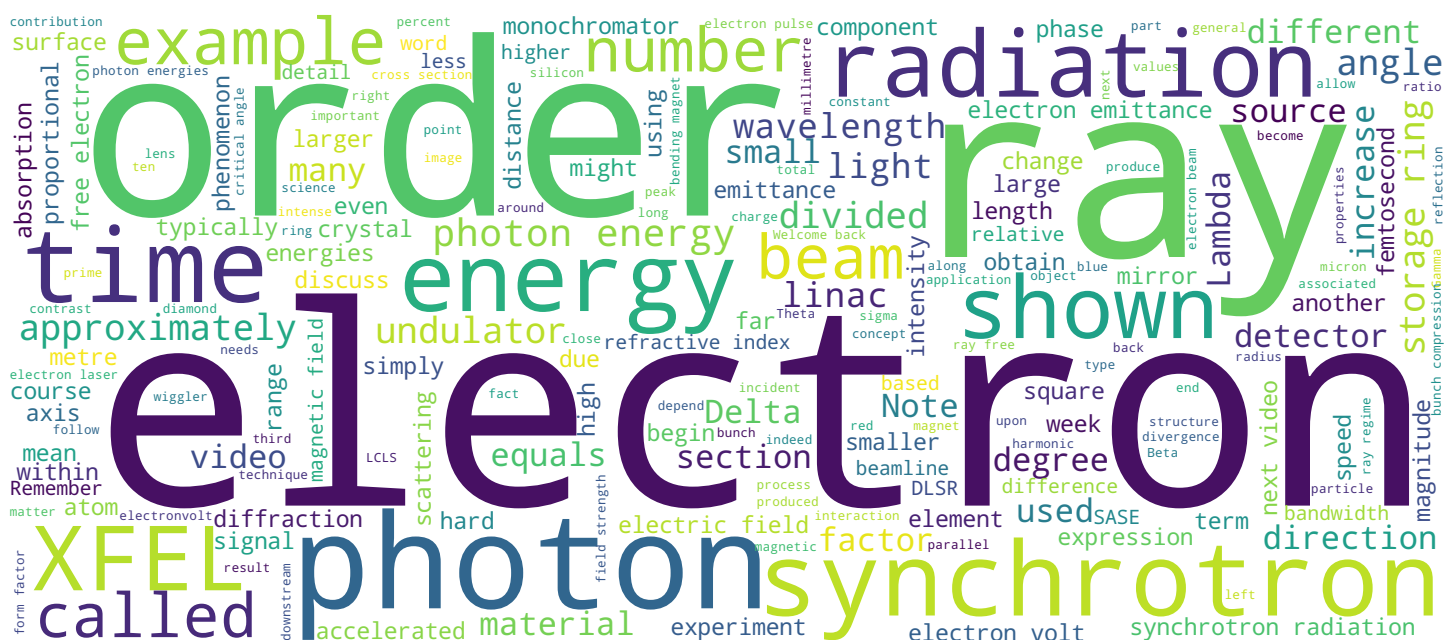


Synchrotrons and x-ray free-electron lasers

Techniques and applications

Prof. Philip Willmott



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Video



Contents and objectives of this video



- Properties of XFELs v synchrotrons
- XFELs around the world
- Architecture of XFELs

Hi, and welcome back to the second video of the third and final section of week four of this course, Synchrotrons, and X-Ray Free-Electron Lasers, Techniques and Applications. In this section we discuss in more detail X-ray free-electron lasers. We begin by considering the very different temporal properties and peak powers of XFELs and synchrotrons. We then look at the basic components of XFELs that, as we shall see in the subsequent video, lead to the phenomenon of self-amplified spontaneous emission, or SASE.

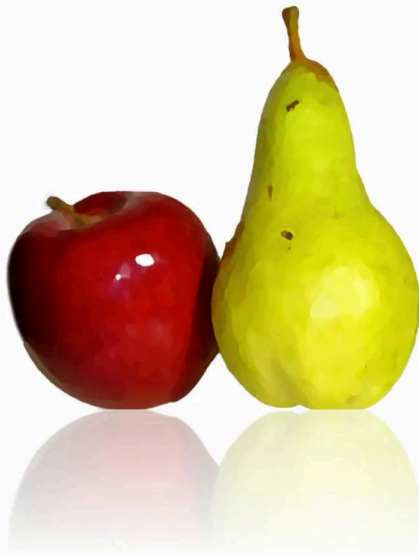
Notes

Summary

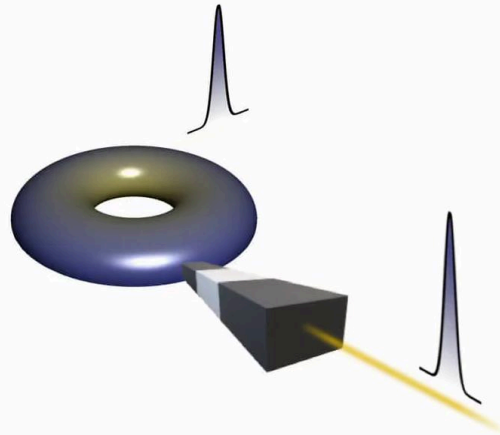


0m 04s

Apples and pears



Synchs and XFELs



As apples and pears are both fruits, but clearly distinct from one another, so are synchrotrons and XFELs both X-ray sources, though their uses are quite distinct in most cases.

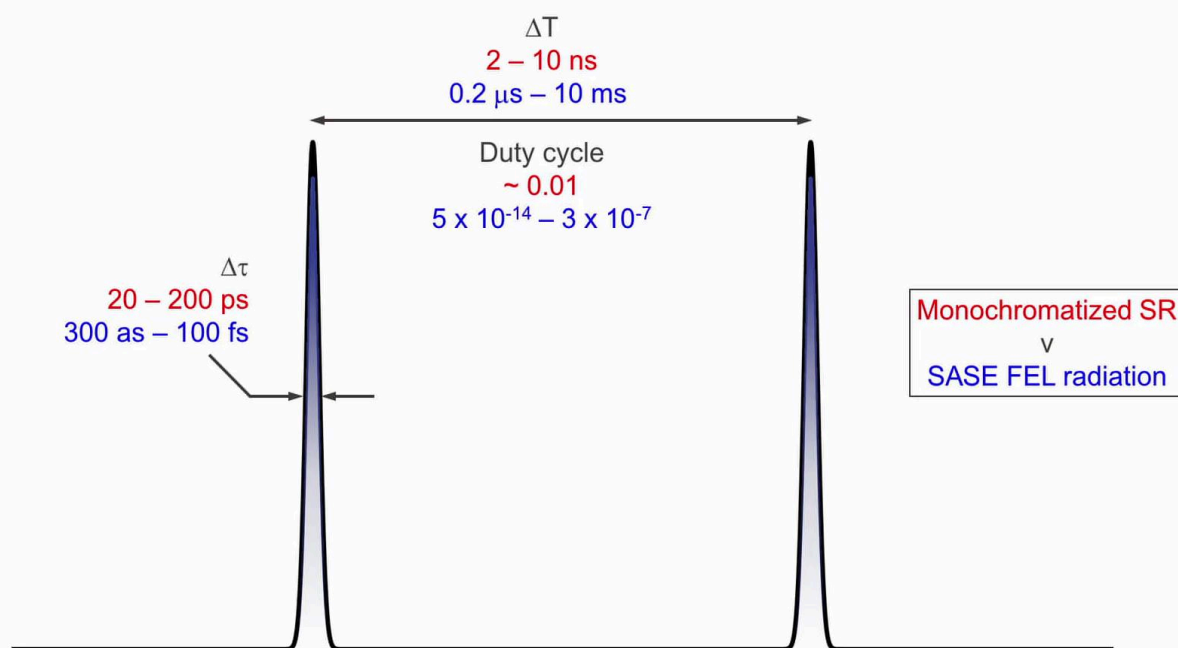
Notes

Summary



0m 42s

Pulse characteristics



The most obvious difference between synchrotrons and XFELs is in the temporal profile of the delivered radiation. It should be noted here that the numbers that come up are for monochromatized synchrotron radiation on the one hand, shown in red, and unfiltered SASE XFEL radiation on the other, shown in blue, as these are the two most commonly used modes. Though of course, there are exceptions. Synchrotron experiments using pink or white polychromatic radiation and XFEL investigations using monochromatized or seeded radiation are both, if not common, also not unheard of. The full width half maximum duration of synchrotron pulses lies typically between a few 10s and a few 100s of picoseconds, while that of XFELs spans a range from well under a femtosecond to about 100 femtoseconds. That is between 1,000 and 10,000 times shorter. The duty cycle of synchrotrons, that is, the ratio of on time divided by repeat time, is typically one percent. This is far more variable at XFELs. At LCLS-I, SwissFEL, Elettra, SACLA, and the PAL-XFEL, the repetition rate is of the order of 100 hertz, while at LCLS-II and the European XFEL, it is more in the megahertz regime, depending on the photon energy.

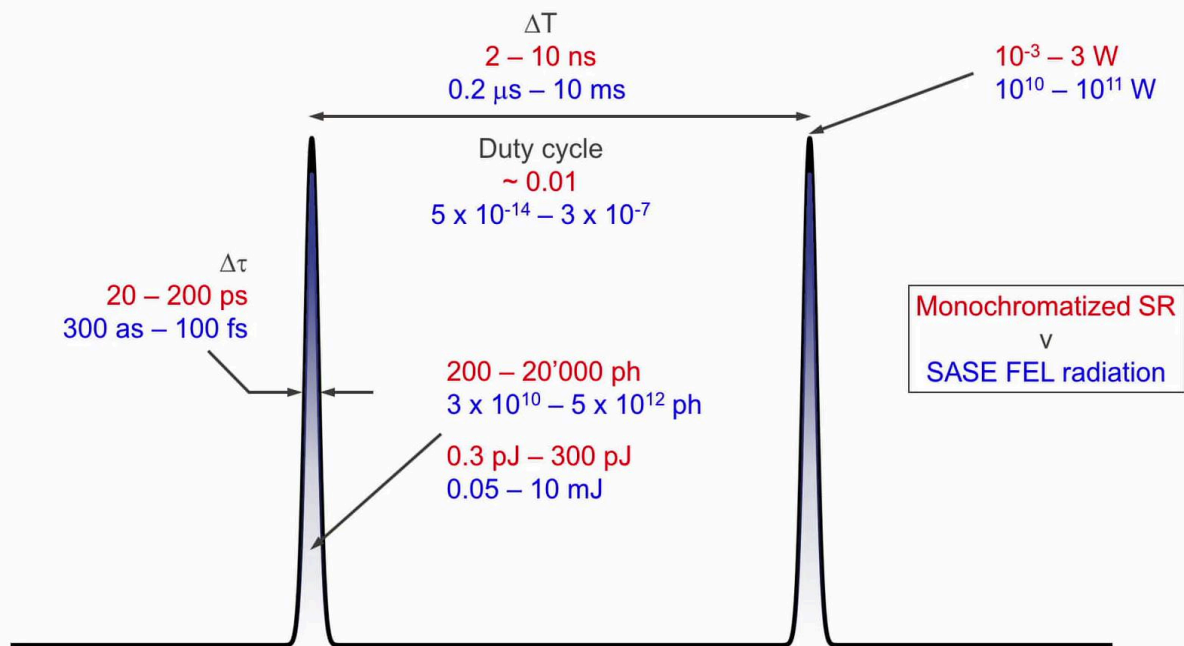
Notes

Summary



0m 55s

Pulse characteristics



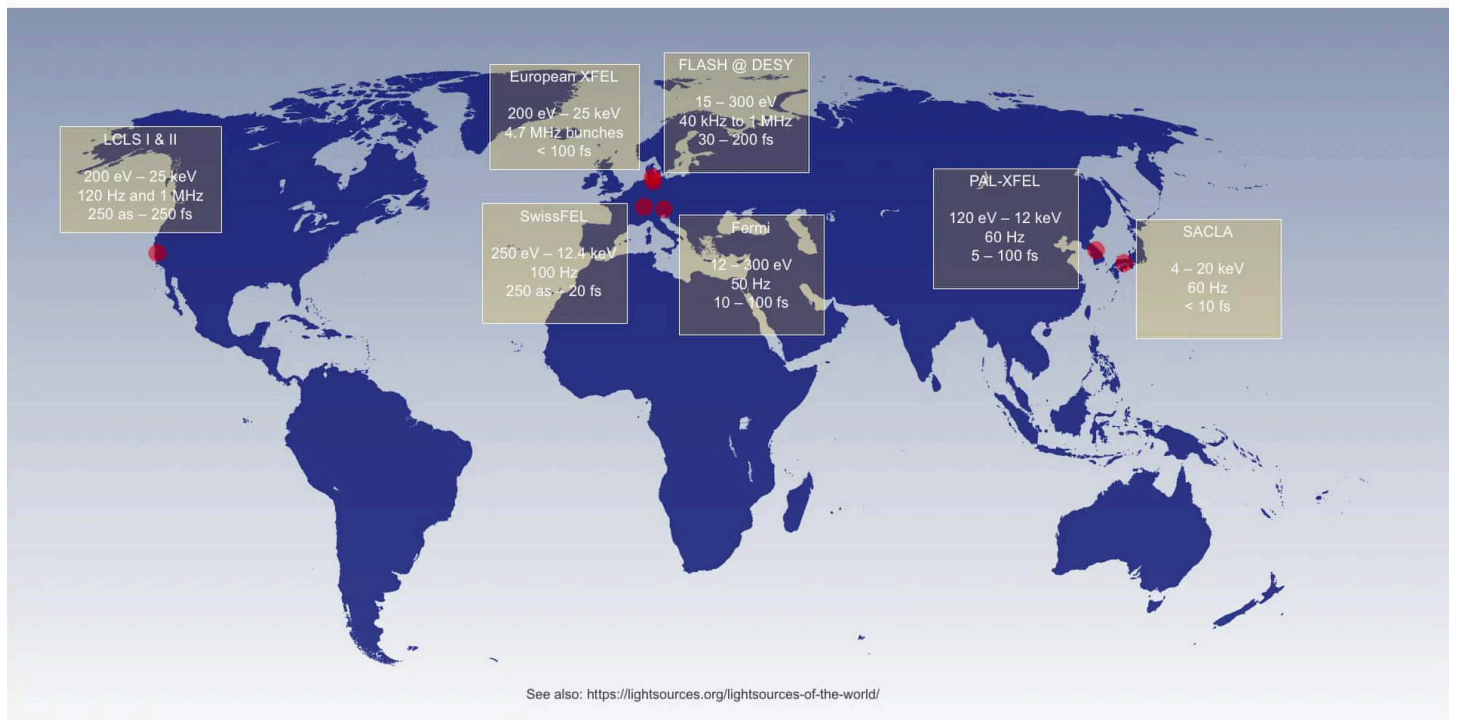
Consequently, the duty cycle can be different by up to seven orders of magnitude, but is always at least 4-5 orders of magnitude smaller than for synchrotrons. How much a given synchrotron or XFEL pulse packs a punch is also extremely different. A synchrotron pulse may contain as few as 200 photons and is rarely more than 100 times this, meaning each pulse delivers energy packets measured in picojoules. XFELs, on the other hand, are mighty beasts in comparison, with as many as 5 times 10_{12} photons per pulse and energies as high as 10 millijoules, greater than synchrotron radiation by a factor of 100 million or more. Remember, too, that this hugely greater number of photons is delivered in pulses that are 3-4 orders of magnitude shorter. Consequently, the peak power of XFELs can be over 10 orders of magnitude larger than at synchrotrons, and is approximately the same as the peak electrical power consumption of a middle-sized Western-European country. Or, put another way, the combined basal metabolic rate of all humankind. But obviously excluding the prodigious mental power of certain heads of state. Well at least until early 2021.

Notes

Summary



XFELs around the world



Today there are seven FELs operating in the VUV up to the hard X-ray regime. The LCLS is based in Menlo Park as part of Stanford University. A second generation branch to the linac at Menlo Park using superconducting cavities is the basis for LCLS-II. The European XFEL is the younger and bigger sister of FLASH, both located in Hamburg, Germany. The SwissFEL is located, not very surprisingly, in Switzerland, some 450 kilometres west, as the crow flies, of FERMI at Elettra in Trieste, Italy. The PAL-XFEL fell in Pohang, South Korea, has similar specifications to the SwissFEL. Finally, SACLA in Japan was the second hard X-ray XFEL to come online after LCLS-I.

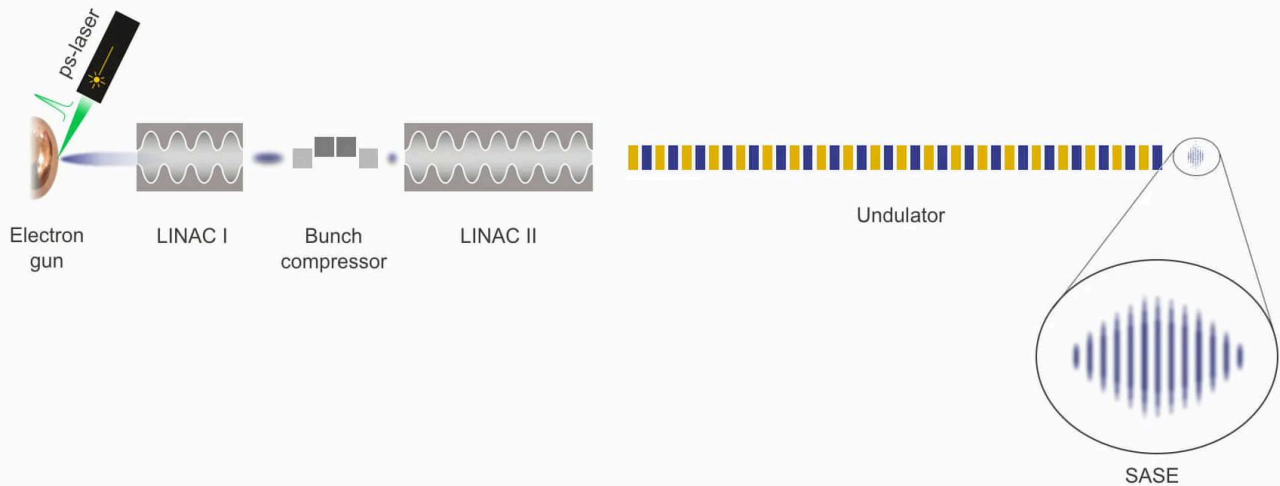
Notes

Summary



3m 55s

XFEL architecture in detail



XFELs are based on linear accelerators, or linacs. In order to generate pulses of electrons, a picosecond laser is focused onto the surface of a photoemitter. The resulting picosecond duration electron pulse is accelerated in a first linac to energies of the order of several hundred megaelectron volts. It's now necessary to shorten or compress the electron pulse towards the femtosecond regime. This is typically achieved through one, or typically two or more, so called bunch compressors, before being further accelerated to several gigaelectron volts in a second linac. We discuss the process of bunch compression in a moment. This shortened electron bunch then travels along a very long undulator measured in several 10s of metres, or even longer, from which it emerges in a transformed state. It has been divided up into a series of micro bunches through the action of SASE, which we will look at more closely in the next video.

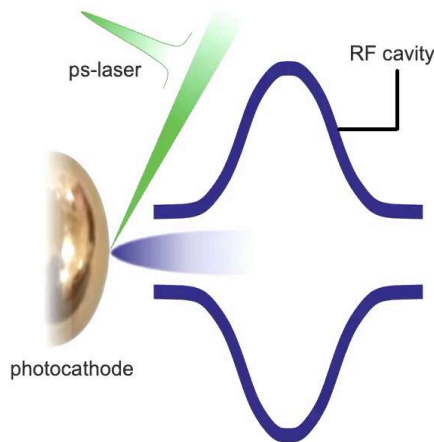
Notes

Summary



4m 50s

XFEL architecture – the low-emittance gun



- Photoemission from cathode
 - GaAs, Cu, Cs₂Te, ...
- ~ **50 Amps** peak current
- Acceleration in RF-cavity
 - Relativity reduces space-charge effects
- Emittance (x, y) ~ 1 mm mrad (or 1 μ m rad)
- SASE high-gain XFELs require ~ **several kAmps**...

The first component of an XFEL is the low-emittance gun. Picosecond laser radiation is focused onto a photocathode made from some appropriate material, such as gallium arsenide, copper, or caesium telluride. The produced cloud of electrons is accelerated in an RF cavity, and has a peak current of the order of 50 amps, or thereabouts. The emittance in both transverse planes is of the order of one millimetre milliradian, or equally one micron radian. In order to induce SASE in the undulator downstream, however, one needs a peak current of the order of several kiloamps, meaning the electron pulses needs to be compressed by a factor of 20-50. Note that one cannot initially produce a femtosecond duration electron pulse using a femtosecond laser as Coulomb repulsion will dilate the pulse beyond the femtosecond regime. Only when the electrons become relativistic can they be squeezed together to femtosecond durations. This is the purpose of the first linac: to push it to these relativistic velocities.

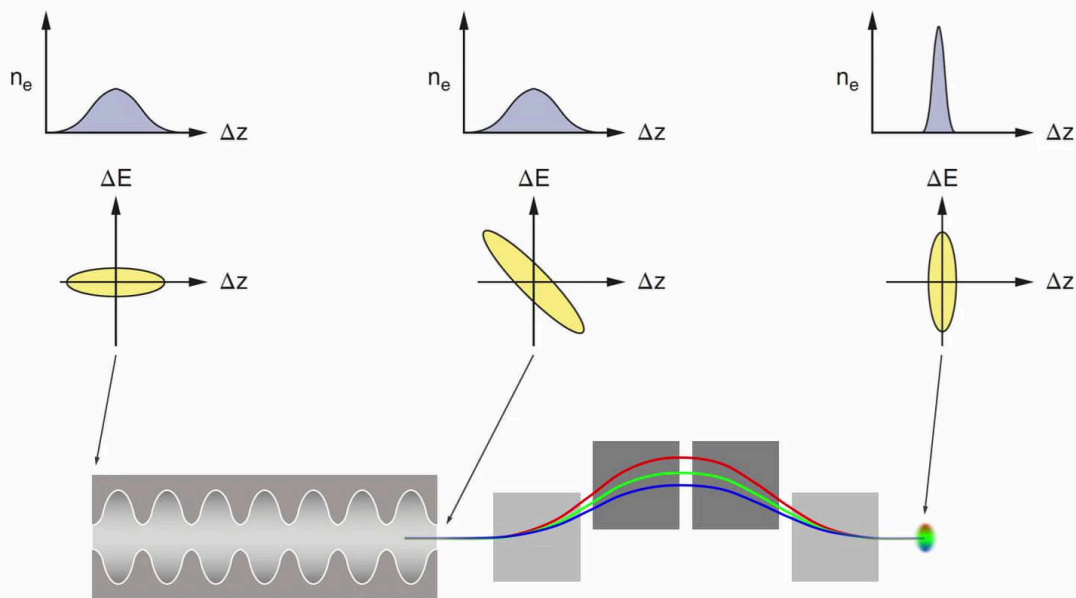
Notes

Summary



5m 59s

XFEL architecture – bunch compression



Bunch compression after the electrons have traversed the first linac is achieved as follows. The RF phase in the first accelerator module is adjusted to allow the electrons to surf down the slope of the sinusoidal RF field. All the electrons are accelerated in the linac, but the phase is set so that the leading electrons are accelerated less than those electrons towards the back of the bunch. This phenomenon is referred to as chirping. Nonetheless, the relativistic electron velocities are so close to the speed of light that their differences are far too small to allow the faster electrons at the back of the bunch to catch up with the slower electrons positioned further forward, and thereby squeeze the bunch length. So it doesn't work like that. What happens is that at the end of the linac, the spatial extent along the axis has not changed significantly, but the electrons at the upstream end are more energetic than those downstream. That's our starting condition. This increase in energy dispersion allows the bunch to be compressed as follows. The bunch passes through a magnetic four-dipole chicane. The trailing high energy electrons execute a shorter path on account of their being less deviated by the magnetic fields.

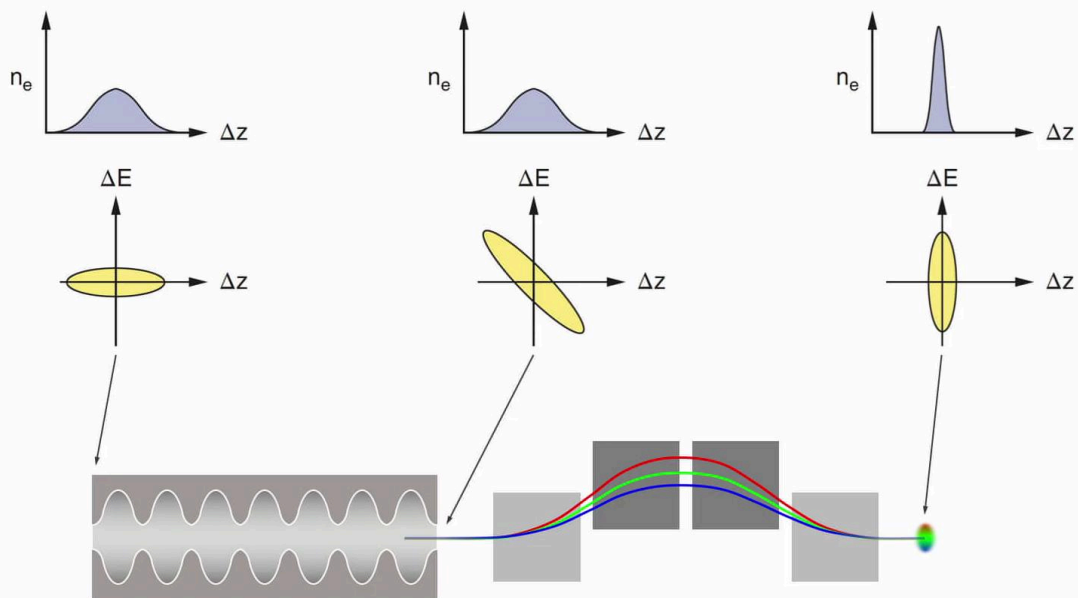
Notes

Summary



7m 18s

XFEL architecture – bunch compression



In this manner, they are able to catch up with the less energetic leading electrons, which are more deviated by the magnet chicane. The resulting bunch after bunch compression and acceleration in another linac as it enters the undulator is approximately 100 microns long, or in terms of time, approximately 300 femtoseconds.

Notes

Summary



8m 46s

In the next video...



In the next video, we will look at the phenomenon of SASE, the production of femtosecond X-ray pulses and why these are so intense. We will see that the intensity of the radiation produced by XFELs is proportional to the square of the number of photons in a pulse, in contrast to synchrotron radiation, which is linearly proportional to the number of photons per pulse. As this number is of the order of 10^9 , we immediately see that XFEL radiation is much more intense. Much more.

Notes

Summary



9m 10s