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Anna Bergamaschi :: Photon Science Detector Group :: Paul Scherrer Institut

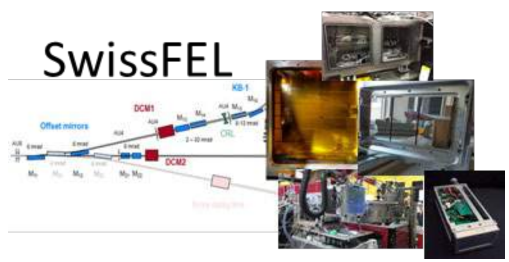
Position sensitive detectors for soft X-rays

Smart-X Symposium :: Trieste :: 7th April 2022

•Federal large scale research facilities

- Proton accelerator
- Muon accelerator
- Neutron source
- **Swiss Light Source**
- **SwissFEL**

The Photon Science Detector group



3

Synchrotron experiments

Light Source

Storage ring

Bending magnets

Insertion devices

Optics

Beamline

Monochromator

Mirrors

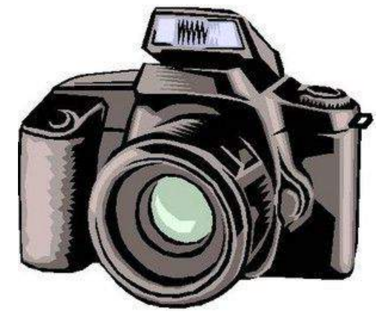
Sample

Preparation

Enviroment

Methods

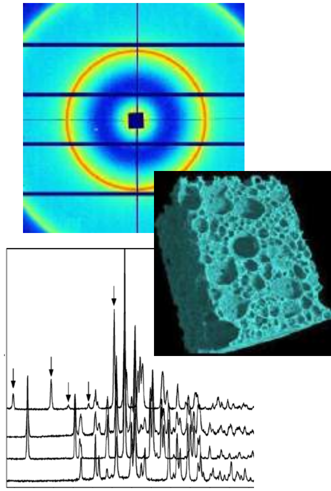
Detector



Position sensitive

Energy dispersive

Data



SCIENCE

Take home message

- The choice of the detector plays an important role for the success of your experiment
- Choose it wisely
- Use it properly

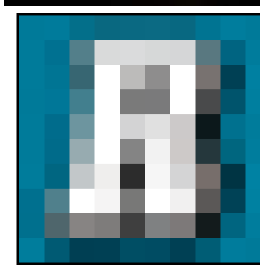
Detector figures of merit

Visibility → • Efficiency

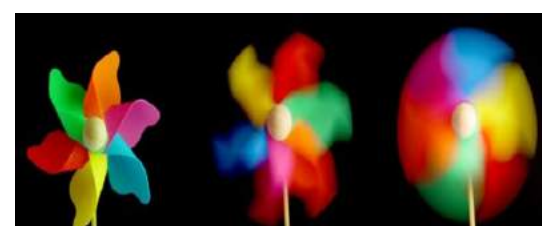
→ • Noise

Intensity → • Dynamic range

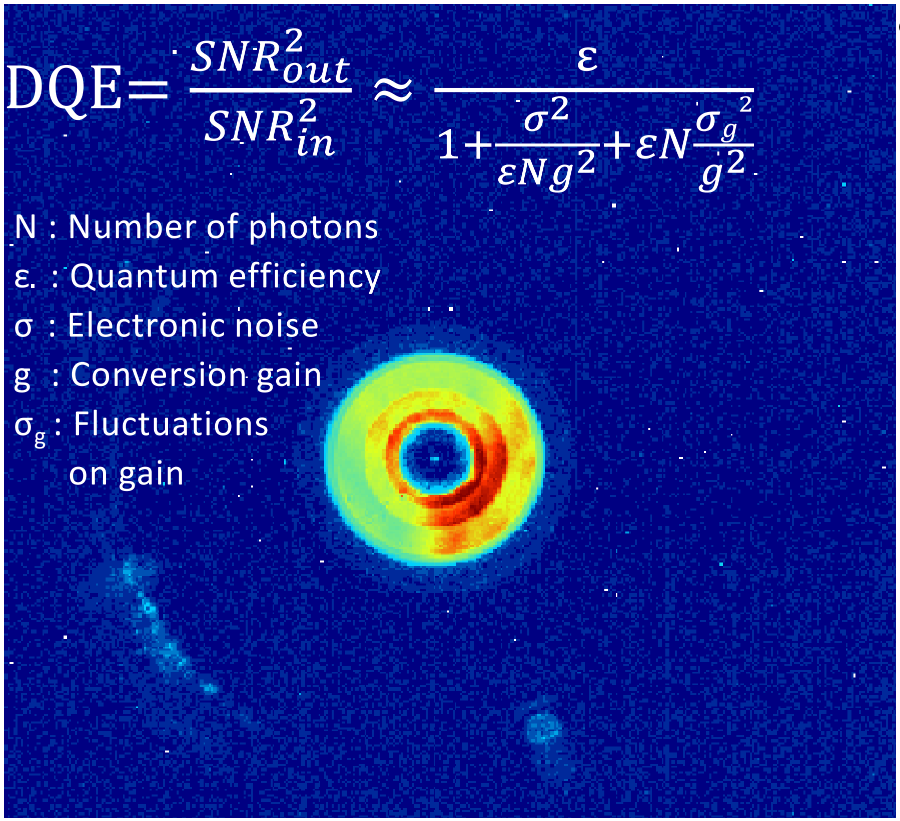
Position → • Segmentation



Time → • Speed



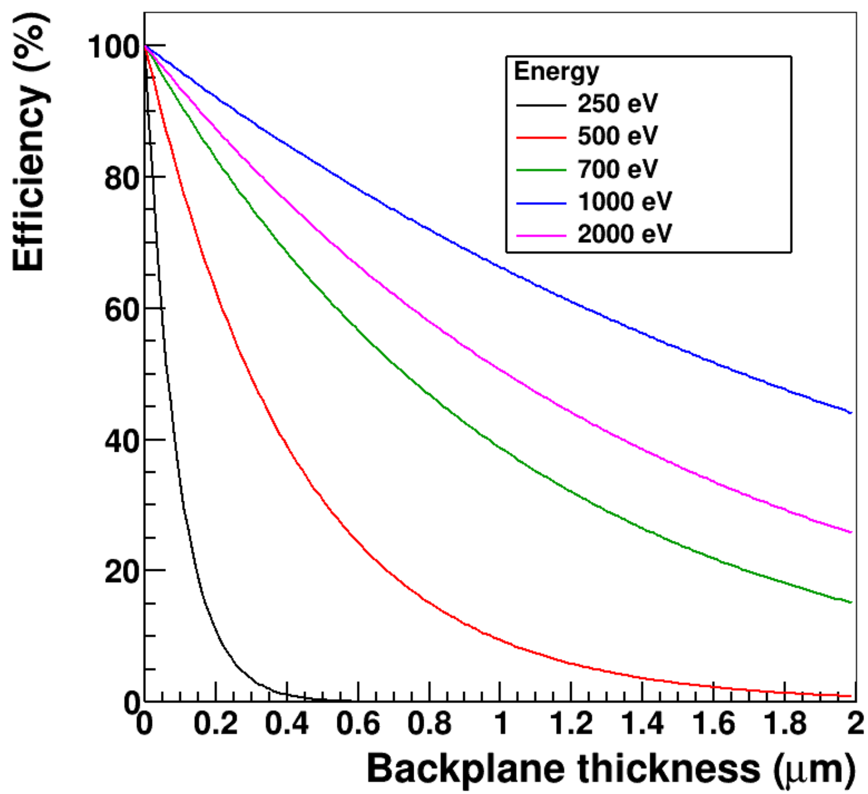
Detective Quantum Efficiency



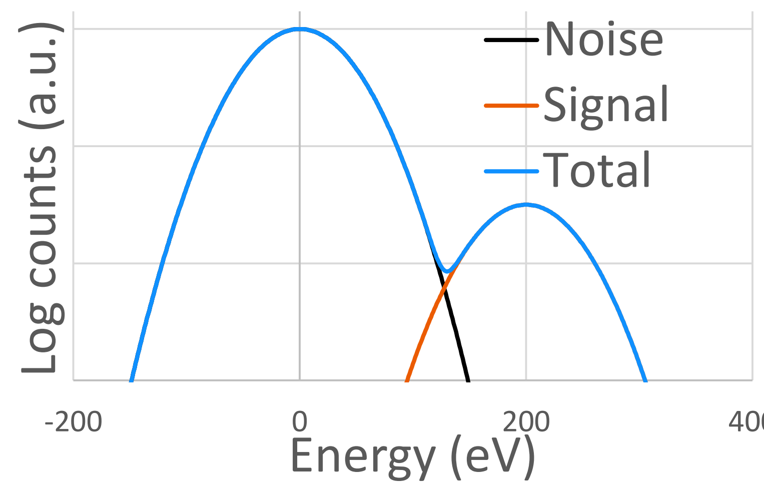
- The Detective Quantum Efficiency describes how well the detector makes use of photons
  - Proportional to the sensor Quantum Efficiency
  - Optimally Poisson limited on the whole dynamic range
    - Photon counting performance
  - Can be plotted as a function of energy, frequency, dynamic range…
  - Very difficult to compare between detectors!

DQE challenges for soft X-rays

- Shallow absorption
  - Poor quantum efficiency



- Small signal per photon
  - In silicon 3.6 eV / e-h pair
    - 1 keV γ generates ca. 280 e-h pairs
    - 200 eV generates < 60 e-h pairs
  - Low noise required to have single photon resolution
    - @1 keV σ_{noise}<60e- for SNR=5
    - @ 200 eV σ_{noise}≈10e- for SNR=5

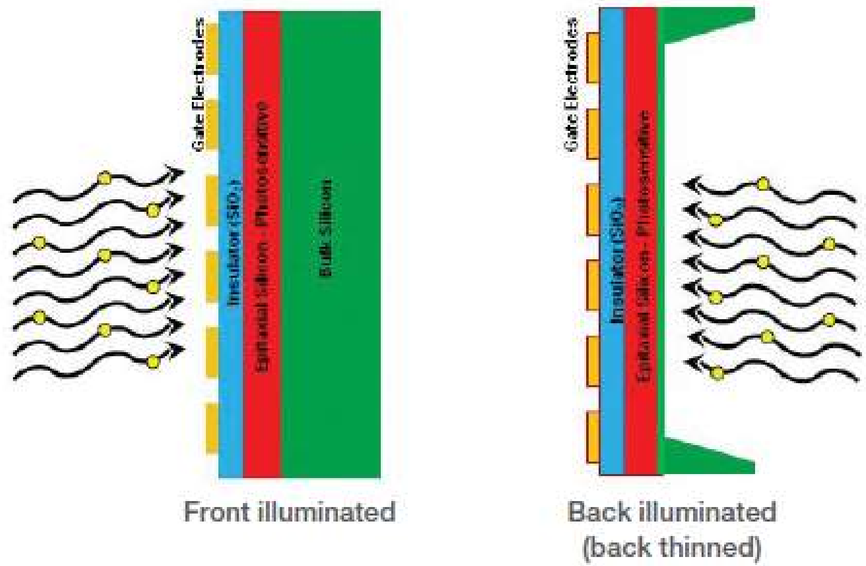


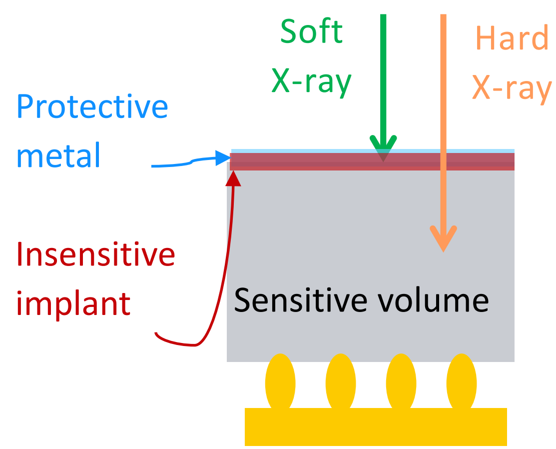
Front vs. back illumination

- Frontside illumination
  - Photons need to be transmitted through metal, implant, passivation
  - Fill factor < 100% for CMOS
  - Impossible for hybrid detectors

- Backside illumination
  - Full wafer depletion or back thinning
  - Low electric field region
    - Special processing to reduce charge recombination
  - Backplane needed to bias the sensor
    - Schottky implant, metallization

○ Metallization for light shielding?





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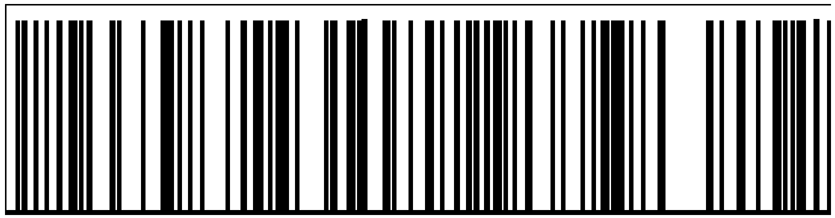
Photons are like chocolates…

Chocolate counting

Chocolate integrating

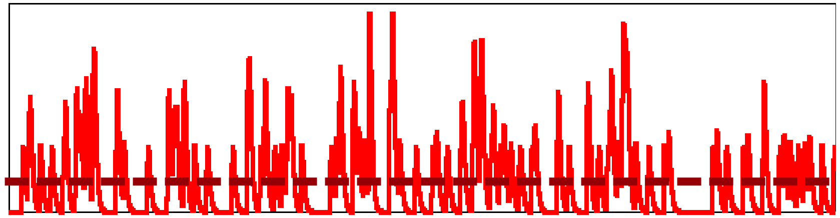
Read Out modes at continuous sources

Photons



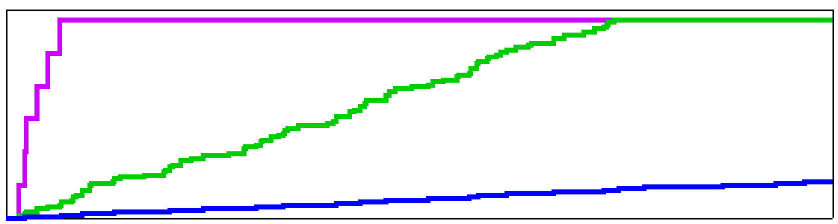
High and low flux on the detector

Photon counter



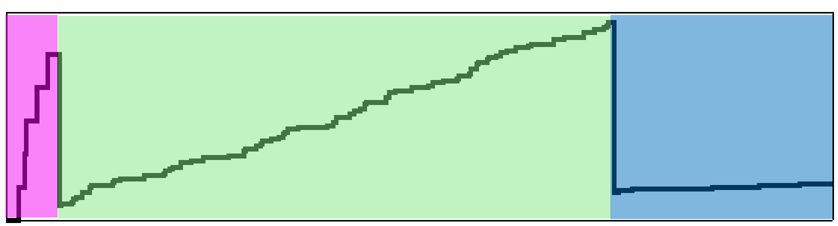
- ✓ Large dynamic range
- ✓ Background rejection
- × Minimum detectable energy
- × Pile-up at high fluxes

Charge Integrating



- ✓ No flux limitation
- ✓ Multiple low energy photons detectable
- × Limited dynamic range
- × Needs fast readout

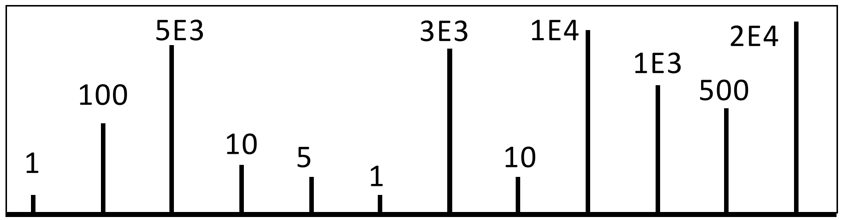
Charge Integrating with adaptive gain



- ✓ No flux limitation
- ✓ Multiple low energy photons detectable
- ✓ Large dynamic range
- × Challenging calibration

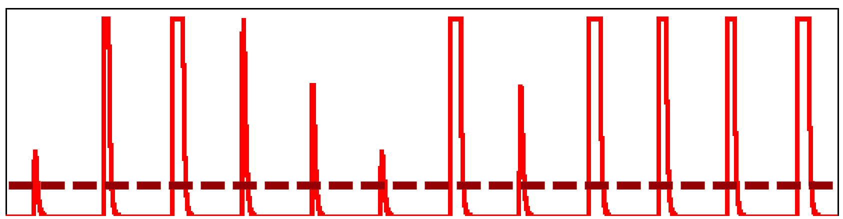
Read Out modes at pulsed sources

Log Photons



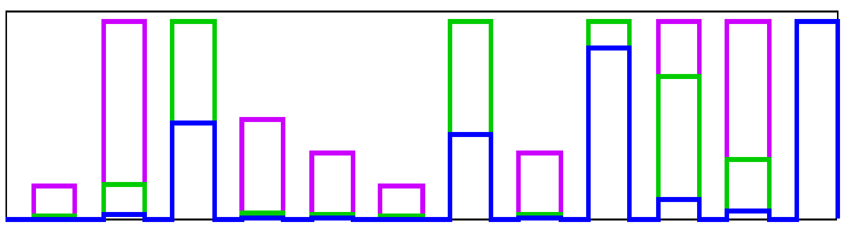
Photons arrive simultaneously

Photon counter



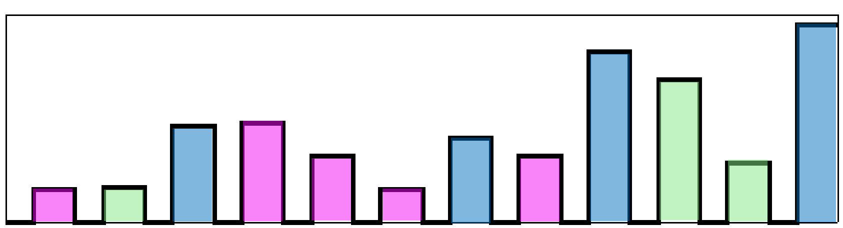
- ✗ Doesn't work

Charge Integrating



- ✗ Multiple low energy photons detectable
- ✗ Limited dynamic range

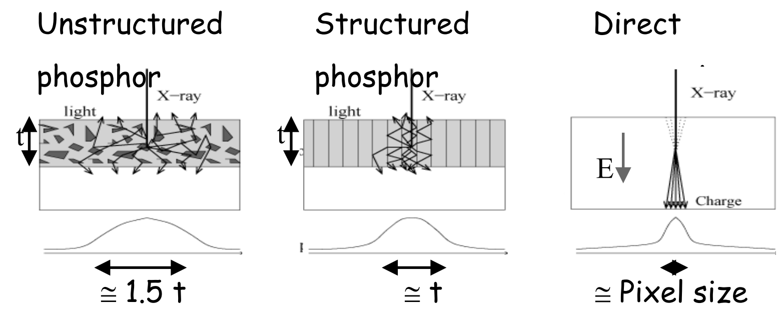
Charge Integrating with adaptive gain

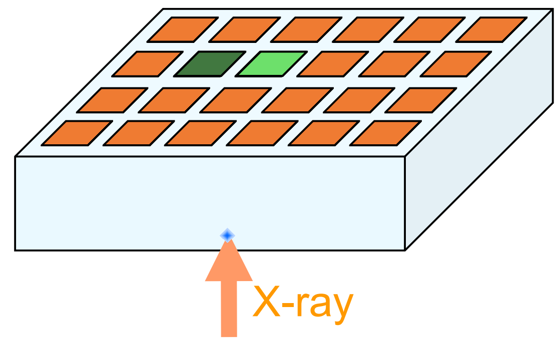


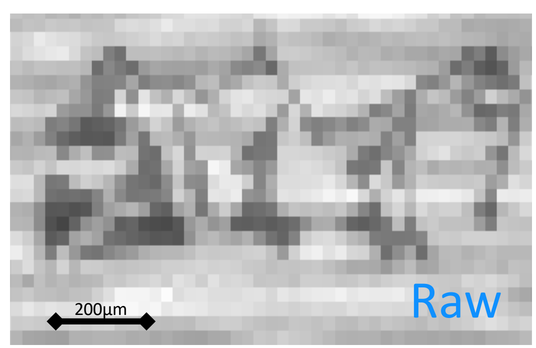
- ✓ Large dynamic range
- ✓ Multiple low energy photons detectable
- ✗ Challenging calibration

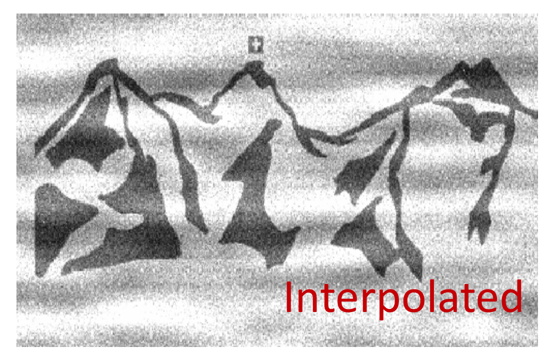
Spatial resolution is not pixel size!

- The spatial resolution is well described by the Point Spread Function
- Mainly depends on:
  - Pixel size
  - Photon conversion process
  - Charge collection speed
- Sub-pixel resolution can be obtained by interpolating the position "photon by photon"



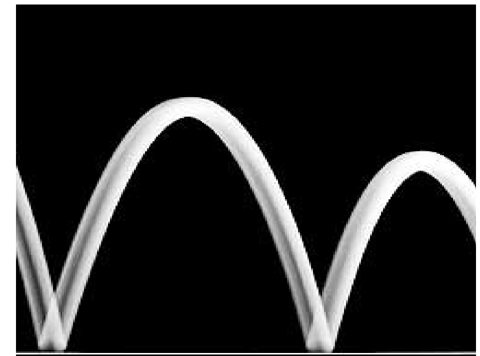


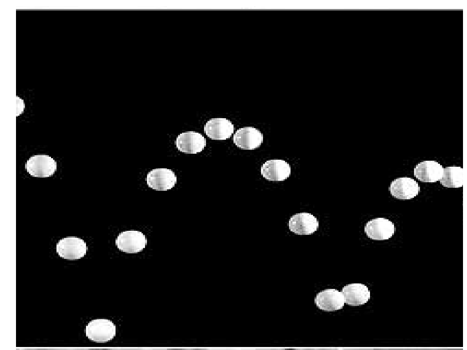




Time resolution

- Time resolution of the detector:
  - Frame rate
  - Response speed (charge collection time)
- At pulsed sources the time resolution is defined by the beam
  - Single shot measurements
    - Detector frame rate > beam rep rate
    - Low statistics, readout noise?
  - Stroboscopic measurements
    - Reproducibility
    - Time jitter





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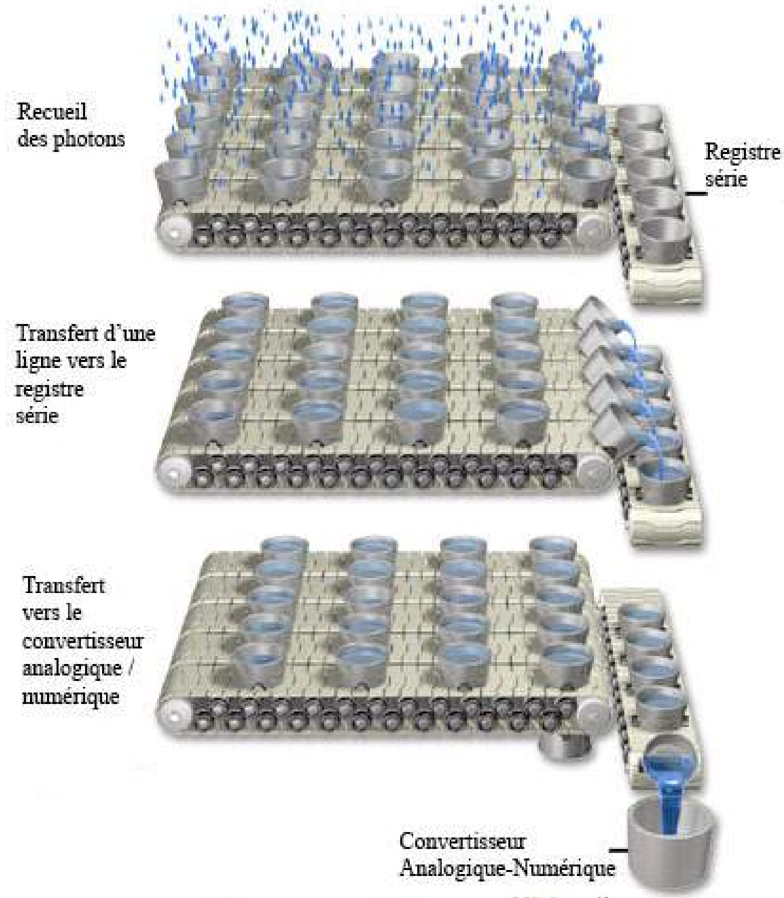
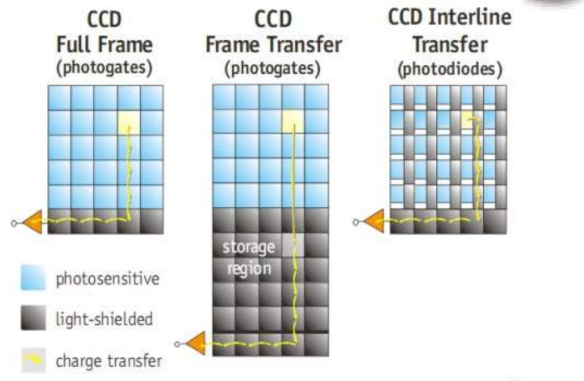
Summary 1

	CCD	CMOS	Hybrid
Quantum efficiency	😐	😐	😐
Single photon sensitivity	🙂	🙂	😐
Dynamic range	😐	😐	🙂
Spatial resolution	🙂	🙂	😐
Frame rate	☹️	😐	🙂
Area coverage	😐	😐	🙂
Radiation hardness	☹️	😐	🙂

Charge Coupled Device

- in 1969 by W.Boyle and E.Smith whom got a Nobel prize for it
- Collects photo-generated charges (electrons) under a bias electrode known as photo-gate
- The charge is shifted towards the readout by shifting the voltage on the electrodes
  - Requires a shutter!
  - Very low capacitance (and low noise!)
  - Readout noise (speed dependent)
  - Slow readout
    - Multi-port CCDs





Stat-of-the-art commercial CCD

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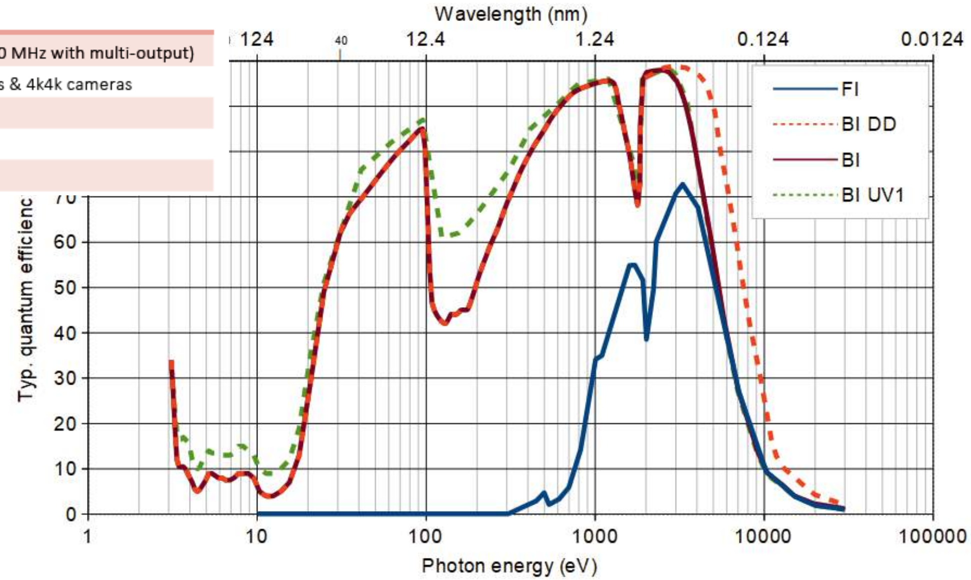
www.greateyes.de

Common specifications

Pixel readout frequency	50 kHz, 250 kHz, 1 MHz, 3 MHz (5 MHz for visualization mode; up to 20 MHz with multi-output)
Readout modes	2 output nodes for 1k1k & 2k2k cameras, 4 output nodes for 2k2k plus & 4k4k cameras
AD converter resolution	18-bit
Linearity	Better than 99%
CCD epitaxial thickness	15 µm standard, 40 µm for deep depletion (DD) models

ALEX-i Series	ALEX-i 4k4k	
Sensor code	BI	BI DD BI UV1
Usable pixels (columns × rows)	4096 × 4112	
Active image area	61.4 mm × 61.4 mm	
Pixel size	15 µm × 15 µm	
CCD sensor cooling	-90°C to 20 °C	
Full well capacity	150 ke⁻	350 ke⁻
Register well / Output node	- / 900 ke⁻	- / 600 ke⁻
Typ. read noise (e⁻) @ 50 kHz @ 1 MHz @ 3 MHz	 4.6 8.5 17.0	 2.8 5.8 10.4
Dark current (e⁻/pixel/s)	@ -90 °C 0.00008	 0.0006
Gain (counts/e⁻): Standard mode High capacity mode	 0.6 0.2	 1 0.34



4 output ports => readout time =npix/4/freq

Max signal: ca. 2500 photons/pixel @ 500 eV

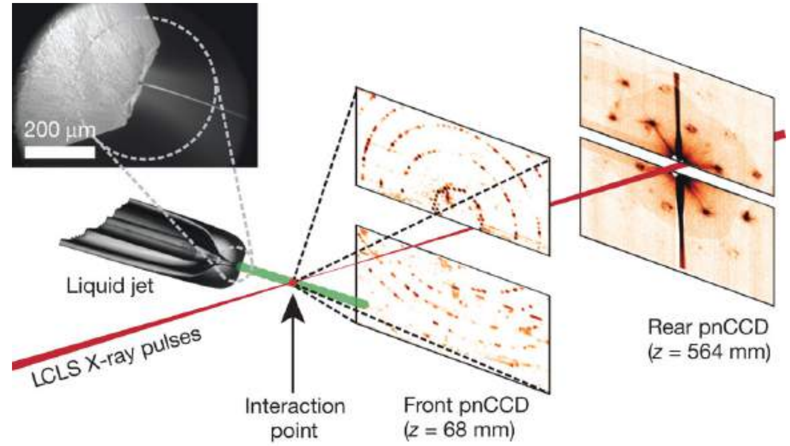
Min energy with single photon resolution=5xσx3.6 eV

50 eV @ 0.01 fps; 100 eV @ 0.2 fps; 190 eV @ 0.6 fps

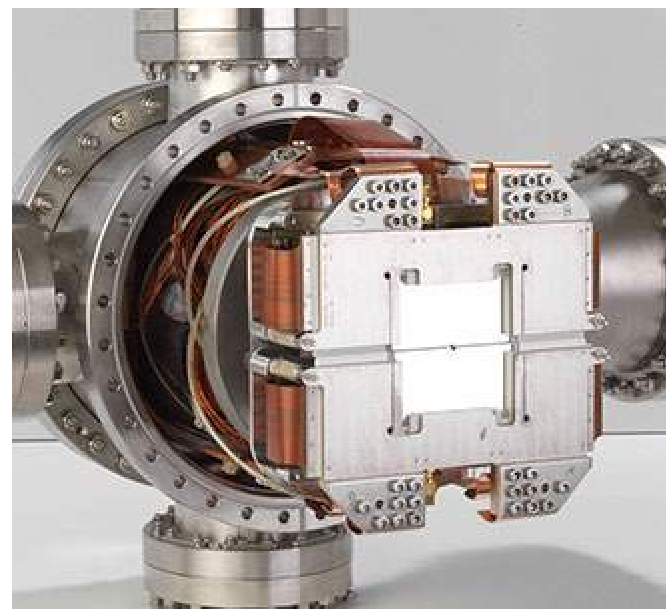
Low leakage current: long exposures possible with deep cooling

pnCCD: the CAMP chamber

Quantum efficiency	>80% range 0.3-12 keV
Pixel size	75 x 75 μm^2
System size	2048x2048 pixels 15.3 x 15.3 cm^2
Dynamic range	$5x10^5$ e-/pixel 10^3@2keV, 166@12keV
Energy range	0.05-25 keV
Energy resolution	2 e- (7.2 eV) high gain 20 e- (72 eV) low gain
Framing rate	200 Hz
External trigger/gate	5 V TTL



MPG HLL HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

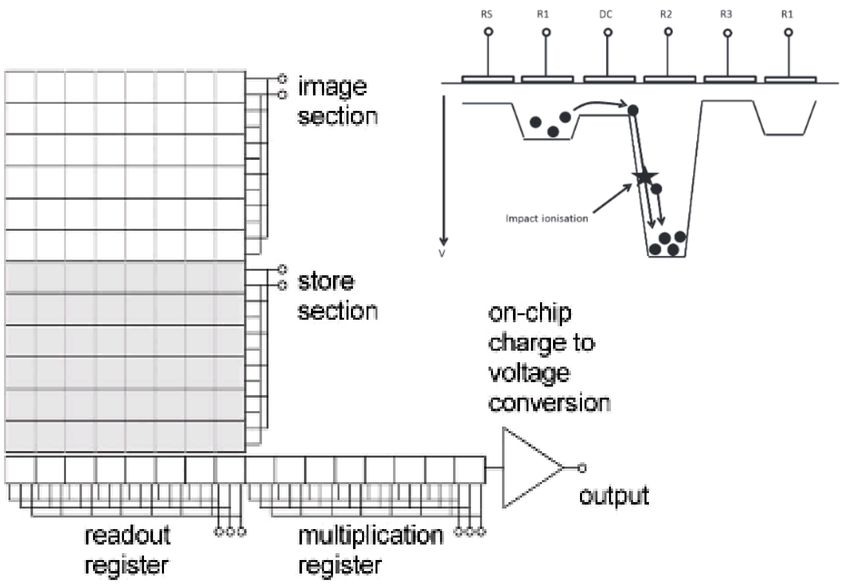


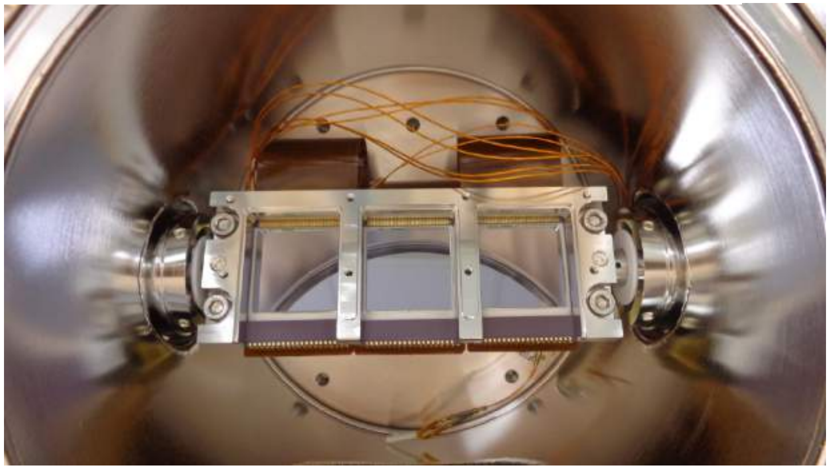
L. Strüder et al.,NIM A, 614(3), 2010, 483–496. doi:10.1016/j.nima.2009.12.053.

HN Chapman *et al. Nature* **470**, 73-77 (2011) doi:10.1038/nature09750

Electron Multiplying CCD

Detector type	EM-CCD
Area	40 mm x 40 mm
CCD pixel size	13um x 13um
Number of pixels	1024 x 1024
Readout noise	<1 e-
Full well capacitance	80 ke-
Cooling type	Thermo-electric Cooler or Peltier

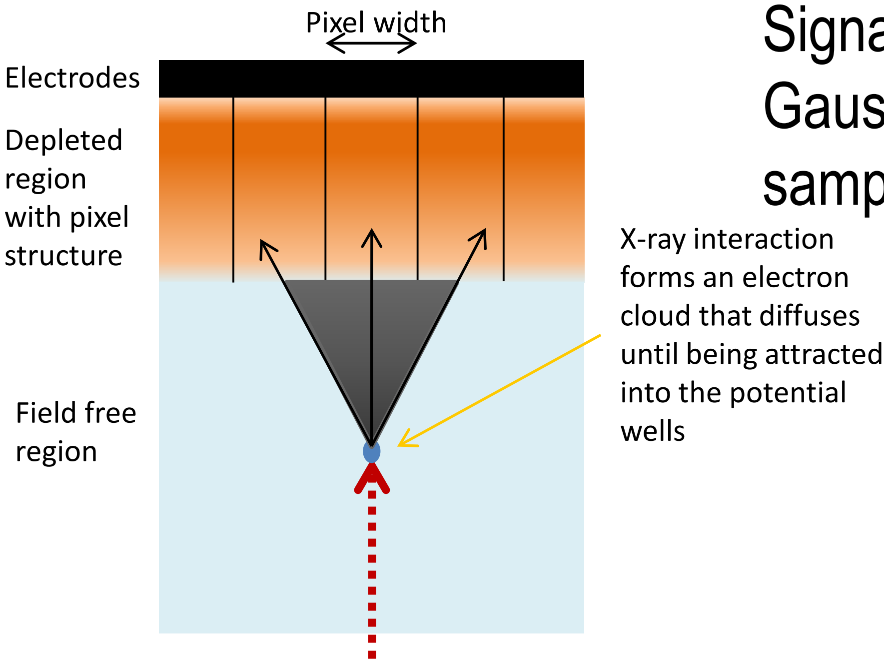




Tutt et al., (2014). Electronics Letters, 50(17), pp. 1224–1226

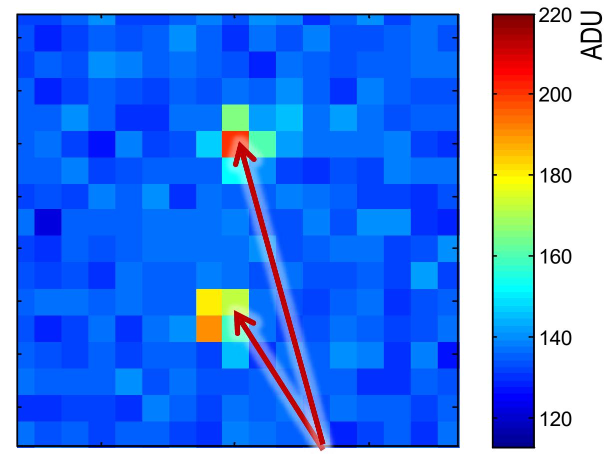
Tutt et al., (2012) IEEE Trans. Electr. Dev., 59(1), pp. 167-175

CCD Soft X-ray interpolation



Soft X-ray is incident on 'back surface' of Back Illuminated device

Signal electrons are spread in a 2D Gaussian-like distribution that is sampled by the pixels.



Single X-ray photon events with their total signal spread over multiple neighbouring pixels

- Possible to improve spatial resolution to around **2 µm** by centroidng single photon events

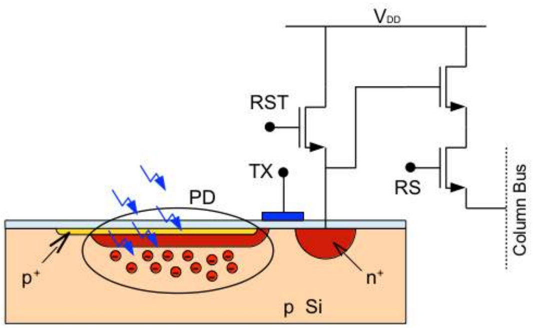
Hall et al., Jour. Inst. 7, C01063 (2012) DOI: 10.1088/1748-0221/7/01/C01063

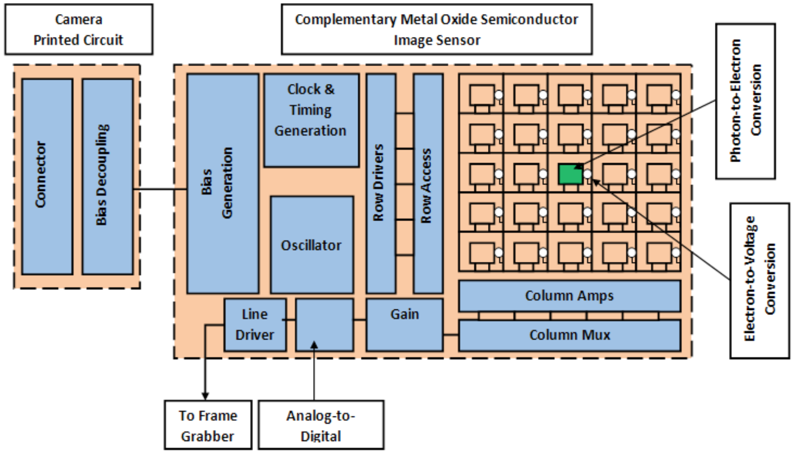
Soman et al., Nucl. Instr. Meth Phys. Res. A 731, 47-52 (2013). DOI: 10.1016/j.nima.2013.04.076

Soman et al., Jour. Inst. 8, C01046 (2013). DOI: 10.1088/1748-0221/8/01/C01046

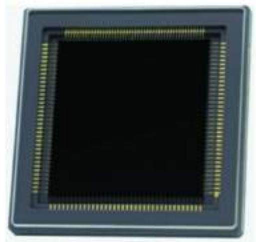
CMOS imagers

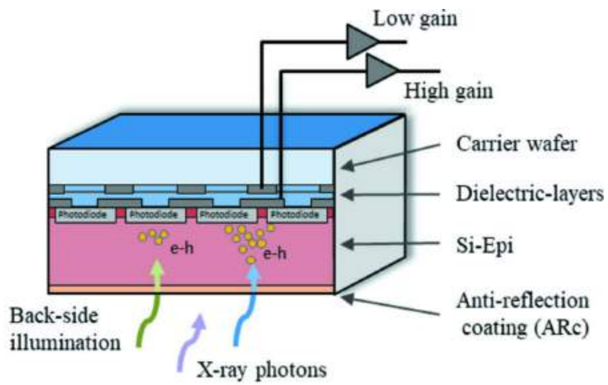
- Invented around 1968 by P. Noble
  - Based on active pixels (CMOS transistors)
- Large fraction of the pixel is (was) occupied by the transistors
  - Low fill-factor in front illumination
- Fully depleted CMOS imagers are emerging for hard X-rays
  - For soft X-rays usually back-thinning
- In principle full wafer imagers possible (but low yield forback-thinning)
- Each pixel can be addressed separately (ROI, high speed)
- Global or rolling shutter possible





State-of-the-art commercial CMOS





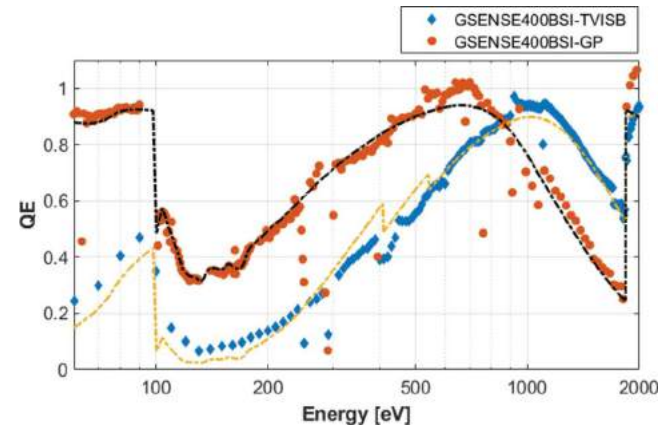
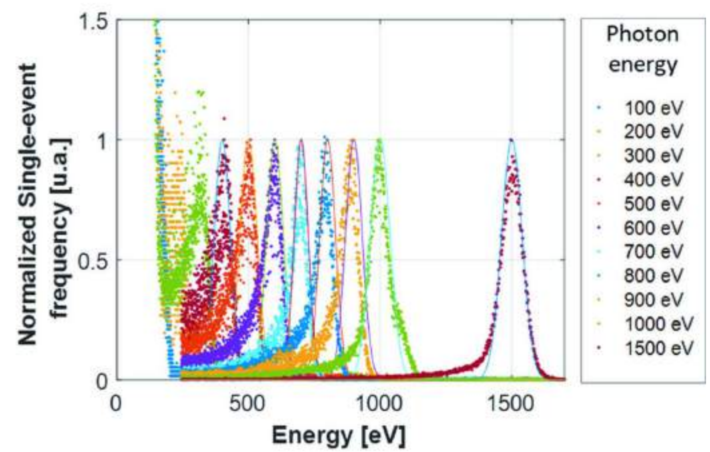


Table 1
Electro-optical characteristics of the GSENSE400BSI sensor specifications and TUCSEN Dh

	Symbol	Value
Gain	K	LG, HG or HDR mode
Frame rate	frames s^{-1}	24 Hz full frame (HDR), 48 Hz full frame (LG or HG)
Readout architecture		Rolling shutter
Pixel size	pixel	11 µm × 11 µm
Sensor size		4 Mpixel, 2048 × 2048 pixels (22.5 mm × 22.5 mm)
Exposure time	t	20 µs–10 s
Binning		No
Readout noise	σ_{read}	<2 e^- r.m.s. (HDR and HG) and <45 e^- r.m.s. (LG)
Dark current	μ_{dark}	~3 e^- s^{-1} $pixel^{-1}$ (−20°C)
Full well capacity	FWC	30 ke^- (HDR), 1700 e^- (HG) and >80 ke^- (LG)
Spatial pixel offset noise	DSNU	<5 e^-
Spatial pixel gain noise	PRNU	<1%



Compromise between noise and maximum intensity

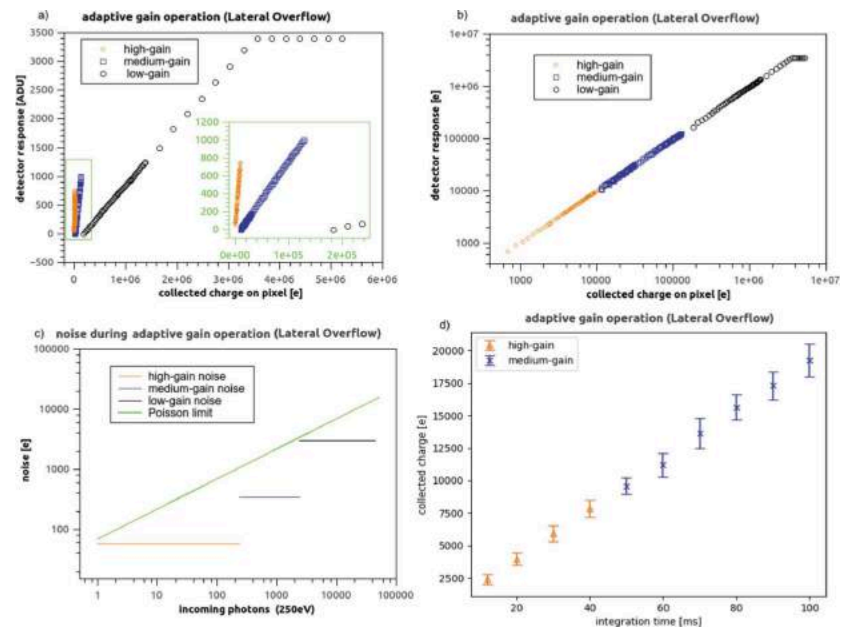
JSR JOURNAL OF SYNCHROTRON RADIATION

Desjardins *et al.* Volume 27 | **Part 6** | Novemeber 2020 | Pages 1577–1589 |
10.11107/S160057752001262X

PERCIVAL: CMOS imager for XFELs

Table 1
Summary of the main performance parameters.

Pixel array	2089472 pixels (+ references), 27 µm pitch
Frame rate	Tested: up to 83.3 frame s^{-1} (design goal: >120 frame^{-1} s^{-1})
e/ADU	Very high gain: 2.1 e/ADU High gain: 12.6 e/ADU Medium gain: 106.0 e/ADU Low gain: 944.2 e/ADU
Noise	Very high gain: 16.1 e ± 2.4 e (~0.23 ph @ 250 eV) reduced <15 e by CMA High gain: 52–82 e ± 15 e (0.75–1.18 ph @ 250 eV) Medium gain: 343 e ± 73 e (~4.95 ph @ 250 eV) Low gain: 3.0 ke ± 638 e (~43 ph @ 250 eV)
One-photon sensitivity: $P(1\|0) < 10 \times 10^{-6}$	350 eV photons and above (very high gain)
Full well (fixed-gain operation)	Very high gain mode: ~5.75 ke ± 585 e (~83 ph @ 250 eV) High-gain mode: 30.5 ke ± 2 ke (~439 ph @ 250 eV) Medium-gain mode: 381 ke ± 17.6 ke (~5.5 kph @ 250 eV) Low-gain mode: 3.56 Me ± 169 ke (~51 kph @ 250 eV)
Adaptive-gain dynamic range (lateral-overflow)	High → medium gain: 16.4 ke ± 6.1 ke (~236 ph @ 250 eV) Medium → low-gain: 165.5 ke ± 23 ke (~2.4 kph @ 250 eV) Low gain (full well): 3.09 Me ± 201 ke (~45 kph @ 250 eV)



JOURNAL OF SYNCHROTRON RADIATION

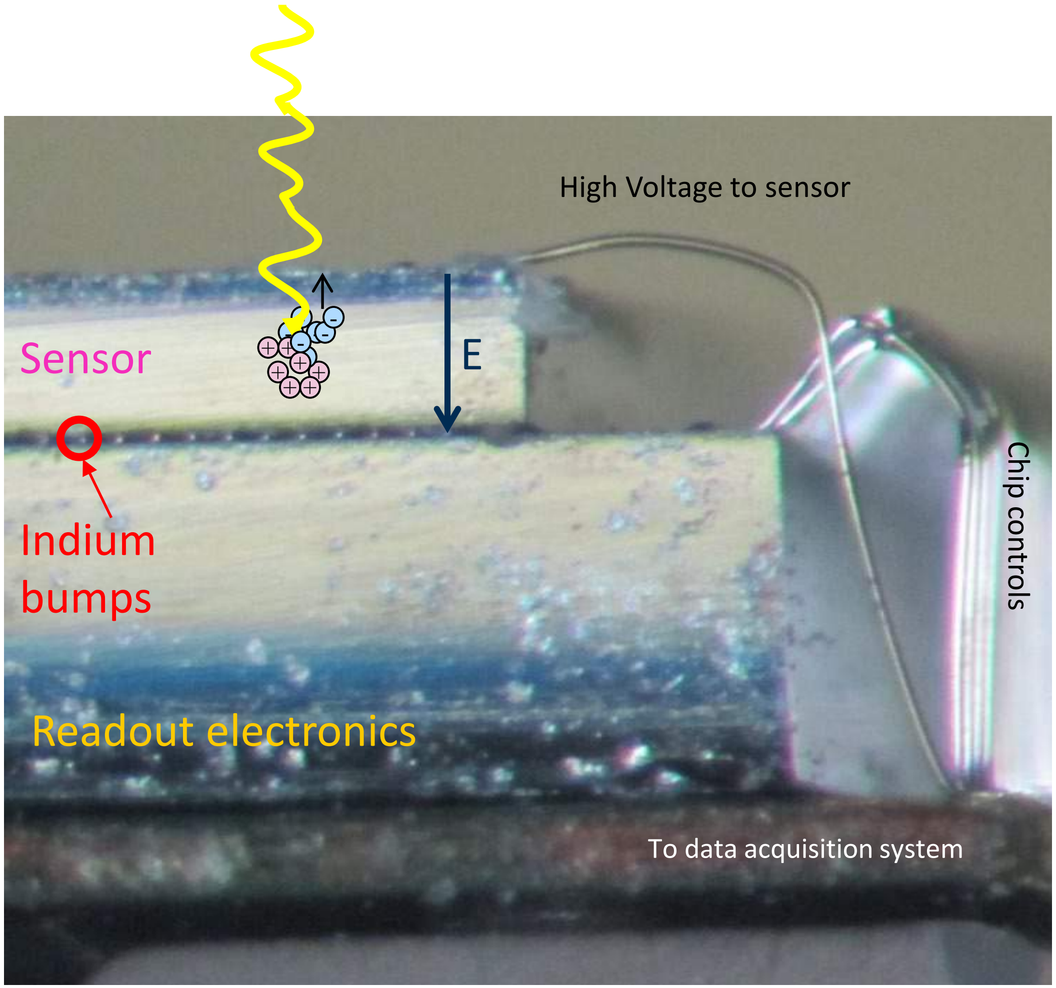
- **Marras *et al.***
- **Volume 28** | **Part 1** | January 2021 | Pages 131–145 | 10.11107/S1600577520013958

Hybrid detectors

Sensor and readout electronics can be optimized separately

- ✓ Direct conversion in semiconductor
- ✓ Fast drifting of charge to the pixel
- ✓ Room temperature operation
- ✓ Fast highly parallelized readout

- ✗ Interconnection (bump bonding) limits the pixel pitch
- ✗ Input capacitance increases the electronic noise



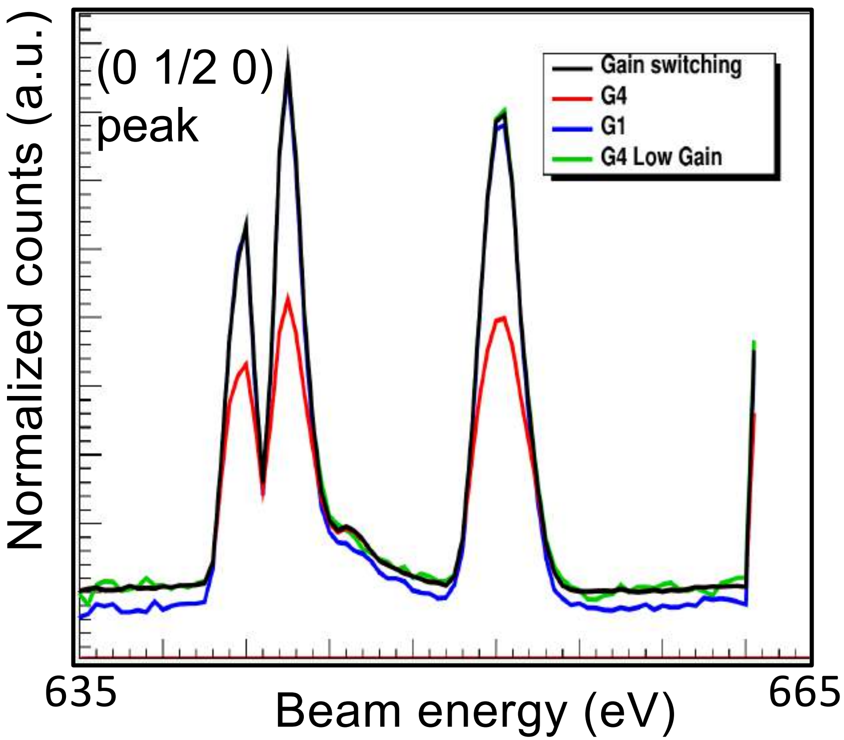
Since 15 years state of the art in hard X-ray applications: diffraction, ptychography…

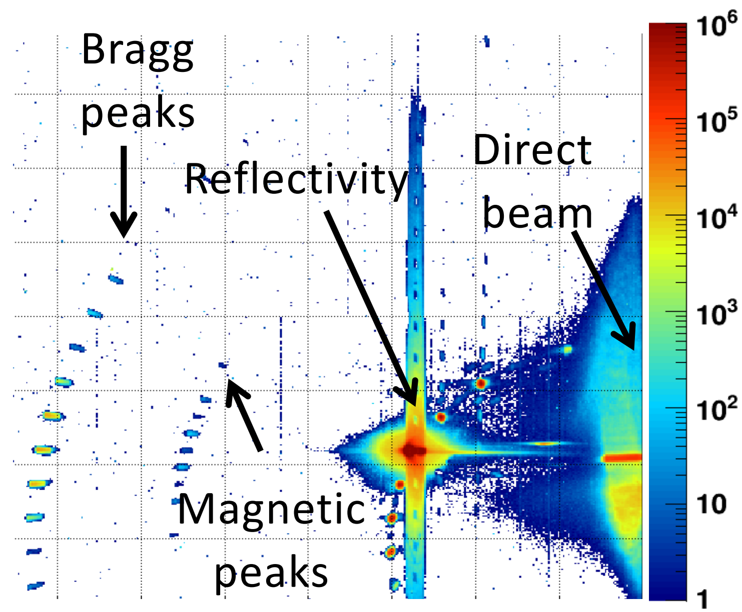
Resonant diffraction

V. Scagnoli, U. Staub, RESOXS endstation, SIM beamline SLS

- No radiation damage even in case of saturation
- Large dynamic range by dynamic gain switching

ErMnO3 film on NdGaO3 substrate





Artificial spin ice, 708 eV

Resonant diffraction

V. Scagnoli, U. Staub, RESOXS endstation, SIM beamline SLS

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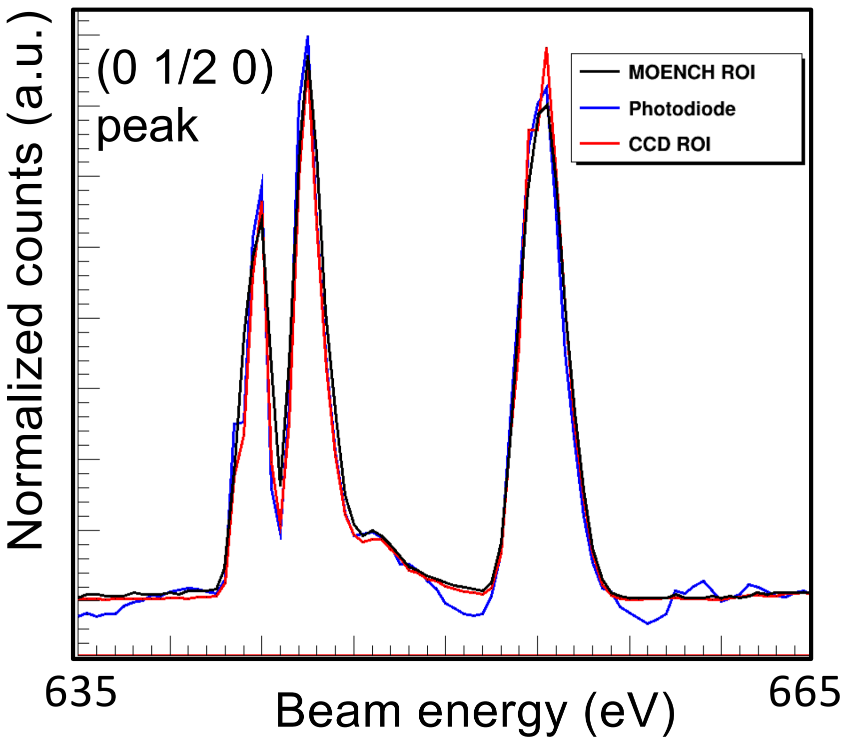
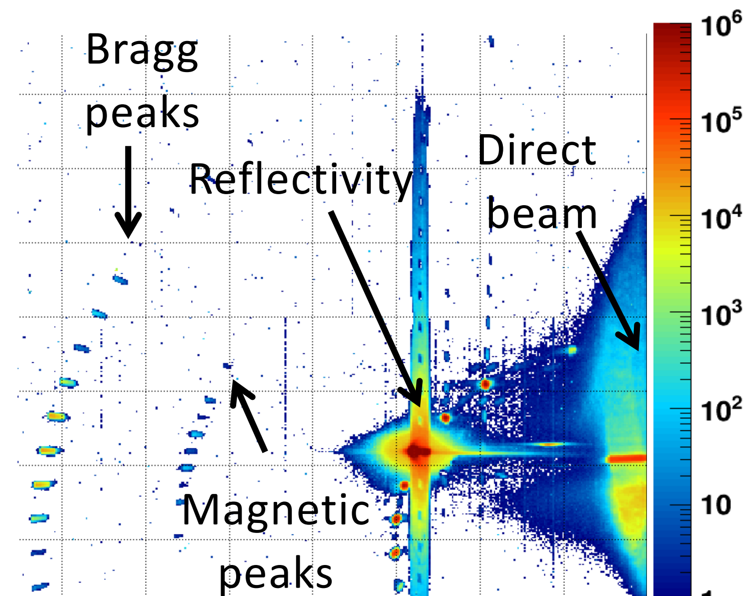
ErMnO3 film on NdGaO3 substrate

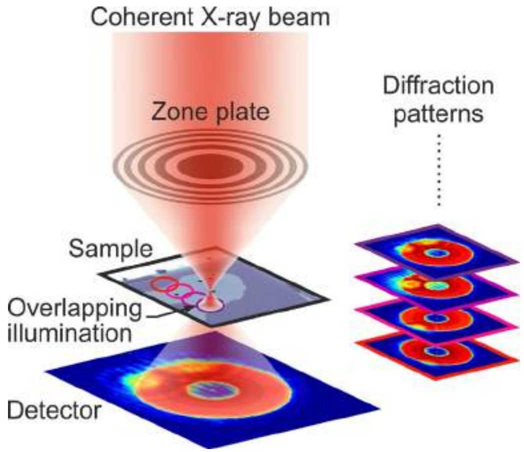




Artificial spin ice, 708 eV

Soft X-ray ptychography

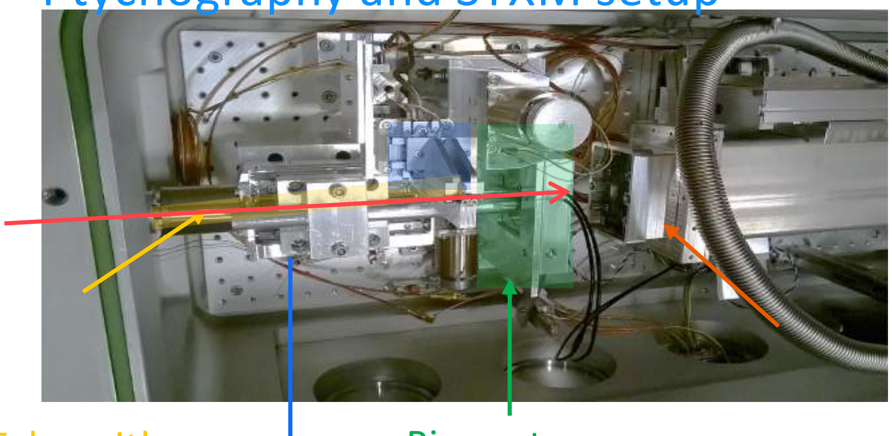
M. Langer, J. Raabe, A. Kleibert et al., SIM beamline SLS

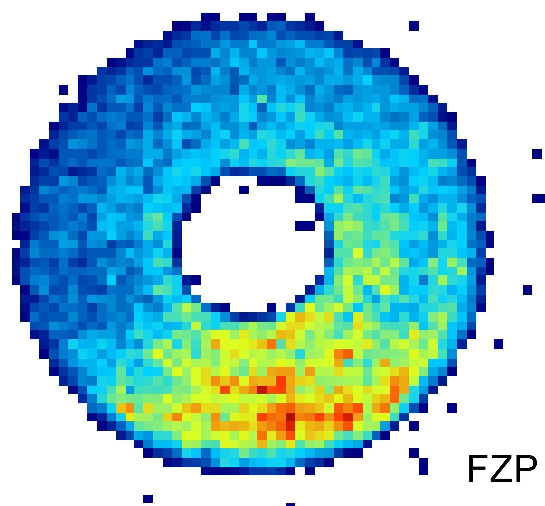


©M. Langer

- Fast frame rate allows rapid scanning and monitoring of the experiment
- No fast shutter required during acquisition

Ptychography and STXM setup





1 kHz movie reveals vibrations

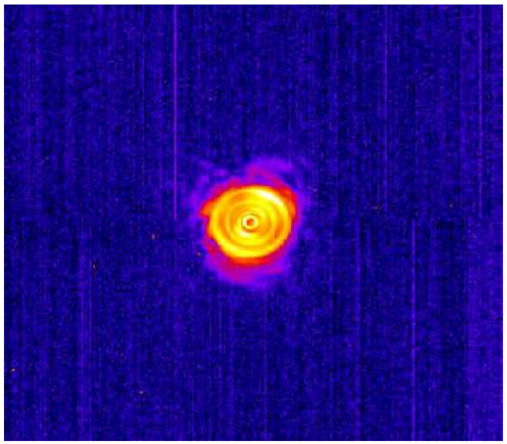
M. Langer et al. (2018) *Microsc. Microanal.* 24, 56.

Preliminary results

M. Langer, J. Raabe, A. Kleibert et al., SIM beamline SLS

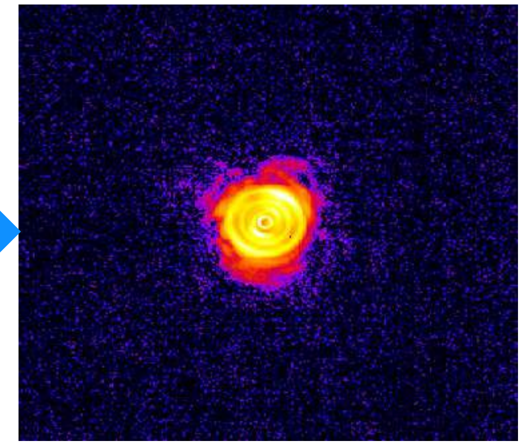
Sample $BiFeO_3$ nanoplatelets, energy 709 eV

©M. Langer

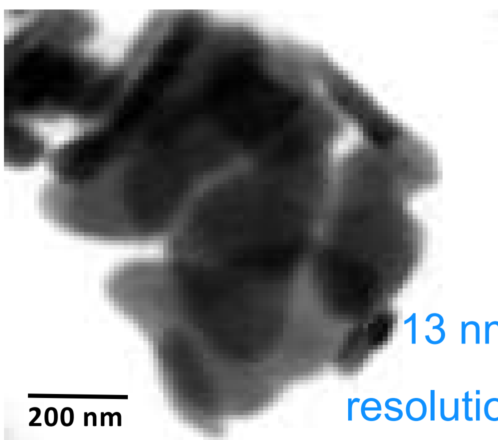


Background due to fixed pattern and readout noise

Detector image

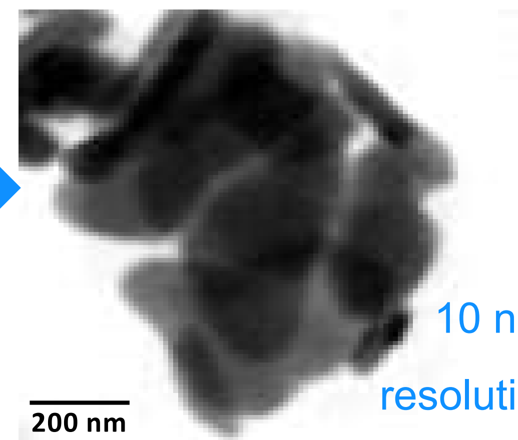


Noise removed using reference image at borders



13 nm resolution

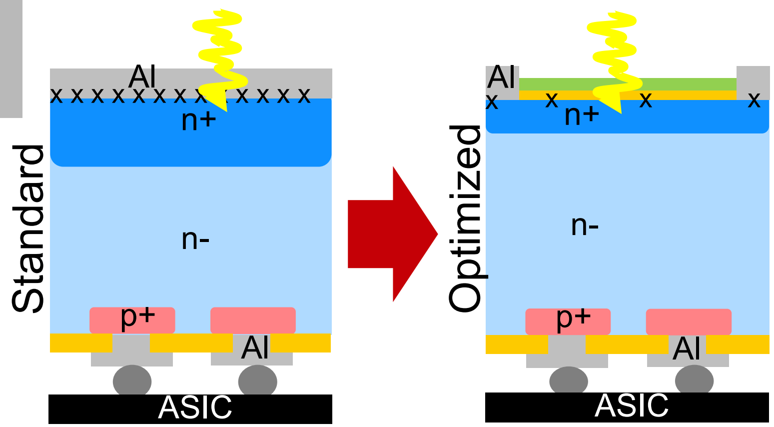
Reconstruction

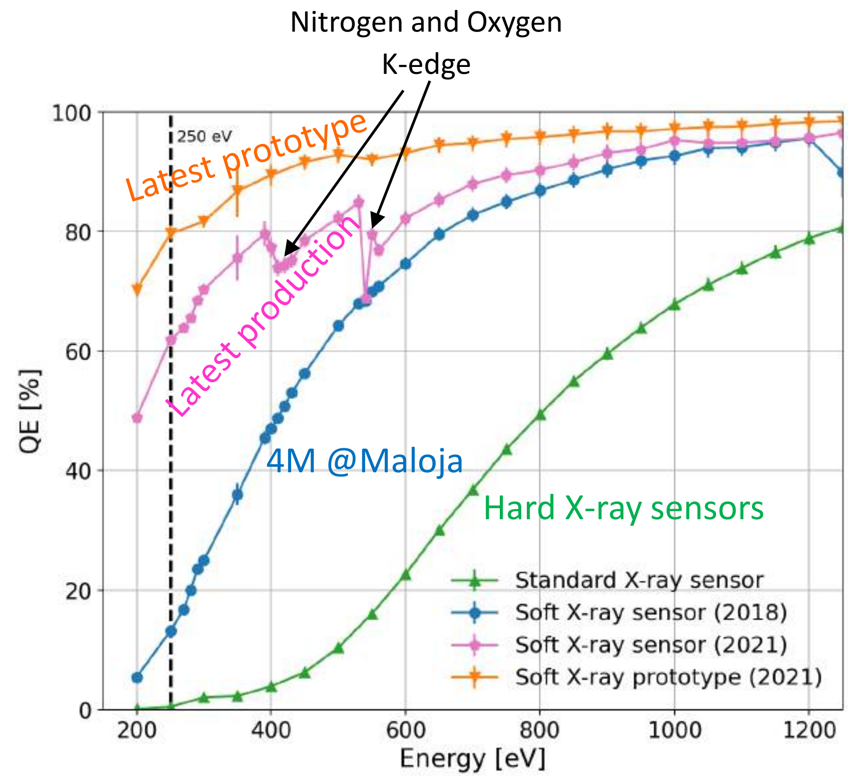


10 nm resolution

Cross pixel calibration could still improve performance

Quantum efficiency for soft X-rays





>80% efficiency above 250 eV

Shallow absorption of soft X-rays

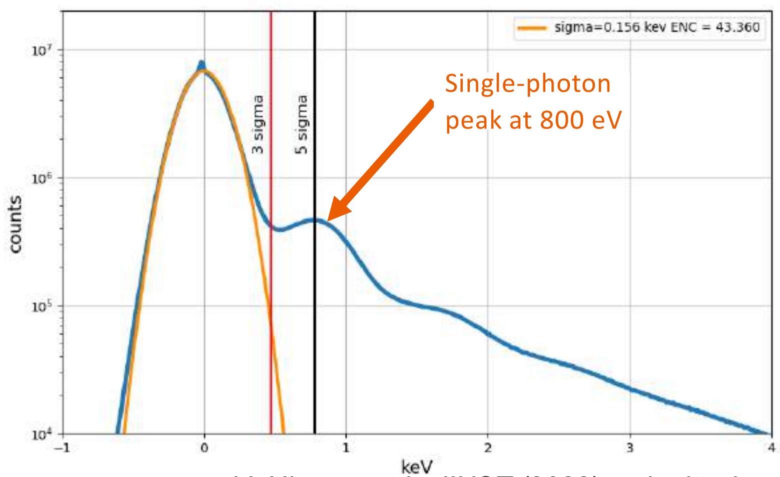
- Requires optimized entrance window technology
  - Reduce the thickness of the layers above silicon
  - Decrease the charge recombination in the silicon interface layer
  - Reduce the charge recombination in the highly doped implants

M. Carulla, J. Zhang et al., unpublished.

Single photon resolution at low energies

- Reduction of electronic noise
  - Noise reduced in JUNGFRAU 1.1 from 52 e- to 34 e- rms (< 2/3)
  - Single photon resolution down to ≈800 eV
  - Less than 10 e- noise rms required for single photon resolution at 200 eV

Cumulative energy spectrum in high gain (1000 frames all pixels)



V. Hinger et al., JINST (2022), submitted.

- Segmented Low Gain Avalanche Diodes (LGADs)
  - Sensors with internal amplification
  - Increase SNR of single photons
  - Gain on the backplane to achieve 100% fill factor (iLGAD)
  - Must be combined with high QE for soft X-rays
  - First batch optimized for soft X-rays ready for testing
  - Soft X-ray single photon counters and RIXS with interpolation?

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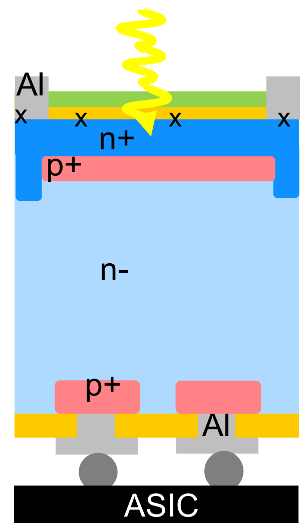
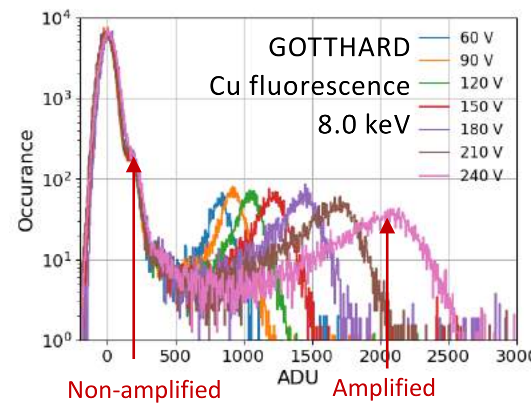
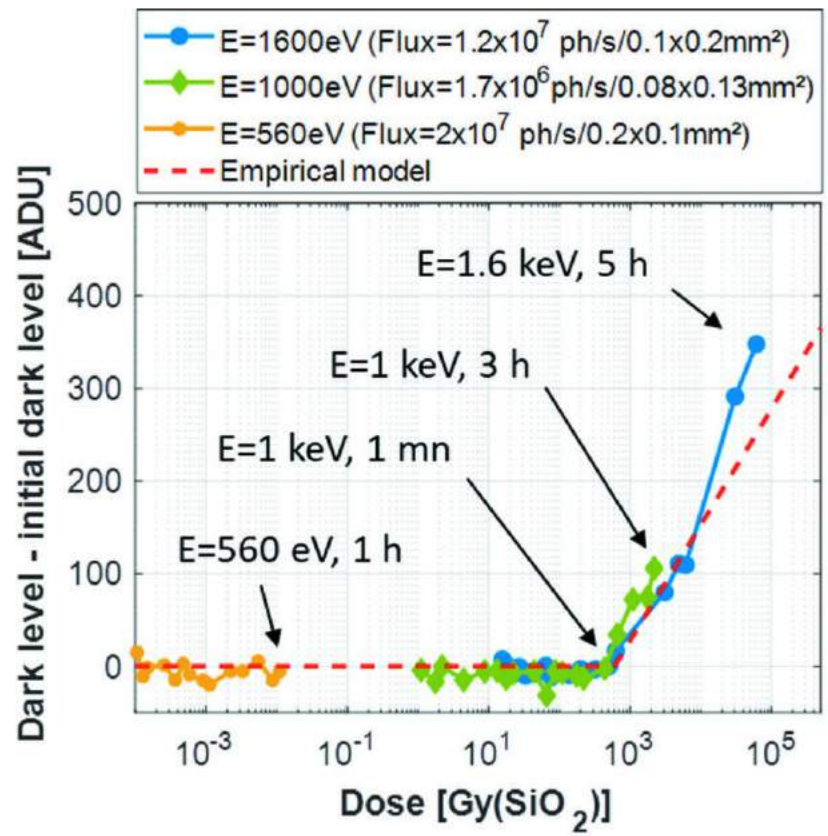




Andrä, Zhang et al., Jour. Synch. Rad. 2019.

Radiation Damage

- CCD and CMOS detectors are quite radiation sensitive
  - Improves with back illumination and sensor thickness
  - Less damage at low energies
  - Can survive ca. 100-1000 Gy
  - Rad-hard design could be implemented in CMOS imagers
- The radiation sensitive structures of hybrid detectors are shielded by ca. 300 µm of silicon
  - Can survive MGy also for hard X-rays
  - Rad hardness of LGADs needs to be studied

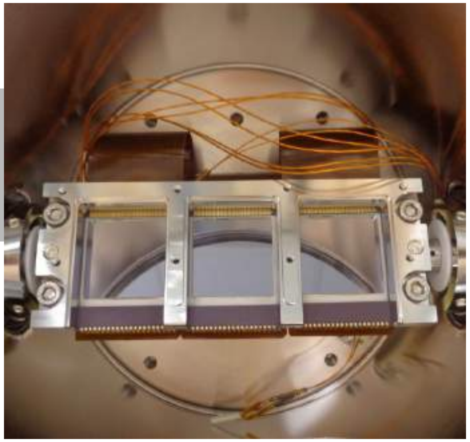
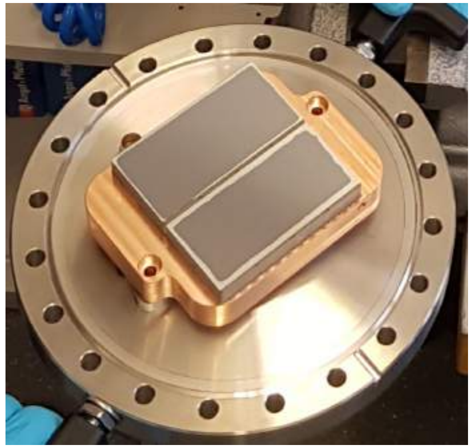
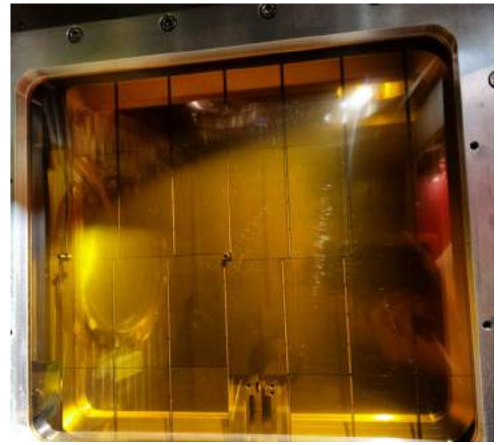
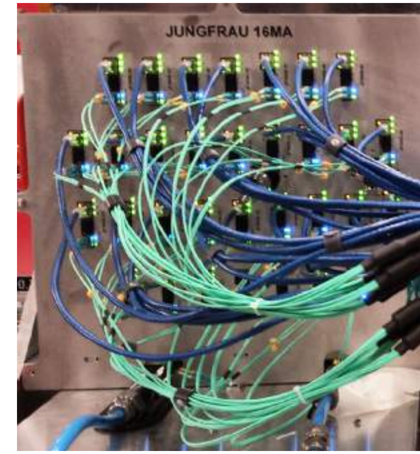


JOURNAL OF SYNCHROTRON RADIATION

Desjardins *et al.*

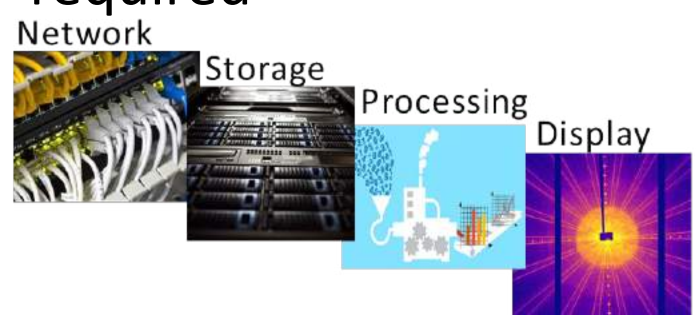
Volume 27 | **Part 6** | Novemeber 2020 | Pages 1577–1589 |
10.11107/S160057752001262X

Large field of view

- Vacuum barrier between sensor and DAQ for vacuum compatibility
  - Density of feedthroughs
  - Movement of the detector
- Temperature control
- Tiling of modules required for larger field of view
  - 0.5-1.5 mm gaps between modules
  - More for CCDs/CMOS

- More pixels ⇨ more data
  - Fully parallel readout at full speed:
    - MÖNCH 0.3 160k ⇨2 GB/s ⇨ 170 TB/day
- Dedicated data backend required



PAUL SCHERRER INSTITUT PSI

Summary

	CCD	CMOS	Hybrid
Quantum efficiency	😐	😐	😐
Single photon sensitivity	🙂	🙂	😐
Dynamic range	😐	😐	🙂
Spatial resolution	🙂	🙂	😐
Frame rate	☹️	😐	🙂
Area coverage	😐	😐	🙂
Radiation hardness	☹️	😐	🙂

Take home message

- The choice of the detector plays an important role for the success of your experiment

- Choose it wisely

- Use it properly

Thanks for listening. Questions?