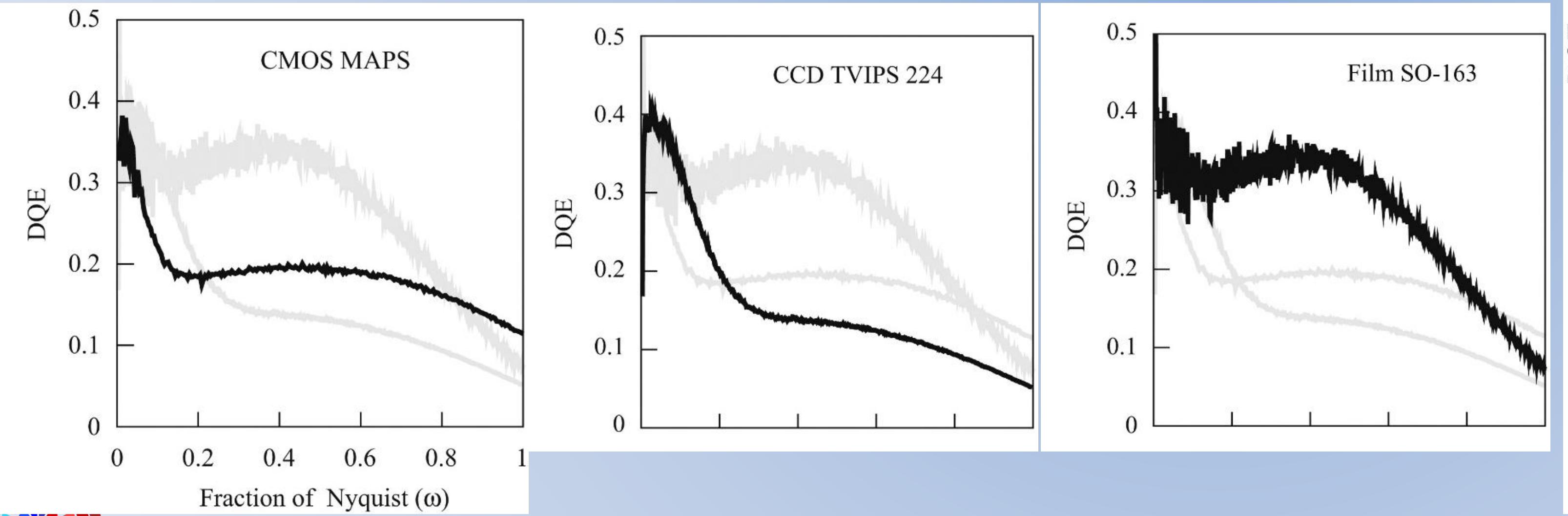
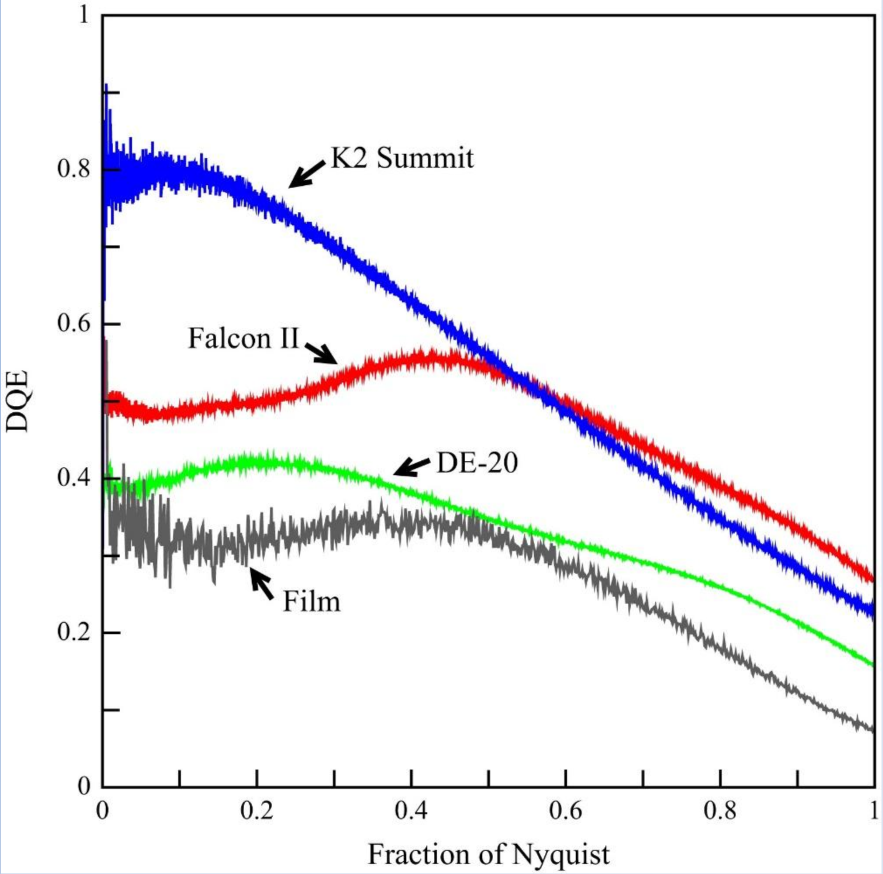
CCD and DED

- DQE comparison (300 kV)

DED

CCD/Films





McMullan G. et al., Ultramicroscopy 109.9 (2009) 1126-1143

McMullan G. et al., Ultramicroscopy 147 (2014) 156-163

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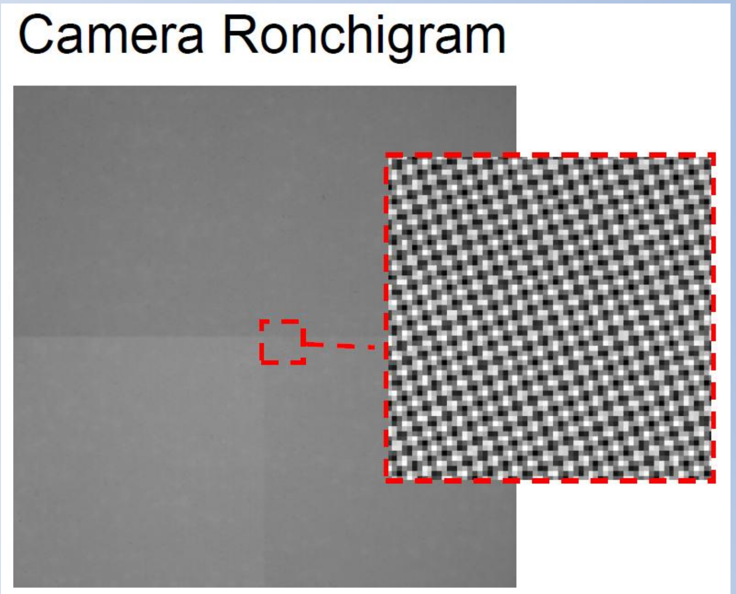
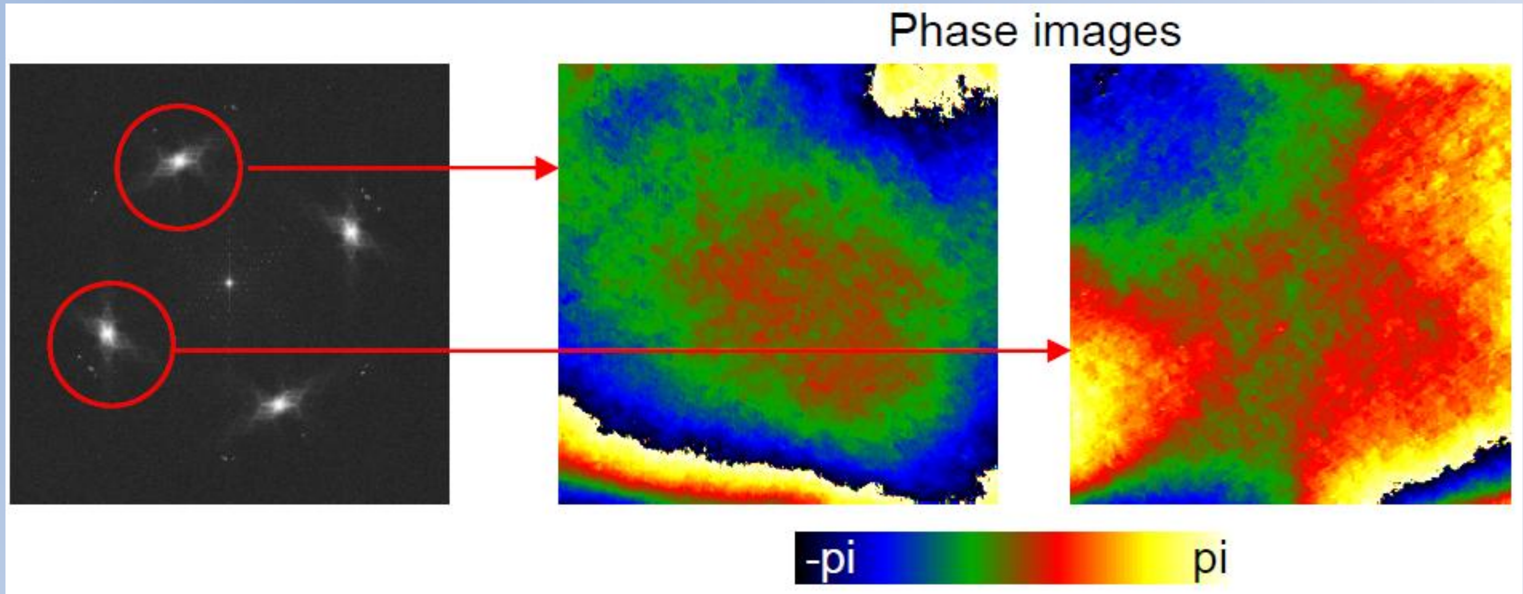
Aberrations and distortions

- Camera distortions
  - Pixels are not perfectly aligned, leading to high frequency distortions
  - Camera ronchigram could be provided by manufacturers to be quantified





Deneulin T. et al., 18th IMC Proceedings, 2014

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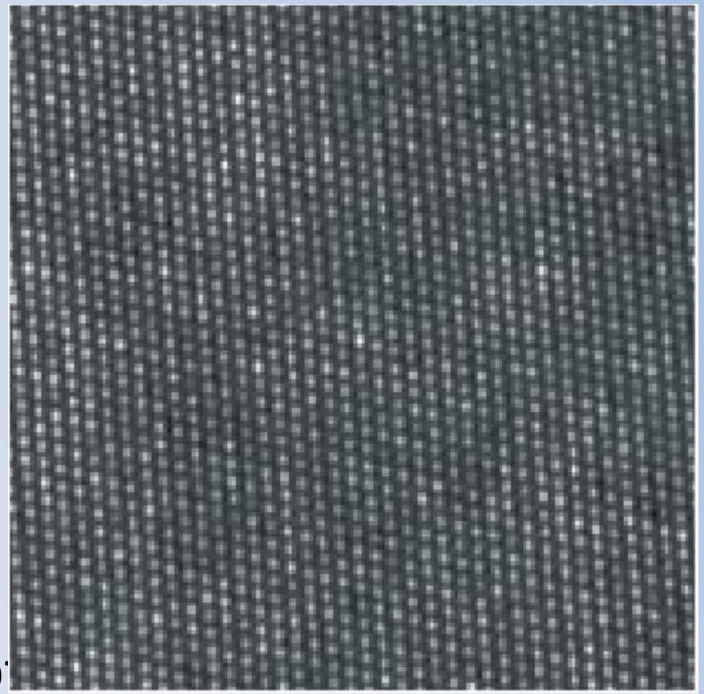
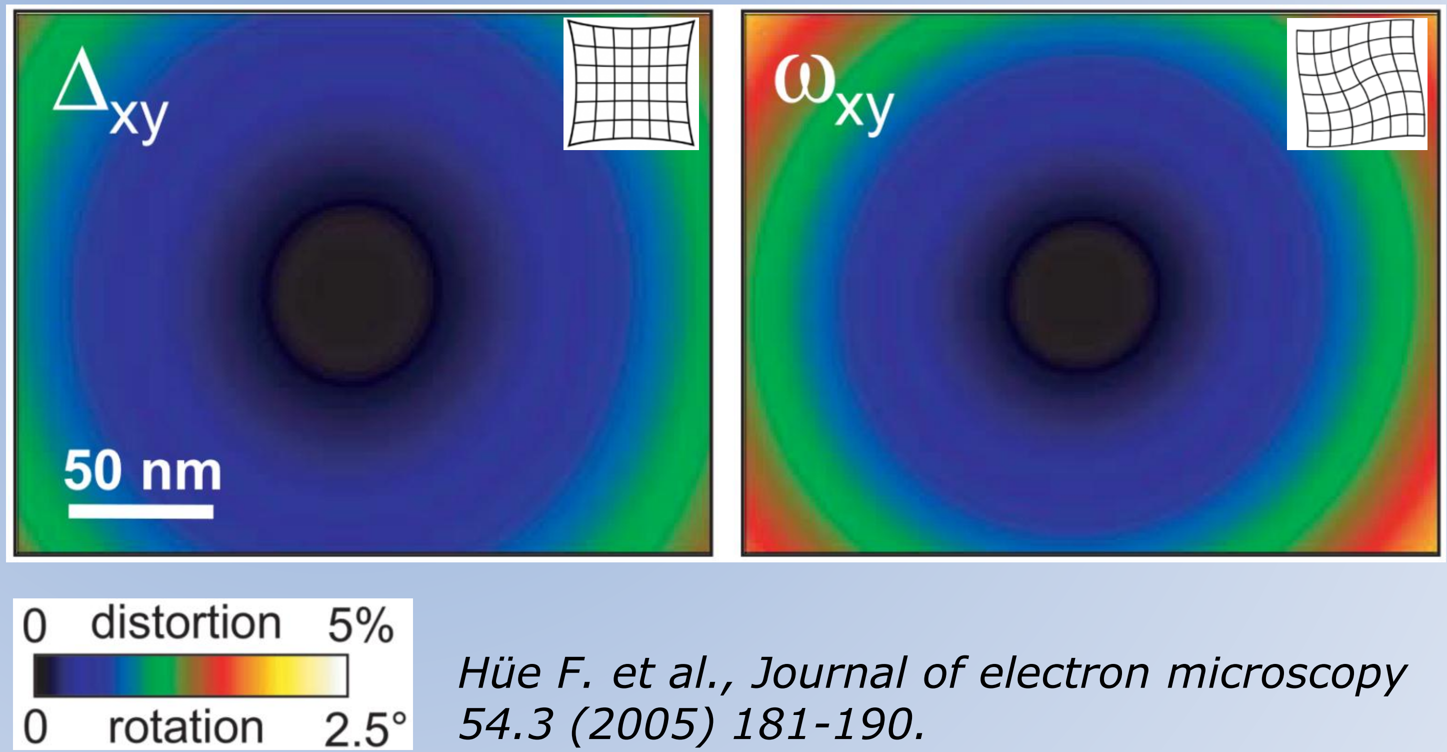
Aberrations and distortions

- Projection system distortions

  - Main image distortions come from the projection (magnification) system
  - Measurable by imaging a monocrystalline sample in high resolution





Hüe F. et al., Journal of electron microscopy 54.3 (2005) 181-190.

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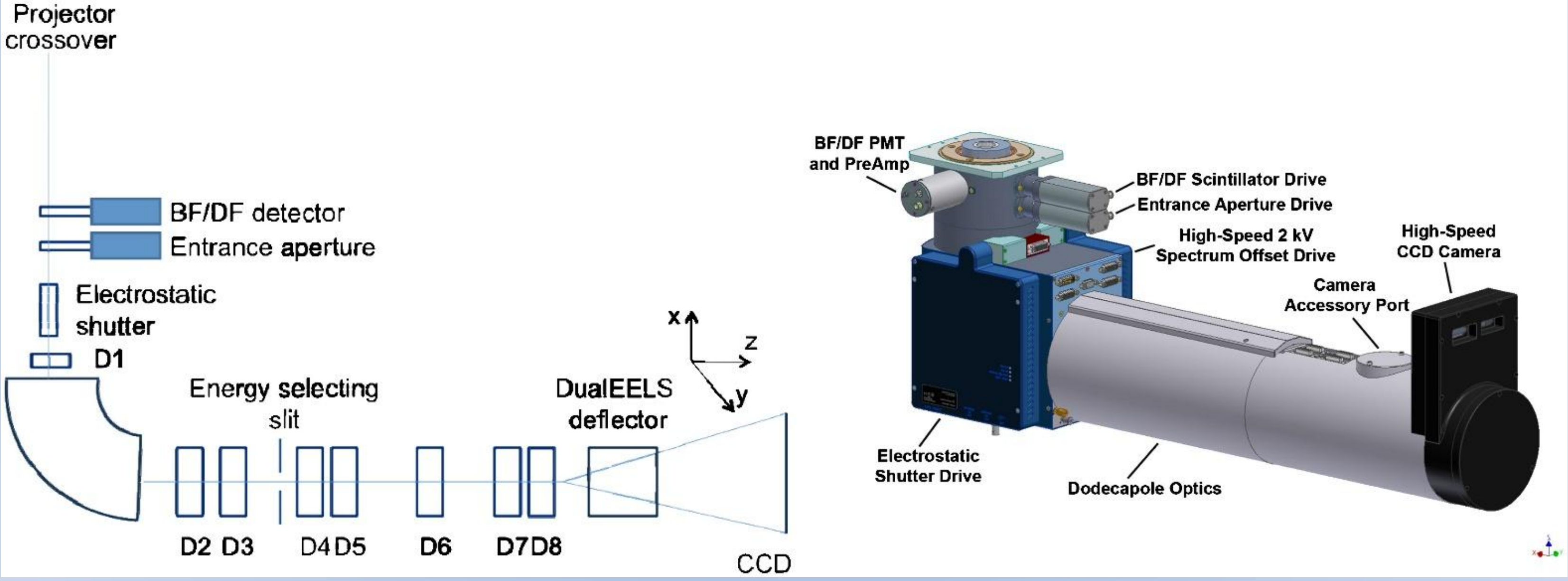
Aberrations and distortions

- Post image filter mount

  - Distortions induced by the multipole optic elements
  - Corrected down to 0.5% but lower distortions remain



Gubbens A. et al., Ultramicroscopy 110.8 (2010): 962-970

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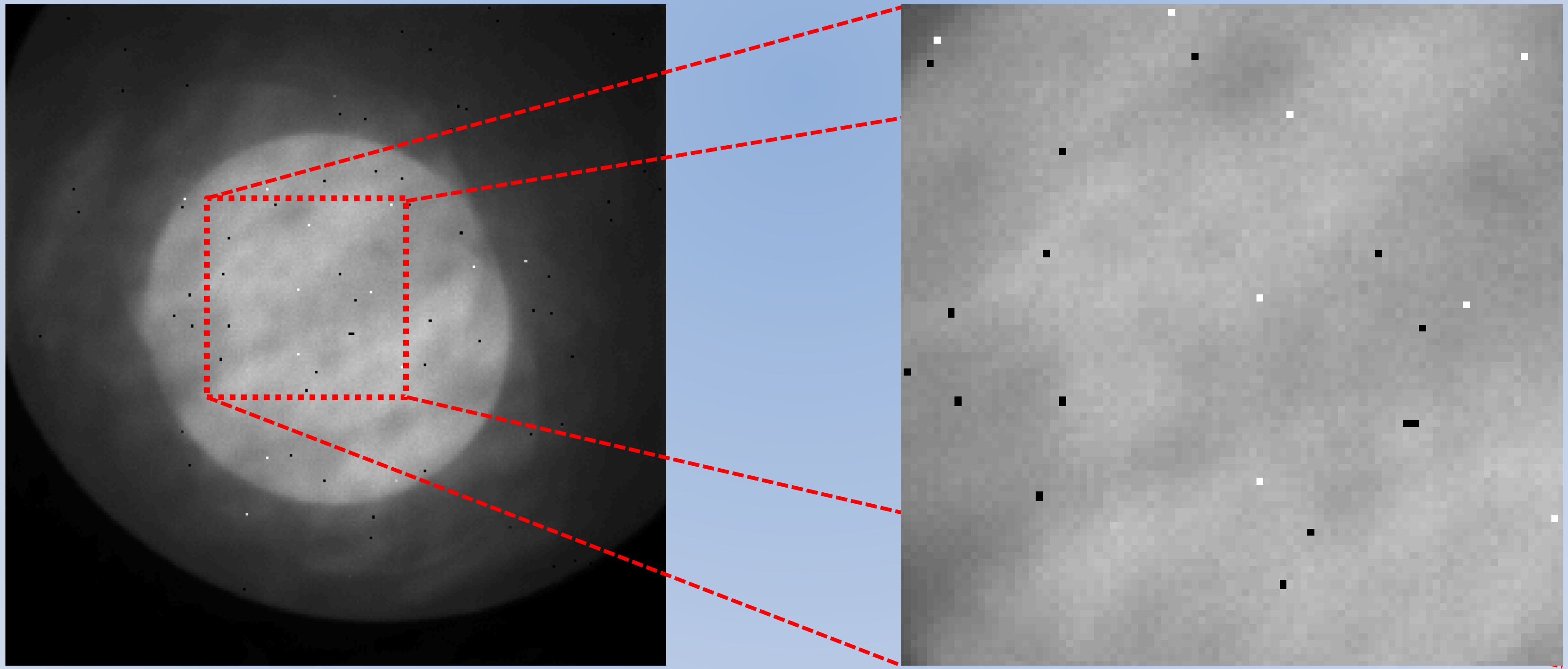
Aberrations and distortions

- Dead pixels/lines

  - Detectors could present non working areas
  - Depending on provider, this area can be automatically interpolated



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Conclusion

- Different type of sensor for different type of applications
  - Diffraction
  - Imaging
  - Low dose
  - 4DSTEM

- Large variety of electron dose sensitivity

- Always work in the best illumination conditions for each sensor

- Know your sensor capabilities

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