Imaging performance of the EDET-80k detector

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Outline

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  - Scenario 2: Pixel and cluster illumination
  - Scenario 3: Pixel and homogenous illumination
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  - Modulation Transfer Function (MTF)
  - DQE versus spatial frequency: DQE(f)
- EDET calibration with Cd-109: simulation vs. measurement
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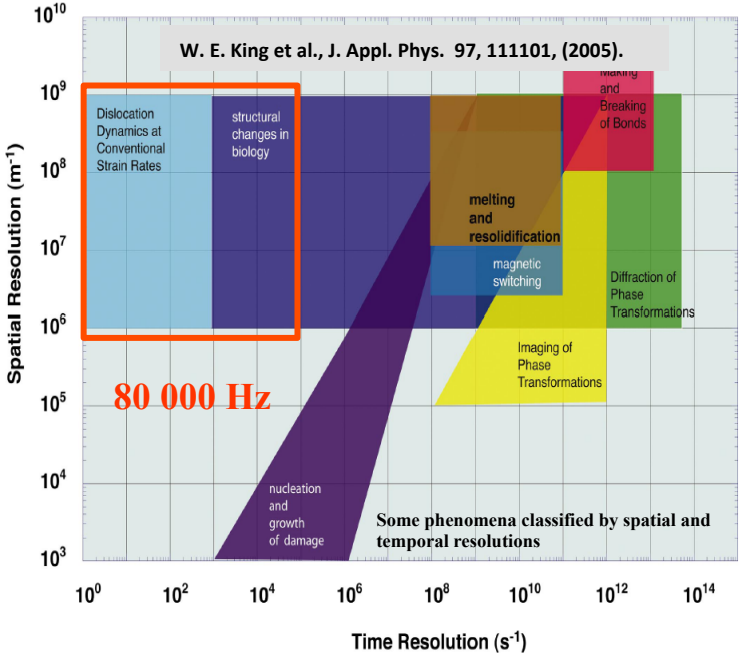
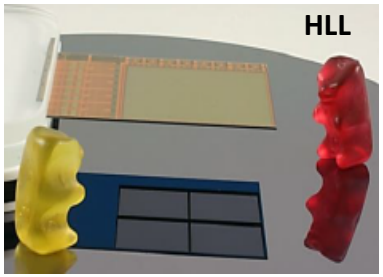
Introduction: EDET- 80 detector for fast TEM imaging

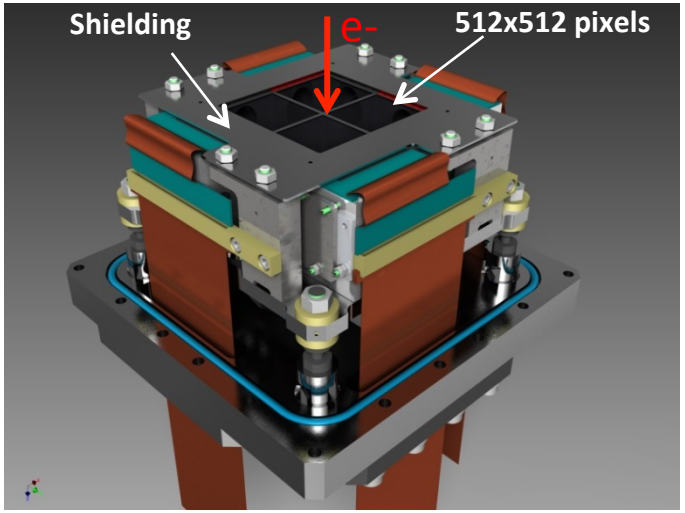
- **Goal: Real space and time imaging using TEM** (e.g, fast molecular dynamics in biology)

Large area detector with high speed: EDET-80kHz



- **Readout time 100 ns/row (4 rows in parallel, t=12.8µs)**
  - 100 frames ⇒ movie of 1.28 ms
- **Single electron resolution ⇒ low dose applications**
  - **Direct electron detection**
  - **High DQE**: key for radiation sensitive samples
- **Large dynamic range ⇒ High intensity**
  - Thin sensor (50 µm) with 100 % detection efficiency
  - Digitization with 8 bit resolution



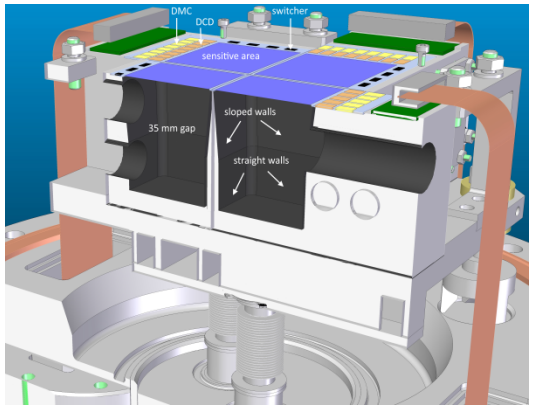


Tools:

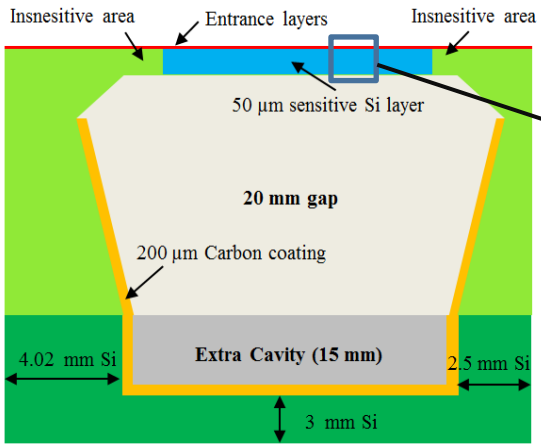
- **Technology:** Non-linear DEPFET
- **Monte Carlo simulation:** Detector modeling

Simulation of EDET-80 response

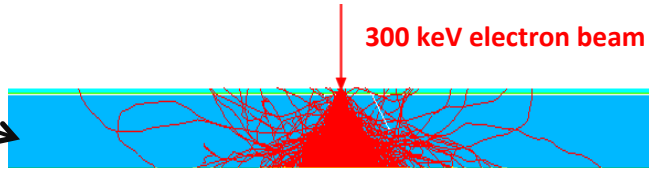
Dynamic range & single electron resolution

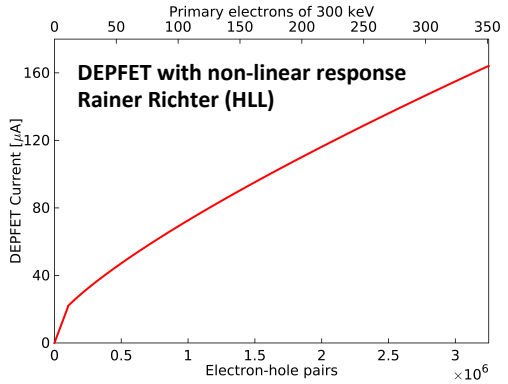


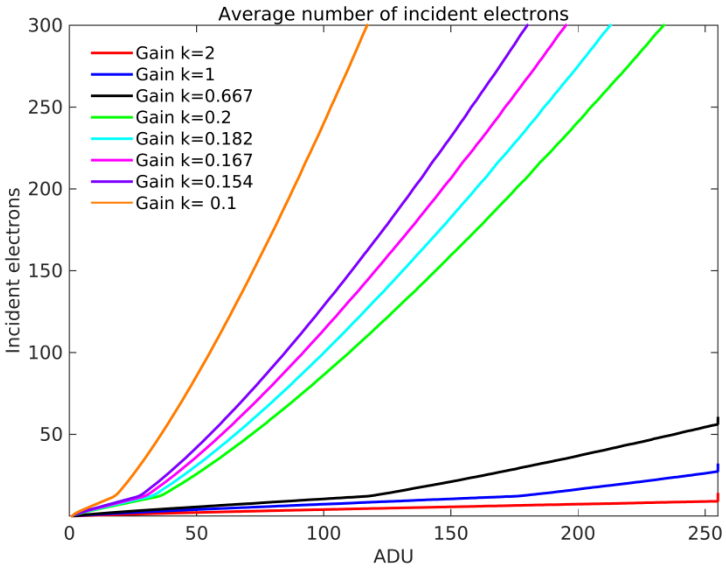
EDET CAD design

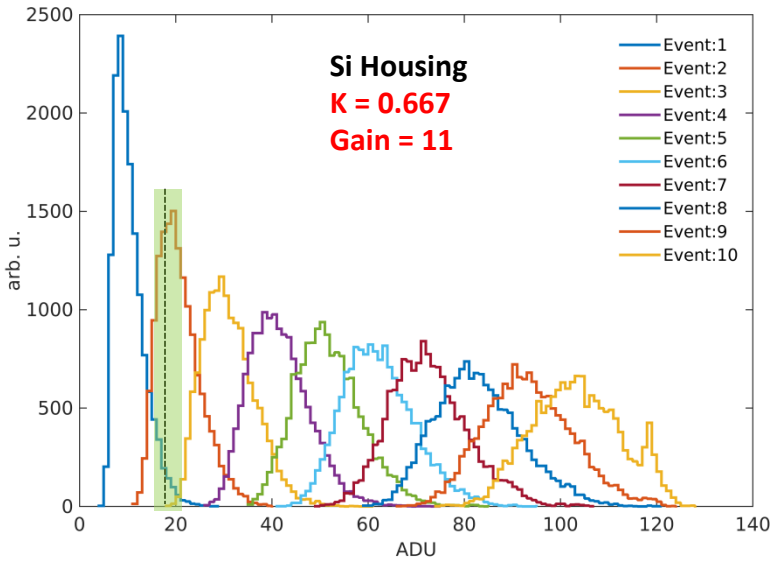


Geometry for lowest backscattering





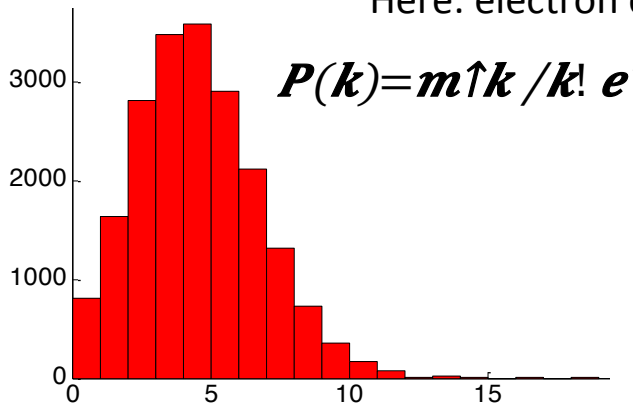




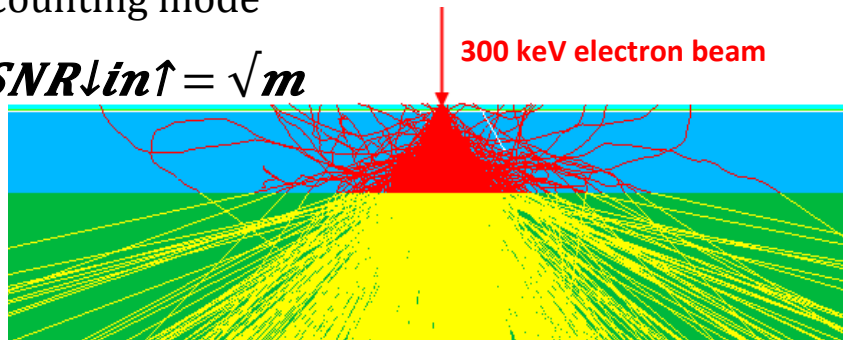
- **High : low dose application**
- **Low gains: large dynamic range**

Non-spatial capabilities of EDET-80: Electron counting
Scenario 1: Infinit pixel

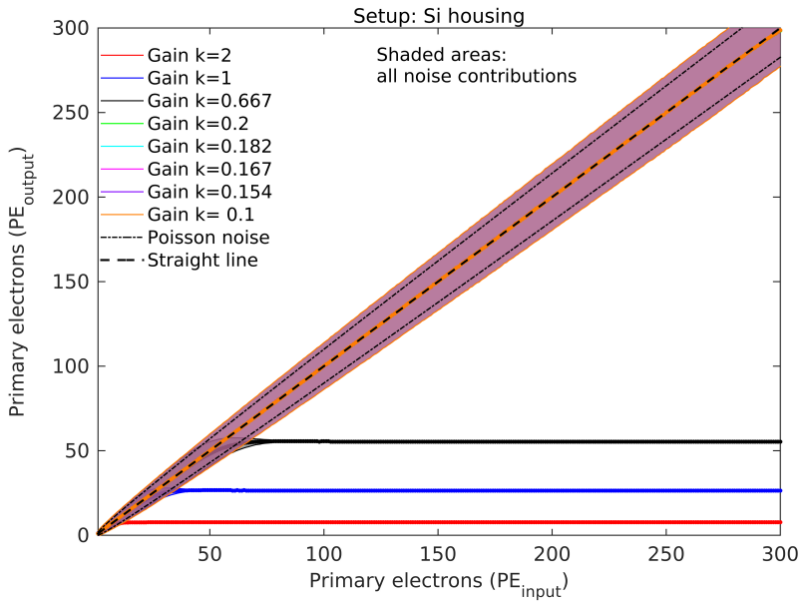
Here: electron counting ≠ counting mode

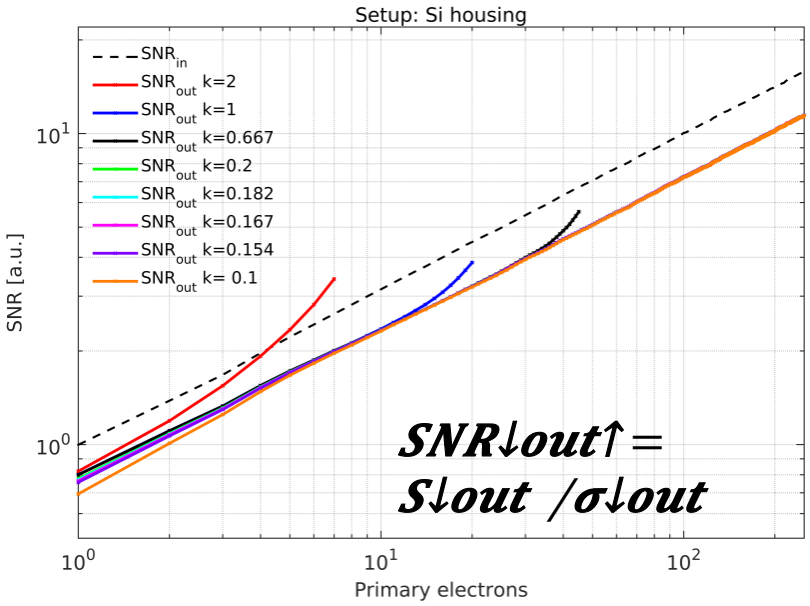


$$P(k)=m^k/k!\ e^{-m} \Rightarrow SNR_{in}=\sqrt{m}$$

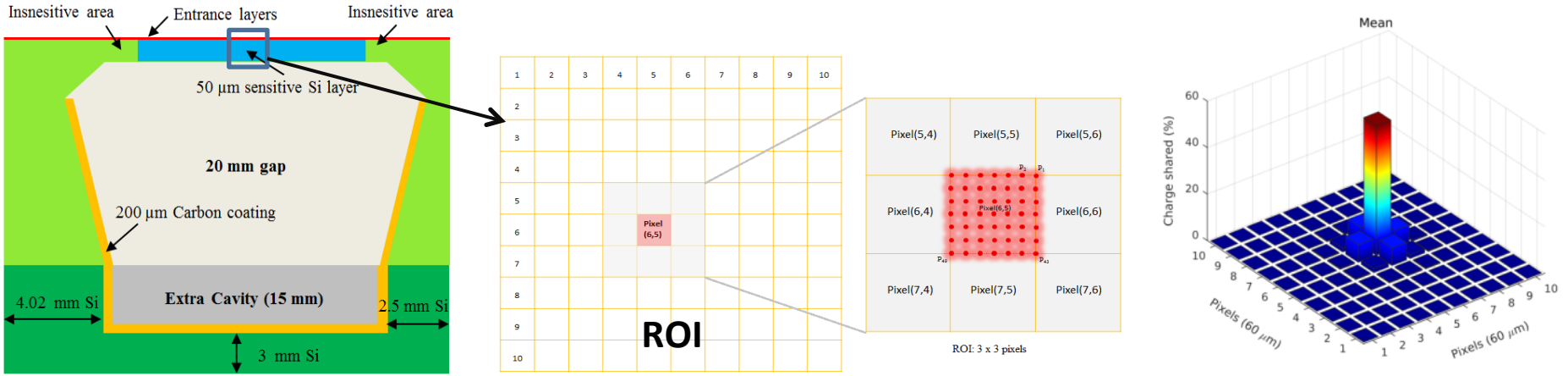


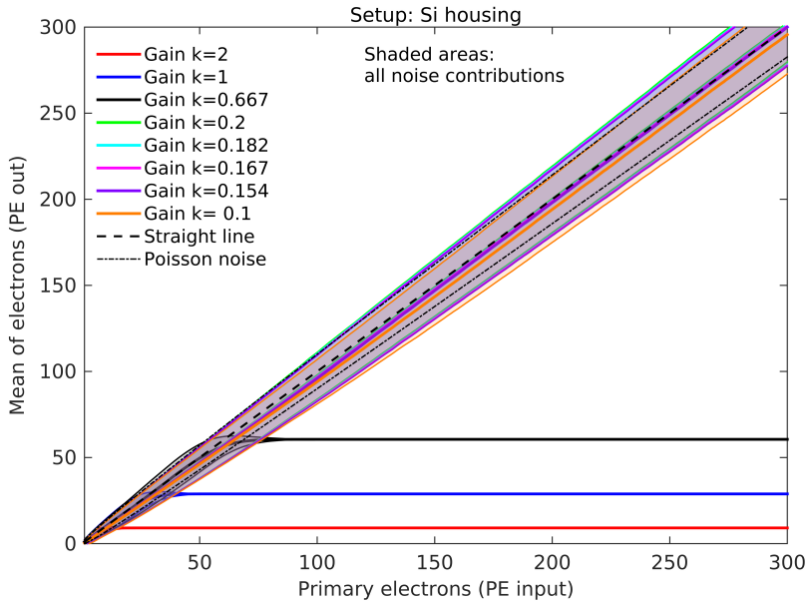
Counting

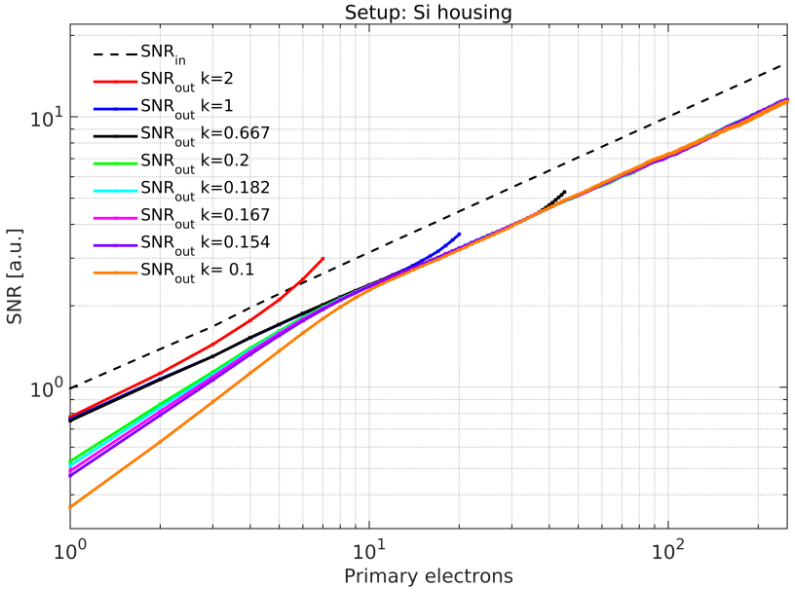




Scenario 2: Pixel and cluster illumination



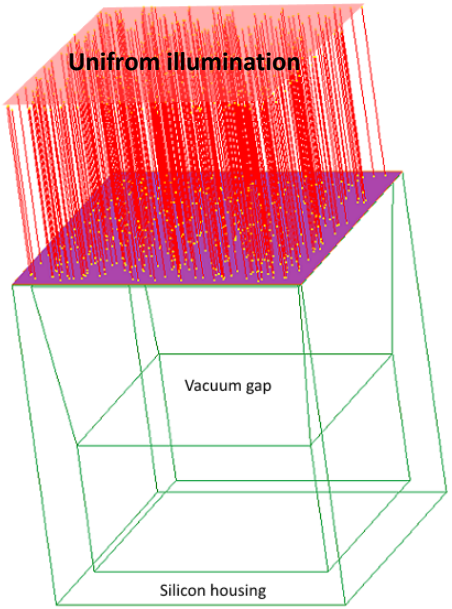




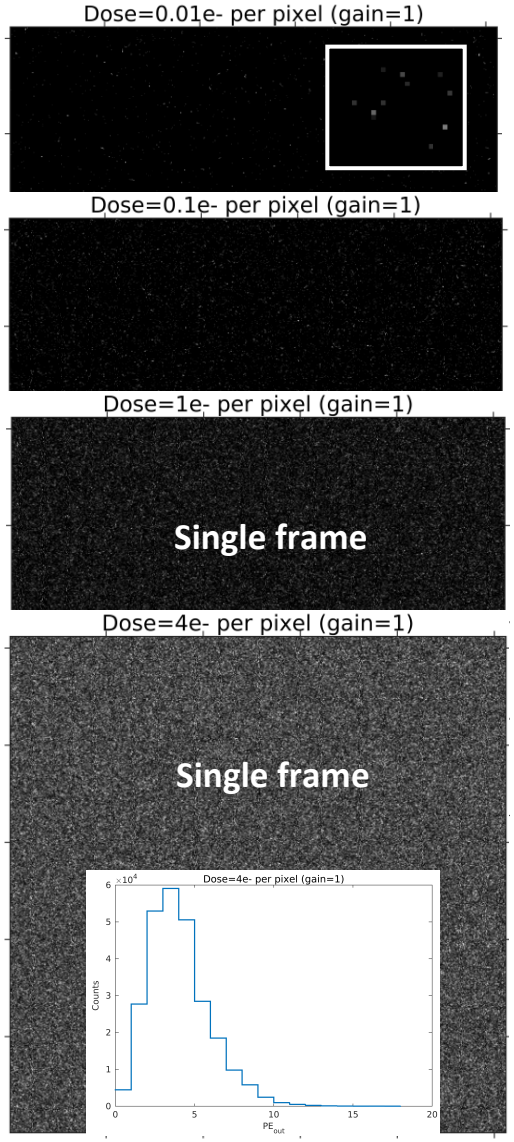
Scenario 3: Pixel and homogenous illumination

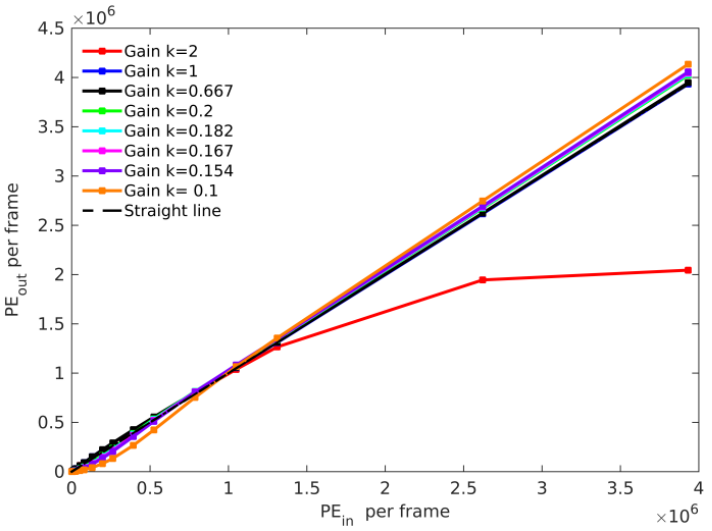
Low dose: Single event resolution

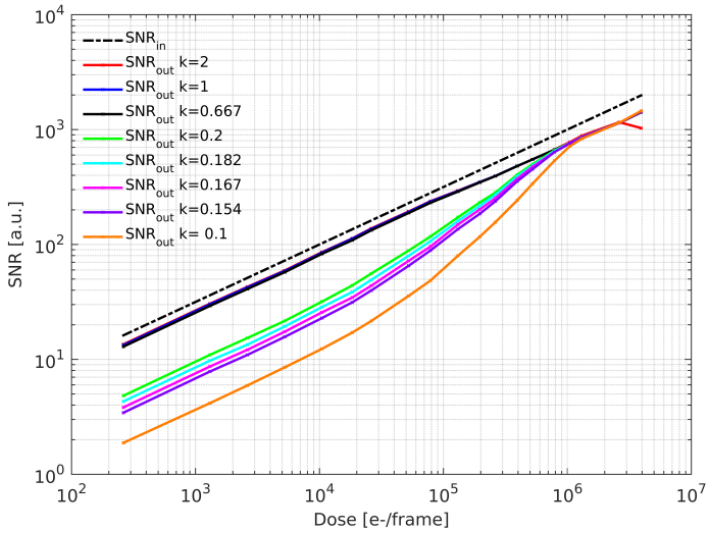
- Low dose: Single event resolution
- High dose: Events overlap.



Dose: 0.001, 0.005, 0.01, 0.02, 0.04, 0.07, 0.1, 0.2, 0.3, 0.5, 0.75, 1. 1.5, 2, 3, 4, 5, 10, 15 electron per pixel

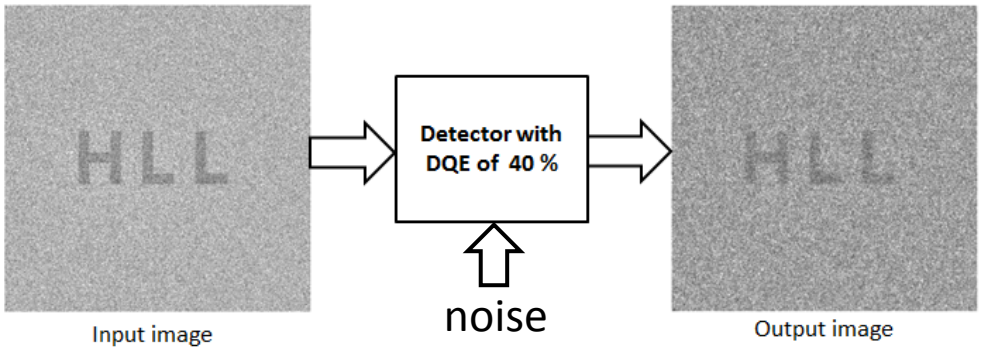






Detective Quantum Efficiency: DQE(0)

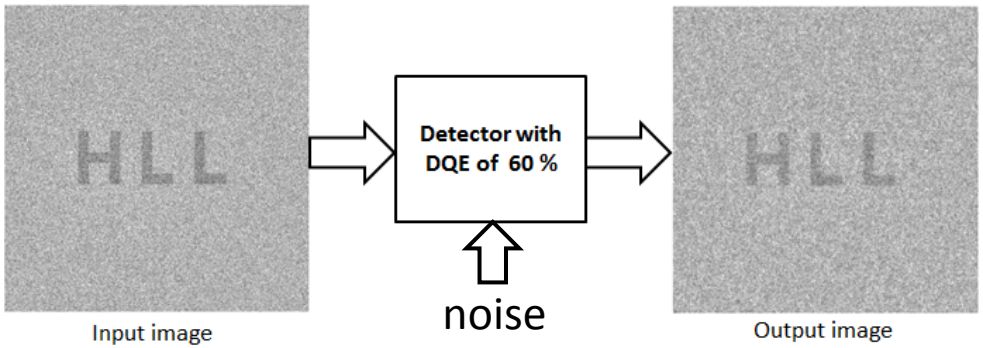
- **DQE** quantifies the detector performance in terms of adding extra noise by the detector to SNR_{in}. It combines **MTF** and **noise performance** of the detector.



$$DQE = SNR_{out}^2 / SNR_{in}^2 \leq 1$$

- The closer the DQE is to 1, the better the image quality

- **Higher DQE improves the image quality**



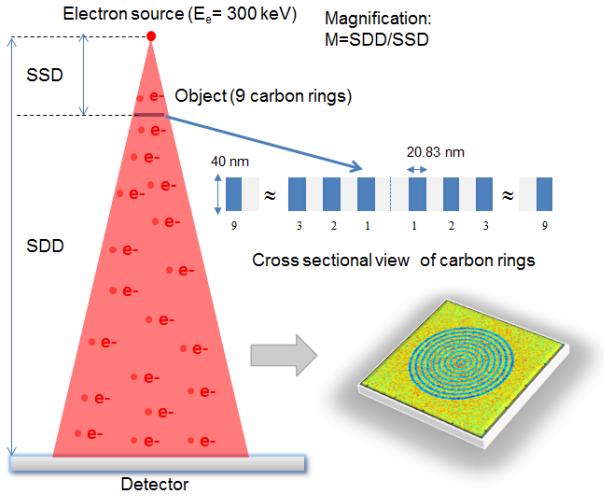
- Ideal detector

$$SNR_{out} = SNR_{in} \Rightarrow$$

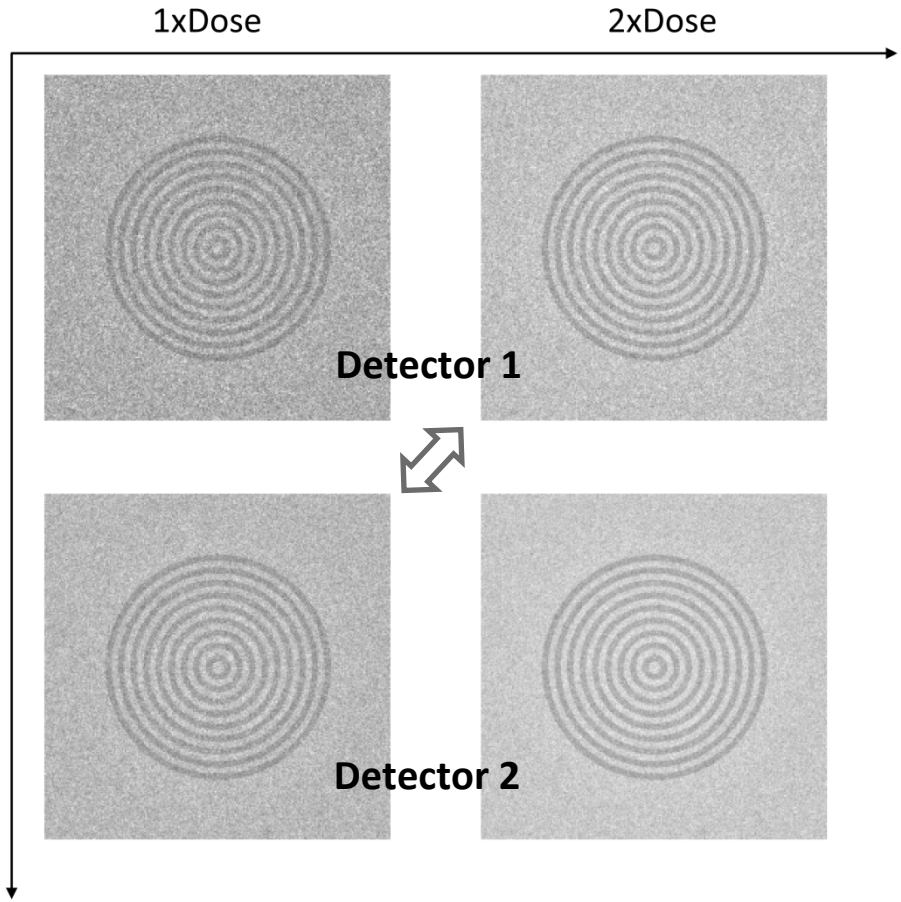
DQE=1

⇒ **No information is lost**

- **Image quality:** depends on electron dose and the DQE of the detector



1xDQE



- Detector2 (2xDQE) achieves the same image quality with half the e- dose.

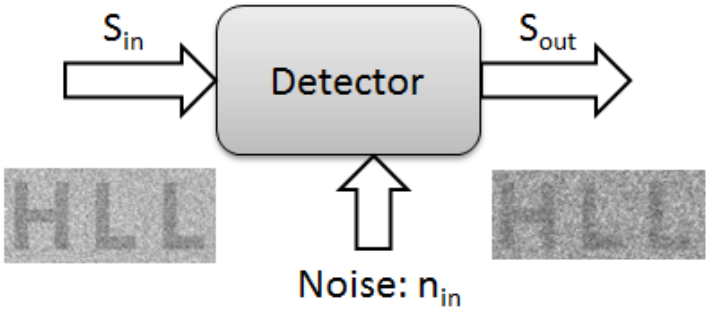
2xDQE

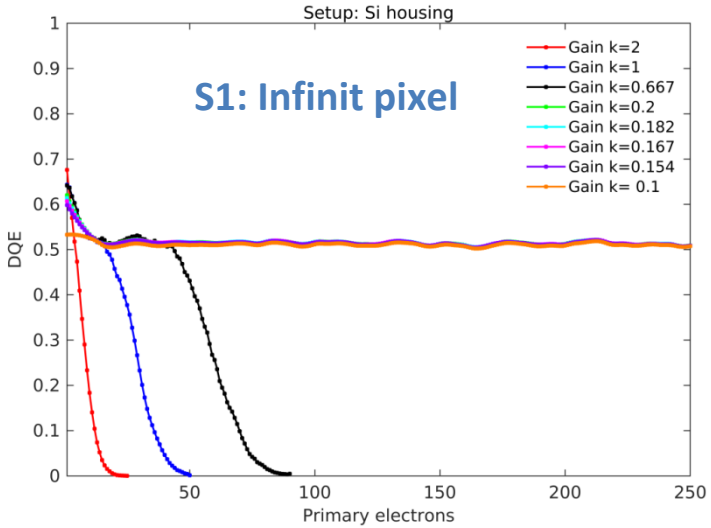
- **Radiation sensitive samples:**

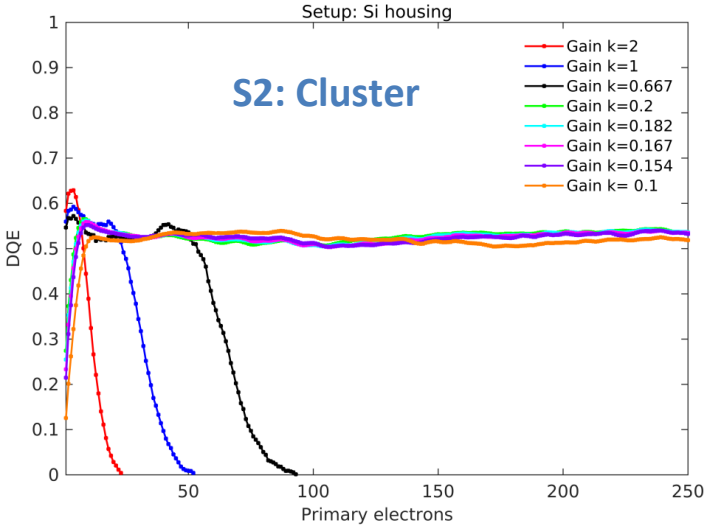
DQE is a key

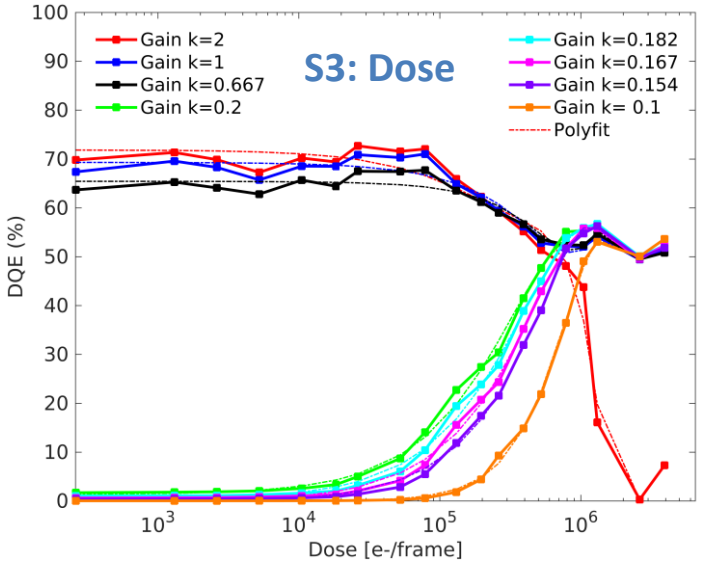
DQE at Zeros spatial frequency

$$DQE = SNR_{out}^2 / \dots$$



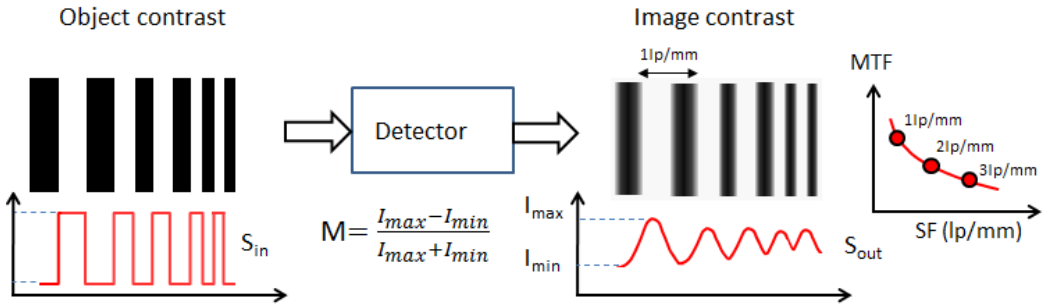


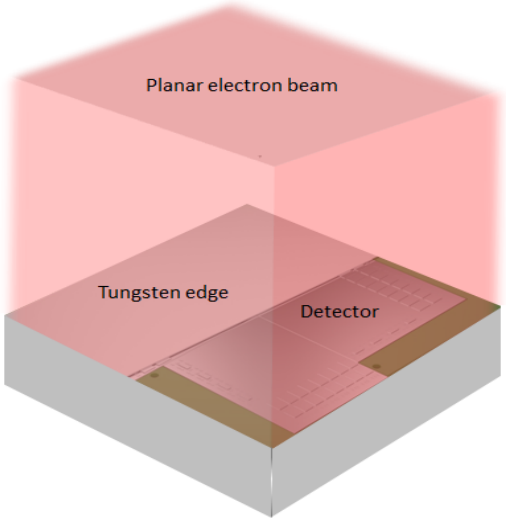




Spatial capabilities of EDET-80: Modulation Transfer Function (MTF)

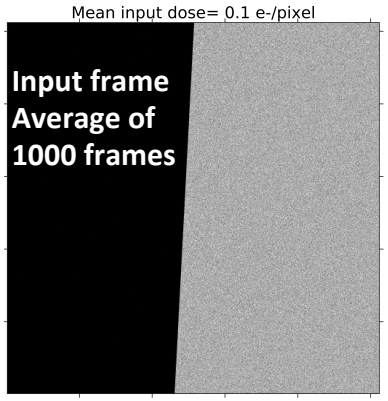
- **MTF** measures the ability of a detector to transfer signals of various spatial frequencies from the input to the output of the detector.
- **Higher MTF**: Better image spatial resolution and sharpness
- **MTF=1:** Ideal detector





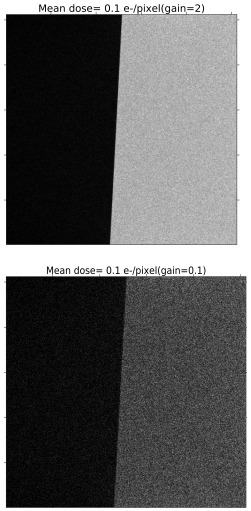
Slanted edge method

Input



Poisson only

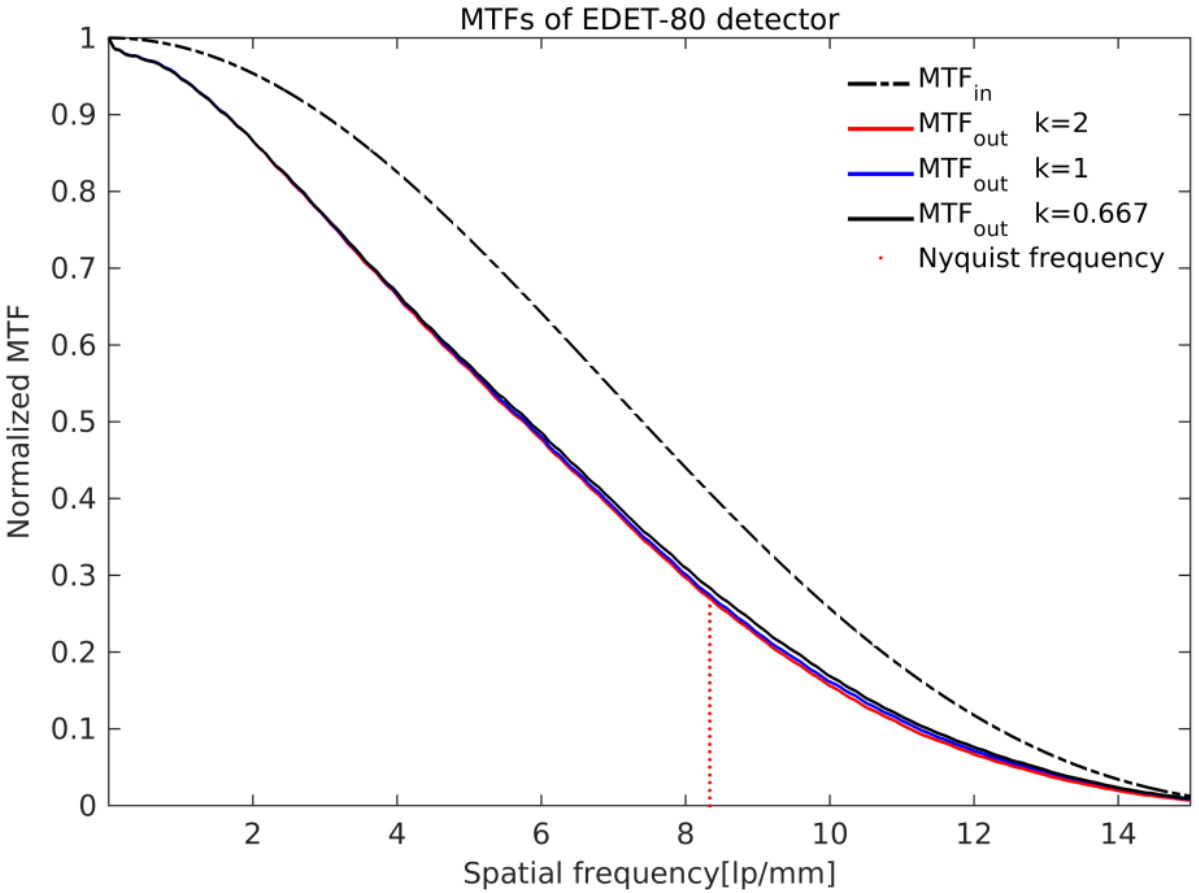
Output

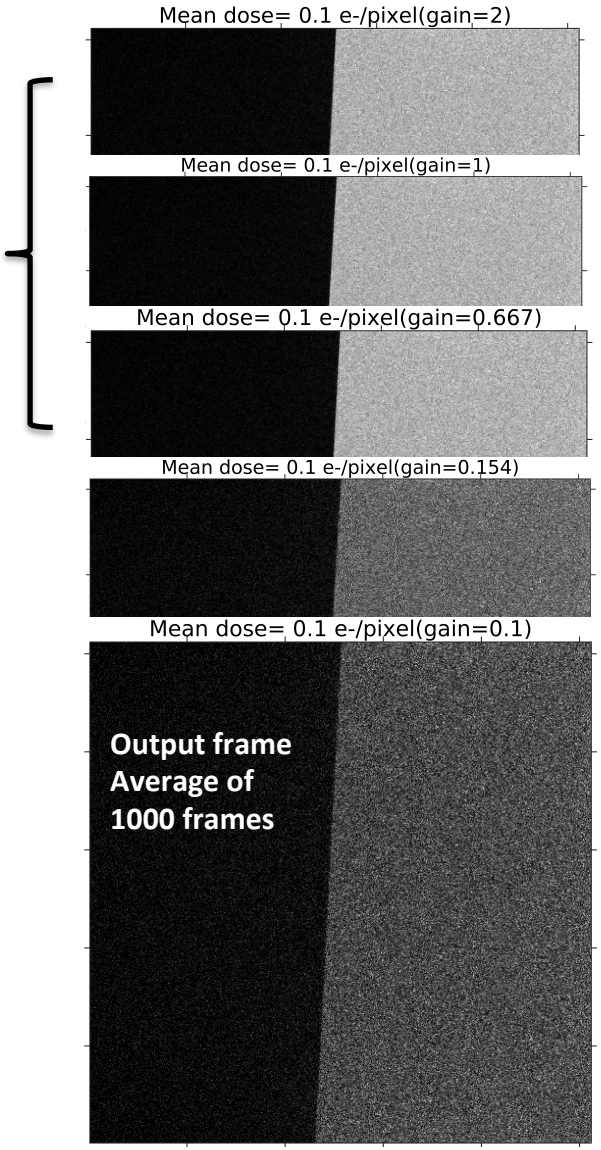


High gain

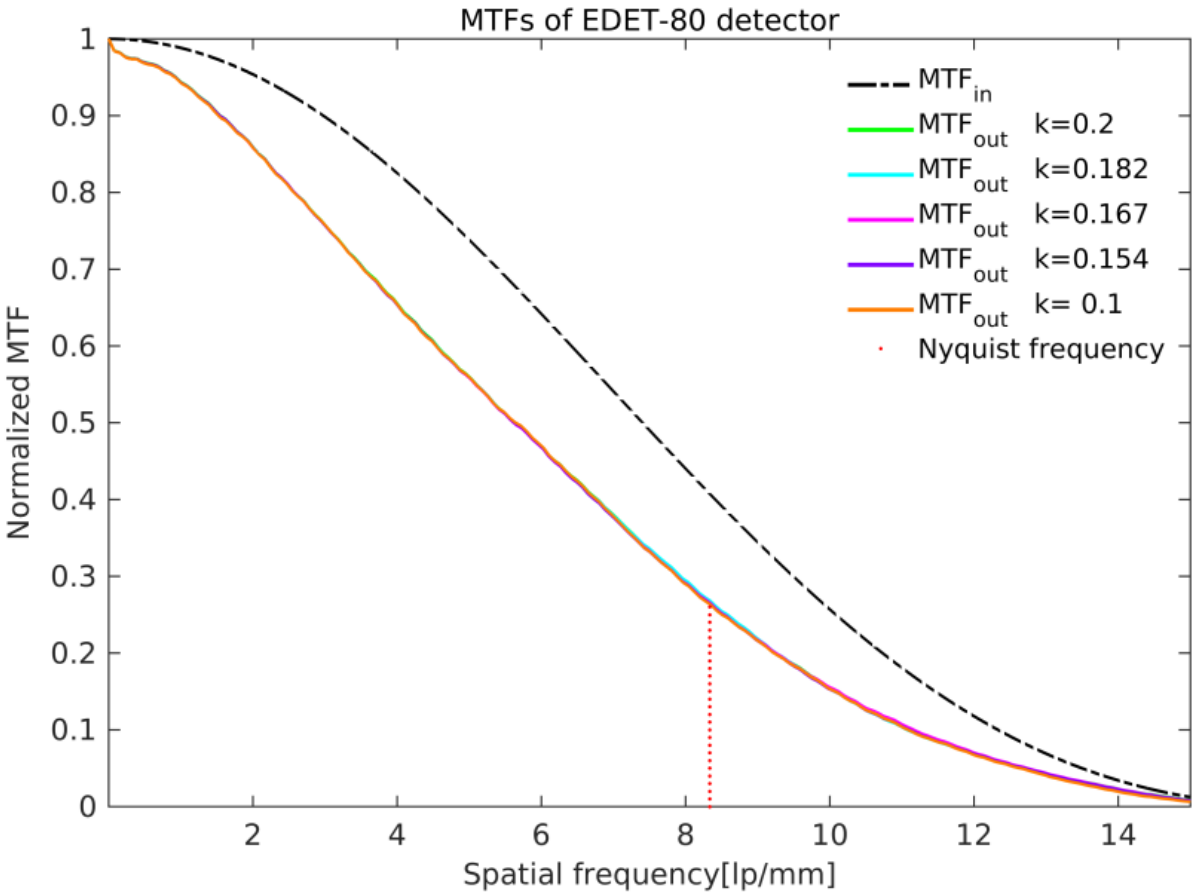
Low gain

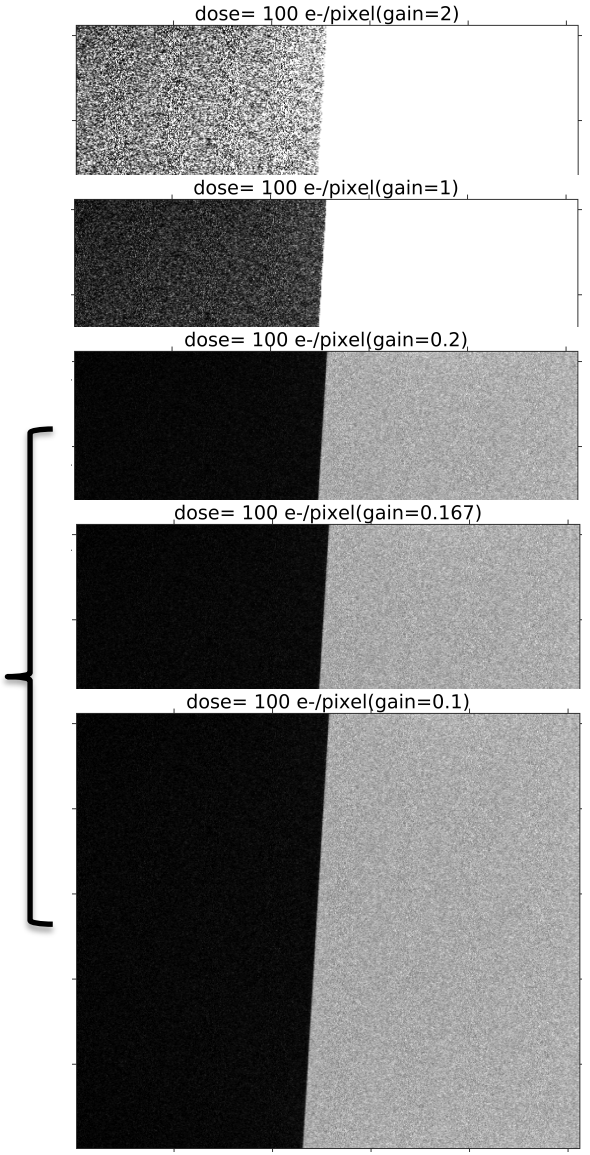
- **MTF at high gain settings (Low dose applications)**





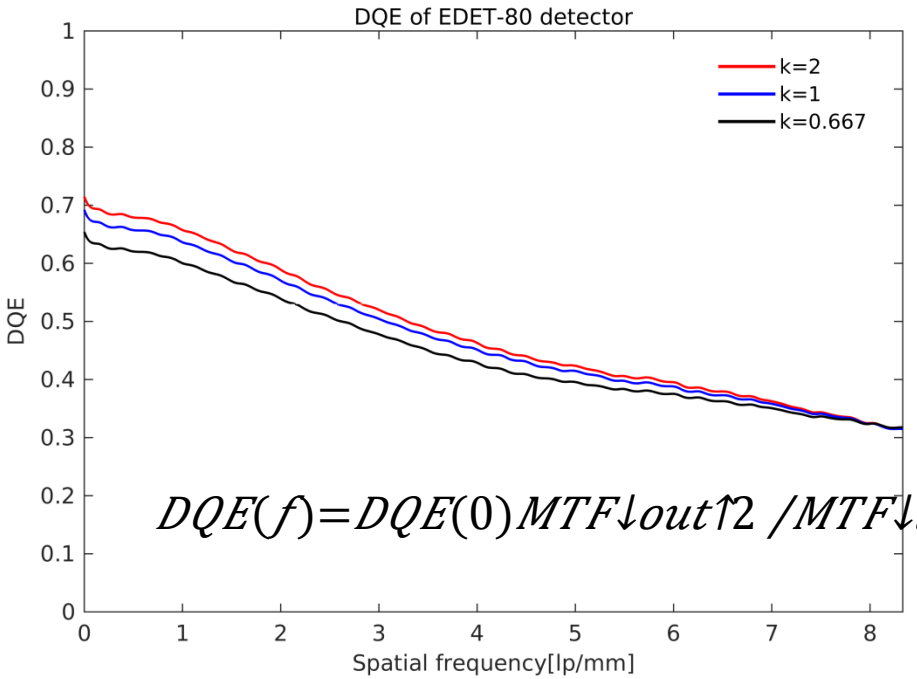
- **MTF at low gain settings (Large dynamic range)**





DQE versus spatial frequency: DQE(f)

- **Comparison with other commercially available detectors**



$$DQE(f) = DQE(0)\, MTF{\downarrow}out{\uparrow}2 \,/ MTF{\downarrow}in{\uparrow}2$$

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

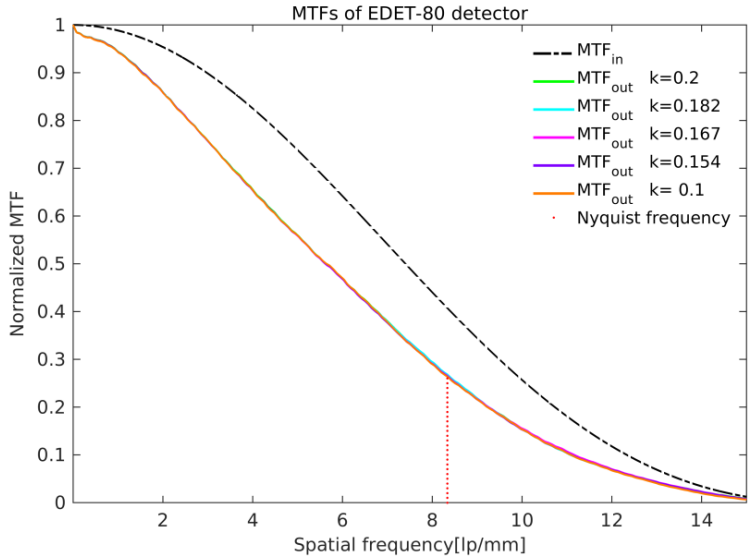
(*) G. McMullan et al. / Ultramicroscopy 147 (2014) 156–163

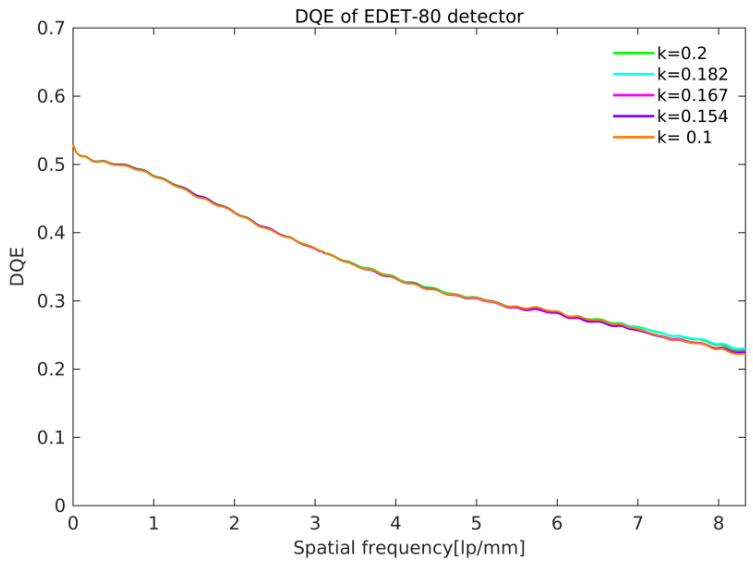
- All detectors are better than films and can capture movies
- These results demonstrate the suitability of high gain settings (k=2, 1, 0.667) for low-electron dose applications.
- EDET-80 shows great promise for low-dose TEM applications

Detector	#pixel	Pixel length [mu]	A per pixel at mag. 50k	Object length at mag. 50k [mu]	Ava. Speed [fps]	Max. Speed [fps]	Sweet flux [e-/px/s]
Falcon III	20 M	14	2.8	0.41	40	->	160
K2 Summit	14 M	5	1	0.38	400	->	<2
DE-20	17 M	6.4	1.3	0.67	20-32	->	100
EDET-80	1 M	60	12	1.2	1000	80 000	20 000

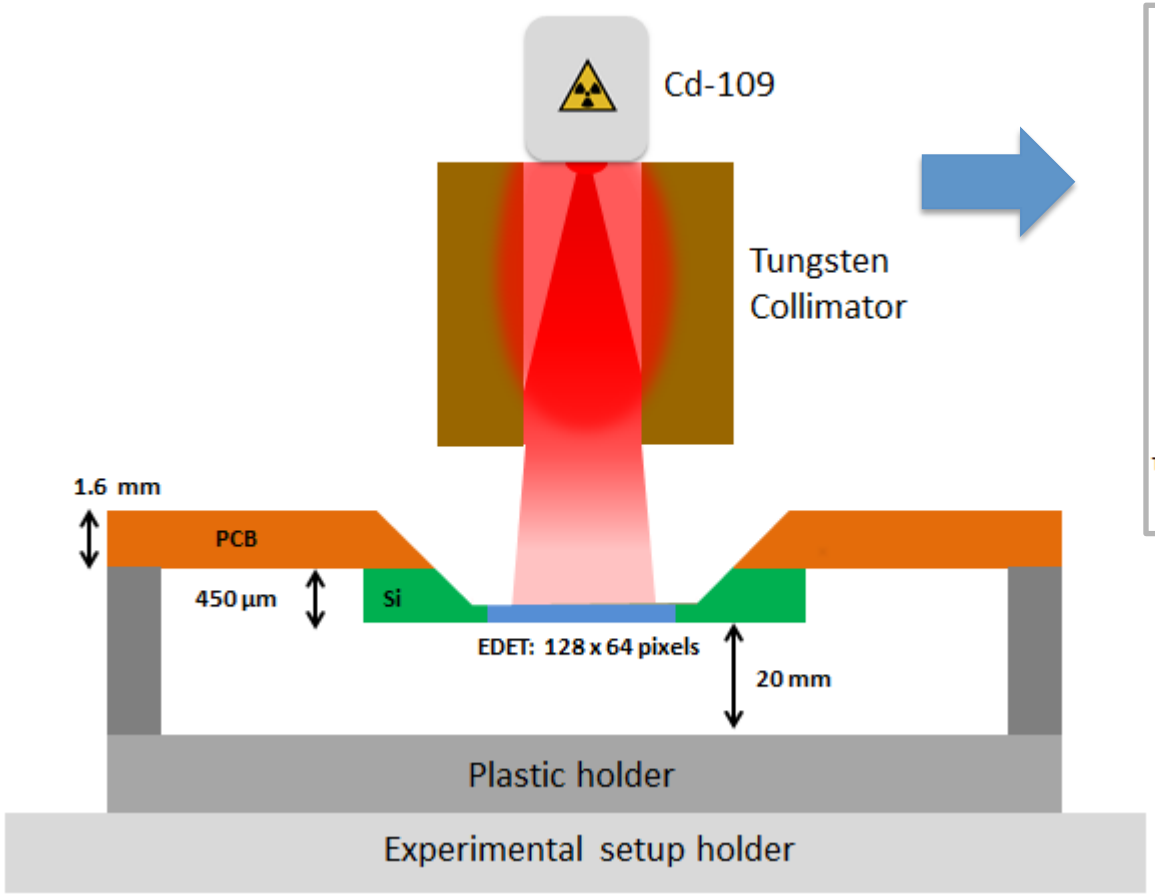
G. McMullan et al, Methods in Enzymology, Volume 579, 2016

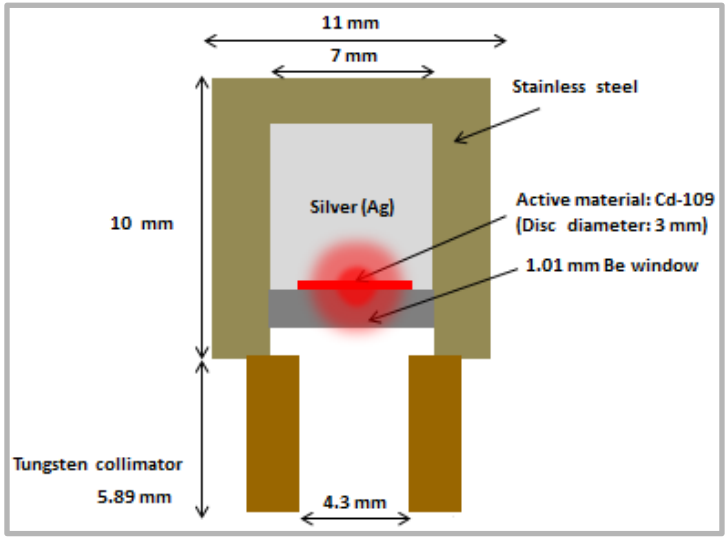
- **Low gain performance (Large dynamic range)**

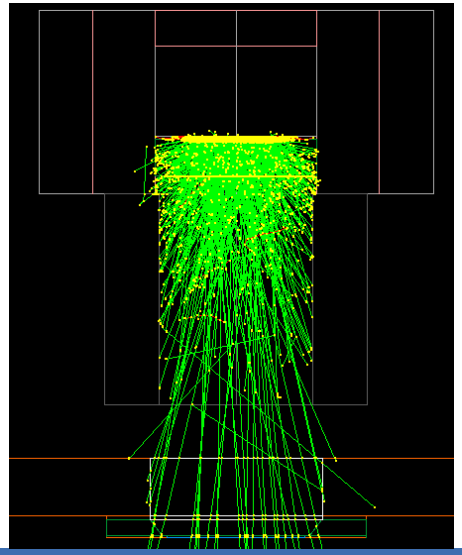




EDET calibration with Cd-109: simulation versus measurement







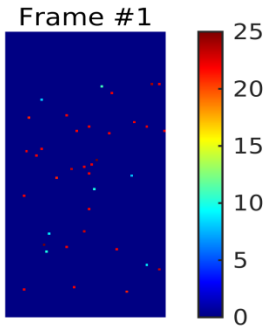
Mean energy of X-Rays emitted by Cd-109:

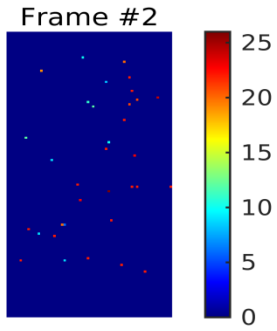
$E_{x\text{-}ray}$ = 22.7 keV

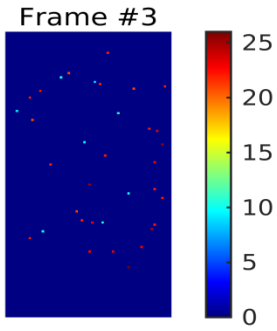
Expected peak position

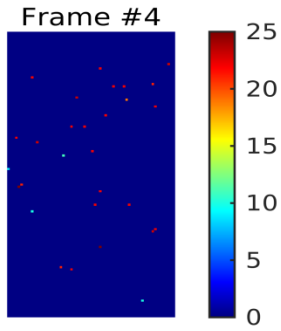
- Mean energy of X-Rays emitted by Cd-109: E_{xray} = **22.7 keV**
- Number of e-h generated in Si : **Ne = 6270 e-h pairs**
- Linear response region of DEPEFT: g_q = **210.64 pA/e-**
- Current generated by 6270 e- is : **I = 1.32 µA**
- Taking into account the gain: k=2 (highest gain, 33): I_d= **I x k=1.28 (µA) x 2=2.64 µA32**
- Maximal current that can be measured by DCD of 8 bit resolution: I_{max}=**32 µA**
- **Expected peak: 21.12 ADU**

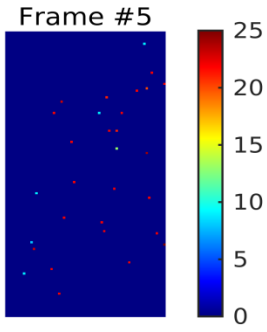
Single frames

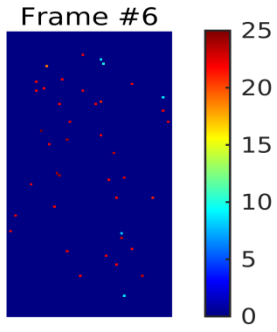


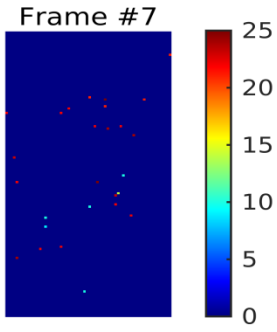


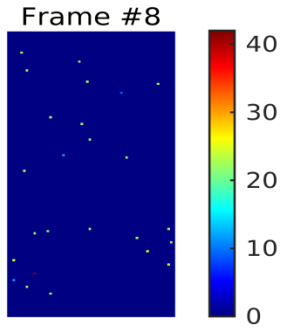


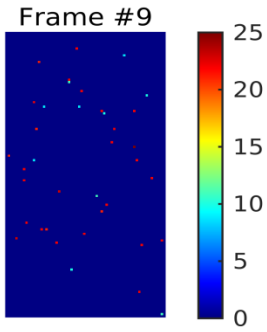


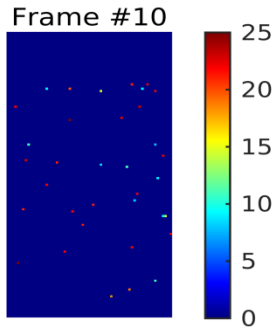


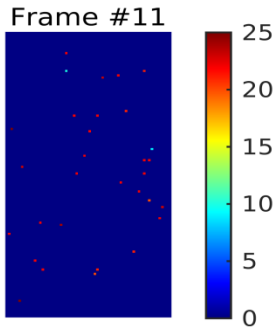


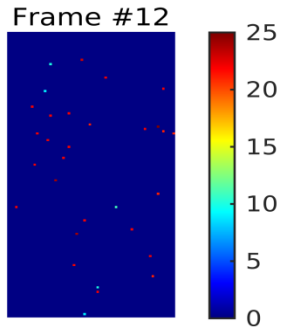






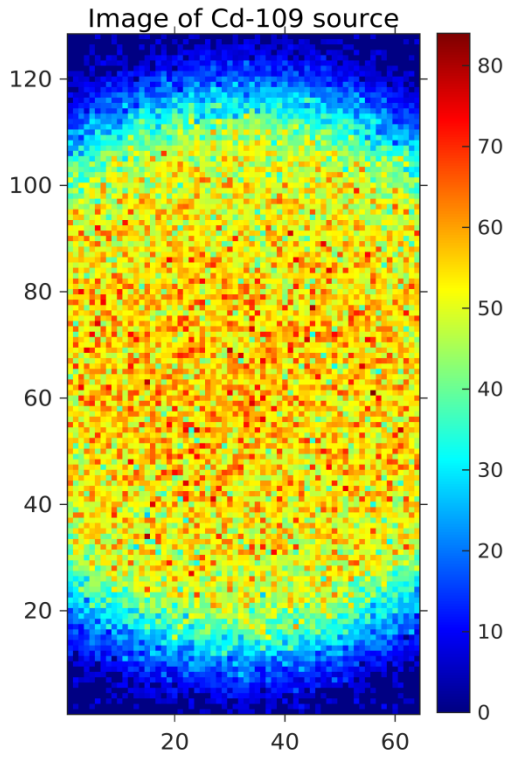






Simulation versus measurement counts

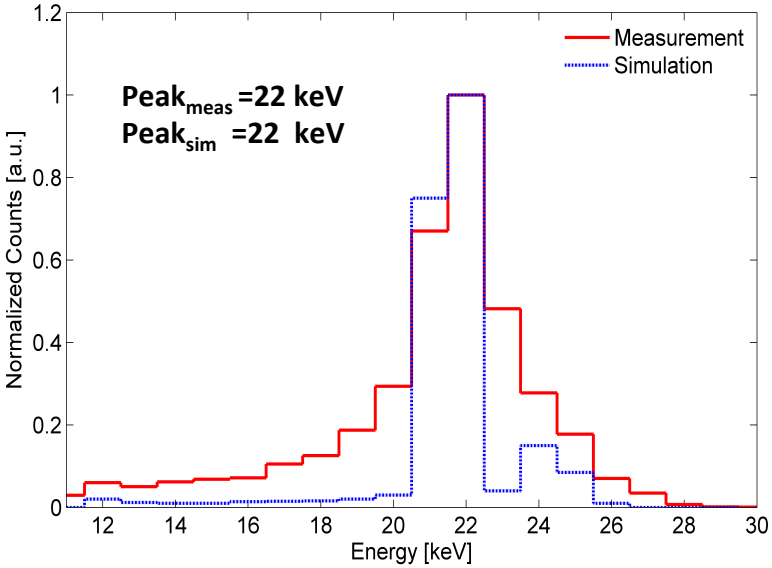
Simulation (10000 frames)



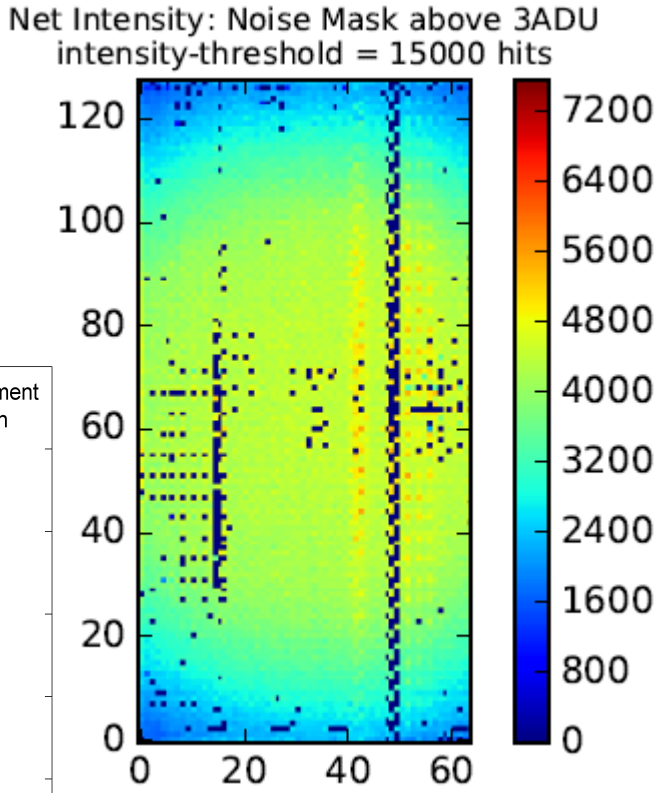
#frames = 108161326
Total Hits = 303173032

Remove noisy Pixels:
Clusters Raw = 43424961

Applying Cuts:
Clusters Filtered = 29006005



Measurement (300 M frames)



Summary & Outlook

- Dominant source of noise in the detector: Poisson noise
- A competitive direct detector with improved imaging performance has been identified.
- EDET-80 shows great promise for TEM applications
- Next step: EDET imaging performance in counting mode (Higher SNR and DQE)

EDET Team: Acknowlegements

HLL ▸ Ladislaw Andricek ● Martin Hensel ● Christian Koffmane ● Jelena Ninkovic ● Gerhard Schaller ● Martina Schnecke ● Florian Schopper ● Andreas Wassatsch ● Christian Zirr ● Rainer Richter ● Eduard Prinker ● Rainer Richter ● Mikhail Polovykh ● Mitja Predikaka ● Mohammed Ibrahim

KIT ▸ Ivan Peric

USI ▸ Klaus Gärtner

MPSD ▸ Ibrahym Dourki ● Sascha Epp ● Djordje Gitaric ● R. J. Dwayne Miller ● Fabian Westermeier

Thank you for your attention

En30	En60	En90	En120	Gain	Times lowest Gain
1	1	1	1	0.061	1.0
0	1	1	1	0.063	1.0
1	1	1	0	0.065	1.1
0	1	1	0	0.067	1.1
1	0	1	1	0.087	1.4
0	0	1	1	0.091	1.5
1	0	1	0	0.095	1.6
0	0	1	0	0.100	1.7
1	1	0	1	0.154	2.5
0	1	0	1	0.167	2.8
1	1	0	0	0.182	3.0
0	1	0	0	0.200	3.3
1	0	0	1	0.667	11.0
0	0	0	1	1.000	16.5
1	0	0	0	2	33

Gain k	2	1	0.667	0.2	0.182	0.167	0.154	0.1
Charge per first LSB	297	594	890	2970	3264	3557	3857	5940

EDET DATA

Fundamental statistics of process

Poisson noise (G4)

Obsevable

e-h pair creation

Landau noise (G4)
Fano noise (ext.)
Backscatter (G4)

DepFET

Charge coll. (ext.)
Current noise (ext.)
*read out
*thermal & leak
*cosmic (-)

?

Digitization

Analog noise DCD (est.)
*b. scatter correction
*pedestals

ADU

Granularity

DAQ

Look-up tables

!

DCDE gain k_1

ADU	e- (primary)	+err	-err
0	0	1	0.5
1	0.2	0.4	0.1
...			
255	150	19	18

Biased Analysis

ESTIMATOR

Biased Results

Simulation

Calibration

Experiment

Max Planck Institute for the Structure and Dynamics of Matter