Ultra fast electron detector – The Molecular Movie –

Sascha Epp

CFEL SCIENCE

Center for Free-Electron Laser Science

Max Planck Institute for Structure and Dynamics of Matter

mpsd

EDET team

Acknowlegements

HLL ► Ladislaw Andricek ● Martin Hensel ● Christian Koffmane ● Jelena Ninkovic ● Gerhard Schaller ● Martina Schnecke ● Florian Schopper ● Andreas Wassatsch ● Christian Zirr

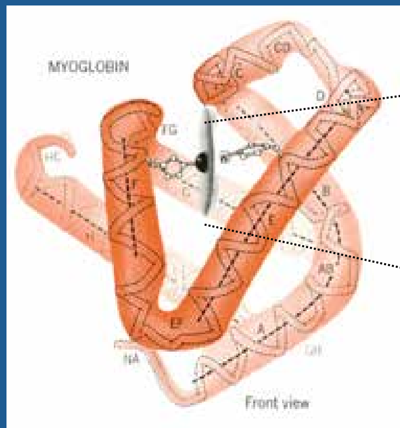
KIT ► Ivan Peric

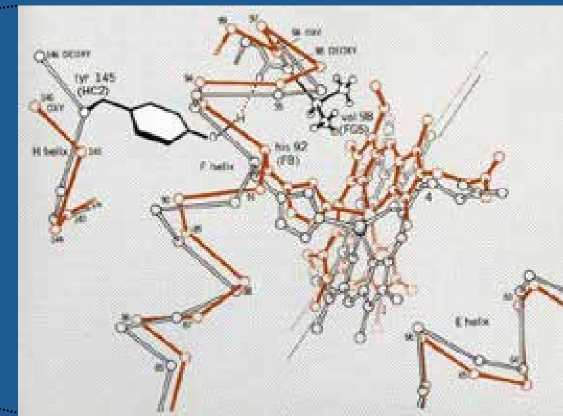
USI ► Klaus Gärtner

MPSD ► Ibrahym Dourki ● Sascha Epp ● R. J. Dwayne Miller ● Fabian Westermeier

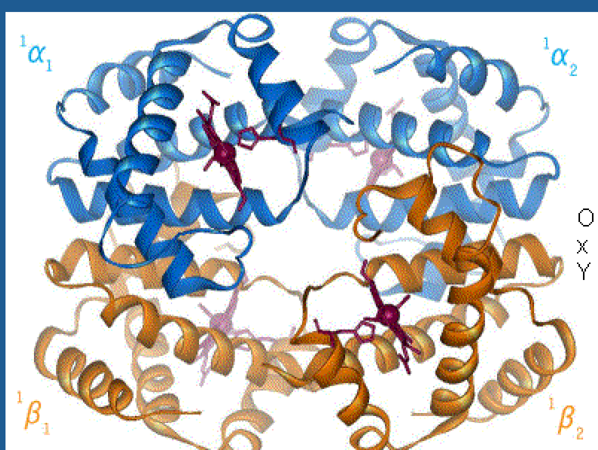
The "Molecular Dance"

Functionally important protein motions

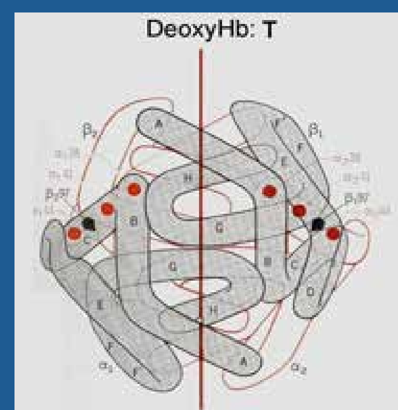


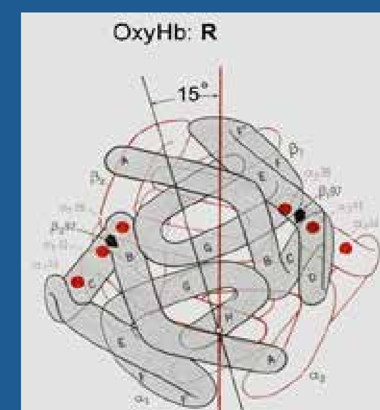


Myoglobin (single subunit)



Hemoglobin

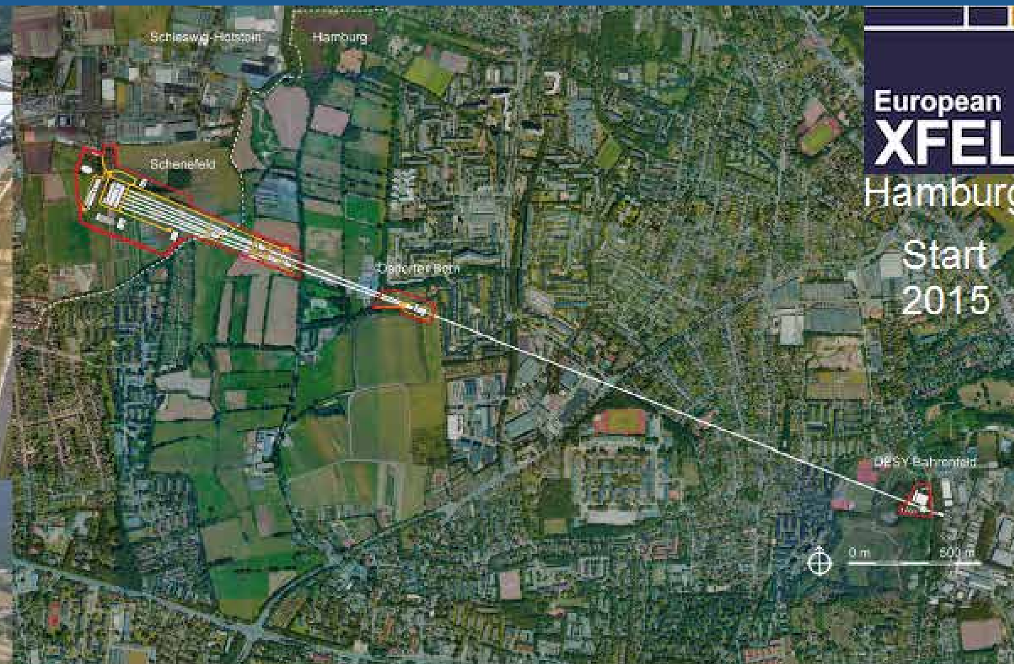




What is the mechanism of correlated atomic displacements?

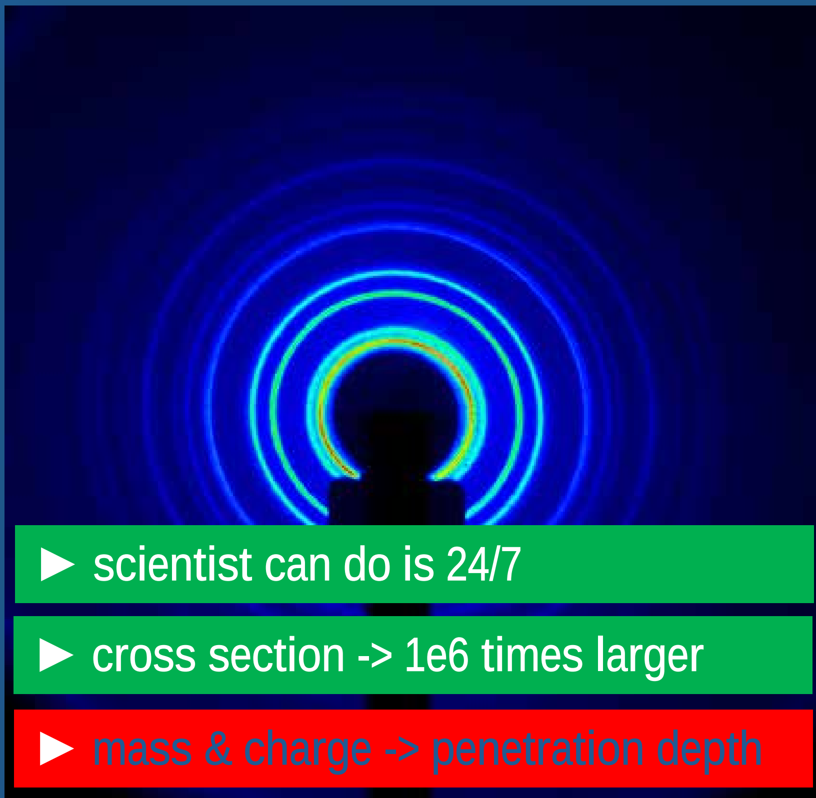
Structure - Function Correlation Þ resolve atomic motions on timescales faster than the onset of diffusive motions…..observe force correlations

Experiments
Large scale



Electron diffraction

The wave-particle duality of particle beams

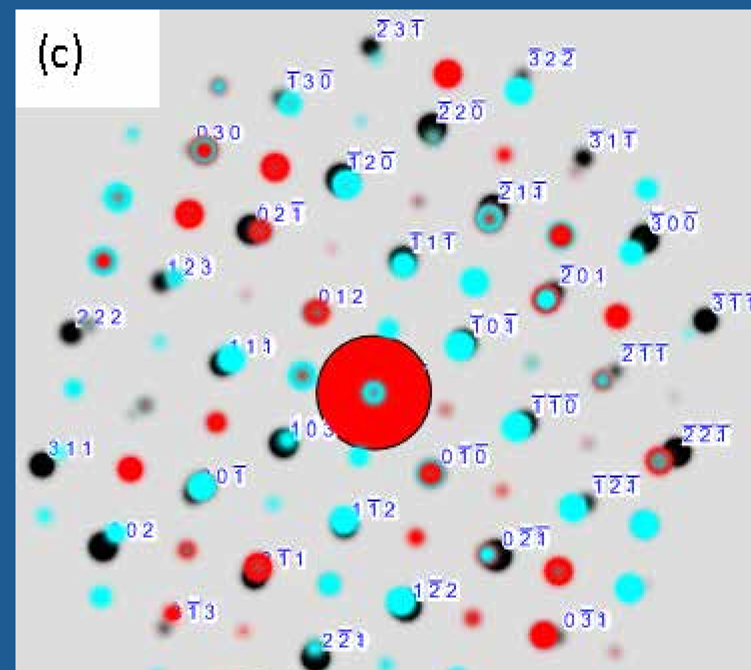


- ▶ scientist can do is 24/7
- ▶ cross section -> 1e6 times larger
- ▶ mass & charge -> penetration depth

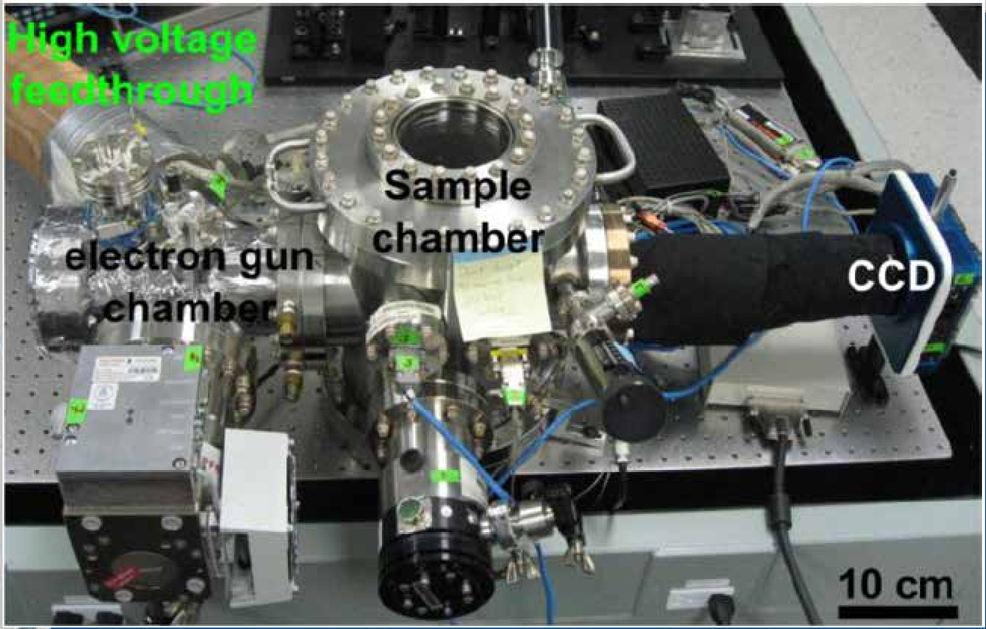
$$l_{dB} = \frac{hc}{\sqrt{2E_{kin}E_0 + E_{kin}^2}} < 0.1\,\dot{A}$$

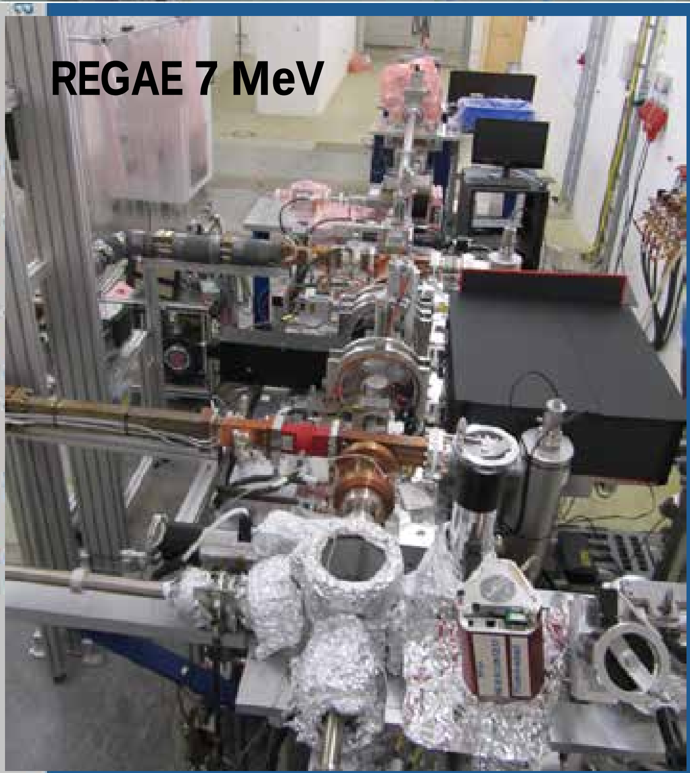
- ▶ 0.1 A corresponds to 100 keV X-rays

- ▶ We exploit the wave nature of the electron
- ▶ Need to detect electrons (sig.-to-noise)
  - ● direct-hit detector
  - ~~● in-direct hit detector~~



Diffraction out to less than 0.2Å!





Experiments

Small scale & with e-

- keV FED – solid state
- keV FED – liquid phase
- keV FED – gas phase
- REGAE Diffraction
- keV time-resolved TEM
- REGAE Dynamic RTEM

Detector requirements

Experiment	Energy / MeV	# Pixels	Single-shot Dynamic range	Frames per second read out
REGAE relativistic electron diffraction (static & time-resolved)	3 – 5	1k x 1k (1M)	10^3 (up to 10^4)	100 Hz
REGAE relativistic TEM[1] mode	3 – 5	2k x 2k (4M)	100	100 Hz
time-resolved TEM[1] (adapted commercial TEM[1])	0.1 – 0.3	1k x 1k (1M)	100	*ca.* 1-10 MHz
keV UED[2] – solid state samples	0.1 - 0.3	1k x 1k (1M)	10^3 (up to 10^4)	1 kHz
keV UED[2] – liquid phase samples	0.1 – 0.3	1k x 1k (1M)	100	1 kHz
keV UED[2] – gas phase samples	0.1 – 0.3	1k x 1k (1M)	>3	1 kHz

Table 1: Most demanding requirement to a detector system for the various types of experiments performed at MPSD. The most demanding requirements are indicated in red. ([1]transmission electron microscope [2]ultrafast electron diffraction)

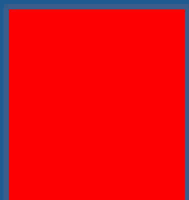
- Want fast detector… as reasonably possible
- Excellent signal to noise (single primary e- detection)

Can one single system serve all requirements?

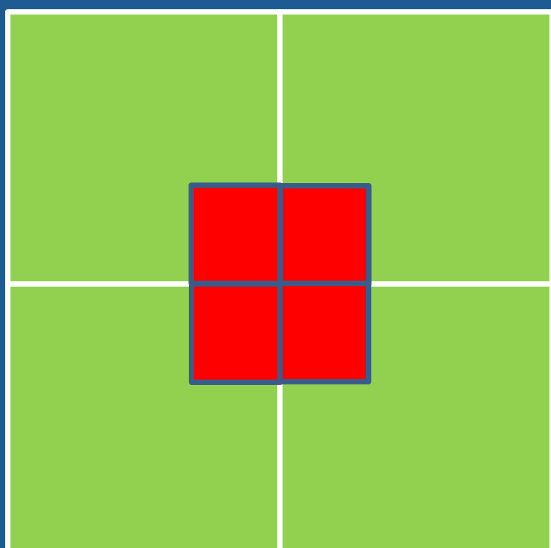
Principally yes, but we make two different (similar) systems!

Pixel detectors

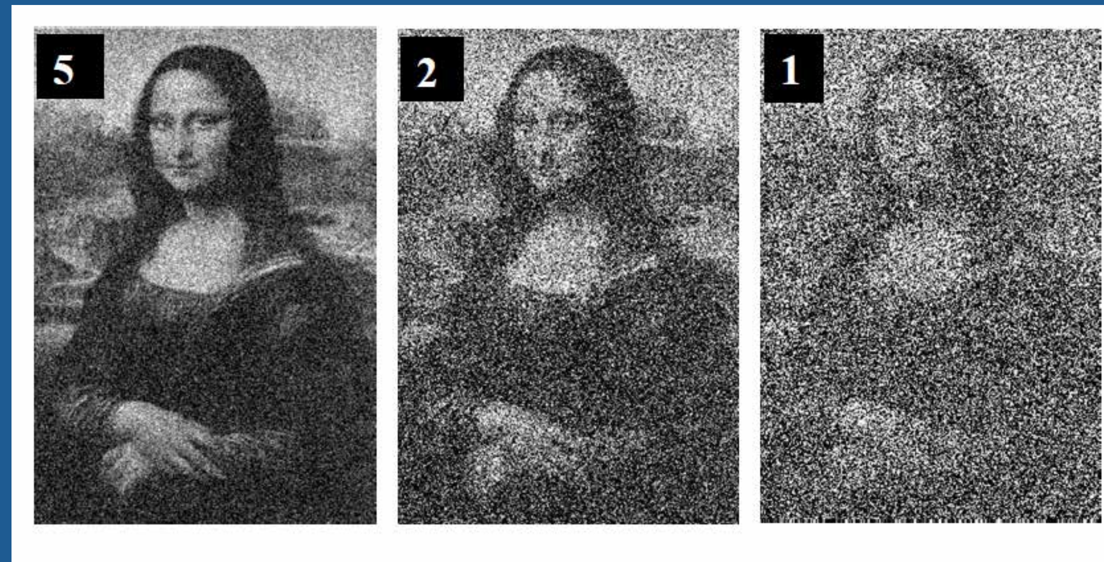
Signal to Noise (SN)



e-h pairs



4 pixel.....25% each split



<u>For 50 µm (110):</u>

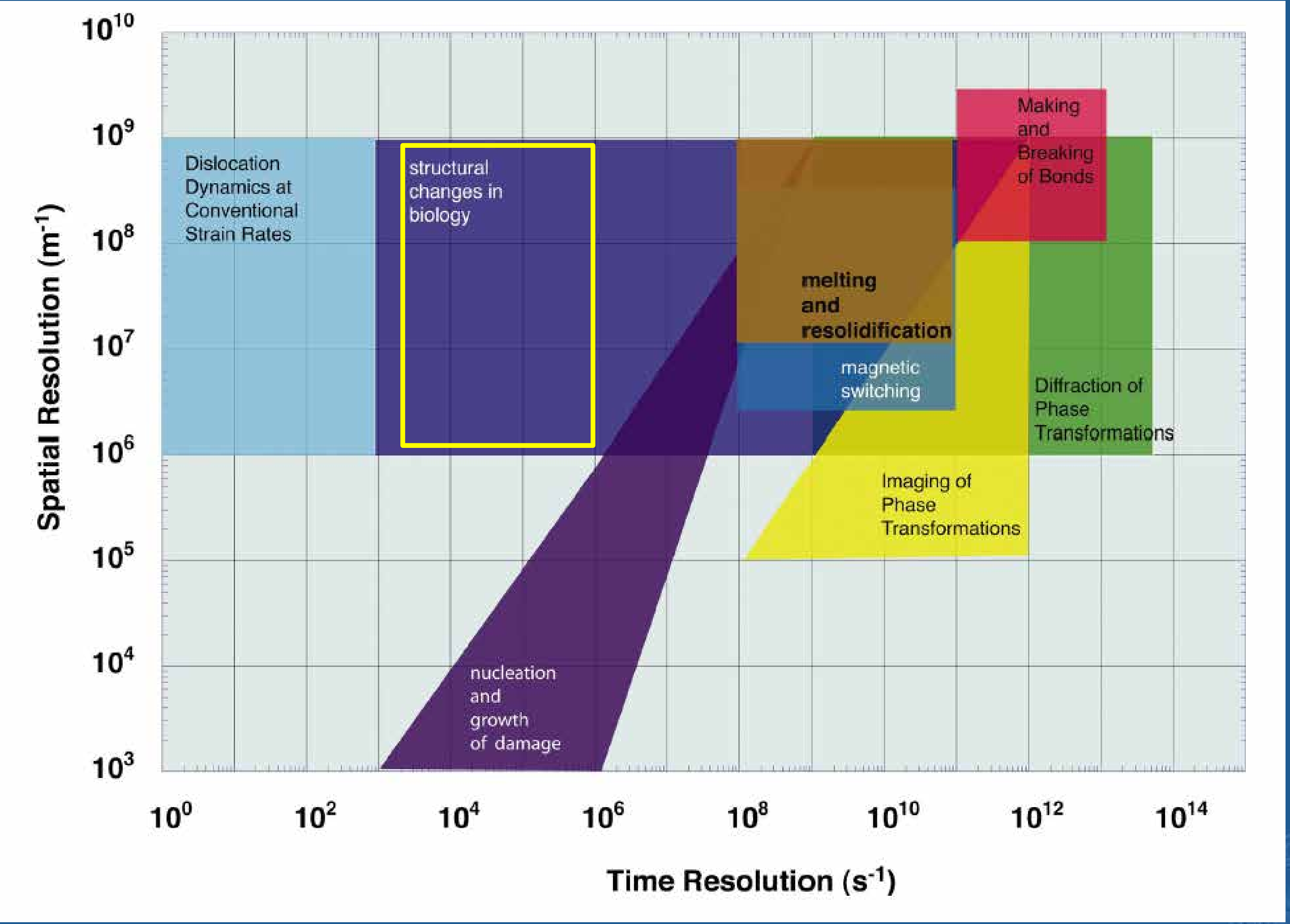
A fraction of 1e(-6) single hit events creates less than 2700 e-h pairs

25% of 2700 is 675 e-h pairs

With a noise of 100 e-h pairs this is 6 sigma from noise.

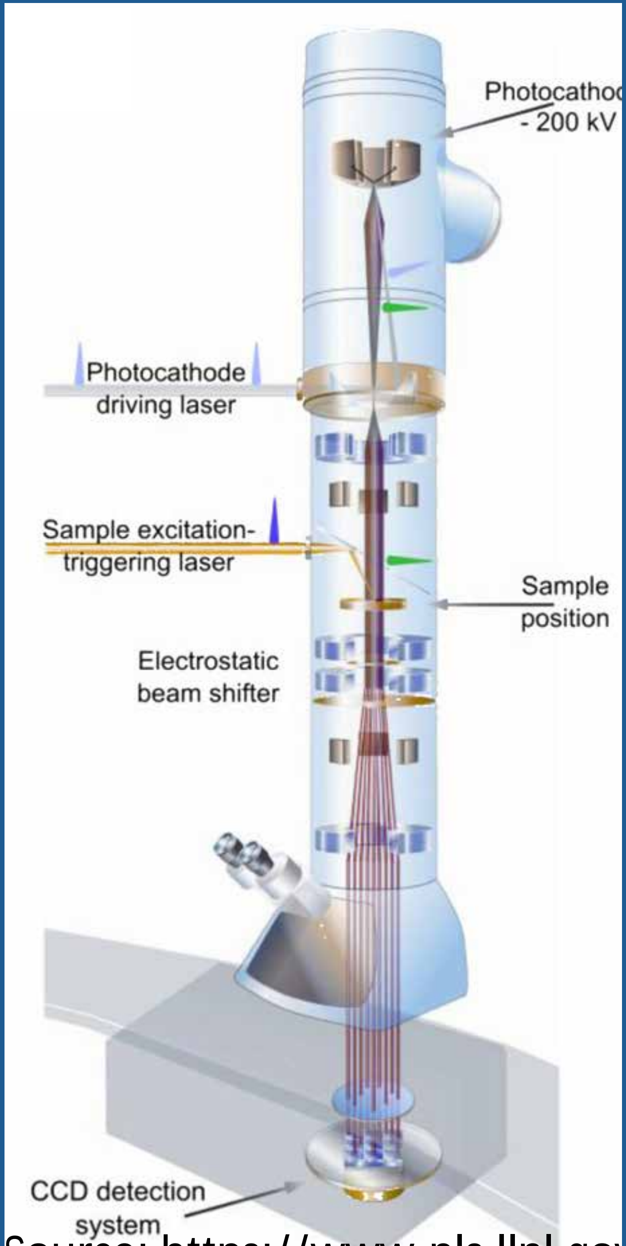
Less than a fraction of 1e-6 of events has a noise of 600.

Static & Dynamic
Time scales

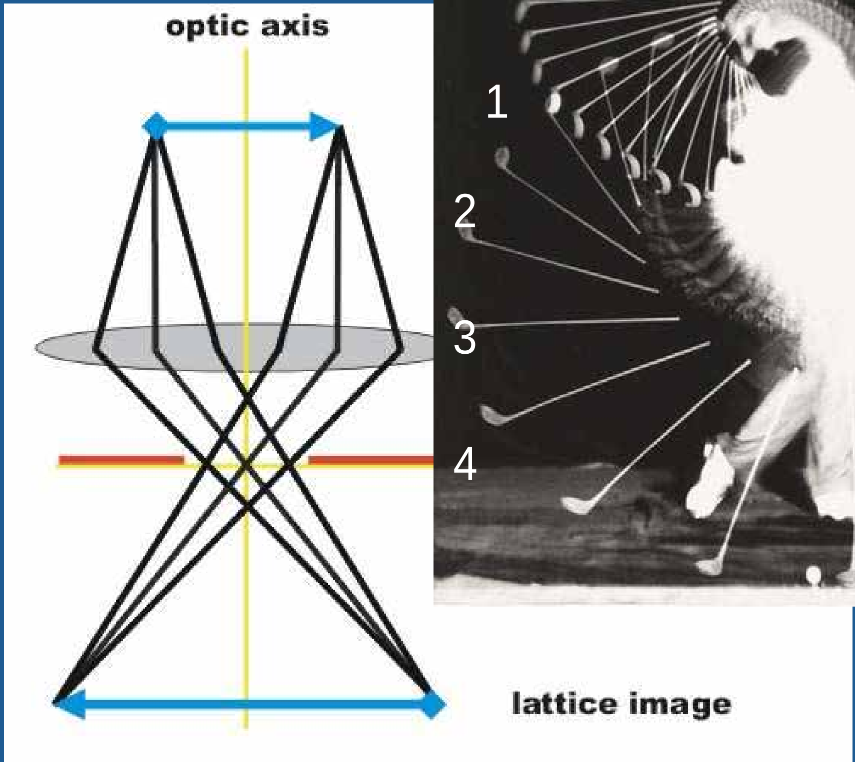


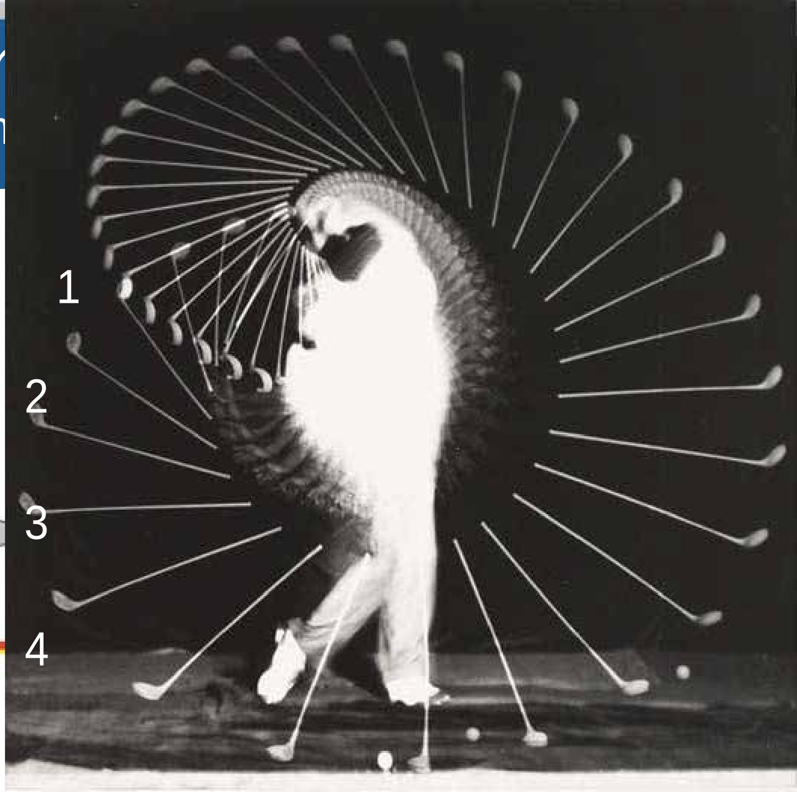
TEM real space im

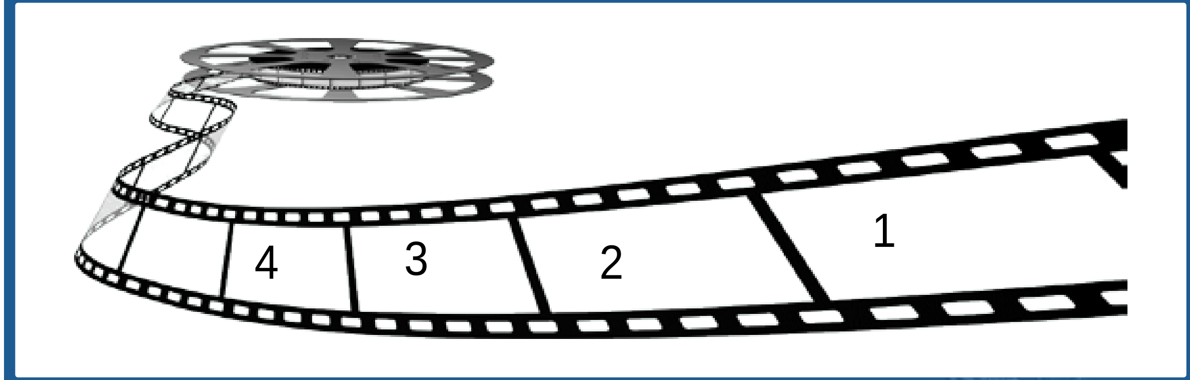
A movie like in cinem



Source: https://www-pls.llnl.gov

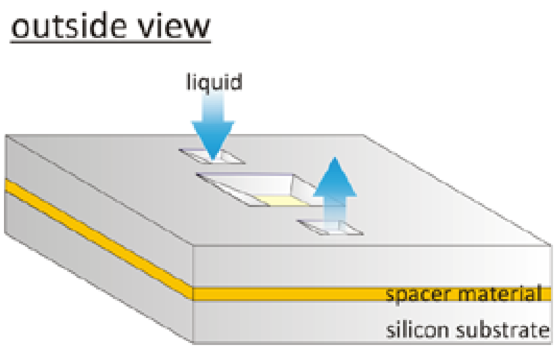


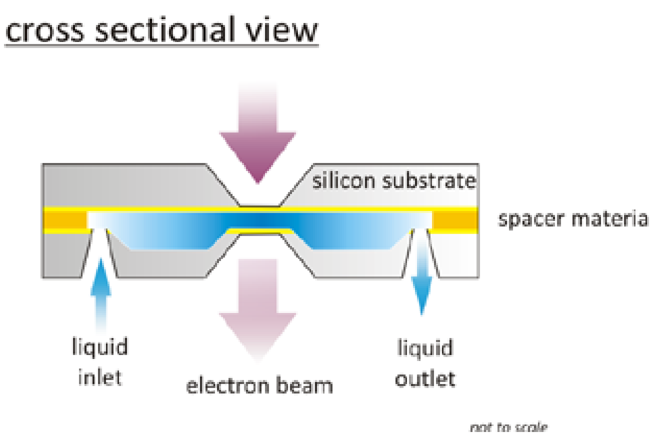




Further Evolution in atom gazing: ……Solution Phase Dynamics

TEM nanocell with flow!

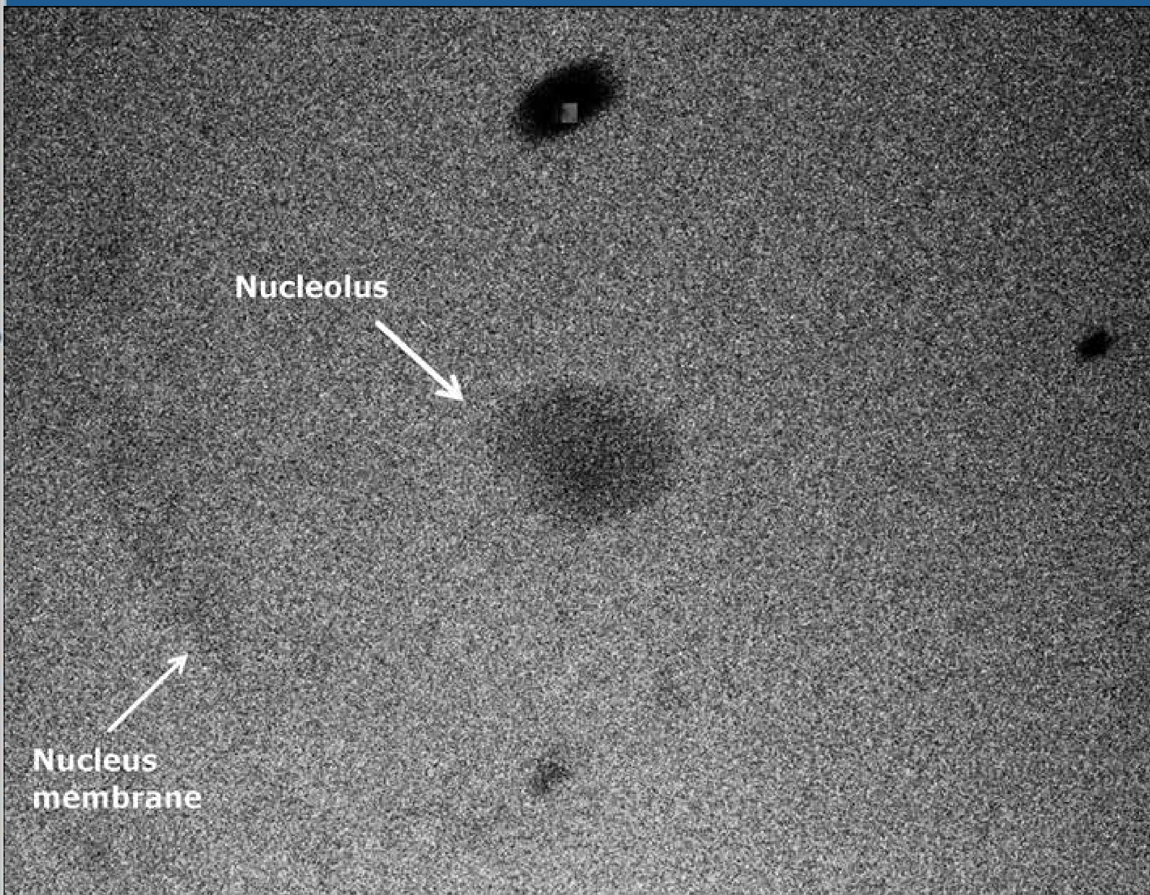


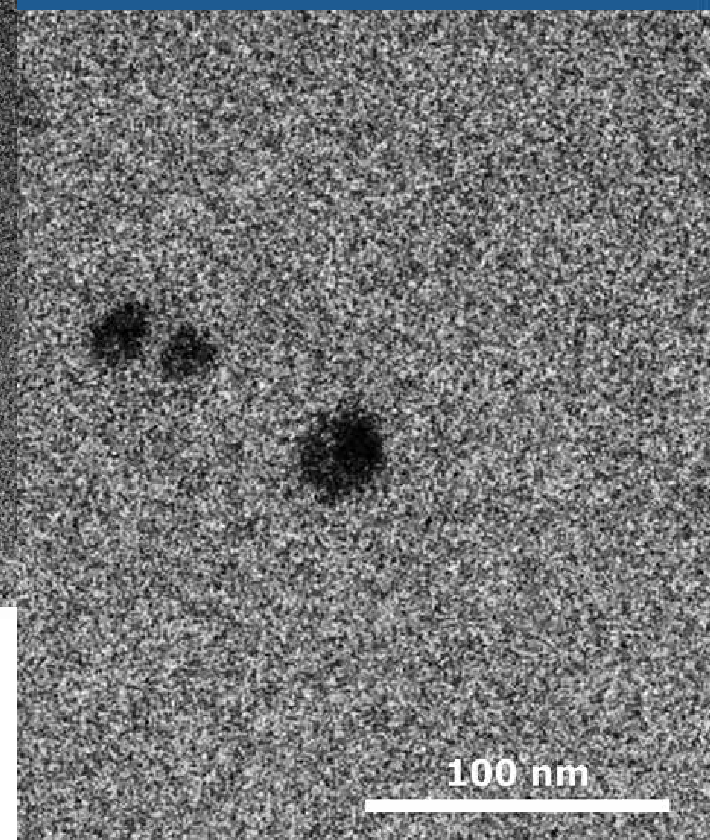


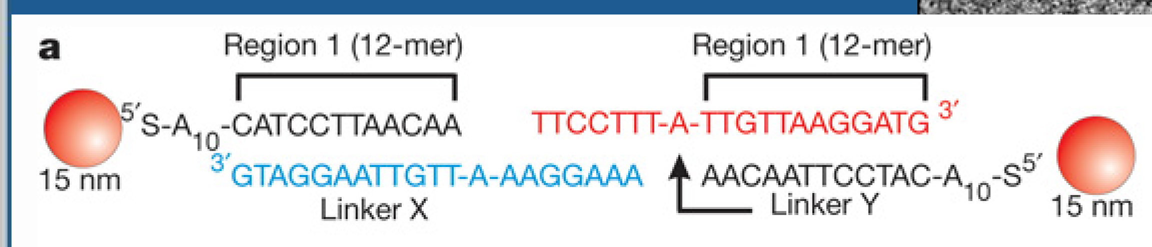
Christina Müller: U Toronto
Sercan Kescin, Stephanie Manz: MPSD

Video

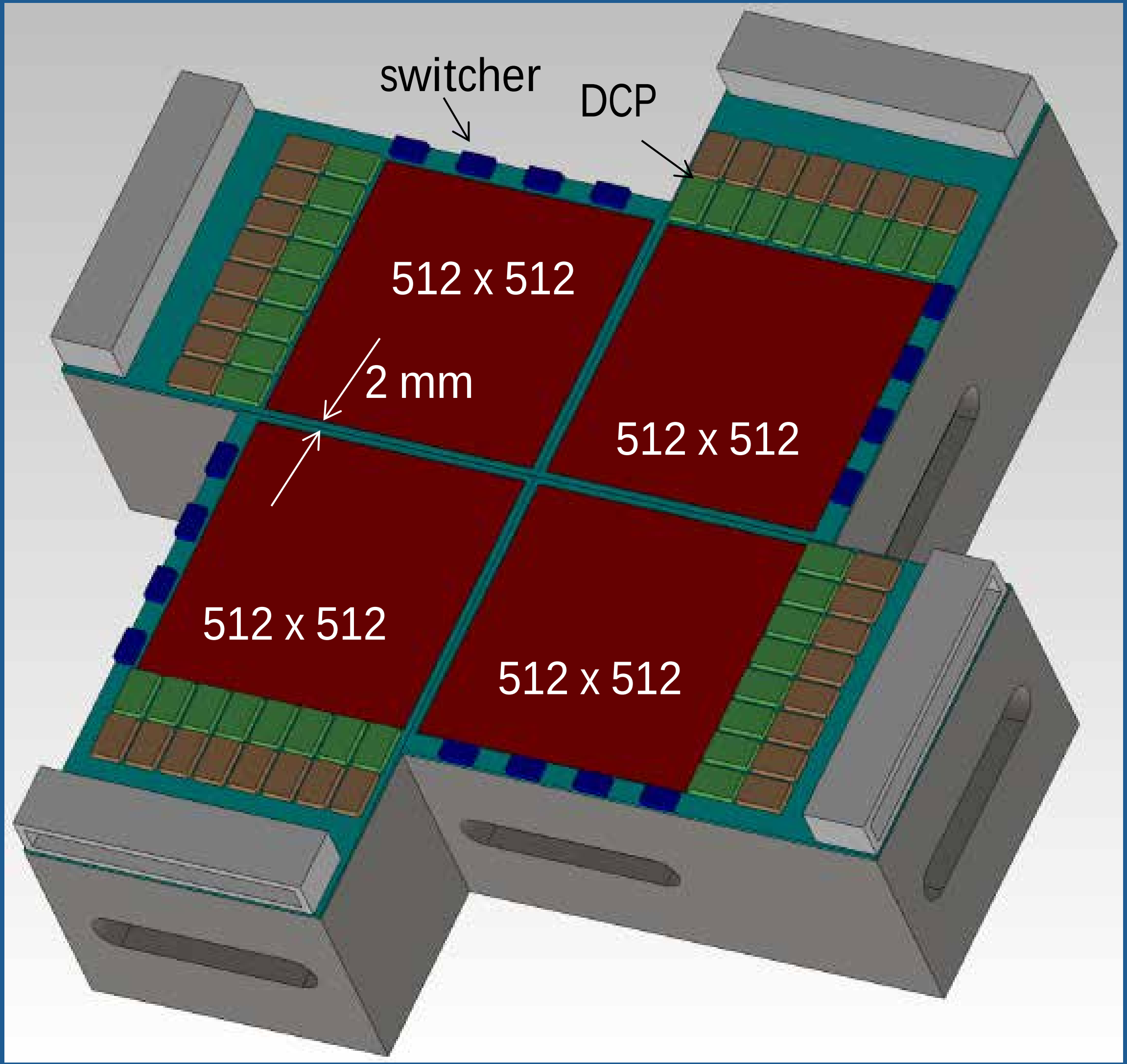
Liquid cell







Edet system (DH80k)
DEPFET direct hit

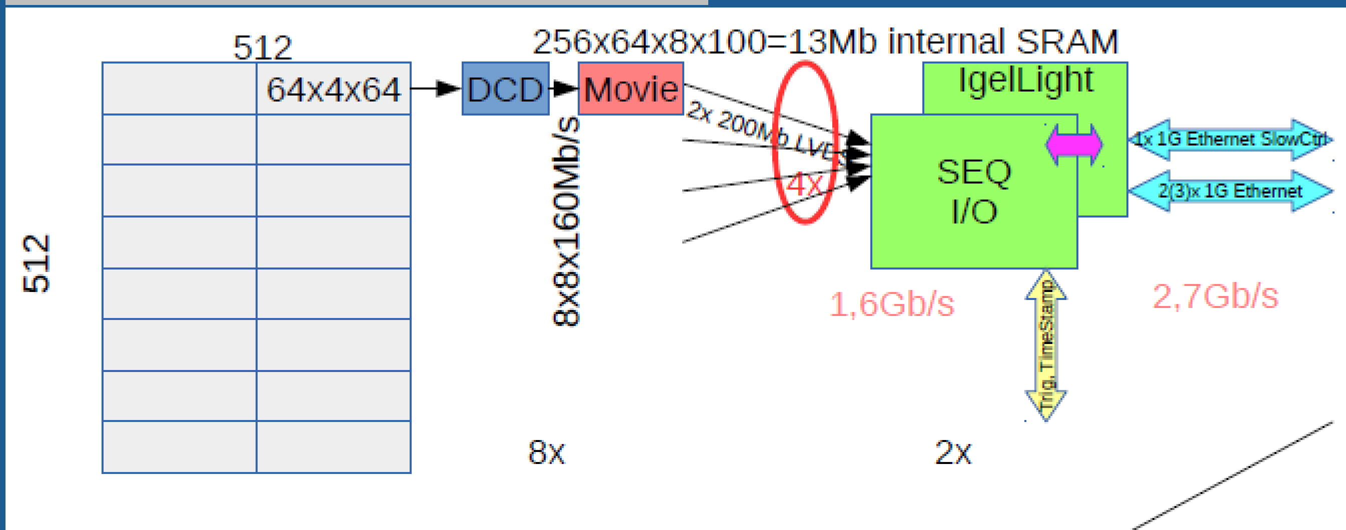


- direct electron detection
- 60 x 60 mm² active area
- 1000 x 1000 px (4 chips)
- pixel size: 60 x 60 µm²
- full frame readout 80kHz by 4-fold rolling shutter mode
- dead joining region < 2 mm

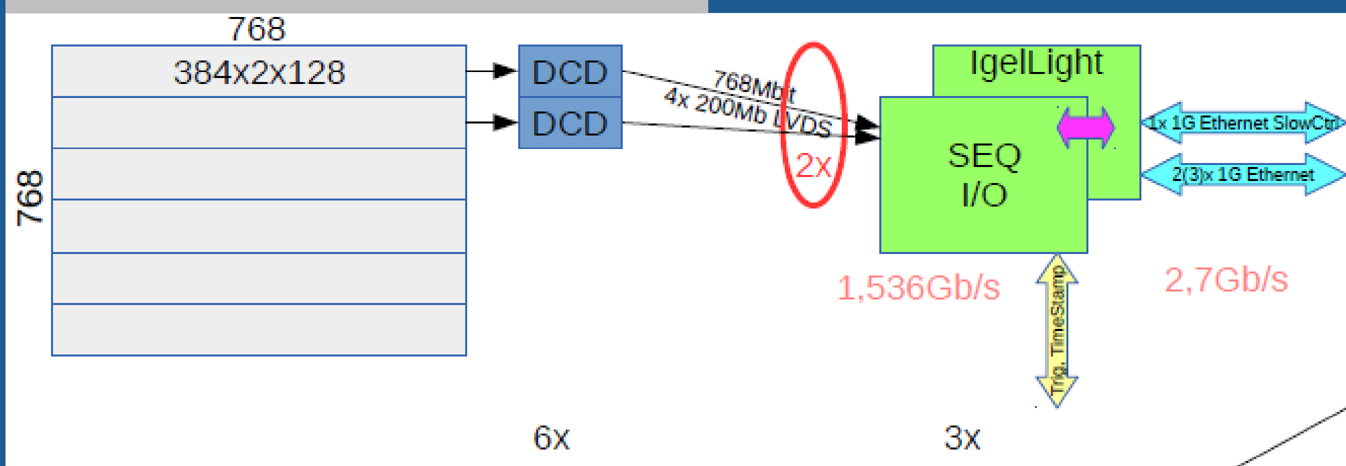
Data stream

Use BELLE-II components where possible: How well do they fit the application

> DH80k



> DH1k



- 80 kHz -> 80 GB/s of data if operated continuously ! (compare DE-CIX with 230 GB/s)

- Solution: burst mode with movie of 100 frames. -> storage needed

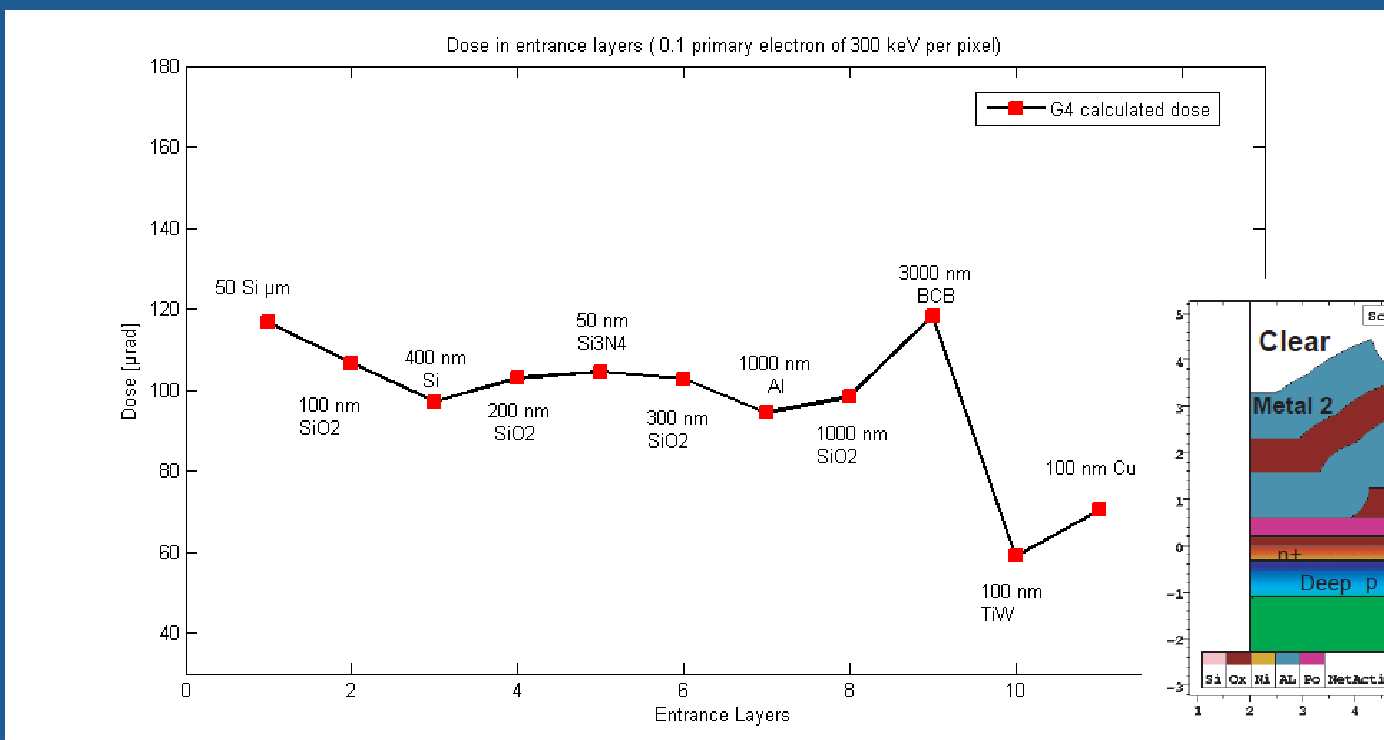
A. Wassatsch

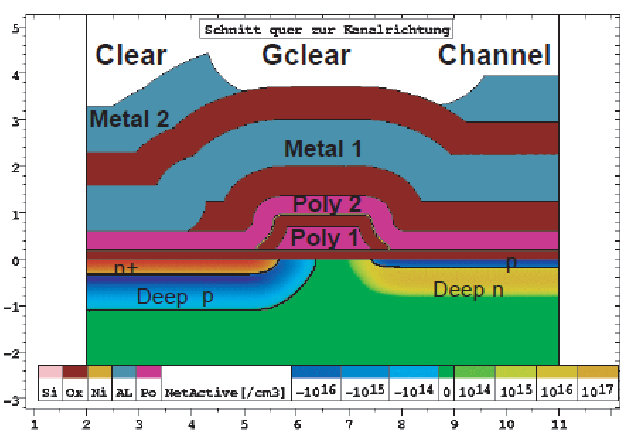
Further main challenges

DCD resolution: Is 8 bit enough? Non linear DEPFET response (Rainer Richter) -> sufficient, more would be better.....

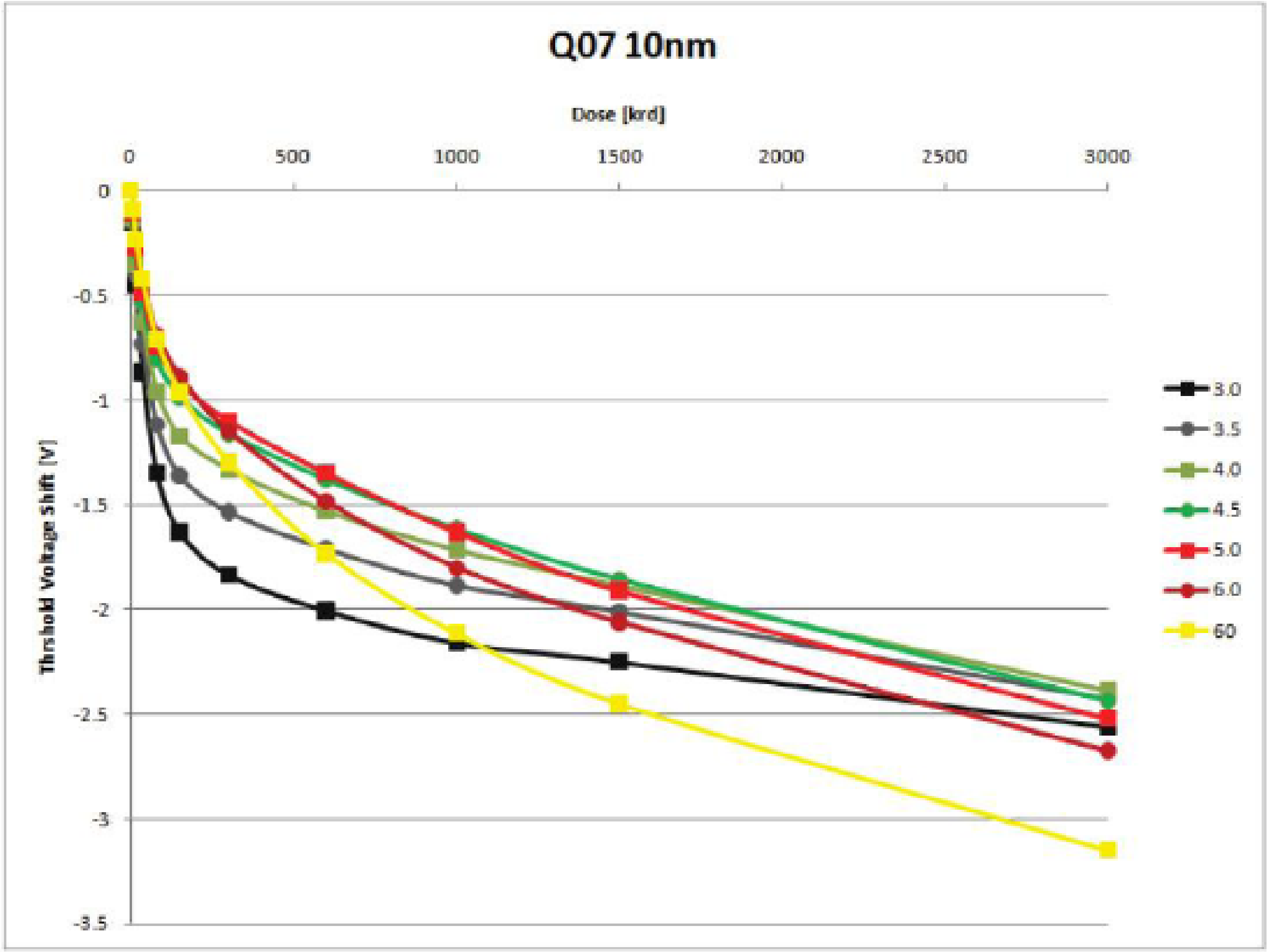
Radiation hardness: Suffer from radiation damage. What happens to the detector towards 10 MRad. Can we cure damage by annealing? To what extend? (Martin Hensel).

Thermal issues: due to low thermal conductivity (not solved, but doable)





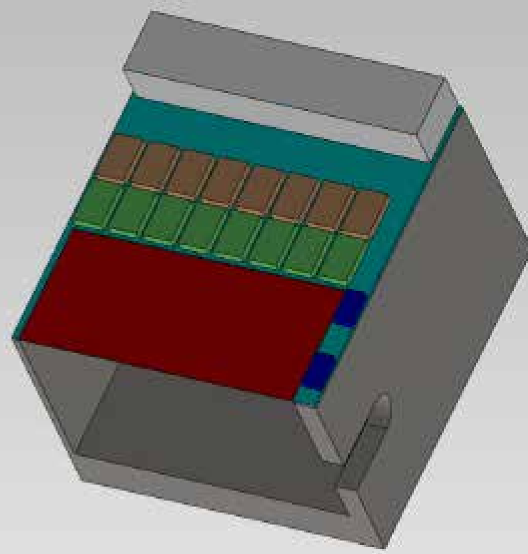
Radiation damage II – best case



2.5V shift after 3Mrad
almost linear increase 0.35V/Mrad (needs confirmation)

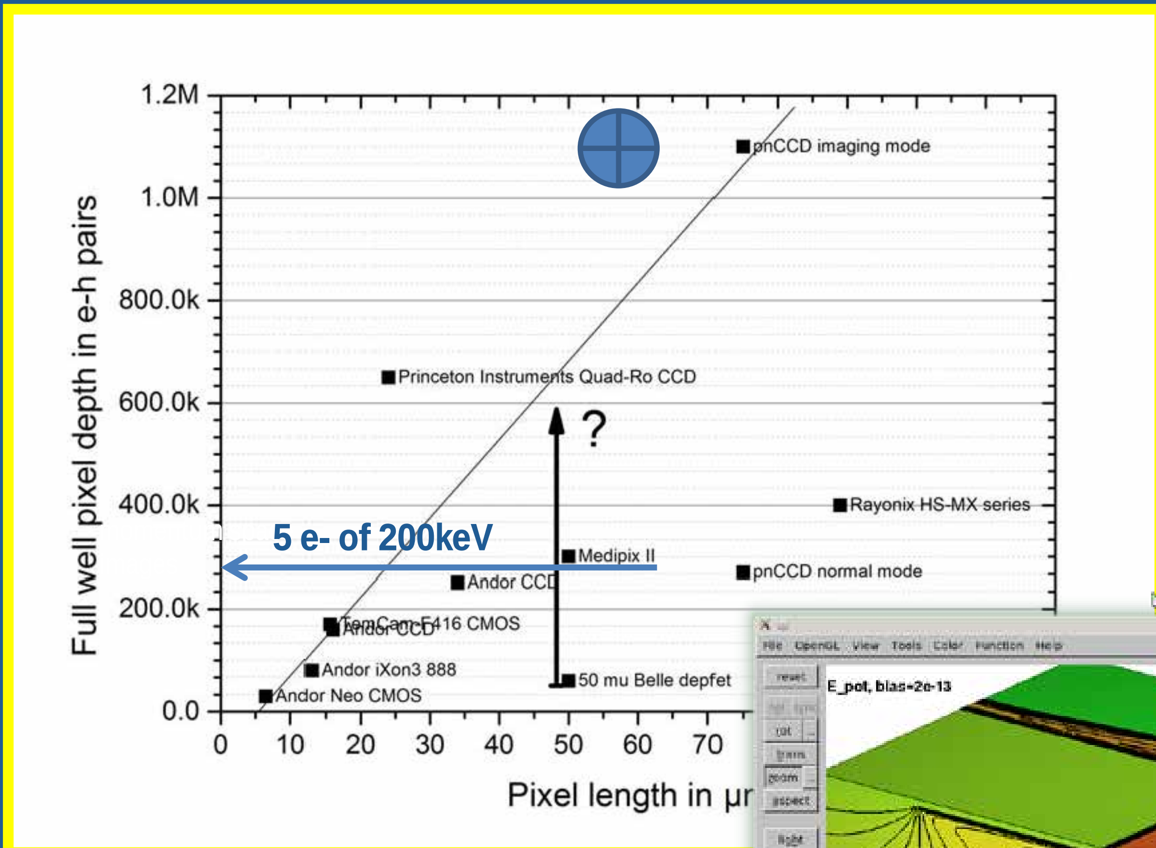
Edet system (DH80k)

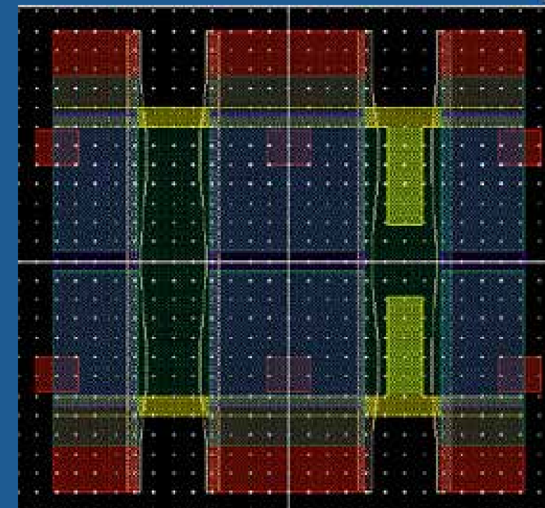
DEPFET direct hit

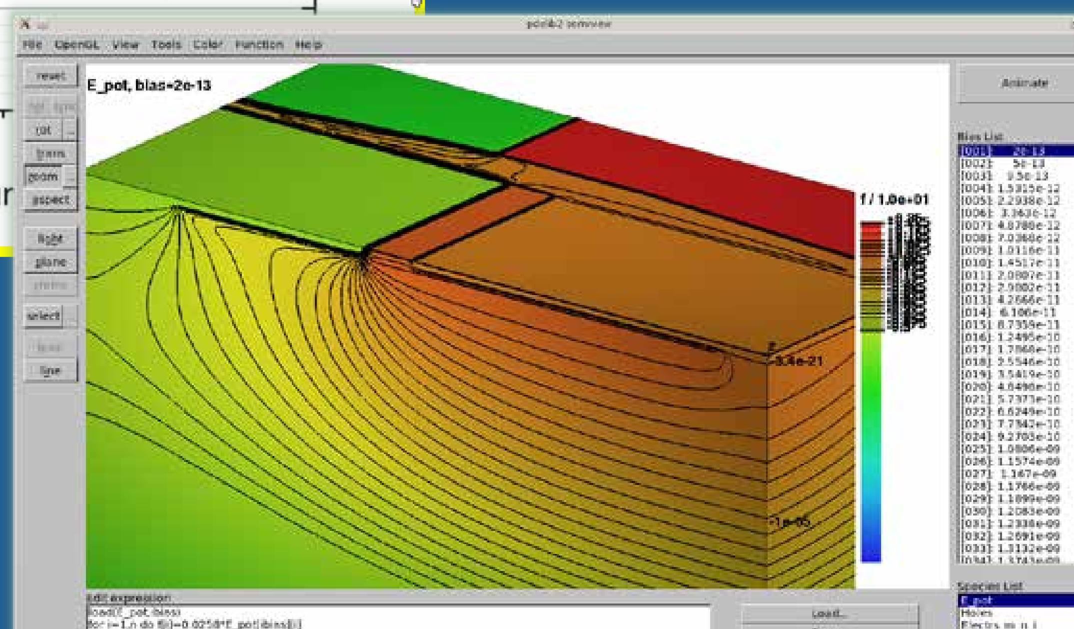


- direct electron detection
- 60 x 60 mm^2 active area
- 1000 x 1000 px (4 chips)
- pixel size: 60 x 60 μm^2
- full frame readout 80kHz by 4-fold rolling shutter mode
- dead joining region < 2 mm

Charge Handling

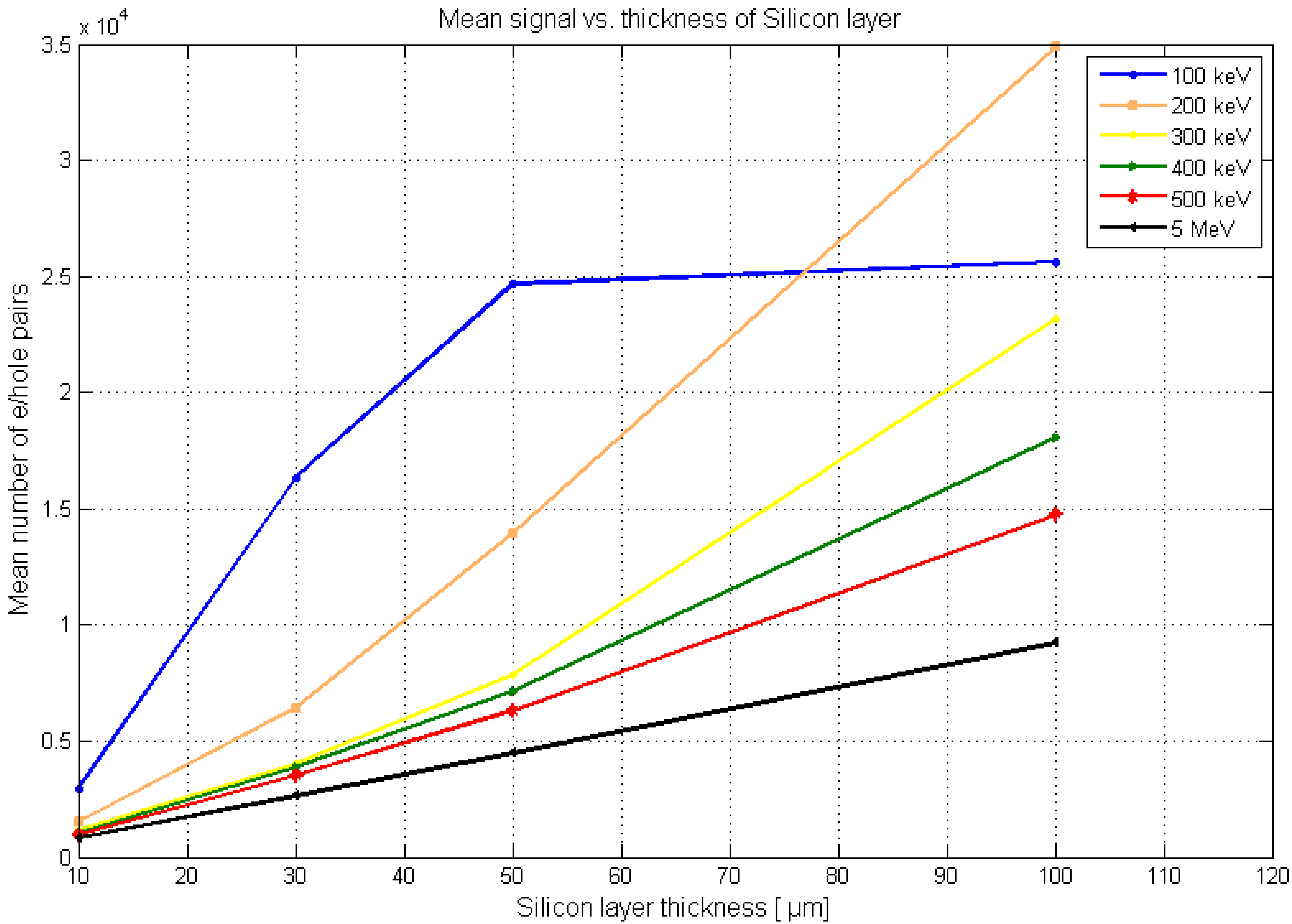






- On average: 1 e-h-pair/3.6 eV
- > 1M e-h pairs

Max Planck Institute for Structure and Dynamics of Matter

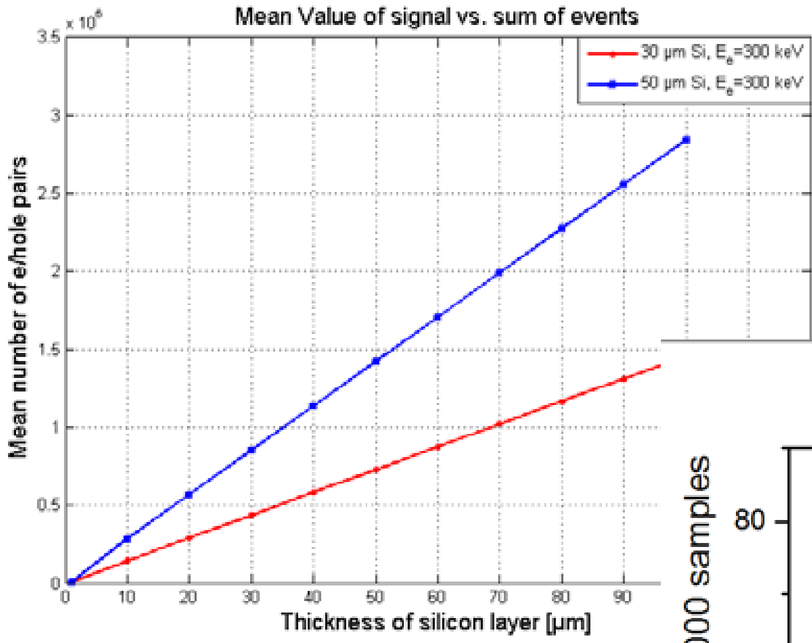


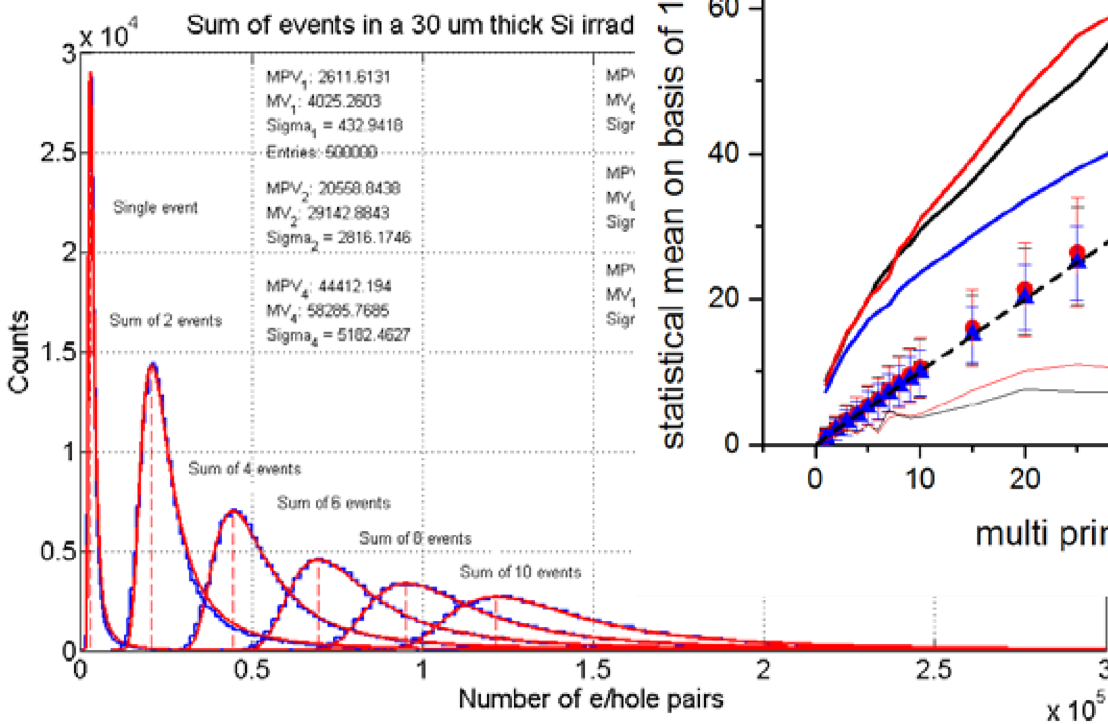
Low energy electrons generate more signal than high energy electrons

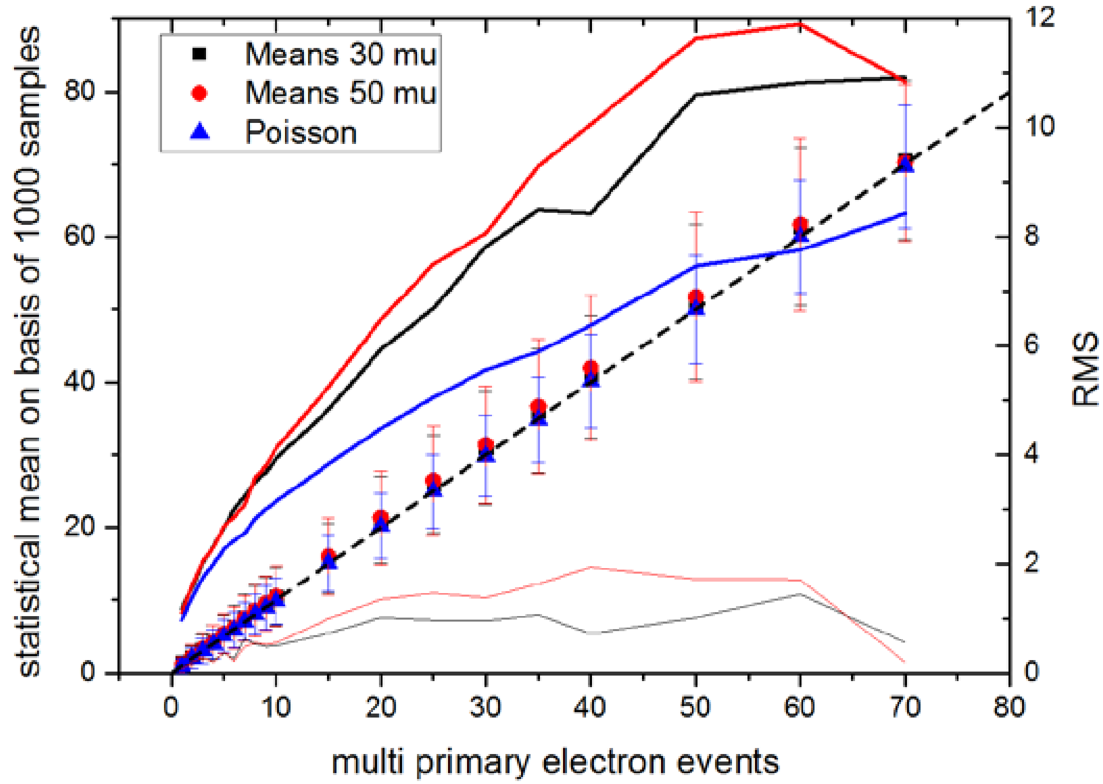
Low energy electron Þ large scattering angles

I.Dourki

Charge Handling & Statistics

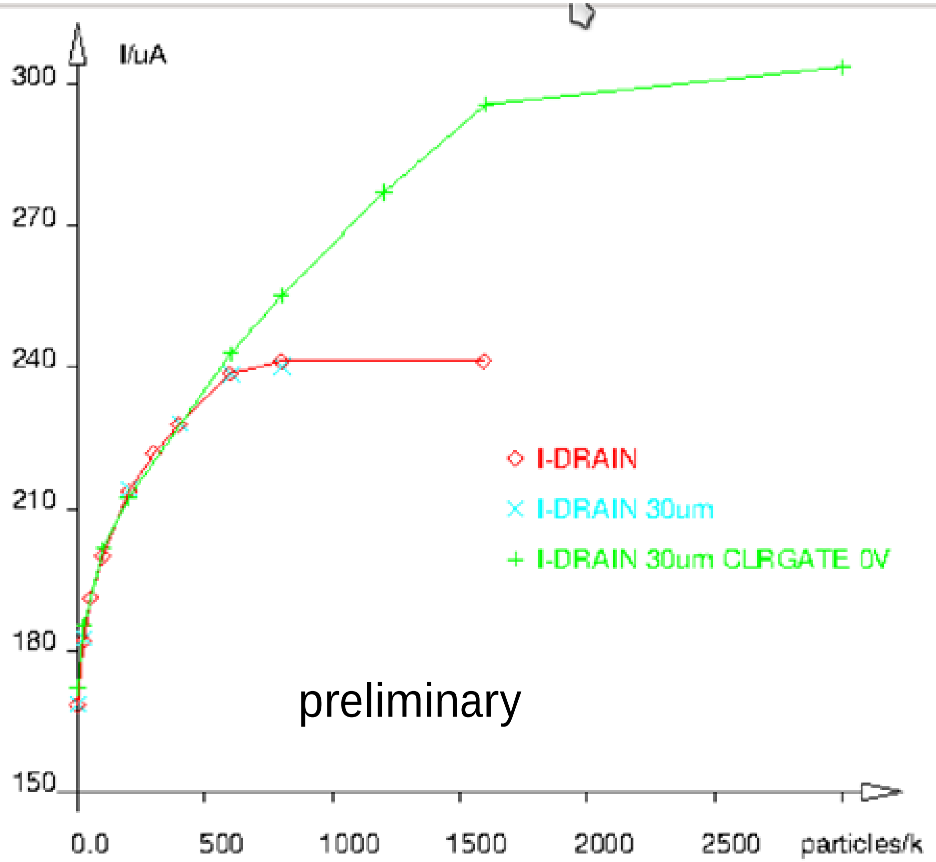






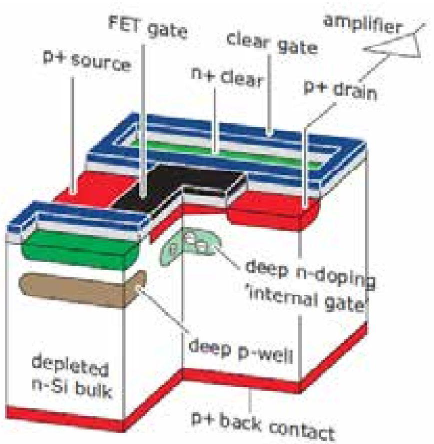
Max Planck Institute for Structure and Dynamics of Matter

Tayloring the response curves



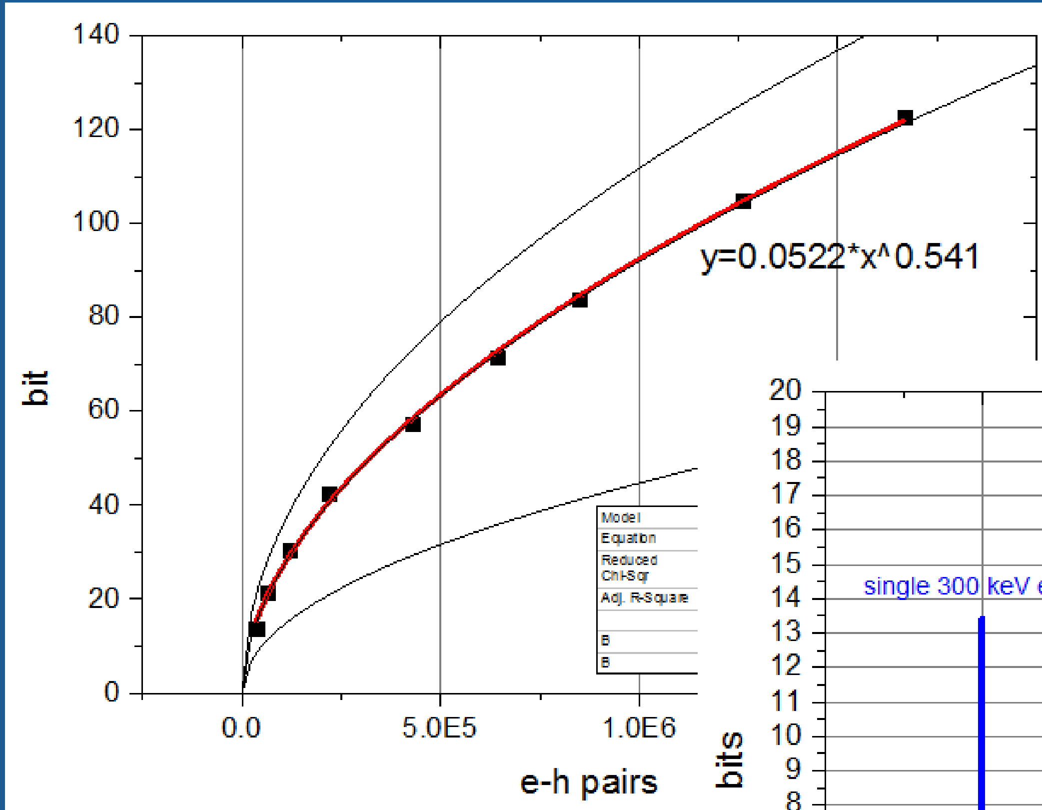
BACK=-20V, CLRGATE1=2.5V, GATE=3V, SOURCE=0V, DRAIN=-5V,

DRIFT=-3V, CLEAR=2V, I DRAIN for different cloud sizes

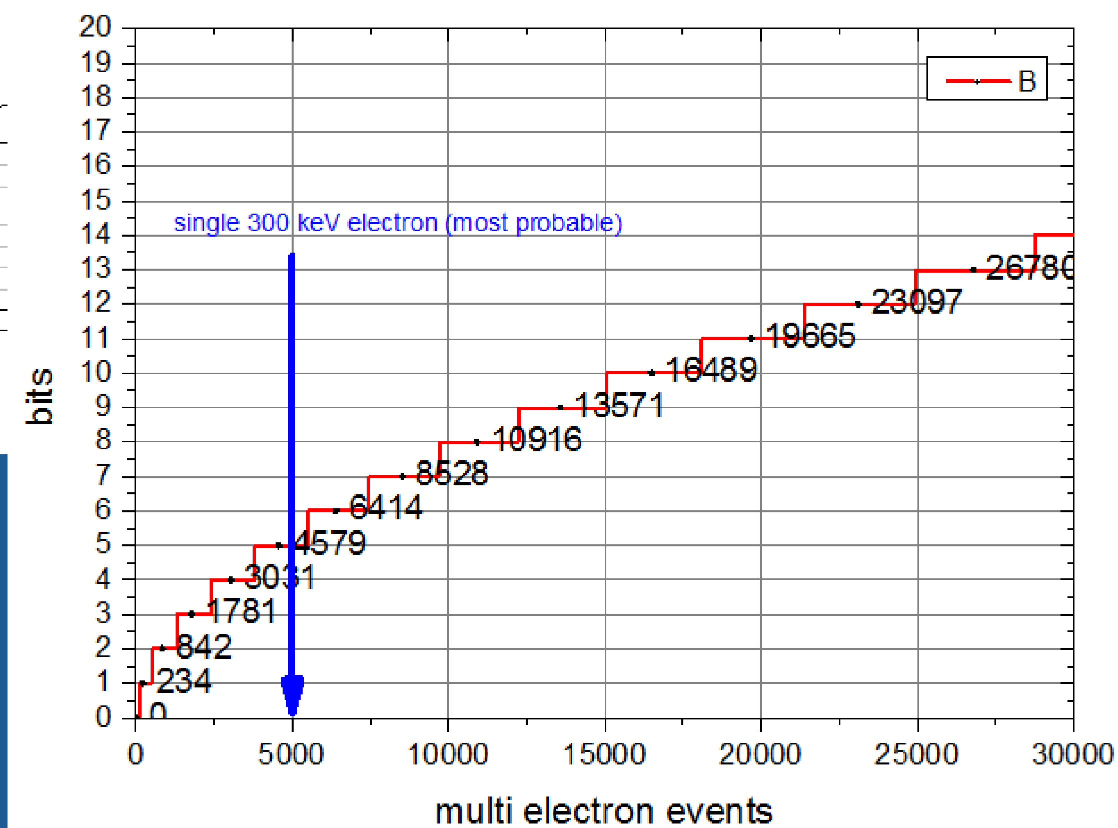


Response curve

Edet with internal gate overflow



- reach high e-h numbers with 7 bit
- have some resolution bellow 1 primary electron (4 bit)

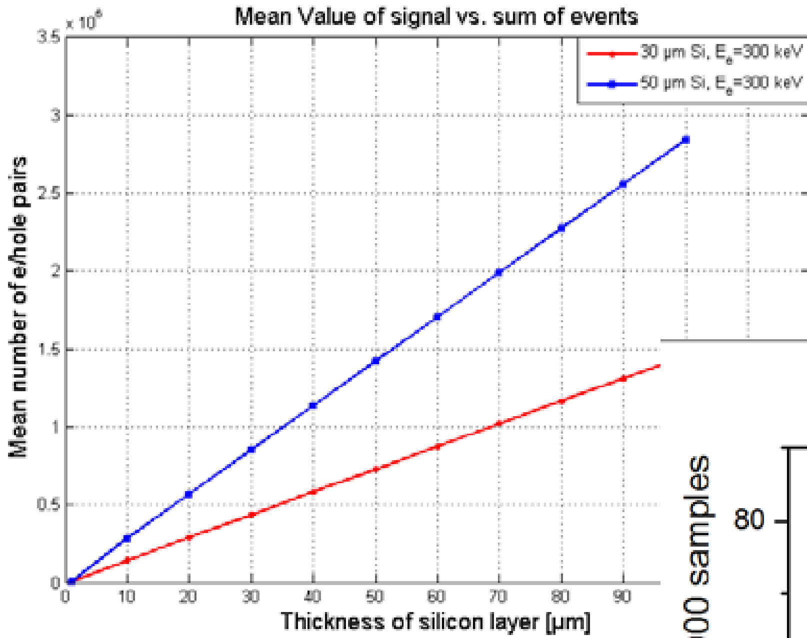


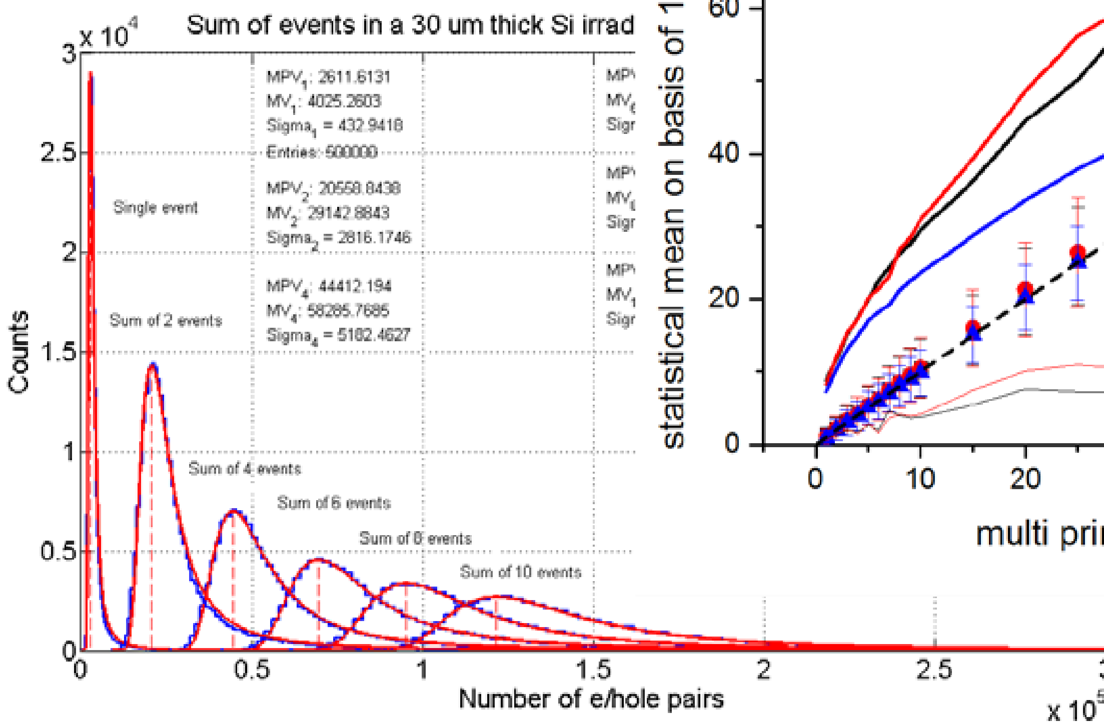
- Delta of 1 bit is bellow the Poisson noise (counting stat.)

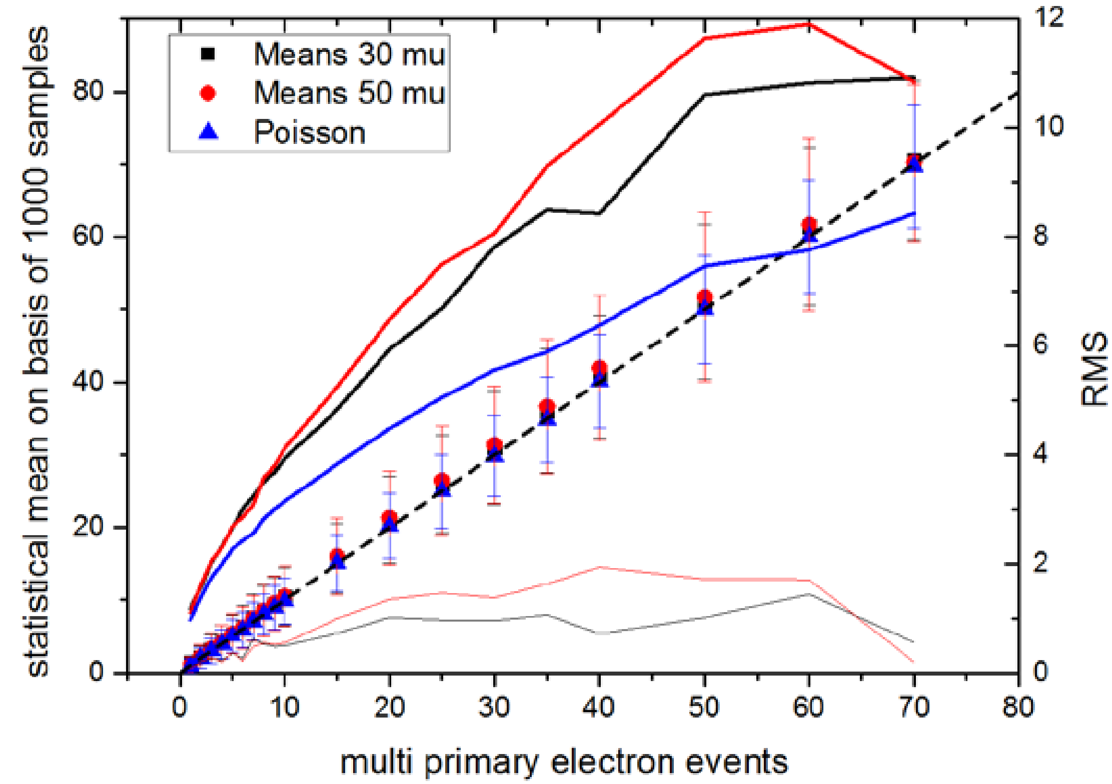
Max Planck Institute for Structure and Dynamics of Matter

mpsd

Charge Handling & Statistics





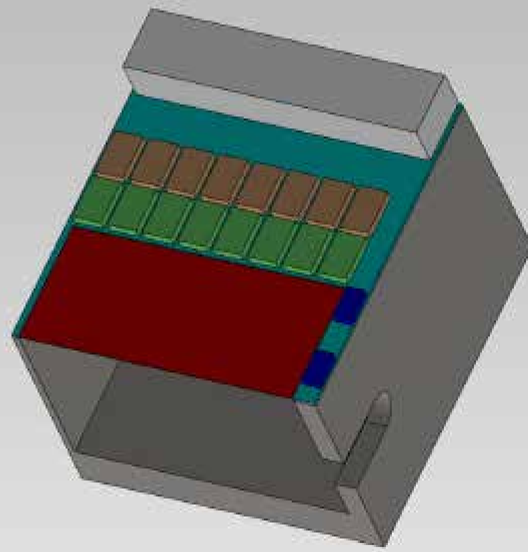


Max Planck Institute for Structure and Dynamics of Matter

mpsd

Edet system (DH80k)

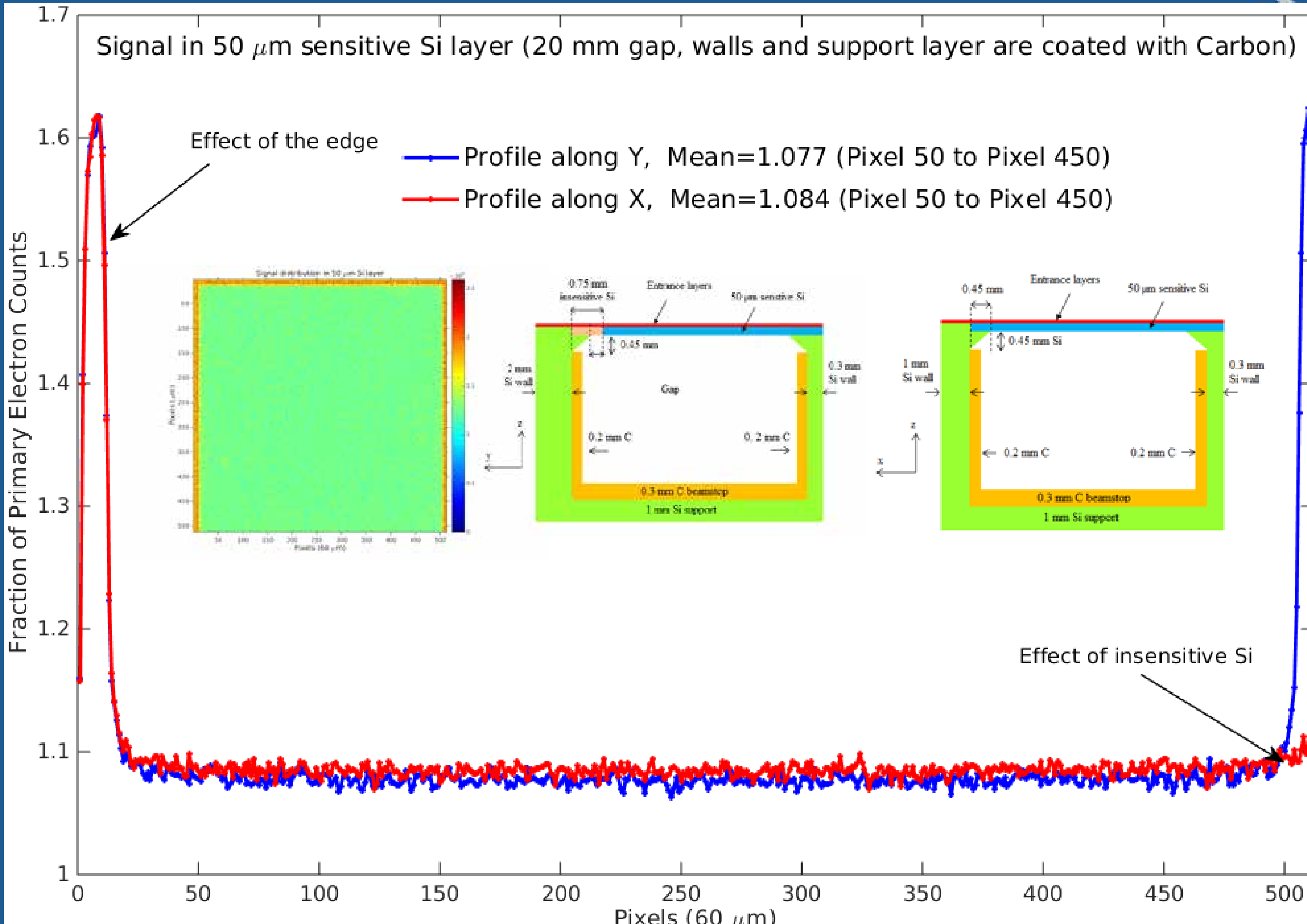
DEPFET direct hit



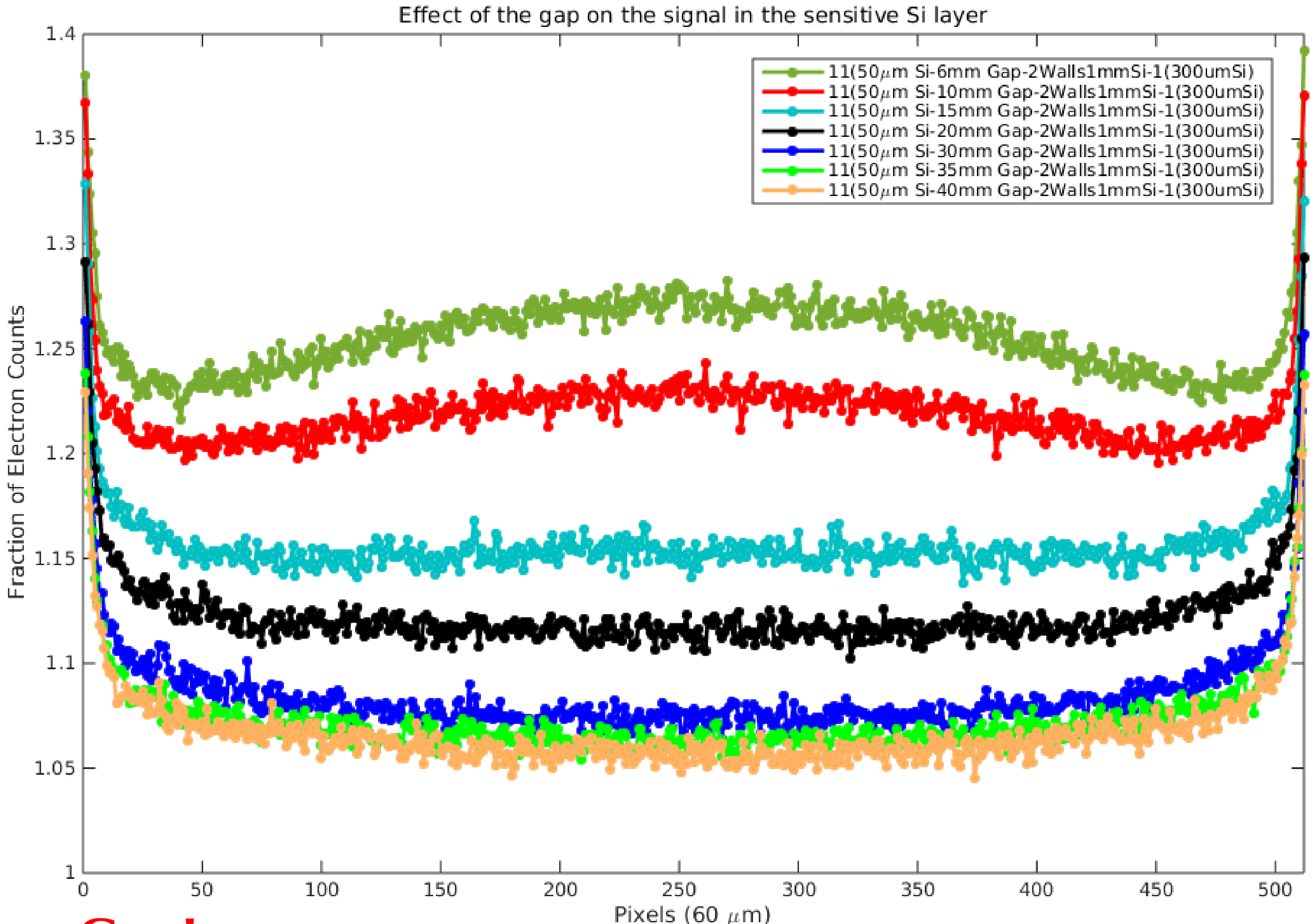
- direct electron detection
- 60 x 60 mm^2 active area
- 1000 x 1000 px (4 chips)
- pixel size: 60 x 60 μm^2
- full frame readout 80kHz by 4-fold rolling shutter mode
- dead joining region < 2 mm

Max Planck Institute for Structure and Dynamics of Matter

mpsd

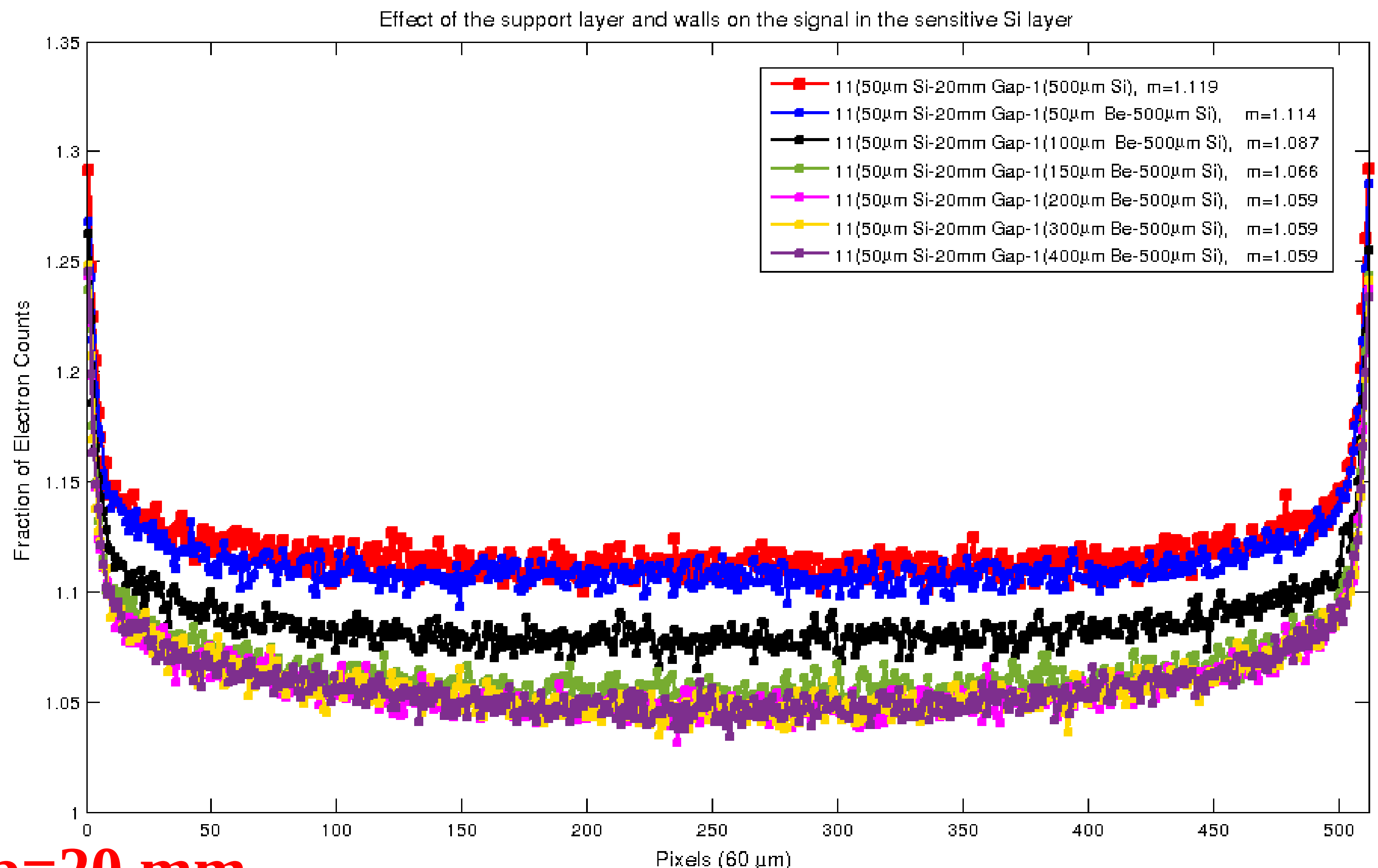


RESULT1: 11(50 µm Si)- Gap-2Walls1mmSi-1(300umSi)



Large Gap!

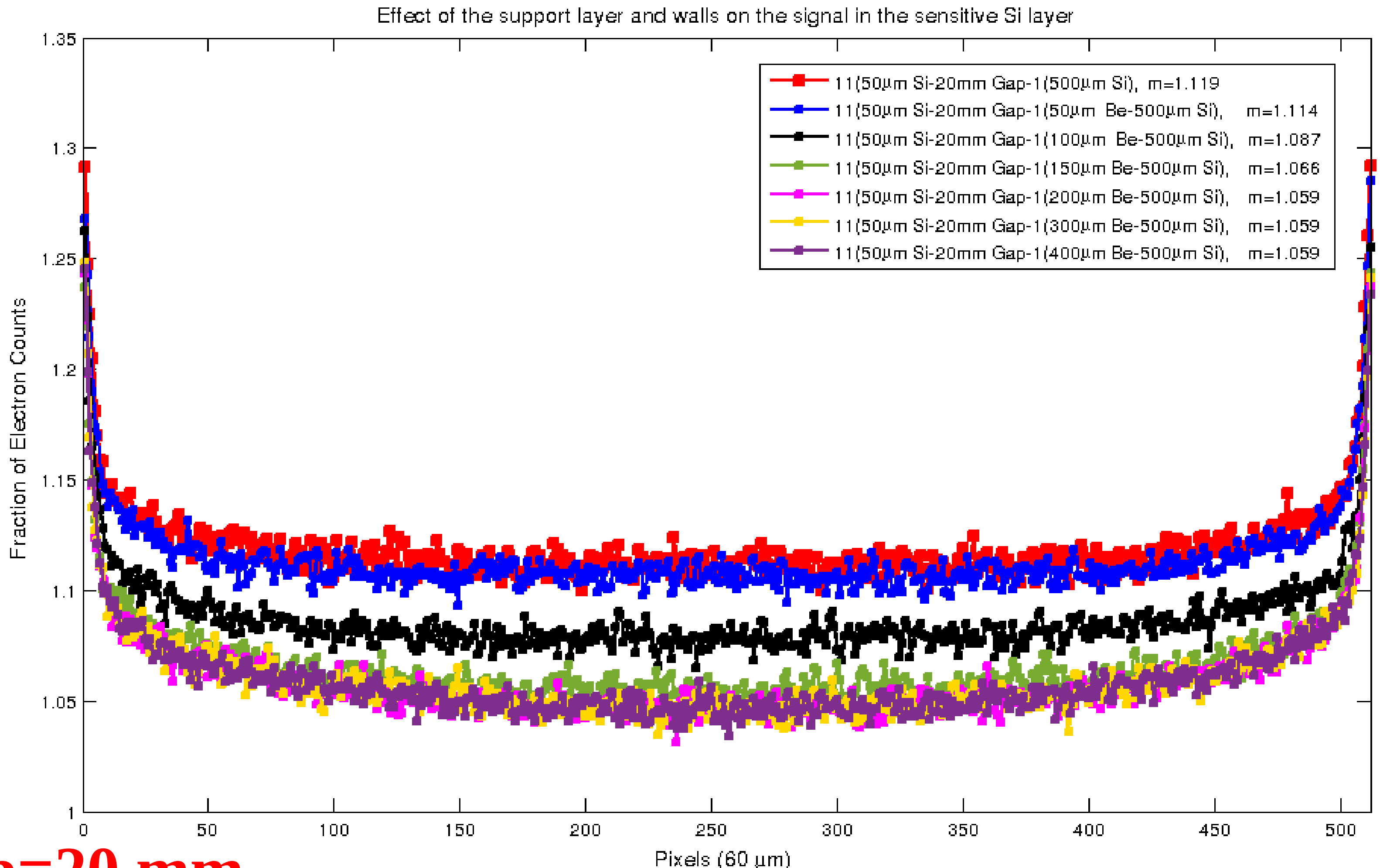
Effect of Be beamstop, walls and support layer on the signal



Gap=20 mm

I.Dourki

Effect of Be beamstop, walls and support layer on the signal

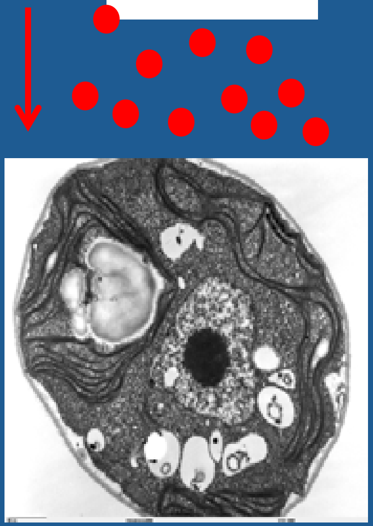


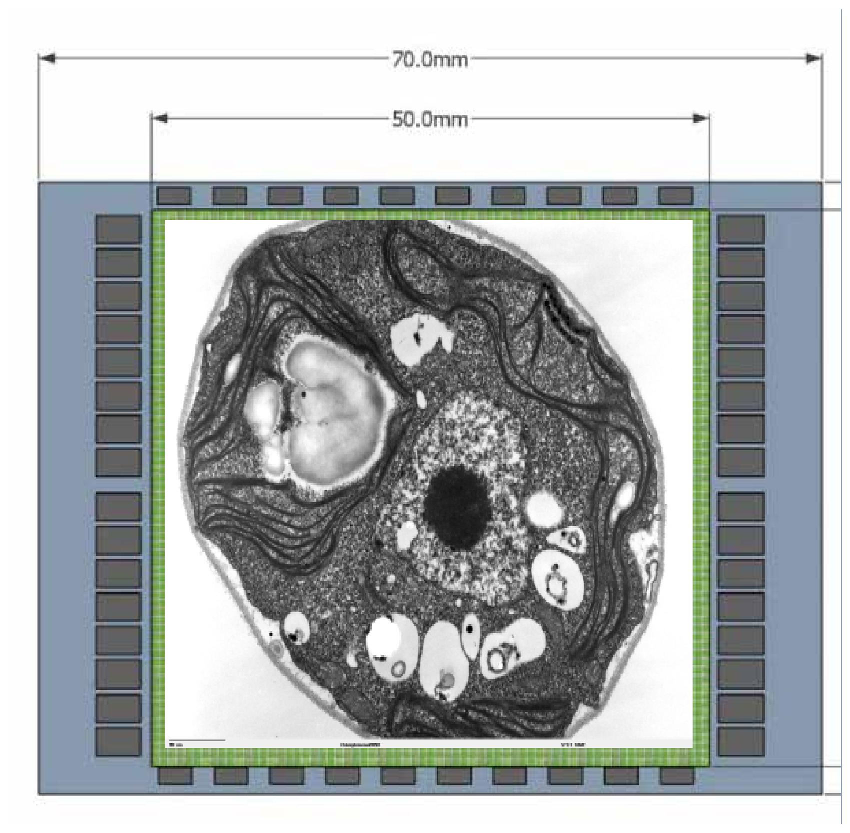
Gap=20 mm

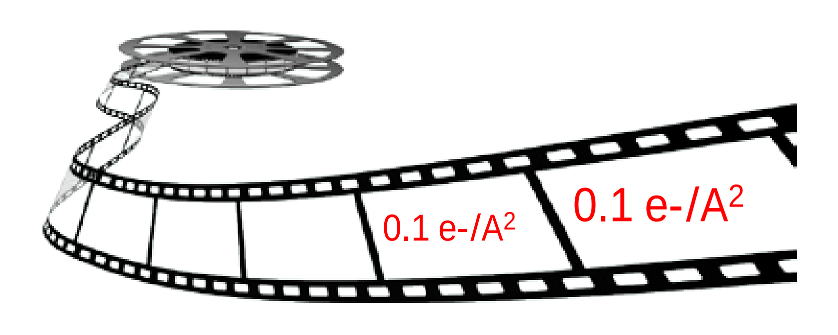
I.Dourki

TEM movie

100e6 e-

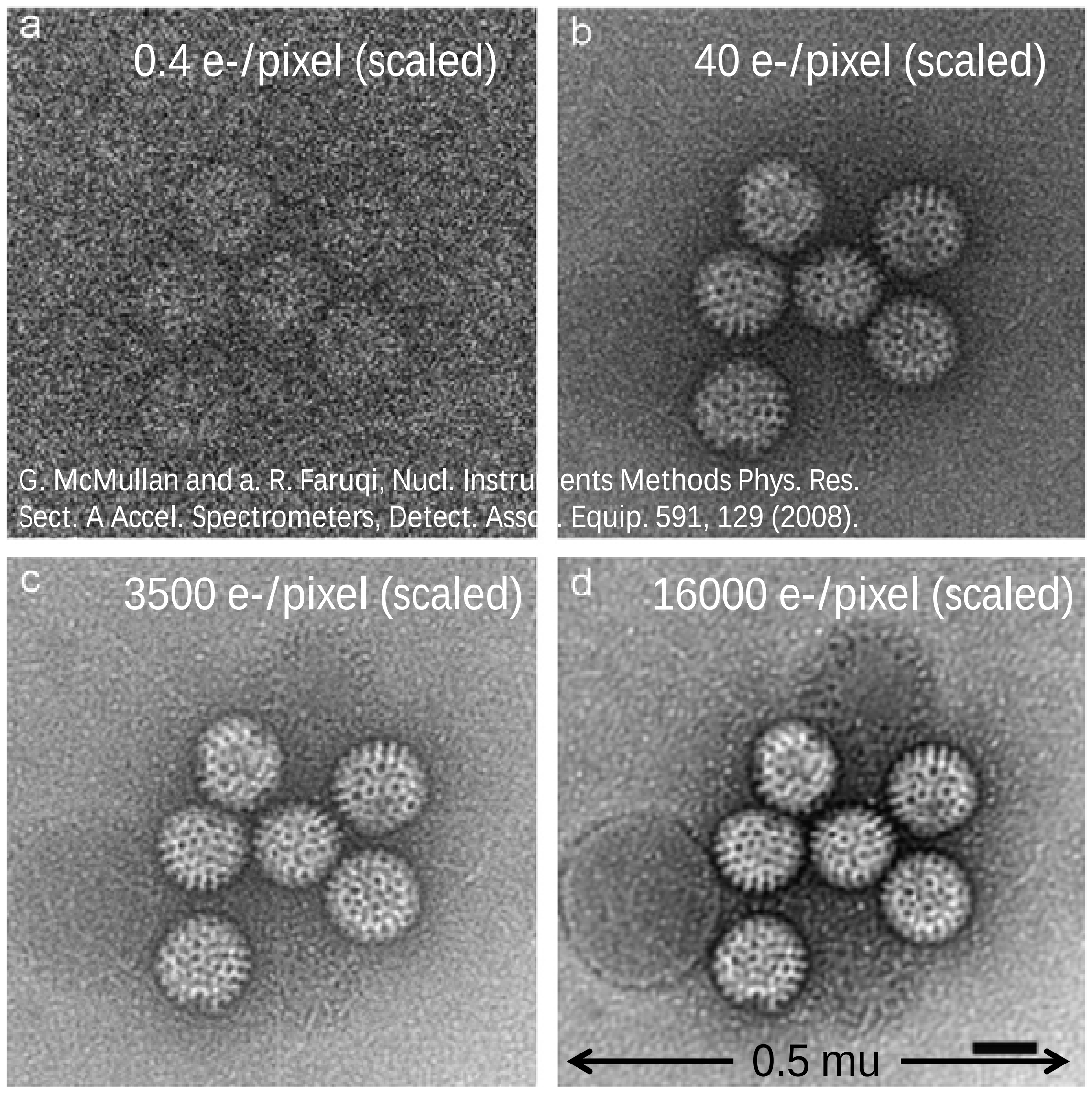




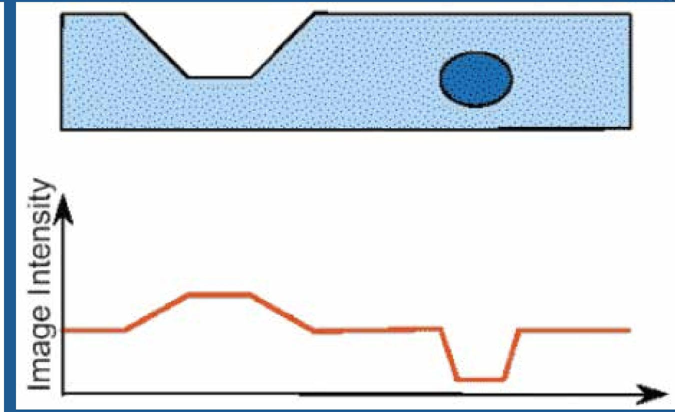


- ► 10 - 100 e- / pixel per single frame
- ► 10 - 100 e- / A^2 total area charge per 100 frame movie
- ► for frames with 10M e- total, this would be 250M frames or 2.5 M movies

TEM movie

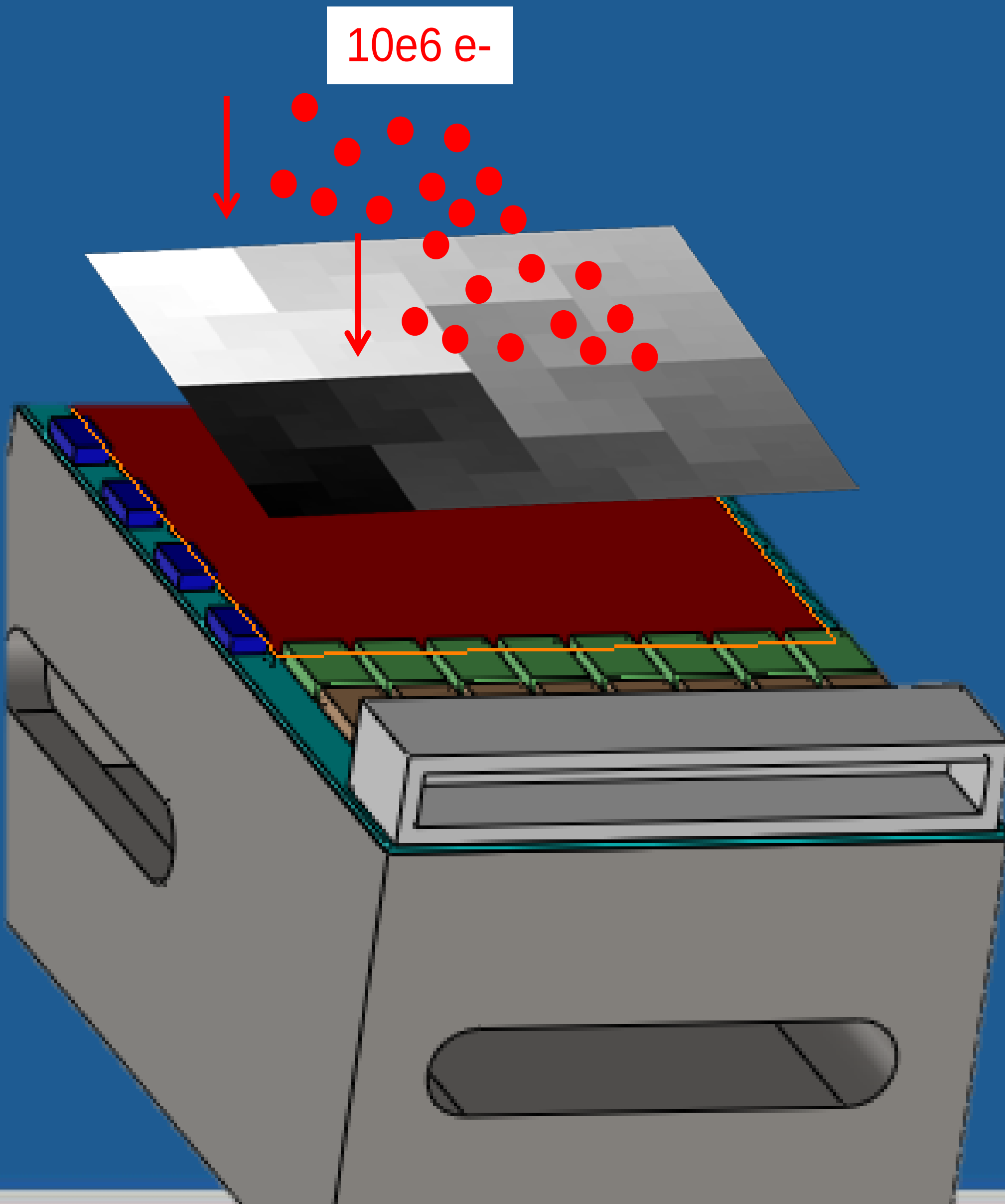


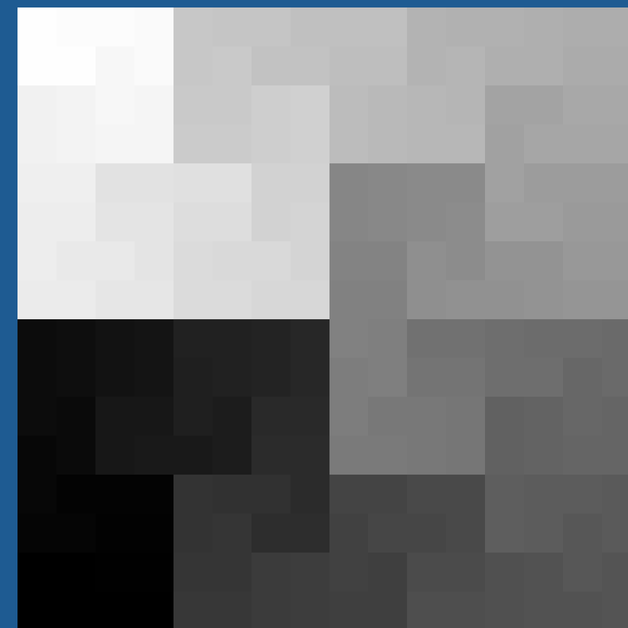
G. McMullan and a. R. Faruqi, Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 591, 129 (2008).



- ► 150 primaries per dynamic frame
- ► 10 000 primaries per pixel for static exposure

TEM movie

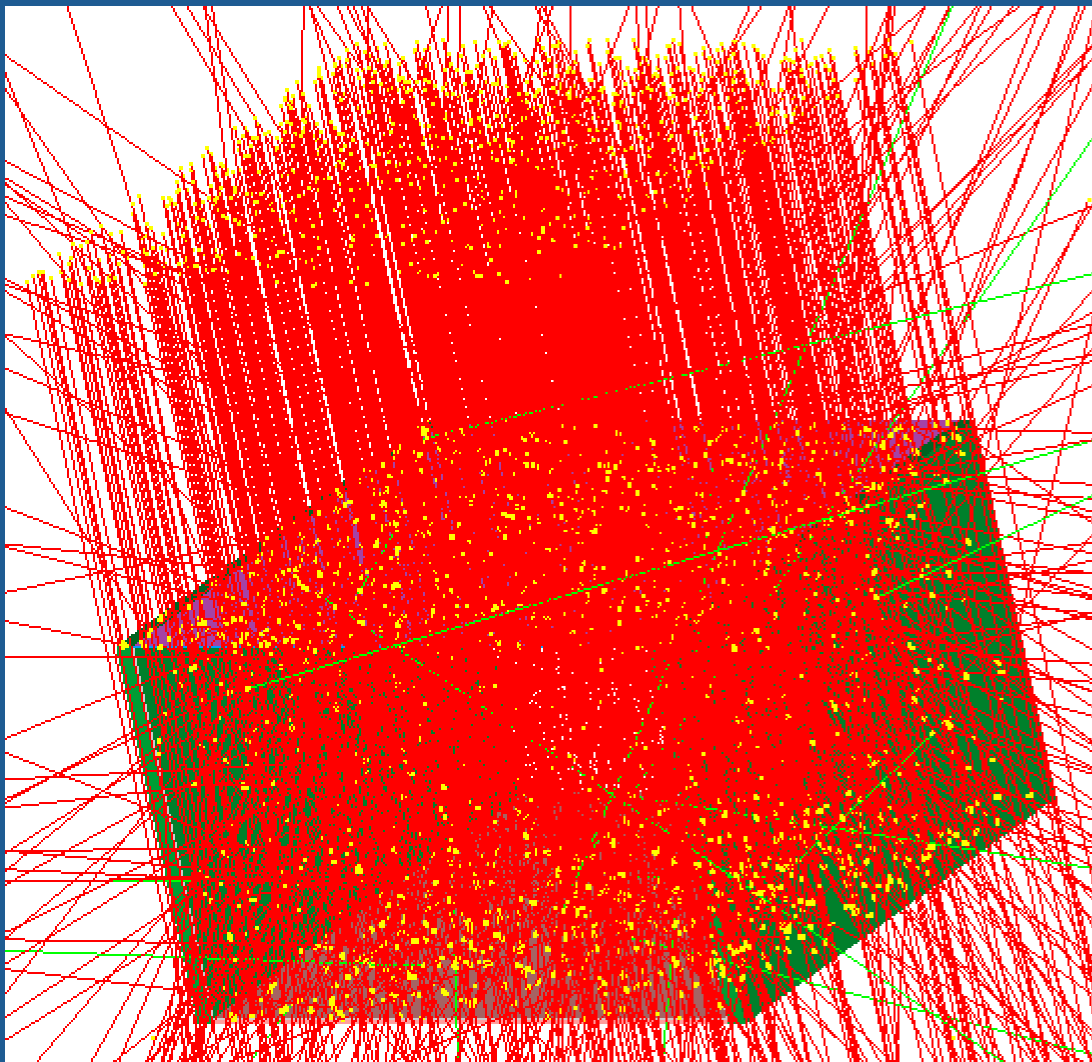


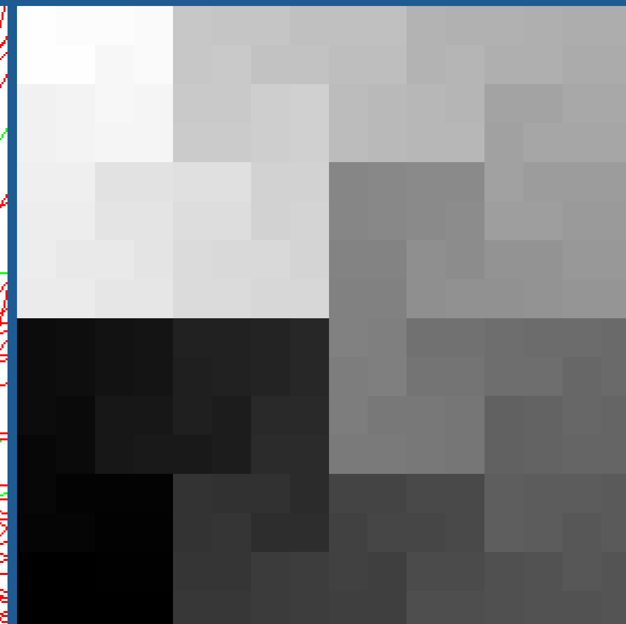


- 300 keV
- pitch black = 1000 A sample
- very white = 0 A sample
- 0..1000A in 256 steps

TEM movie

100e-/px in white area

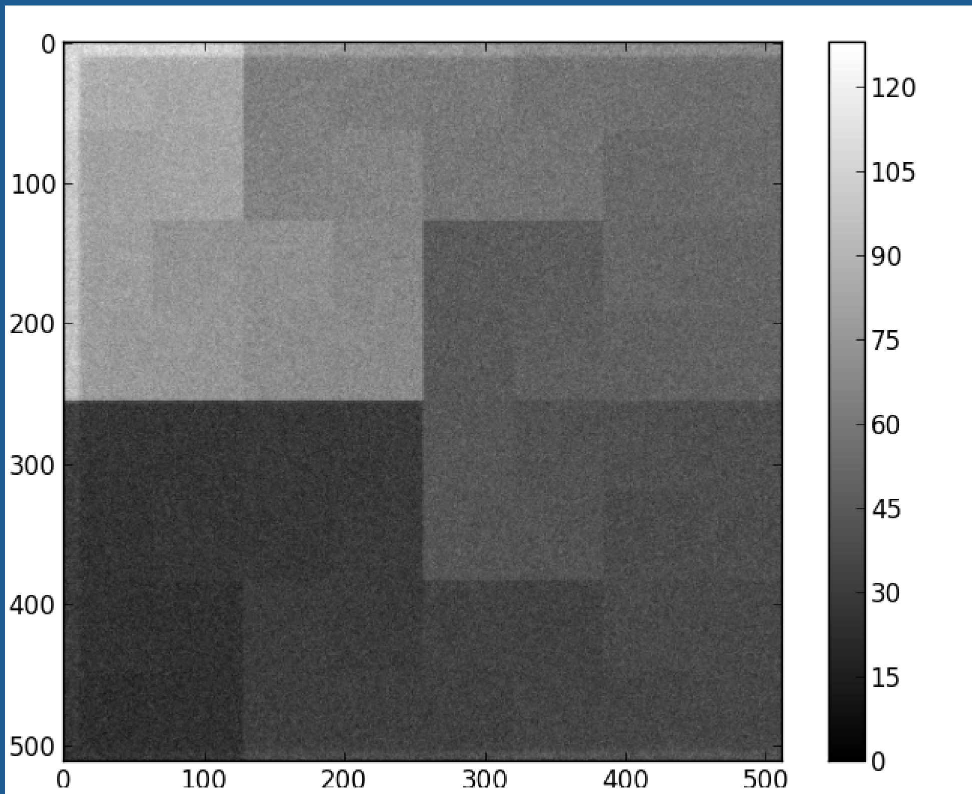




- 300 keV
- pitch black = 1000 A sample
- very white = 0 A sample
- 0..1000A in 256 steps

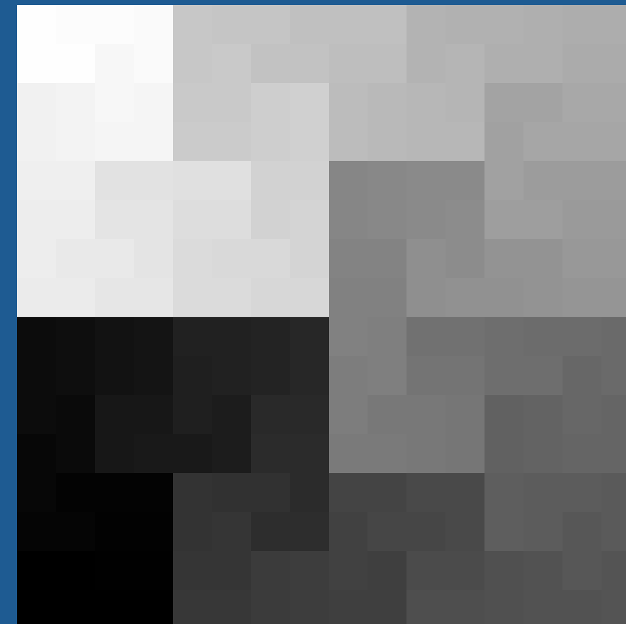
TEM movie

100e-/px in white area



▶ bits read out

▶ Works nicely!!!



▶ 300 keV

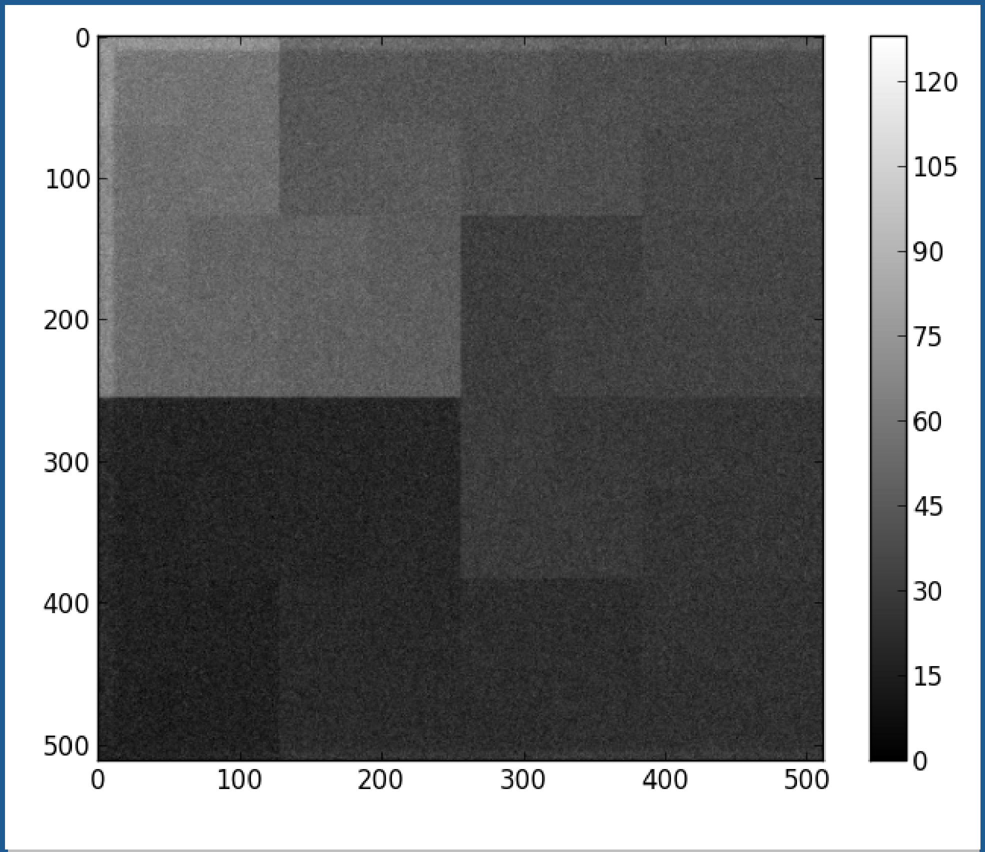
▶ pitch black = 1000 A sample

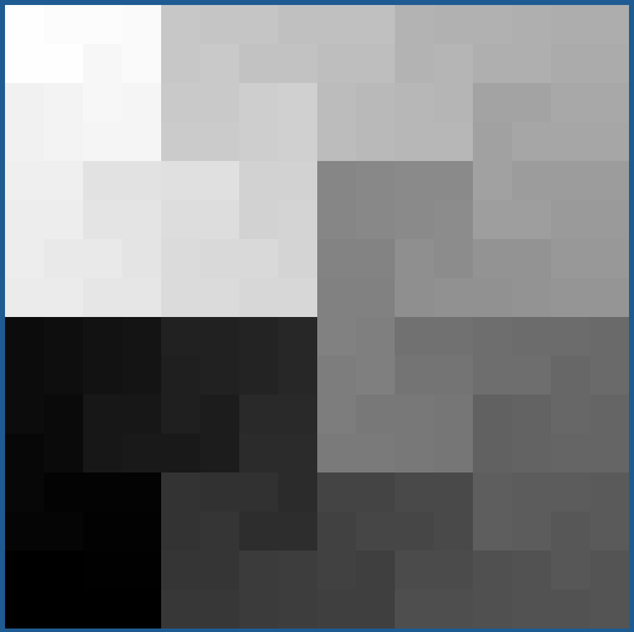
▶ very white = 0 A sample

▶ 0..1000A in 256 steps

TEM movie

50e-/px in white area

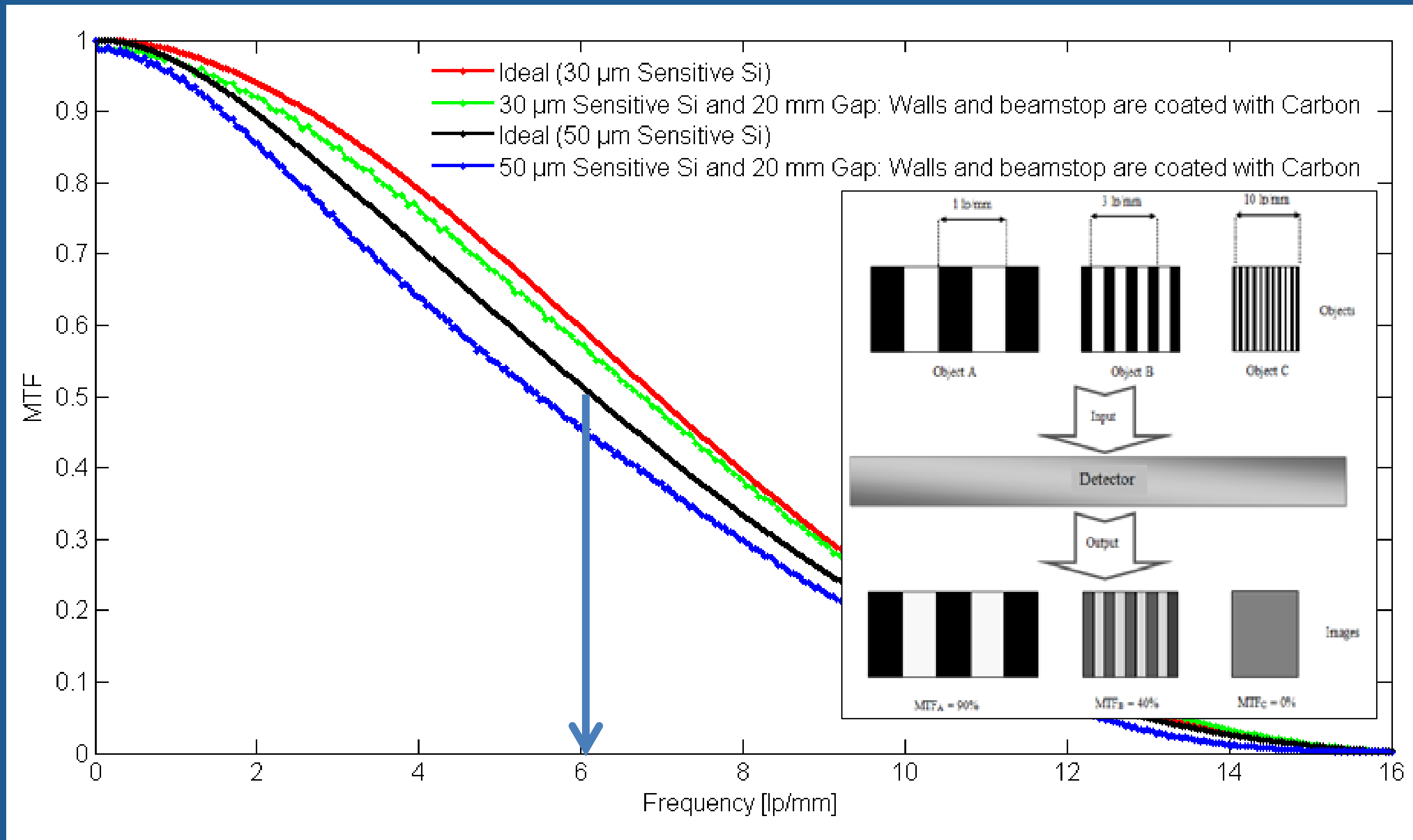




- bits read out
- Works nicely!!!
- 300 keV
- pitch black = 1000 A sample
- very white = 0 A sample
- 0..1000A in 256 steps

Some spatial investigations

MTF (modulation transfer function)



Spatial resolution ► Point Spread Function, Line Spread Function, Modulation Transfer Function: all inter-connected by operations like Differentiation, Fourier Transform etc.

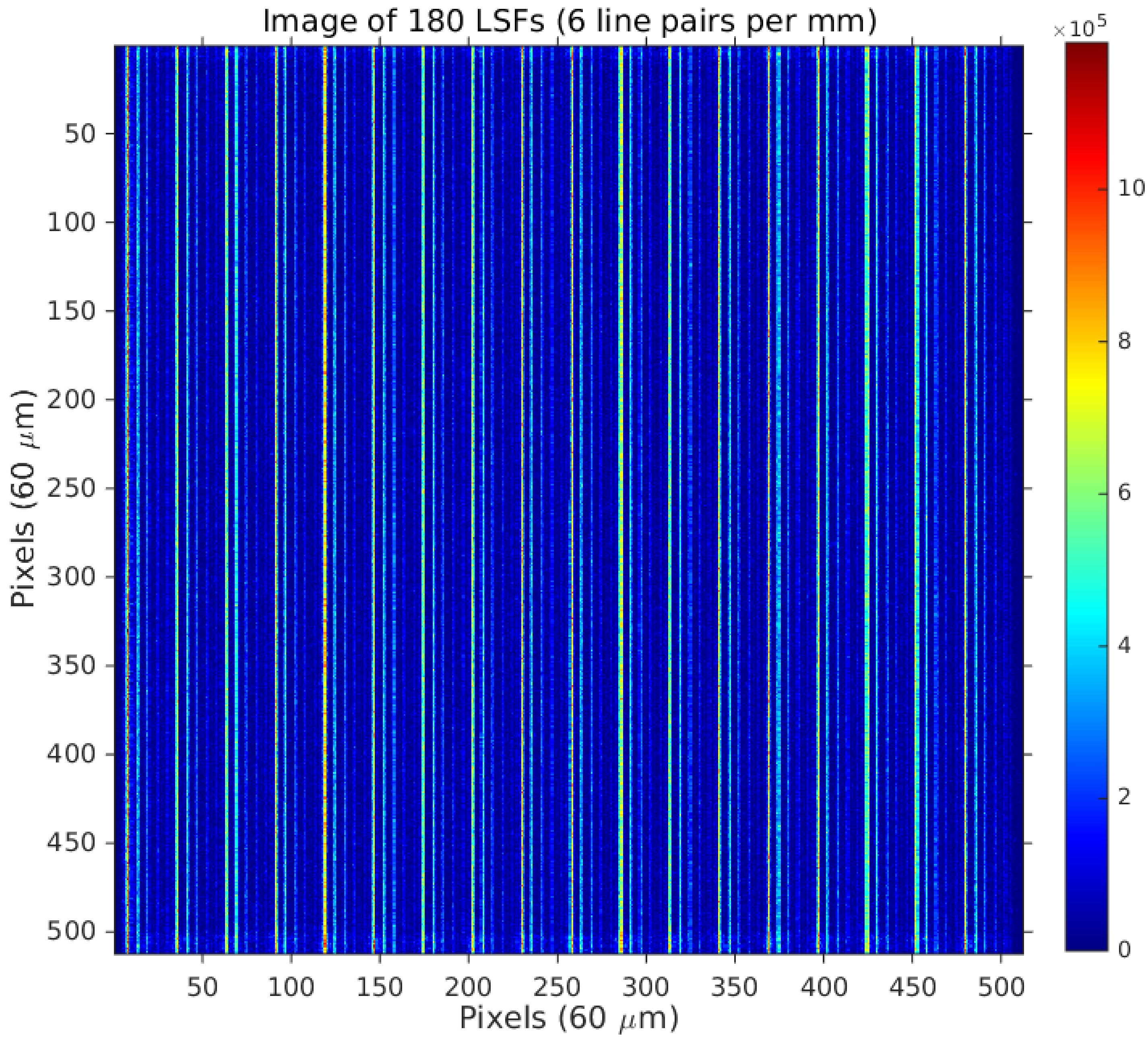


Image of 180 LSFs (6 line pairs per mm)
Pixels (60 μm)
Pixels (60 μm)
50
100
150
200
250
300
350
400
450
500
×10^5
0
2
4
6
8
10

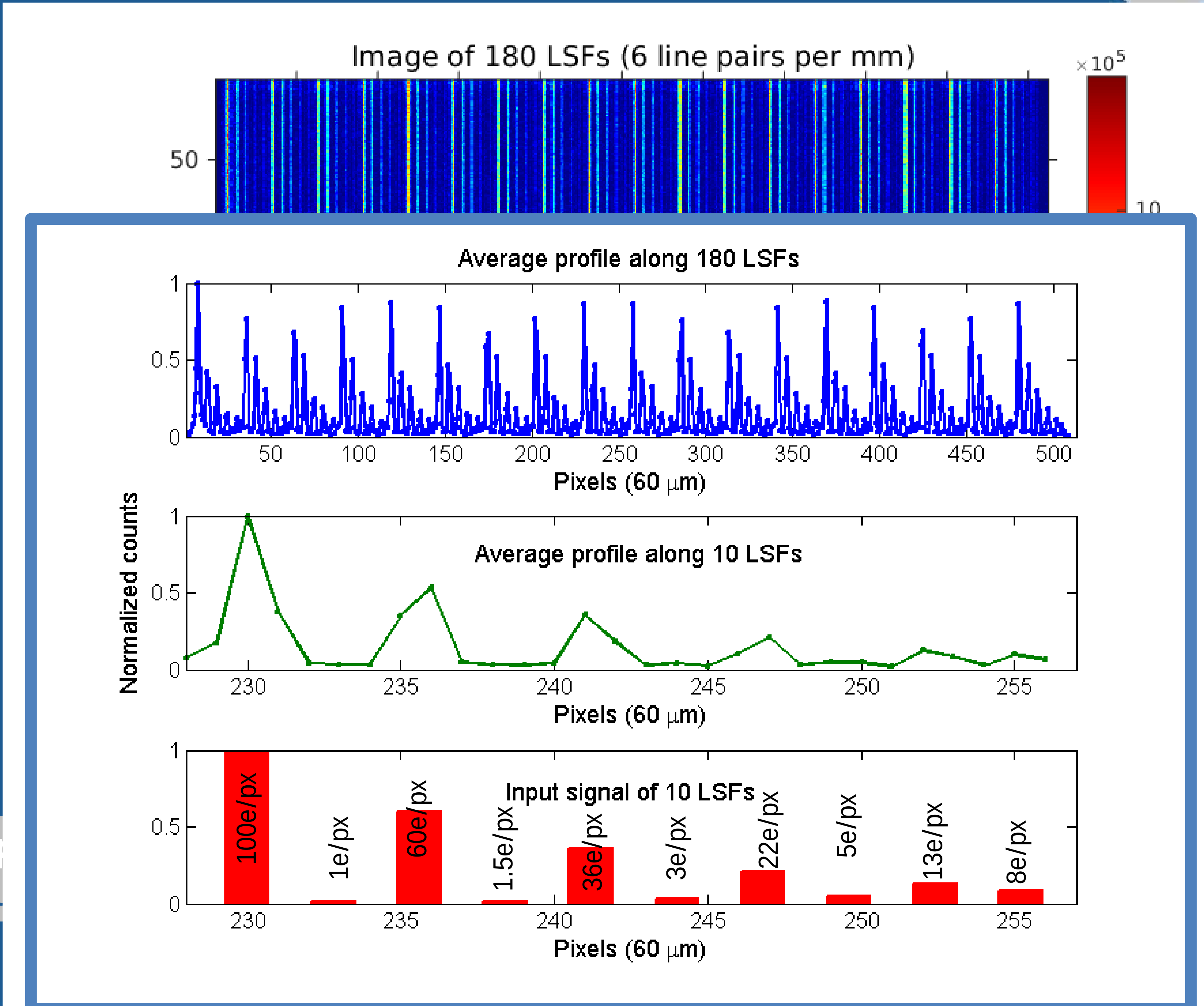
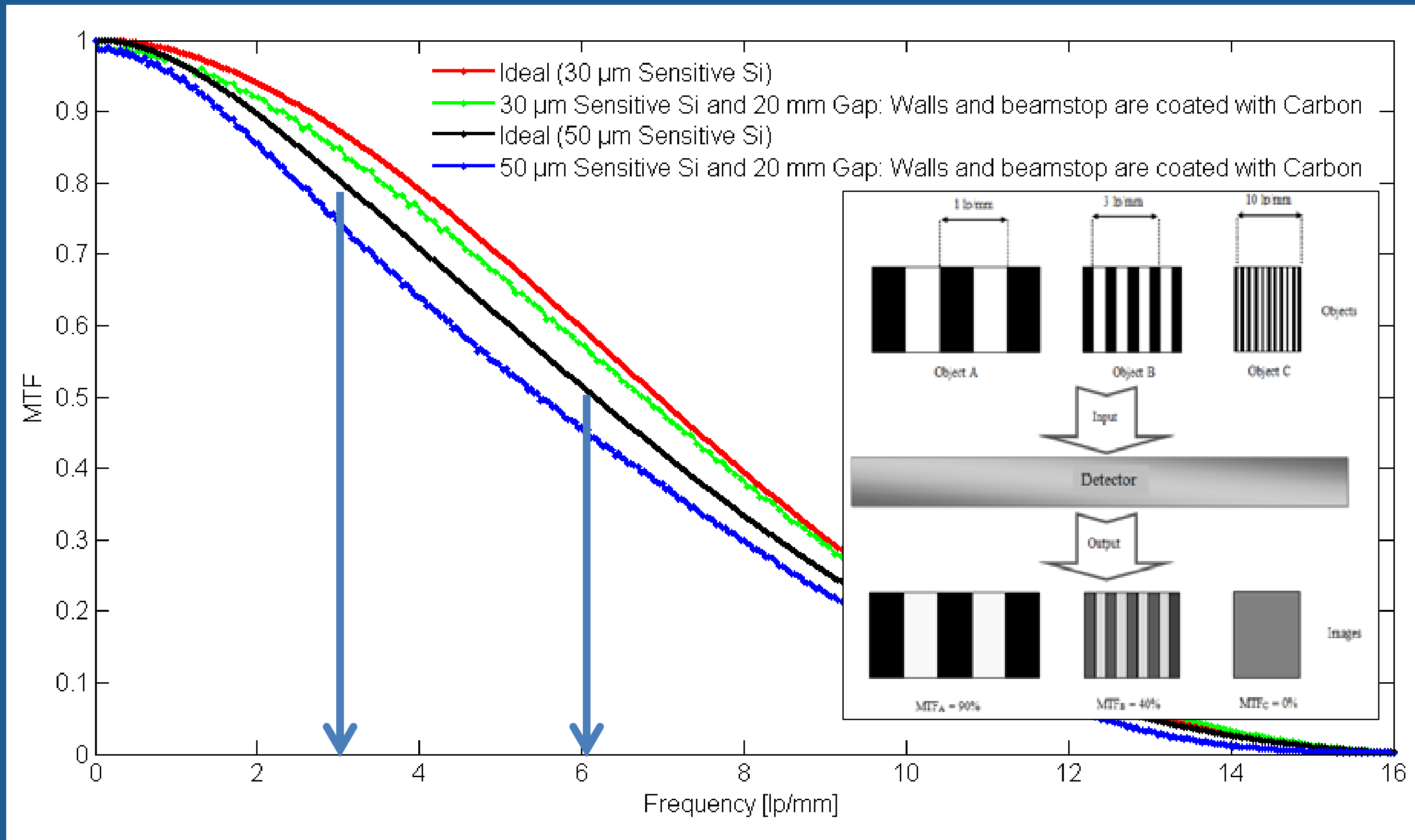


Image of 180 LSFs (6 line pairs per mm)
50
$\times 10^5$
10
Average profile along 180 LSFs
1
0.5
0
50 100 150 200 250 300 350 400 450 500
Pixels (60 μm)
Normalized counts
Average profile along 10 LSFs
230 235 240 245 250 255
Pixels (60 μm)
Input signal of 10 LSFs
100e/px
1e/px
60e/px
1.5e/px
36e/px
3e/px
22e/px
5e/px
13e/px
8e/px
Pixels (60 μm)

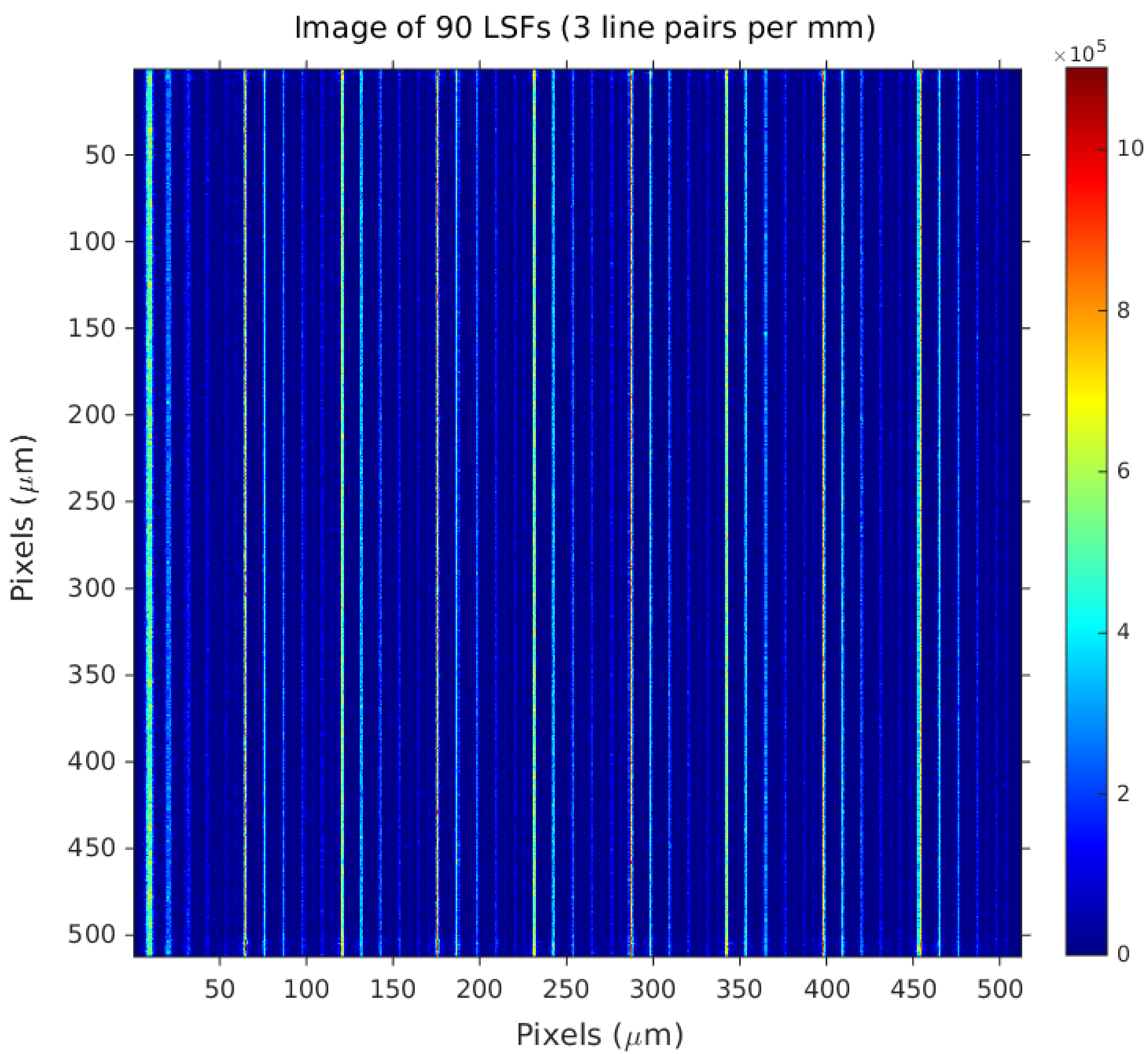
Some spatial investigations

MTF (modulation transfer function)



Spatial resolution ► Point Spread Function, Line Spread Function, Modulation Transfer Function: all inter-connected by operations like Differentiation, Fourier Transform etc.

Max Planck Institute for Structure and Dynamics of Matter



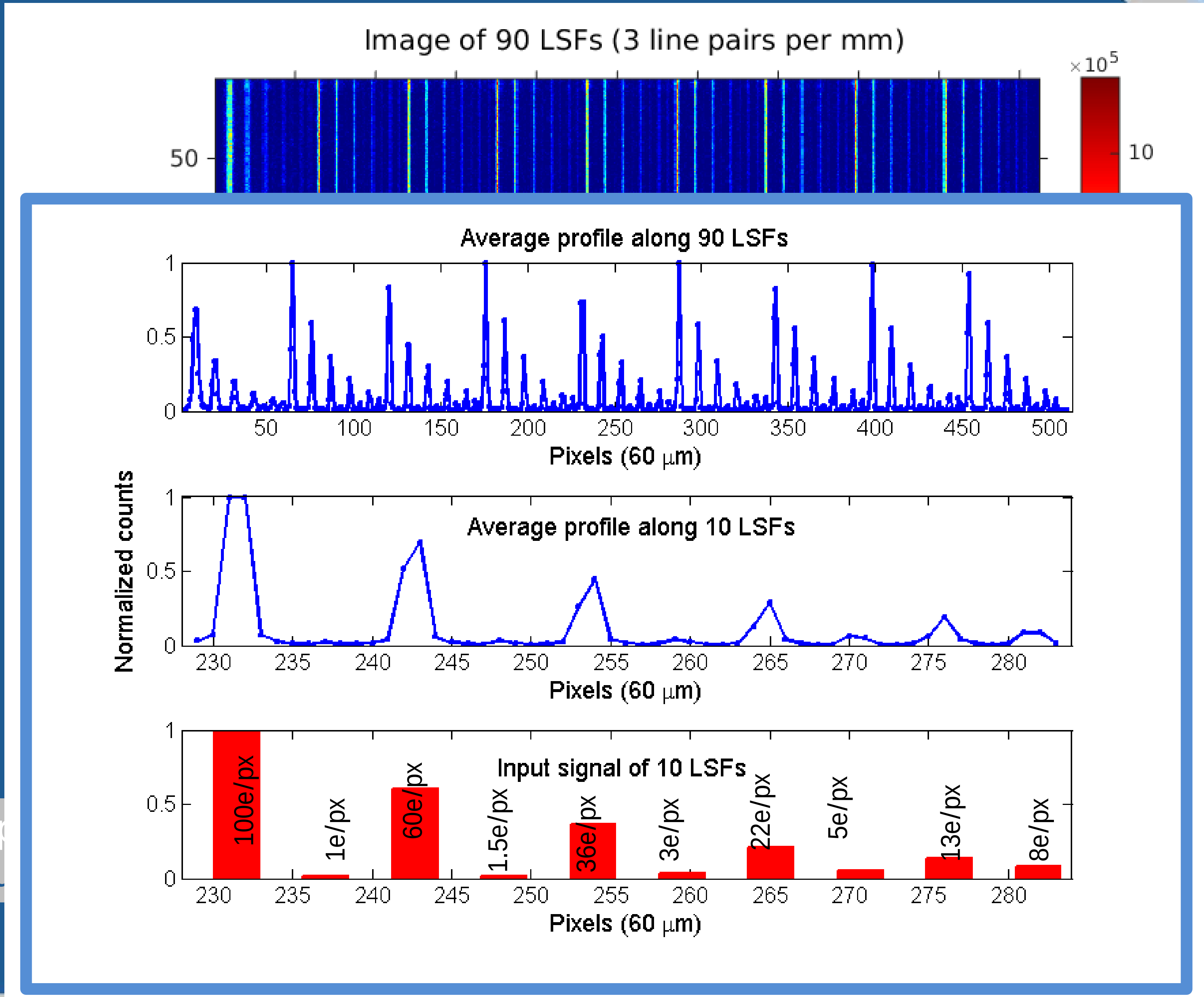


Image of 90 LSFs (3 line pairs per mm)
50
$\times 10^5$
10
Average profile along 90 LSFs
Normalized counts
Pixels (60 μm)
Average profile along 10 LSFs
Input signal of 10 LSFs
100e/px
1e/px
60e/px
1.5e/px
36e/px
3e/px
22e/px
5e/px
13e/px
8e/px

Sp

Fu

r

Timeline
revised

Last Milestone ► Sensor production of wafer has started at HLL (Oct. 2014)

► around 10 wafers are in processing (for 50µm and 30 µm thick det.)

Next important step ► ASICSs: DCD, Movie Chip

March 2016 ► DEPFET production start (DH1k) (Phase III)

March 2016 ► Completion of sensor production (DH80k) (Phase IV)

July 2017 ► Completion of DH80k detector system (Phase VI)

Dec. 2017 ► Completion of sensor production (DH1k) (Phase V)

2018 ► Completion of DH1k detector system (Phase VII)


Thank you !!!