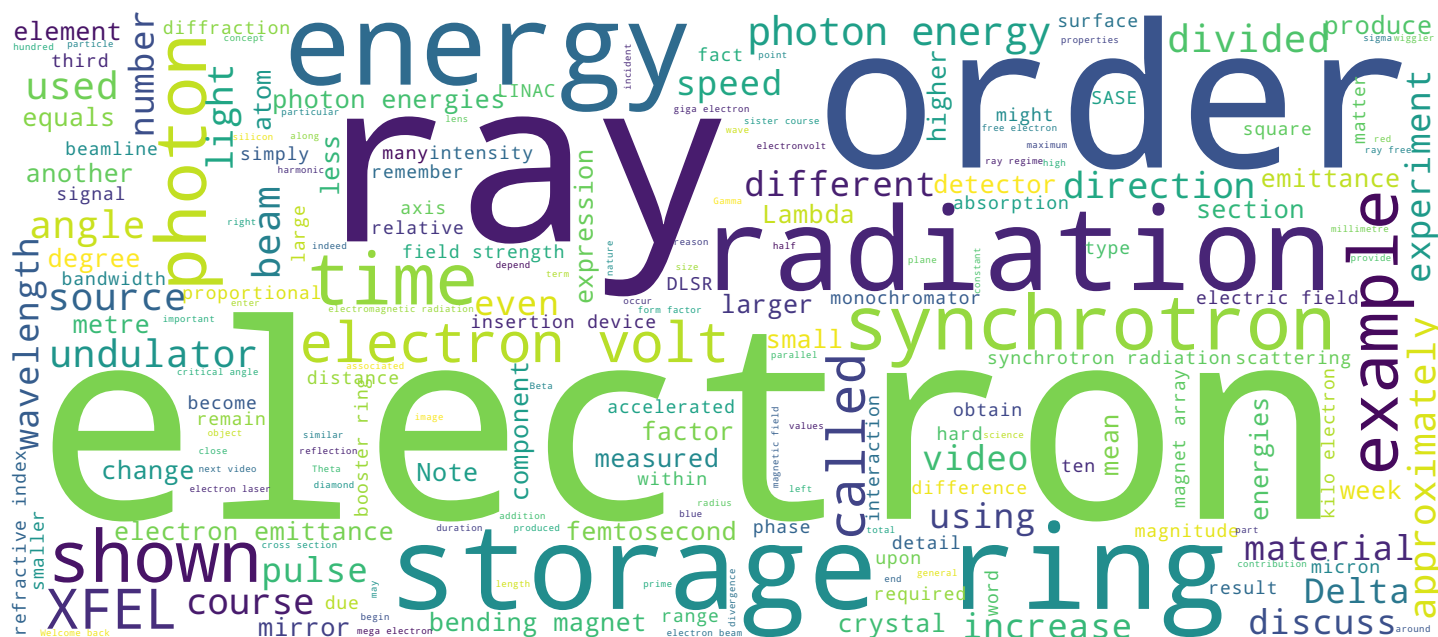


# Synchrotrons and XFELS for photon science – a brief overview

Synchrotrons and x-ray free-electron lasers  
Techniques and applications

Prof. Philip Willmott



Search MOOC



Video



# Contents and objectives of this video



- Components of a synchrotron
- Electron and photon energies at synchrotrons
- Architecture of an XFEL

Welcome back. In this third and last video of this, the first week of this course, we discuss the components of synchrotrons and XFELs, in preparation in particular for the third and fourth weeks. We will also see that the photon energies produced by synchrotrons, are orders of magnitude smaller than the electrons' energies within the storage ring, but also that they are nonetheless correlated.

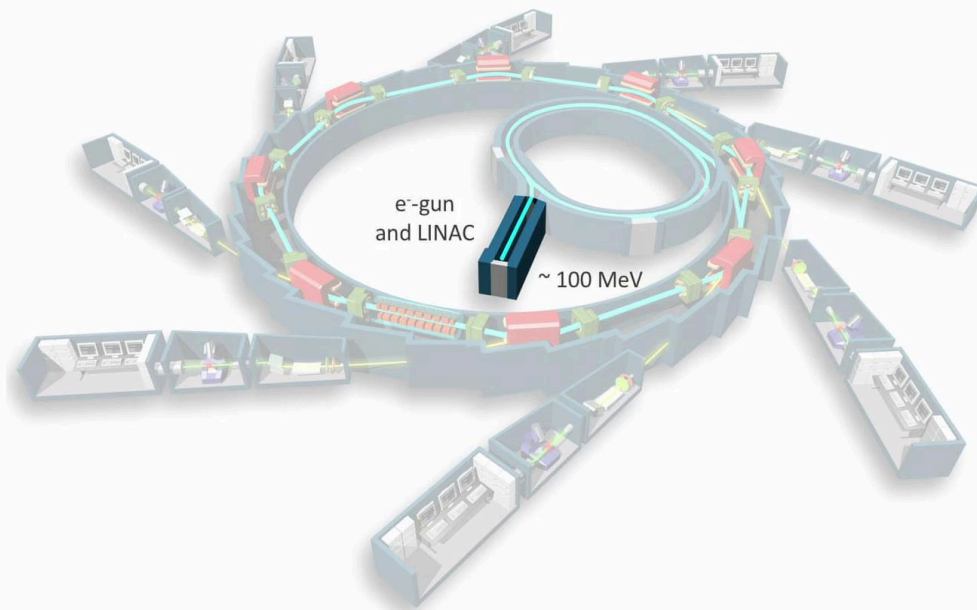
Notes

Summary



0m 05s

# Architecture of a synchrotron



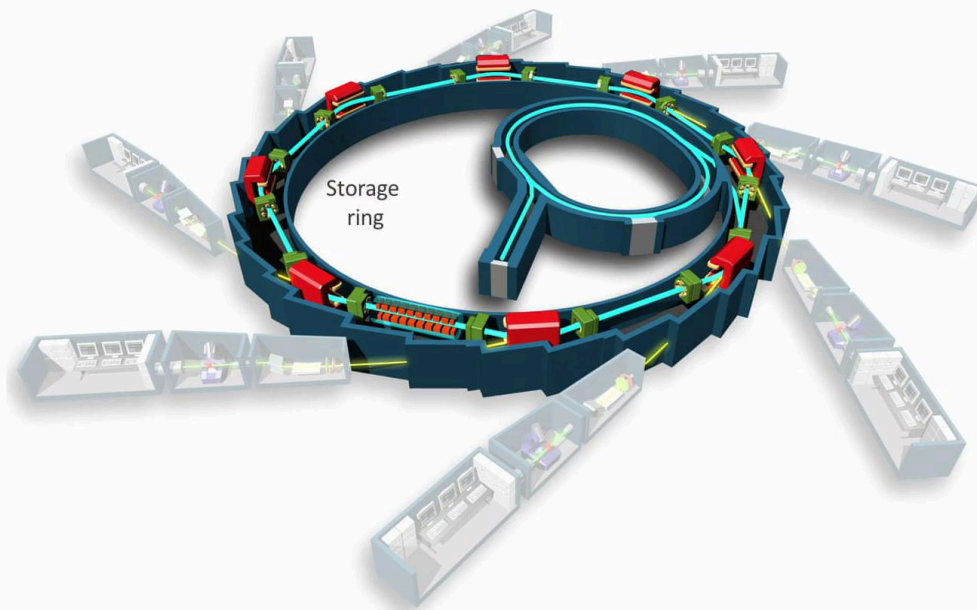
Okay. We now know qualitatively, what synchrotrons provide. Very brilliant beams of radiation. What actually are synchrotrons? What do they look like? Well, here's a schematic of a synchrotron facility. To put this into perspective, the larger ring structure shown here typically has a circumference of the order of a few hundred metres. So let's break down the components of a synchrotron, beginning with a source of electrons, the so-called electron gun, which may be a heated metal filament, typically tungsten, or an alloy thereof, injecting electrons by thermionic emission. The electrons are essentially just boiled off. These electrons are then accelerated in an evacuated linear accelerator, or LINAC, to energies measured in tens or hundreds of mega electron volts. Now remember, that if the energies of these electrons are similar to or greater than the electron rest mass energy of 511 kilo electron volts, they are considered to be at relativistic energies. Therefore, even at the end of the LINAC, the electrons are highly relativistic. For example, for a 100 mega electron volt electron, the fractional difference between the electron's velocity, and the speed of light, is only about 1 part in 100,000.

Notes

Summary



# Architecture of a synchrotron



It should be noted that in order for the electrons not to be scattered by air molecules as they are accelerated, they always experience ultra high vacuum conditions, with pressures typically of the order of a thousandth, of a billionth, of an atmosphere, or even less. The electrons then enter a so-called booster ring, in which their energy is further ramped up, until they attain the design energy of the main storage ring. The booster ring is actually a true synchrotron. The term 'synchrotron' comes from the required synchronisation between the increasing electron energy, and the ramping up of the field strength of the magnets, that redirect the electrons into a closed orbit within the booster ring. Without this synchronisation, the electrons would simply collide into the outer walls of the evacuated ring chamber. Now, once the electrons have attained their design energy, they are injected into the storage room where they remain, or are stored, hence the term storage ring, and used to generate synchrotron radiation. The storage ring is therefore a special case of a synchrotron, where the energy is constant and hence the magnet's field strengths are also held constant.

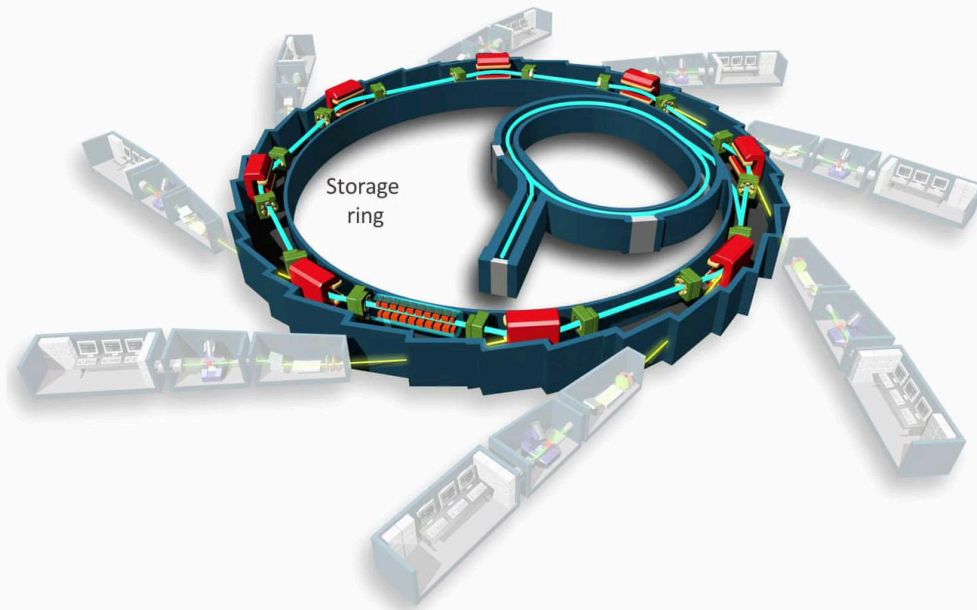
Notes

Summary



2m 07s

# Architecture of a synchrotron



The design energies of the electrons in the storage ring are typically measured in giga electron volts, that is billions of electron volts. At these energies, the electrons are so highly relativistic, that the difference between their speed and the speed of light, is measured in a few metres per second. We will see later that the strong relativistic effects associated with these velocities have important consequences on the nature and direction of the electromagnetic radiation that the electrons produce.

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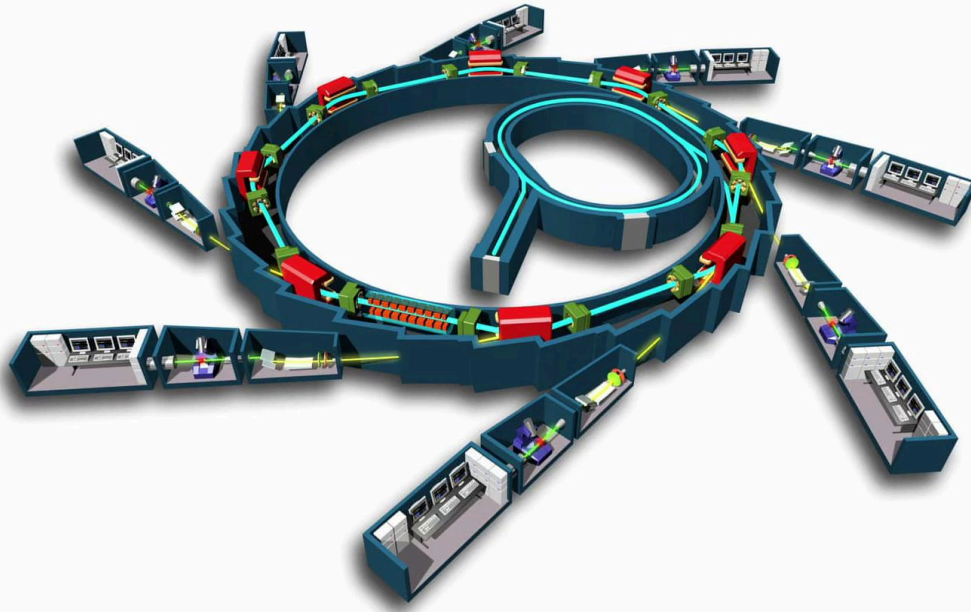
Summary



3m 30s



# Architecture of a synchrotron



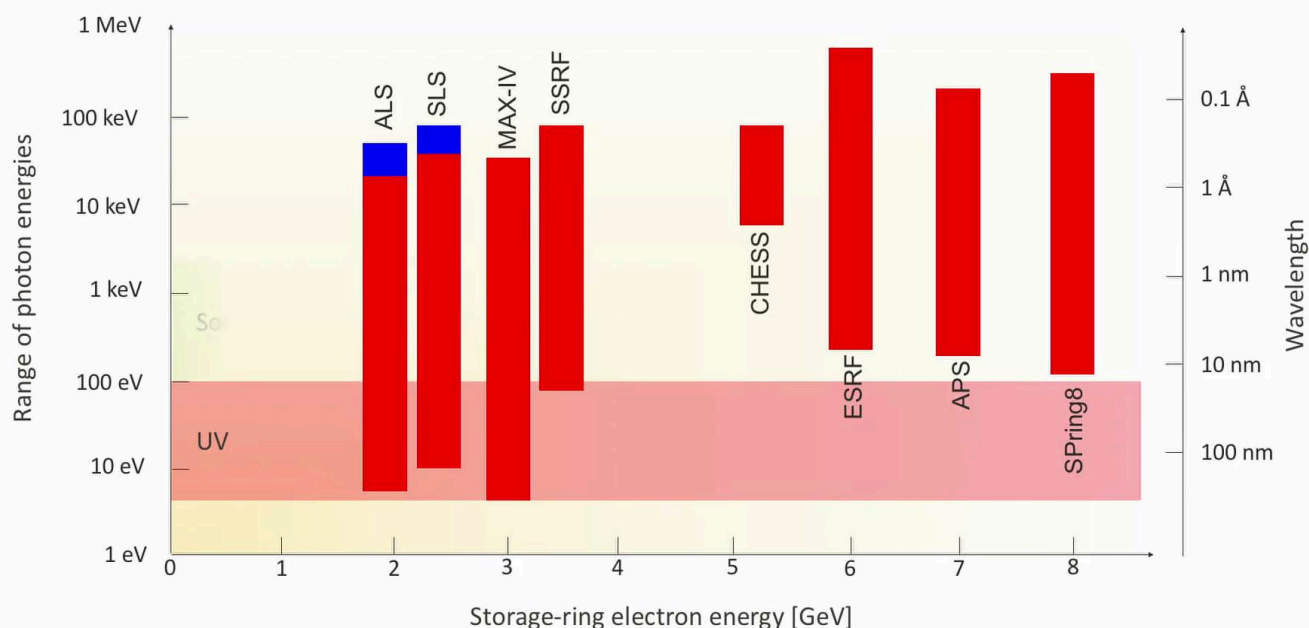
Now, in both the booster ring and the storage ring, the electrons are required to remain on a closed path, which is shown here in blue. This is achieved using bending magnets, highlighted here in red. As we shall discuss in detail later in the course, forcing electrons to execute a curved trajectory, causes them to emit electromagnetic radiation. This is your synchrotron light. In addition, the straight sections between the bending magnets are used to insert alternating arrays of north-south, south-north dipole magnets. These so-called insertion devices are even more brilliant sources of synchrotron radiation, than are the bending magnets. There are other important magnetic structures around the storage ring, such as quadrupoles, sextupoles, et cetera, plus other devices, including the RF power supply, the beating heart of a synchrotron ring, and beam position monitors, to name just a few of the most important components. Tangential to the bending magnet and insertion devices, are positioned the beamlines. These are the things which use the radiation where experiments are carried out. And the radiation is shown here as polychromatic and green beams produced by the magnet devices within the storage ring. A typical synchrotron might have anything between 10 and 50 beamlines, depending on the size of the facility.

Notes

Summary



# Electron and photon energies @ synchrotrons



Now, a common mistake made by the complete novice to synchrotron science, is to confuse the photon energies and the storage ring electron energies. The energy of even the most energetic photons produced at synchrotrons is less than a mega electron volt. Well over three orders of magnitude smaller, than the energies of the electrons that produce them. This actually shouldn't come as a surprise, if one considers the conservation of energy. If the photons generated by the electrons had similar energies to those electrons, the electrons would have much lower energies after emitting the photons, which would make them unable to remain in the orbit of the storage ring. The range of offered photon energies, at some representative synchrotron facilities, are shown here, plus the corresponding wavelength range. Note that the y axis is logarithmic. As a rule of thumb, the higher the storage ring energy, the higher the photon energy range on offer. For some medium energy and small energy storage rings, the photon energy range is extended to higher values, by using so-called super bands. The increases in range are shown for the SLS and the ALS, as these blue blocks. The ranges of the UV, soft X-ray and hard X-ray regimes are provided here.

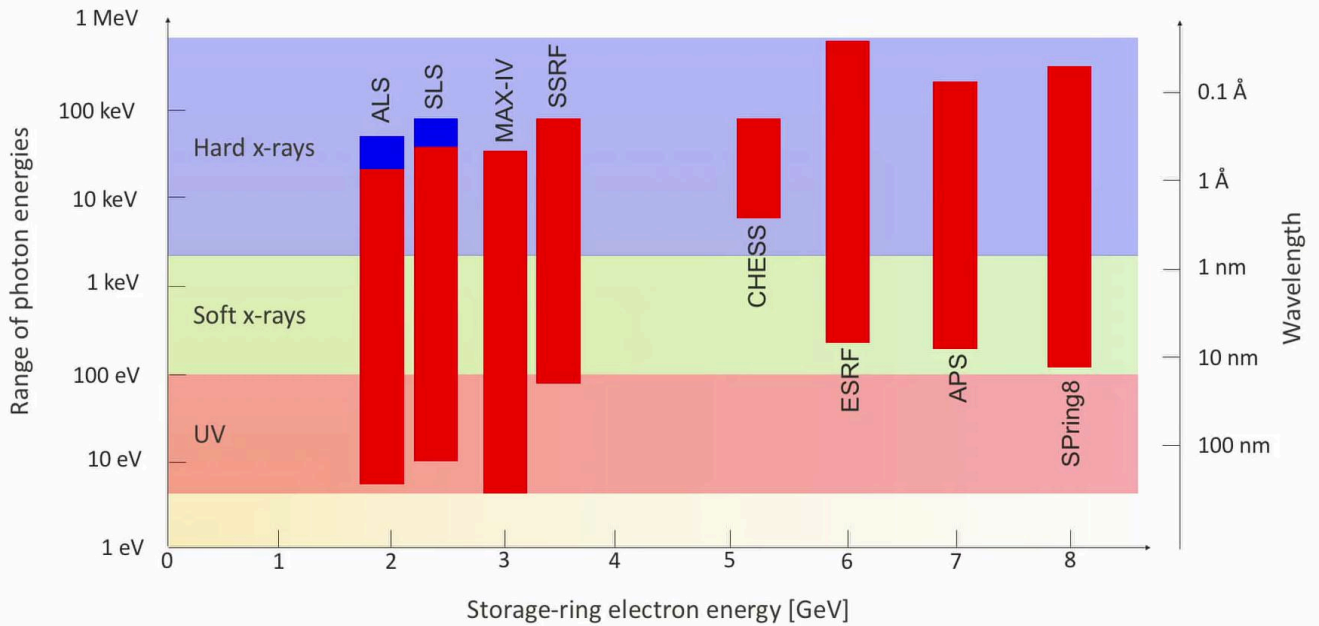
Notes

Summary

5m 53s



# Electron and photon energies @ synchrotrons



So for example, the ALS has historically, primarily, though certainly not exclusively, served experimenters interested in using UV and soft X-rays, such as in some electron spectroscopies, and magnetic dichroism. While, for example, the ESRF tends to concentrate on experiments demanding hard X-rays, such as in diffraction, lenseless imaging, and tomography.

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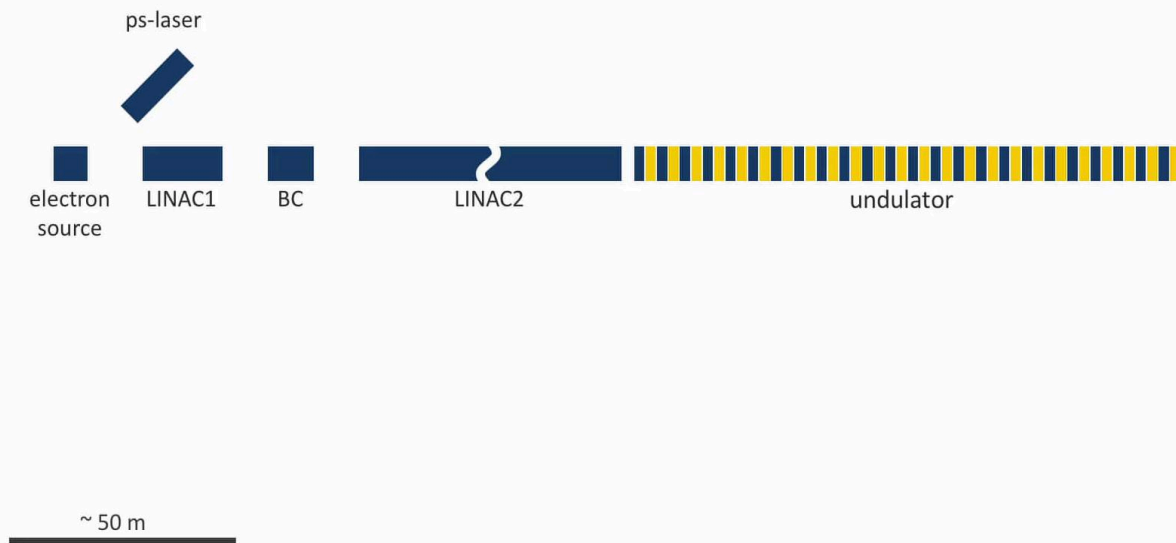
Summary



7m 31s



# Architecture of an XFEL



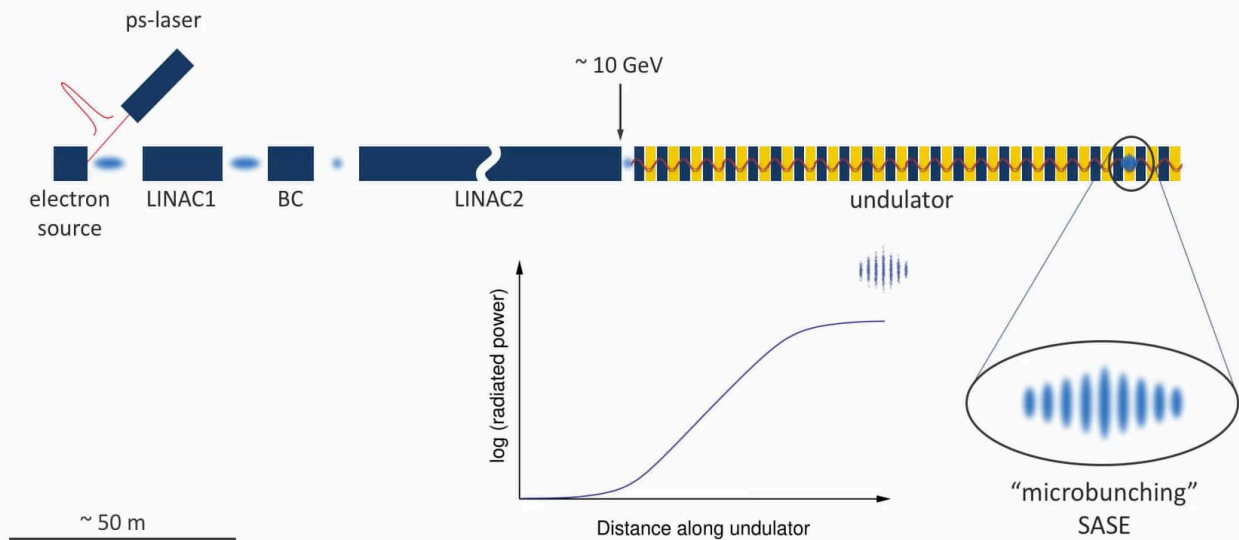
The first hard X-ray free electron laser, the LCLS at Stanford, California, came online in 2009. XFELs have peak brilliances, approximately ten orders of magnitude greater still, than those of modern synchrotrons. In addition, they produce trains of pulses with durations between a few femtoseconds, to a few tens of femtoseconds. Femtosecond is  $10^{-15}$  of a second. That is a millionth of a billionth of a second. This is over three orders of magnitude shorter than pulse lengths produced by synchrotrons, and sufficiently sure to follow chemical reactions as they occur in real time. Thus, XFELs marry the temporal advantages of femtosecond lasers in the visible and near visible regime, with the spatial resolution associated with X radiation. The exceedingly high brilliance of XFELs compared to synchrotrons, means that in general, changes in the approaches to experiments using XFELs compared to synchrotrons, are not incremental in nature, but rather represent a completely new paradigm shift. Synchrotrons and XFELs are thus complementary to one another, and one should not think that XFELs will somehow supplant synchrotron sources.

Notes

Summary



# Architecture of an XFEL



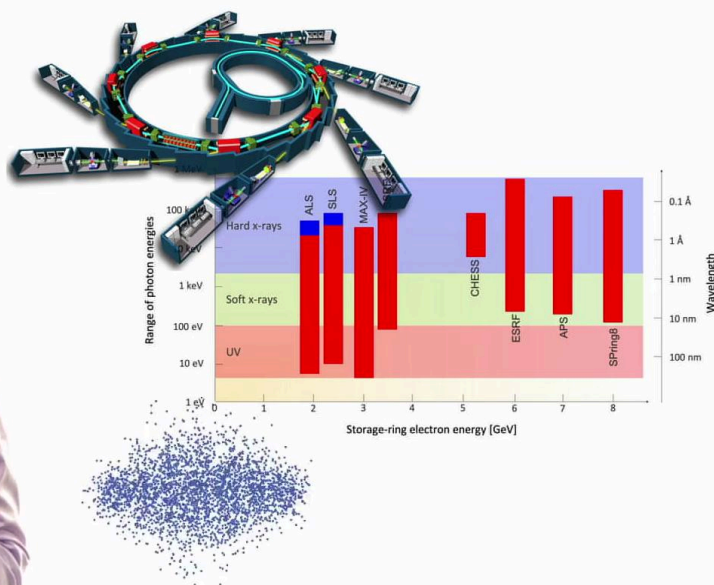
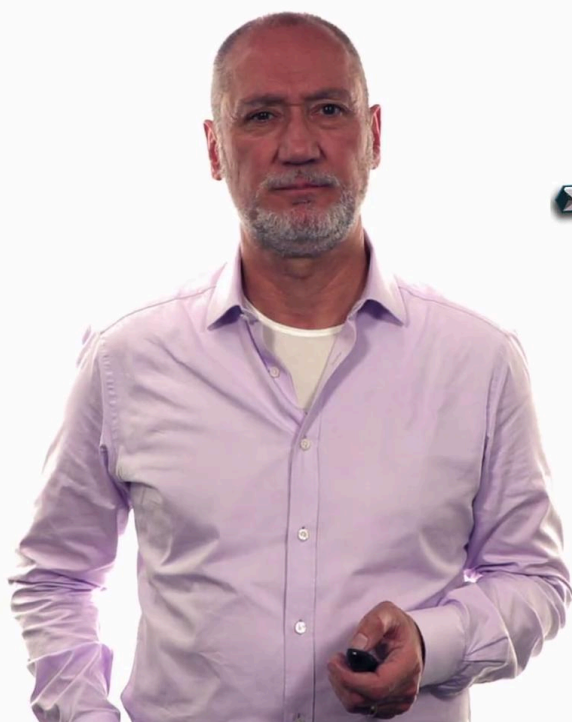
The architecture of XFELs is also very different from that of synchrotrons: a shorter electron bunch is generated by irradiating a metallic target with a picosecond laser pulse. This is accelerated in a LINAC, and then undergoes one or more bunch compressions to make the pulse shorter, by approximately a factor of 100. The shortened electron pulse is then further accelerated along the LINAC to several giga electron volts, and then enters a long array of alternating north-south, south-north magnet poles. As we will discuss later, this magnet array, which we know to be called an undulator, is essentially identical to the devices also used in the straight sections of synchrotron storage rings, the insertion devices mentioned earlier in this video, in the context of synchrotron facilities. Apart from the fact that they are over an order of magnitude longer, typically several tens of metres long. For reasons that will become apparent later in this course, this long magnet array is required in order to induce a phenomenon known as self amplified, spontaneous emission, or SASE. The result of SASE is that after exiting the long undulator magnet array, the electron bunch has been altered such that it now is divided into many micro bunches, each having a duration of only a few femtoseconds. These bunches produce the femtosecond X radiation characteristic of XFELs.

Notes

Summary



# Summary of this section



In this brief one video section, I have shown the overall architecture of synchrotrons and XFELs, which we will discuss in much more detail later in the course. It was also pointed out that the energies of the photons and the electrons that produce them, are very different from one another. The former being measured in a few electron volts, up to hundreds of kilo electron volts, the latter being measured in giga electron volts. Next week, we will discuss in detail the interactions of X-rays with matter. This will be invaluable to make sense of the design and specifications of X-ray optics, which we cover in the last two weeks of this course. Plus, provide a bedrock to understand the experimental techniques described in the sister course.

Notes

Summary

11m 13s

