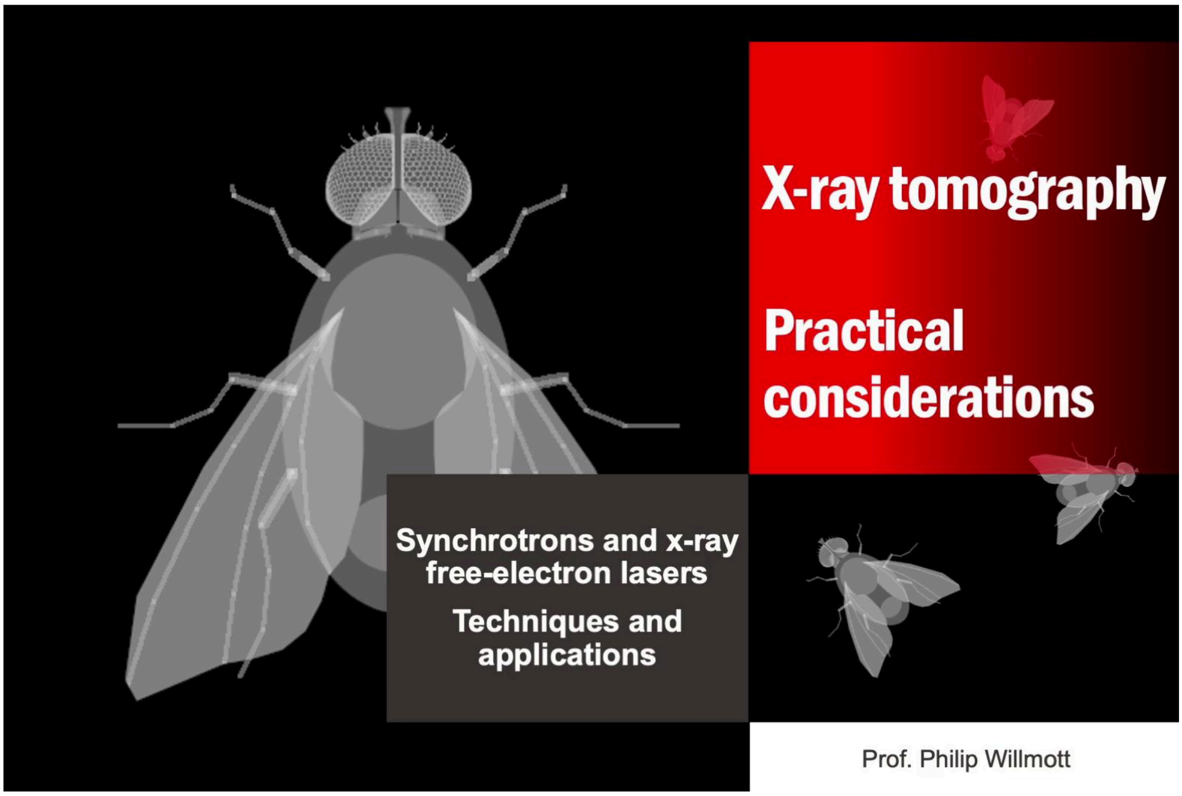
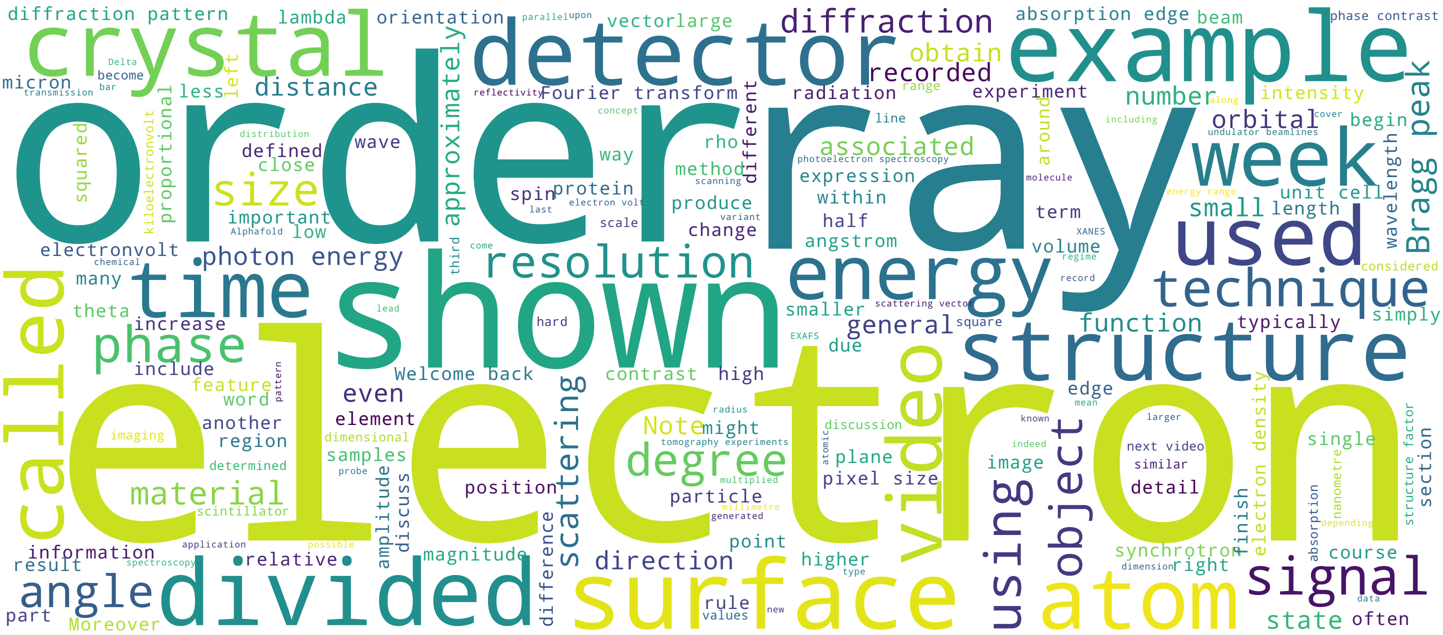
EPFL



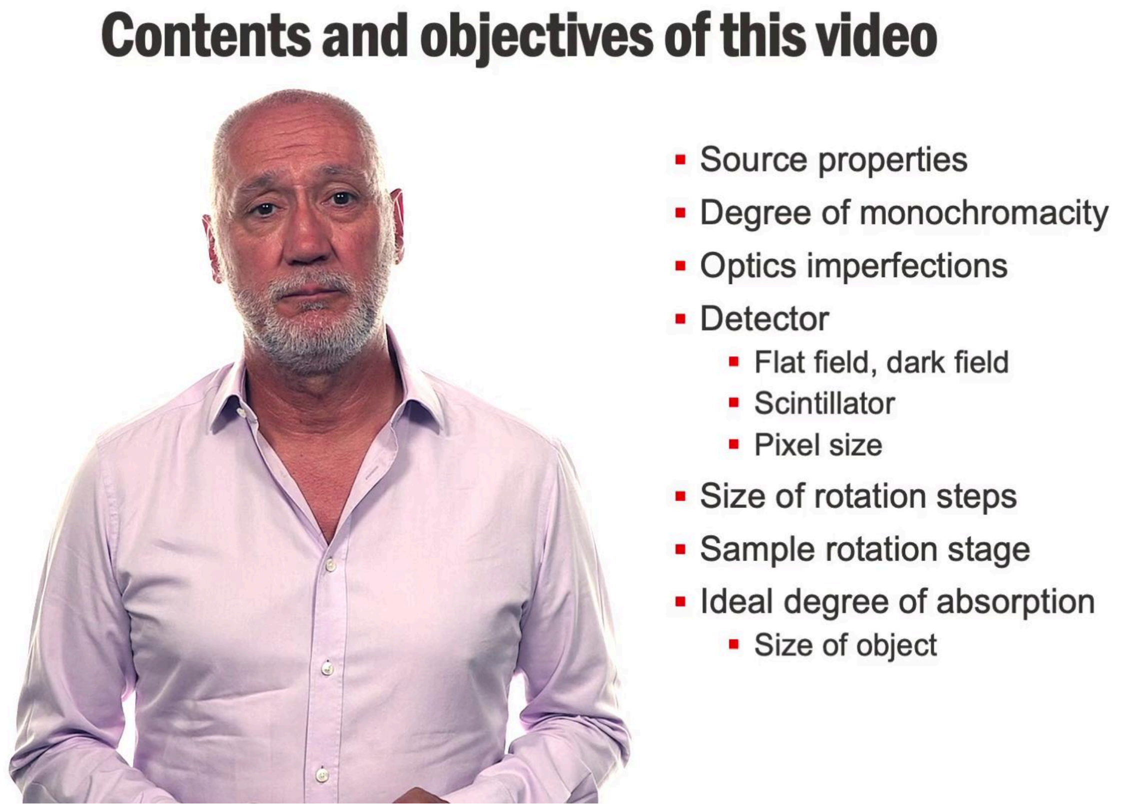
École polytechnique fédérale de Lausanne



Search MOOC

Video

EPFL



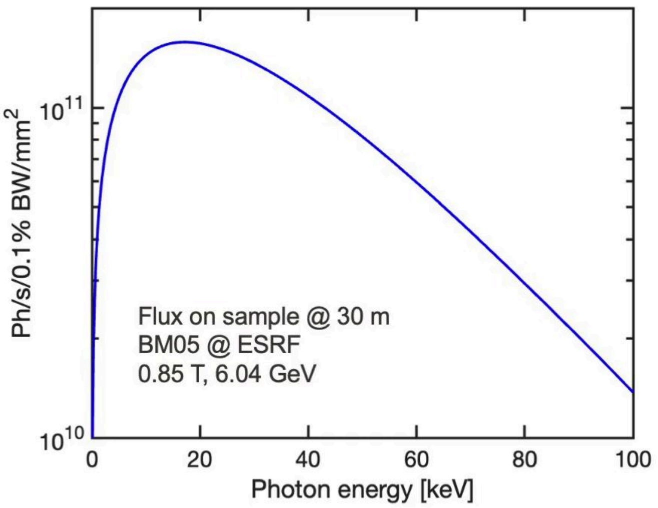
Hello again. This final video of the 1st section of this week in tomography basics, we will consider practical aspects associated with tomography beamlines from the different source types through the appropriate X-ray optics, and finally, aspects of detector and sample manipulation technologies. We finish with a brief discussion about the interrelationship between sample size, sample composition, and the used photon energy.

Notes

Summary

0m 05s

X-ray sources for tomography



- Typically somewhere between ca. 10 – 100 keV
- Bending magnets, superbends, wigglers, or wavelength shifters
  - Larger samples
  - Divergence ~ 1 – 10 mrad
  - Width @ 40 m ~ 100 mm
- Undulators
  - Smaller samples
  - Divergence ~ 50 µrad @ DLSRs
  - Width @ 40 m ~ 2 mm

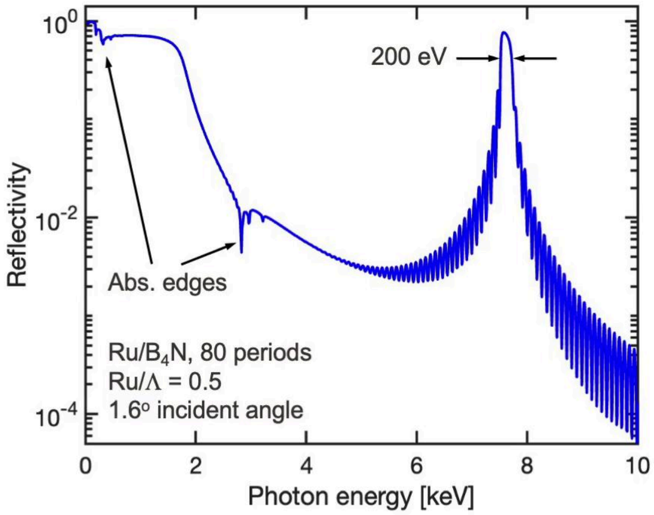
We begin upstream now with the X-ray source. XTM beam lines provide energies between approximately 10 kiloelectronvolts, all the way up to 100 kiloelectronvolts, or even higher. For example, the bending magnet BM18 hierarchical phase contrast tomography beamline, at the newly upgraded ESRF extremely bright source in Grenoble, used to map entire human organs with micron resolution, has an energy range that extends all the way up to 250 kiloelectronvolts, necessary to get through large objects, the size of a human body. A more typical spectrum is shown here on the left for the BM05 beamline, also at the ESRF, which has a useful energy range between 6 and 60 kiloelectronvolts. Note that bending magnets, superbend, wiggler, and wavelength shifter sources are all broadband, with generally larger vertical, but especially horizontal divergences than those associated with undulator beamlines, typically, of the order of 1 to 10 milliradians. This leads to beam widths, of the order of 10 centimeters at a distance of 40 meters from the source. Undulator beamlines in contrast have much tighter beams, and are usually reserved for samples on the millimeter scale or smaller.

Notes

Summary

0m 36s

Optics and detectors for tomography



- Tomography doesn't normally require a very narrow bandwidth from the monochromator
  - Si(111): $\Delta\nu/\nu \simeq 10^{-4}$ BW
  - Multilayers: $\Delta\nu/\nu \sim 0.01$ BW $\Rightarrow$ 100 x more flux
- Example BM05 @ ESRF
  - @ 1.6° incident angle
  - 1st Bragg maximum @ 7.6 keV
  - FWHM = 200 eV
  - $\Delta\nu/\nu = 0.026$

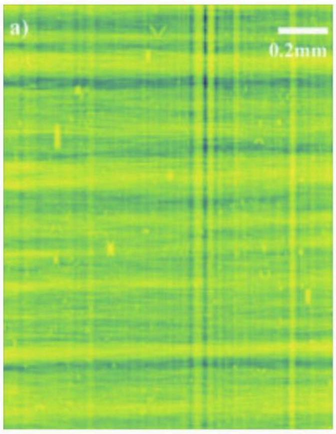
Tomography normally doesn't require large longitudinal coherence lengths, which thereby relaxes the specifications of the relative photon bandwidth of the source. While a silicon 111 monochromator provides a relative bandwidth of the order of 10 to the -4, multilayer monos typically have bandwidths a hundred times larger, providing concomitantly more photons on the sample. The BM05 beamline at the ESRF, has its first Bragg maximum for an incident angle of 1.6 degrees at 7.6 kiloelectronvolts, and a bandwidth of 200 electronvolts, or a relative bandwidth of 2.6%.

Notes

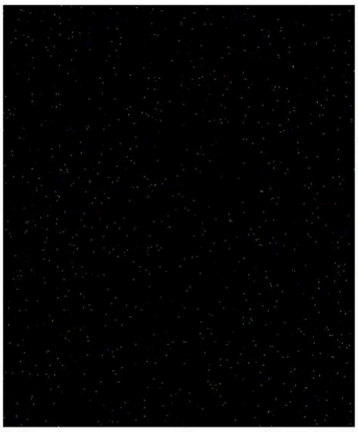
Summary

2m 09s

Optics and detectors for tomography



Flat field



Simulated dark-field image
with 1 in 200 pixels that are “hot”

- Recorded image on detector R
- Flat-field F
  - X-rays but no sample
- Dark field D
  - No x-rays, no sample
- Corrected image N

$$N = \frac{R - D}{F - D}$$

Left image from L. Hu *et al.*, https://doi.org/10.1364/OE.417030

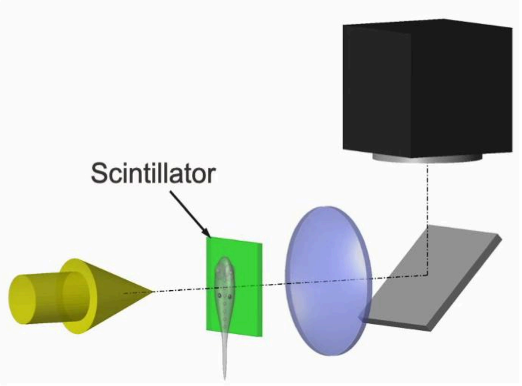
Now, a common bugbear of direct imaging X-ray techniques, is the quality and homogeneity of the illuminating beam. In general, each optics component, whether it be a mirror or a monochromator crystal, will deteriorate the beam profile leading to the mantra that "the best optics is no optics". In order to overcome these irregularities, that often manifest themselves as stripes in the field of view, flat fields are recorded, and the recorded images of samples divided by this. Moreover, the detector can have a non-homogeneous response that includes not only moderate variations in sensitivity from pixel to pixel, but also hot pixels that must often be masked out. Note that in the case of undulator beamlines, the beam divergence is generally sufficiently small that no collimation of the beam is needed, and thus collimating mirrors are dispensed with. Hence, a raw image R, will be corrected first by removing hot pixels found in a dark image field D, for a detector that has all X-rays blocks, and then divided by a flat field image that has also been corrected for the dark field of pixels.

Notes

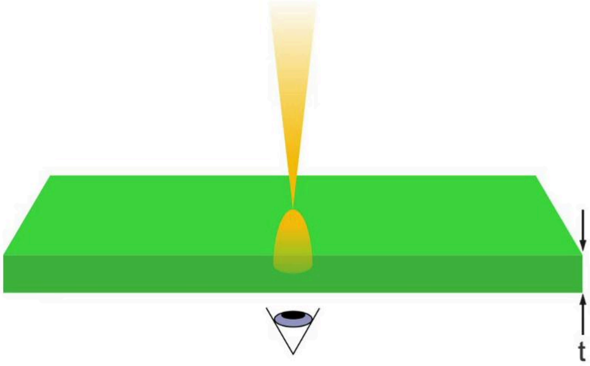
Summary

2m 53s

Optics and detectors for tomography



- Scintillators
  - Speed required?
    Thick scintillators ~ 100 μm
  - Resolution required?
    Thin scintillator ~ 10 μm
  - Intrinsic resolution r ~ t/10
  - Match pixel size Δ to resolution: Δ ~ r/3



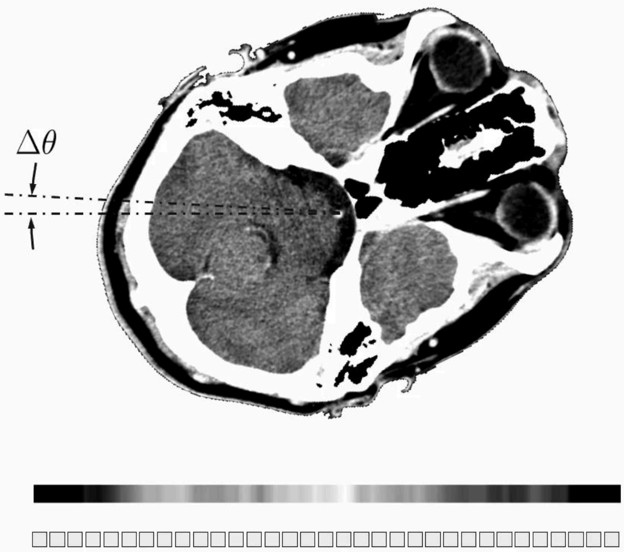
Detectors in tomography, are typically either CCDs or CMOS devices. The large pixel size of hybrid photon counting pixel detectors, normally precludes them from their use in tomography. The transmitted radiation after the sample is captured using a scintillator plate to produce a visible or near-visible image, and this is magnified onto the detector using standard optics. The efficiency of the scintillator is determined by the material and dopant-type in concentration. In general, the thicker the scintillator, the poorer will be the resolution as the light is scattered laterally as it passes through the scintillator. As a rule of thumb, fast tomography experiments sacrifice some resolution and use thicker scintillators of the order of 100 microns in order to obtain a sufficient signal to noise ratio in the limited exposure times. On the other hand, if resolution is most important, the scintillator thickness may be as small as 10 microns. The intrinsic resolution, that is, ignoring any broadening due to the detector, is approximately a tenth of the scintillator thickness. Note that magnification using a microscope lens increases the resolution accordingly, though of course, at the cost of signal intensity. Lastly, as a rule of thumb, one should match the pixel size of the detector delta to be approximately one third of the desired resolution.

Notes

Summary

4m 15s

The Crowther criterion



- $\Delta\theta$?
- Sampling theorem:

$$N_\theta = \pi \, N_p/2$$

$$N_\theta \, \Delta\theta = \pi$$

$$\Rightarrow \Delta\theta = \frac{2}{N_p}$$

$$\Delta\theta = \frac{d}{D}$$

Detector row, N_p pixels, linear size = d

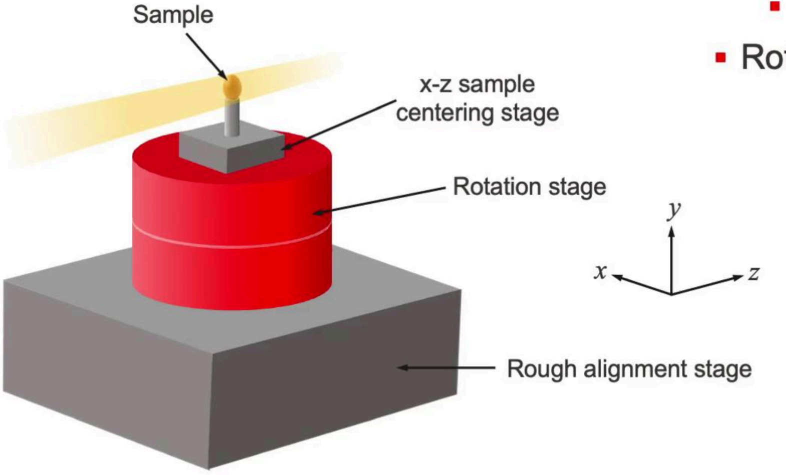
The Crowther criterion determines Delta theta, the angular step size one should choose for a desired spatial resolution. From sampling theorem, the number of sampling steps N theta equals pi multiplied by half the number of relevant pixels in the detector row N_p. But these N theta steps should cover 180 degrees or pi radians from which we obtain an angular step size of 2 divided by N_p. This can alternatively be expressed as Delta theta is equal to d divided by D, where d is the linear pixel size, and D is the linear sample extent.

Notes

Summary

5m 51s

The sample manipulator



- Drift in x, y, z
  - ~ few nm
- Wobble in sample-rotation axis
  - < μrad
- Rotation rates up to > 100 Hz

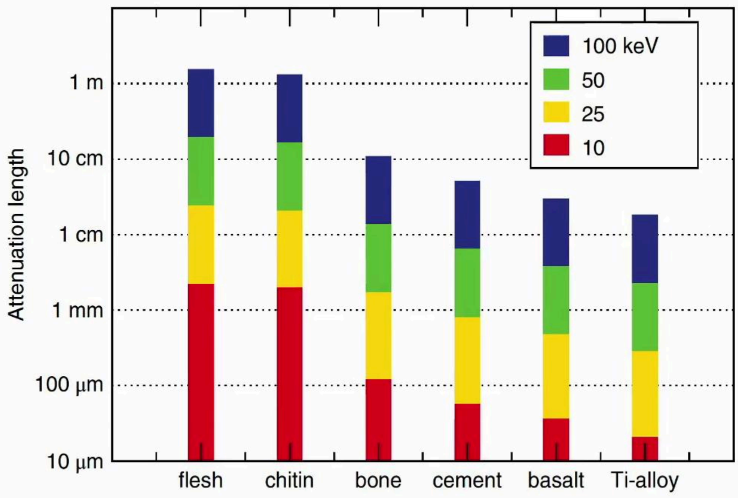
Any sample manipulator requires linear movements in all 3 orthogonal directions, plus a rotation axis. Ideally, one wants drifts in linear movements of just a few nanometers and a rotational axis wobble of less than a microradian, and that for rotation rates that today can easily exceed 100 hertz.

Notes

Summary

6m 37s

Degree of sample absorption



- Sample, characteristic size in x-z plane = D
- Optimal absorption coefficient

$$\mu_{\text{opt}} = 2/D$$

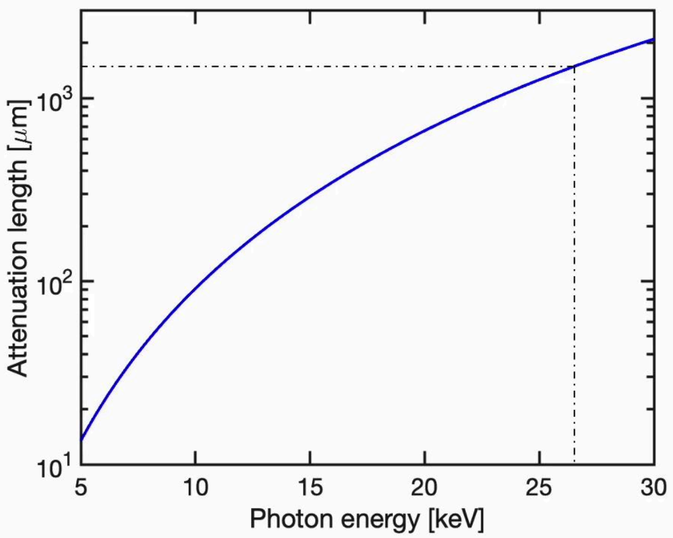
Finally, for a sample which has a characteristic length D, in the horizontal plane of propagation, the optimal absorption coefficient should be 2 divided by D. This criterion thus dictates the best photon energy to use. We see on the left typical values of 1 upon mu for common materials investigated in synchrotron based absorption tomography experiments.

Notes

Summary

7m 00s

Degree of sample absorption



- Sample, characteristic size in x-z plane = D
- Optimal absorption coefficient

$$\mu_{\text{opt}} = 2/D$$

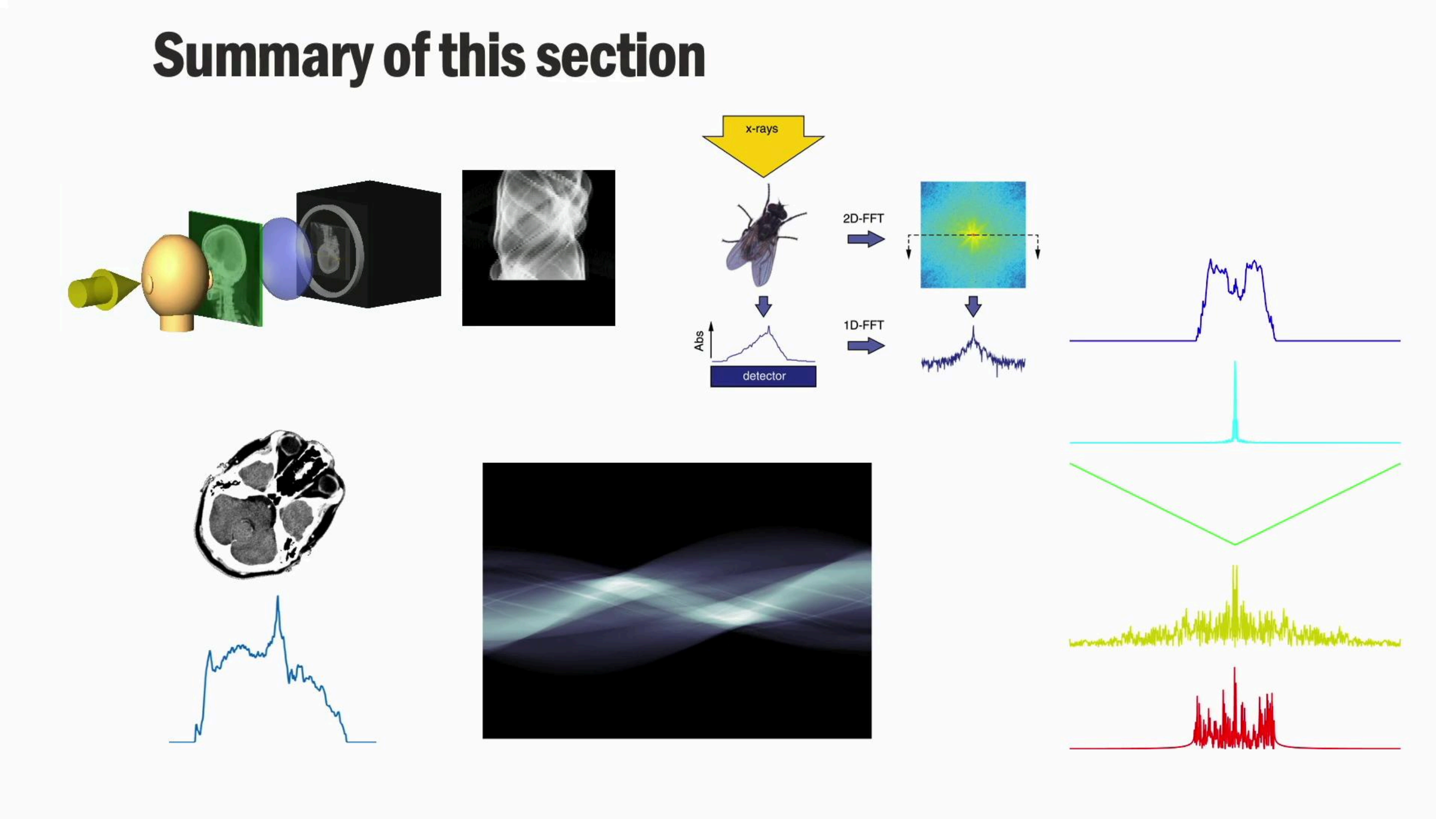
- e.g. fossil sample
  - D = 3 mm
  - Fossil density = 2.71 g/cm^3
  - Attn length = $1/\mu_{\text{opt}}$ = 1.5 mm
  - ⇒ $h\nu_{opt}$ = 26.5 keV

As an example, a fossil sample may be approximately 3 millimeters in size and come from rock with an average density of 2.71 grams per cubic centimeter. The optimal attenuation length is thus 1 and half millimeters, half of 3 millimeters, resulting in an optimal photon energy of 26.5 keV. There is, of course, quite some flexibility around this value.

Notes

Summary

7m 25s



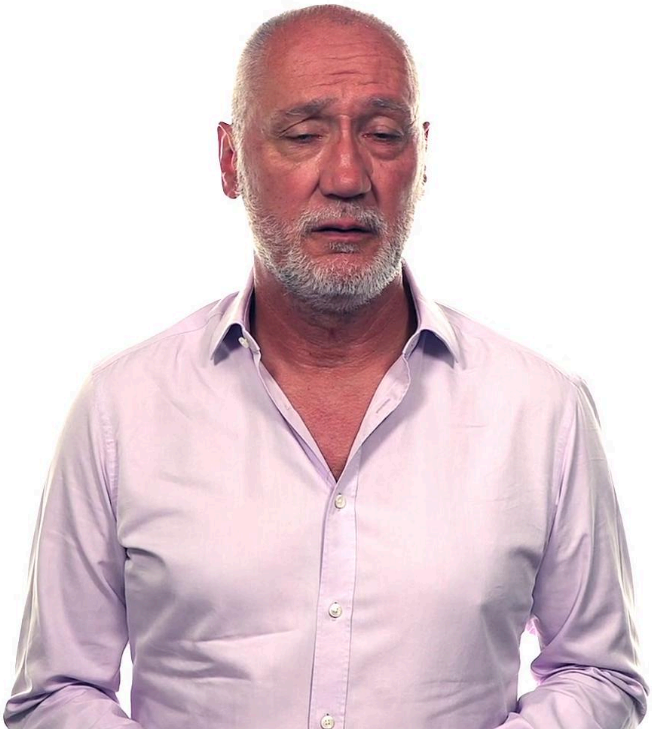
To summarize this first section of Week 5, we have been discussing tomography experiments in general, so far concentrating on absorption contrast. We considered the Radon transform and how sinograms are generated. We then went through the mathematical derivation of the Fourier slice theorem and the need to remove the halo artefact of simple unfiltered back projections, which we achieve by the use of frequency domain filters.

Notes

Summary

7m 51s

In the next section...



In the next section, we will discuss phase-contrast tomography and fast tomography, techniques used primarily on soft condensed matter and biological samples.

Notes

Summary

8m 21s