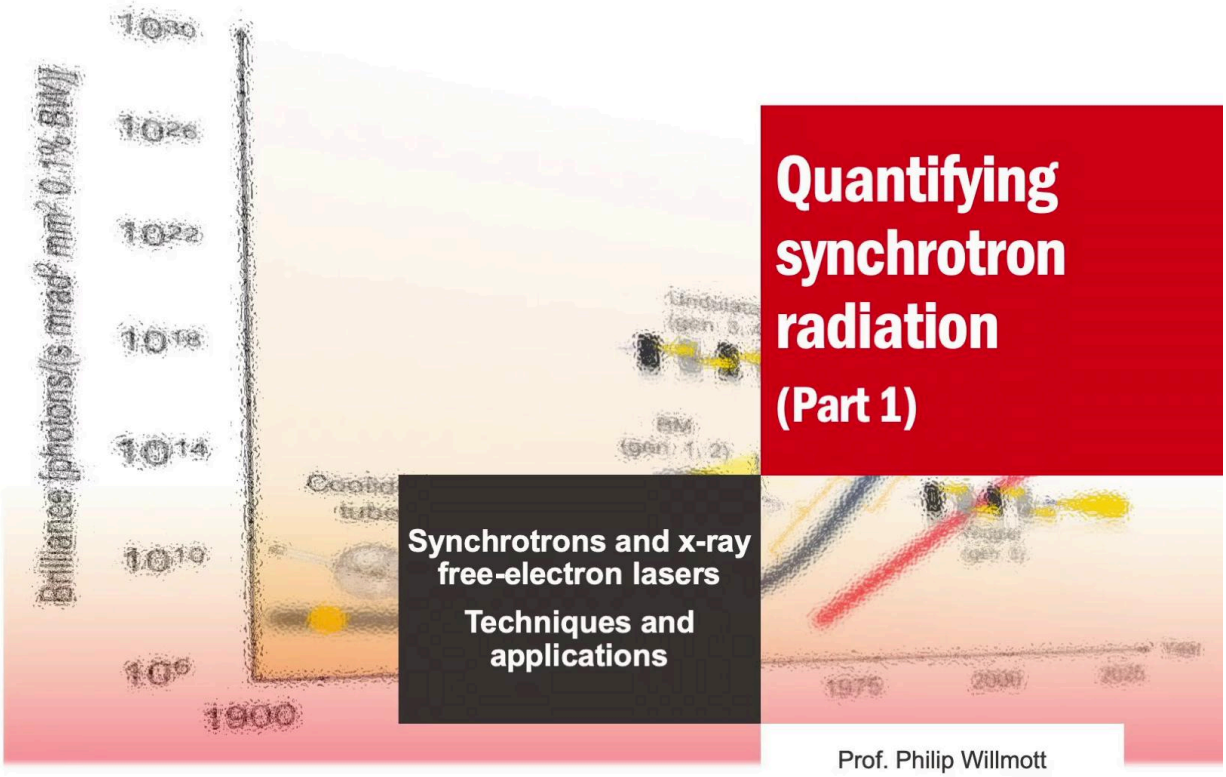
EPFL



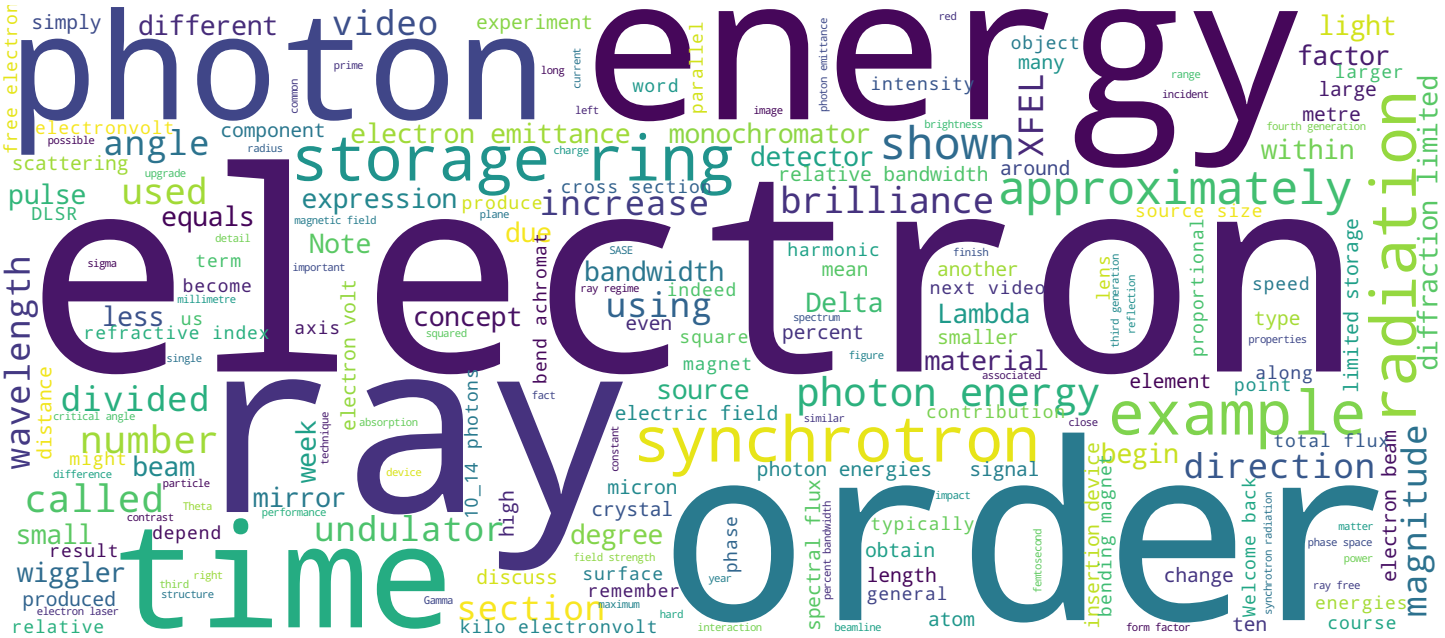
Quantifying synchrotron radiation (Part 1)

Synchrotrons and x-ray free-electron lasers

Techniques and applications

Prof. Philip Willmott

École polytechnique fédérale de Lausanne



Search MOOC

Video

EPFL

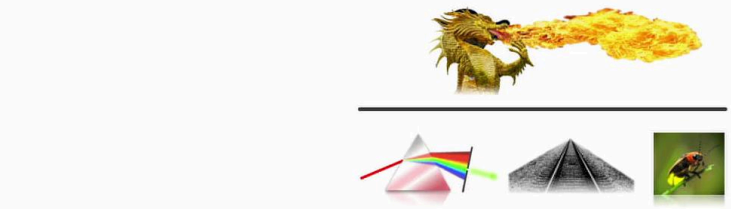
Welcome back to the second section of Week Three of this six week course on synchrotrons and XFELs. We are shortly going to look at the guts of a synchrotron, namely the magnet lattice, and in the last section we will complete this survey by examining insertion devices and the increased performance of fourth generation facilities by the introduction of so-called multi-bend achromats. In order to make a comparison between, for example, the ESRF facility, as it was in 2018, and its performance after its upgrade to a so-called diffraction-limited storage ring in 2020, we need to understand the figures of merit of spectral flux, emittance, brightness; also called brilliance, and coherence. These are the goals of this section of Week Three.

Notes

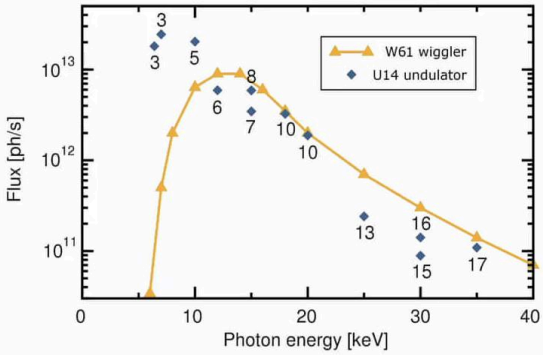
Summary

0m 05s

Brightness in more detail



Flux



Adapted from Willmott *et al.*, J. Synchrotron Rad. 20: 667 (2013).
doi:10.1107/S0909049513018475

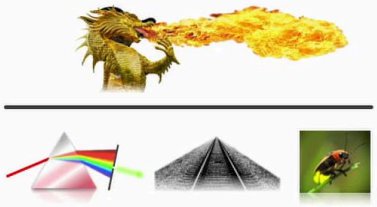
We've already been introduced to the concept of brightness or brilliance in Week One. Brightness and brilliance are interchangeable terms, the former more common in the US, the latter more so in Europe. The use of one or the other seems to be a terrific source of contention amongst certain scientists. As I don't personally consider this to be a worthy hill to die on, I will be using both terms at random, so just deal with it. Brilliance, you'll remember, is the figure of merit describing the number of photons per second within a given bandwidth, for a given beam divergence, and source size. Let's begin with the flux; the photons per second on your sample. Obviously, radiation damage apart, you want in general this number to be as large as possible. The time average number of photons per second is of the order of 10_13 to 10_14 for third and fourth generation beamlines for a quasi-monochromatic beam. Shown here are recorded values of the flux on a silicon diode at the material science beamline for its original wiggler source, shown in gold, and its replacement, a U14 undulator given by the blue diamonds.

Notes

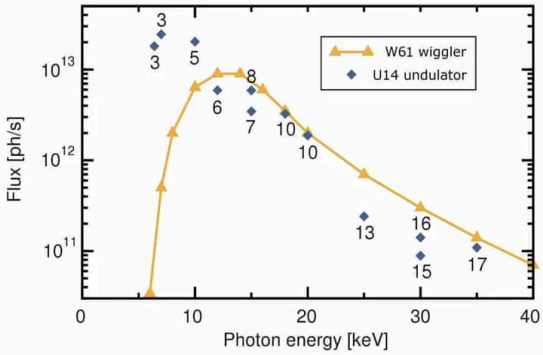
Summary

1m 02s

Brightness in more detail



Flux



Adapted from Willmott *et al.*, J. Synchrotron Rad. 20: 667 (2013).
doi:10.1107/S0909049513018475

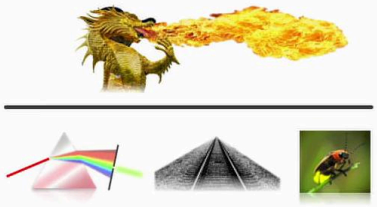
Although the undulator clearly outperforms the wiggler below 10 kilo-electronvolts, the flux values are very similar at higher energies and the wiggler is marginally superior at the highest photon energies. So why then the 1.5 million Swiss franc investment fund to go from wiggler to undulator? This is due to the much improved emittance of the undulator compared to the wiggler. We will discuss this very shortly.

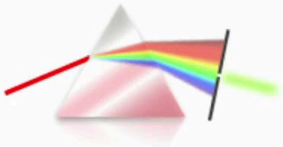
Notes

Summary

2m 29s

Brightness in more detail





Relative bandwidth

$$\frac{\Delta\nu}{\nu} \text{ c.f. } 0.1\,\%\,\text{BW}$$

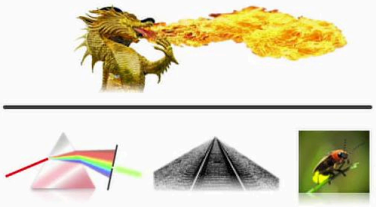
For experiments requiring a certain photon energy, the radiation from the source needs to be monochromatised. For example, X-ray absorption spectroscopy measurements might require a bandwidth of less than one electronvolt in order to distinguish features in a spectrum at several kilo-electronvolts. This would therefore demand a relative bandwidth of approximately 10_minus 4 or better. So a beamline that produces 10_14 photons per second, but that within a bandwidth of one percent would need to be further monochromatised, by another factor of 100 to be useful for such experiments, reducing the total flux by approximately the same factor. No dispersive device such as a monochromator can produce an infinitely narrow bandwidth. In the visible regime, it is possible nowadays to obtain lasers with an absolute bandwidth of less than one hertz corresponding to a relative bandwidth: Delta Mu upon Mu, better than 2 times 10_ minus 15. In the X-ray, regime, bandwidths between 10_minus 5 and 0.01 are more common. The spectral flux is therefore defined as the number of photons per second per unit bandwidth, which for synchrotrons was decided to be 0.1 percent or Delta Mu upon Mu is equal to 0.001.

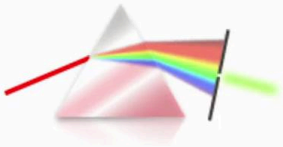
Notes

Summary

2m 58s

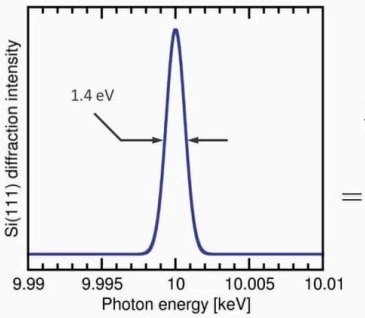
Brightness in more detail





Relative bandwidth

$$\frac{\Delta\nu}{\nu} \text{ c.f. } 0.1\,\%\,\text{BW}$$



$$\frac{\Delta\nu}{\nu} = 1.4 \times 10^{-4}$$

$$= 0.14 \text{ c.f. } 0.1\%\,\text{BW}$$

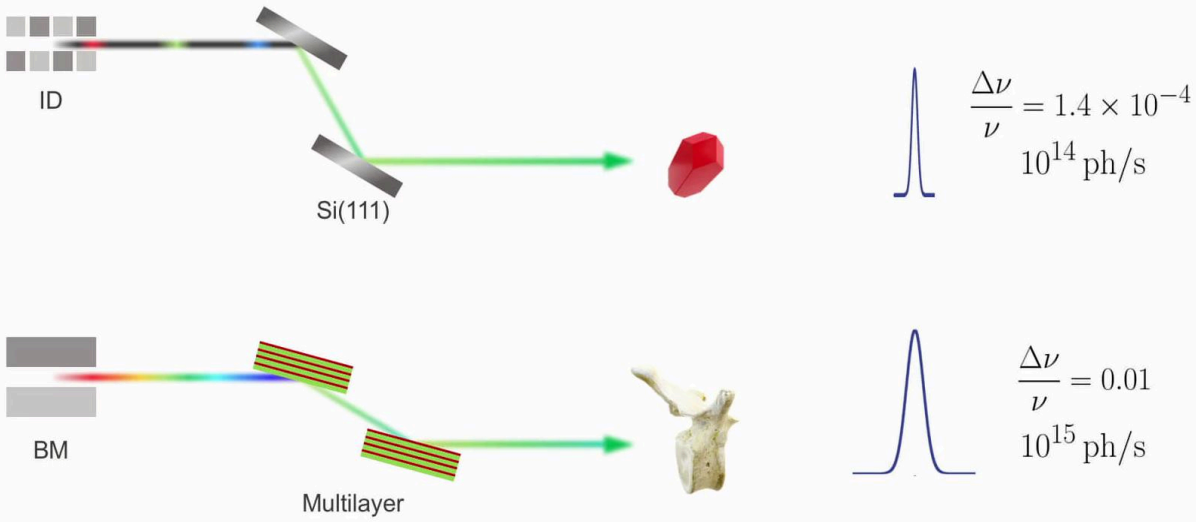
I've found that in the past this concept has proved confusing to the uninitiated, so here is an example. Imagine a beamline that uses a monochromator that filters down to a relative bandwidth of 1.4 times 10_minus 4. I use this somewhat specific number because it is the natural bandwidth of high quality silicon 111 crystals. Now, this relative bandwidth is only 0.14 of the normalised bandwidth of 0.001 used in defining brilliance. So if the flux measured is 10_13 photons per second at 10 kilo-electronvolts, the spectral flux is 10_13 divided by 0.14, which is equal to 7 times 10_13 photons per second per 0.1 percent bandwidth.

Notes

Summary

4m 35s

Brightness in more detail



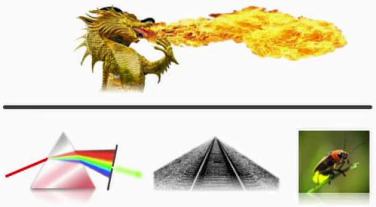
So what bandwidth is appropriate for your experiment? As already mentioned, some experiments require the narrowest bandwidths, while others comfortably tolerate larger bandwidths and profit from the increased total flux. Consider, for example, a diffraction experiment using undulator radiation and a silicon 111 crystal monochromator on a protein crystal with a large unit cell size. The bandwidth of 1.4 times 10_minus 4 is justified, and the total flux of 10_14 photons per second allows measurements to be recorded rapidly. The spectral flux is approximately 7 times 10_14 photons per second per 0.1 percent bandwidth. Now, another beamline may carry out fast tomography experiments, for example, requiring frame rates of tens of kilohertz. Here, the number of photons on the sample is at a premium. So a multilayer monochromator is used, which has a relative bandwidth of about one percent. The total flux after monochromatisation of the bending magnet radiation is 10_15 photons per second, an order of magnitude more than in the diffraction experiment. Note, however, that the spectral flux is at 10_14 photons per second per 0.1 percent bandwidth, approximately an order of magnitude smaller than at the diffraction beamline due to the larger bandwidth.

Notes

Summary

5m 29s

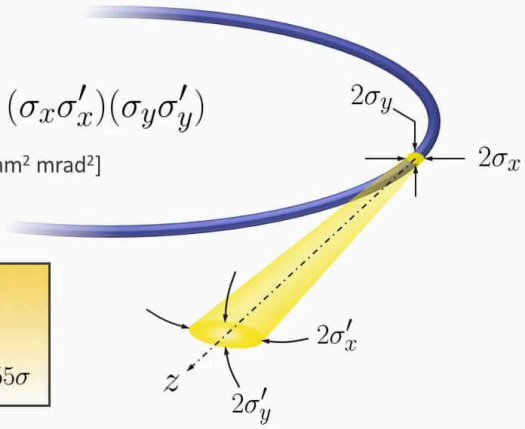
Brightness in more detail



Emittance

$$\epsilon = \epsilon_x \epsilon_y = (\sigma_x \sigma'_x)(\sigma_y \sigma'_y)$$

units [mm² mrad²]



NB: σ = standard deviation

$$\exp(-x^2/2\sigma^2)$$

$$\text{FWHM} = \sqrt{8 \ln 2}\,\sigma = 2.355\sigma$$

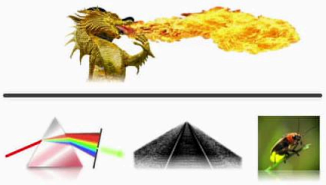
The final component to defining brilliance is the emittance. This is the product of the source size, and beam divergence, given a standard deviations in the X and Y directions. It combines the contributions from the electron beam and the fundamental so-called diffraction-limited contribution from the photon beam. Like I say, this second contribution is a consequence of wave optics and diffraction phenomena, and depends only on the photon energy. In contrast, the electron emittance depends on the design of the storage ring. Up until the newest fourth generation of synchrotrons, the electron emittance, has always been the dominant contribution, except for beamlines producing very low photon energies below approximately 20 electronvolts. With the dramatic improvements in the electron beam emittance provided by multi-bend achromats installed in the newest synchrotron facilities such as MAX IV, Sirius, and the ESRF-EBS upgrade, the energies below which the photon emittance begins to dominate has jumped to approximately one kilo-electronvolt or potentially, an order of magnitude higher still in plant facilities in the next decade. This newest generation of synchrotrons has thus been dubbed: diffraction-limited storage rings. We discuss this in more detail later in this section.

Notes

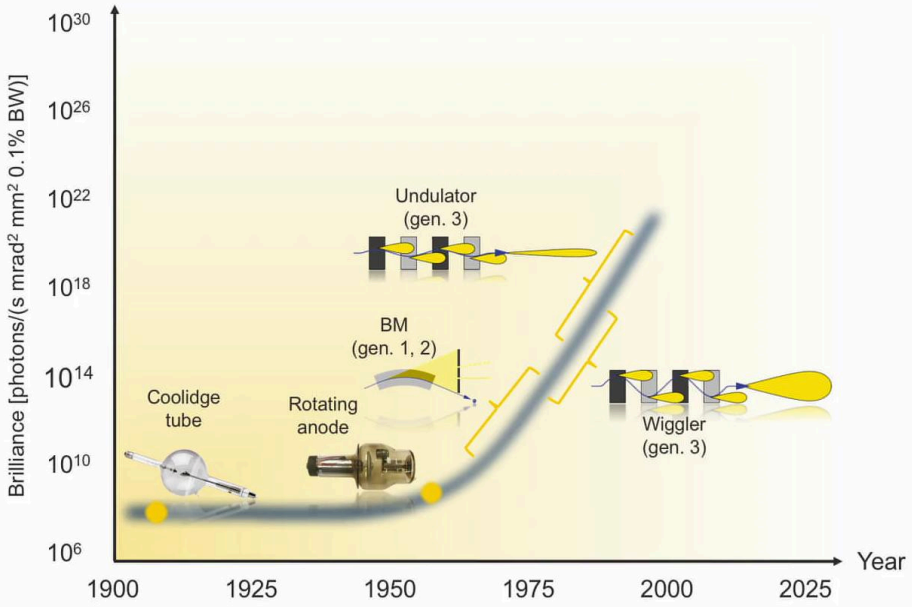
Summary

7m 08s

Brightness since Röntgen



Units: $\frac{[\text{ph/s}]}{[\text{mm}^2\ \text{mrad}^2][0.1\ \%\ \text{BW}]}$

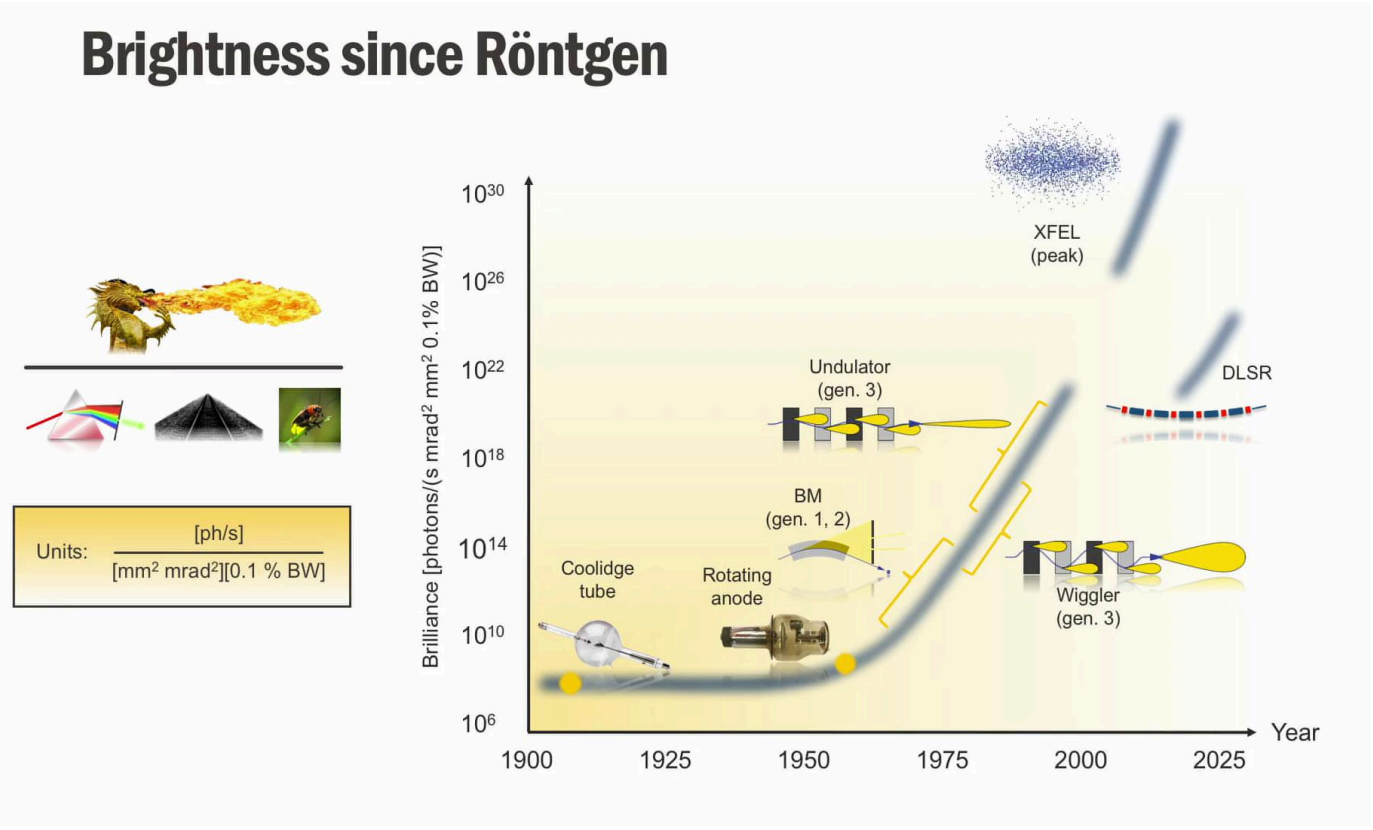


We finish this video with a historical perspective of the progress of brilliance since the discovery of X-rays by Röntgen, more than a century ago. There was very little improvement in the brilliance for the first half century, the standard source being the Coolidge Tube. The brilliance of this device was limited by the current of accelerated electrons on the anode surface, which would begin to melt if the current was increased too much. An order of magnitude was gained by the advent of a rotating anode tube in which the anode was rotated in order to distribute the heat over a larger, effective area. A further 5-6 orders of magnitude were gained at the first generation parasitic facilities, primarily thanks to the highly collimated nature of the synchrotron light compared to the approximately hemispherical or two Pi-star radiant divergence of the Coolidge and rotating anode tubes. By introducing insertion devices in the third generation facilities, first as wigglers, but then increasingly in the form of undulators, the brilliance jumped up a further 6-8 orders of magnitude. We discuss insertion devices, especially undulators, next week.

Notes

Summary

8m 46s

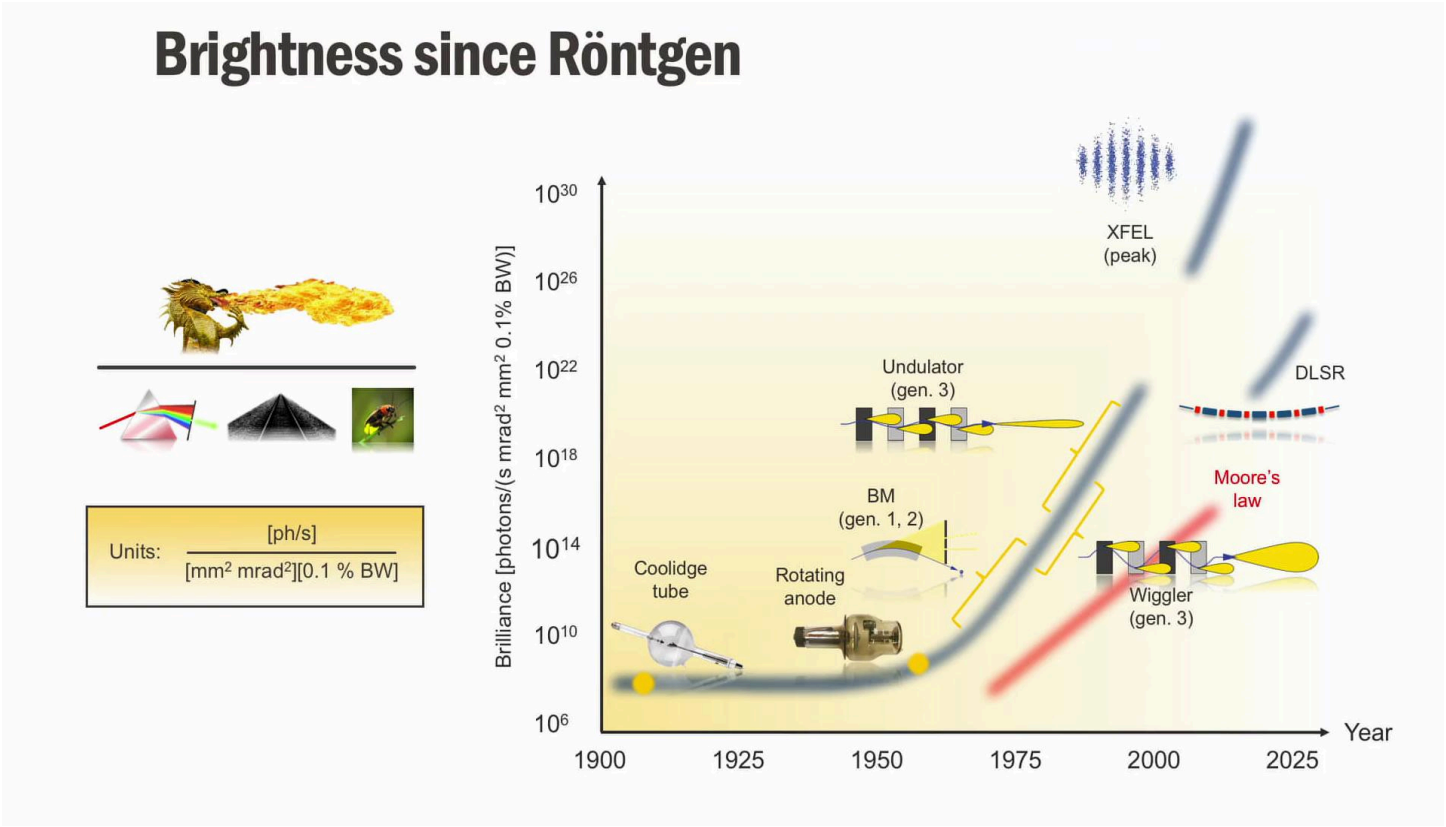


In 2009, the first heard X-ray free electron laser, or XFEL, came online at SLAC in Menlo Park, California. The LCLS has been in operation now for over a decade, and is undergoing an upgrade to include superconducting Linac cavities, promising another three orders of magnitude pre peak brilliance. This is some 13 orders of magnitude greater than that produced at synchrotrons. Such increases are not incremental. The handling of XFEL radiation, its impact on the sample, and the type of experiments had to be completely re-evaluated and rejigged. More standard synchrotron activities could, however, gain hugely by a more modest improvement and brilliance of the order of around 100. This was signalled by the first green-field diffraction-limited storage ring MAX IV in Lund, Sweden, which was inaugurated in the summer of 2016. The second green-fields facility is Sirius, in Campinas, Brazil, which should begin its first pilot experiments this year, 2020. In parallel, the ESRF in Grenoble, France, underwent an upgrade of its storage ring to DLSR status, and obtained the target ring current of 200 milliamps in early March 2020, just before being temporarily put on hold by the coronavirus pandemic.

Notes

Summary

10m 17s



2020 was really quite the year. Finally, note that the increase in brilliance in the last half century fairly comprehensively outstrips the much vaunted improvement in computer performance given by Moore's Law. This exhibits a doubling in performance every two years, whereas the brilliance of storage rings and XFELs shows the same exponential growth with a doubling time of only 14 months. In the next video, we will quantify the concept of emittance in general, including the concept of phase space, which will prepare us for understanding the so-called Beta function and phase space matching between the electron and photon beam emittances, something which is crucial to the performance of diffraction-limited storage rings.

Notes

Summary

11m 54s