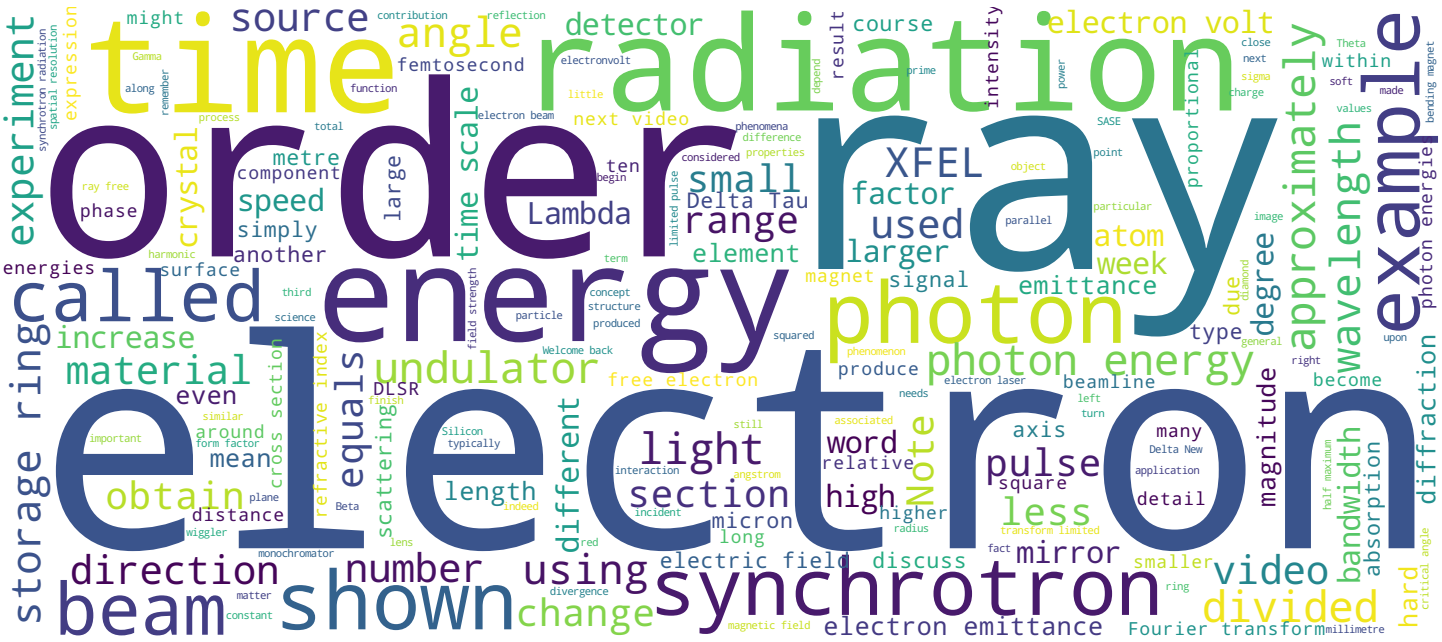
EPFL

École polytechnique fédérale de Lausanne



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Video

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Contents and objectives of this video

- Why XFELs?
- Time scales in the natural sciences
- Fourier-transform limited pulses

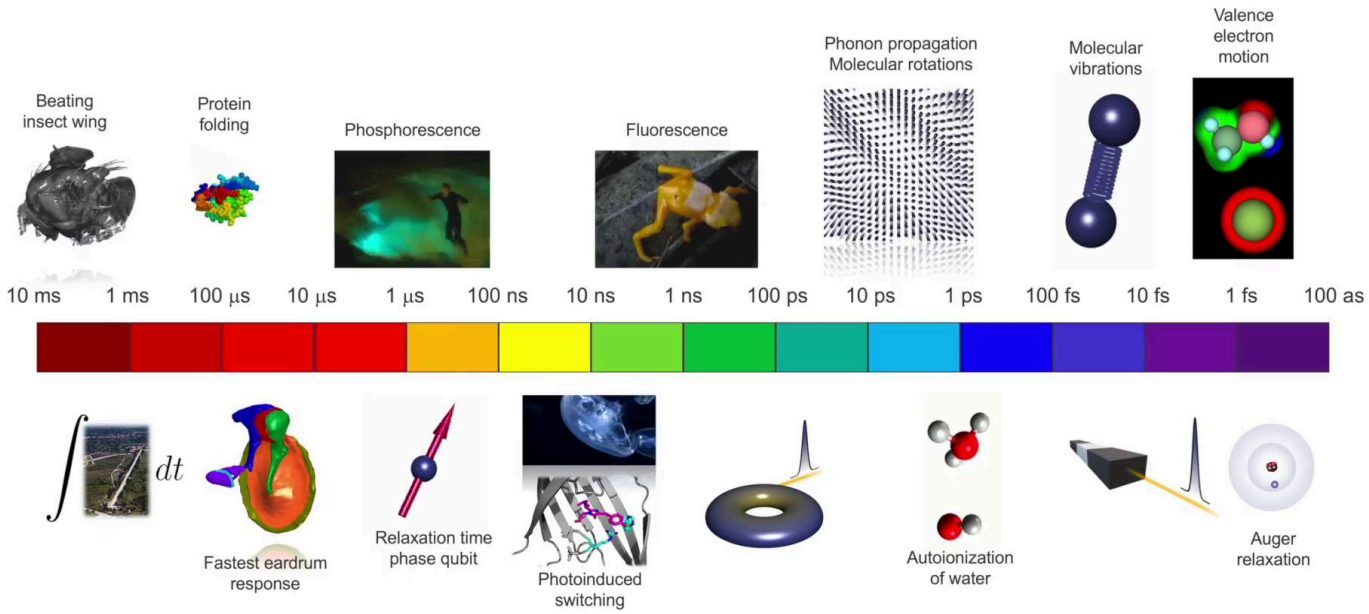
Hi, and welcome back to the third and final section of week four of this course, synchrotrons and X-ray-free electron laser techniques and applications. In this section, we will discuss in more detail X-ray-free electron lasers. In this first of five videos, we consider time scales in the natural sciences and why XFELs can serve a particular and very important niche. We finish this short video by looking at the fundamental limit to how pure or monochromatic a pulse of light can be for a given pulse duration in so called Fourier transform-limited pulses.

Notes

Summary

0m 05s

Time scales

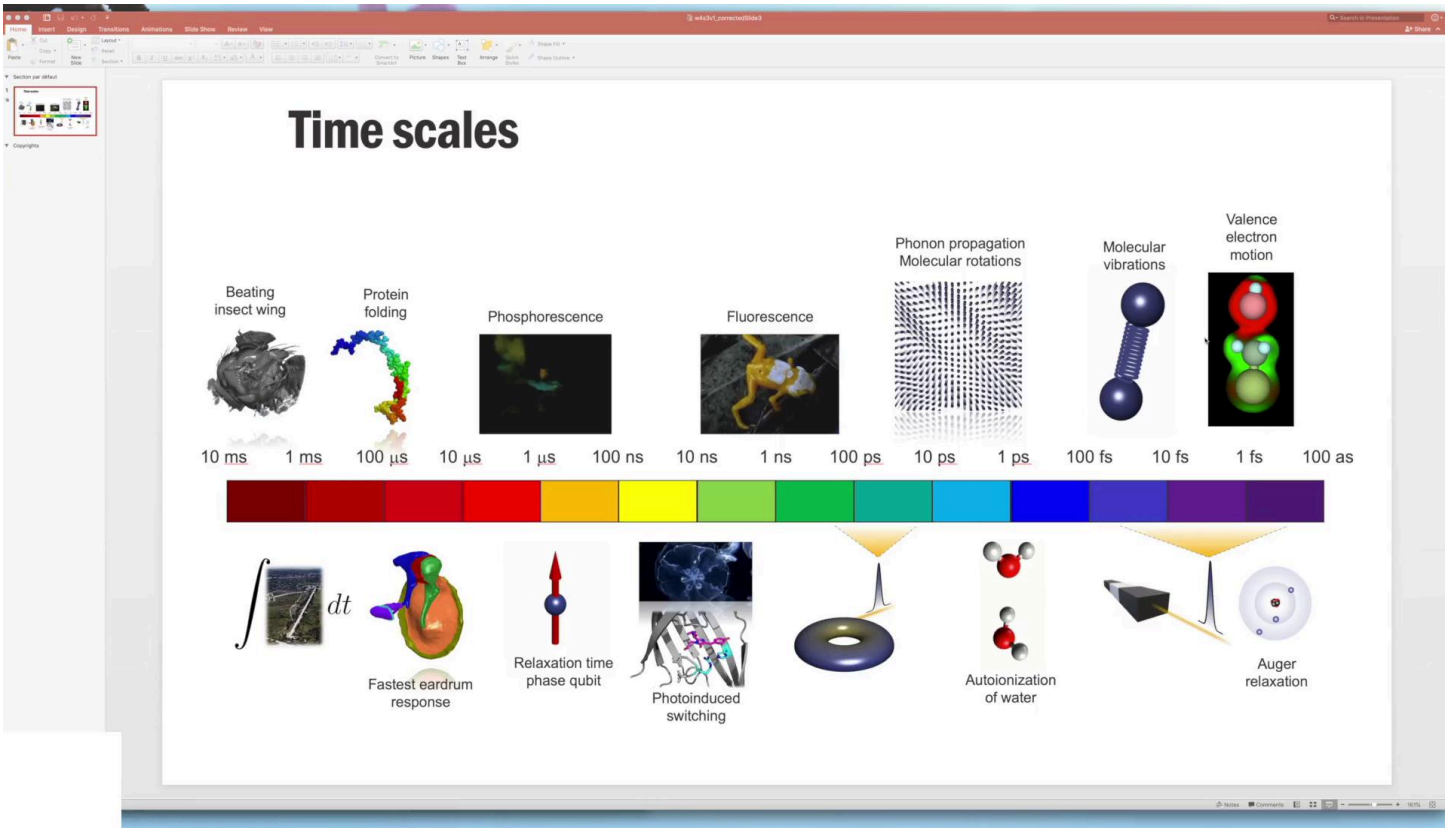


Shown here are systems and phenomena with characteristic time scales from approximately one-one Hundredth of a second down to 100 attoseconds. That is tenth of the -16 of a second. A useful ruler in considering many of these phenomena is the speed of light. A beam of light will travel from the Earth to the moon and a little over a second. Note that it took the Apollo 11 crew three days or 250,000 times longer to put the same distance behind them. It covers 300 metres in a microsecond, only 30 centimetres in a nanosecond and 300 nanometres in a femtosecond. For visible light, 300 nanometres is actually less than a single wavelength. For hard X-rays on the other hand, 300 nanometres corresponds to a wave train of a few thousand wavelengths. A fly might beat its wings 200 times per second. That is, with a temporal periodicity of five milliseconds. Interestingly, the integrated on-time of the LCS since first light in 2009 is less than a millisecond, though admittedly in this time it has delivered over 100 megajoules of photonics energy equating to a power output of the order of 100 gigawatts. Many biological processes occur on time scales ranging from under a millisecond to approximately a nanosecond.

Notes

Summary

0m 48s



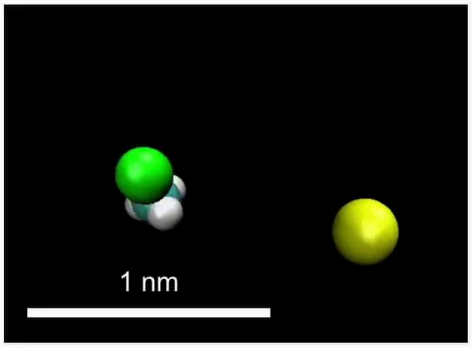
Though some of the underlying biochemical reactions might have time scales in the picosecond regime, including photoabsorption, ionisation, or even shorter time scales on the femtosecond regime when considering valence electron motion. Note also the two ranges in time associated with synchrotrons and XFELs shown as yellow gradient triangles. Synchrotrons generate pulses that might be as short as 20 picoseconds but can be as long as a few hundred picoseconds. XFELs typically generate X-ray pulses of a few tens of femtosecond, but can also produce sub-venter second pulses in special circumstances.

Notes

Summary

2m 32s

Why XFELs?



$Cl^- + CH_3I \Rightarrow ClCH_3 + I^-$

Atomic motion: v ~ 1 km s^{-1}

1-Å resolution: (10^{-10} m)/(1000 m/s) = 100 fs

- Chemical reaction dynamics
  - Breaking bonds
  - Making bonds
  - Reconfiguration of atomic structure

The Holy Grail of physical chemistry is the direct observation of the making and breaking of chemical bonds and following a reaction through the reconfiguration of the atomic structure. In order to achieve this, one needs a probe that can spatially resolve the atomic positions measured in angstroms, thus necessitating the use of hard X-rays. Moreover, in order to record a movie of chemical processes, each frame of that movie must be shorter than the speed of the process, divided by the desired resolution, which we have just stated should be of the order of an angstrom. Typical velocities associated with atomic motion are of the order of a kilometre per second. Hence, each movie frame should be separated by no more than approximately 100 femtoseconds. If you rewind to the previous slide, you'll see that phonons and molecular rotations have time scales of approximately 100-1000 femtoseconds, while molecular vibrations crucial to the process of chemical reactions are shown to have periodicities of the order of 10-100 femtoseconds.

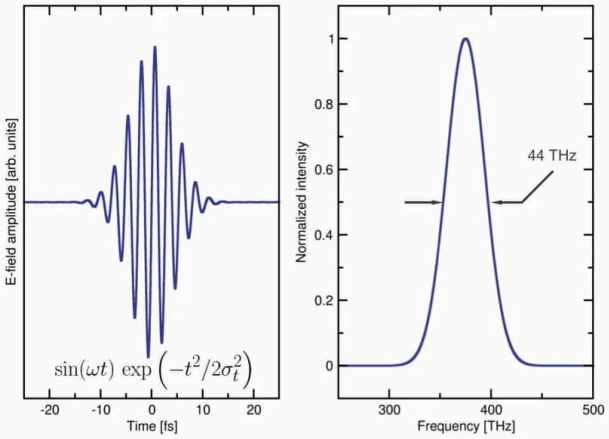
Notes

Summary

3m 21s

Why XFELs?

- Femtosecond pulses
  - FT-limited bandwidth
    - $\Delta\tau\,\Delta\nu = \frac{2}{\pi}\ln 2 = 0.44$
    - $\frac{\Delta\nu}{\nu} = 1.472 \times 10^{-4}\frac{\lambda\,[\text{Å}]}{\Delta\tau\,[\text{fs}]}$
  - e.g. 800 nm, 10 fs $\Rightarrow \frac{\Delta\nu}{\nu} = 0.118$
  - Abbe limit: $d = \frac{\lambda}{2n\sin\theta}$
    - λ = 800 nm, d ~ 250 nm



See also description of Fourier-transform limited pulses in the supplementary text "Fourier-transform limited pulses"

So given that femtosecond lasers have been around for over three decades, why don't we just use these? To appreciate this more deeply, we need to understand the concept of the Fourier transform-limited bandwidth. I'm not sure if you picked this up, but a little earlier in this video, I stated that in one femtosecond light travels only 300 nanometres, that is 25 percent shorter than the shortest wavelength of visible light and only about twice as long as two wavelengths of the highest photon energy laser radiation at around 150 nanometres. If we mathematically model a pulse of light be it from a conventional laser or from an EXFEL as being a sine wave of a fixed frequency New, which is equal to Omega, divided by 2Pi multiplied by a Gaussian envelope with a full width half maximum Delta Tau, as shown in the left-hand plot, it emerges that the bandwidth Delta New is equal to nought point four divided by Delta Tau. That is, it is inversely proportional to Delta Tau. The shorter the pulse, the larger the bandwidth. This should come as no surprise. A source with an infinitely narrow bandwidth requires a single wavelength and an infinitely long wavetrain.

Notes

Summary

4m 41s

Why XFELs?

- Femtosecond pulses
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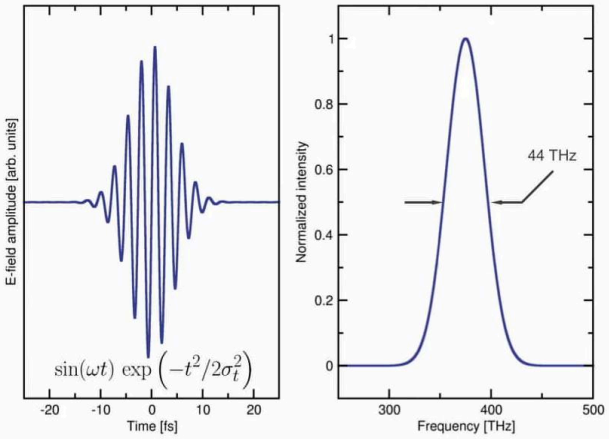

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If this wave train is terminated or effectively made to be finite by the envelope curve of a Gaussian, the bandwidth will become non-zero. Moreover, if the carrier frequency as a range of values, in other words it can't be described by a single sine wave with value New, the bandwidth will be larger still, This is the meaning of a Fourier transform-limited pulse. The bandwidth is only defined by the pulse duration and is not further spread by there being a range of carrier frequencies. So let's use this simple expression Delta Tau Delta New equals 0.44 and work out the bandwidth of an 800-nanometer laser source generating 10 femtosecond pulses. Plugging these numbers into our equation, we obtain a bandwidth of 44 terahertz centred around the central frequency of 375 terahertz. In other words, the laser radiation has a full width half maximum bandwidth of nearly 12 percent of the central frequency. It can't be considered to be very monochromatic. Moreover, the ultimate resolution given by the Abbe limit is approximately 250 nanometres, or approximately 2000 times larger than that needed for atomic spatial resolution.

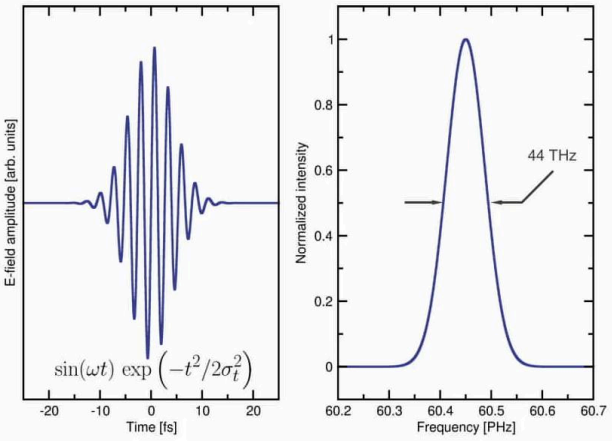
Notes

Summary

6m 09s

Why XFELs?

- Femtosecond pulses
  - FT-limited bandwidth
    - $\Delta\tau\,\Delta\nu = \frac{2}{\pi}\ln 2 = 0.44$
    - $\frac{\Delta\nu}{\nu} = 1.472\times10^{-4}\frac{\lambda\,[\text{Å}]}{\Delta\tau\,[\text{fs}]}$
  - XFEL, 250 eV, 10 fs $\Rightarrow \frac{\Delta\nu}{\nu} = 7.3\times10^{-4}$
  - Abbe limit: $d = \frac{\lambda}{2n\sin\theta}$
    - E = 250 eV, λ = 4.96 nm, d ~ 10 nm



See also description of Fourier-transform limited pulses in the supplementary text "Fourier-transform limited pulses"

If we now turn to the same calculation but now made for X-rays, let's say a soft X-ray close to the carbon K-edge at 250 electron volts, which corresponds to a wavelength of approximately 50 angstroms, we obtain the same absolute bandwidth of 44 terahertz as we are still considering a pulse of the same duration of 10 femtoseconds. However, this is now centred around a frequency of 60.45 petahertz. Note the change in the units of the X-axis in the right-hand plot compared to the previous slide. And the relative bandwidth Delta New upon New is now equal to 7.3 times 10 to the -4. This is similar to the relative bandwidth produced by a Silicon 111 monochromator. Femtosecond pulses of X-ray radiation can still be considered therefore to be quasi-monochromatic. This is unsurprising as even soft X-rays, like the example here contain approximately 600 wavelengths within the pulses full with half maximum Incidentally, I decided not to replace the plot on the left for the temporal form of a laser pulse with that of the EXFEL pulse as at this resolution one could not distinguish the oscillations and the Gaussian envelope would be entirely filled in with the squiddles.

Notes

Summary

7m 41s

Why XFELs?

- Femtosecond pulses
  - FT-limited bandwidth
    - $\Delta\tau\,\Delta\nu = \frac{2}{\pi}\ln 2 = 0.44$
    - $\frac{\Delta\nu}{\nu} = 1.472\times10^{-4}\frac{\lambda\,[\text{Å}]}{\Delta\tau\,[\text{fs}]}$
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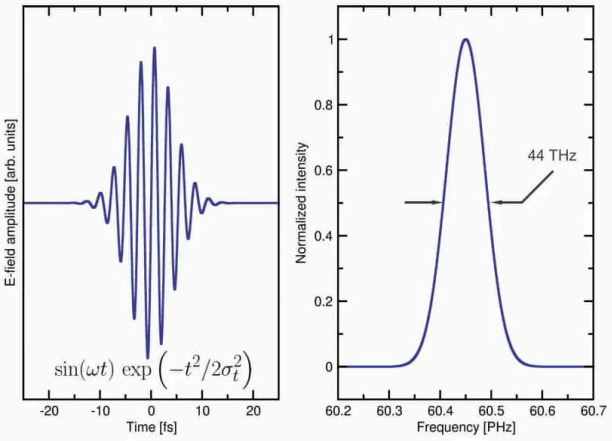

See also description of Fourier-transform limited pulses in the supplementary text "Fourier-transform limited pulses"

Lastly, the Abbe limit for the spatial resolution for these soft X-rays is approximately 10 nanometres. Still not sufficient for atomic resolution but useful for nanoscaled experiments. For true atomic resolution, one requires approximately one angstrom radiation or expressed in electron vaults over 10 kiloelectron volts photons. For a detailed derivation of the expression Delta Tau Delta New is equal to 0.44. See the supplementary text Fourier transform-limited pulses.

Notes

Summary

9m 06s

In the next video...

In the next video, we consider why you would use an apple for one type of experiment, and a pear for another, figuratively speaking. We will then look at the basic components of XFELs that as we shall see in the subsequent video, leads to the phenomenon of self-amplified spontaneous emission, or SASE.

Notes

Summary

9m 42s