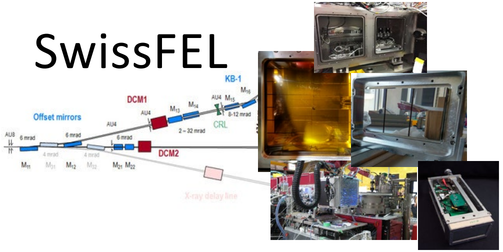
PAUL SCHERRER INSTITUT

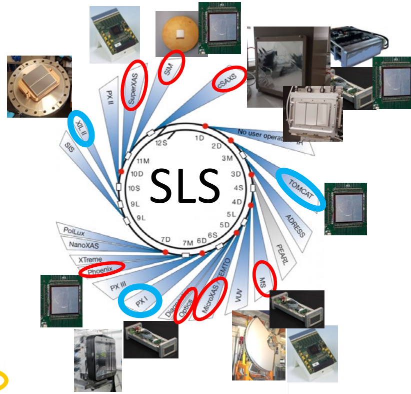
Anna Bergamaschi :: Photon Science Detector Group :: Paul Scherrer Institute

Advances in hybrid detector development for synchrotrons and XFELs at PSI

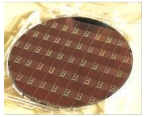
HPXM 2021 :: 9th June 2021

The Photon Science Detector Group at PSI

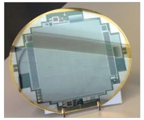




Chips

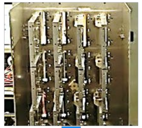


Sensors

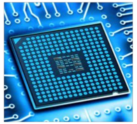


Electronics

Mechanics



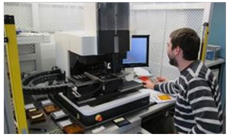
Firmware



Software

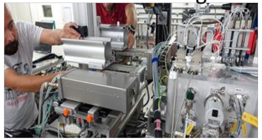
Lithography

Bump and wire bonding



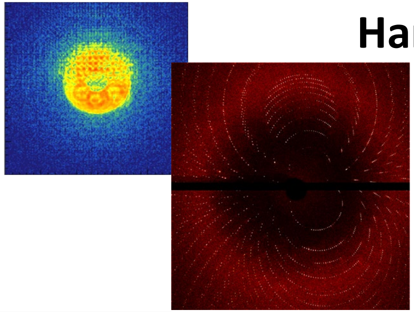
Assembly

Commissioning



Users support

Motivation

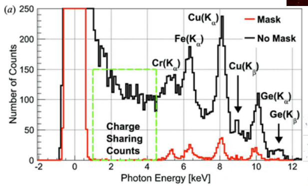


Hard X-ray diffraction and imaging experiments

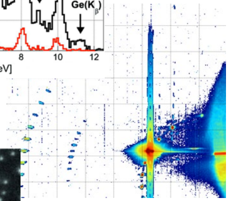
Large dynamic range

Large area

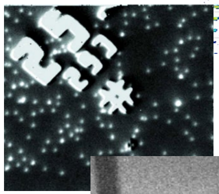
Moderate spatial resolution



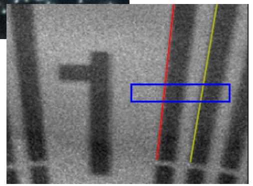
•Energy dispersive



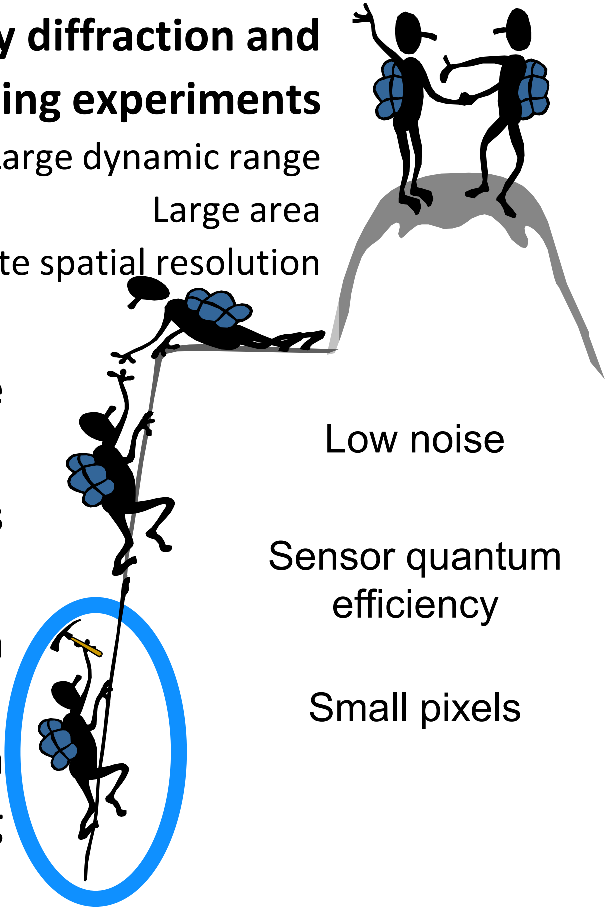
•Soft X-rays



•Electron detection



•High resolution Imaging



Low noise

Sensor quantum efficiency

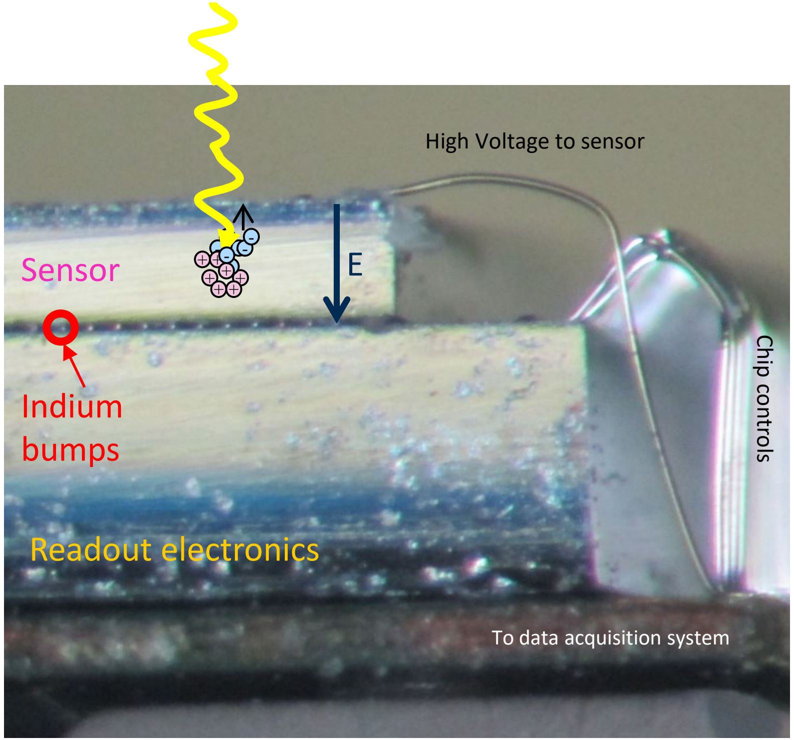
Small pixels

Hybrid detectors

Sensor and readout electronics can be optimized separately

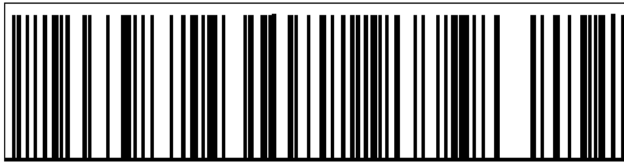
- ☺ Direct conversion in semiconductor
- ☺ Fast drifting of charge to the pixel
- ☺ Room temperature operation
- ☺ Fast highly parallelized readout

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



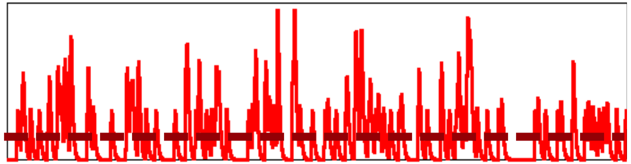
Dynamic range at diffraction limited light sources

Photons



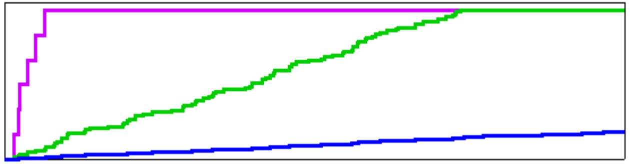
High and low flux on the detector (>10MHz per pixel)

Photon counter



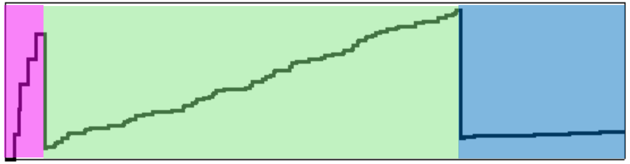
- ☺ Large dynamic range
- ☺ Fluorescence rejection
- ☹ Pile-up at high fluxes
- ☹ No energy information

Charge Integrating



- ☺ No flux limitation
- ☹ Limited dynamic range
- ☹ Needs fast readout

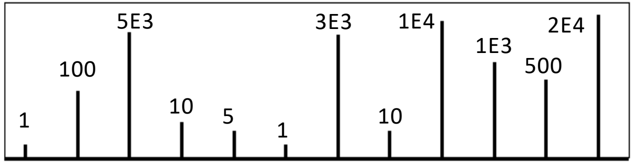
Charge Integrating with dynamic gain switching



- ☺ Large dynamic range
- ☺ No flux limitation
- ☹ Needs fast readout
- ☹ Challenging calibration

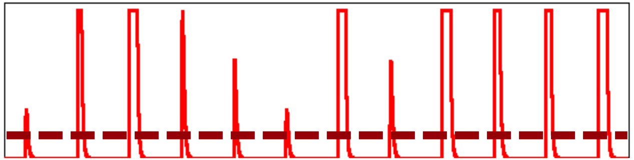
Dynamic range at XFELs

Log Photons



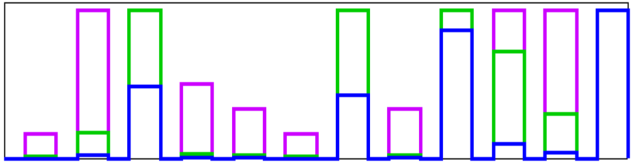
Photons arrive simultanously

Photon counter



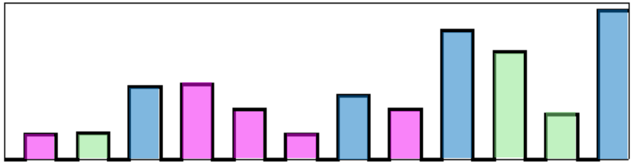
☹ Doesn’t work

Charge Integrating



☹ Limited dynamic range

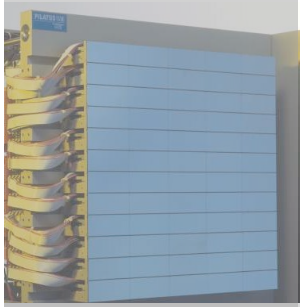
Charge Integrating with dynamic gain switching



☺ Large dynamic range
☹ Challenging calibration

PSI detectors

Microstrips | Pixels

	50 µm	25 µm	75 µm	> 150 µm
Single Photon Counting	 MYTHEN		 EIGER	 PILATUS (172 µm)
Charge Integrating	 GOTTHARD	 MÖNCH	 JUNGFRAU	200 um  AGIPD (200 µm)

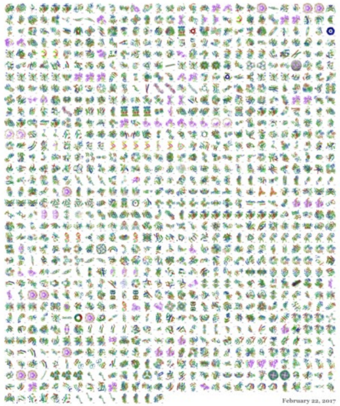
Single photon counting detectors

9M EIGER

- “Noiseless”, stable, reliable, user friendly, rad-hard, fluorescence suppression, large area systems, fast frame rate, pump-probe…

15 years ago

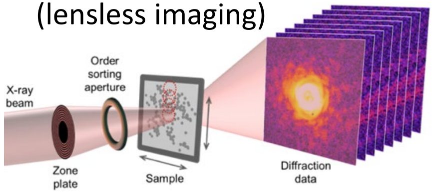
Replaced CCDs/Flat panels for PX



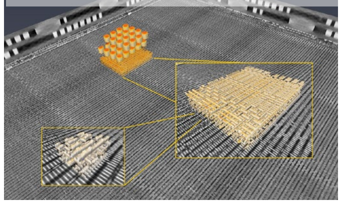
Thousands of protein structures solved using PILATUS/EIGER

10 years ago

Enabled ptychography (lensless imaging)

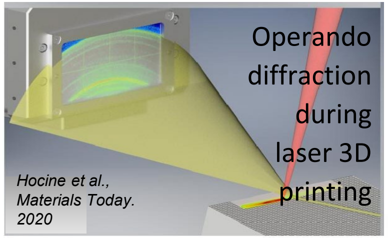


Holler et al., Nature Electronics. 2019

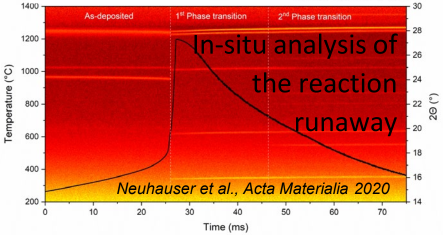


Now few nanometers resolution can be achieved in 3D

Time resolved experiments



Hocine et al., Materials Today. 2020



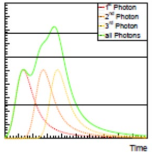
Neuhauser et al., Acta Materialia 2020

Time resolution better than 50(15)µs (20(70)kHz) possible with EIGER

Future developments

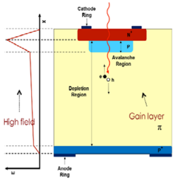
- Count rate capability up to 20MHz/pixel

Andrä, et al. JINST (2019)

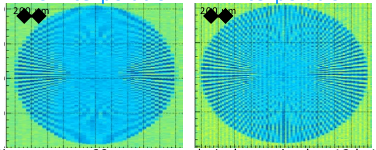


- Soft X-rays
  - LGADs

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



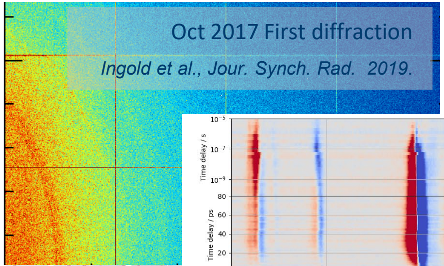
- Sub-pixel resolution

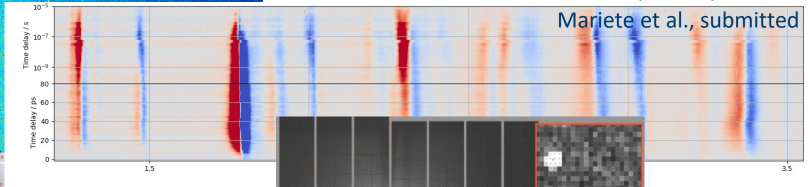


Siemens star 60 µm external pitch acquired at 12 keV
Vertical resolution given by slit and scanning step

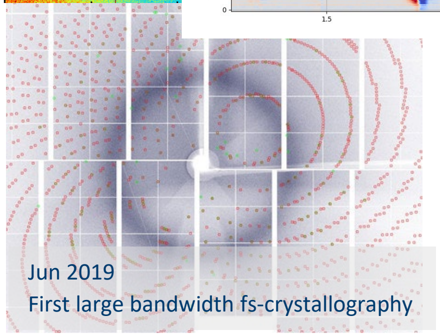
Charge integrating with dynamic gain switching

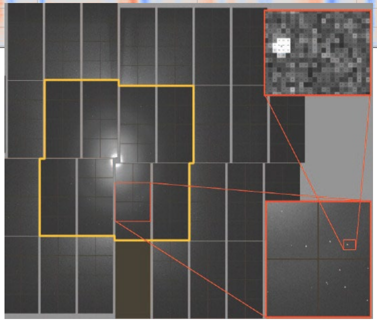
- JUNGFRAU @ SwissFEL
  - 85 modules, >40Mpixels installed
  - Works also at the new beamline for soft X-rays (even without single photon resolution)
- At synchrotron
  - Improves data quality for protein diffraction
    - higher count rates, no corner effect
  - Enables pink beam serial crystallography
  - Large area systems require optimized data backend

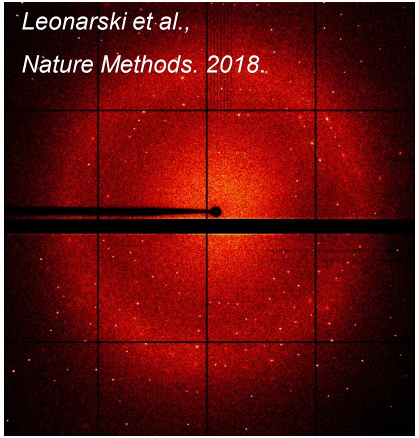

Oct 2017 First diffraction
Ingold et al., Jour. Synch. Rad. 2019.



Nov 2017 First time resolved pilot experiment
Mariete et al., submitted


Jun 2019
First large bandwidth fs-crystallography

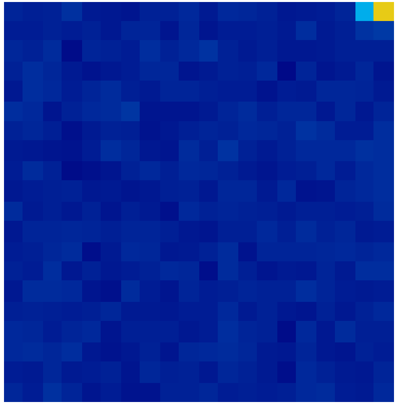

Aug 2018 First fs-crystallography
Nass et al., IUCrJ 2020.


Leonarski et al., Nature Methods. 2018.


Tolstikova et al., IUCrJ. 2019.

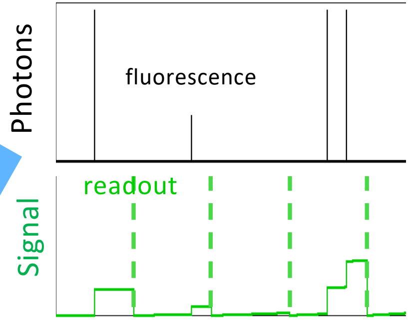
Single photon detection with charge integrators

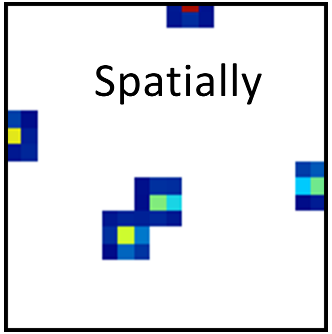
Photons must be separated



Pixel pitch	25 µm
Area	1 cm^2
Number of pixels	160k
Frame rate	1 kfps
Max flux per area	1E5 ph/s/mm^2
Max total flux	1E7 ph/s

In time





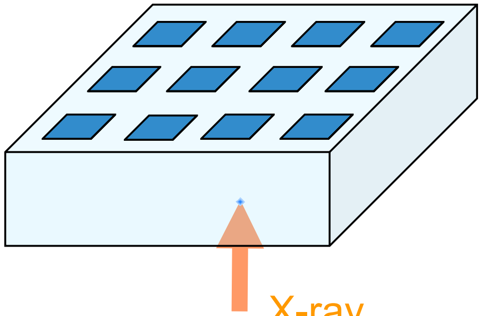
Fast readout

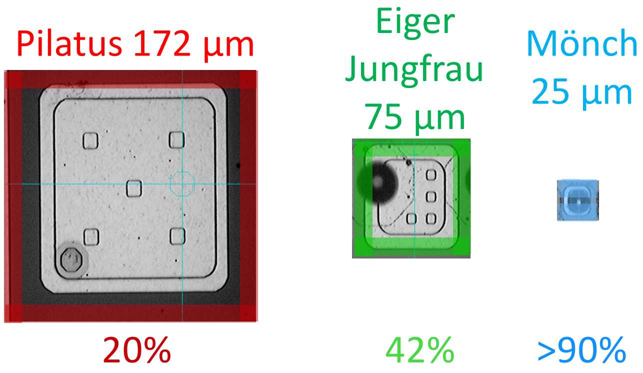
Clustering

Small pixels

Charge sharing

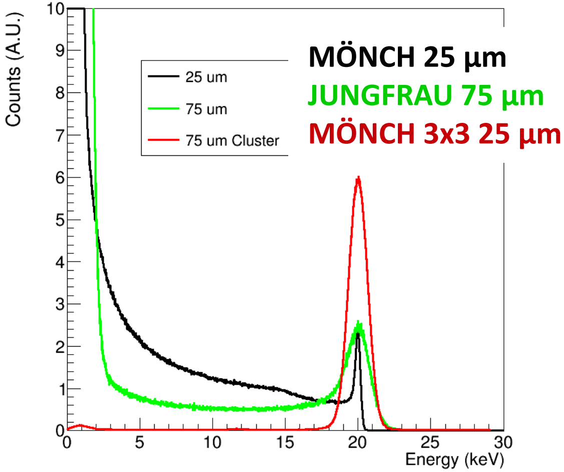
- The charge diffuses while drifting to the electrodes
- The diffusion length depends on the drift time:
  - Charge mobility
  - Applied bias voltage
  - Absorption depth
    - Sensor thickness
    - X-ray energy
- The charge can be collected by several pixels
  - Partial signal collection
  - Inter-pixel correlation
  - Charge sharing region ca. 15-20 µm for 320 µm thick silicon at 120 V





Spectral analysis

- Exploit the information contained in the analogue readout
- The full charge can be retrieved by clustering
  - Photon counting –like performance
  - Preserves spectral information
    - Suppresses charge sharing
    - Noise is increased depending on the size of the cluster



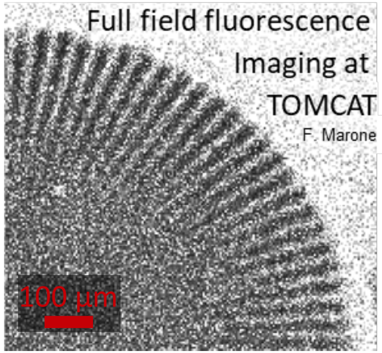
Intrinsic energy resolution

1x1 ⇨ 320 eV FWHM

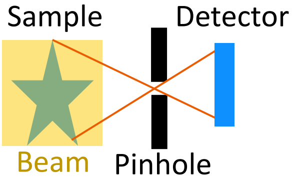
2x2 ⇨ 740 eV FWHM

3x3 ⇨ 960 eV FWHM

Combined energy and spatial resolution

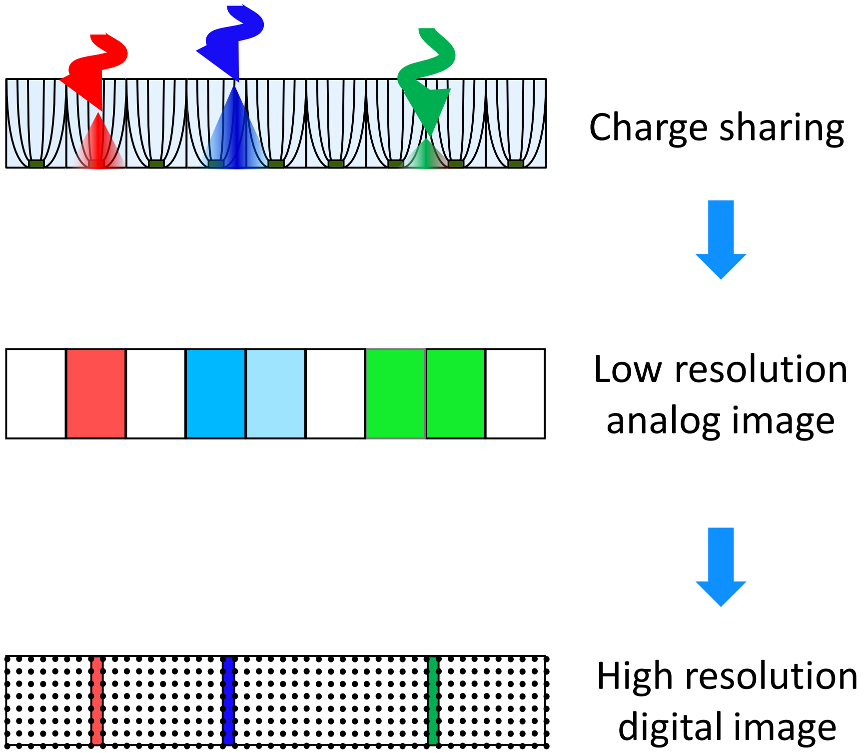


Spatial resolution currently limited by pinhole size



Position interpolation

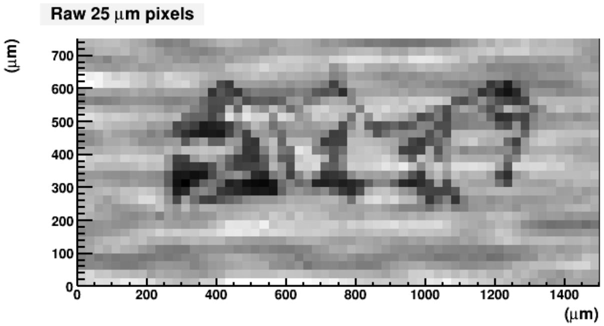
- Division of charge between pixels is strongly position dependent
- Can improve the spatial resolution
  - Pitch ≈ charge sharing distance
    - 320 µm thick Si, 120V ≈ 20 µm
  - High SNR
    - Low noise
    - Hard X-rays
  - Isolated photons
    - Fast frame rate
    - Low flux

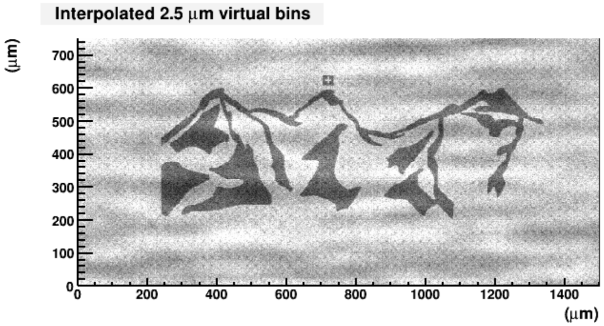


Does it work?

- Acquired with MÖNCH 650 µm thick silicon with 300 V bias voltage at the TOMCAT beamline (SLS) @ 10 keV
- 2 µm thick Gold on 200 µm silicon sample
  - Fabricated at LMN (PSI) by M. Lebugle
  - Eiger, Mönch and Jungfrau mountains
  - The size of the flag is 25 µm
  - The width of the Swiss cross is 7 µm

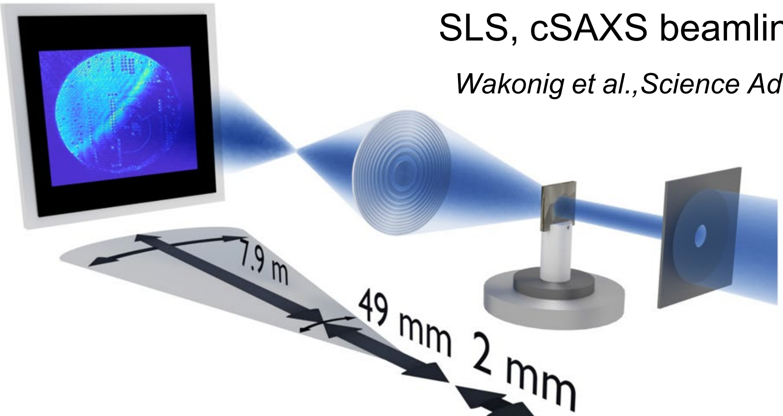
The spatial resolution is enhanced of ≈ one order of magnitude!





Courtesy S. Chiriotti

Fourier ptychography

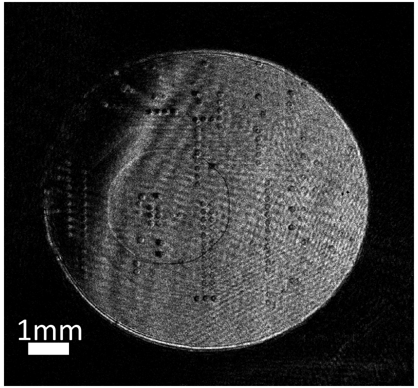


SLS, cSAXS beamline, 8.7 keV

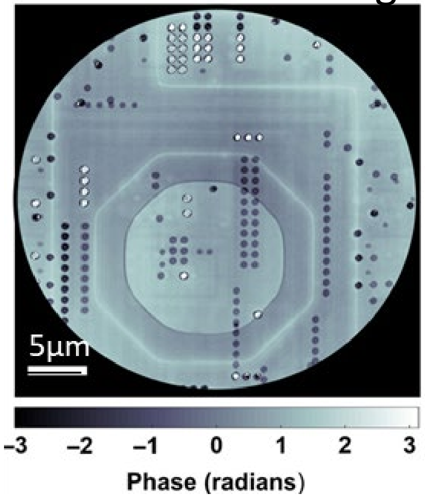
Wakonig et al.,Science Advances (2019).

- Interpolation to 6.25µm to compare with 6µm pixel indirect detector
- The reconstruction didn’t work with the CCD
  - Single photon resolution is necessary!
- Fourier ptychography quantitatively reproduces results obtained with traditional methods
  - 47nm resolution after reconstruction
  - Robust reconstruction, insensitive to aberrations/misalignements
  - Significantly lower dose than TXMs
- Larger area faster detector desirable for users operation

Image on detector

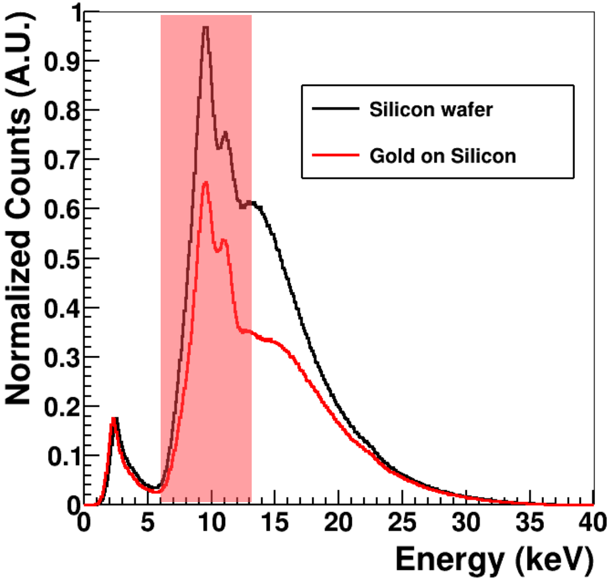


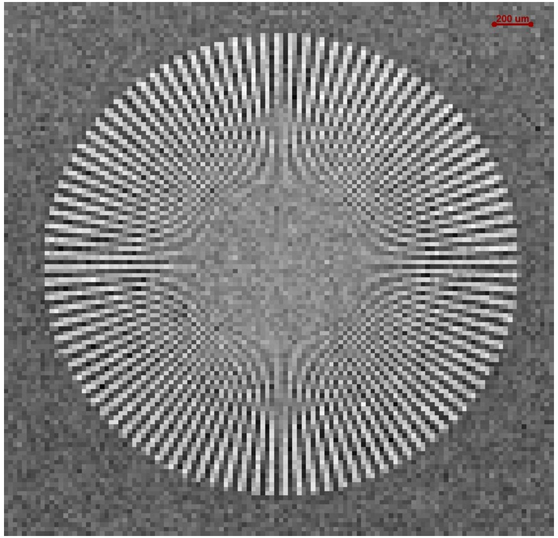
Reconstructed image



Energy resolved imaging with X-ray tubes

A full spectrum with an energy resolution of about 750 eV FWHM is acquired for each pixel



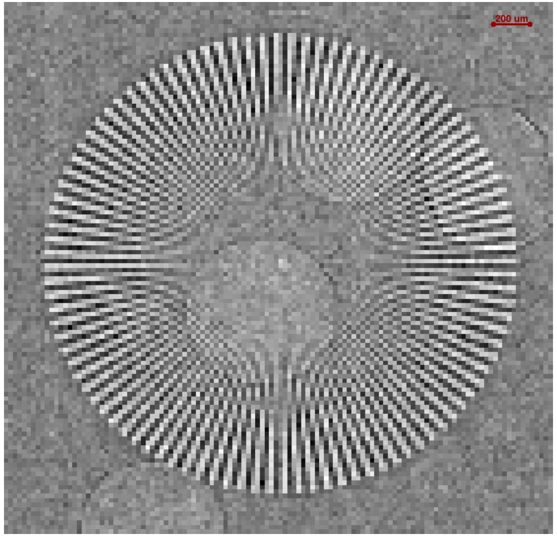


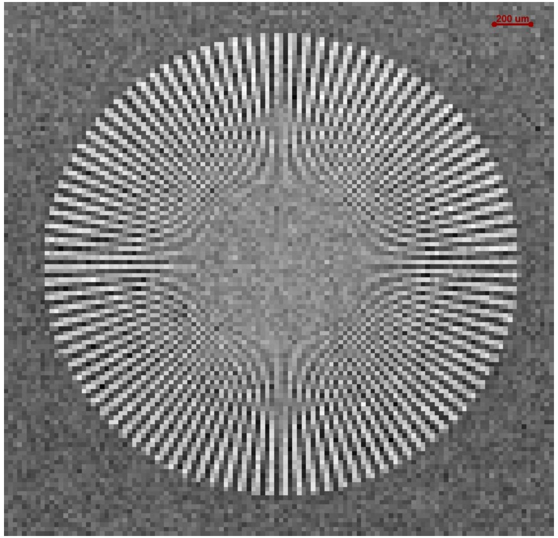
Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 µA

Edge subtraction imaging

Images can be binned in energy

Gold becomes “transparent” to X-rays below the L-edge





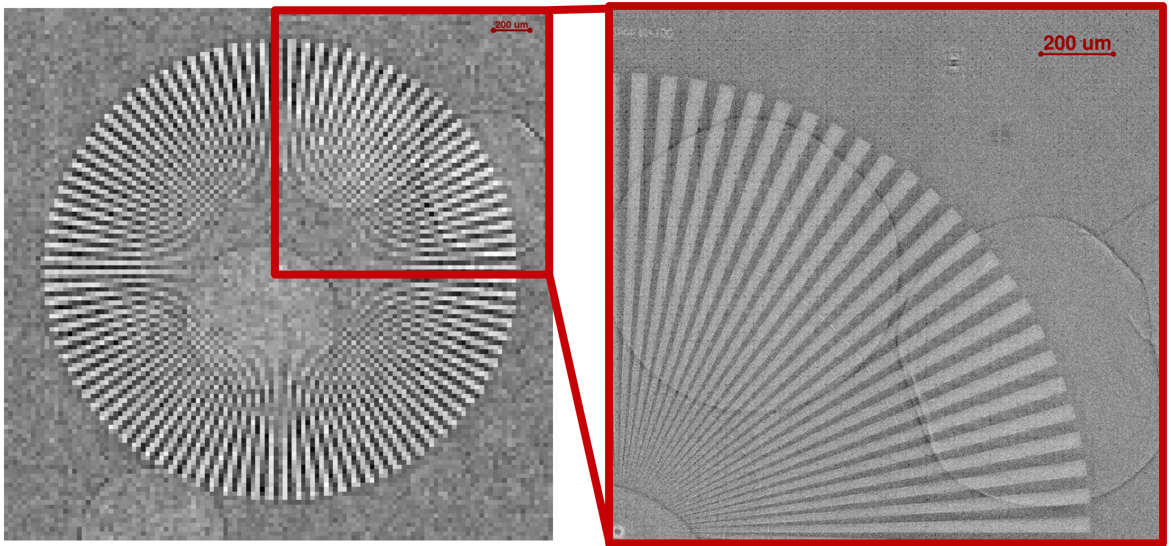
Below Au L-edge

Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres

W-anode X-ray tube 40 kV 200 µA

High resolution energy resolved imaging

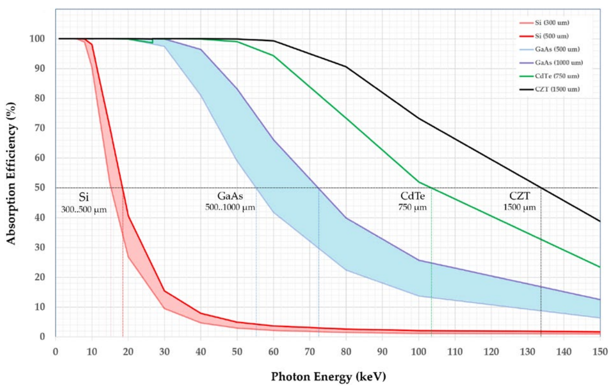
Color imaging works also in combination with interpolation.
Challenges due to polychromatic beam.

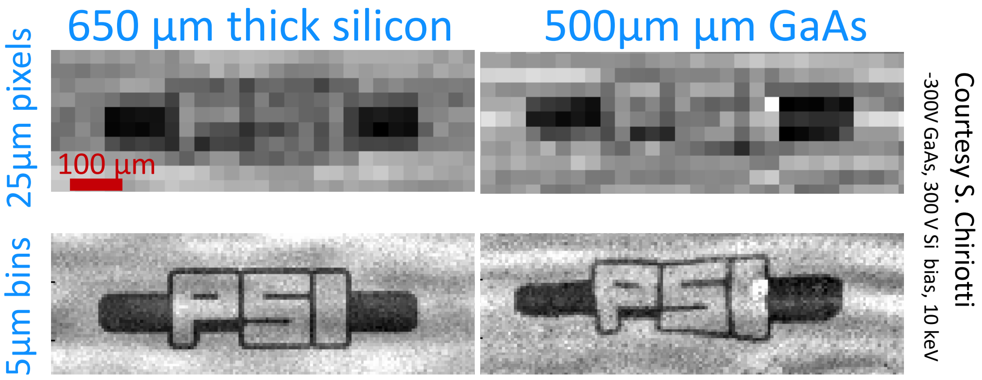


Below Au L-edge Interpolated to 1 µm bins

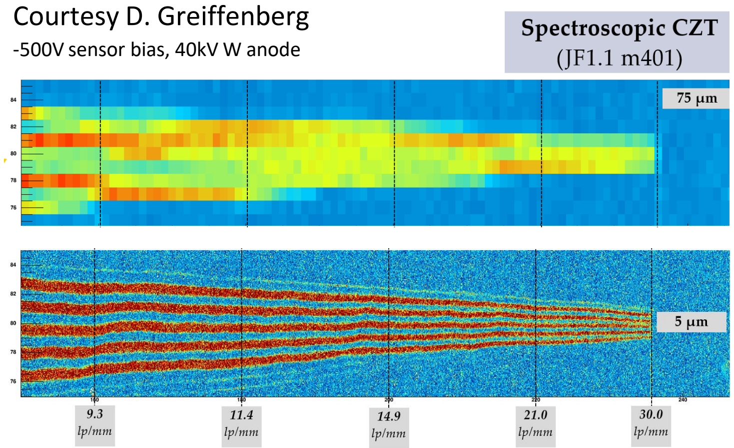
Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 µA

High-Z materials for higher energies





- Silicon is too light to achieve good QE above 20 keV
- High-Z materials under test (GaAs, CdTe, CdZnTe)
  - Material quality often challenging in terms of yield, uniformity, stability…
  - Thicker sensors give more charge sharing and interpolation is possible also with 75µm pixels
  - With small pixels and interpolation we can observe strange effects



The Photon Science detector group at PSI…

… delivers outstanding detectors worldwide.

… strives to optimize hybrid detectors in every aspect.

Next challenges…

… soft X-ray detectors.

… new single photon counting pixel detector for diffraction limited light sources.

… faster frame rates and data backend.

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