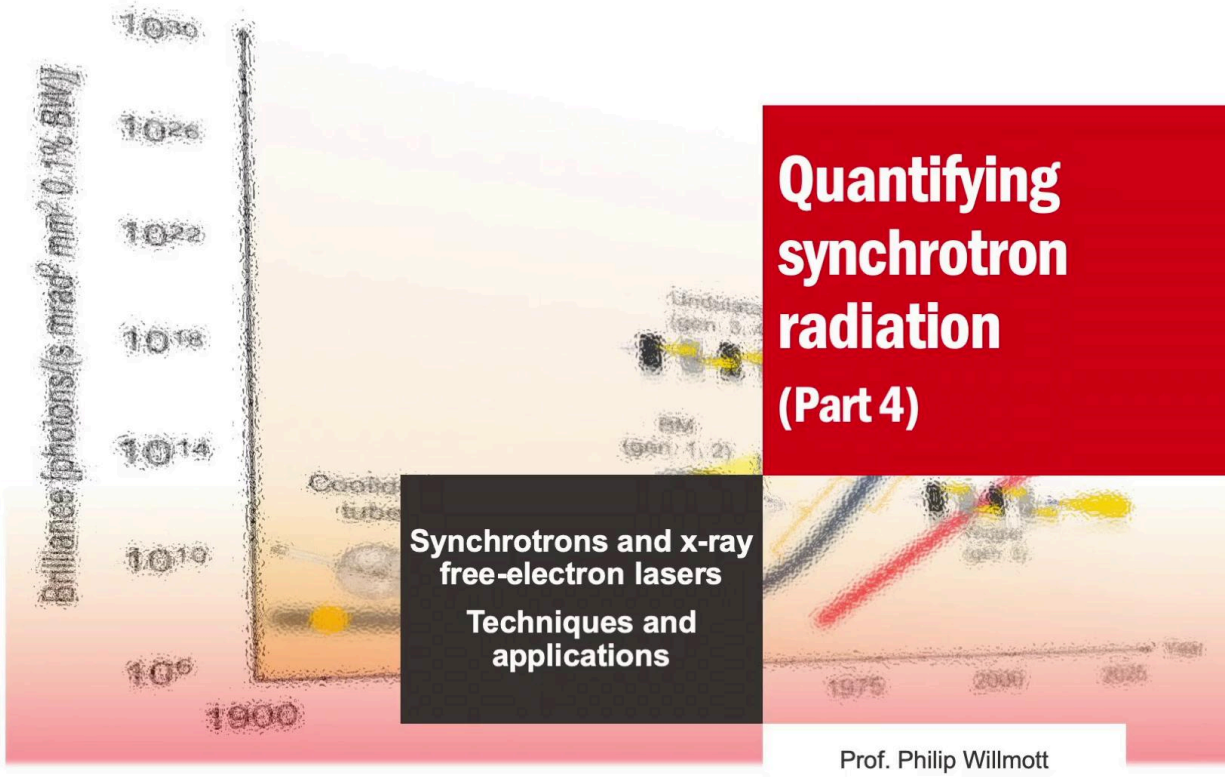
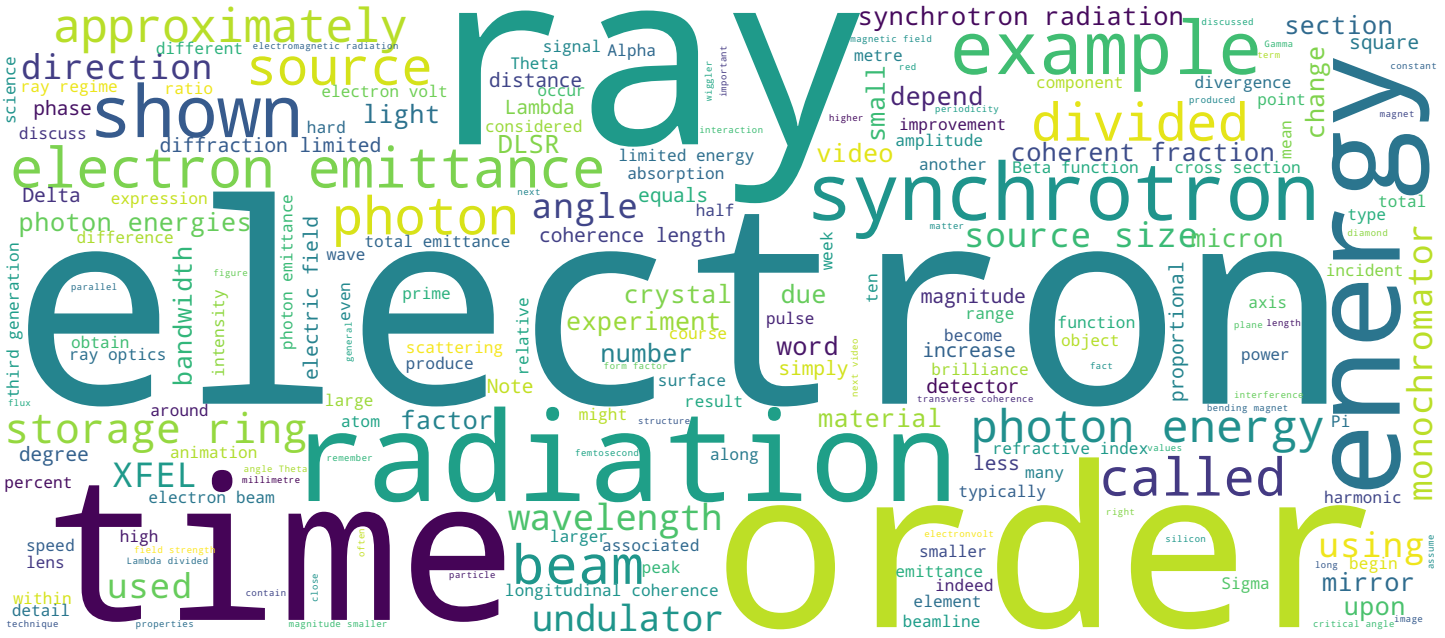


École polytechnique fédérale de Lausanne



Search MOOC

Video

EPFL

Contents and objectives of this video

- Concept of coherence
- Transverse and longitudinal coherence
- Coherent fraction
- Scrambling of coherence by imperfect optics

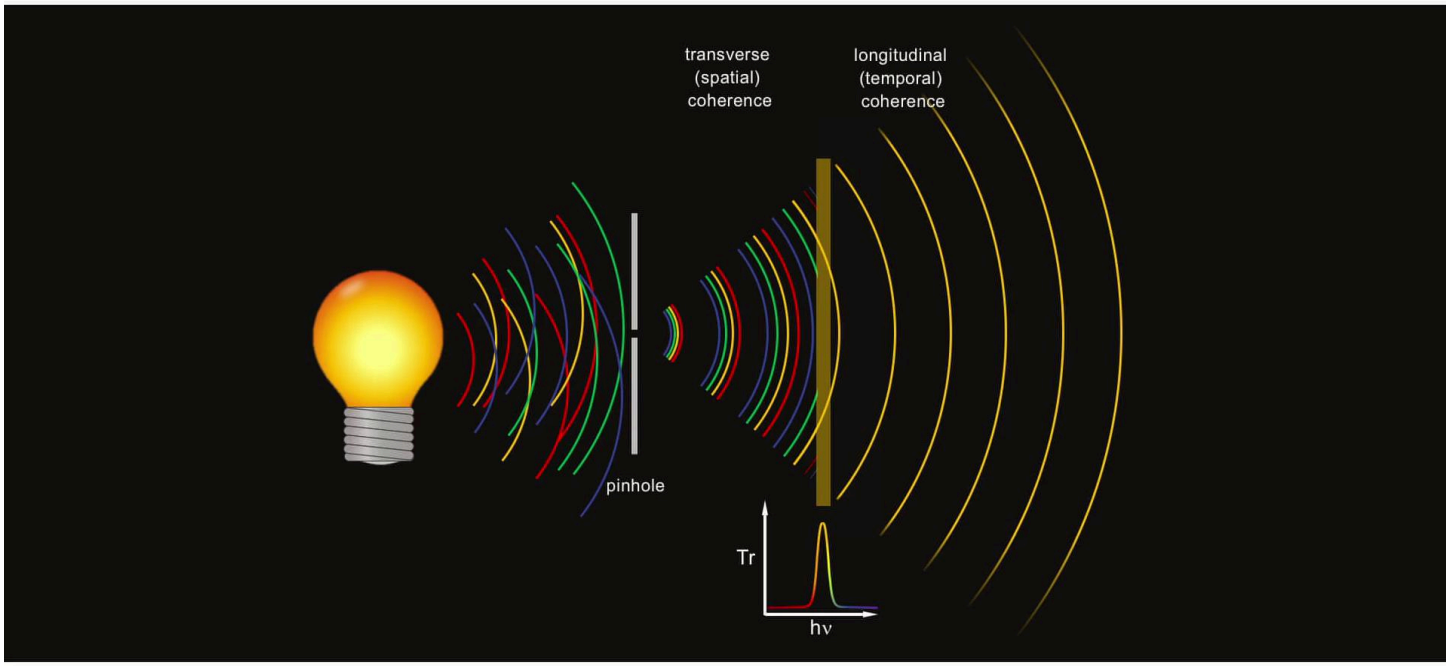
In this last video of the second of three sections this third week, we consider coherence, including transverse coherence, which depends on the source size and divergence of the photon beam— in other words, it depends on the admittance— and longitudinal coherence, which depends on the bandwidth. The coherent fraction of a beam is critically important in lensless imaging techniques and photon correlation spectroscopy, plus also in phase contrast, tomography. Lastly, we consider the mantra of the X-ray imaging scientist that the best X-ray optics are no X-ray optics, and the characteristics we need to consider when trying to preserve coherence when manipulating X-ray beams with dispersive and reflecting optical elements.

Notes

Summary

0m 04s

Coherence



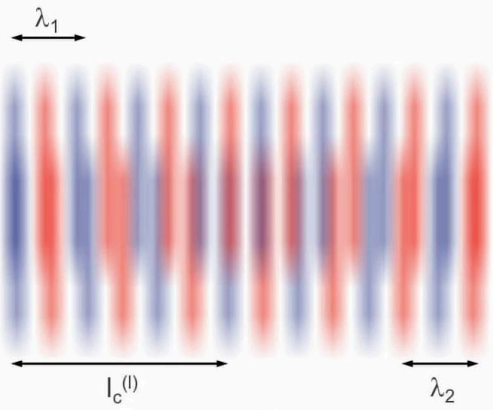
Let's ponder for a moment how we might improve the coherence of a light bulb. First, let there be light bulb. And I see it isn't very good. For a start, it's not a point source. And secondly, it's broadband. So how should we pimp it up a bit? Well, we can reduce the effective source size by inserting a simple pinhole. This imparts an improvement in so-called transverse or spatial coherence, which depends only on the emittance or, in other words, the source size and divergence. Next, we introduce some sort of dispersive element, such as a monochromator, which allows through only a narrow band of frequencies. This improves the so-called longitudinal or temporal coherence.

Notes

Summary

0m 54s

Types of coherence



$$l_c^{(l)} = \frac{\lambda^2}{2\Delta\lambda}$$

Longitudinal (temporal) coherence

@ 1 Å ~ 1 μm [Si(111) mono]

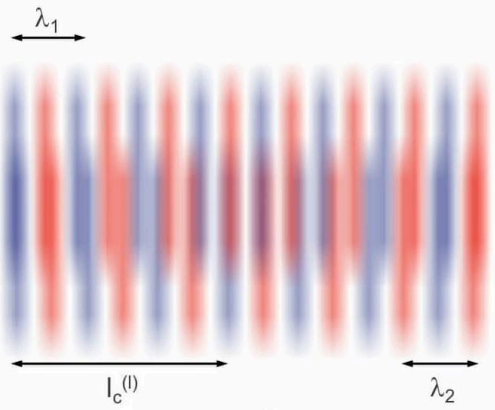
Now, we need to quantify these concepts. Bound up in the figure of merit of brilliance are the parameters that quantitatively define coherence, namely the emittance and the relative spectral bandwidth. Because no X-ray source has an infinitely narrow bandwidth, the different frequencies within the bandwidth of the beam will sooner or later drift out of phase with one another. The time required for the phase between two sinusoidal waves differing in frequency by an amount Delta Nu to change by Pi radians, that is, from fully constructive to fully destructive, is simply one upon two Delta Nu, and is called the longitudinal coherence time Delta Tau C L. During that time, the waves have travelled in vacuum a distance L-C-L, which is equal to C Delta Tau C L upon two, referred to as the longitudinal or temporal coherence length of the light source, given by L C L is equal to Lambda squared upon two Delta Lambda. The longitudinal coherence after filtering by a monochromator is usually determined by the quality of the crystal or grating used in that monochromator, which defines Lambda divided by Delta Lambda. This can easily exceed 10 to the four, and the longitudinal coherence length can, as a result, be several microns, even in the hard X-ray regime.

Notes

Summary

1m 44s

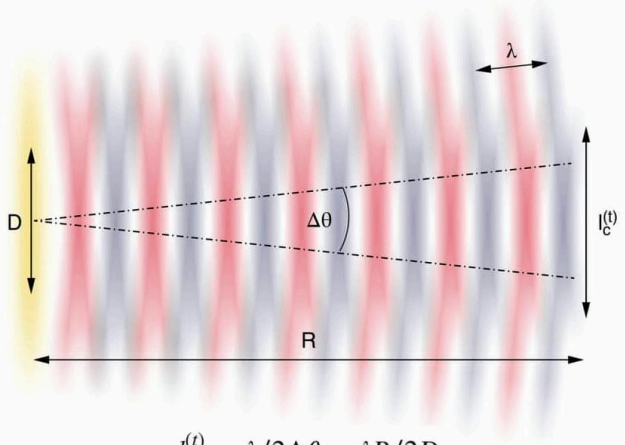
Types of coherence



$$l_c^{(l)} = \frac{\lambda^2}{2\Delta\lambda}$$

Longitudinal (temporal) coherence

@ 1 Å ~ 1 μm [Si(111) mono]



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

Transverse (spatial) coherence

@ 1 Å ~ 100 μm (R = 40 m)

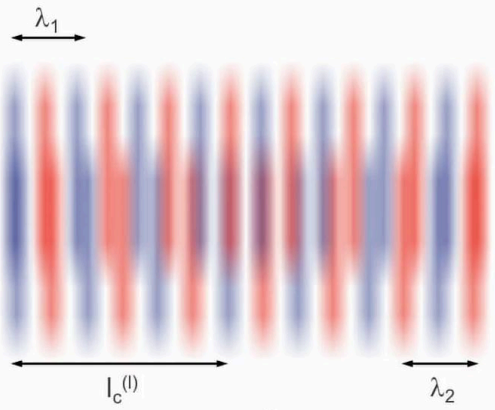
We define the transverse coherence length LCT, resulting from the interference of waves of the same wavelength with slightly different directions of propagation. This arises because all sources have a finite size D, which can be defined, for example, by the size of the pinhole in the previous cartoon, and a non-zero divergence Delta Theta. In this case, LCT is equal to Lambda divided by two Delta Theta, which by the principle of similar triangles is also equal to Lambda R divided by 2D, where D is the lateral extent of the finite source, and R is the distance from the source to the observation point. If we assume the source as a Gaussian profile, determination of D requires integration of interference contributions across the entire source's intensity distribution. In such a case, it emerges the LCT is related to the standard deviation of the beam Sigma X Y by LCT is equal to Lambda R divided by two Pi to the half Sigma X Y. In the vertical direction the source size at an undulator of, say, two-metre length is of the order of Sigma Y is equal to two microns. For one Angstrom radiation, this yields a vertical spatial coherence for an observer at 40 metres of well over 500 microns.

Notes

Summary

3m 18s

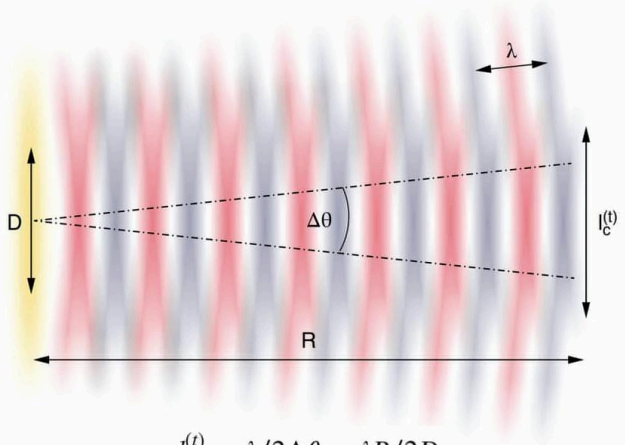
Types of coherence



$$l_c^{(l)} = \frac{\lambda^2}{2\Delta\lambda}$$

Longitudinal (temporal) coherence

@ 1 Å ~ 1 μm [Si(111) mono]



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

Transverse (spatial) coherence

@ 1 Å ~ 100 μm (R = 40 m)

Until the advent of DLSRs, the horizontal spatial coherence has traditionally been two orders of magnitude smaller than this, due to the very much larger extent Sigma X of the electron beam in the orbital plane. In the case of DLSRs, however, the source size in the horizontal direction may be as small as Sigma X is equal to 10 microns, and the corresponding coherence length is of the order of 100 microns. It should be noted that interference or diffraction phenomena, such as X-ray diffraction or small-angle X-ray scattering, can only occur between scattering elements within the coherence volume of the source. As the largest unit cells found in X-ray diffraction are over an order of magnitude smaller than the longitudinal coherence length, and approximately three orders of magnitude smaller than the horizontal coherence lengths, sharp diffraction maxima originating from 10 to the seven or more repeat units are typically obtained. So, although synchrotron light is often said to be incoherent, it can be made to be sufficiently parallel and monochromatic by the use of beamline optics to be an excellent source for X-ray interference and diffraction experiments.

Notes

Summary

4m 53s

Coherent fraction

$$f_{\mathrm{coh}} = \left\{ \left[1 + \left(\frac{\sigma_x^e}{\sigma^p} \right)^2 \right] \left[1 + \left(\frac{\sigma_x'^e}{\sigma'^p} \right)^2 \right] \left[1 + \left(\frac{\sigma_y^e}{\sigma^p} \right)^2 \right] \left[1 + \left(\frac{\sigma_y'^e}{\sigma'^p} \right)^2 \right] \right\}^{-1/2}$$

$$= \frac{(\epsilon^p)^2}{\epsilon_x \, \epsilon_y}$$

total emittances

NB: if $\varepsilon^p = \varepsilon_x^e = \varepsilon_x/2$ and $\varepsilon_y \simeq \varepsilon^p$, $f_{coh} = 50\%$

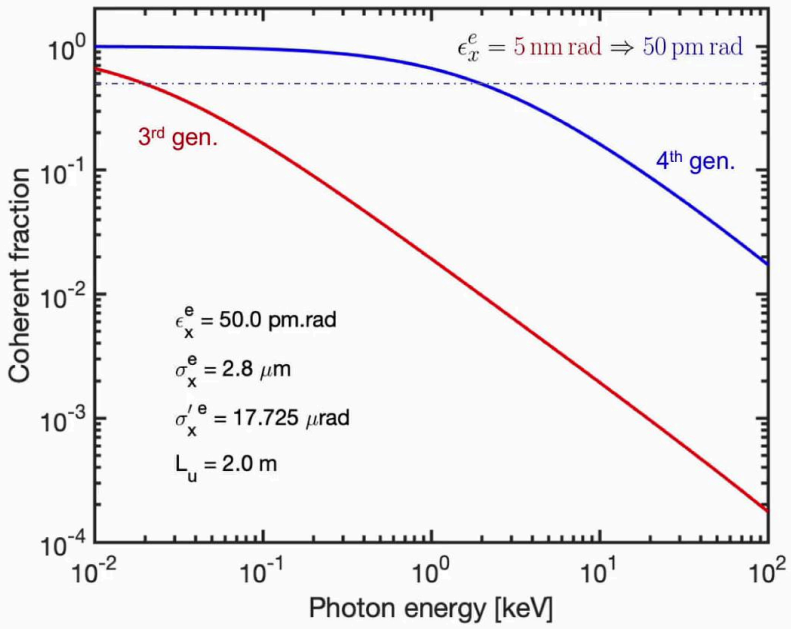
The coherent fraction describes the fraction of the flux that can be considered to be coherent—that is, be less than Pi radians out of phase with each other due to divergence of the source. As such, it describes the transverse coherence, and not the longitudinal coherence. It contains four independent contributions, namely the source size and divergence in both transverse directions, and is given by the long expression shown here. This can be reduced to the much more accessible expression that F C is equal to the square of the photon emittance divided by the product of the total emittance in the x and y directions. Note that if the vertical electron emittance Epsilon Y E is much smaller than Epsilon P, then the last two terms shown here in the square brackets reduce to unity. Moreover, if in the x direction a photon and electron admittances are equal, which is the case at the diffraction- limited energy, then the beam has a coherent fraction of 50 percent.

Notes

Summary

6m 13s

Increase in coherent fraction with reduced emittance



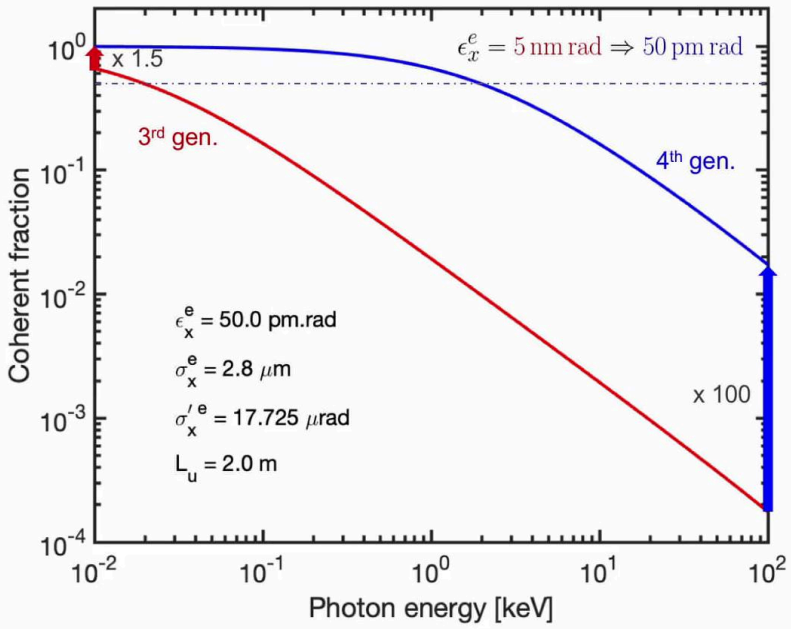
We can see how the electron emittance has an impact on the coherent fraction for different photon energies, beginning with a third-generation facility with a horizontal electron emittance of five nanometer radians, and progressing through two orders of magnitude to an as yet to be constructed DLSR with an electron emittance of 50 peak metre radians. In this animation, the Beta function of the electron emittance has been set to perfectly match the photon Beta function of L divided by four Pi, which equals approximately 0.16 metres for a two-metre undulator. Note also the horizontal dot-dash line at a coherent fraction of 50 percent. The diffraction-limited energy for a given electron emittance is where the coherent fraction curve crosses this line. As we see for the third generation source, this lies at approximately 20 eV in the vacuum ultraviolet. Okay, let's now begin the animation. For energies marginally above the diffraction-limited energy, the curve assumes a gradient of minus one in this double logarithmic plot, indicating a reciprocal relationship between the coherent fraction and photon energy in this higher energy regime. At lower energies below the diffraction-limited energy, the change is much flatter.

Notes

Summary

7m 27s

Increase in coherent fraction with reduced emittance



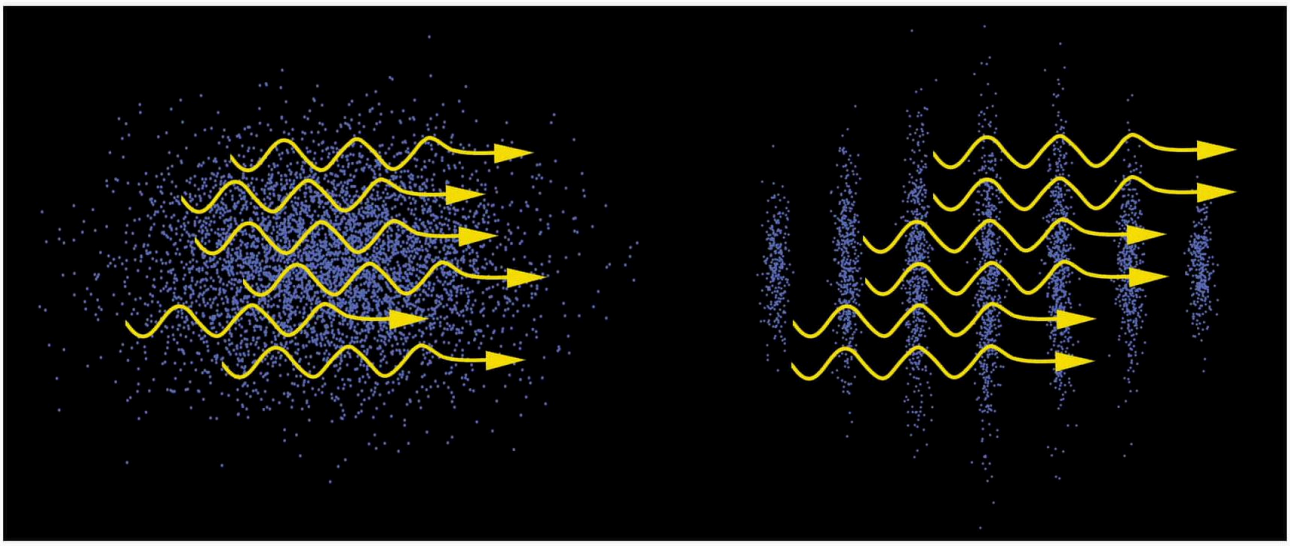
As in this regime, the total emittance is dominated by the photon's contribution. Indeed, we see that in the Vu V the improvement has only been approximately a factor of 1.5, whereas in the hard X-ray regime, the improvement is about 100, almost exactly equal to the improvement in horizontal electron emittance. As for high photon energies, this term dominates the total emittance. The diffraction-limited energy is also approximately 100 times higher, at two kiloelectronvolts.

Notes

Summary

9m 03s

The difference between SR and XFEL coherence



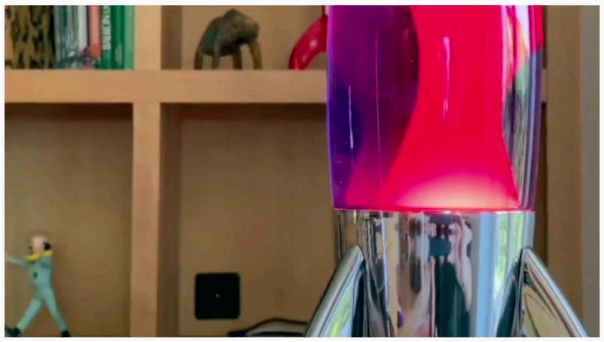
There remains an important difference between coherent radiation as regarded for synchrotron radiation, and coherent radiation from a conventional laser, or indeed an EXFEL. In the former, even though the wavelength of the photons may all be identical, and they all propagate in precisely the same direction, there is no defined phase relationship between the individual photonic contributions, leading to partial destructive interference. It can be shown that, if N photons contribute individually the same amplitude wavelets in a coherent synchrotron source, the resulting electric field amplitude is proportional to N to the half. The intensity, which scales with a square of the amplitude, is therefore directly proportional to N. N to the half times N to the half is equal to N. In the case of the coherent radiation produced at EXFELs, all the contributions are in phase with one another due to the SASE process, as we will cover in next week's videos. The radiation amplitude is therefore proportional to N, and the intensity to N squared. As N is of the order of 1 billion, the transient intensity of EXFEL pulses is also a billion times greater than the pulses produced at synchrotrons.

Notes

Summary

9m 40s

XFEL coherence leads to XFEL brilliance



20 W

16 GW

Space shuttle footage adapted from:
https://www.youtube.com/watch?v=OnoNITE-CLc

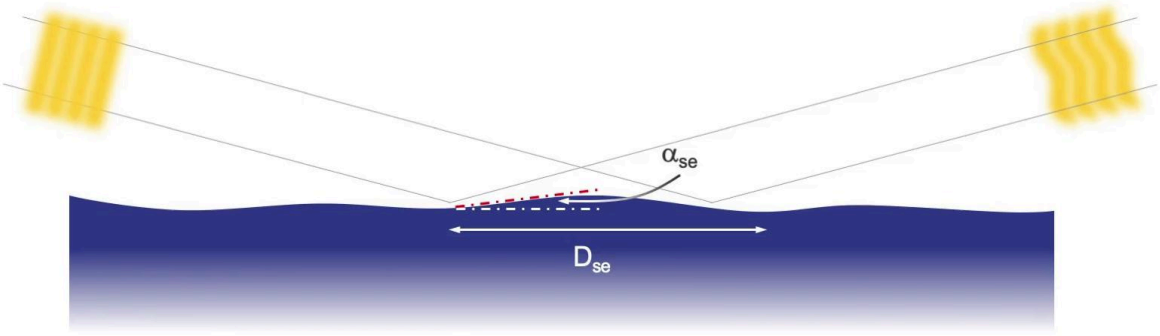
It should be noted that this simple distinction in the coherent properties of synchrotrons and XFELs leads to a difference in power that equates to the ratio in the power output of a lava lamp, including both light and heat, and the initial thrust of the space shuttle at take off.

Notes

Summary

11m 06s

Practical reality and the need for perfect optics



$$\Delta_{se} = \frac{\alpha_{se} D_{se}}{2} \qquad \phi_{se} = \frac{2\pi}{\lambda} D_{se} \alpha_{se} \theta = \frac{4\pi}{\lambda} \Delta_{se} \theta$$

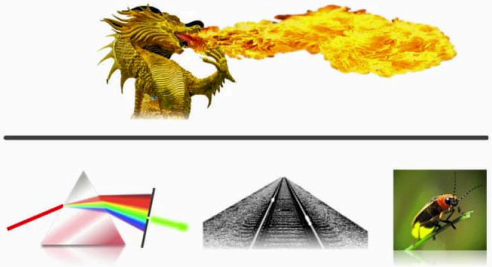
A maxim oft-used by X-ray imaging scientists at synchrotrons is "The best optics is no optics". What they are whimsically implying here is that X-ray optics mess up the wavefront of synchrotron radiation. This is particularly true of reflective and refractive optics, somewhat less so for diffractive elements such as crystal monochromators. For a wobbliness given by variations in the flatness, or the so-called slope error of Alpha S E, and the periodicity of the wobbliness of D S E, the peak to valley variation is Delta S E is equal to Alpha S E D S E upon two. This will induce a phase shift across the waveform of a beam incident at an angle Theta of four Pi divided by Lambda Delta S E Theta, which can result in destructive stripes at Phi S E equals Pi for very modest slope errors of one microradian or less. Because the instant angle Theta is often very shallow, the footprint of the X-rays can extend across tens of centimetres, thus setting very stringent specifications for mirrors, which are therefore extremely expensive.

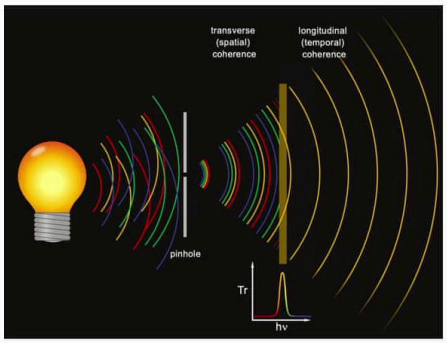
Notes

Summary

11m 26s

Summary of this section



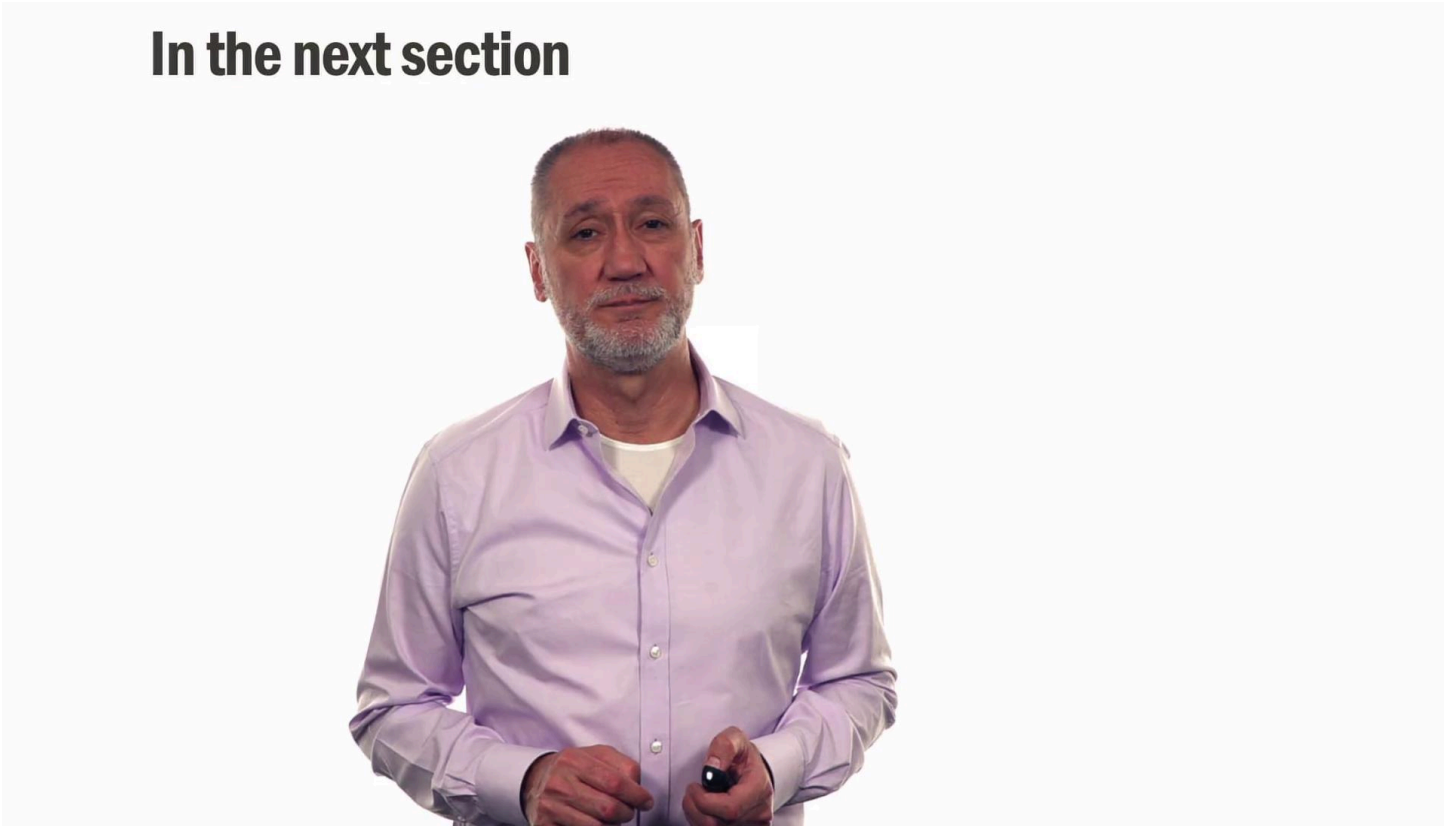


To summarise this section, we have investigated the most important properties of synchrotron radiation in the figure of merit, known alternatively as brilliance or brightness. The omittance of the synchrotron radiation has contributions from the electron beam, and then natural photon emittance. The former is a function of the storage ring design and house, until recently, always dominated over the latter, which is a fundamental diffraction-determined phenomenon. In the fourth generation synchrotron facilities beginning now to come online, the electron emittance only dominates at higher photon energies, thereby significantly improving the performance of the machine. Lastly, we considered the coherence of synchrotron light, determined by the source size, divergence, and bandwidth of the radiation. In other words, the three properties that combine to make up the denominator of the brightness figure of merit.

Notes

Summary

12m 46s



We've now covered the basic interactions of electromagnetic radiation with electrons and discussed the most important properties of synchrotron radiation that make it so useful in modern experimental sciences. In the upcoming and last section of this week, we will look at the so-called magnet lattice of a synchrotron. This is the suite of magnets and other components that combine to keep the electrons on a closed path and with a narrow range of kinetic energies, and is composed, among others, of the bending dipole magnets, the quadrupoles and sextipoles, and the RF supply. We will finish the week by finally discussing AcroMaps and, in particular, multi band AcroMaps that are at the heart of DLSRs.

Notes

Summary

13m 44s