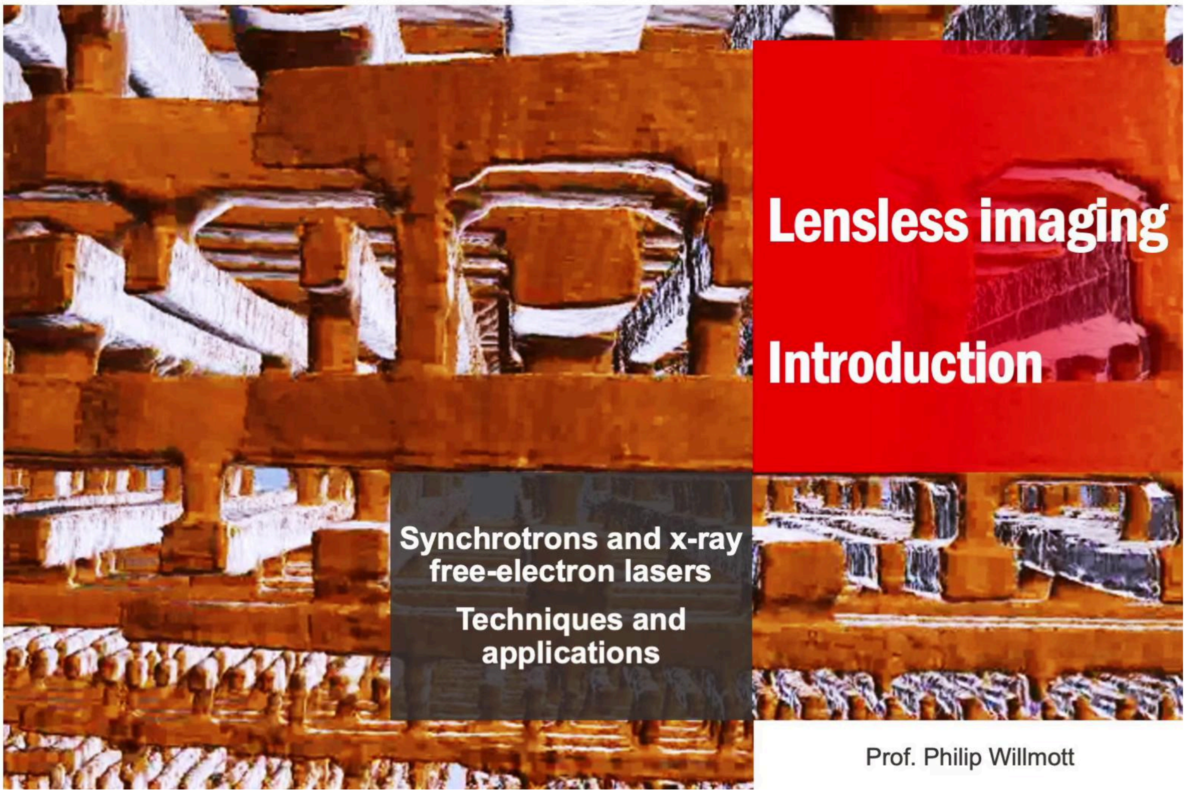
EPFL



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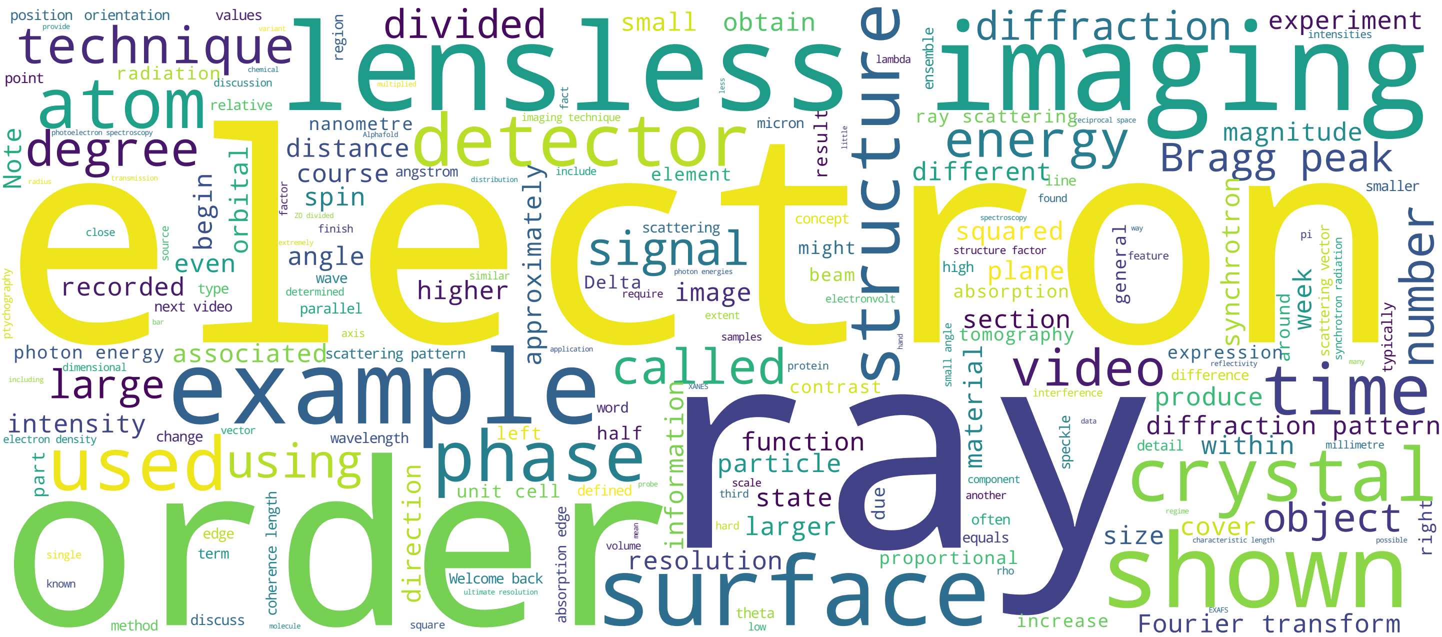


Search MOOC

Video

EPFL

Contents and objectives of this video

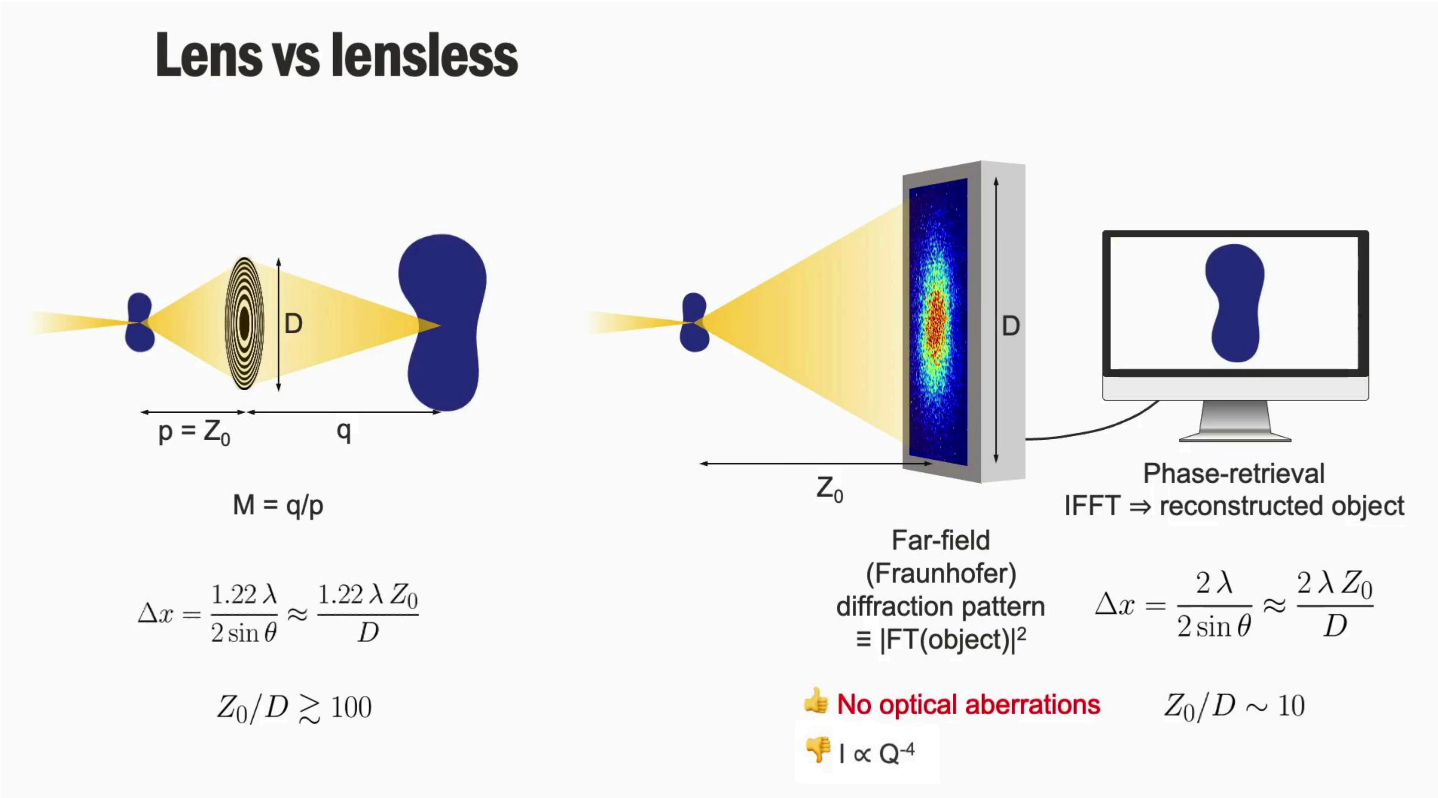
- Imaging with lenses v lensless imaging
- Lensless imaging vs SAXS
- Speckle

Welcome back to the sixth and final week of this introductory course on synchrotron radiation, in which we will discuss imaging techniques that don't use lenses to form images, though lenses can be and mostly are used to form a focal spot on the sample. These are thus generally termed as being lensless imaging techniques. We begin by seeing how these differ from more conventional microscopies and from small-angle X-ray scattering, or SAXS. Incidentally, we will also include in the last week scanning SAXS tensor tomography, as this uses similar experimental approaches as does ptychography. To understand lensless imaging, one must first understand the concept of speckle, which we will cover in this first video.

Notes

Summary

0m 05s



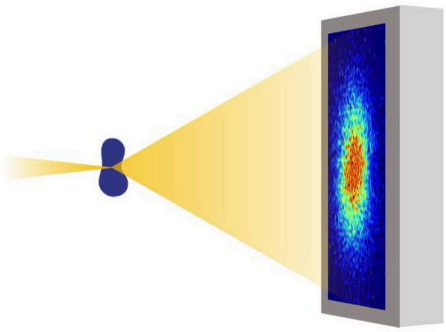
How does lensless imaging differ from imaging using a set of lenses associated with conventional microscopes? In imaging with lenses, the ultimate resolution is given by the Abbe condition, which for X-rays is accurately approximated by Delta X is equal to 1.22 Lambda Z0 divided by d. Values for Z0 divided by d are typically greater than 100, meaning that for angstrom radiation, the ultimate resolution, is larger than 10 nanometres or thereabouts under ideal conditions. Now, in contrast, lensless imaging simply records the far-field scattering pattern produced by a coherently illuminated object. This is nothing more than the absolute square of the Fourier transform of that scattering object. In order to obtain a reconstruction of the object, one must retrieve the phases via some algorithm, as is always the case in X-ray scattering. Now, in lensless imaging, the ratio, Z0 divided by d, is approximately equal to 10, allowing ultimate resolutions close to one nanometre. Another important advantage of lensless imaging is that there are no optical aberrations. A major challenge, on the other hand, is the fact that on average, the signal intensity drops with the inverse fourth power of the scattering vector, thus requiring high fluxes and detectors with large dynamic ranges.

Notes

Summary

0m 58s

Lensless imaging and SAXS



- Also "coherent x-ray diffractive imaging" CXDI
- Coherent illumination of sample
- Transverse (spatial) coherence

$$l_c^{(t)} = \frac{\lambda}{2\Delta\theta} = \frac{\lambda R}{2D}$$

- Lensless-imaging beamlines
  - Long source–sample distance (R)
  - Small source size (D)
  - Highly collimated beam (θ)
  - Transverse coherence length ~ 200 – 1000 μm
  - Minimize optical elements that disrupt wavefront
- DLSRs: increase in coherent flux ~ 10^3 – 10^4!!

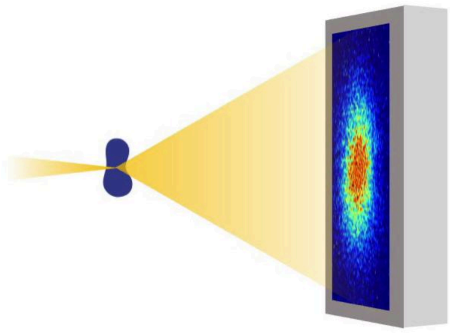
Lensless imaging, also known as Coherent X-ray Diffractive Imaging, requires the coherent illumination of the sample. The transverse or spatial coherence length is determined by the degree of emittance of the beam incident on the sample. The tighter and more parallel the beam, the higher will be the coherence. Consequently, lensless imaging beamlines are characterised by their having long source to sample distances, small source sizes, and highly collimated beams, resulting in coherence lengths, which can be as large as one millimetre. They all use undulators as a source. In general, in order to preserve the quality of the X-ray wavefront, the number of optical elements are also kept to a minimum. The capability of these beamlines received a huge boost with the recent advent of diffraction-limited storage rings.

Notes

Summary

2m 36s

Lensless imaging and SAXS



- Diffraction pattern
  - Noncrystalline samples
    - In forward-scattering direction only
  - Crystalline objects
    - Convolution of diffraction pattern due to periodicity and 'shape function' defining boundary of object
    - ⇒ regular array of replicas of same pattern
    - Bragg-CXDI

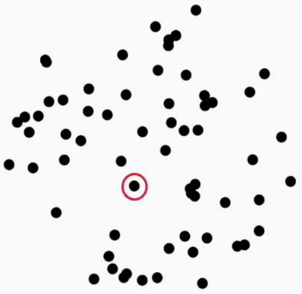
The scattering or diffraction pattern recorded in lensless imaging need not come from crystalline samples, and indeed, many experiments are performed on biological samples with no long-range order. In this case, the signal can only be found in the forward scattering direction. For crystalline objects, the encoded scattering pattern is repeated across a regular array in reciprocal space as a consequence of the convolution theorem. Signal around selected Bragg peaks can thus be recorded in so-called Bragg Coherent X-ray Diffractive Imaging. We'll cover this in the third and last video of this section.

Notes

Summary

3m 34s

Lensless imaging vs SAXS



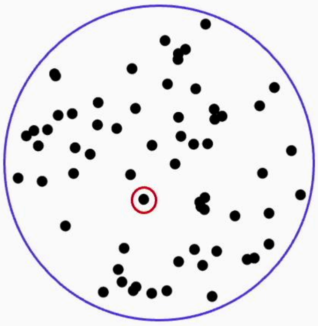
The experimental setup for small-angle X-ray scattering and lensless imaging are very similar, and many lensless imaging beamlines carry out both types of experiment. But the fundamental difference between the two, is in the degree of coherence of the incident beam. Let's consider this ensemble of n identical particles illuminated by an X-ray beam.

Notes

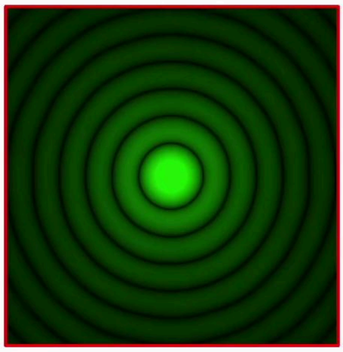
Summary

4m 18s

Lensless imaging vs SAXS



Ensemble of
n identical spheres



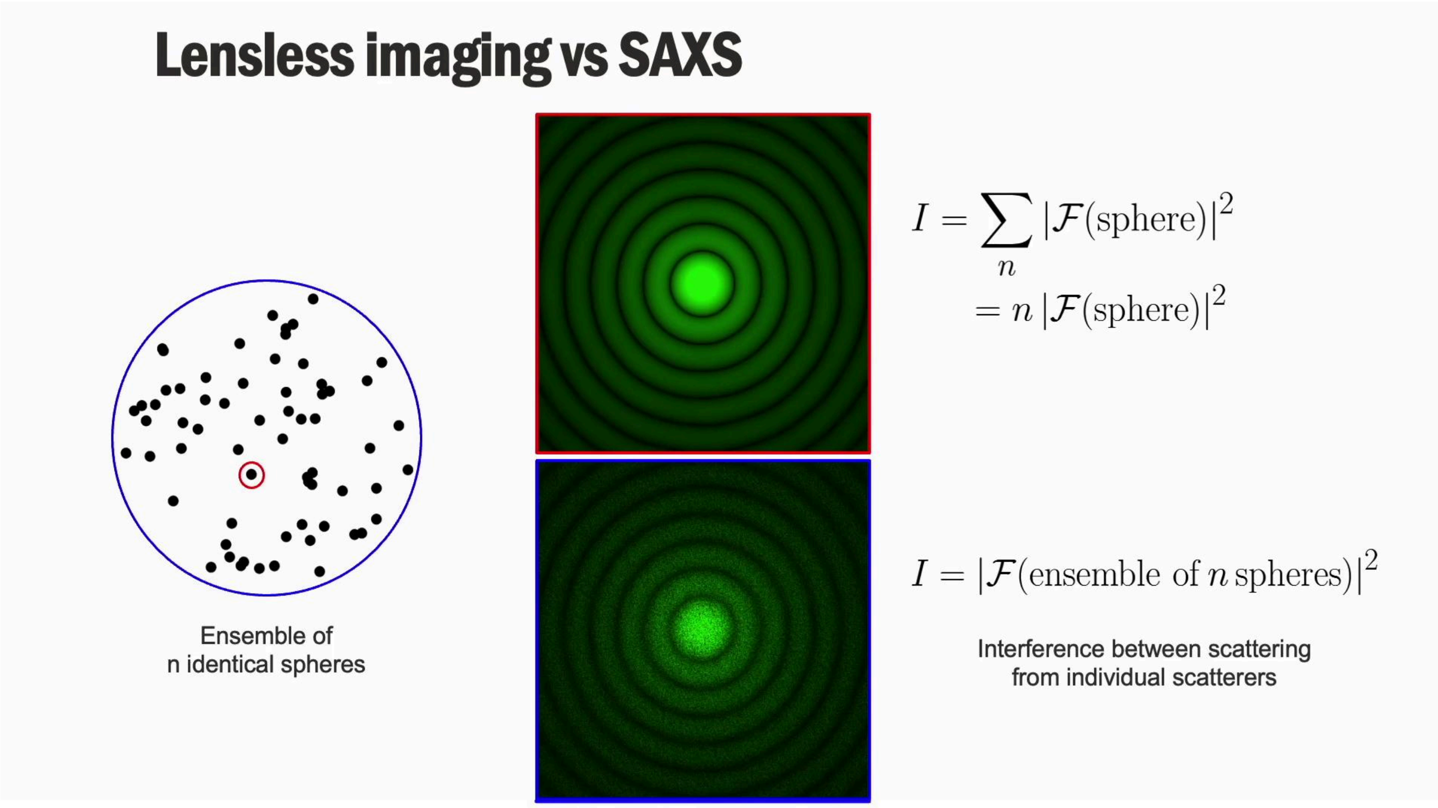
$$I = \sum_n |\mathcal{F}(\text{sphere})|^2 = n\,|\mathcal{F}(\text{sphere})|^2$$

If the coherence length is small, and can only cover a single particle, the scattering pattern will reflect the shape function of that particle, and the signal is formed by the incoherent addition of individual contributions from each particle, the intensity thus being proportional to the number of illuminated particles n. This is just SAXS.

Notes

Summary

4m 44s



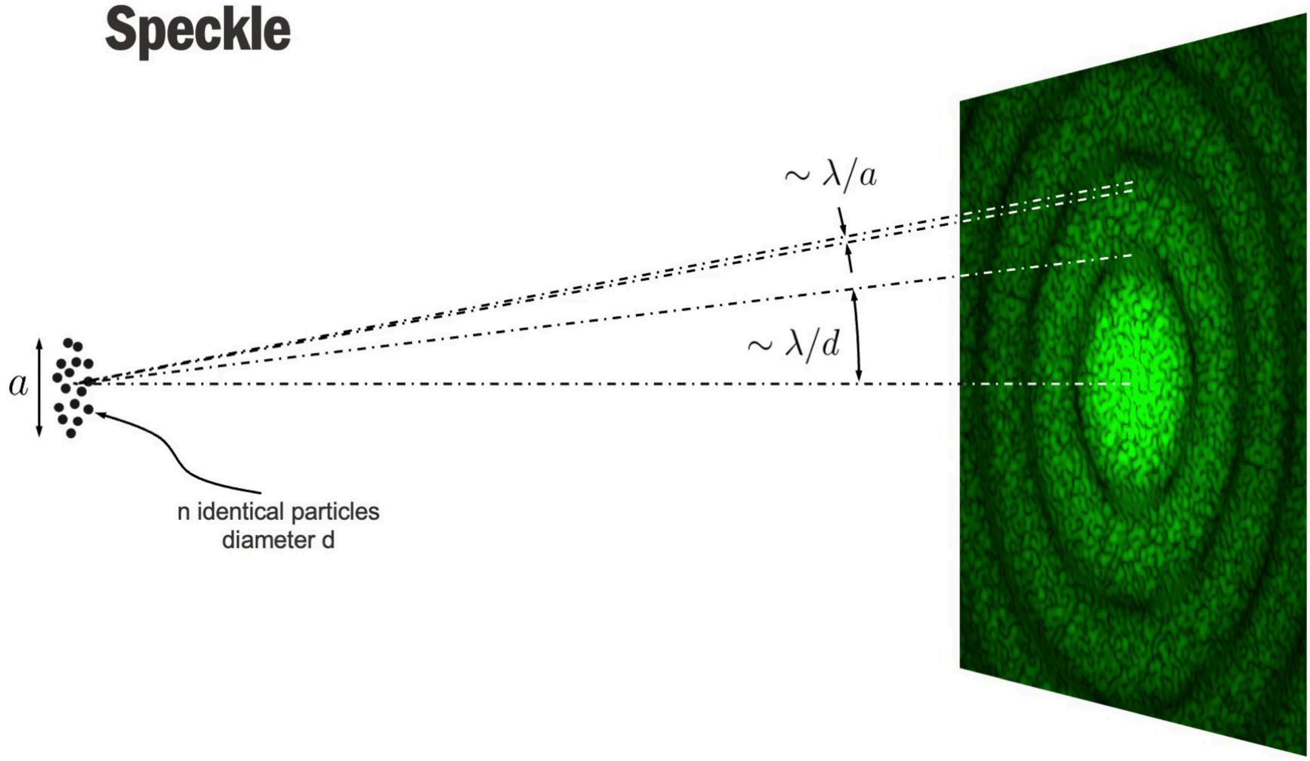
If, on the other hand, the transverse coherence length is large and covers the entire ensemble, the intensity is proportional to the absolute square of the Fourier transform of that ensemble. The scattering amplitudes, rather than their intensities, therefore, add up vectorially, leading to interference and a graininess in the pattern, which is referred to as speckle.

Notes

Summary

5m 14s

Speckle



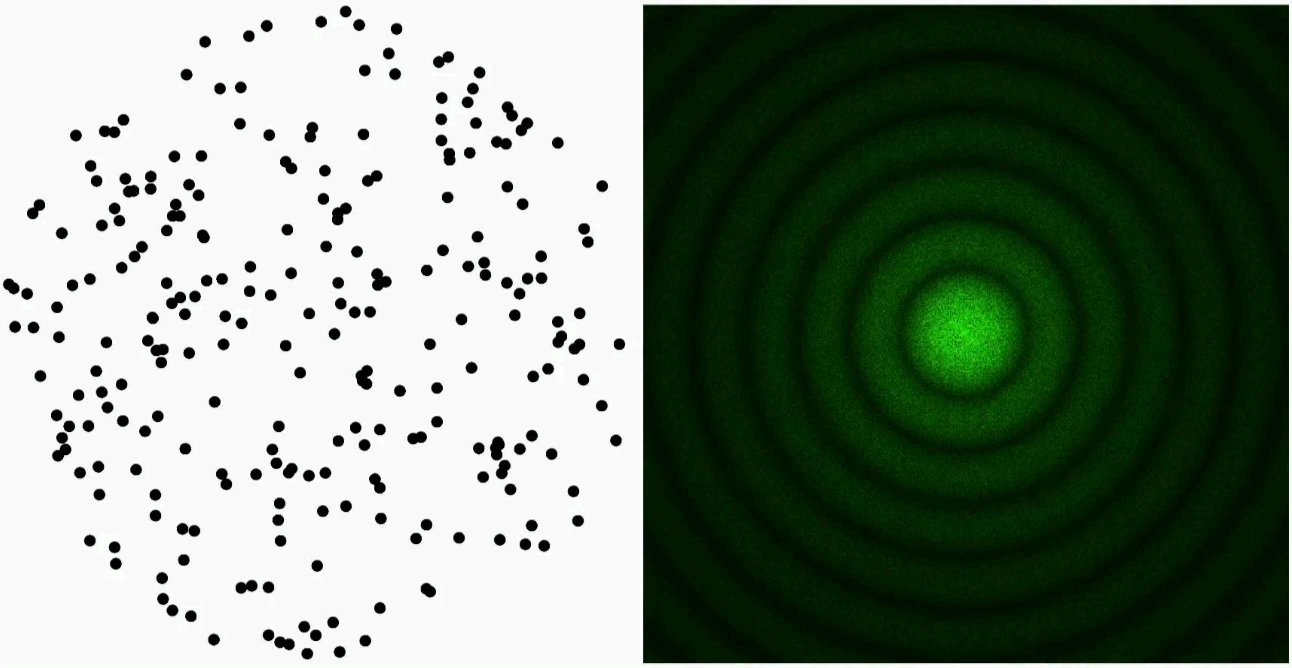
Speckle has got two characteristic lengths, or more precisely, angles. The envelope signal encompasses angles of the order of lambda divided by d, where d is the characteristic size of the individual scattering centres. The speckle, on the other hand, varies in intensity across the subtended angles of the order of lambda divided by a, where a is the extent of the whole illuminated ensemble.

Notes

Summary

5m 41s

Speckle



Progression of speckle pattern for increasing ensemble of identical spheres with constant average areal density

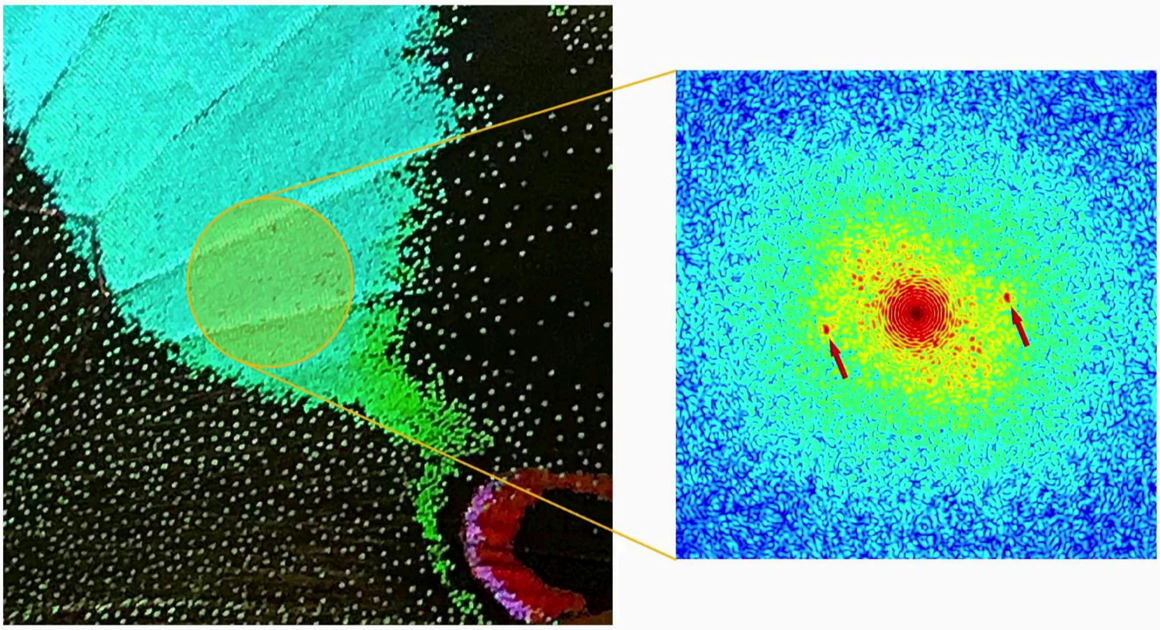
Let's look at how a diffraction pattern changes, as the number of illuminated particles increases. With just one particle, we obtain the SAXS pattern. We now double the number of particles step by step, to 2, 4, 8, and so on, and position them quasi-randomly, while ensuring also that the particle density on average remains the same. As we do this, the extent of the ensemble therefore increases approximately by a factor of the square root of two, and the detailed graininess or speckle reduces in size by this same factor.

Notes

Summary

6m 10s

Speckle



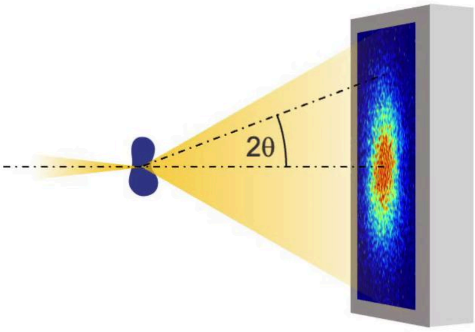
Now, if we look at another simulation of something perhaps a little more interesting than a set of spheres, namely part of a butterfly wing, we also see speckle, with characteristic lengths inversely proportional to the diameter of the illuminated area. Looking carefully at the pattern, you might recognise two sharp features opposite one another, relative to the centre of the pattern. These are caused by the almost perfectly periodic repetition of the butterfly scales.

Notes

Summary

6m 48s

Lensless imaging and DLSRs



- Signal strength $\propto 1/Q^4 \simeq 1/\theta^4$
- 10^4 increase in coherent flux $\Rightarrow$ x 10 increase in resolution ~ nm or smaller
- Sample manipulation accuracy becomes impossible
  - Becomes less competitive with e.g., electron imaging
- Exploit higher flux otherwise
  - Faster scanning
  - Higher photon energies
    - Less integrated dose
    - Larger penetration depths

As we've already briefly mentioned, DLSRs are opening new vistas in lensless imaging by increasing the available coherent flux by as much as four orders of magnitude. As the signal strength drops with the inverse fourth power of the scattering vector Q, we could therefore expect an increase in resolution using DLSRs by up to an order of magnitude. That said, the resolution is also determined practically by the accuracy of sample positioning and vibrations. It also turns out that for resolutions much less than a few nanometres, X-ray lensless imaging becomes less competitive than, for example, electron-based imaging, particularly with regards to sample dosage. It therefore makes sense to exploit this increase in coherence flux, in other ways than just simple improvements in resolution, for example in faster scanning and in the use of higher photon energies, which induce a smaller integrated dose and penetrate deeper into the sample.

Notes

Summary

7m 18s

In the next video...

In the next video, we consider some practical aspects of lensless imaging, including the sampling density and the Nyquist frequency, oversampling, and redundancy.

Notes

Summary

8m 29s