

<https://github.com/jaianthv/IRT-doctoral-school>

Synchrotron X-ray imaging

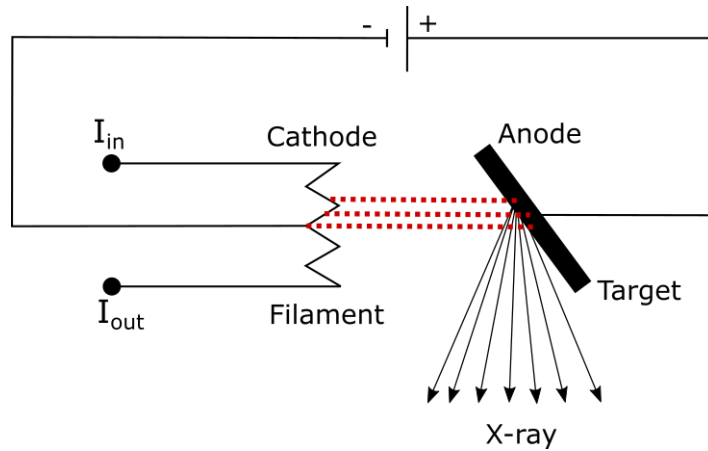
IRT Doctoral school – 09.04.2024

Jaianth Vijayakumar

Beamline scientist – BM18 and BM05

X-ray source

Lab-based source



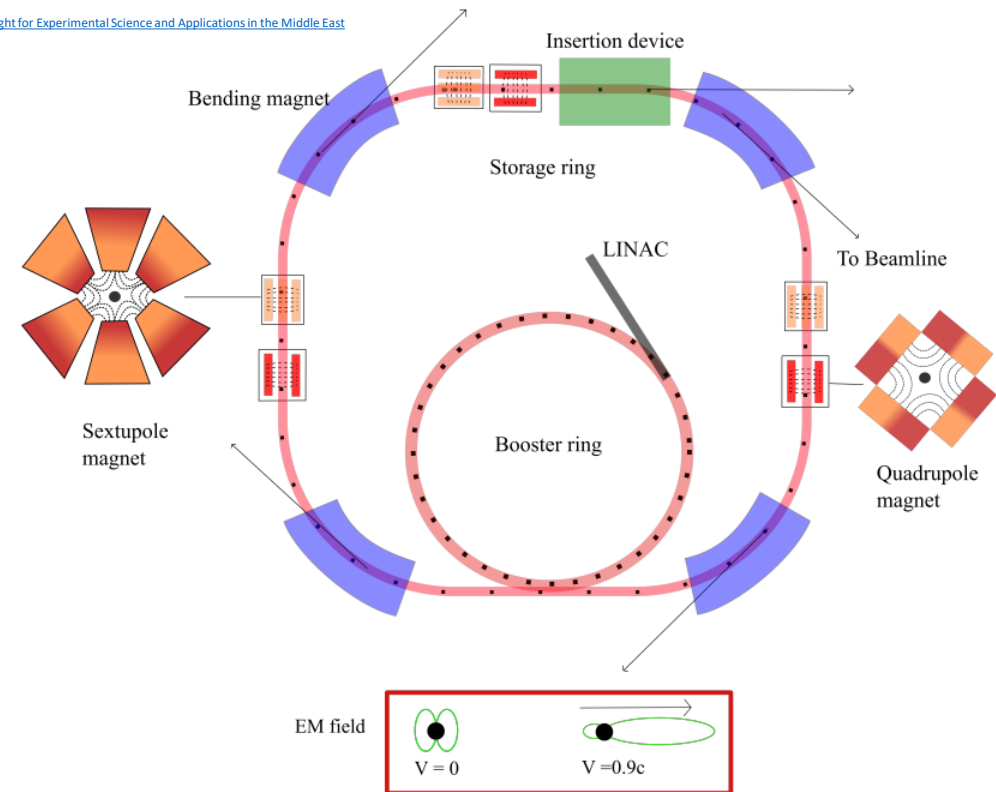
Filament – W

Target – W, Mo or heavy metals



[Magnets and IDs | SESAME | Synchrotron-light for Experimental Science and Applications in the Middle East](#)

Synchrotron source

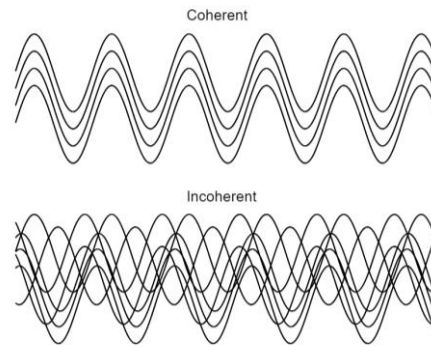
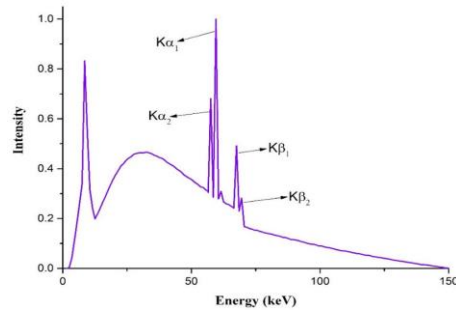


[U100 - Helmholtz-Zentrum Dresden-Rossendorf, HZDR](#)

Figure 3.7: Schematic representation of a synchrotron facility.

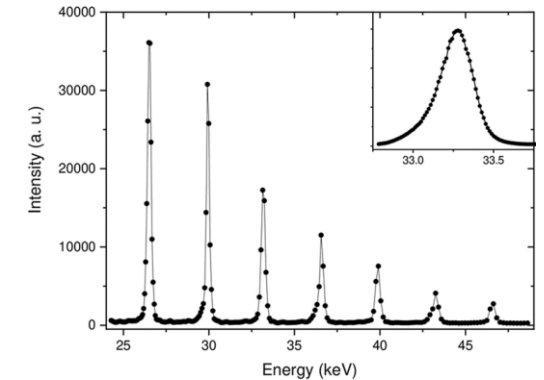
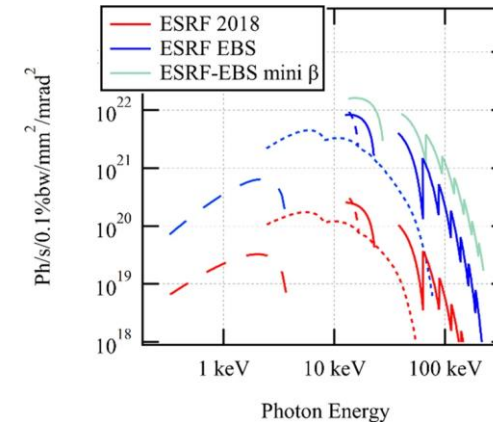
X-ray source – benefit of a synchrotron

Lab-based source



1. Polychromatic
2. Conical beam – large divergence
3. Non-Coherent
4. Low intensity
5. Suitable for only absorption based imaging – e.g. tomography

Synchrotron source



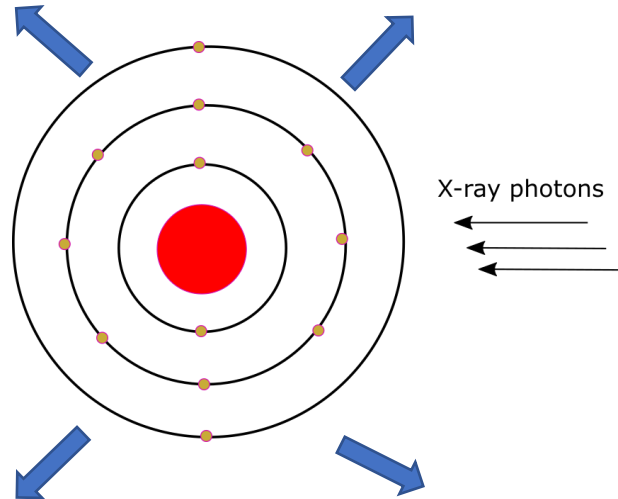
1. Polychromatic/ Monochromatic
2. Parallel beam – less divergence
3. Highly Coherent
4. High intensity – EBS !!
5. Possible to do many imaging modalities 😊

X-ray interaction with matter

Microscopic origin

Elastic scattering

Inelastic scattering

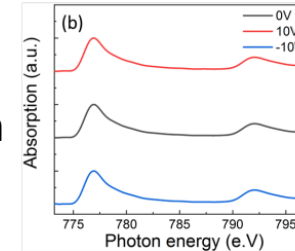


Emission of
secondary
electron/photoelec
tric effect

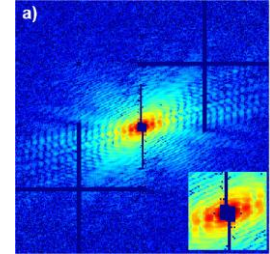
Pair production –
electron/positron/nuclear
absorption

Macroscopic effect

X-ray absorption
(Chemical)

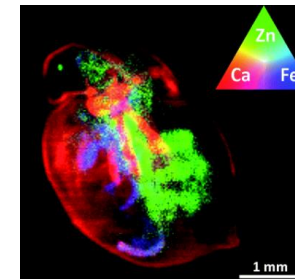


X-ray diffraction
(structural)



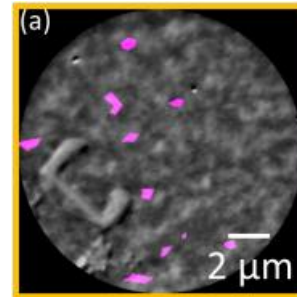
[3D imaging of whole cells using cryocooled coherent X-ray diffraction \(esrf.fr\)](https://www.esrf.fr/science/news/3D%20imaging%20of%20whole%20cells%20using%20cryocooled%20coherent%20X-ray%20diffraction)

Fluorescence
(chemical)

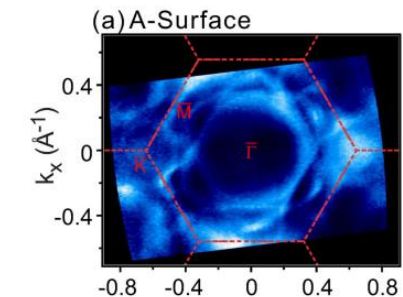


Bojrn et al., JAAS, **34**, 2083-2093 (2019)

Photoemission
(Electronic)



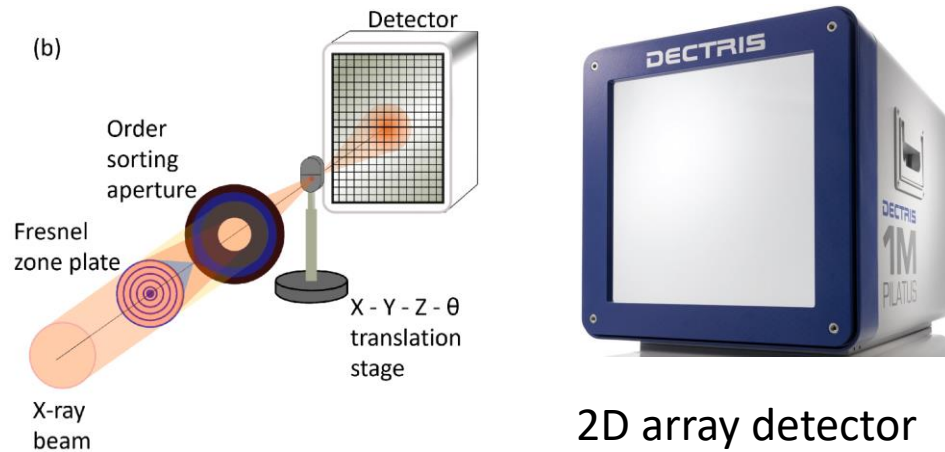
X-ray scattering
(form factor, refractive
index)



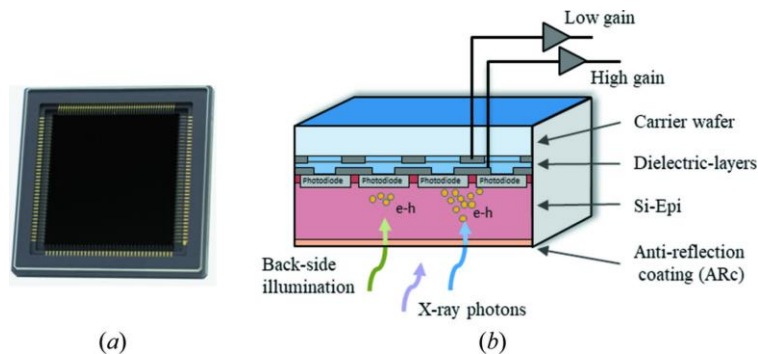
W. Jiang et al., J. Appl. Phys. 128, 135103 (2020)

X-ray detector

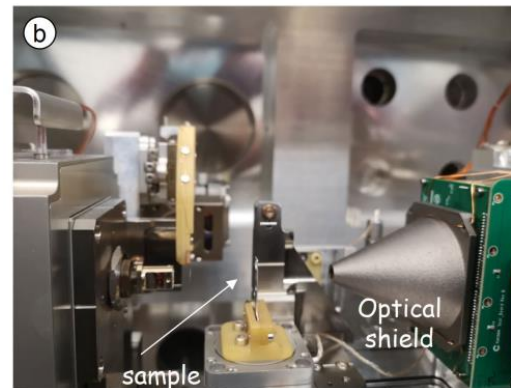
Goal is X-ray imaging is to spatially resolve the X-ray interaction



2D array detector

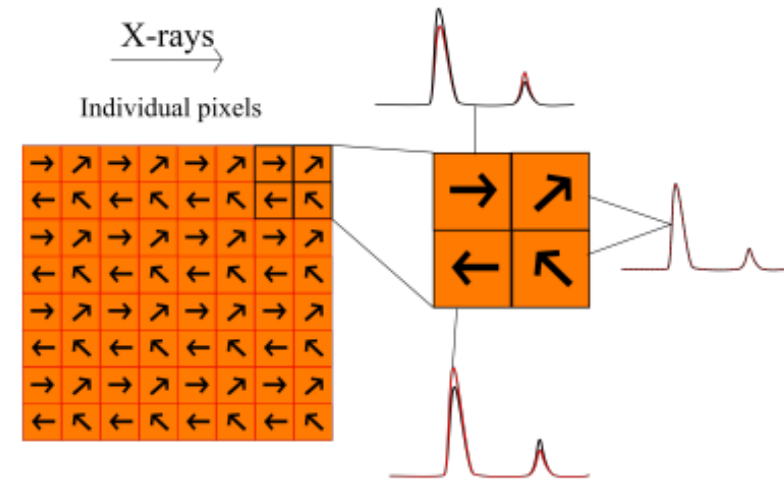


CMOS/CCD



Point detector

Each pixel is a spectrum,
diffraction/scatting information



Other detectors

1. Scintillator + microscope detector
2. Diode
3. phosphor screen

Modalities – X-ray photoemission electron microscopy

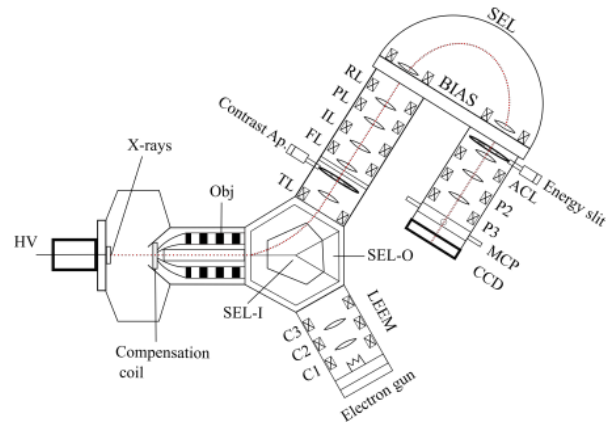
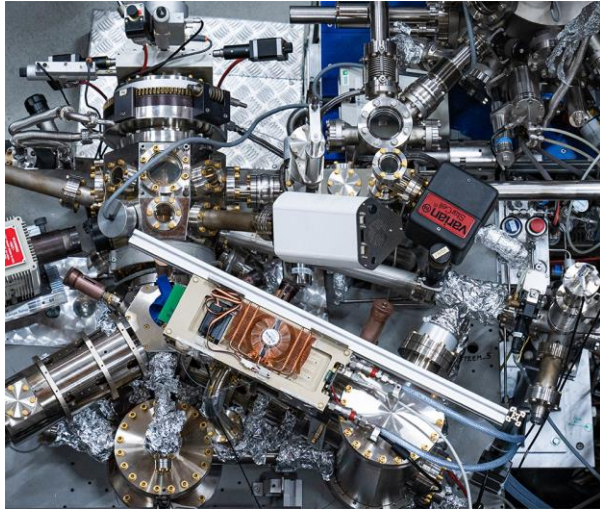
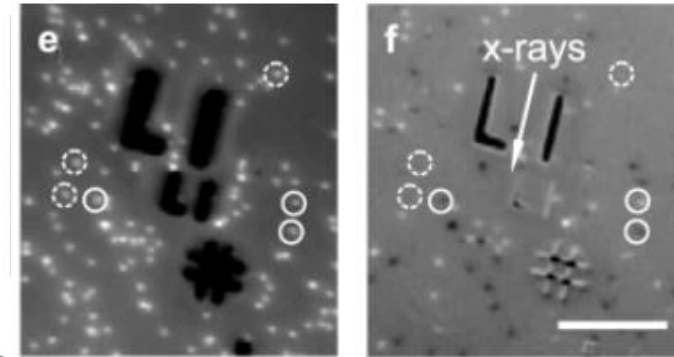
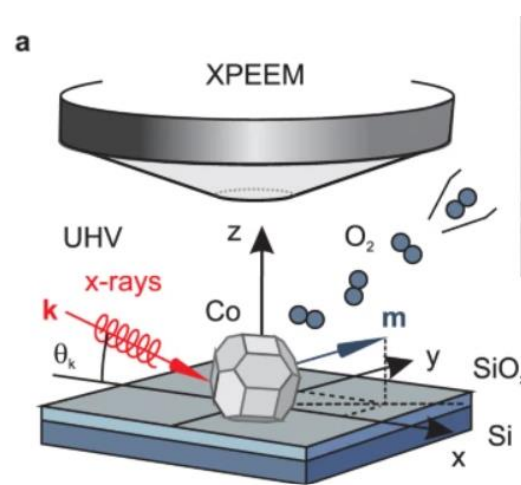
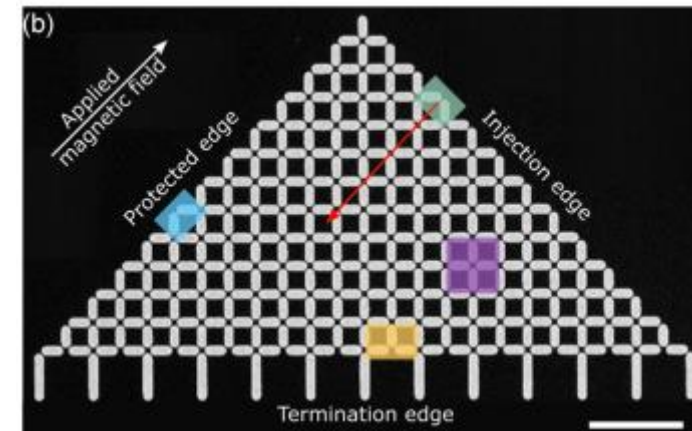
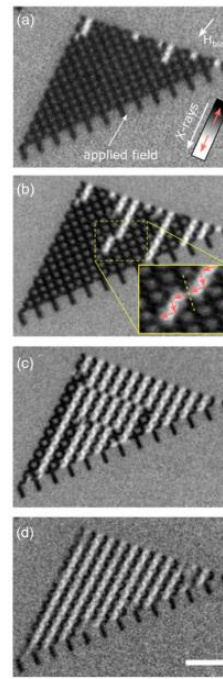


Figure 3.11: ELMITEC XPEEM set-up.

SIM – beamline – SLS, PSI



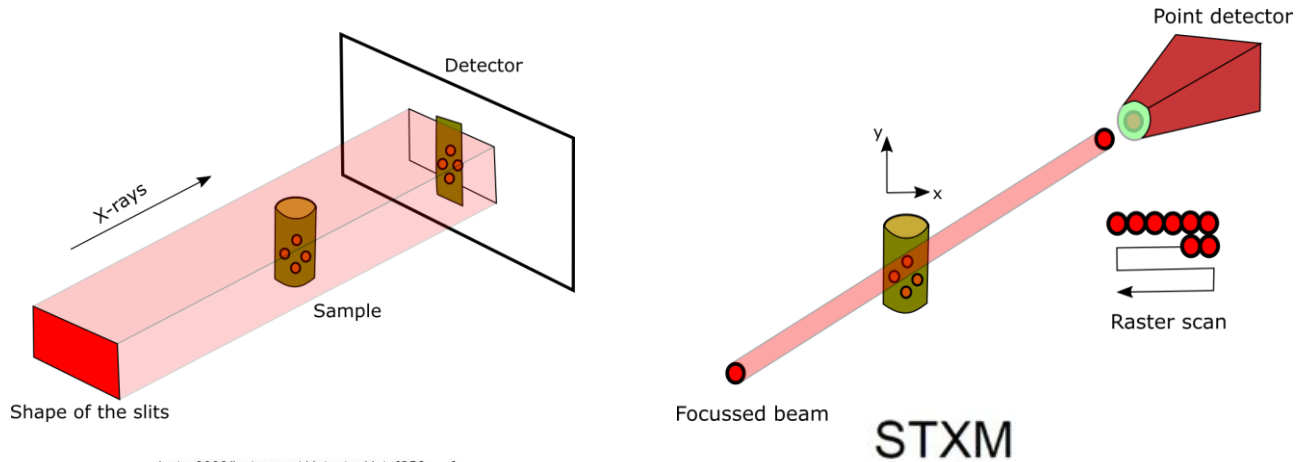
J. Vijayakumar et al., Nat. Comm.
14, 174 (2023)



H. Arava et al., PRB, 102, 144413 (2020)

Modalities – X-ray transmission microscopy

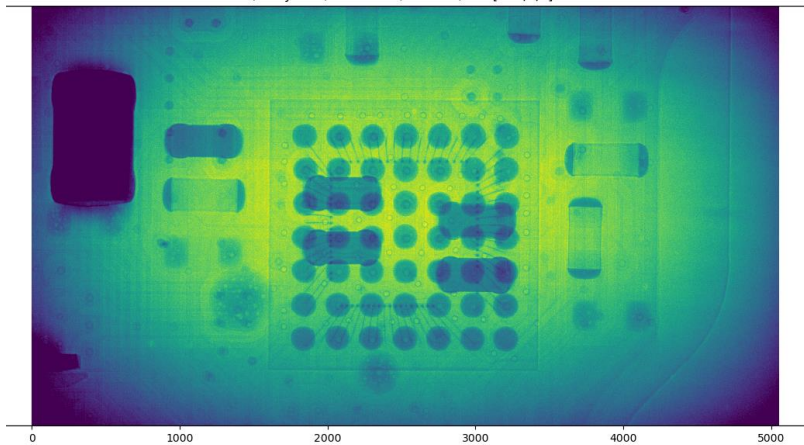
Transmission image/ absorption image/ radiography image/ projection image



Resolution depends on:

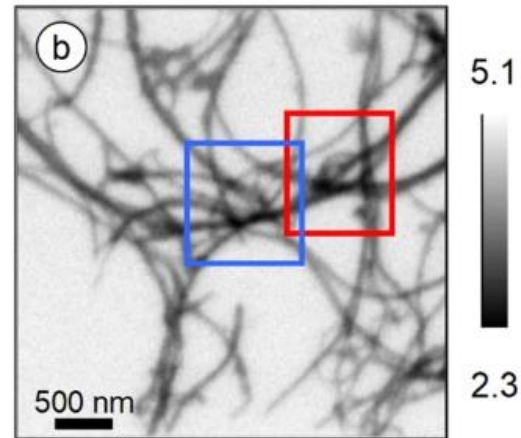
1. Size of the beam (~ 10 nm, default – 60 - 100 nm)
2. Precision of the stage

/entry0000/instrument/detector/data[258, :, :]



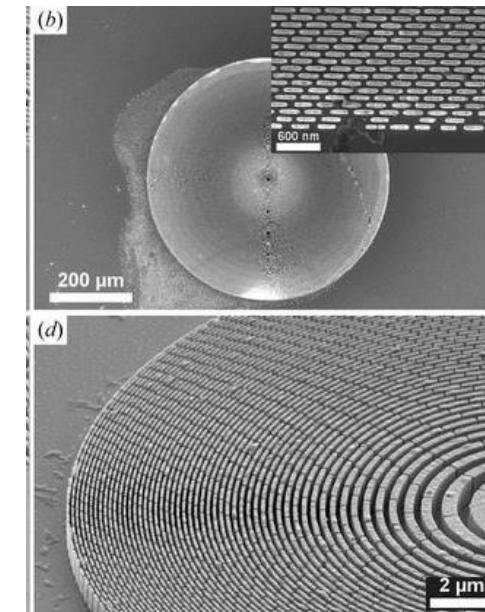
Radiography/transmission

Acquisition time > 50 ms



Raster scan

Acquisition time > 15 min



N. Mille et al., Communications materials, 3,8 (2022)

S. Gorelick et al., JSR, 18, 442-446 (2011)

Modalities – Phase contrast imaging

Why phase contrast imaging?

- Measure non-absorbed region
- Suitable for organic materials
- Particularly at high energy

Refractive index = $1 - \delta + i\beta$

Phase shift $\rightarrow 2\pi \delta \text{ thickness}/\lambda$

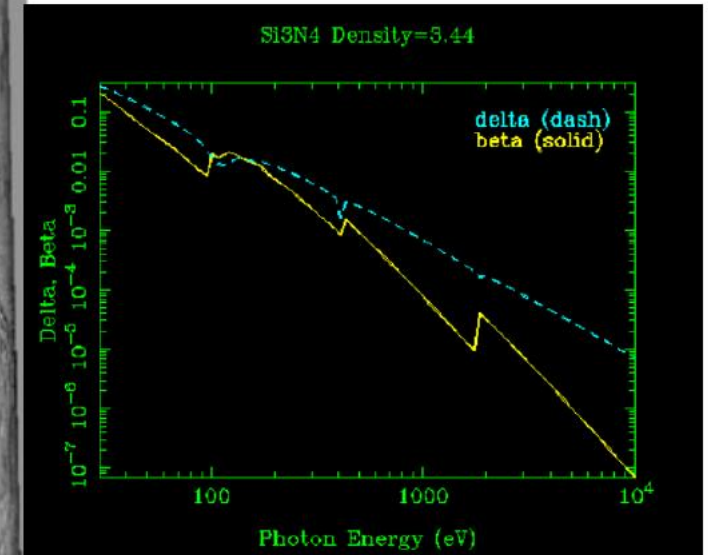
By Zernike phase imaging

Interferometry, analyzer and propagation based methods. At high energy – it the default!

(a) Transmission

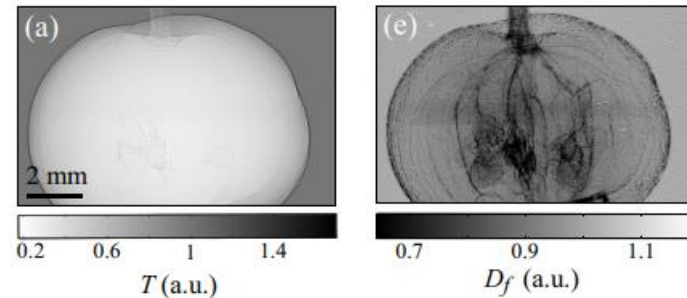
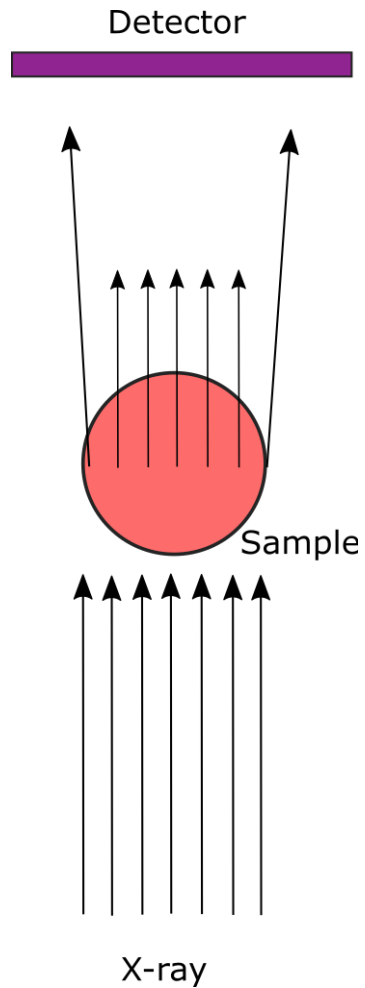


(b) Phase contrast



1. F. Pfeiffer et al., Zeitschrift fur Medizinische Physik, 23, 176-185 (2013)
2. B. L. Henke et al., Atomic Data and Nuclear DATA Tables, 54, 181-342 (1993)
3. U. Bonse and M. Hart, APL, 6, 155-156 (1965)
4. V. N. Ingal and E.A. Beliaevskaya, Journal of physics D: applied physics, 54, 181-342 (1993)
5. K. A. Nugent et al., PRL, 77, 2961 (1996)

Modalities – dark field imaging



Extract details smaller than the voxel size

Information exist – just need to separate them 😊

(a) Transmission



(b) Phase contrast



(c) Dark-field contrast



1. F. Pfeiffer et al., Zeitschrift fur Medizinische Physik, 23, 176-185 (2013)
2. S. Berujon et al., PRA, 92, 013837 (2015)

Modalities – Spectral imaging

An approach to obtain chemical contrast

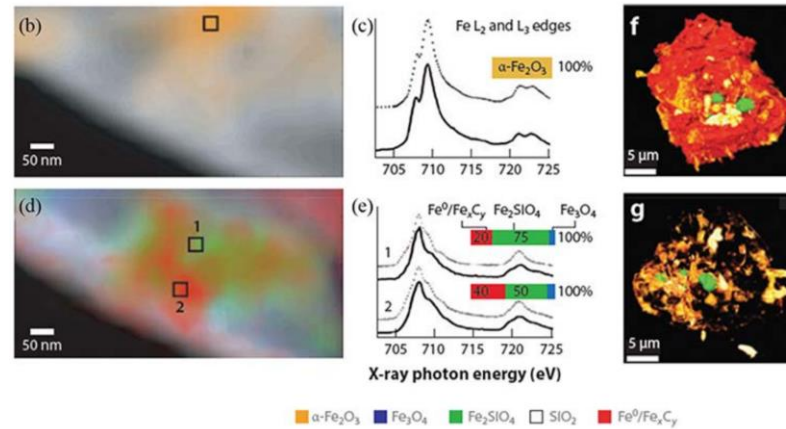
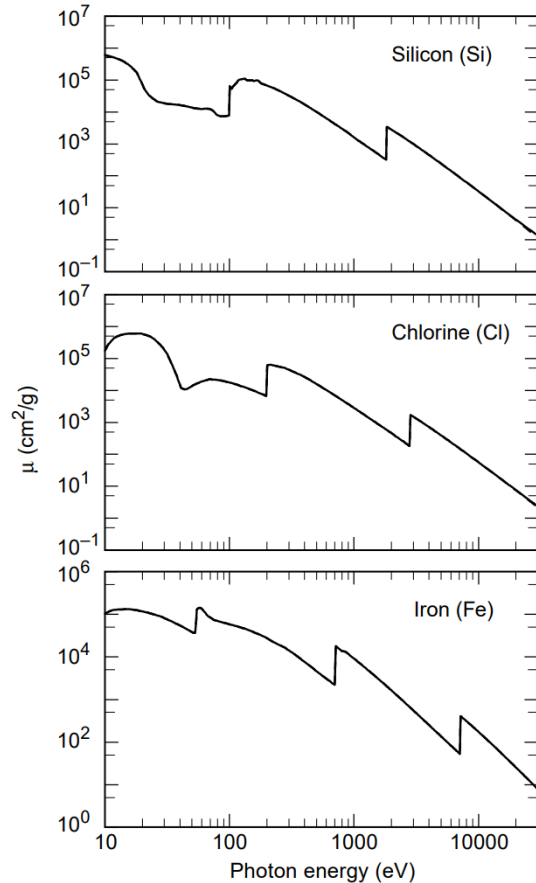
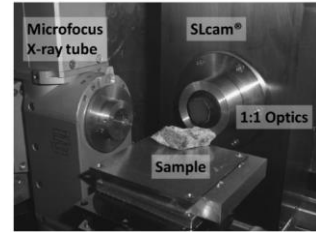
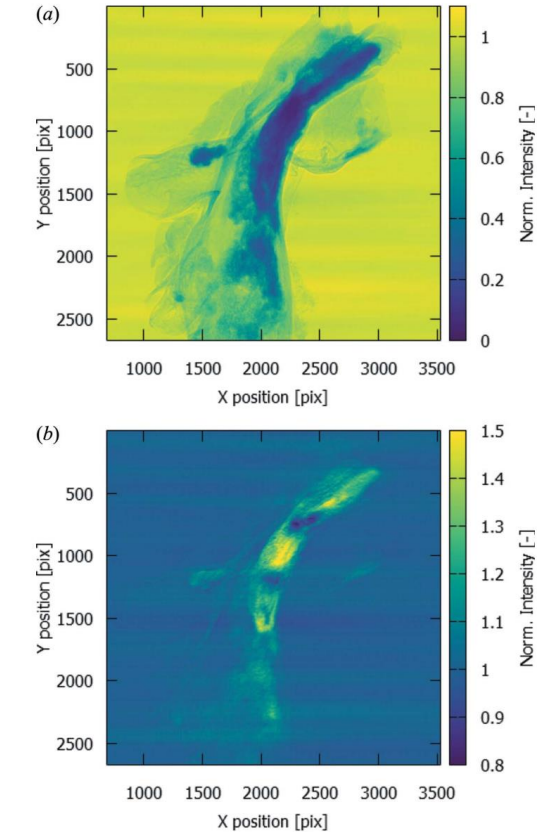


Image a sample with different absorption edges



Spectral/hyperspectral imaging -Detector level, create bins to separate interacted photons

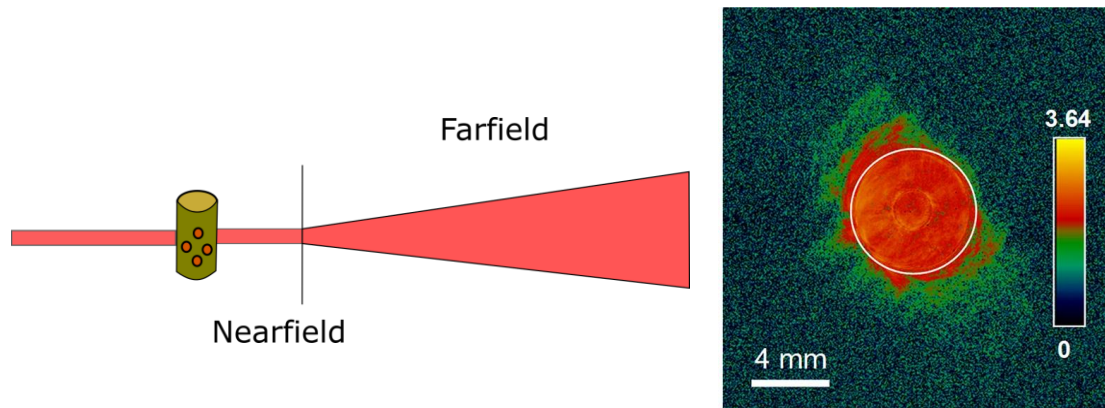
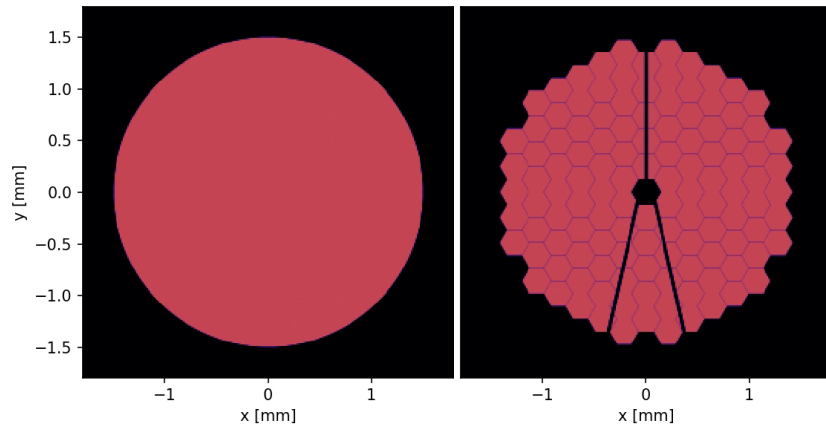
Absorption vs photon energy

1. M. Gogate, Chemical Engineering Communications. 204,1-27(2017)
2. B. L. Henke et al., Atomic Data and Nuclear DATA Tables, 54, 181-342 (1993)
3. M. N. Boone et al., Nuclear Instruments and Methods in Physics Research Section I: Accelerators, Spectrometers and Detector and Associated Equipments, 735, 644-648 (2014)
4. M. Boone et al., JSR, 27, 110–118 (2020)
5. A. Bjeoumikhov et al., Journal of Instruments, 7 (2012)
6. K. Desjardins et al., JSR, 27, 1577-1589 (2020)

Modalities – X-ray diffraction imaging

Coherent diffraction imaging → Near field diffraction and far-field diffraction (resolution less than 10 nm)

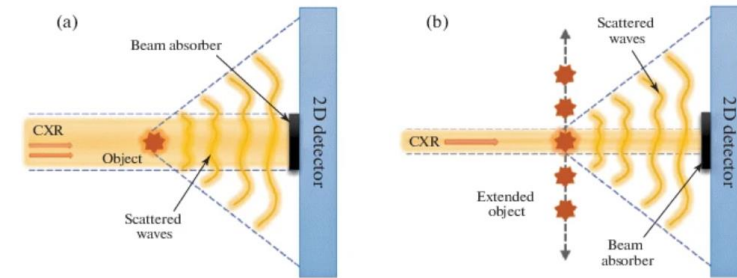
Distance: 0.000 meter



Coherent diffraction imaging

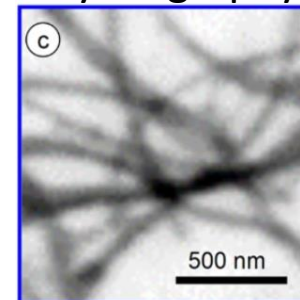
Ptychography

Fig. 1.

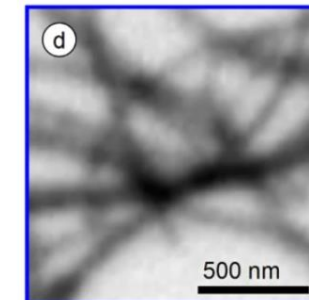


More the beam scatters → kind of magnification!

Ptychography



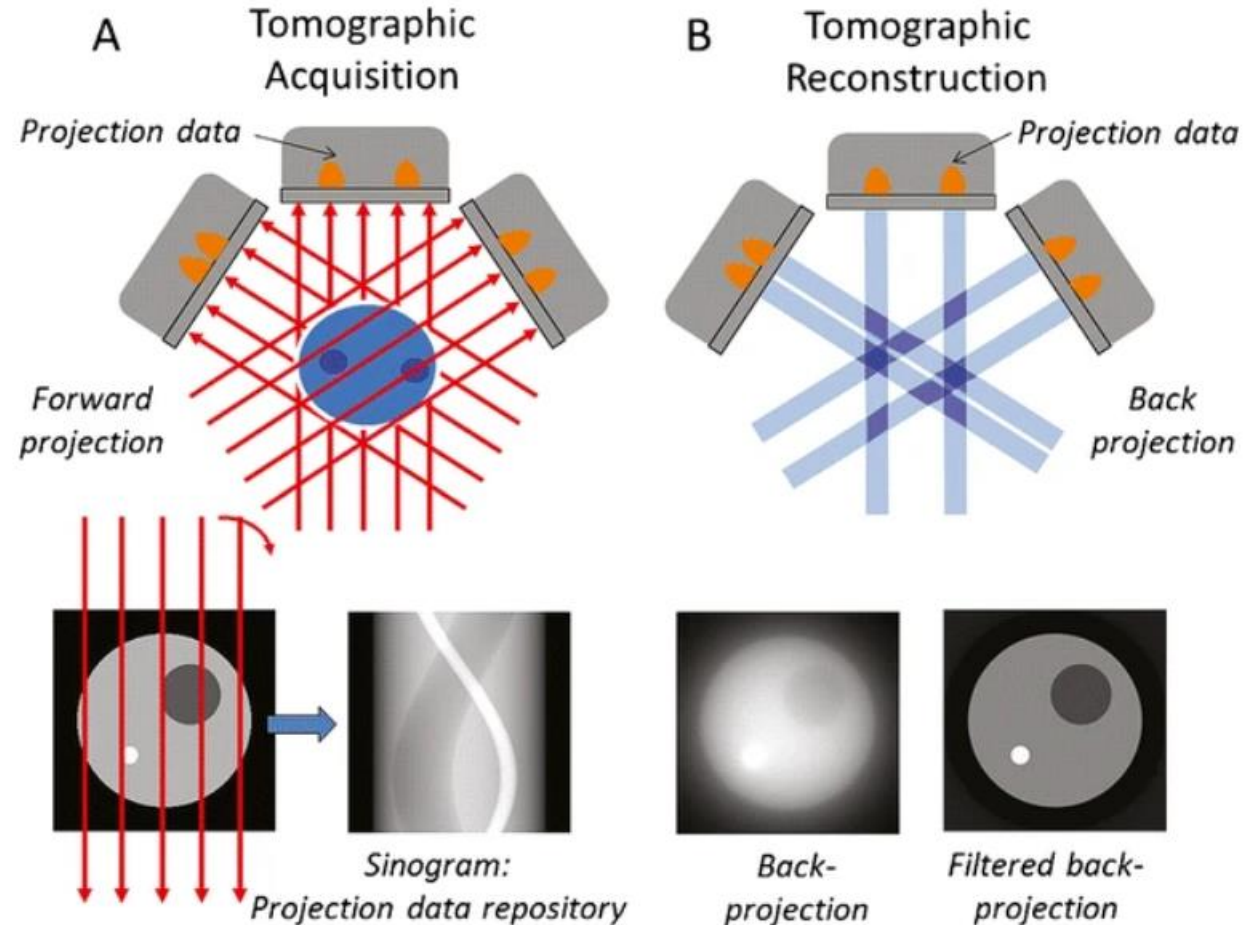
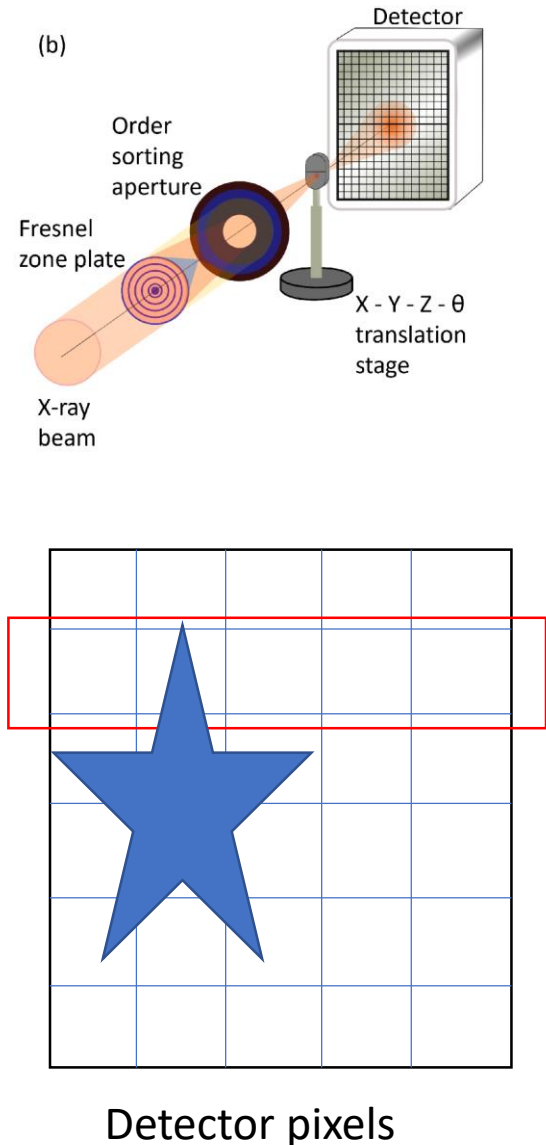
STXM



P. A. Prosekov et al., Methods of Coherent X-ray Diffraction Imaging, 66, 867-882 (2021)

N. Mille et al., Communications materials, 3,8 (2022)

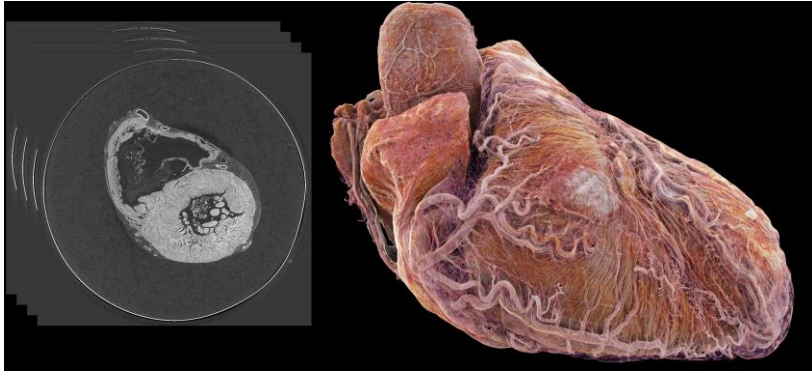
Modalities – Computed Tomography



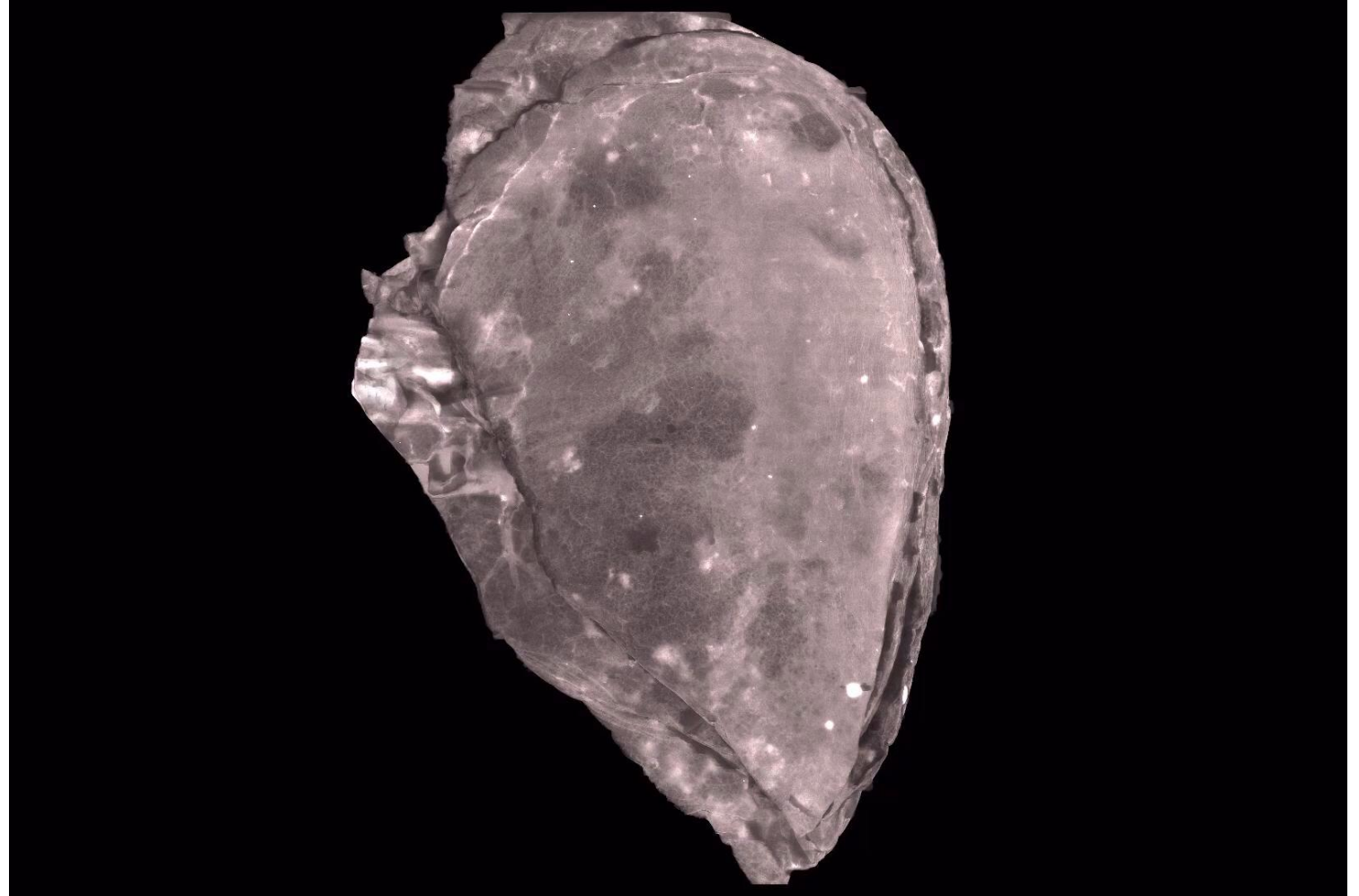
J. A. Seibert, *Pediatr. Radiol* 44 (Suppl 3), 431-439 (2014)

[Human Health Campus - 3D image reconstruction \(iaea.org\)](http://iaea.org)

Modalities – microtomography



Courtesy - J. Brunet (BM18 - ESRF/UCL) - human heart



Human Lung

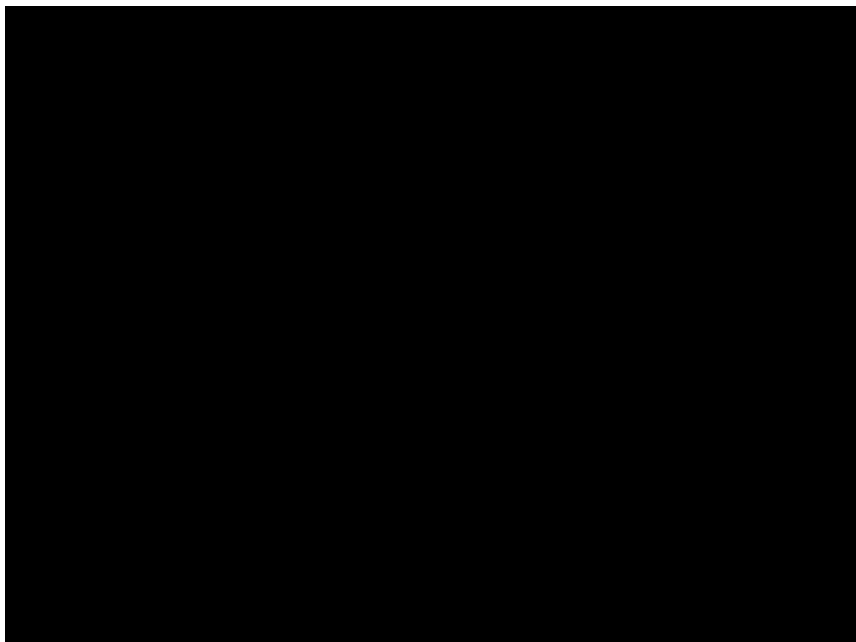


[Human Organ Atlas \(esrf.eu\)](https://www.esrf.eu)

C. L. Walsh et al., Nature Methods, 18, 1532-1541 (2021)

J. Vijayakumar et al., Pharmaceuticals, 16(5), (2023)

Modalities – microtomography



Lobster - Courtesy – K. Dollman and R Garrouste (MNHN) (BM18)



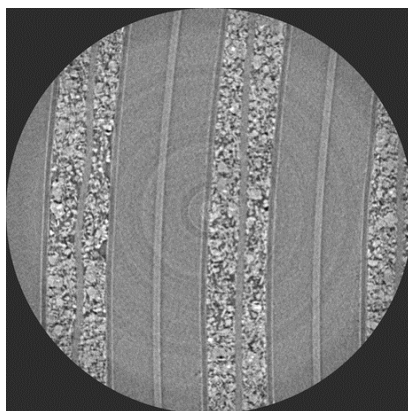
Shrimp - Courtesy – P. Tafforeau (BM18)

France TV 'Mystérieux insectes, sur la piste des origines

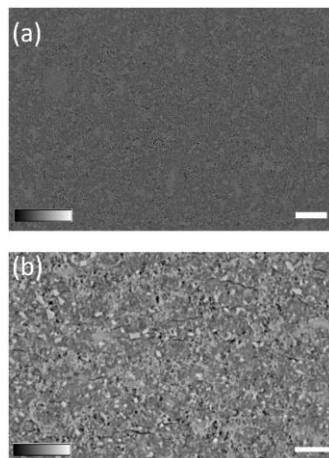


Dinosaurs and birds - Courtesy – V. Beyrand (BM18)

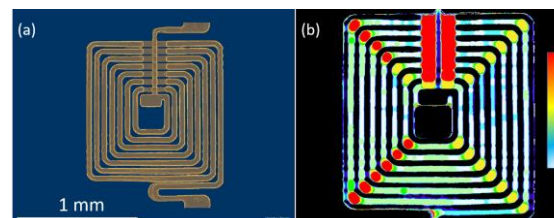
Nanotomography



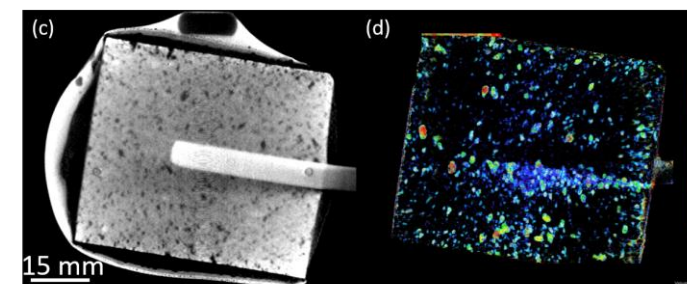
Battery



Tablet



Inductor



Capacitor

Modalities – Diffraction contrast tomography

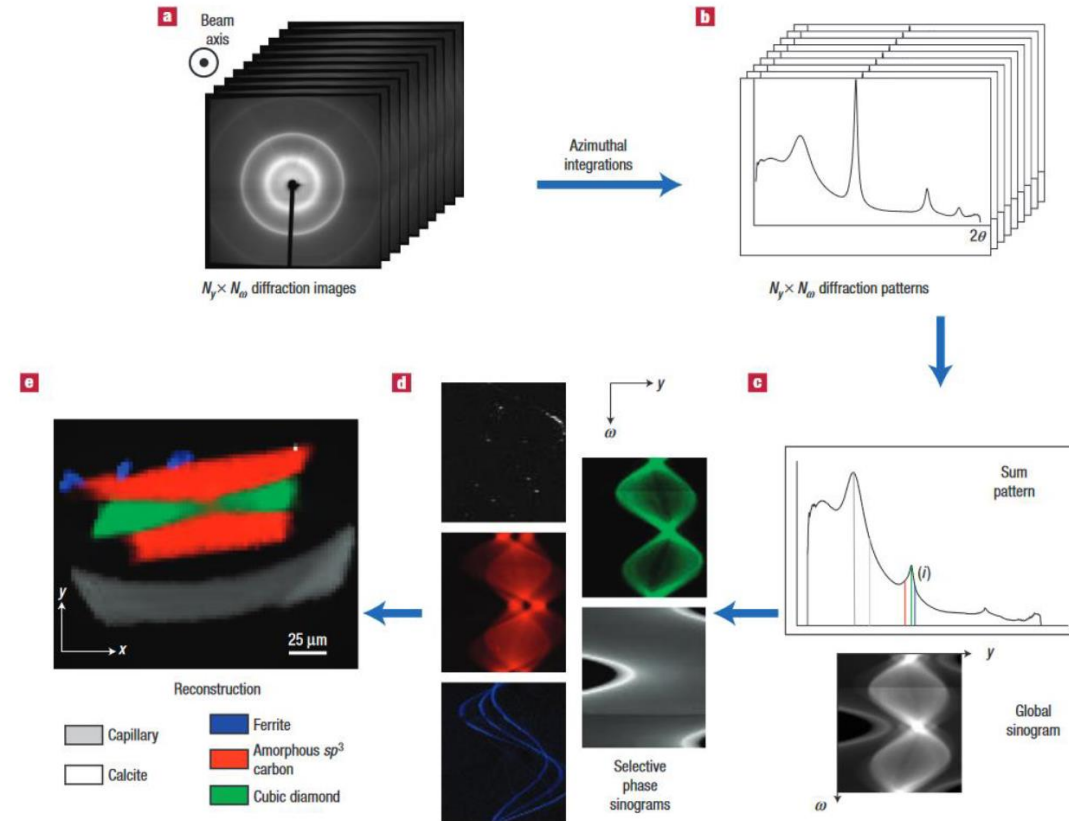
To measure local crystallinity

There are two types – DCT/XDT

Computationally intense

Resolution depends on beam size

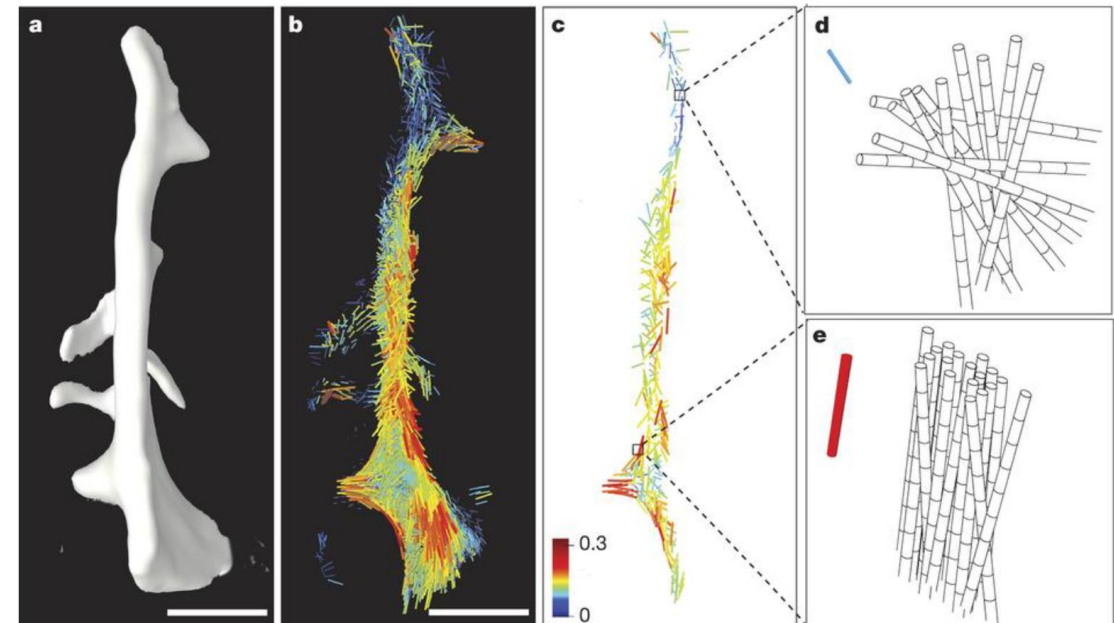
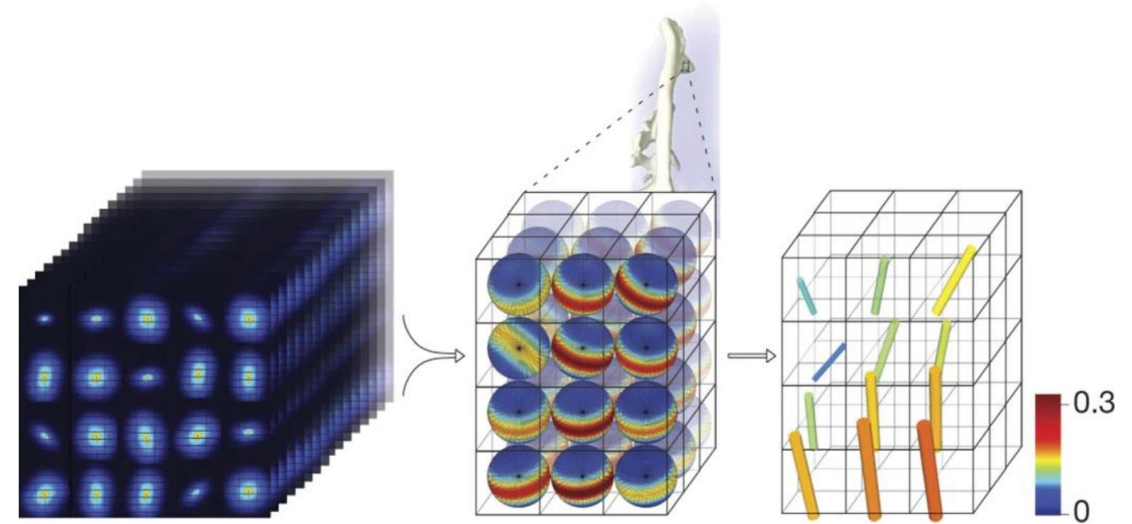
Lab based sources – not implemented



1. Henning Friis Poulsen, Three-dimensional X-ray diffraction microscopy: mapping polycrystals and their dynamics, Vol. 205 (Springer Science & Business Media, 2004).
2. P. Bleuet, et al., "Probing the structure of heterogeneous diluted materials by diffraction tomography," Nature materials7,468–472 (2008)
3. Wolfgang Ludwig et al., "High-resolution three-dimensional mapping of individual grains in polycrystals by topotomography," Journal of Applied Crystallography40, 905–911 (2007).
4. Peter Reischig et al., "Advances in X-ray diffraction contrast tomography: flexibility in the setup geometry and application to multiphase materials," Journal of Applied Crystallography46, 297–311 (2013).
5. W. Ludwig et al., "X-ray diffraction contrast tomography: a novel technique for three-dimensional grain mapping of polycrystals. i. direct beam case," Journal of Applied Crystallography41, 302–309 (2008).
6. G. Johnson et al., "X-ray diffraction contrast tomography: a novel technique for three-dimensional grain mapping of polycrystals. ii. The combined case," Journal of Applied Crystallography41, 310–318 (2008).
7. W. Ludwig et al., "Three-dimensional grain mapping by x-ray diffraction contrast tomography and the use of Friedel pairs in diffraction data analysis," Review of scientific instruments80,033905 (2009)

Modalities – SAXS Tensor tomography

- Absorption – scalar quantity
- 3D X-ray scattering vector – tensor quantity



1. G. Gullberg et al., "Tensor tomography," *IEEE Transactions on Nuclear Science* 46, 991–1000 (1999).
2. Marianne Liebi et al., "Nanostructure surveys of macroscopic specimens by small-angle scattering tensor tomography," *Nature* 527, 349–352 (2015).
3. Marianne Liebi et al., "Small-angle x-ray scattering tensor tomography: model of the three-dimensional reciprocal-spacemap, reconstruction algorithm and angular sampling requirements," *Acta Crystallographica Section A: Foundations and Advances* 74, 12–24 (2018)

Thank you!

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