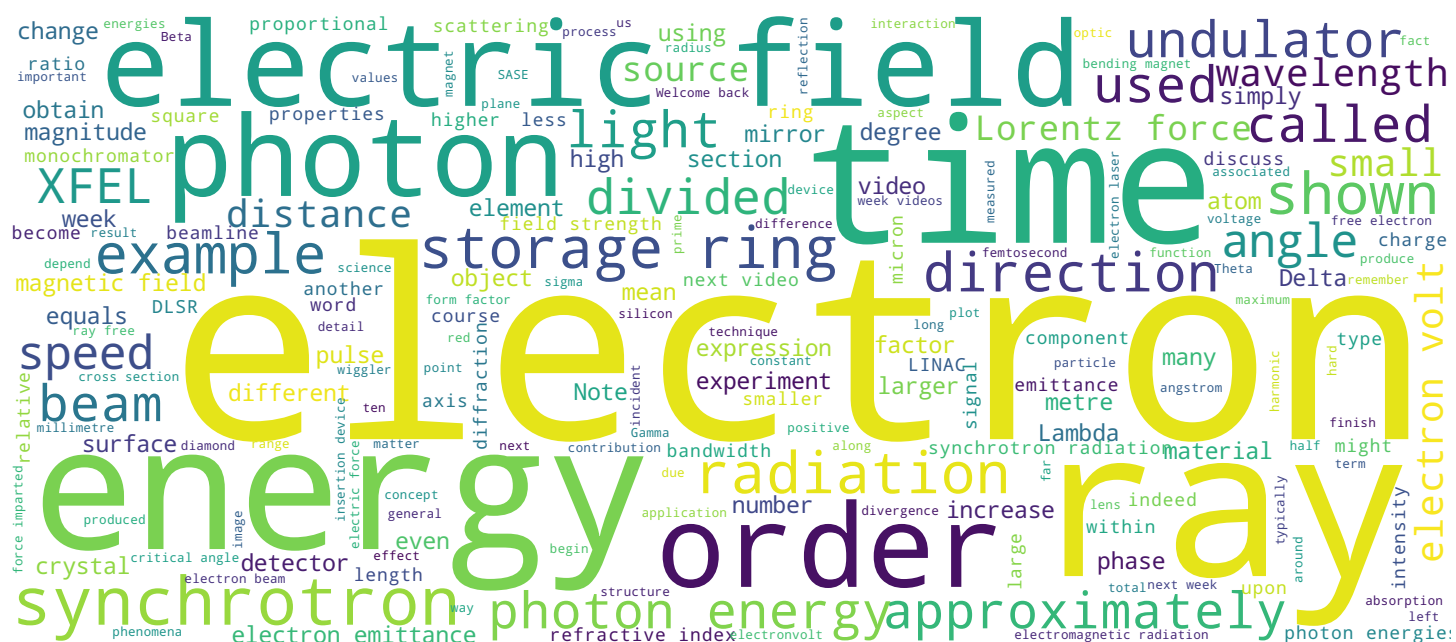


# Synchrotrons and x-ray free-electron lasers

## Techniques and applications

Prof. Philip Willmott



## Search MOOC



## Video



# Contents and objectives of this video



- Synchrotron components
- Electric and magnetic forces
- Forces induced by electromagnetic waves

Hello and welcome back to week three of this course, synchrotrons and X-ray free-electron lasers, techniques and applications. This week, we will cover the basics of machine physics. We start with a recap of the main components of a synchrotron ring, and which forces and phenomena we need to consider where. This will lead us to a brief discussion of aspects of special relativity within the context of synchrotron radiation. We then discuss the properties of synchrotron light, that define a facility, including the concepts of flux, emittance, brilliance and coherence. We will finish by looking at individual components of the so-called magnet lattice that make up the storage ring of a synchrotron facility.

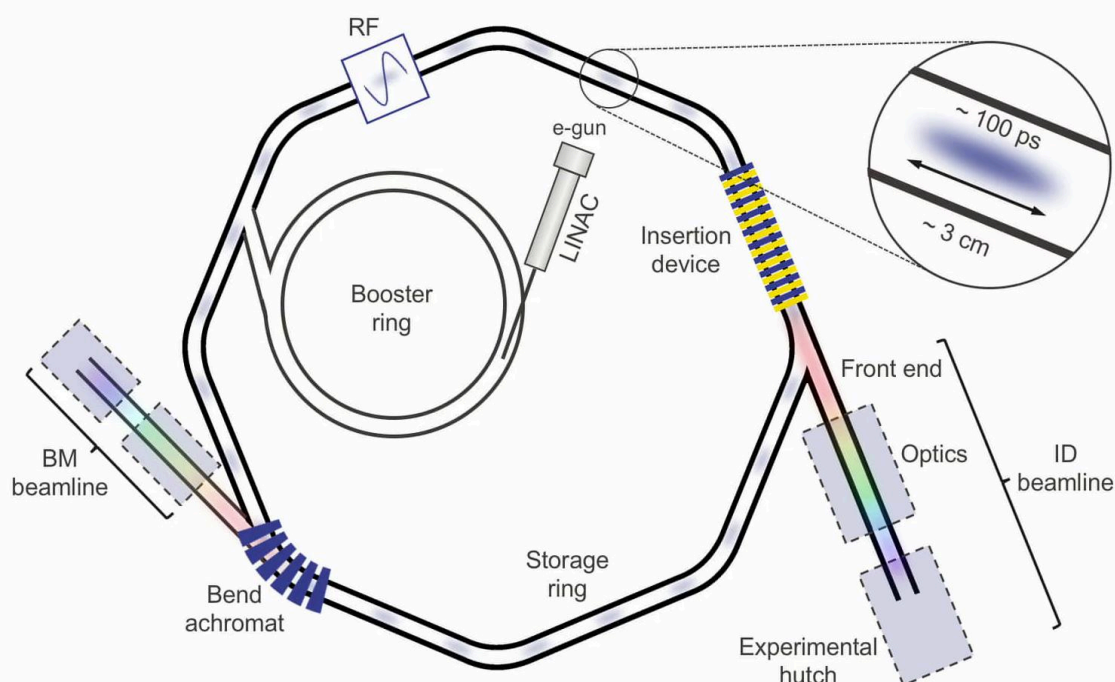
Notes

Summary



0m 05s

# Overview of synchrotrons



We see here a schematic of a synchrotron. A question you might ask is, what forces act on an electron in its journey, from leaving the surface of the electron gun, to it circulating around the storage ring and emitting photons, and thereby losing energy in the process? Well, firstly, the energy of the electrons as they leave the surface of the electron gun, is measured in fractions of an electron volt. The linear accelerator, or LINAC, then accelerates them to the order of 100 mega electron volts, which is approximately 200 times the electron's rest mass. From this, we know that they are already highly relativistic. How did the LINAC get them to this high energy? Well, a LINAC is a serial array of conducting cavities. Each of these is connected to a high frequency oscillating voltage and the phases of these voltages are tuned in a way so that an electron, as it passes through one cavity, will experience an accelerating electric field, before entering the next cavity where the phase of the voltage is being so set, that it again experiences an acceleration. This process continues down the entire length of the LINAC. There are RF cavities in the booster ring and also in the main storage ring, only one is shown in this schematic.

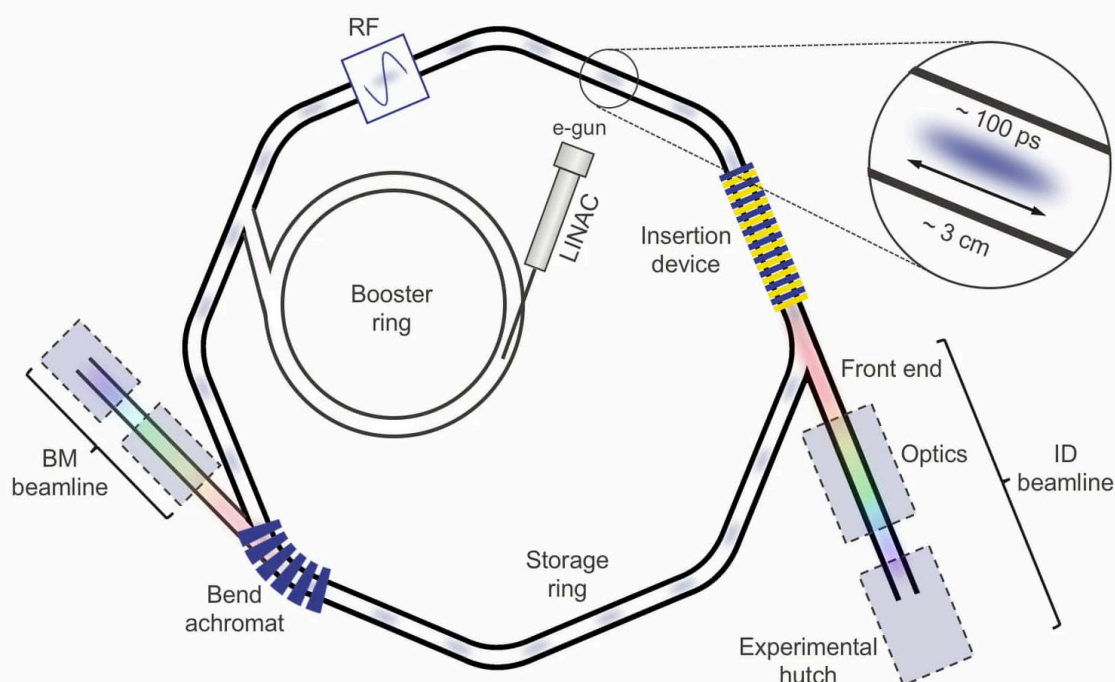
Notes

Summary



0m 59s

# Overview of synchrotrons



These RF cavities are essentially the same as the single cavity within the LINAC. They are the multiple beating heart of the synchrotron, giving the electrons an encouraging kick up the backside, through their radio frequency electric field, to ensure that the electrons do not run out of puff through emitting X-rays. So electrons are accelerated using devices that generate electric fields. Now here by accelerate, I have meant the conventional usage: increased speed and energy. Note, however, that physicists use the term 'accelerate' to mean speed up or increase energy, slow down or decrease energy, in other words, brake, and change direction, as in executing a curved path. Indeed, acceleration happens any time the velocity changes. Remember, velocity is a vector quantity, with both magnitude and direction. So even by changing the direction, but not the speed, is a form of acceleration called centripetal acceleration. Accelerations of any kind require a force. Magnetic devices in a synchrotron are used to impart centripetal acceleration. The magnetic or Lorentz force is thus the tool used to keep the electrons on a closed orbit in the storage ring, and is also used in so-called insertion devices to force the electrons into a slalom path.

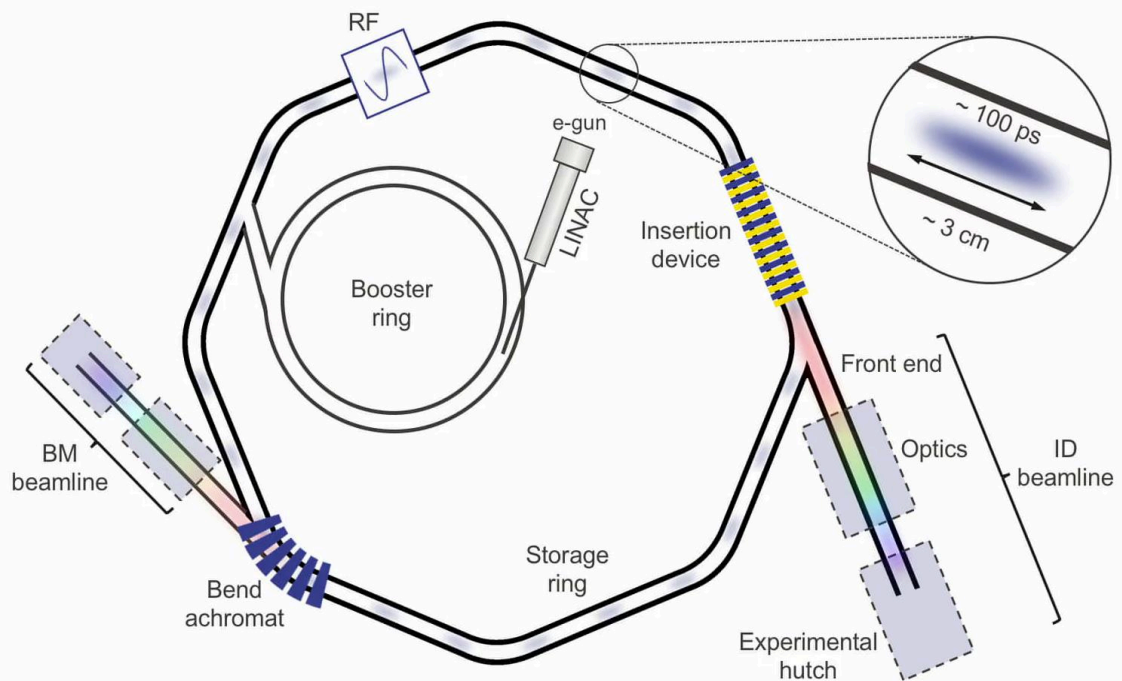
Notes

Summary



2m 30s

# Overview of synchrotrons



The magnetic Lorentz force does not, and indeed cannot, change the speed of the electrons. So it seems we need to consider both electric and magnetic forces, which we do now.

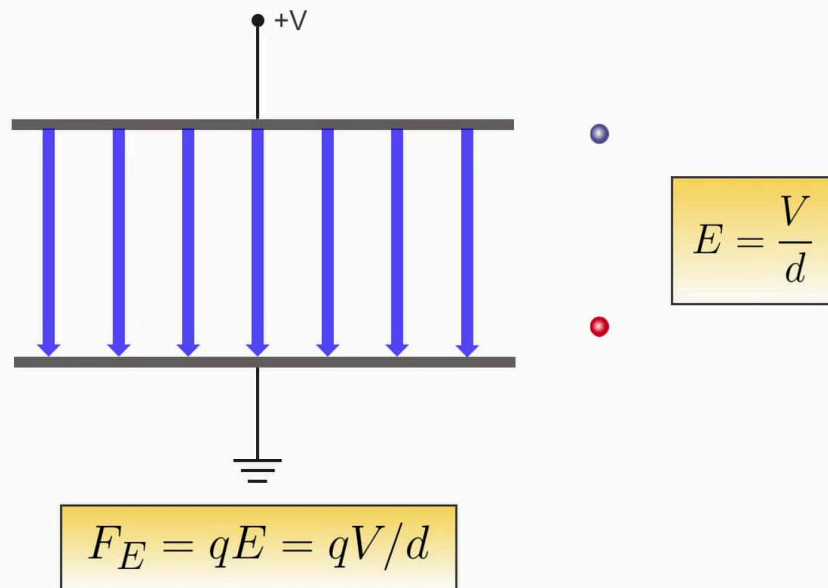
Notes

Summary

4m 08s



# Electric fields and forces



As we have already discussed in week two, an electric field is generated by two conducting parallel plates of different electrical potential.  $\Delta V$  separated by a distance  $D$ . The electric field  $E$ , is simply  $\Delta V$ , divided by  $D$ , and has electric field lines with a positive direction from the more positive plate to the more negative plate. The force imparted on a particle of charge  $Q$ , is  $FE$  is equal to  $qE$ . Note that because an electron has a negative charge,  $Q$  equals minus  $E$ , the electric force imparted on it is in the anti-parallel direction to that of the electric field. So an electron would, in the shown configuration, be bent upwards, a positron downwards.

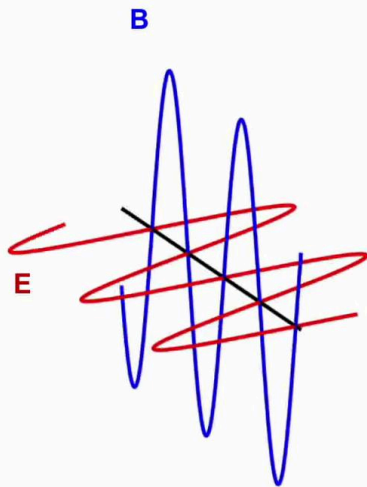
Notes

Summary





# Electric field strength of EM radiation



$$\frac{P}{A} = \frac{E_0^2}{2\mu_0 c}$$

$$\Rightarrow E_0 = \sqrt{\frac{2P\mu_0 c}{A}}$$

- Peak P/A from micron-focused monochromatic x-rays @ undulators  $\sim 1.6 \times 10^{12} \text{ W/m}^2$
- $\mu_0 = 4\pi \times 10^{-7} = 1.26 \times 10^{-6} \text{ Vs/(A m)}$
- $E_0 \sim 35 \text{ MV/m}$ 
  - Seems a lot but insufficient to remove any electrons from atoms
  - Electron free @ ca. 100 Å  
 $\Rightarrow V \sim 0.35 \text{ V}$ ; energy  $\sim 0.35 \text{ eV}$   
 Even valence electrons have binding energies  $\sim 5 \text{ eV}$

A plane wave of electromagnetic radiation has an oscillating electric field with a wave length equal to that of the associated light, and at right angles to this, a magnetic field with the same phase. The aerial power density is related to the electric field strength by  $P / A$ , is equal to  $E_0$  squared, divided by  $2\mu_0 c$ , where  $E_0$  is the electric field amplitude,  $\mu_0$  is equal to  $4\pi$  times  $10$  to the  $-7$ , volt seconds per amp metre, and is the permittivity of free space, and  $c$  is the speed of light. From this, we can estimate that the maximal electric field strength from a micron focus beam at an undulator beam line is of the order of 35 mega volts per metre. This might seem quite a lot, but on the atomic scale, the voltage drop is small, only about 0.35 of a volt, across a distance of 100 angstroms. This is a relevant distance, as it equates approximately to the distance that an electron needs to be away from its parent atom, to be considered to be free. Now, seeing as even valence electrons require typically five or so electron volts energy to be removed from an atom, it should be clear that the electric field generated by undulator radiation is insufficient to tear away an electron simply through its electric field, in a classical manner. Instead, it requires quantum effects, such as resonant absorption discussed last week, to ionise atoms using undulator X-rays.

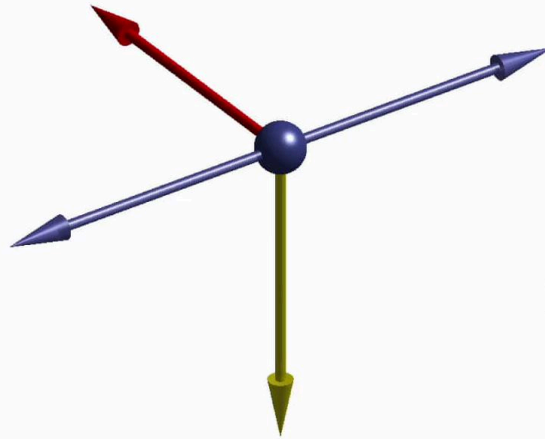
Notes

Summary



5m 18s

# Magnetic (Lorentz) forces



$$\mathbf{F}_L = e \mathbf{B} \times \mathbf{v}$$
$$= e |B| |v| \sin \theta$$

The magnetic, or Lorentz force acting on a charge  $E$  minus, is the cross product of the magnetic field vector, and the charge velocity. This is maximal, if the angle  $\theta$  between  $\mathbf{v}$  and  $\mathbf{B}$  is 90 degrees, and is equal to zero, if they are parallel. Note that A, conventional current is in the opposite direction of the actual electron flow, B, that the magnetic field points from the North to the South Pole, and C, the Lorentz force,  $\mathbf{F}_L$ , is in the positive Z direction. If  $\mathbf{B}$  is in the positive X direction, and  $\mathbf{v}$  in the positive Y direction.

Notes

Summary



7m 07s



# L is for Lorentz. L is for lazy

$$d\mathcal{E} = \mathbf{F} \cdot d\mathbf{x}$$

$$\mathbf{F}_L = e \mathbf{B} \times \mathbf{v}$$

$$\frac{d\mathcal{E}}{dt} = \mathbf{F}_L \cdot \mathbf{v} = 0$$

- Magnitude of  $v$  unchanged
- Direction only changed
- $\Rightarrow$  magnetic fields cannot transfer energy to or from electrons!!



An important property of the Lorentz force is that it does no work. The work done on any object is equal to the scalar product of the force acting on the object, and the distance it travels while experiencing this force. Note that here, I have used the calligraphic  $\mathcal{E}$  to designate the electron energy, in order to avoid confusion with the electric field given simply by capital  $E$ . As the Lorentz force is always perpendicular to this velocity, the rate of energy transfer is zero and hence magnetic fields cannot transfer energy to or from electrons. This is important to remember when discussing the electrodynamics in undulators, and particularly so when we encounter the phenomena of micro punching and SASE and XFELs, in next week's videos.

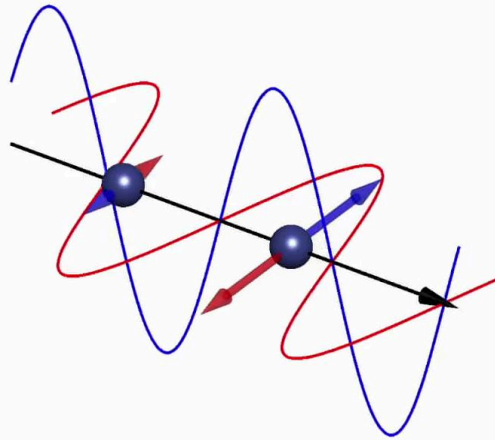
Notes

Summary



7m 52s

# Electromagnetic wave acting on an electron



$$\left. \begin{aligned} B &= \frac{E}{c} \\ F_E &= -eE \\ F_L &= eBv \end{aligned} \right\} F_L/F_E = -v/c$$

From our discussions so far, we can generate a cartoon of the electric and magnetic forces acting on an electron from an electromagnetic wave. They act in opposite directions. Now, this begs the question, what are their relative magnitudes? Well, another important relationship in electromagnetism is that between the electric and magnetic field amplitudes, which we also briefly touched upon in the second of last week's videos, namely that  $B$  is equal to  $E$  upon  $c$ . From this and the expressions for the Electric and Lorentz forces, we obtain a ratio for these of  $F_L$ , divided by  $F_E$ , is equal to minus  $v / c$ . . In other words, unless the electron is travelling at a good fraction of the speed of light, the force imparted by the electric field of the electromagnetic wave will dominate. As we will see in the next video, however, the electrons and storage rings do indeed have velocities exceedingly close to the speed of light. Not only has this a direct impact on the ratio of the Lorentz and electric forces imparted by electromagnetic radiation, but it also plays a critical role in the appearance and properties of synchrotron radiation, due primarily to special relativity. We will look at this in the next video.

Notes

Summary



8m 43s