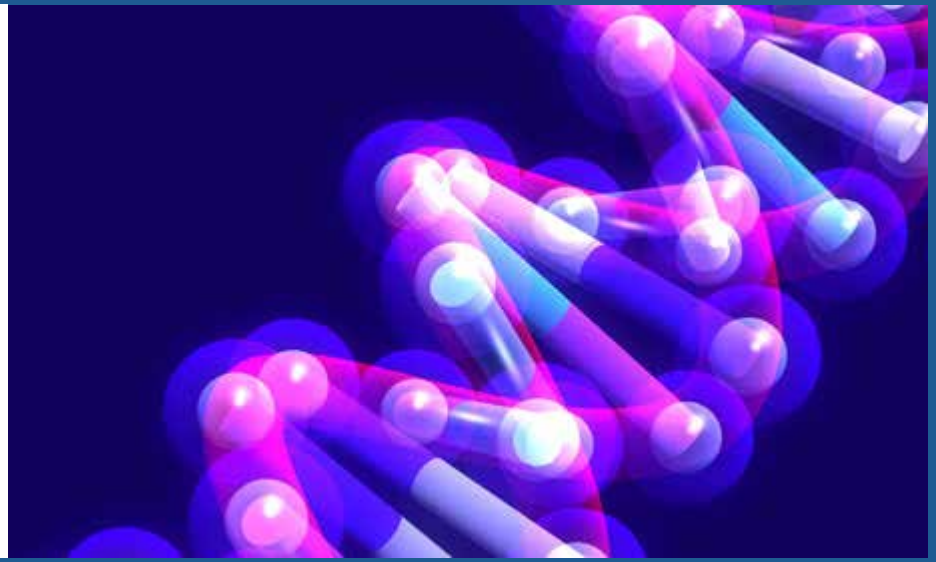
DEPFETs for electron detectors – The Molecular Movie –

Sascha Epp



Max Planck Institute for Structure and Dynamics of Matter

mpsd

CFEL SCIENCE

Center for Free-Electron Laser Science

We seek for help!

Join the team…!

Laci Andricek, Christian Koffmane,
Jelena Ninkovic, Rainer Richter,
Florian Schopper, Johannes Treis,
Andreas Wassatsch
Ivan Peric (U-HD)

S. W. E Dwayne Miller (Head of Department)
Ibrahym Dourki
Fabian Westermeier
Stuart Hayes, Stephanie Manz, Kostya Pichugin
Hossein Delsim-Hashemi, Shima Bayetesh

Electron diffraction

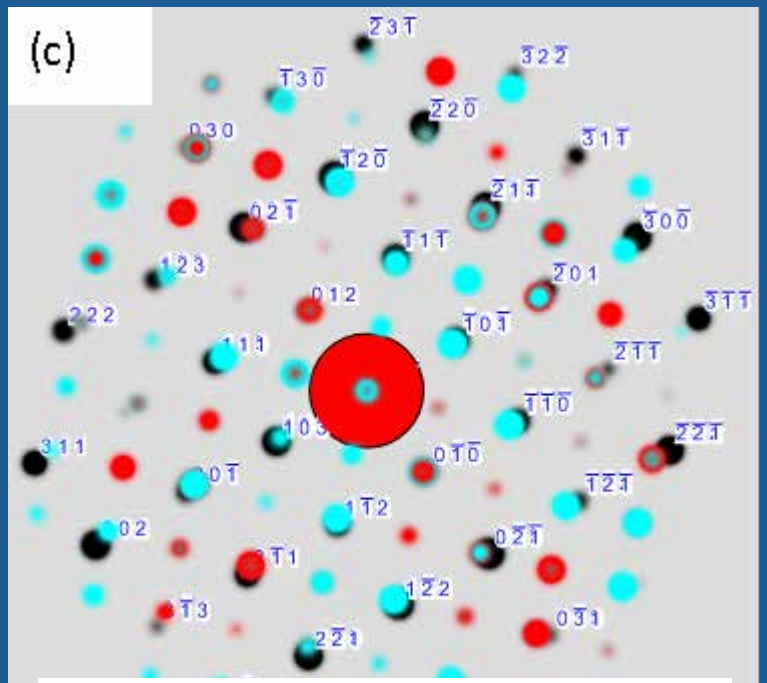
The wave-particle duality of particle beams

► mass & charge -> penetration depth

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

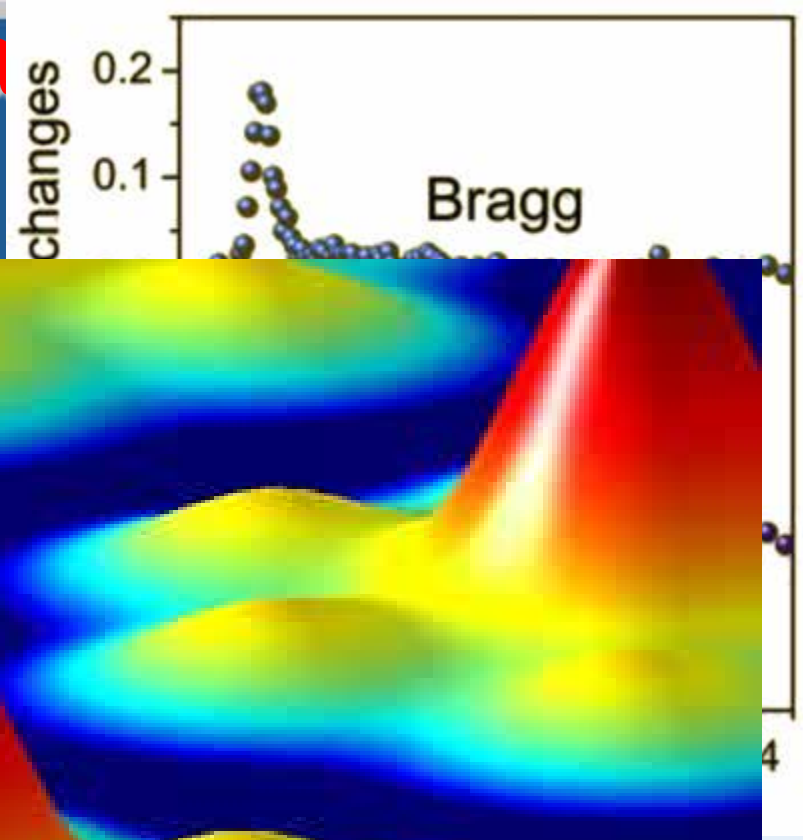
$$\lambda_{dB} = \frac{hc}{\sqrt{2E_{kin}E_0 + E_{kin}^2}} < 0.1\ \text{Å}$$

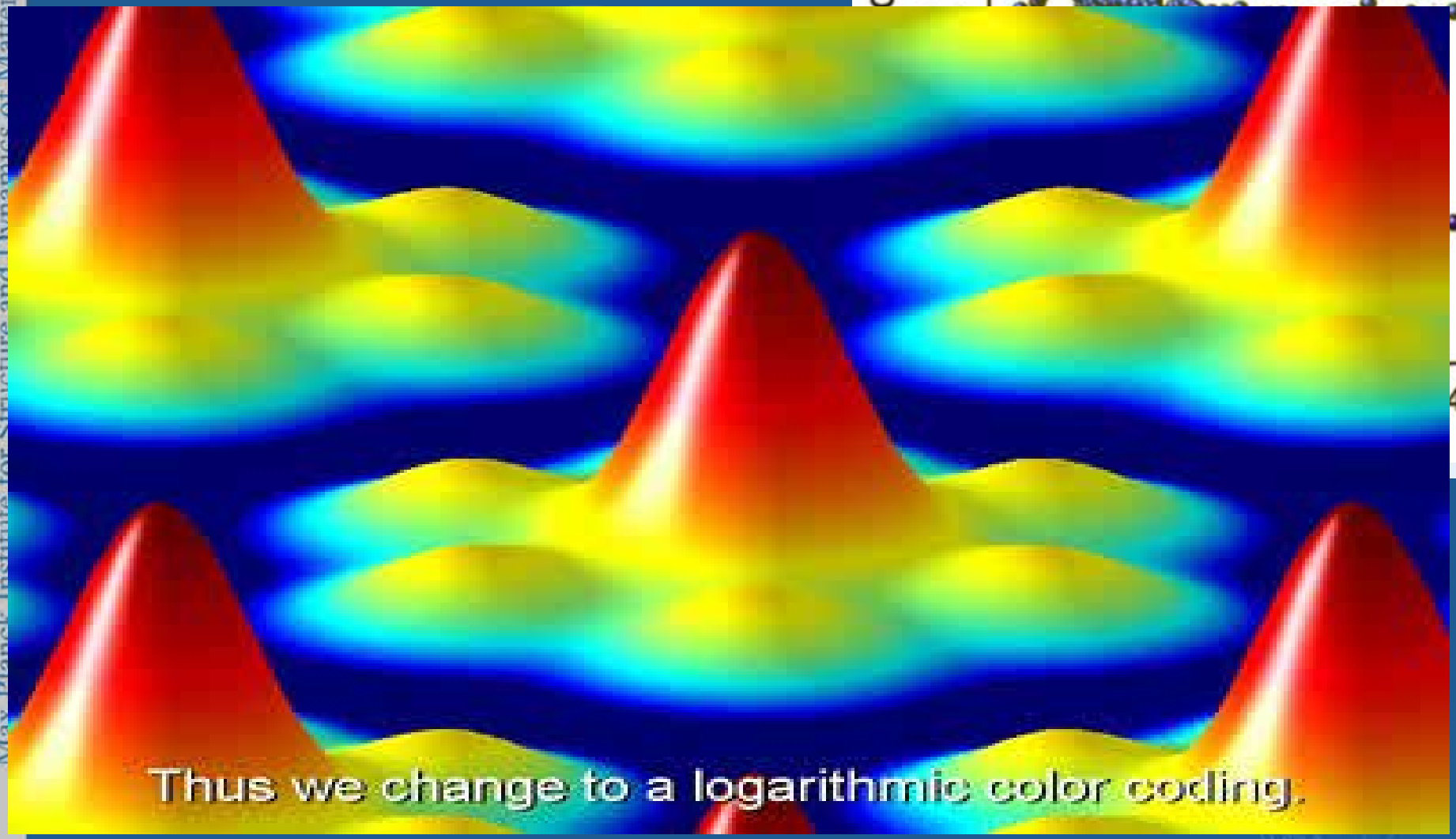
► 0.1 A corresponds to 100 keV X-rays



Diffraction out to less than 0.2Å!

Direct Observa
Structural

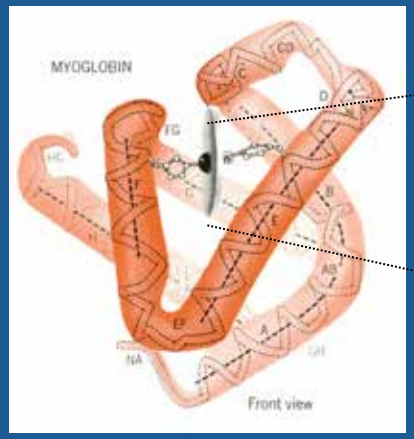




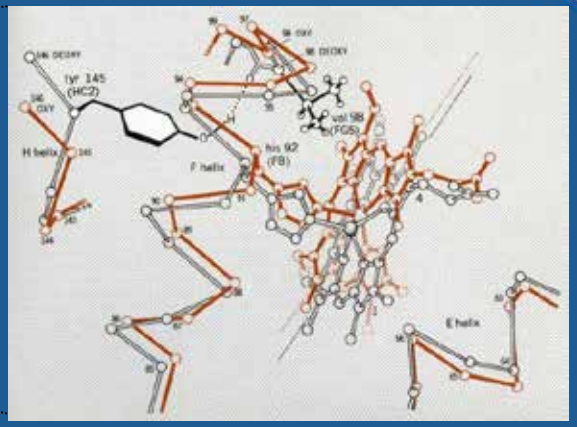
Eicherberger, Sciaini et al, Nature 2010

The "Molecular Dance"

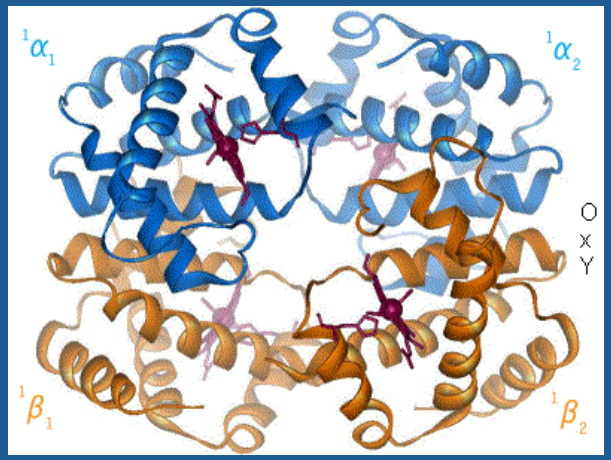
Functionally important protein motions

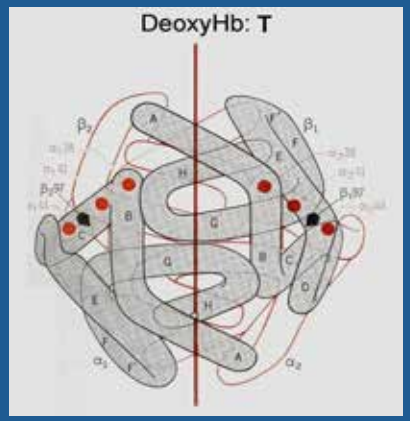


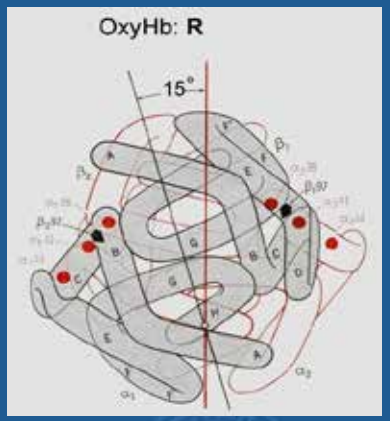
Myoglobin (single subunit)



Hemoglobin





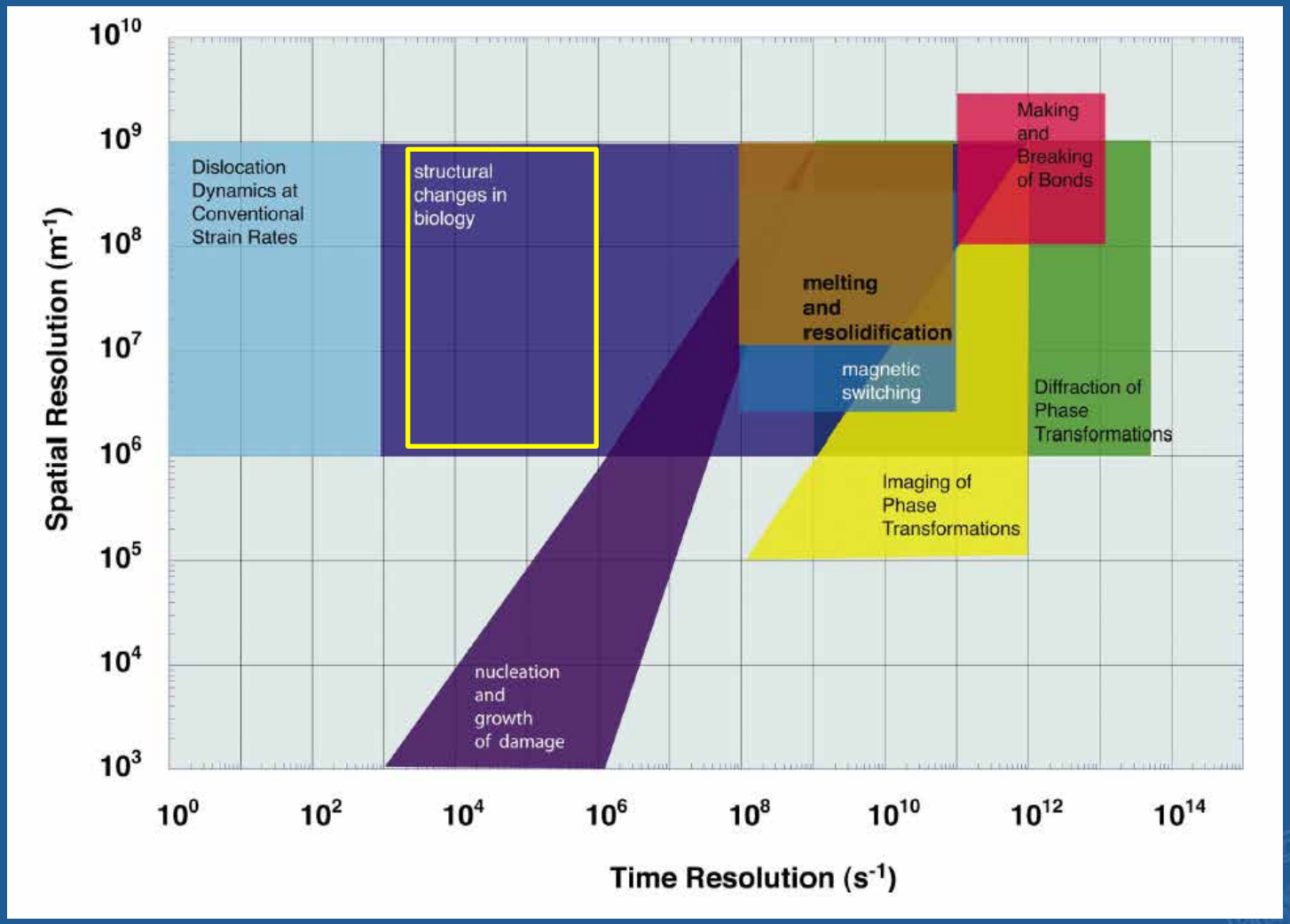


What is the mechanism of correlated atomic displacements?

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

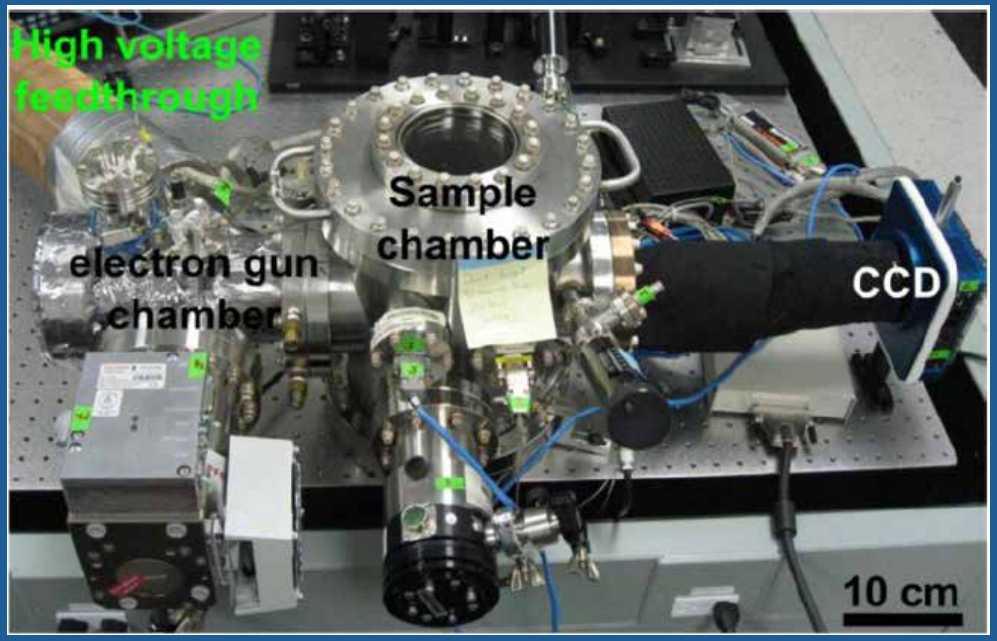
Static & Dynamic

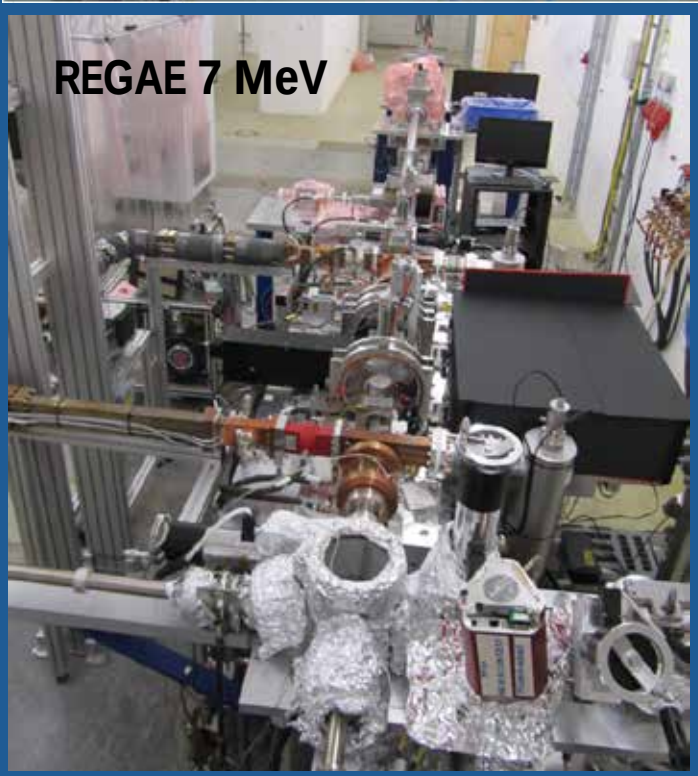
Time scales



Experiments

Large scale





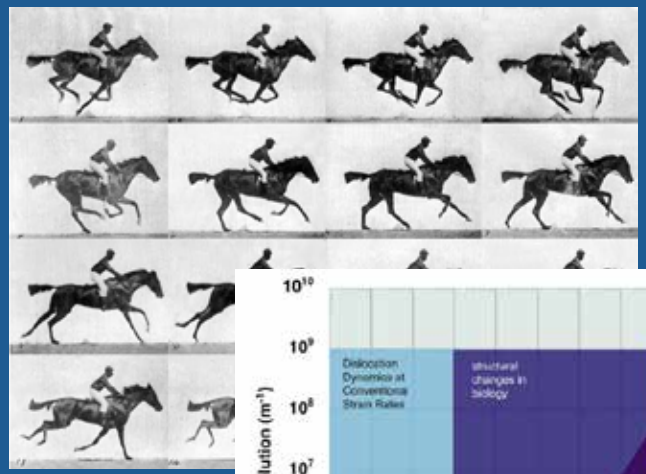
Experiments

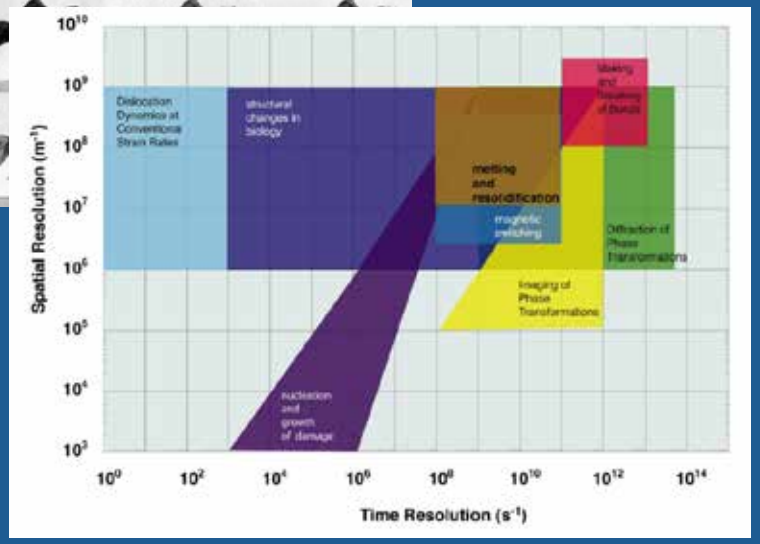
Small scale & with e-

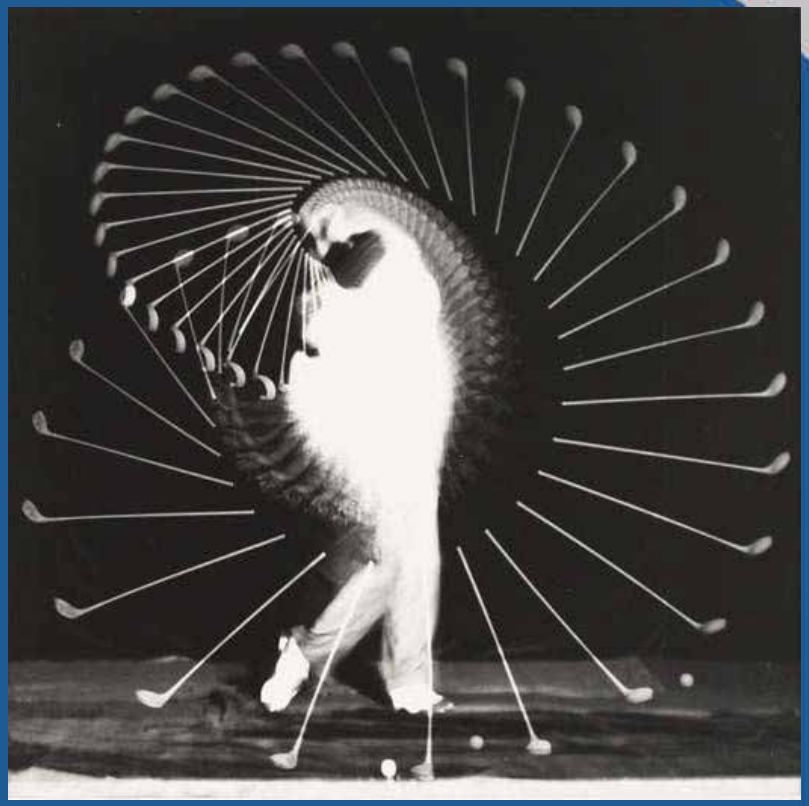
- keV FED – solid state
- keV FED – liquid phase
- keV FED – gas phase
- REGAE Diffraction
- keV time-resolved TEM
- REGAE Dynamic RTEM

Different types of movies

Stroboscopic & real time





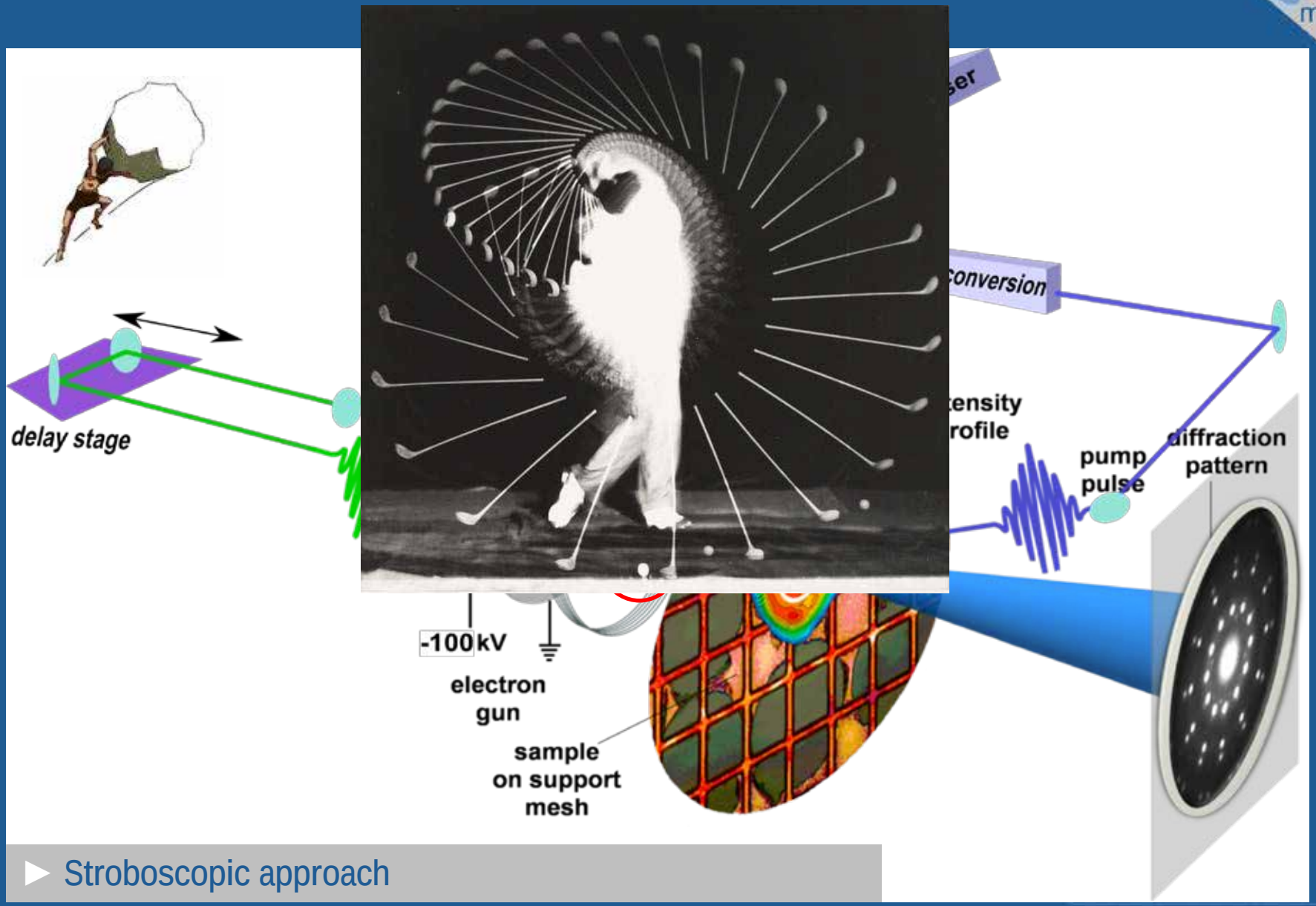


► Imposes different requirements on the detector !

Shutter speed = fast	Repetition rate = high
Shutter speed = super fast	Repetition rate = low

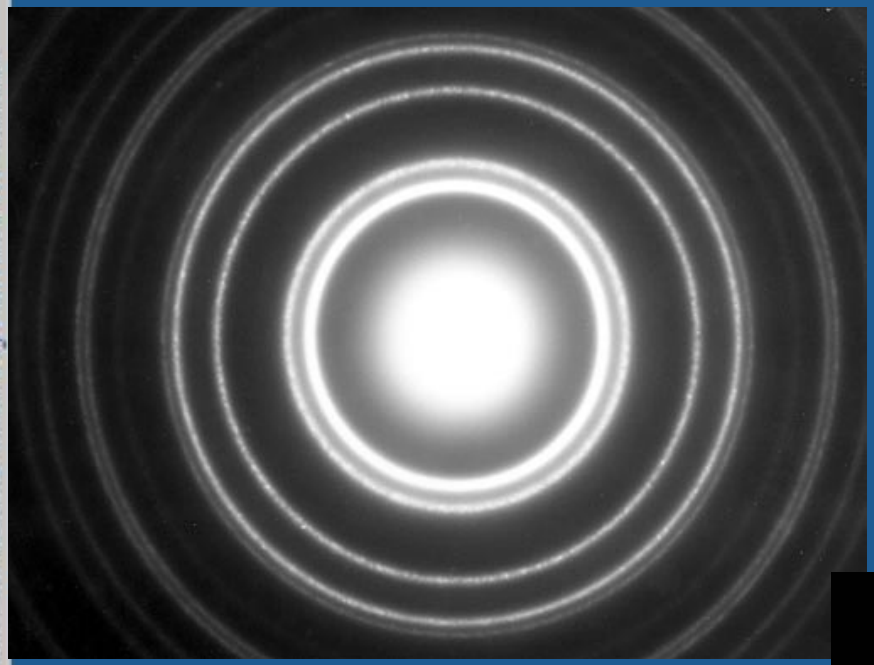
Femtosecond electron diffraction

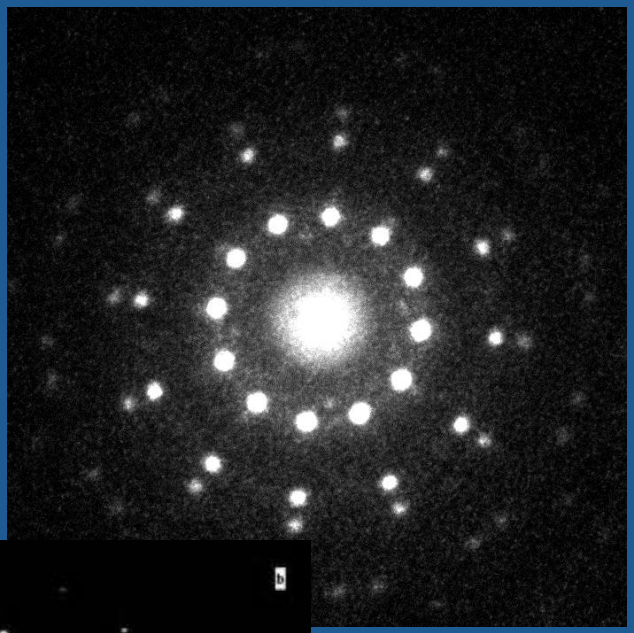
Typical setup



► Stroboscopic approach

UED k-space

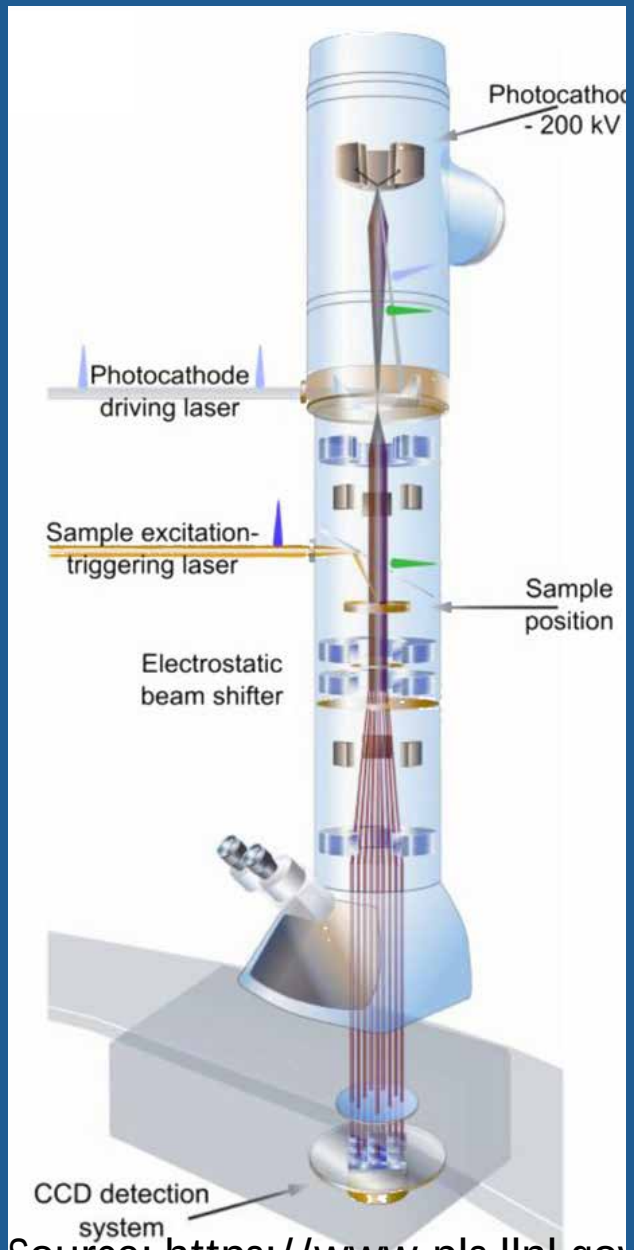




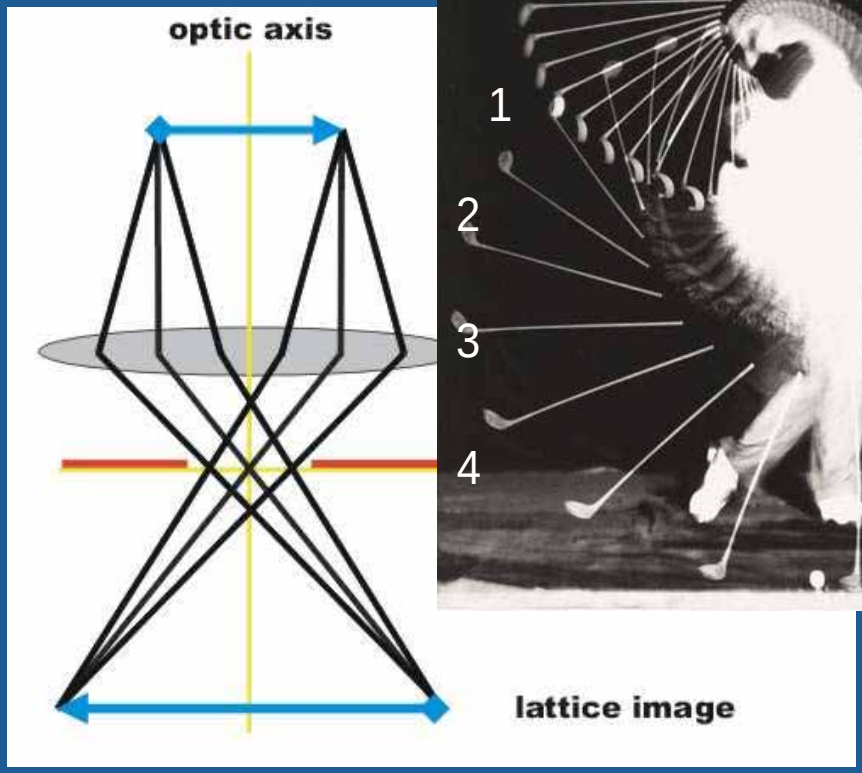
- ► >10,000 electrons on detector are need to attain qualitative diffraction information
- ► problem dependent: more electrons on detector are need to attain quantitative diffraction information

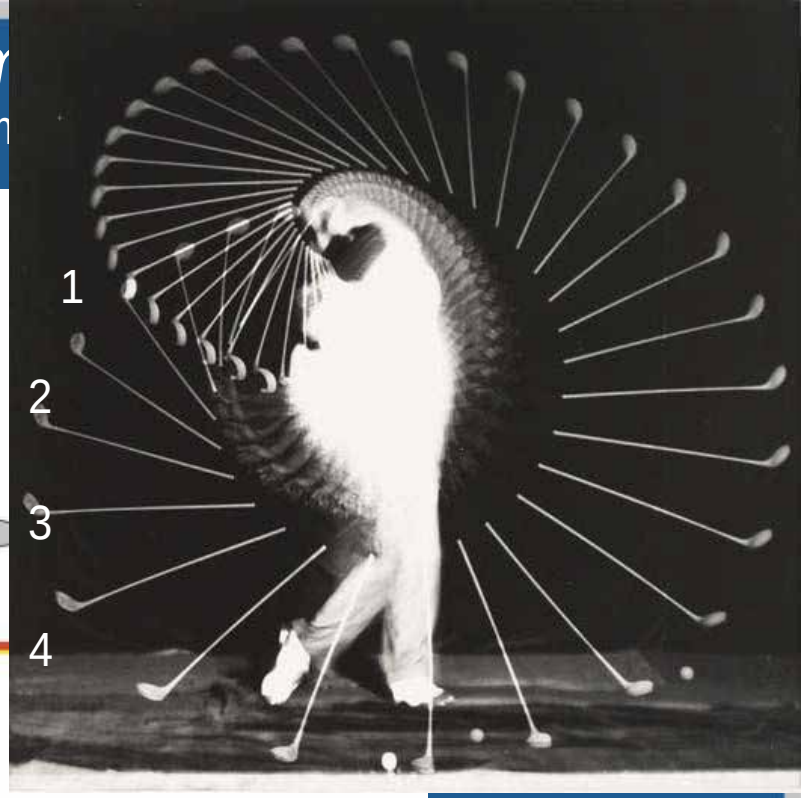
TEM real space im

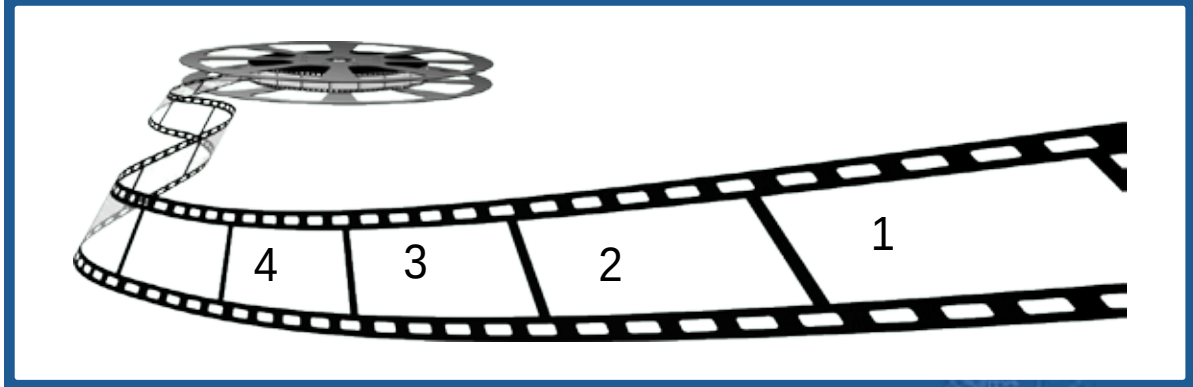
A movie like in cinem



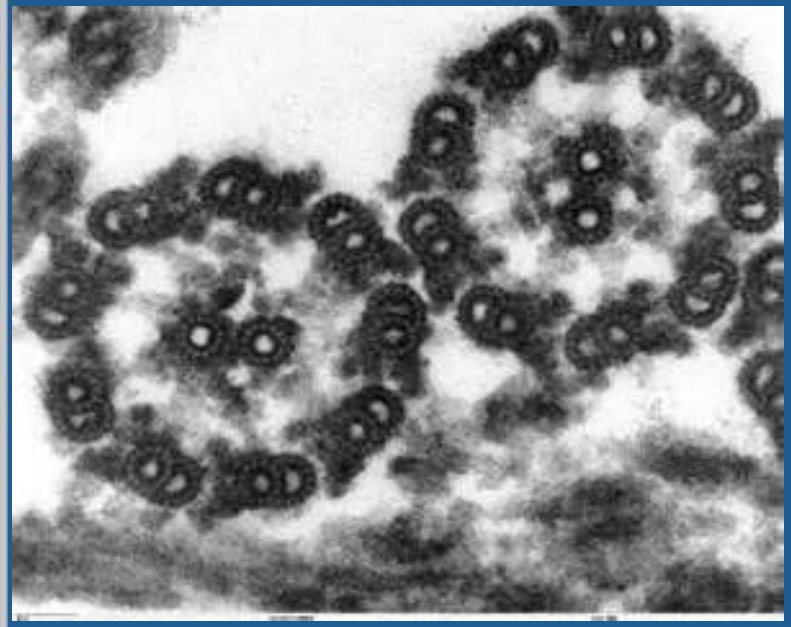
Source: https://www-pls.llnl.gov



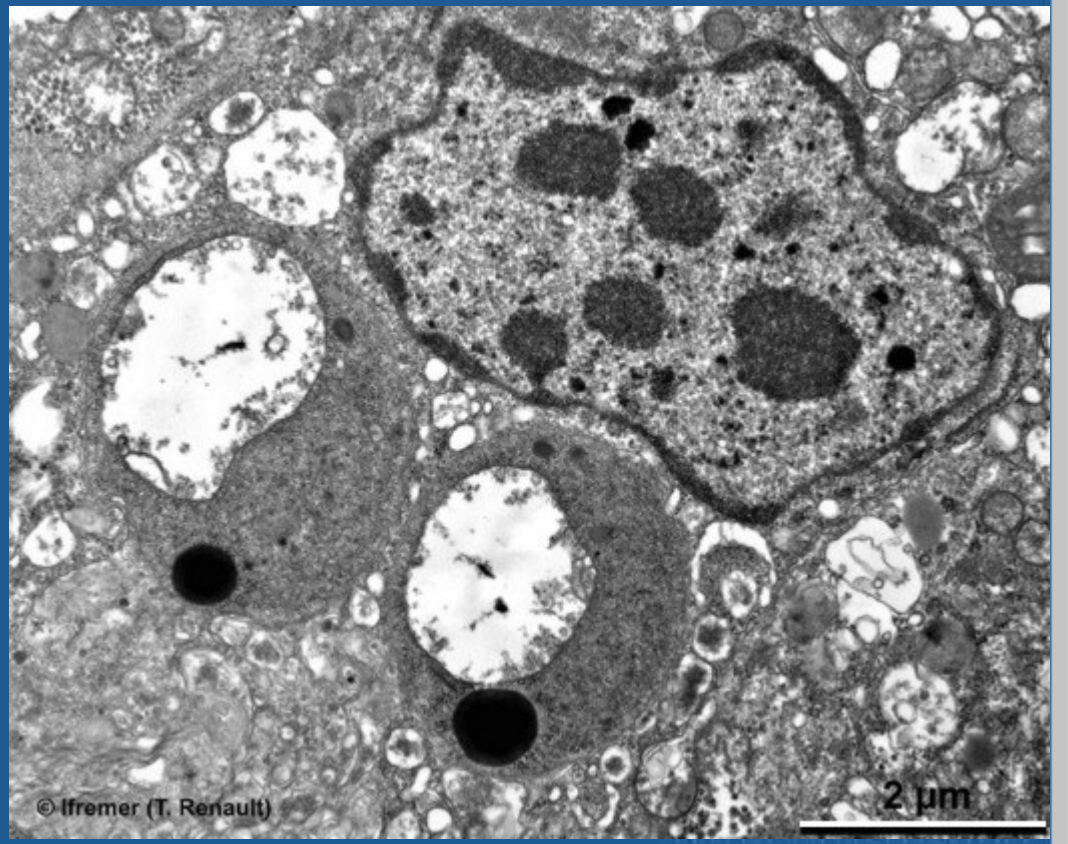




TEM real space

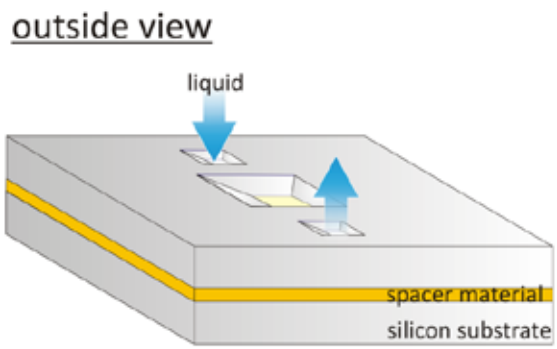


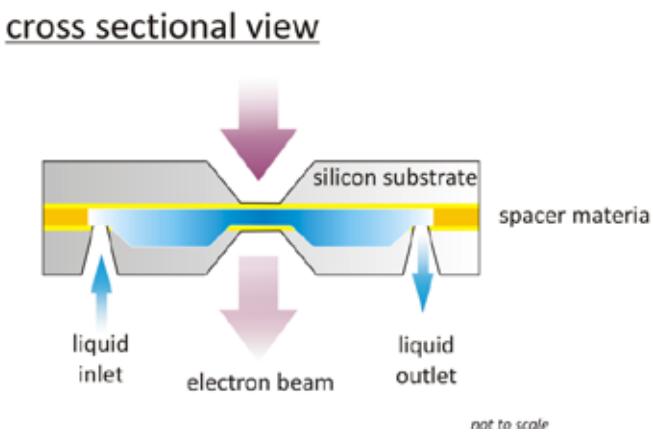
- ► up to 1e8 electrons on detector are need to attain sufficient information
- ► accordingly more need to be produced at the cathode



Further Evolution in atom gazing: ……Solution Phase Dynamics

TEM nanocell with flow!



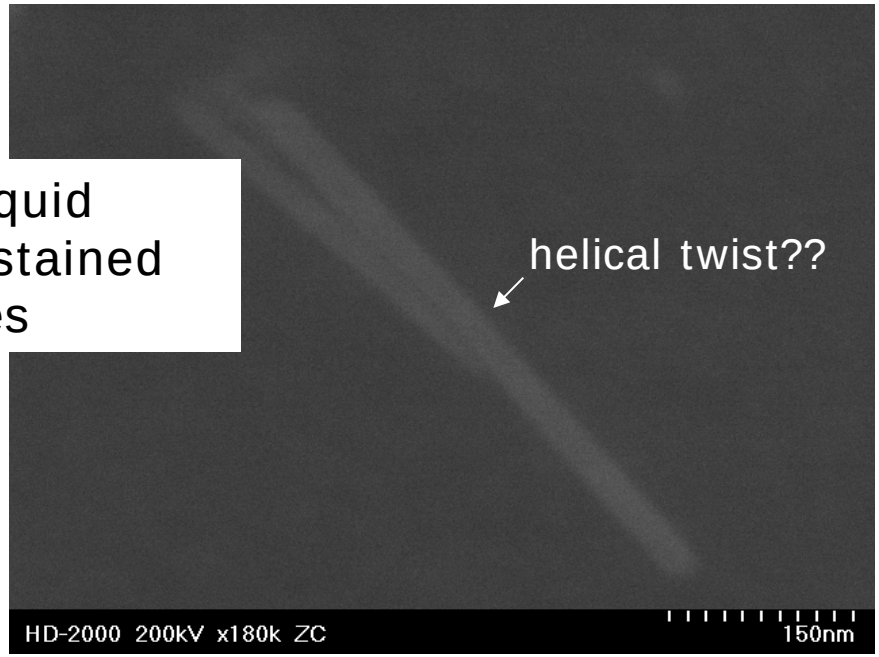


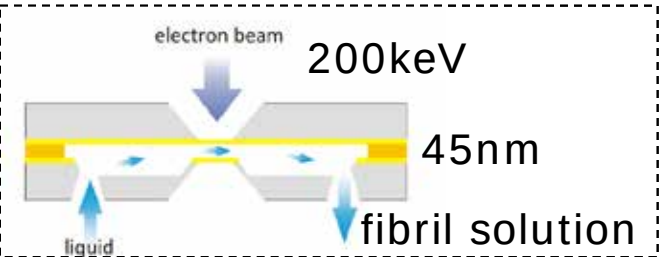
Christina Müller, U Toronto

amyloid fibrils

- fragments of the initial amyloid fibrils
- solvent here: DMF/water (destruction of the fibril structure)

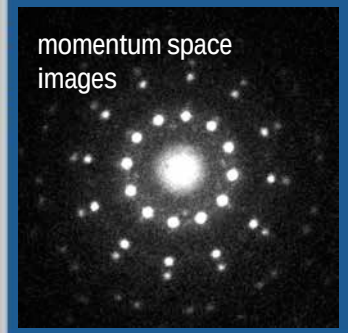
<u>remarkable:</u> in liquid imaging of NON stained biological samples





Detector specifications

Two different detector systems



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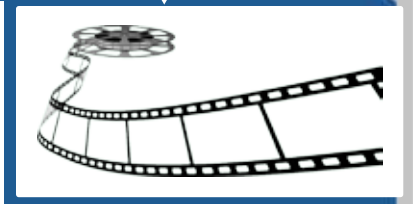
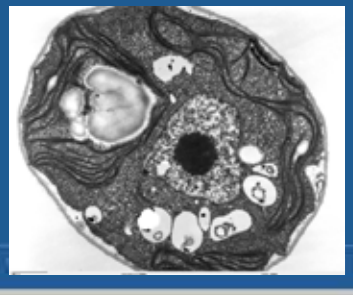
Electronic noise contribution	100 e-	
Sensor thickness	50 µm (down to 30 µm possible) 50 µm + support	450 µm
Pixel well depth (TCH)	60 000 (improvement is part of work package #1) 0.5M – 1M	
Operating temperature	~~ambient temperature~~ moderate cooling...0 °C	
Radiation hardness (pixel)	10Mrad	~~protected~~
Primary e- energy range	80 keV-5 MeV	80 keV-350 keV
Range of Ø num. secondary e-	between 5k-12k →	~~typically 1000 per 0.1 MeV~~

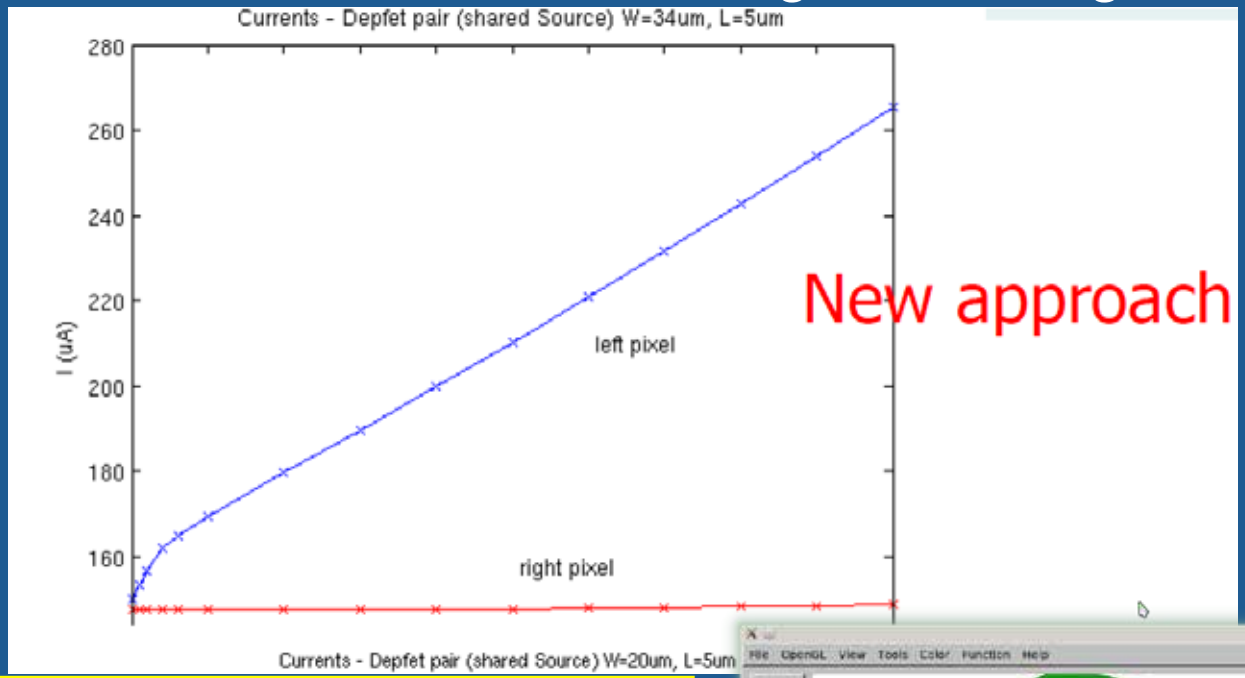
Table 2: Detector specifications.

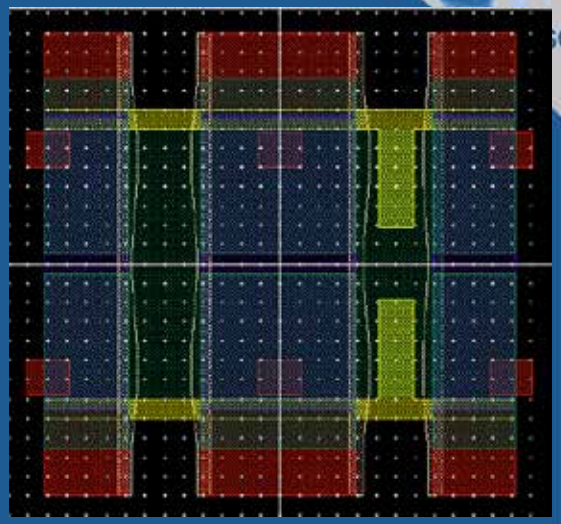


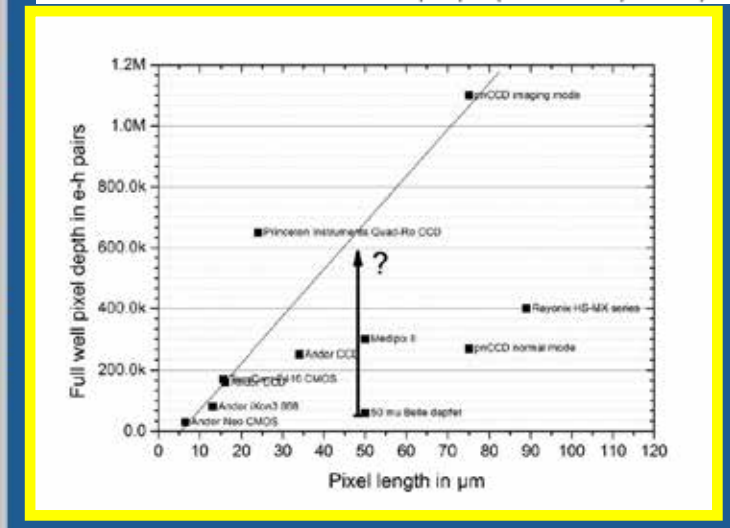
Real space images

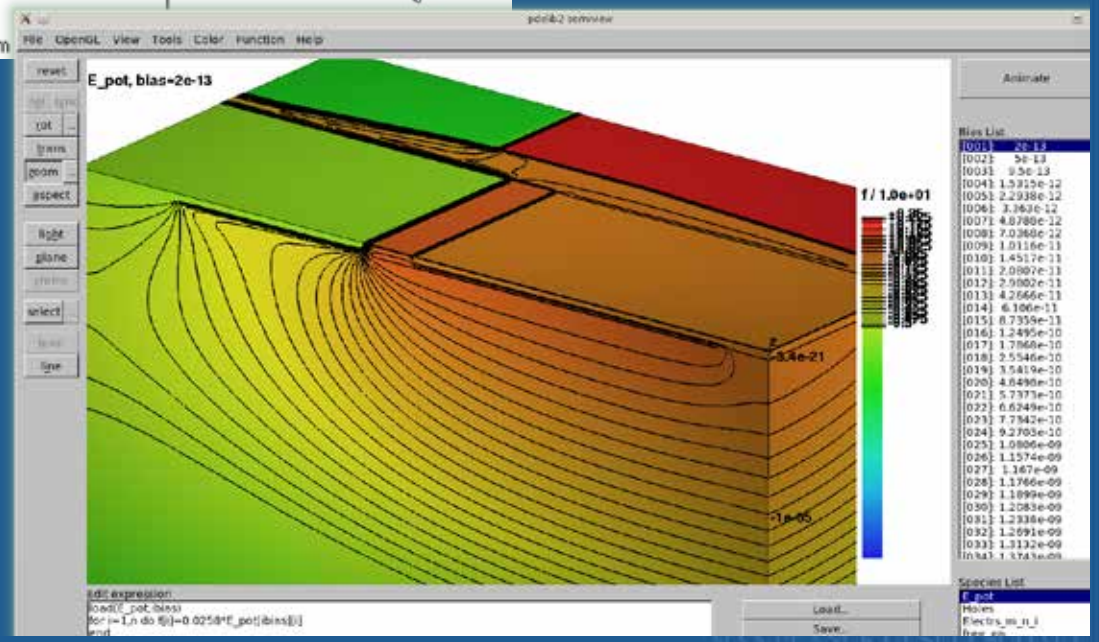


Charge Handling



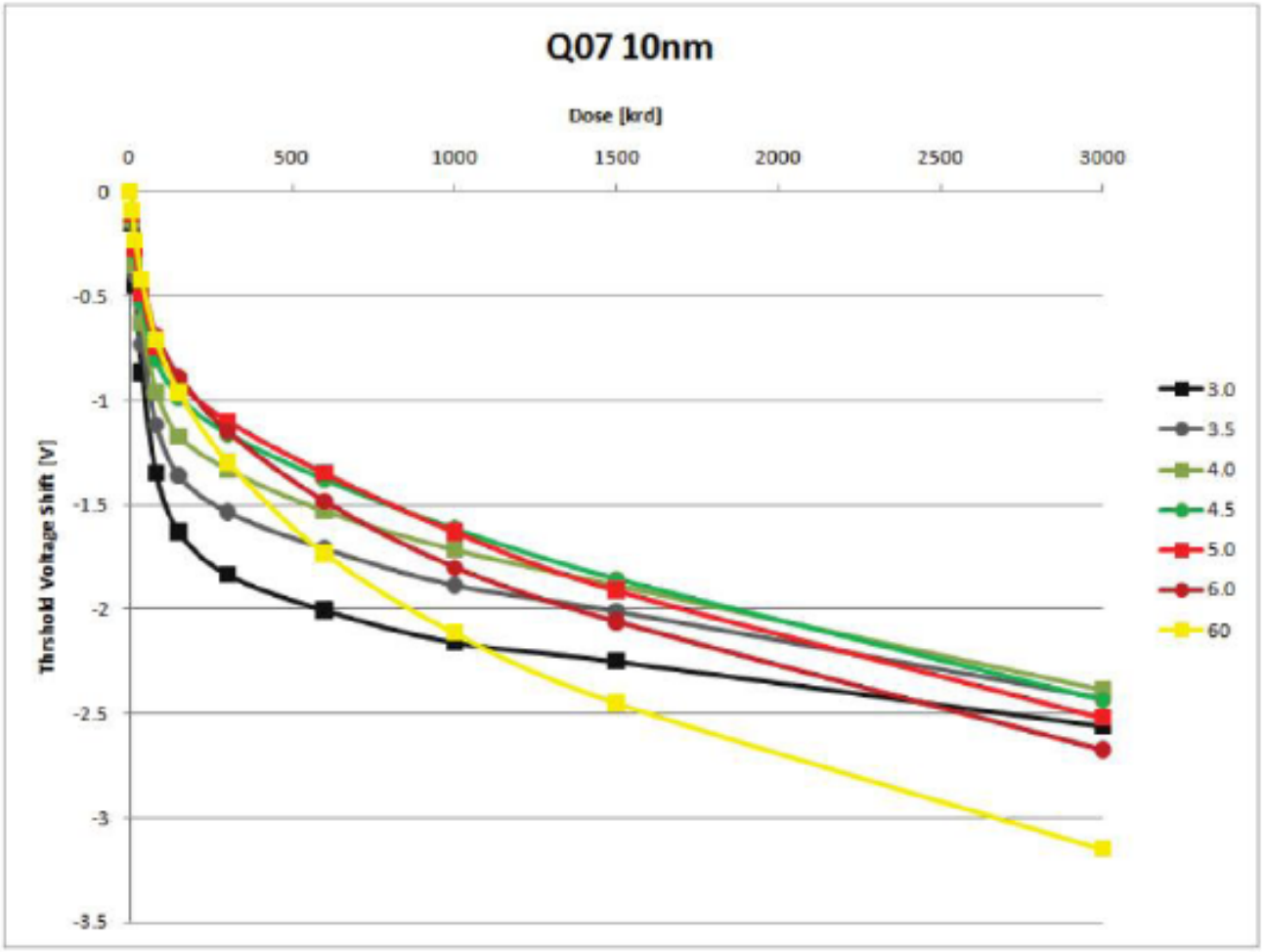






R. Richter

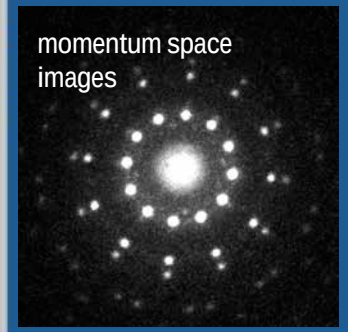
Radiation damage II – best case



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

Detector specifications

Two different detector systems



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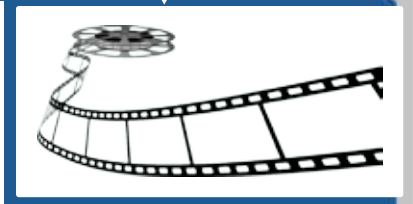
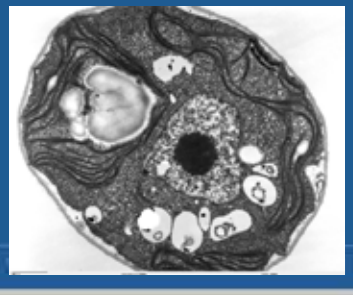


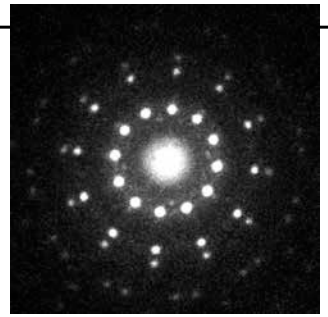
Real space images

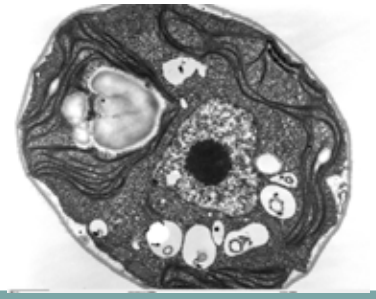


Electron Detector – DAQ Overview

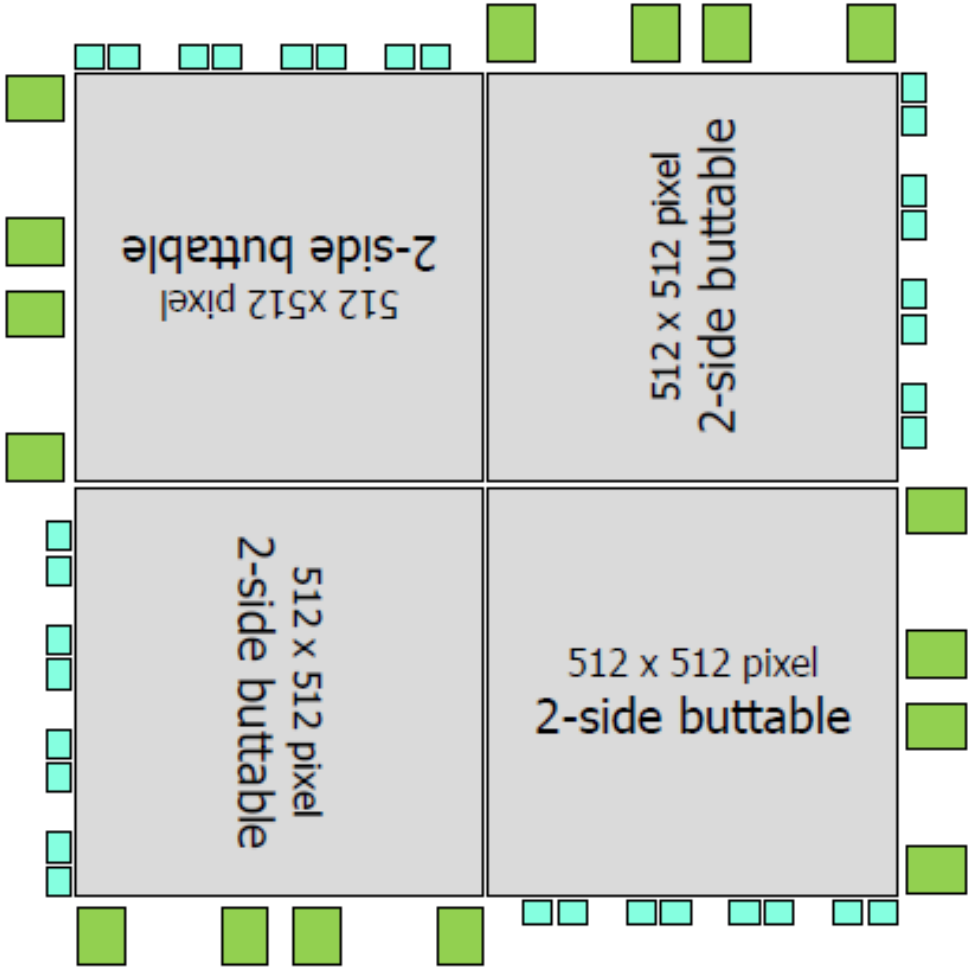
- Direct Hit (DH1k) and ultra fast detector DH80k need different read-out due to their different frame rates:

	Direct Hit (DH1k)	**DH80k**
Frame Rate	1 kHz	80 kHz
Data Stream	Continuously	Burst with 100 frames
Read-out	DCDEMCv1 + FPGA or DCDEMCv2 +DEPFET Movie chip	DCDB? + DEPFET Movie Chip
Pixel arrangement	512 x 512 2 fold readout	512 x 512 4-fold readout
ADC resolution	8 bit?	8 bit
Image type	Momentum space image	Real space image (additional pixels for Common Mode correction needed)

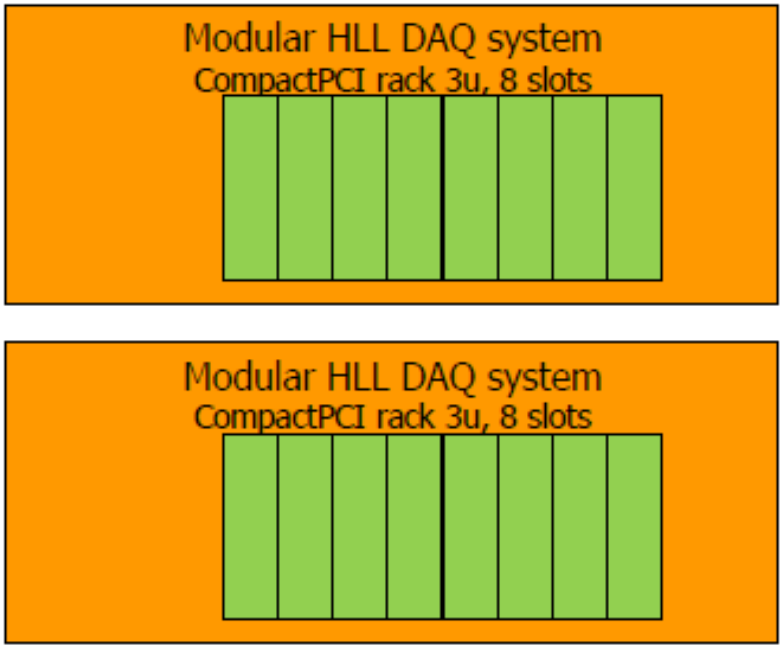




Direct Hit Detector – DH1k

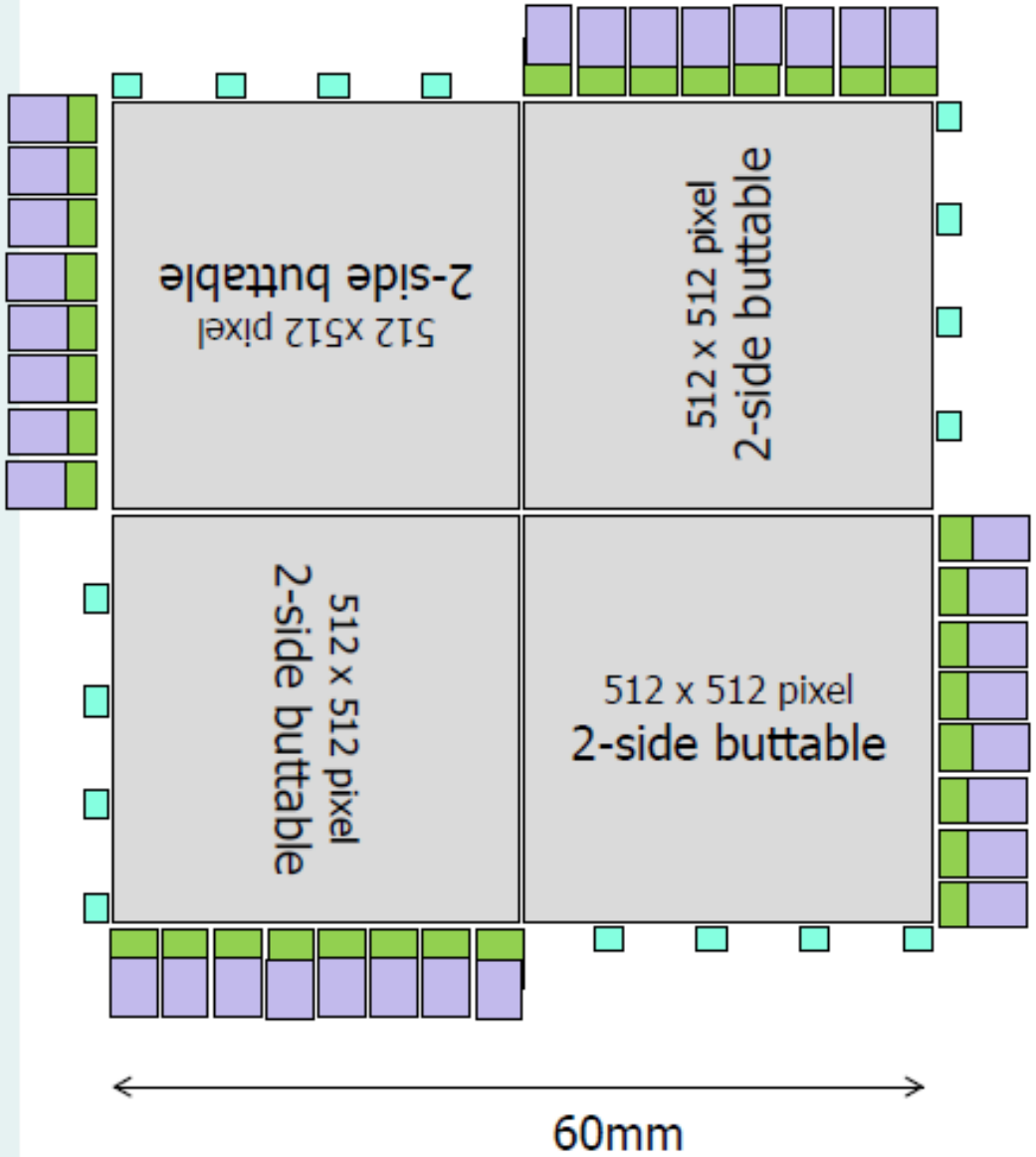


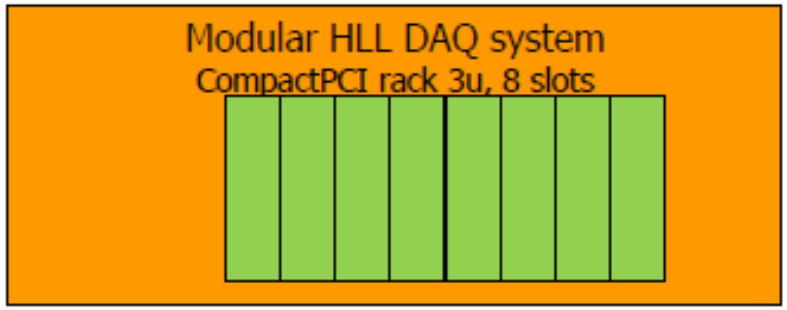
2 fold read-out

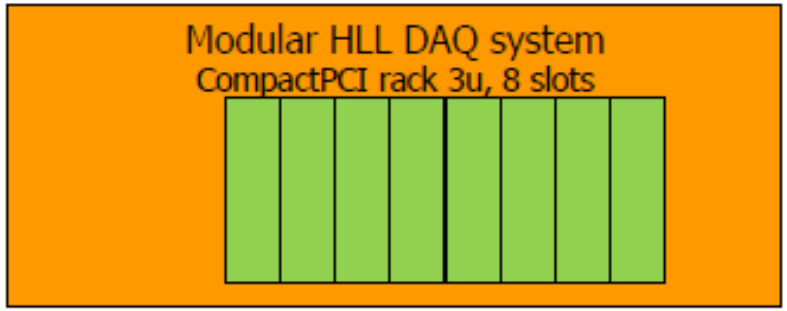


Large Direct Hit detector would need 2 compactPCI racks with 16 I/O and communication boards

Direct Hit Detector – FDH80k



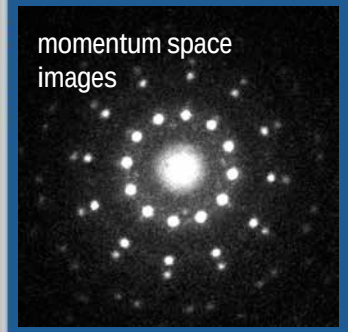




4 fold read-out

Detector specifications

Two different detector systems



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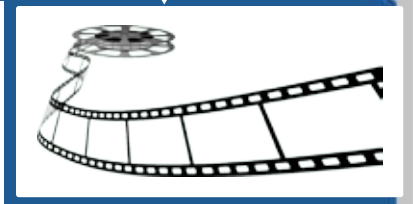
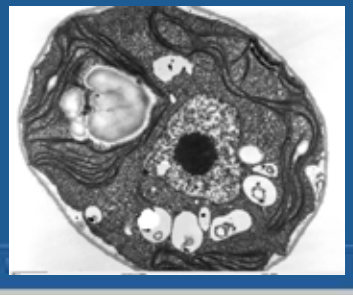
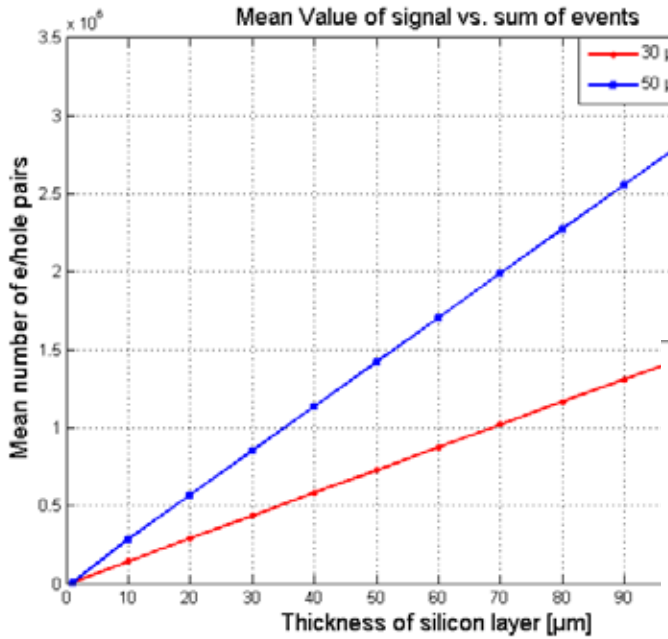
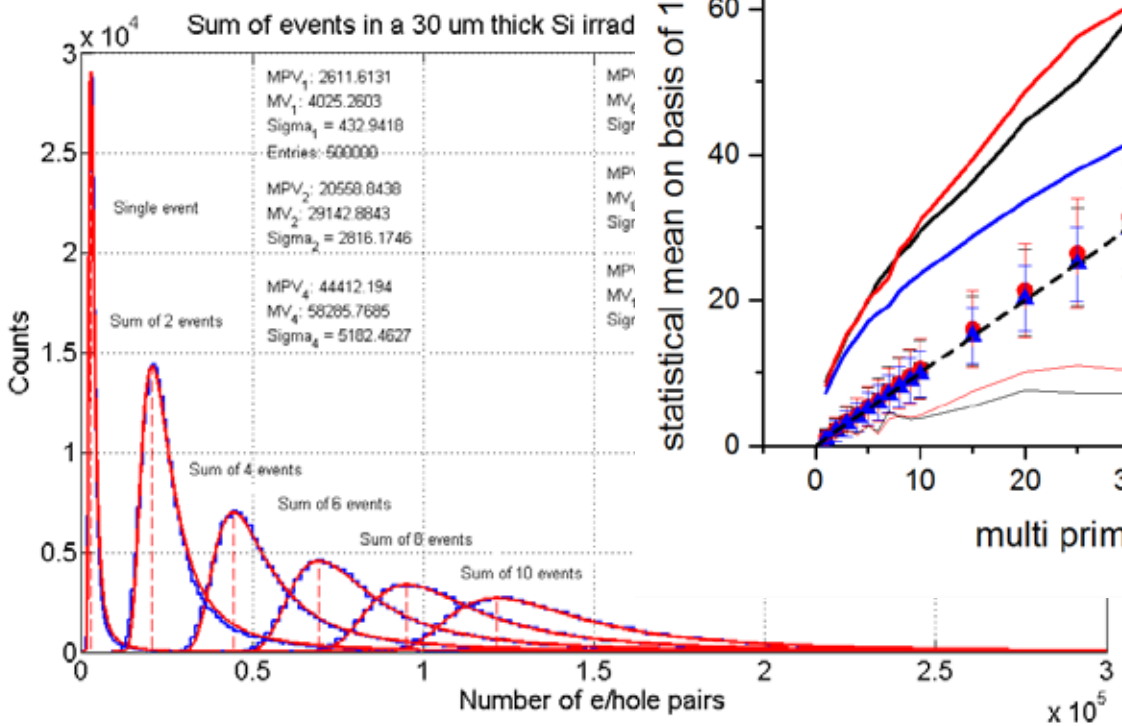


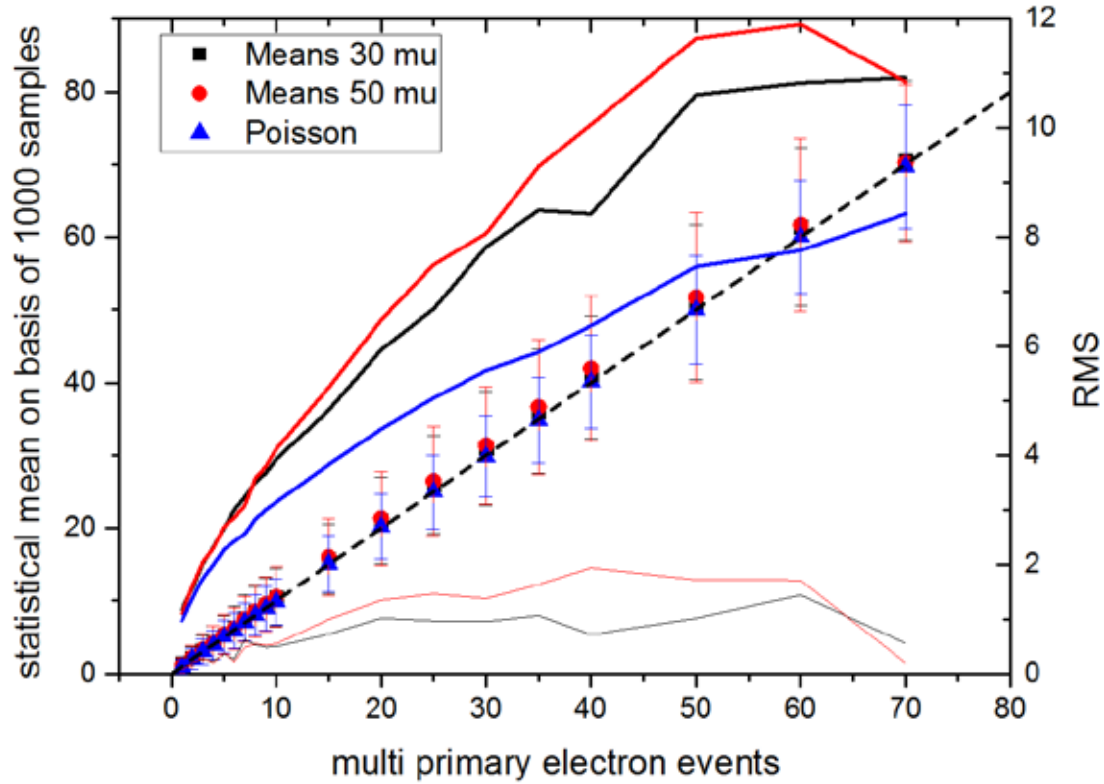
Real space images



Statistics

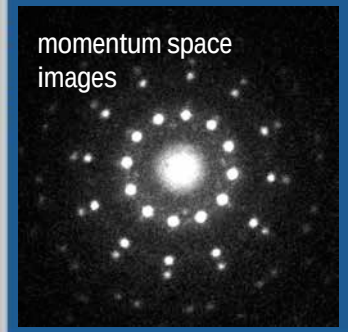

Mean Value of signal vs. sum of events
x 10^6
30 µm Si, E_e=300 keV
50 µm Si, E_e=300 keV
Mean number of e/hole pairs
Thickness of silicon layer [µm]


Sum of events in a 30 um thick Si irrad
x 10^4
MPV_1: 2611.6131
MV_1: 4025.2603
Sigma_1 = 432.9418
Entries: 500000
MPV_2: 20558.8438
MV_2: 29142.8843
Sigma_2 = 2816.1746
MPV_4: 44412.194
MV_4: 58285.7685
Sigma_4 = 5182.4627
Single event
Sum of 2 events
Sum of 4 events
Sum of 6 events
Sum of 8 events
Sum of 10 events
Counts
Number of e/hole pairs
x 10^5


Means 30 mu
Means 50 mu
Poisson
statistical mean on basis of 1000 samples
RMS
multi primary electron events

Detector specifications

Two different detector systems



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Sensor active area	(50 x 50) mm² 60mm x 60mm	
Sensor size in pixel	1000 x 1000 4 x (500 x 500)	
Physical pixel size	50 µm (subject to change) 60 µm	50 µm (subject to change)
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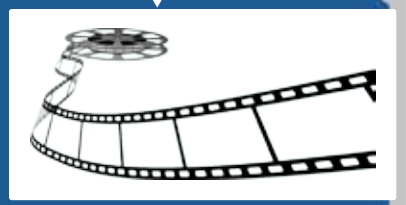
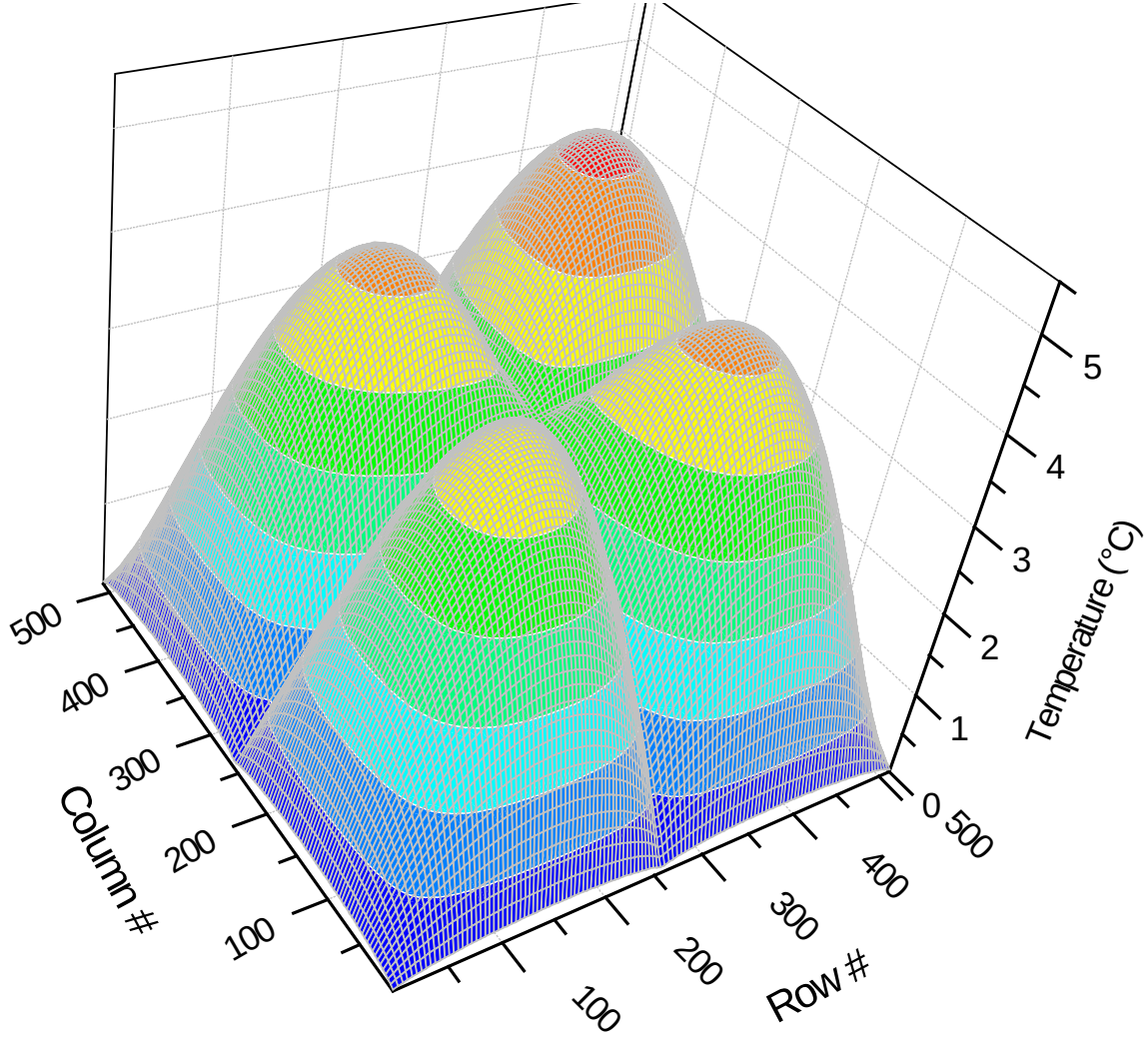
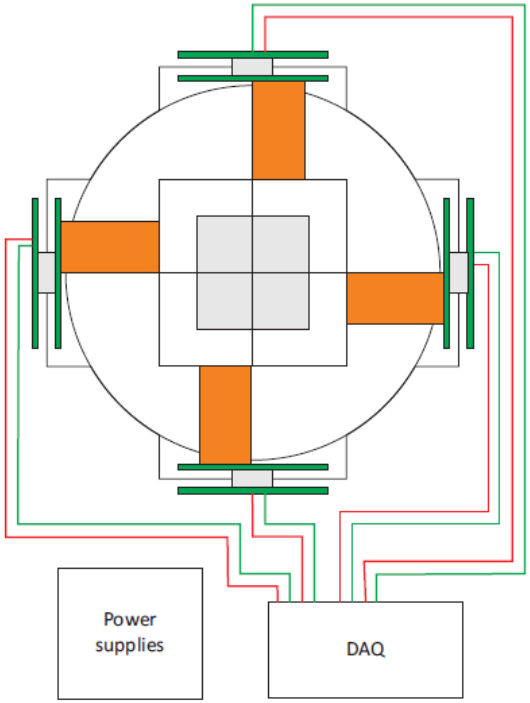
Read out mode	2x rolling shutter 4x	4x
Read out speed	>1000 Hz full frame rate (continuously)	~0.1 MHz full frame rate for 100 frames 80kHz
Electronic noise contribution	100 e-	
Sensor thickness	50 µm (down to 30 µm possible) 50 µm + support	450 µm
Pixel well depth (TCH)	60 000 (improvement is part of work package #1) 0.5M – 1M	
Operating temperature	~~ambient temperature~~ moderate cooling...0 °C	
Radiation hardness (pixel)	10Mrad	~~protected~~
Primary e- energy range	80 keV-5 MeV	80 keV-350 keV
Range of Ø num. secondary e-	between 5k-12k →	~~typically 1000 per 0.1 MeV~~

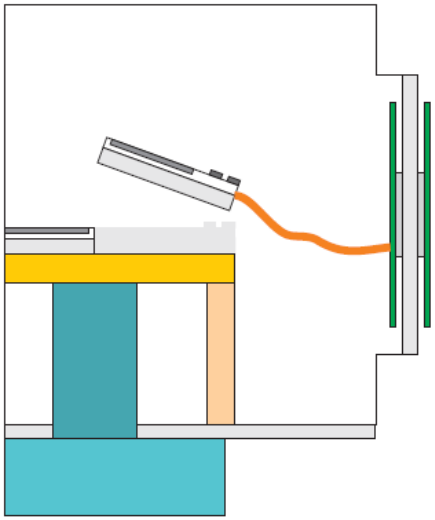
Table 2: Detector specifications.



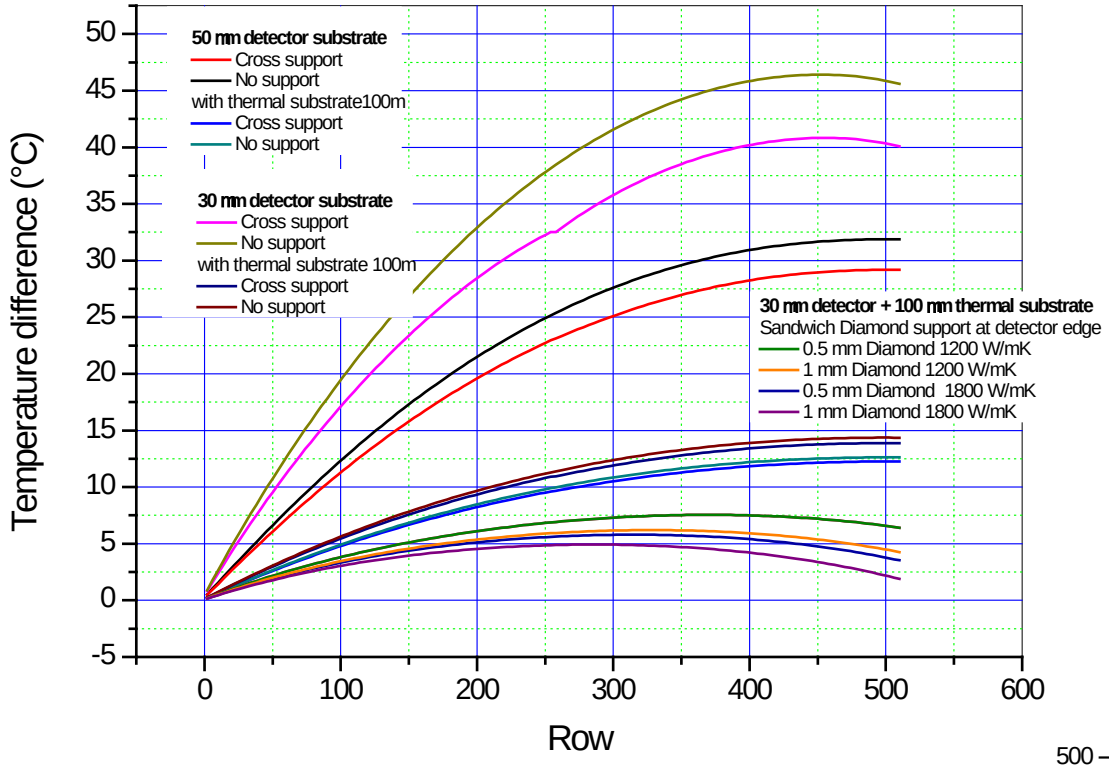
Real space images

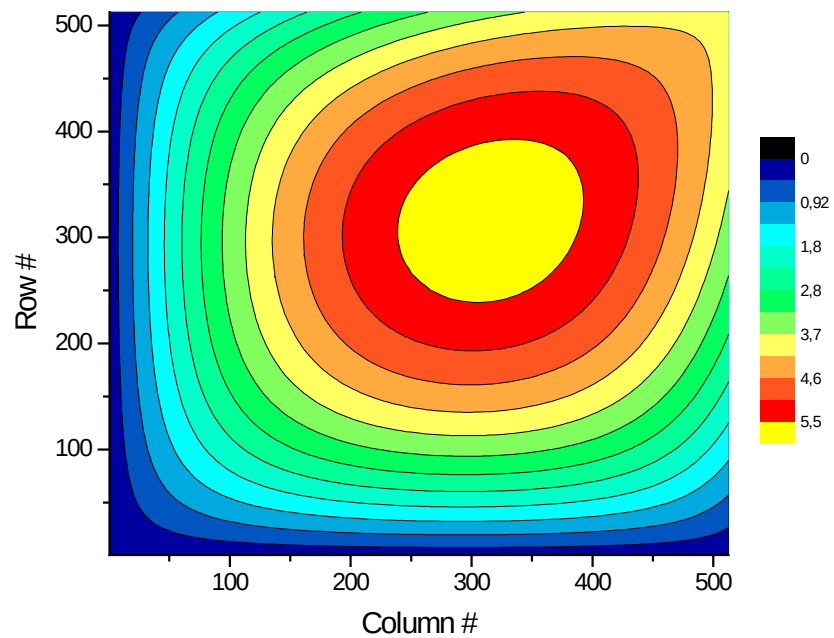






Johannes Treis /
Halbleiterlabor der MPG



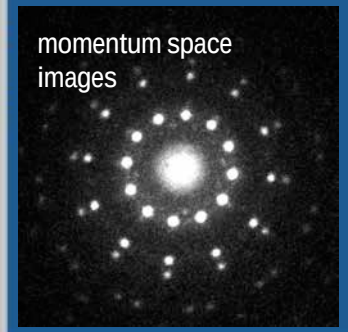


- **30 mm detector + 100 mm thermal substrate**
- **No cross support**
- **0.5 mm CVD diamond with 1800 W / (m x K) thermal conductivity**
- **Maximal gradient 5.8°C (!)**

Johannes Treis /
Halbleiterlabor der MPG

Detector specifications

Two different detector systems



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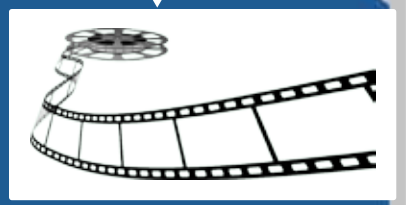
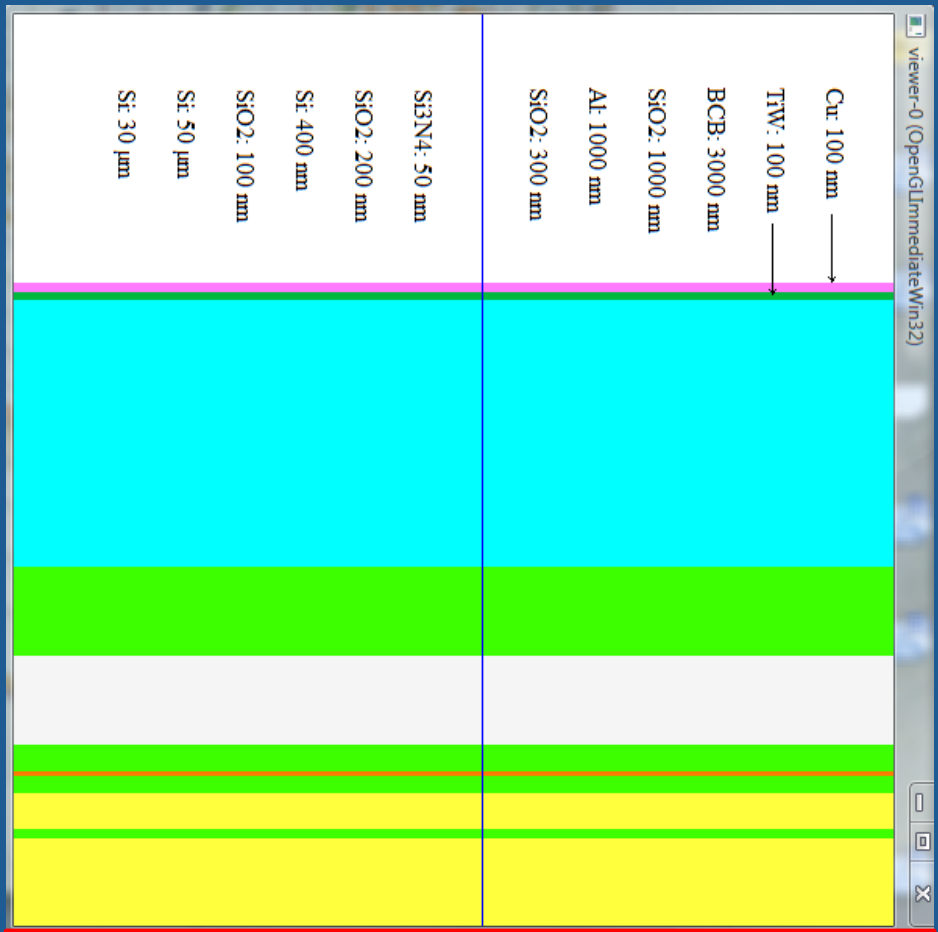


Real space images

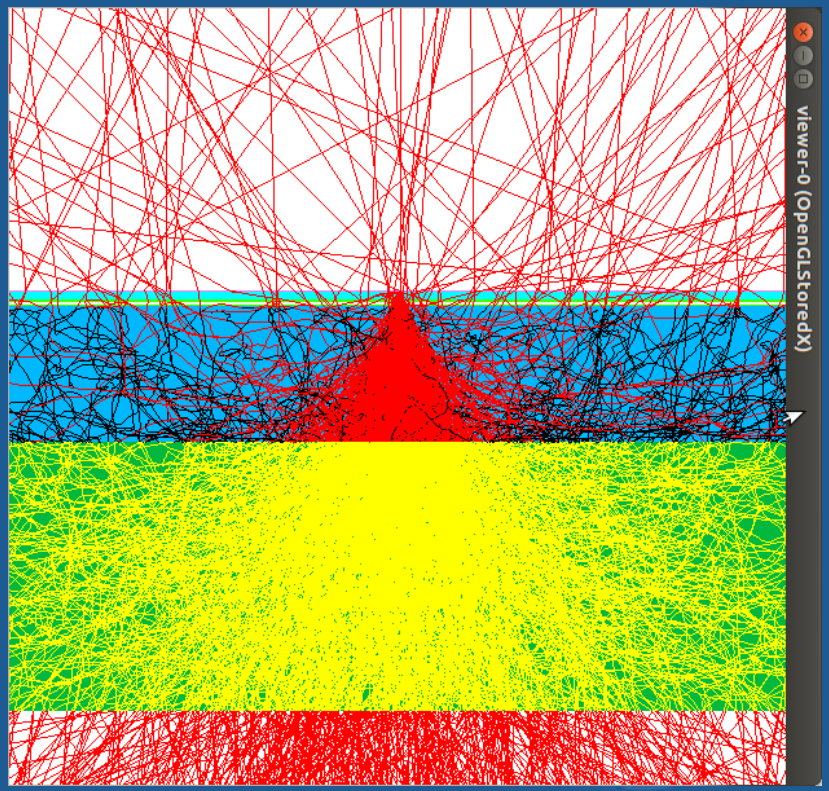
Detector layers

Pixel direction (Straggling)



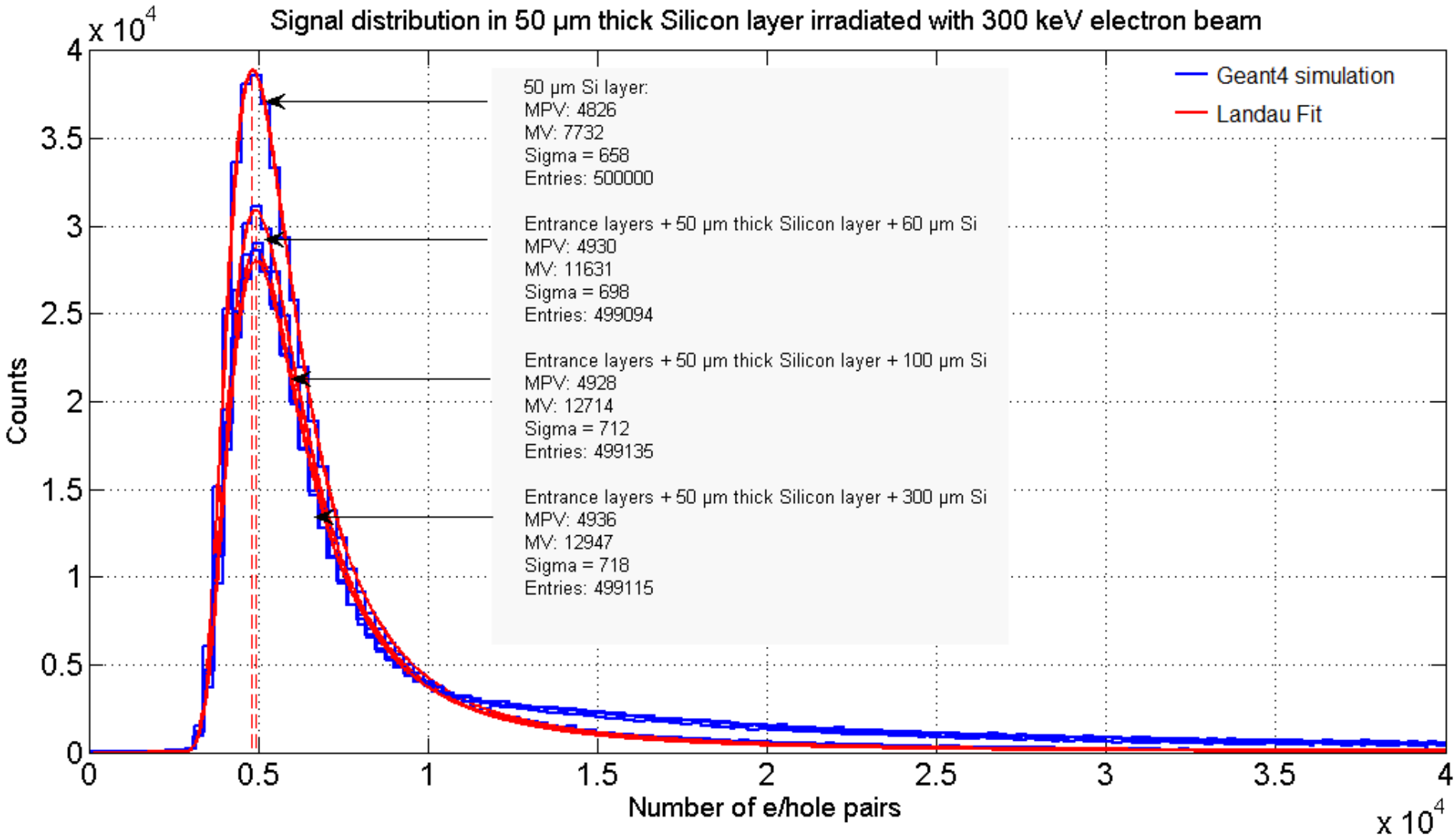
Sensitive Si (50µm)

Mechanical support Si (100 µm ?)



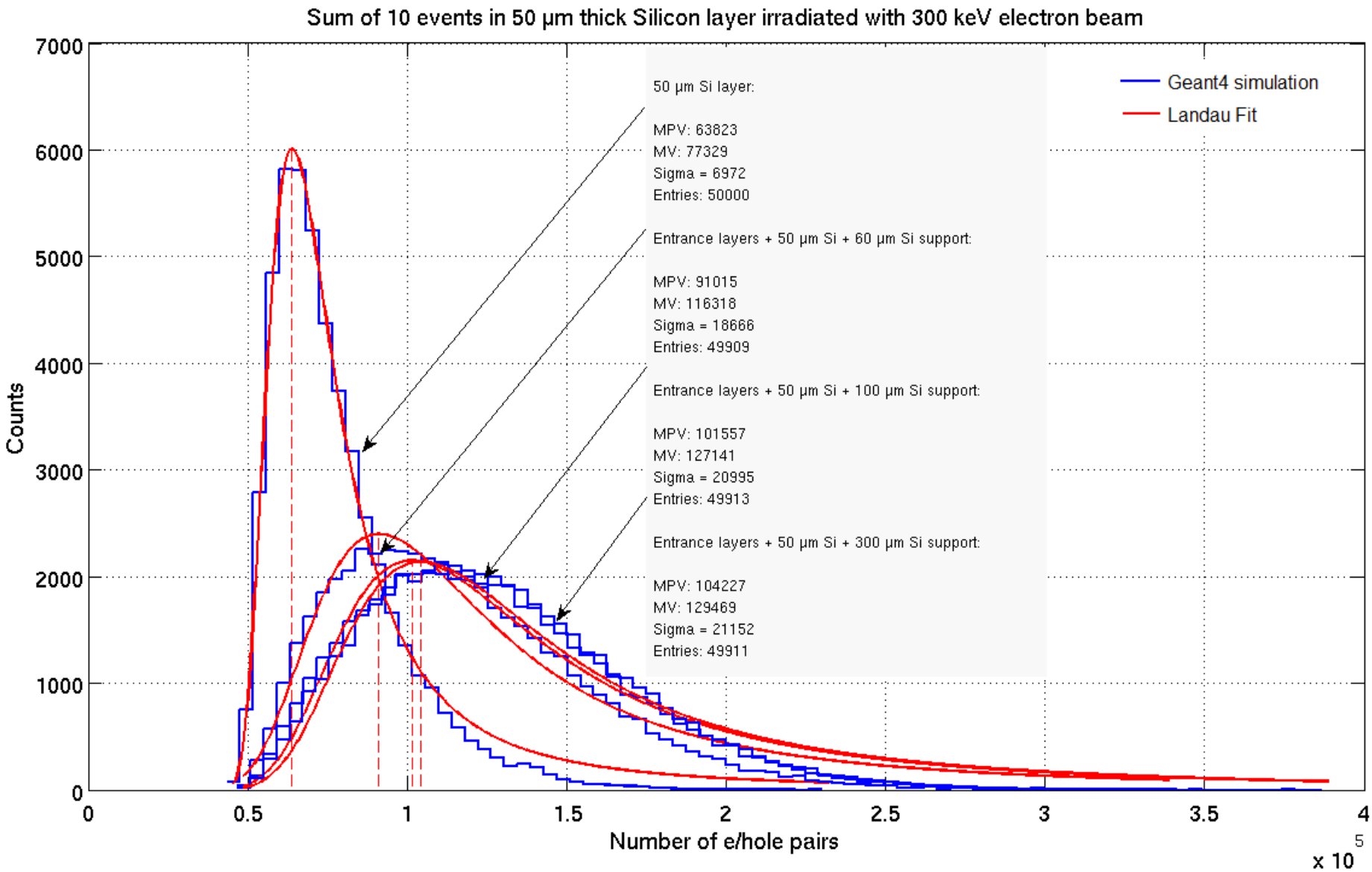
Statistics

Energy direction



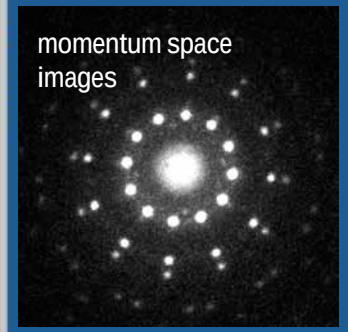
Statistics

Energy direction



Detector specifications

Two different detector systems



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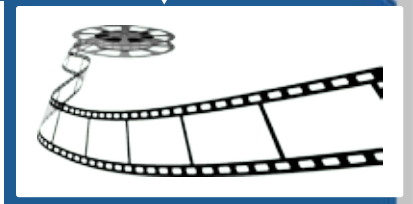
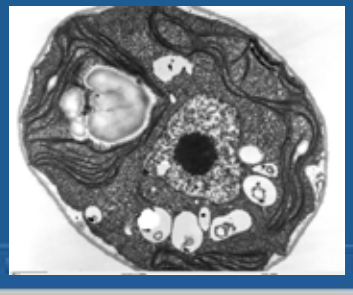
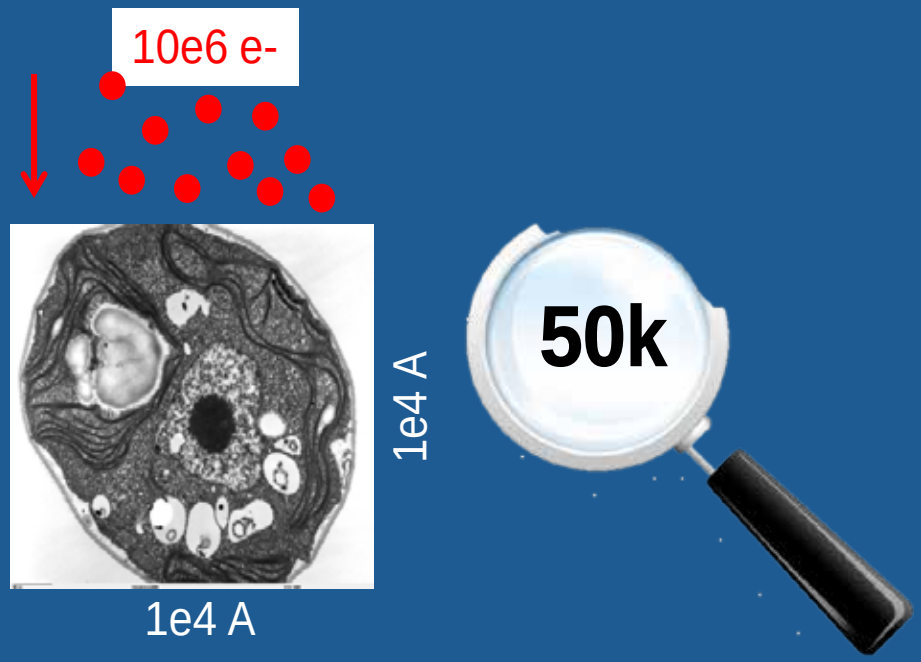
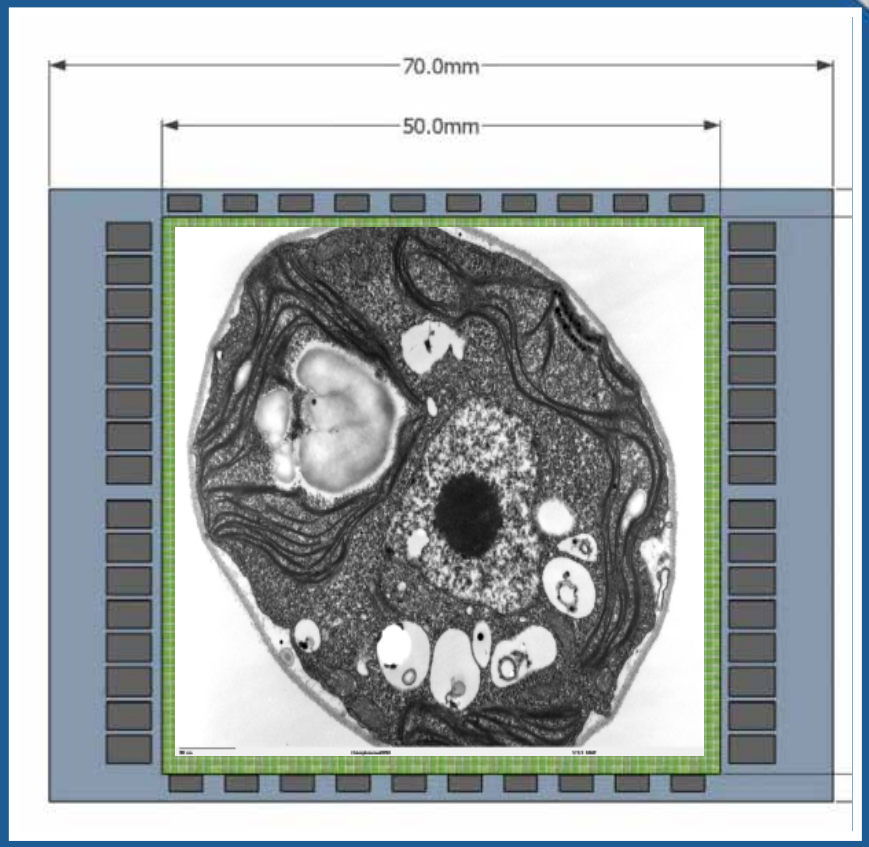


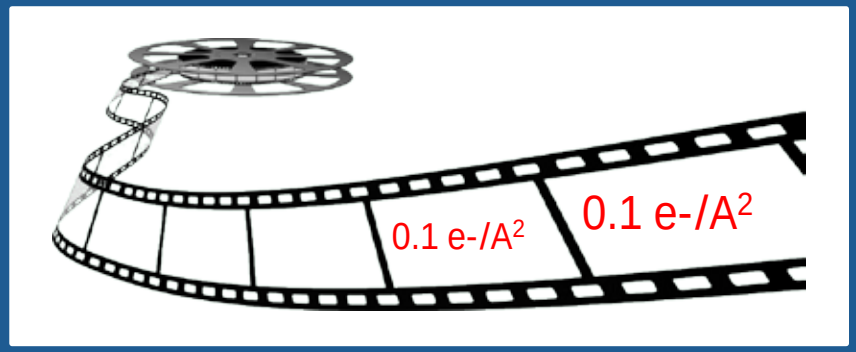
Real space images



TEM movie





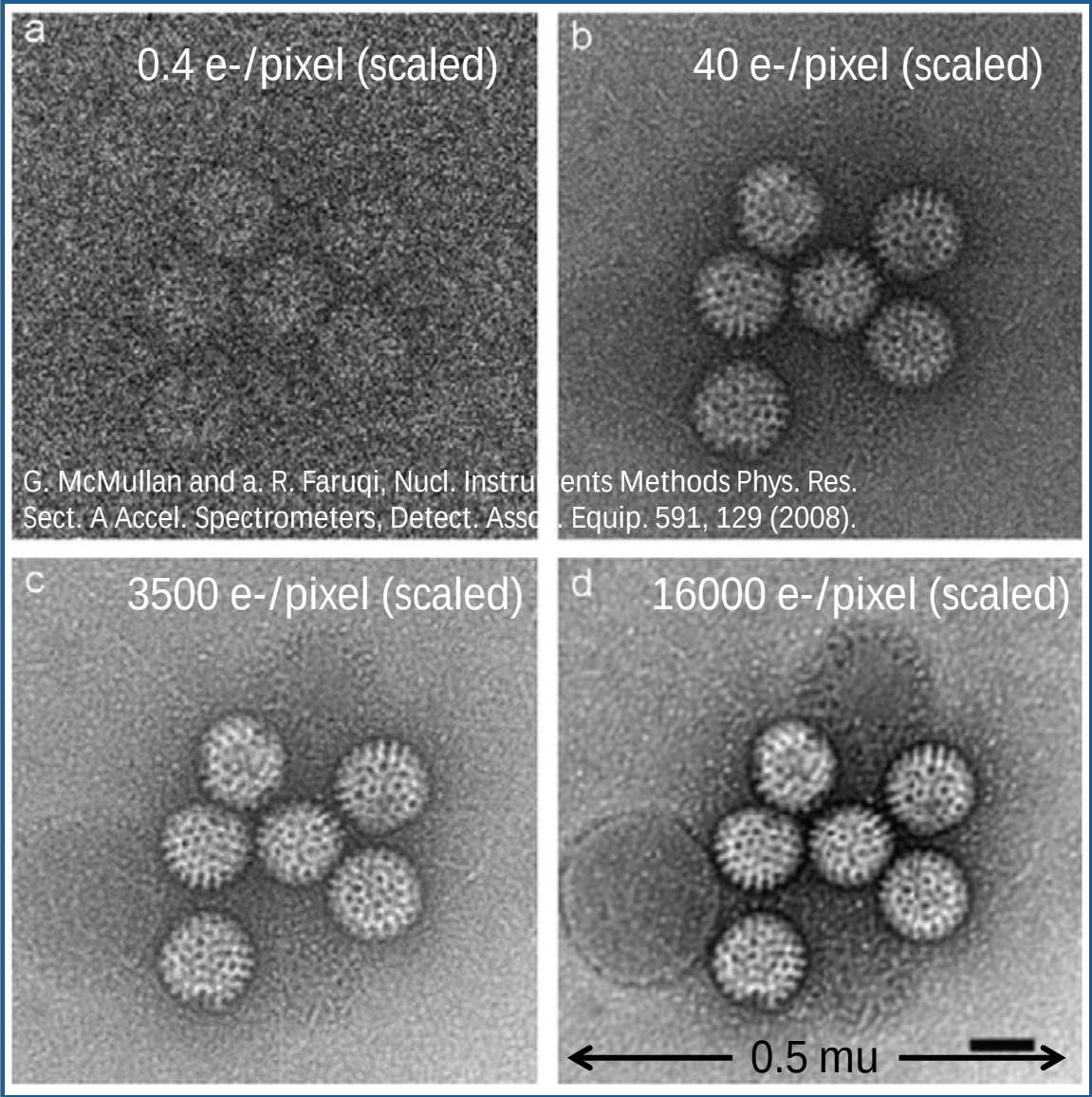


- 10 e- / pixel per single frame

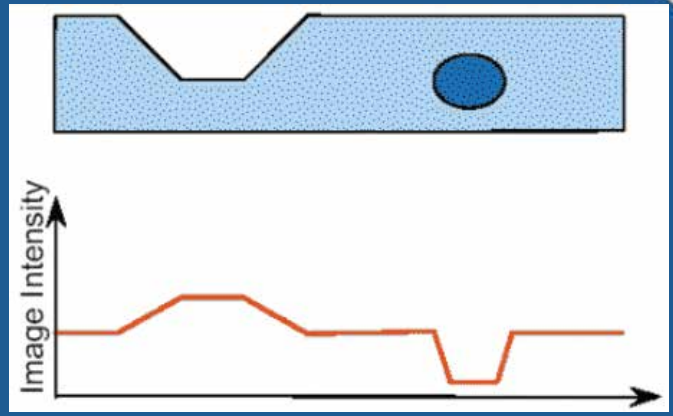
- for frames with 10M e- total,
this would be 250M frames or 2.5 M movies

- 10 e- / A^2 total area charge per 100 frame movie

TEM movie

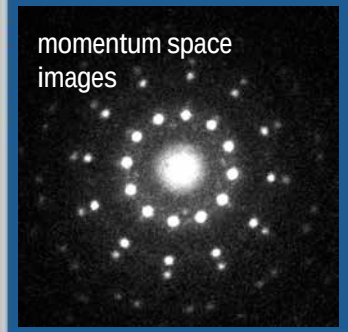


G. McMullan and a. R. Faruqi, Nucl. Instru ents Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Asso . Equip. 591, 129 (2008).



Detector specifications

Two different detector systems



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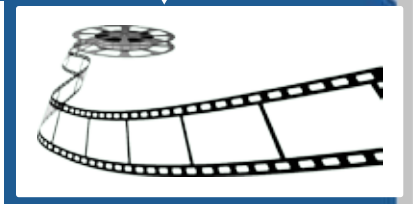
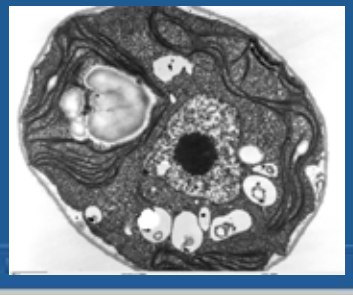


Real space images



Work packages

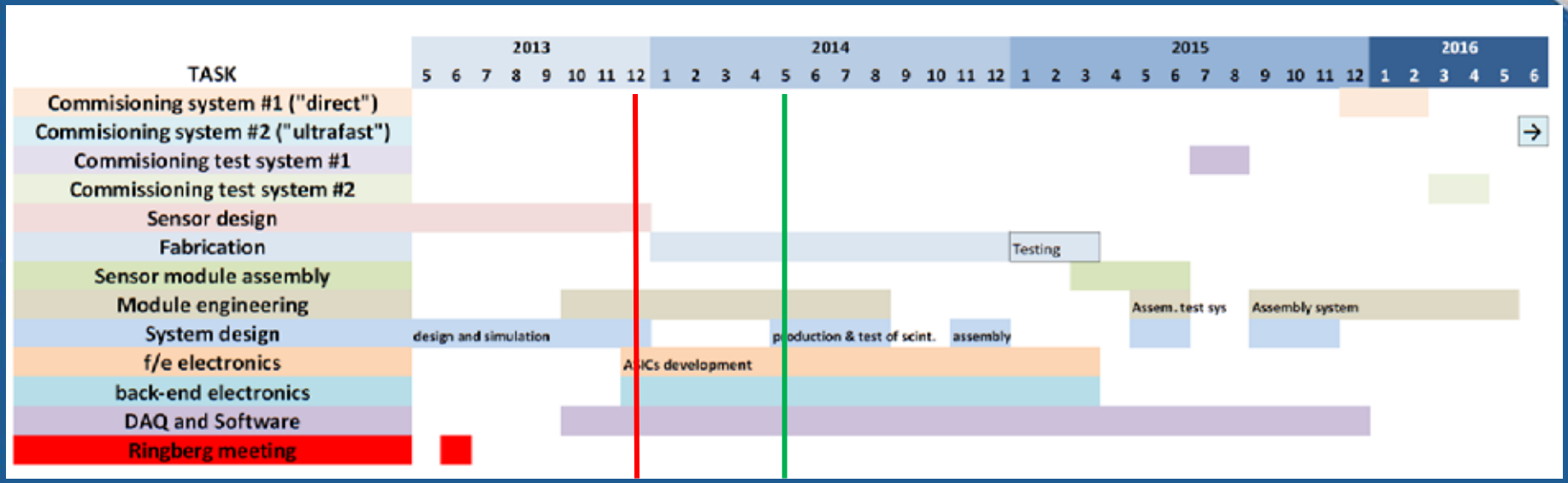
Responsibilities

In total there are 8 work packages devoted to:

1. **Sensor design, fabrication and tests [HLL]:** pixel cell and technology, defining chip parameter, simulations, radiation hardness, layout of wafer for production, fabrication and processing of wafer, tests
2. **Sensor module assembly [HLL]:** definition of materials, assembly
3. **Module integration [MPI-SD]:** Thermal and electrical engineering and performance, definition of materials, fabrication of mechanical parts
4. **System design [MPI-SD]:** Scintillator optics, R&D for scintillator design, simulations, integration to sensor, definition and optimization of operation modes
5. **f/e electronics [?]:** ASICs design
6. **back-end electronics [?]:** FPGA system design, definition of protocols and interfaces between sensor and DAQ, Power supplies, slow control and housekeeping
7. **DAQ and Software [MPI-SD]:** definition of hardware, programming of user interface, data representation and analysis
8. **Commissioning [HLL, MPI-SD]:**

Timeline

Commissioning 2016……



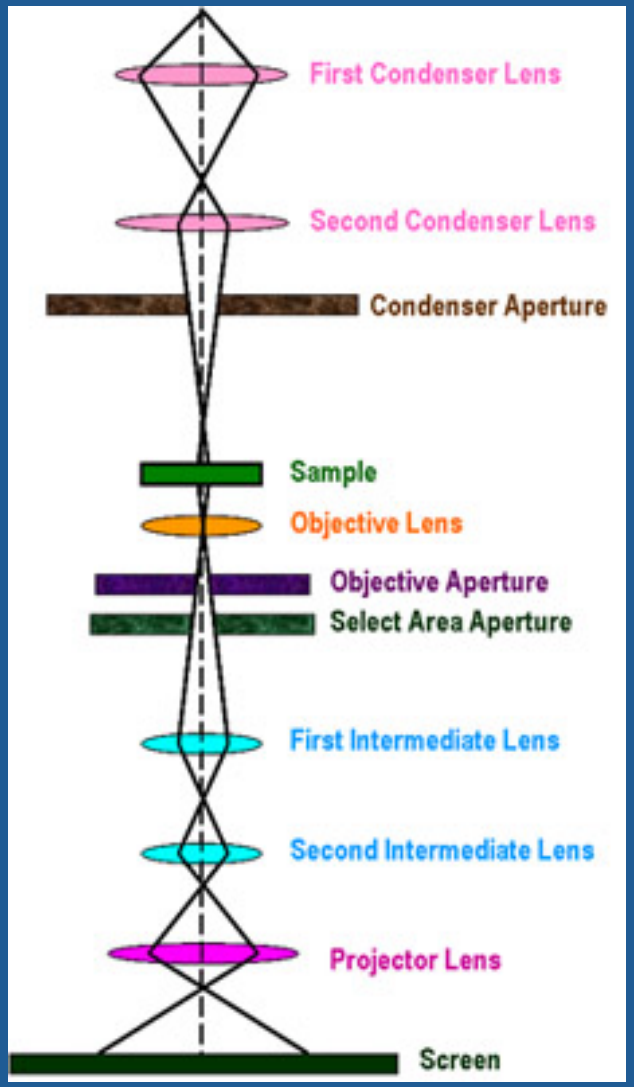
Next milestones:

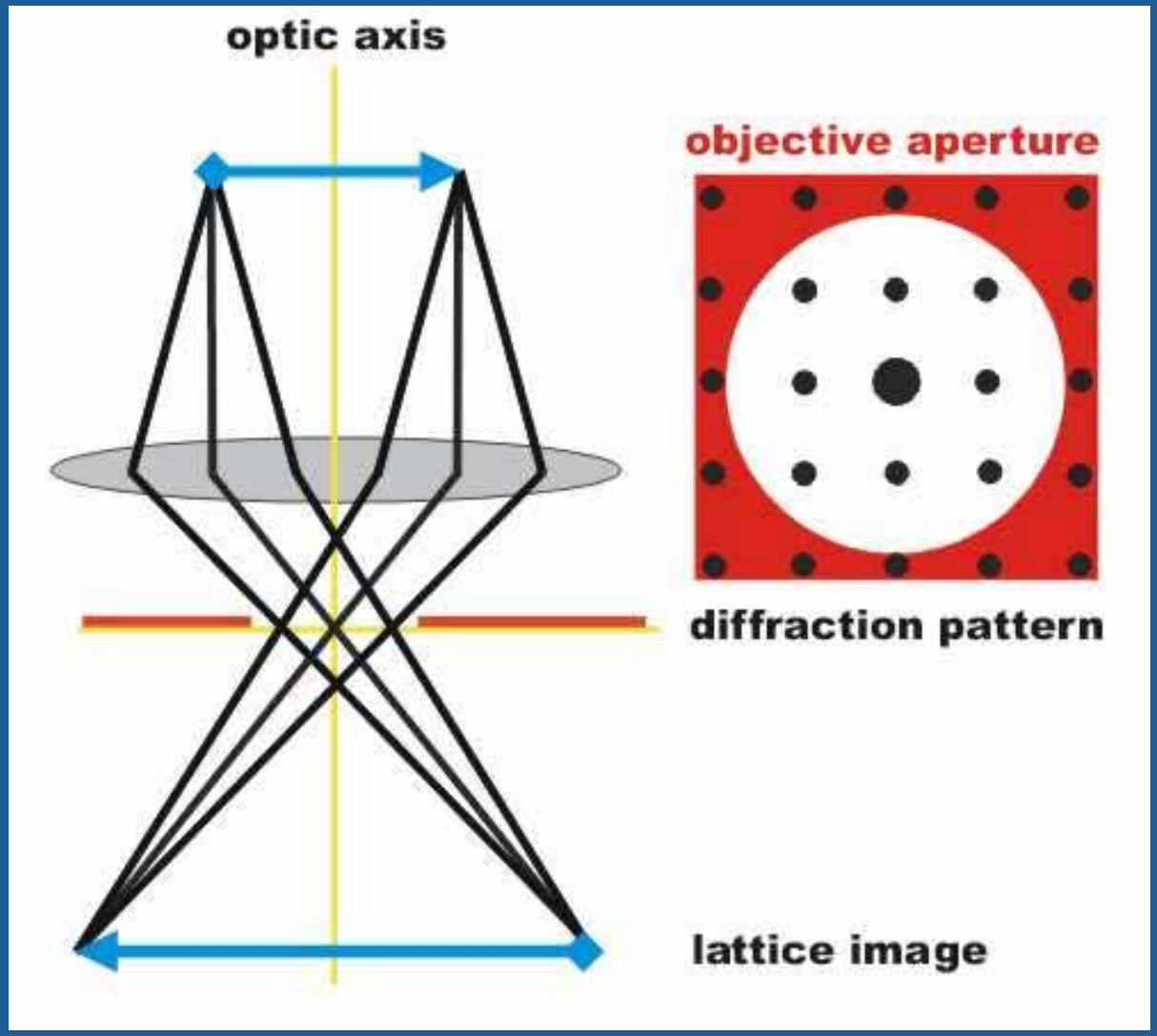
- decide on sensitive layer thickness (50 µm)
- SOI wafer production
- decide on ASICs
- 01.01.15 start DEPFET fabrication

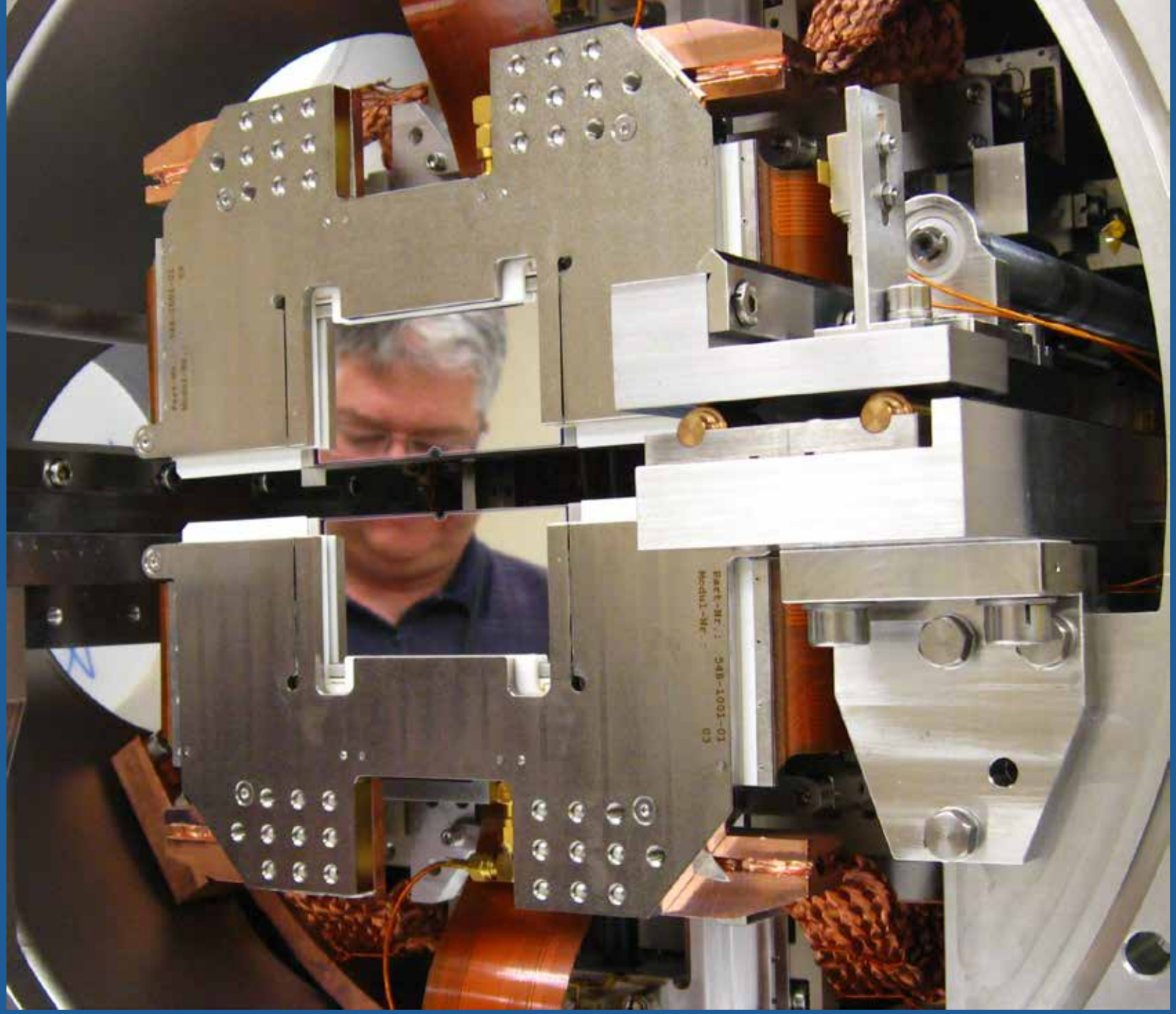
Thank you !!!

ENDE


900 nm
Chlamydomonas#8563
S/V/I EMF


First Condenser Lens
Second Condenser Lens
Condenser Aperture
Sample
Objective Lens
Objective Aperture
Select Area Aperture
First Intermediate Lens
Second Intermediate Lens
Projector Lens
Screen


optic axis
objective aperture
diffraction pattern
lattice image

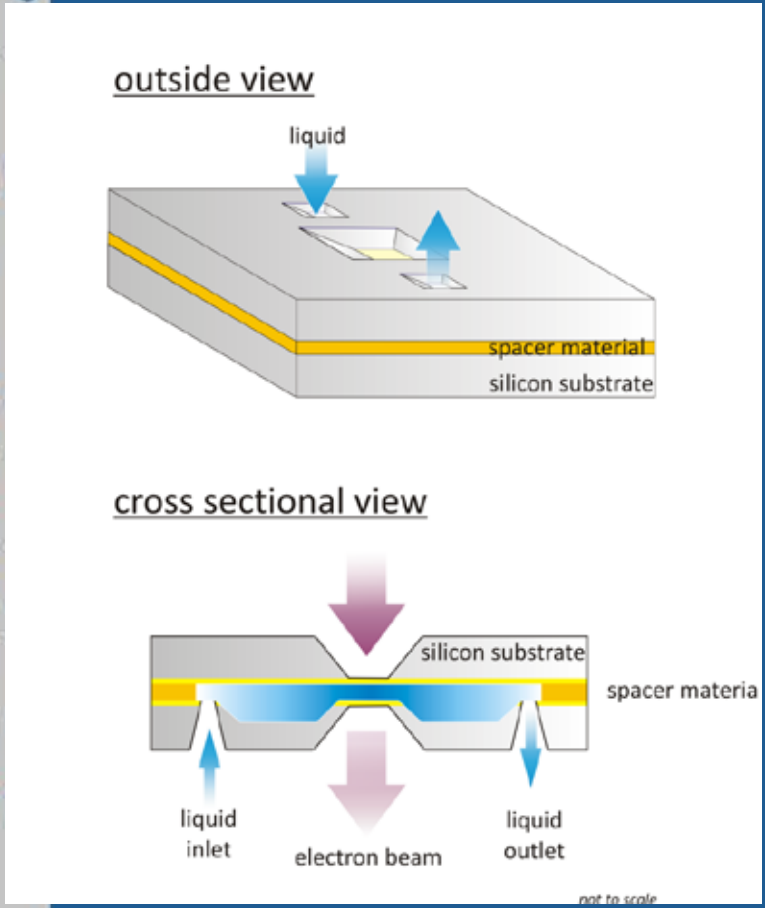

Part-Nr.: 548-1001-01
Modul-Nr.: 03

TASK	COSTS [k€]		NOTES
WP1: Sensor design, fabrication and test		-530	Includes all personnel costs at HLL
Processing of 6 thin wafers	240		40k each
Processing of 6 thick wafers	240		
Components for tests	50		
WP2: Sensor module assembly		-20	
WP3: Module engineering		-180	
Engineering system #1	70		consumption 20k + invest 50k
Engineering system #2	70		
Engineering test system #1	20		
Engineering test system #2	20		
WP4: System design		-80	
Fiber optic face plate	50		
Scintillator coating	10		
Scintillator nano structuring	10		
test structures	10		
WP5: f/e electronics		-340	
ASICs switcher (system 1 & 2)	40		# 40 ASICs
DCD (system 1 & 2)	80		# 90 ASICs
DHP (system 1 "direct")	50		# 100 ASICs
DHP2 (system 2)	90		# 100 ASICs "on chip memory"
Development	70		1 man year extern (Coll.)
ASIC tests	10		
WP6: back-end electronics		-125	
Read out boards (system 1 "direct")	40		4 x Struck SFP->PCIexp
Read out boards (system 2 "ultrafast")	10		Struck SFP->PCIexp
Computer	30		10 workstations
Ethernet 10G	15		10 cards
Power supplies for 2 systems	20		100 channels -100..20 V
Fast ethernet switches	10		
WP7: DAQ and Software		-200	
Fast storage system #1 (direct)	90		Raid system
Long-term storage	20		DESY facility
Fast storage system #2 (scint.)	90		Raid system
WP8: Commissioning		-15	Travel expenses
TOTAL WP		-1490	
20 % Contingency		-317	
1.5 positions engineering staff (65k/year)		-293	
CFEL detector lab		-300	
Financial contribution MPI-SD		300	
FINANCIAL NEEDS (Phase I; 3 years)		**-2100**	**700k/year**

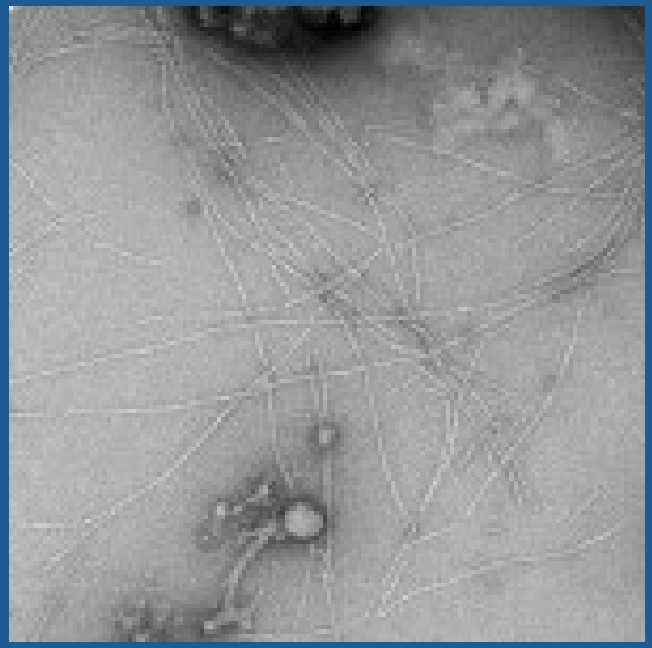
Table 4: Budget & financial needs for initial Phase-I (3 years)

Further Evolution in atom gazing: ……Solution Phase Dynamics

TEM nanocell with flow!



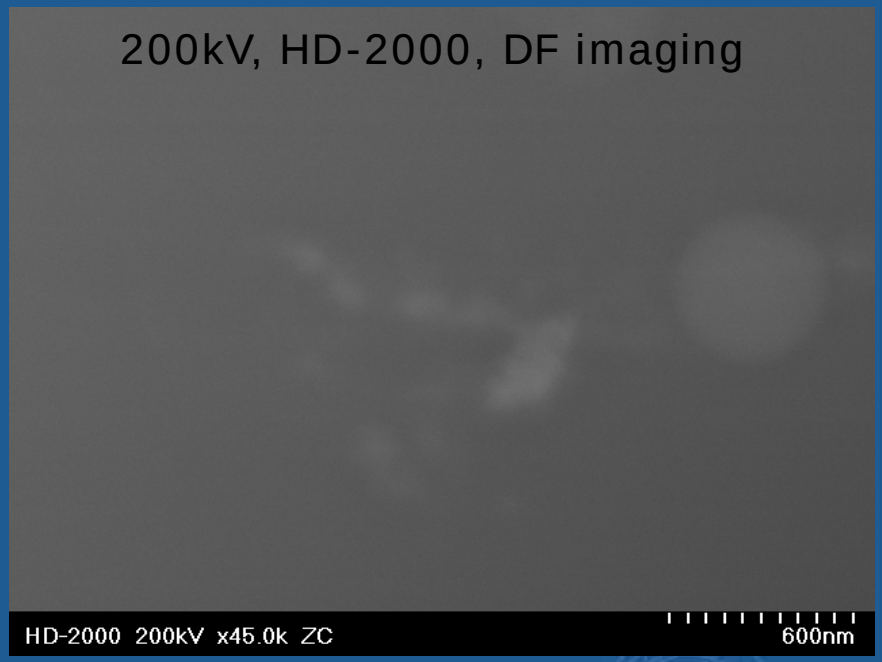
amyloid fibrils



negative stain image of amyloid fibrils

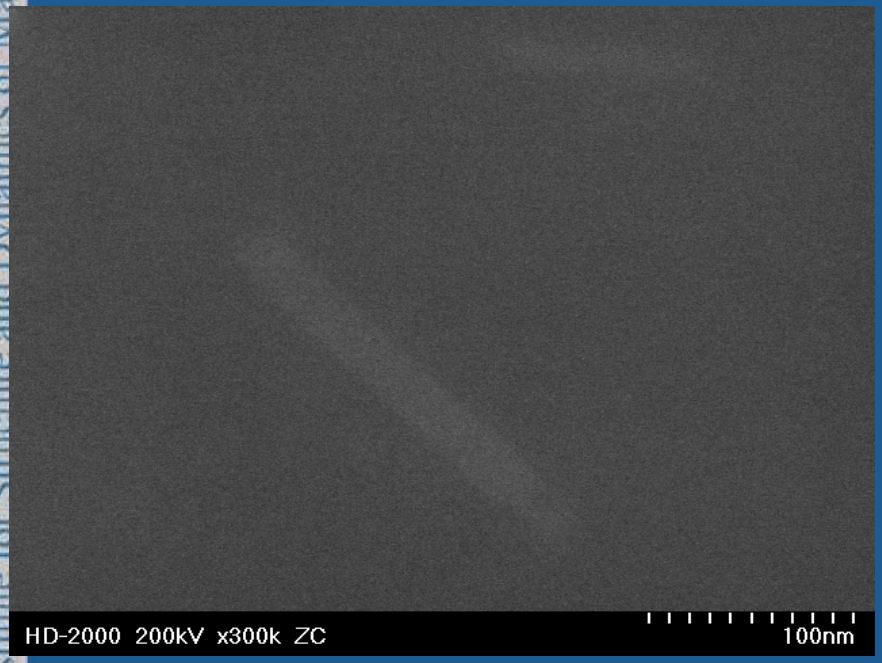
here: dried on TEM grid
no scale bar available

non stained amyloid sample in 115nm spaced nano-cell

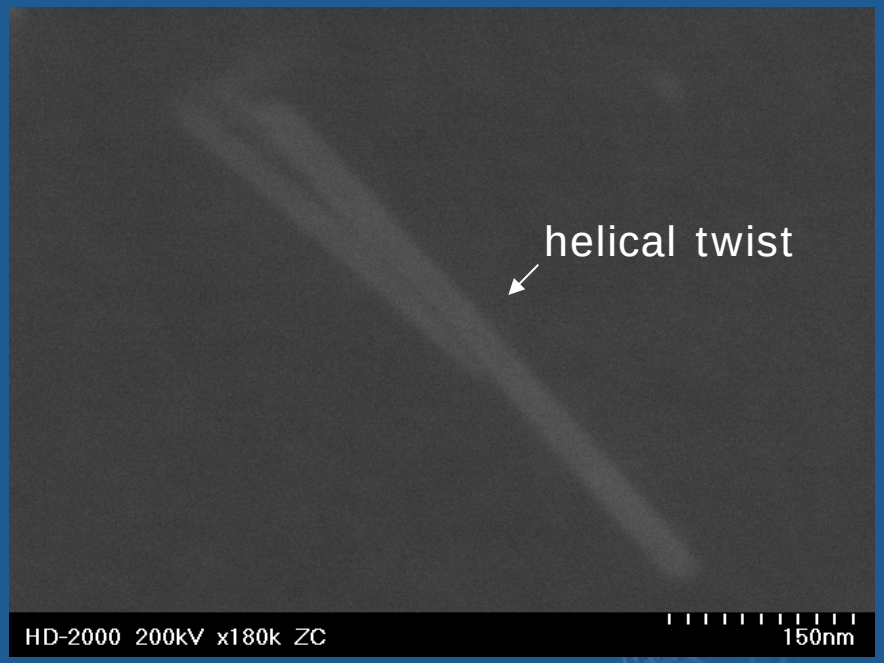


http://atp.ncifcrf.gov/imaging-and-nanotechnology/electron-microscopy-laboratory/eml-protocols-and-resources/eml-image-gallery/

amyloid fibrils



amyloid fibril parts, chopped by organic solvent and flown into the viewing area



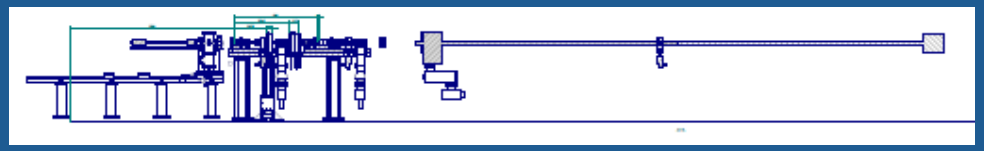
in 45nm spaced nanocell
200kV, HD-2000 (STEM)

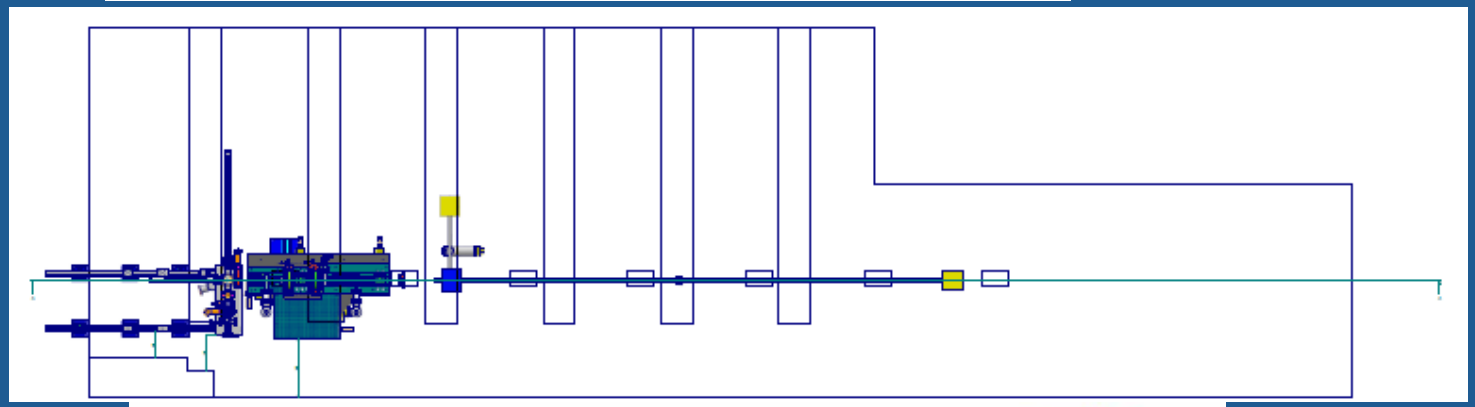
6th Generation : Relativistic Electron Gun for Atomic Exploration (REGAE): Citius, Altius, Fortius

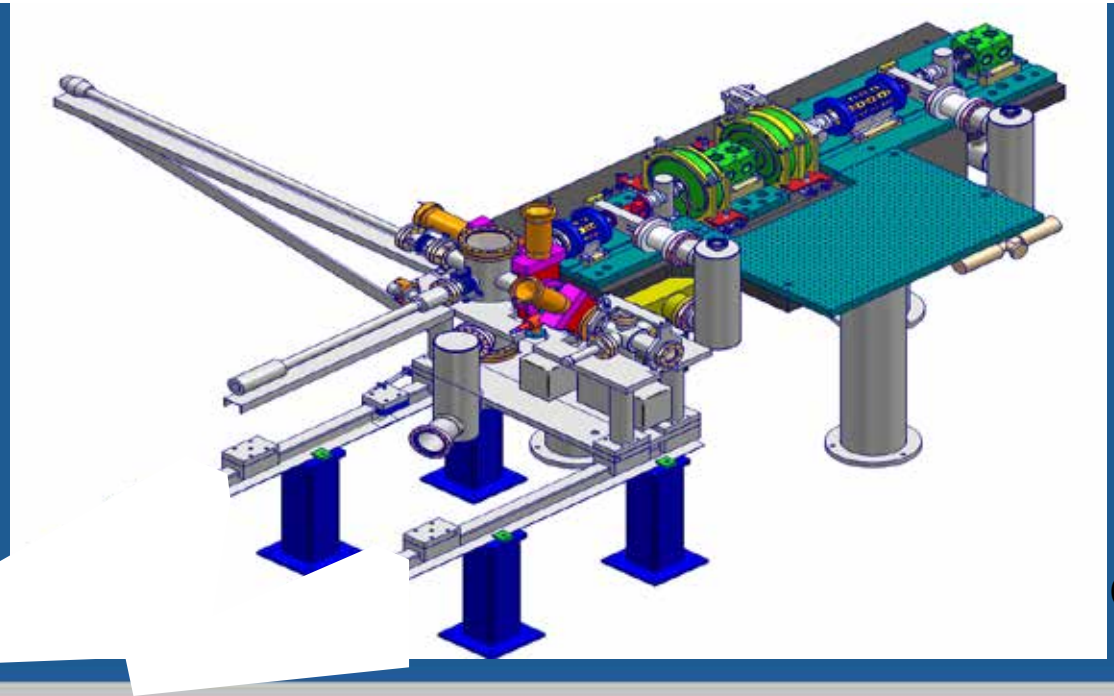
- **REGAE defines new limits in Atom Gazing**
- **Higher bunch density/Fortius**
- **Micro-scale samples/Altius**
- **Higher Time Resolution/Citius**

Hastings, J.B. et al. Appl. Phys. Lett. 89, 184109 (2006)
Musumeci, P. et al. Appl. Phys. Lett. 97, 063502 (2010).
Yang JF, Kan K, Kondoh T, Yoshida, Y., Tanimura, K., Urakawa, J., Nuclear Instr. & Methods Phys. Res. A, Accelerators Spectrometers Dectors and Assoc. Equip. 637, S24-S29, 2011

Layout of REGAE

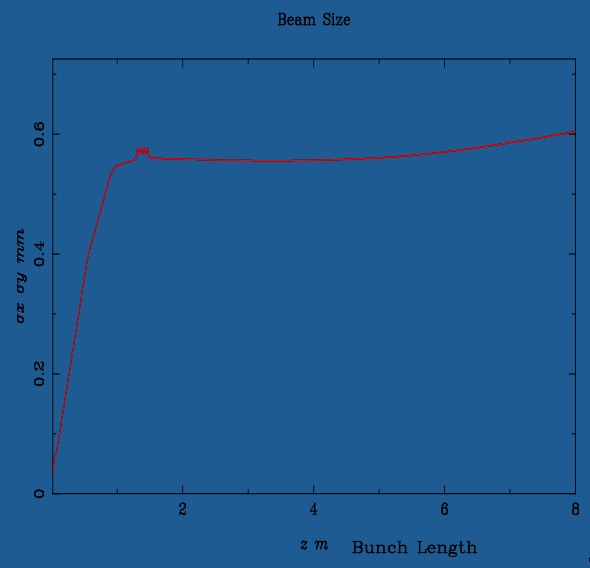


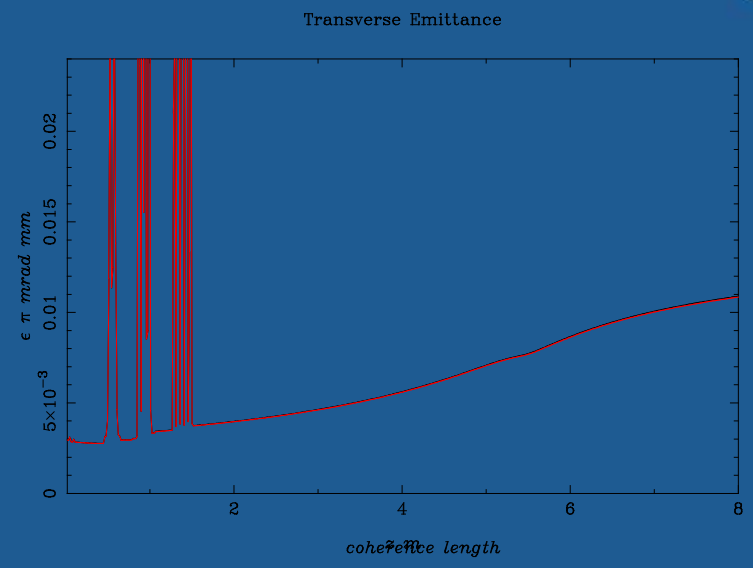


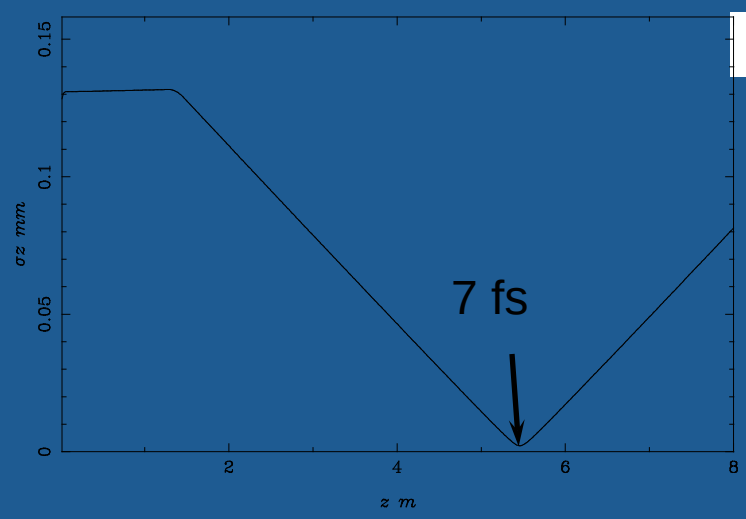


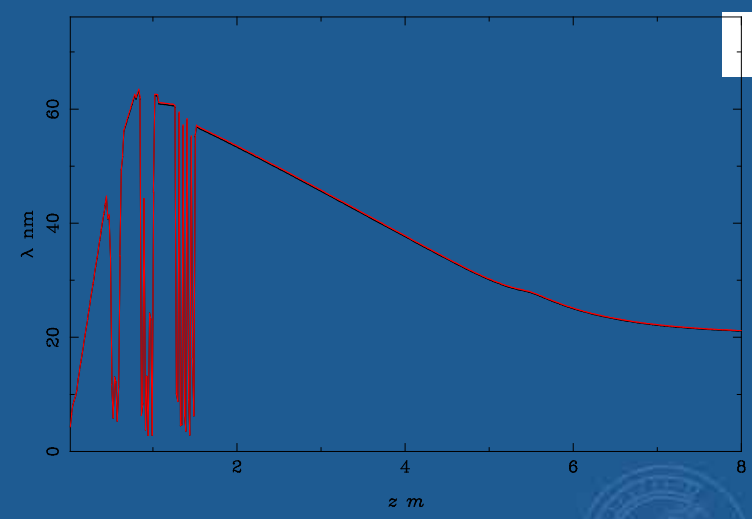
Courtesy K.F./H. D.-H.

Simulation of Beam Properties: 10^6 – 10^7 e Bunch Charge

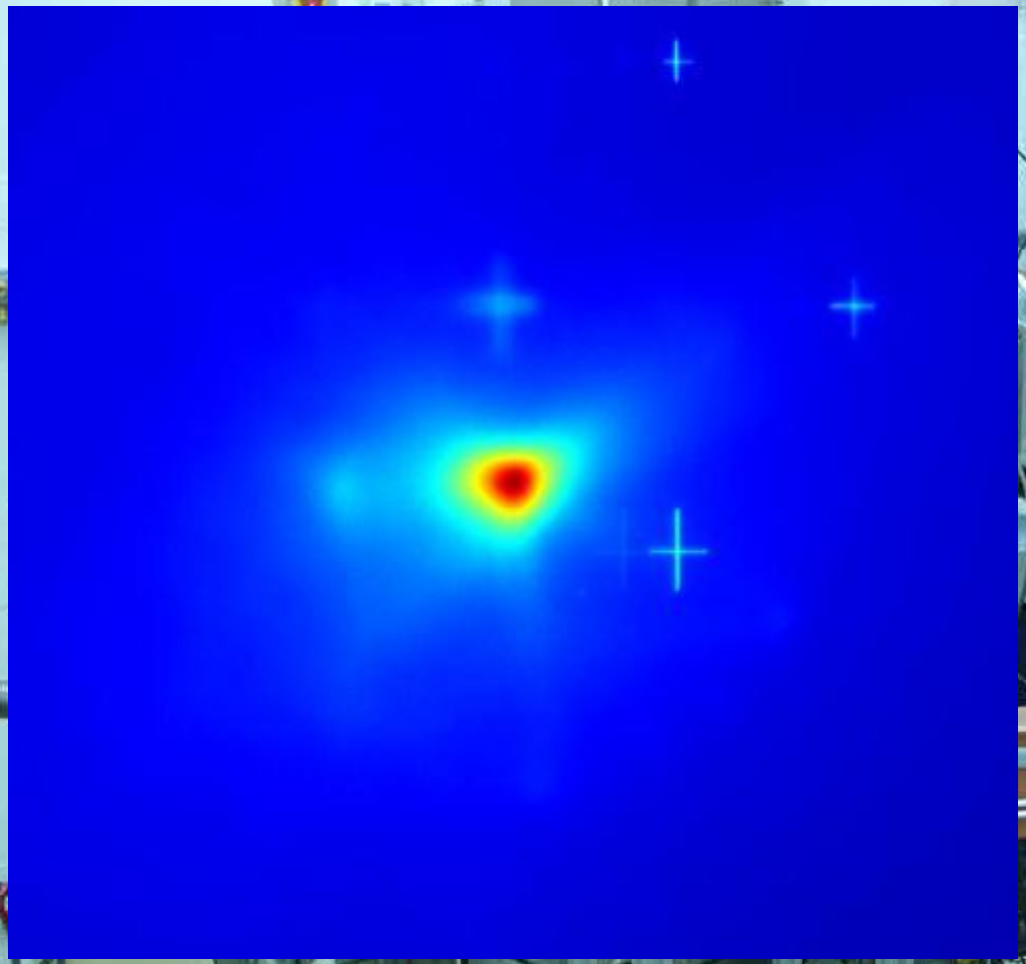


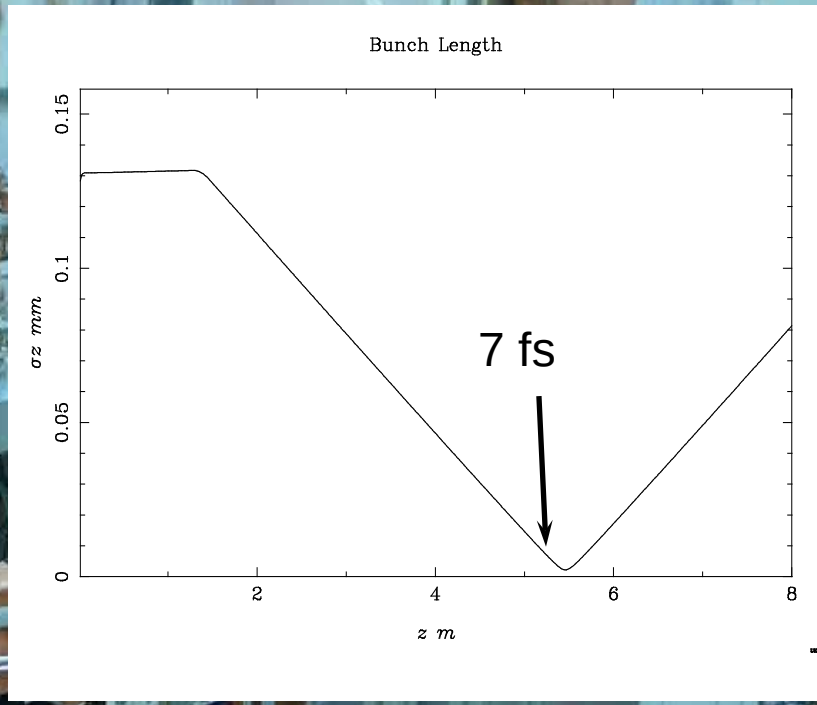






Þ equivalent diffracted particle flux to greater than 10^{11} 10+ KeV x-ray photons….4th Generation Light Sources



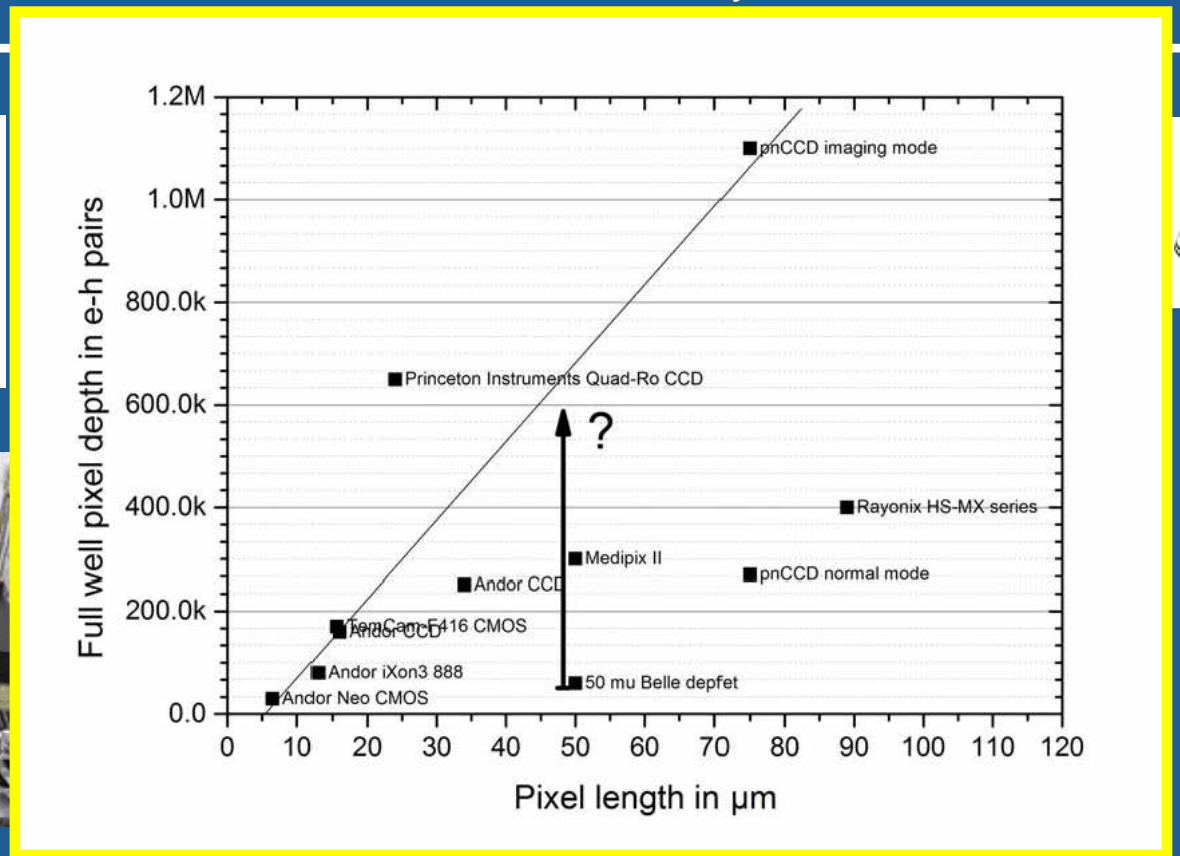


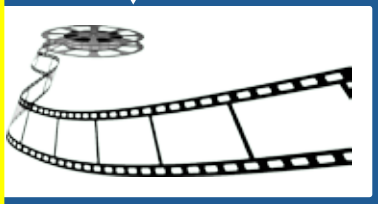
"First Light“ ¾ The very first shot gave a beautiful electron beam.

10^7 electrons/10 fs Þ single shot movies to capture even the fastest atomic motions….proteins, solution phase rxn dynamics, real space imaging of cells…..

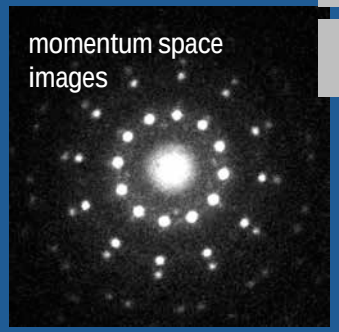
Detector specifications

Two different detector systems





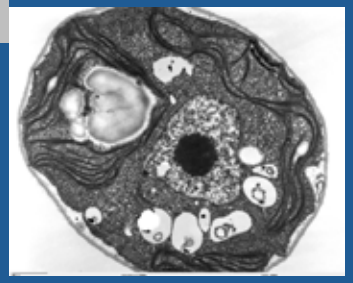
- Rainer Richter wants to do some VooDoo for Factor 5-10
- Might slow down the detector……



Operating temperature		ambient temperature
Primary e- energy range	80 keV-5 MeV	80 keV-350 keV
Range of Ø num. secondary e-	between 5k-12k	typically 1000 per 0.1 MeV

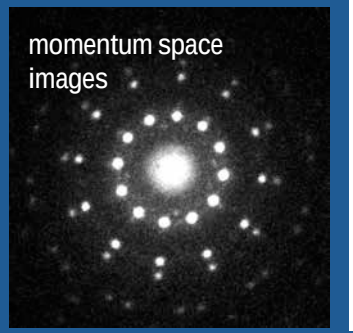
Table 2: Detector specifications.

Real space images



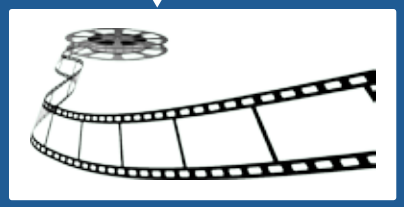
Detector specifications

Two different detector systems

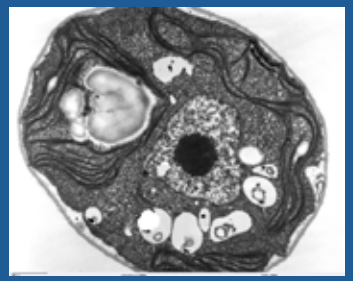


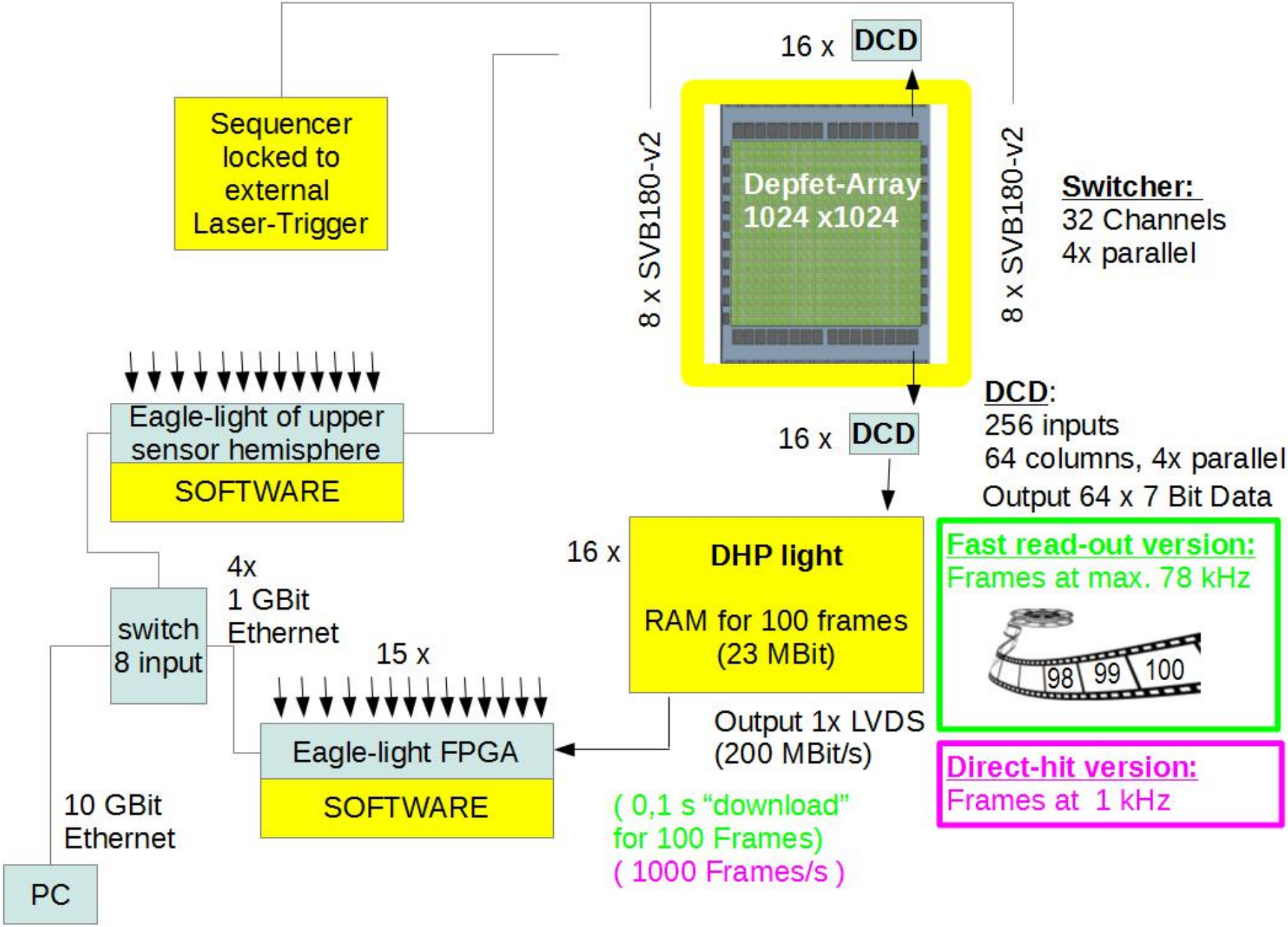
	Direct hit detector	Ultrafast detector
Sensor active area	(50 x 50) mm^2	
Sensor size in pixel	1000 x 1000	
Physical pixel size	50 µm (subject to change)	50 µm (subject to change)
Detection principle	DEPFET direct e- hit	DEPFET with scintillator
Read out mode	rolling shutter 4x	
Read out speed	>1000 Hz full frame rate (continuously)	~0.1 MHz full frame rate for 100 frames
Electronic noise contribution	100 e-	
Sensor thickness	50 µm (down to 30 µm possible)	450 µm
Pixel well depth (TCH)	60 000 (improvement is part of work package #1)	
Operating temperature	ambient temperature	
Radiation hardness (pixel)	10Mrad	protected
Primary e- energy range	80 keV-5 MeV	80 keV-350 keV
Range of Ø num. secondary e-	between 5k-12k	typically 1000 per 0.1 MeV

Table 2: Detector specifications.



Real space images




Sequencer locked to external Laser-Trigger
16 x DCD
8 x SVB180-v2
Depfet-Array 1024 x1024
8 x SVB180-v2
Switcher:
32 Channels
4x parallel
Eagle-light of upper sensor hemisphere
SOFTWARE
16 x DCD
DCD:
256 inputs
64 columns, 4x parallel
Output 64 x 7 Bit Data
16 x
DHP light
RAM for 100 frames (23 MBit)
Fast read-out version:
Frames at max. 78 kHz
98
99
100
4x 1 GBit Ethernet
switch 8 input
15 x
Eagle-light FPGA
SOFTWARE
Output 1x LVDS (200 MBit/s)
Direct-hit version:
Frames at 1 kHz
10 GBit Ethernet
(0,1 s "download" for 100 Frames)
(1000 Frames/s)
PC