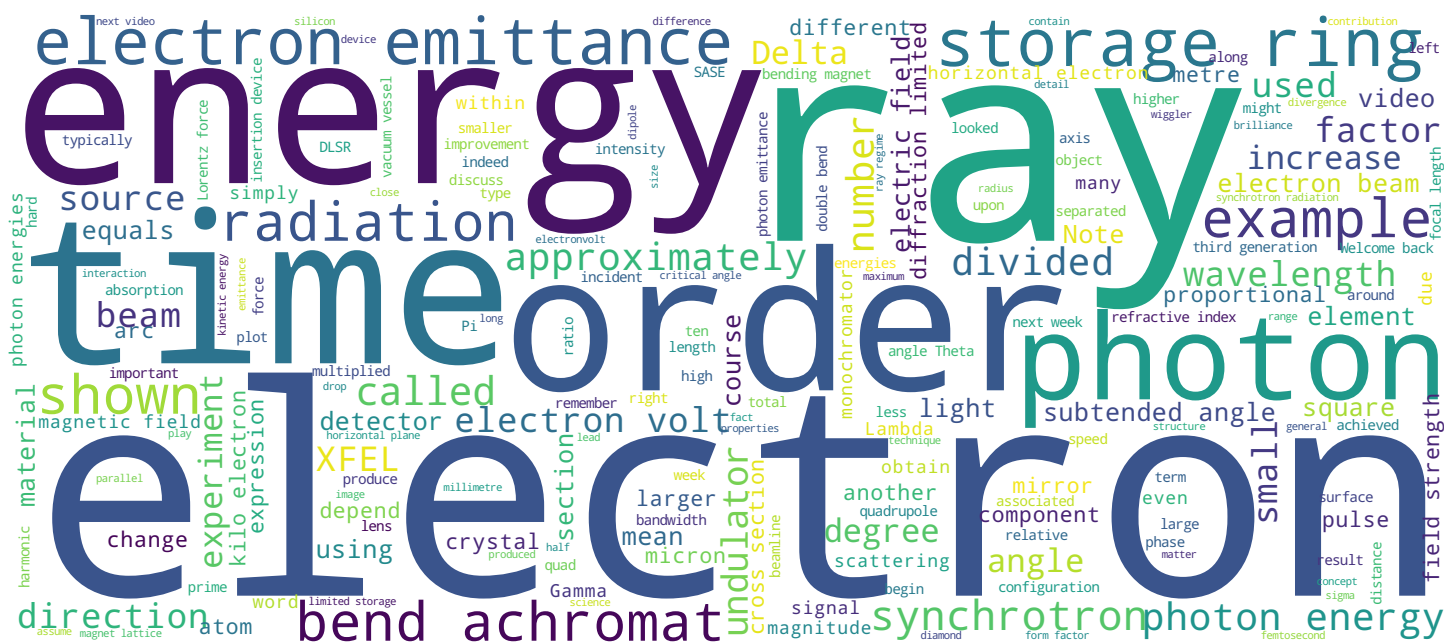


Prof. Philip Willmott



Search MOOC



Video



Contents and objectives of this video



- Quadrupoles
- Sextupoles
- Achromats
 - DBAs
 - MBAs

Welcome back. In this last video of week three, we consider two other components of the magnet lattice, namely quadrupoles and sextupoles, and how they can be combined to form so called achromats. The simplest achromat is the double bend achromat, or DBA, which involves two dipole bends. Achromats involving several dipoles, typically between five and nine, are called multi bend achromats, or MBAs. These are the cornerstone of the fourth generation diffraction limited storage rings.

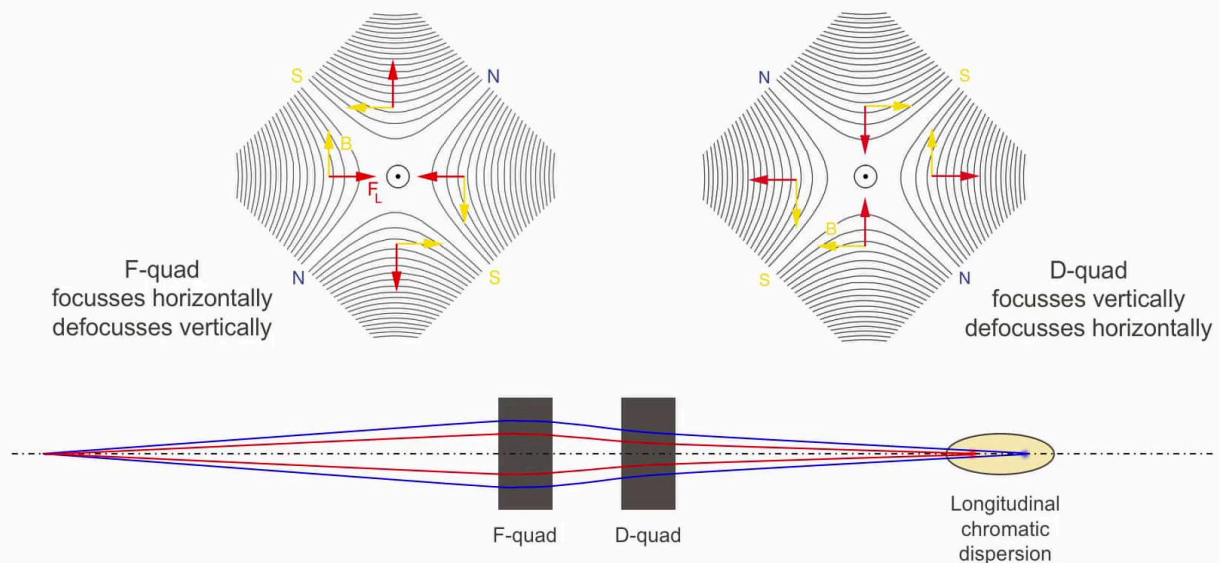
Notes

Summary



0m 05s

Quadrupoles



So let's begin with quadrupoles. As their name implies, they consist of four magnets whereby the north and south poles alternately face towards the geometric centre of that quadrupole. The exact centre of a quadrupole has zero magnetic field strength. If one considers the direction of the Lorentz force, it becomes apparent that for electrons in the central horizontal plane flowing perpendicularly out of the image towards you, the configuration on the left will squeeze electrons away from the centre towards that centre in the horizontal plane and defocus them in the vertical plane. The left configuration is called an F-quad, F standing for horizontal focusing. On the right, the opposite occurs, and this configuration is called a D-quad as it defocuses horizontally but focuses vertically. If an F-quad and a D-quad are separated by a carefully chosen distance, the combined effect is an overall focusing in both the horizontal and vertical planes. Unfortunately, electrons with different kinetic energies are focused at different points along the axis. They are thus dispersed longitudinally.

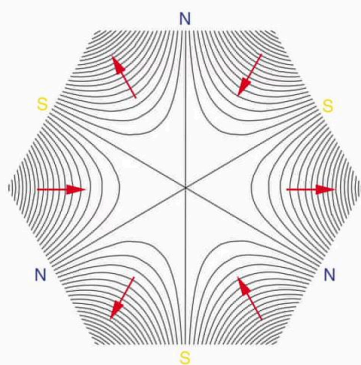
Notes

Summary

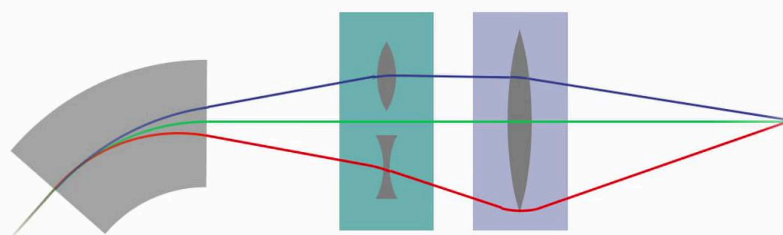


0m 50s

Sextupoles



Focal length $\propto 1/r$
If focusing @ r ,
defocussing @ $-r$



Chromatic correction using
sextupole + quadrupole

Now this is where sextupoles come into play. Their configuration is such that if the Lorentz force is focusing at a vector position r away from their geometric axis, it is defocusing at $-r$. The focal length is proportional to r . By combining sextupoles with quadrupoles, the focal length dispersion of the quads shown in the previous slide can be corrected for, as shown schematically on the right here.

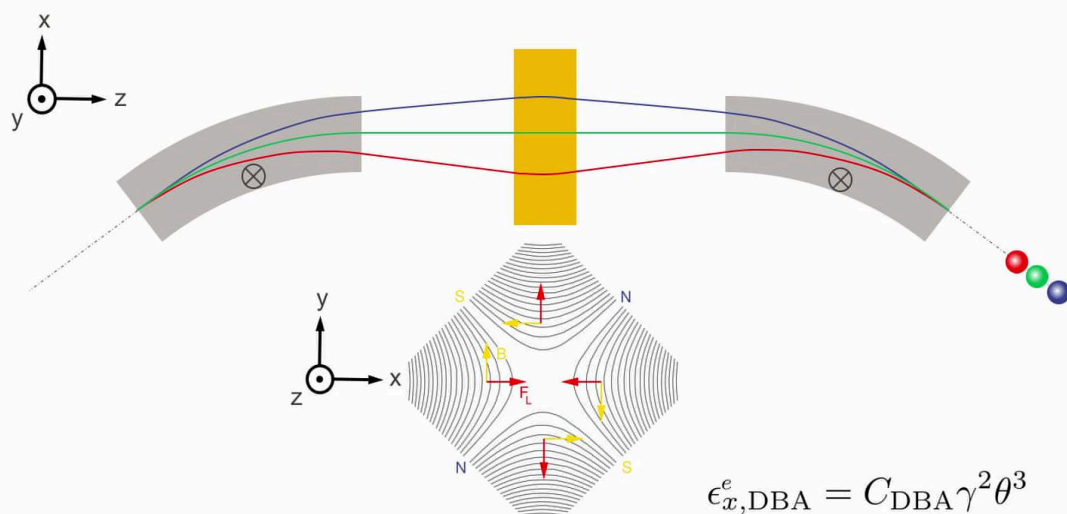
Notes

Summary



2m 34s

Bend achromats



$$\epsilon_{x,DBA}^e = C_{DBA} \gamma^2 \theta^3$$

$$C_{DBA} = \frac{11\sqrt{5}\hbar}{384 m_e c} = 2.474 \times 10^{-5} \text{ nm} \cdot \text{rad}$$

Energy dispersion of the electron beam will result in a spatial broadening after passing through one dipole as the bending radius is proportional to the electron's kinetic energy. If one inserts a quadrupole and another dipole positioned as the mirror image of the first across the central plane of the quadrupole, focusing becomes naturally achromatic. It emerges for reasons substantially beyond the introductory level of this course that the intrinsic best electron emittance in the horizontal plane is equal to a constant CDBA given here, multiplied by the square of Gamma and the cube of Theta, the angle subtended by a single dipole. This cubic dependence is very important, so please try to remember it.

Notes

Summary



3m 10s

Emittance of double-bend achromats

- Typical values for ϵ_x^e

- e.g., 20 straights, 20 DBAs

- $\theta = 360^\circ/40 = 9^\circ = 0.157$ radians ($\pi/20$)

$$\epsilon_{x,DBA}^e = C_{DBA} \gamma^2 \theta^3$$

- 3 GeV ring; $\gamma = 5871$

$$C_{DBA} = \frac{11\sqrt{5}\hbar}{384 m_e c} = 2.474 \times 10^{-5} \text{ nm} \cdot \text{rad}$$

$$\epsilon_x^e = 3.3 \text{ nm} \cdot \text{rad} \gg \epsilon^p$$

- Representative of emittance values for 3rd-generation facilities

- \Rightarrow total emittance of 3rd-generation facilities in orbital plane dominated by the electron emittance

$$\epsilon^p = \frac{\lambda}{4\pi}$$

So let's now try to calculate a typical horizontal electron emittance at a third generation synchrotron installed with double bend achromats. We assume that there are 20 sectors in the synchrotron, implying a subtended angle per arc of 18 degrees, and therefore a subtended angle per dipole of nine degrees, because there are two dipoles per double bend achromat. This equates to Theta equals 0.157 radians. We take a 3 Giga electron volt ring, such as a MAX IV, corresponding to Gamma is equal to 5,871. This leads to an ultimate horizontal electron emittance of 3.3 nanometer radians, which is indeed representative of current third generation facilities. Note that for photon energies much above 30 eV, the total emittance combining both photon and electron contributions will be dominated by the electron emittance at third generation facilities.

Notes

Summary



From double- to multibend achromats



$$\left. \frac{\epsilon_{x,DBA}^e}{\epsilon_{x,MBA}^e} \right|_{2\theta_{DBA}=M\theta_{MBA}} = 3 \frac{M-1}{M+1} \left(\frac{\theta_{DBA}}{\theta_{MBA}} \right)^3 = \frac{3}{8} \left(\frac{M-1}{M+1} \right) M^3$$

$$\frac{\epsilon_{x,DBA}^e}{\epsilon_{x,7BA}^e} = 3 \frac{7-1}{7+1} (7/2)^3 = 96.5$$

First, let's consider the improvement in electron emittance simply by increasing the number of dipoles per arc, but keeping the subtended angle Theta per dipole constant. It turns out that the relative improvement, in other words, the reduction in emittance is equal to three times M minus one divided by M plus one. We can do a sanity check on this by setting M is equal to two, in which case the ratio is unity as expected. If we make, for example, M equal to five, the improvement is a factor of two. But of course, we would never use the approach of simply increasing the number of dipoles per achromat, but at the same time keeping the angle Theta per dipole constant, as this produces, at best, asymptotically an increase by a factor of three for large values of M. Moreover, this will use up an unacceptable fraction of the entire synchrotron with arcs, leaving too little room for the straight sectors where most of the fun happens. Clearly, a better strategy is to slice up a given subtended angle into more dipoles. By doing this, the third power dependence of the emittance of a multi bend achromat on the dipole subtended angle Theta comes into play.

Notes

Summary



5m 28s

From double- to multibend achromats



$$\left. \frac{\epsilon_{x,DBA}^e}{\epsilon_{x,MBA}^e} \right|_{2\theta_{DBA}=M\theta_{MBA}} = 3 \frac{M-1}{M+1} \left(\frac{\theta_{DBA}}{\theta_{MBA}} \right)^3 = \frac{3}{8} \left(\frac{M-1}{M+1} \right) M^3$$

$$\frac{\epsilon_{x,DBA}^e}{\epsilon_{x,7BA}^e} = 3 \frac{7-1}{7+1} (7/2)^3 = 96.5$$

For a given subtended angle per arc, which contains the entirety of the bend achromat, the improvement in emittance is three eighths multiplied by M minus one divided by M plus one, multiplied by M cubed. So for example, by going from a double bend achromat to a seven bend achromat, the theoretical improvement in horizontal electron emittance is almost a factor of 100, as we see here.

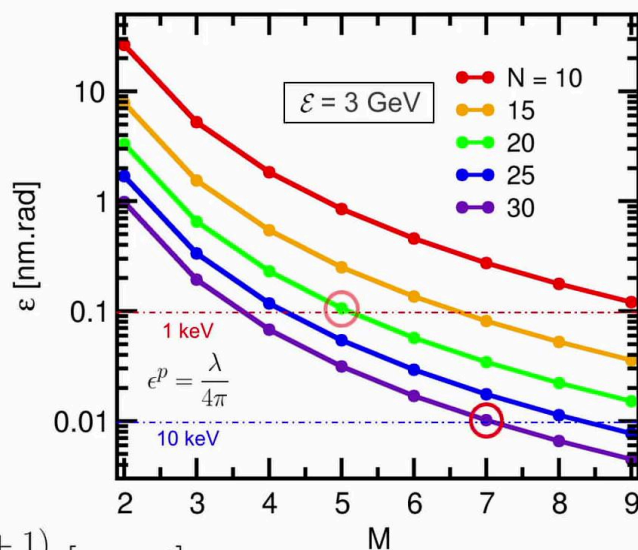
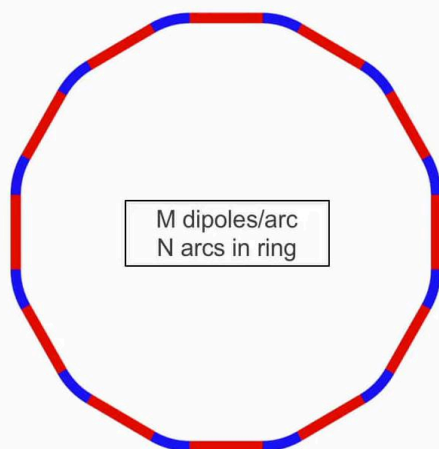
Notes

Summary



7m 08s

From double- to multibend achromats



$$\epsilon_x^e = 252.67 (\mathcal{E} [\text{GeV}])^2 \left(\frac{\pi}{MN} \right)^3 \frac{(M+1)}{(M-1)} [\text{nm rad}]$$

The absolute horizontal electron emittance also depends on the square of the storage ring energy. The equation is provided here, and plots are shown for double bend achromats for M equals two, up to a nine bend achromat for M equals nine, for differing numbers of arcs M within the ring. Now remember, arc here means the entire sector containing the bend achromat, so each arc has a subtended angle of M times Theta, and M times N times Theta must equal to Pi, a whole circle. I now include the photon emittance Lambda divided by four Pi for one kilo electron vault and 10 kilo electron vault photons for comparison. We see, for example, that a storage ring with 30 arcs each housing a seven bend achromat has an electron emittance approximately equal to the 10 kilo electron volt photon emittance. Such a ring would be truly diffraction limited in the hard X ray regime. A five bend achromat lattice containing 20 arc sectors, will become diffraction limited past a photon energy of one kilo electron volt.

Notes

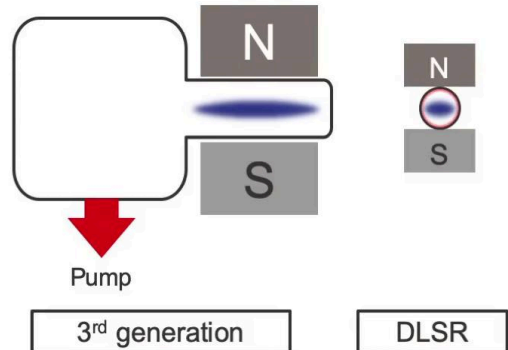
Summary



7m 44s

Why only now?

- Using present-scale (3rd-generation) magnets would result in
 - An unacceptable increase in ring circumferences
 - Unavoidable alignment errors
- Reduce
 - Magnet sizes
 - More compact 🙌
 - Reduces B 🙌
 - Distances between magnet poles
 - Increases again B 🙌
- Small vacuum vessels
 - Require special “NEG” coating
 - Porous alloys of Al, Ti, Fe, V, Zr



This begs the question as to why this seemingly obvious and long understood approach to improve the horizontal electron emittance and thereby the brilliance, is only now being pursued. First, until recently, the costs and the introduction of mechanical misalignments associated with increasing the number of elements in the magnet lattice were considered to be unacceptable. Miniaturisation of these magnet lattice components is absolutely necessary, as otherwise, an MBA will occupy too much real estate. Accurate miniaturisation and the development of multi functional magnets machined from a single magnetic yoke block are capabilities that have only in the last decade become at all feasible. These technological developments have decreased both costs and the necessary circumference of a storage ring to accommodate the MBAs and thus achieve these goals. The triple bend achromat of the SLS and the seven bend achromat of MAX IV are shown here for comparison.

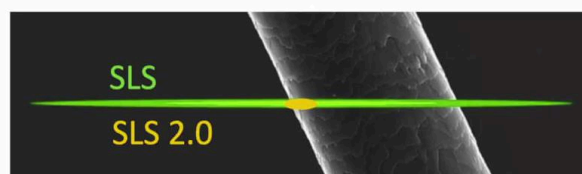
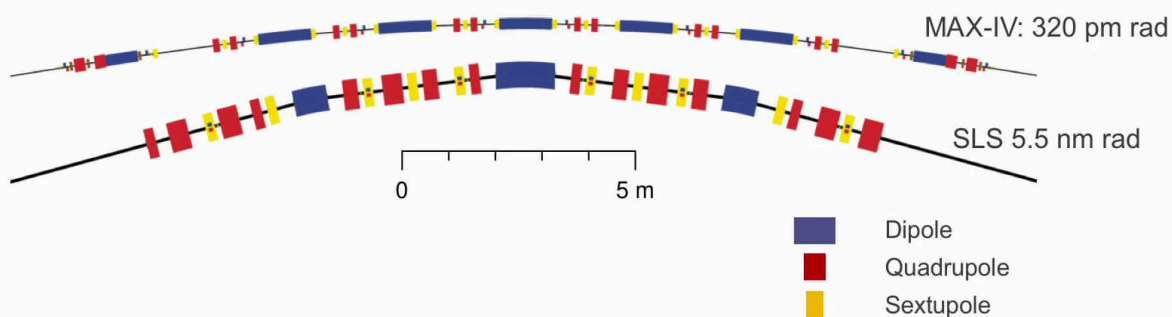
Notes

Summary



9m 14s

DLSRs – smoothing the path to ultimate performance



Courtesy Andreas Streun, Paul Scherrer Institute

Bottom right, the expected electron beam size of the upgrade to the Swiss light source is laid over the beam cross section of the electron beam in the present configuration of the SLS, in the low beta straight sections. Both are shown to scale with an electron micrograph of a human hair. A further obstacle to reducing the size of the magnets is that the cross section of the vacuum vessel containing the electron beam needs to be so small that pumping them with traditional pumping equipment. In particular, ion getter pumps, becomes increasingly inefficient through the narrow piping.

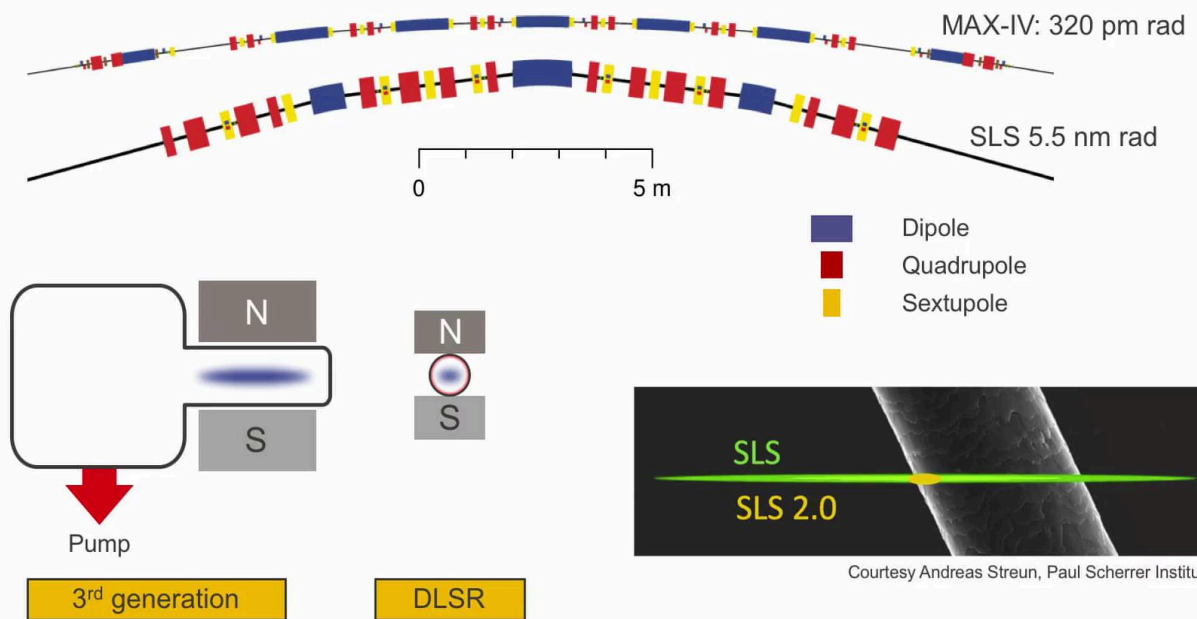
Notes

Summary

10m 33s



DLSRs – smoothing the path to ultimate performance



Courtesy Andreas Streun, Paul Scherrer Institute

This will limit the ultimate vacuum that can be achieved, which in turn results in more frequent collisions between the electrons and residual gas particles, thereby increasing the loss rate and production of Bremsstrahlung. In recent years, however, a novel approach to achieving ultra high vacuum conditions has been developed, namely the use of non evaporable getter, or NEG, coatings of the inner walls of the storage ring vacuum vessels shown schematically here, as the red inner surface of the small vacuum vessels used are DLSRs. NEGs are porous alloys of aluminium, titanium, iron, vanadium, and zirconium deposited to a thickness of the order of a micron or even less. After installation, the vacuum vessels, which are coated with NEG, are pumped to a moderately high vacuum using traditional pumps and then they are heated out to temperatures as high as 200 degrees centigrade. This activates the NEG material, allowing pressures to drop to approximately 10 to the minus 10 millibars. We discuss in detail DLSRs and DLSR Science in next week's videos.

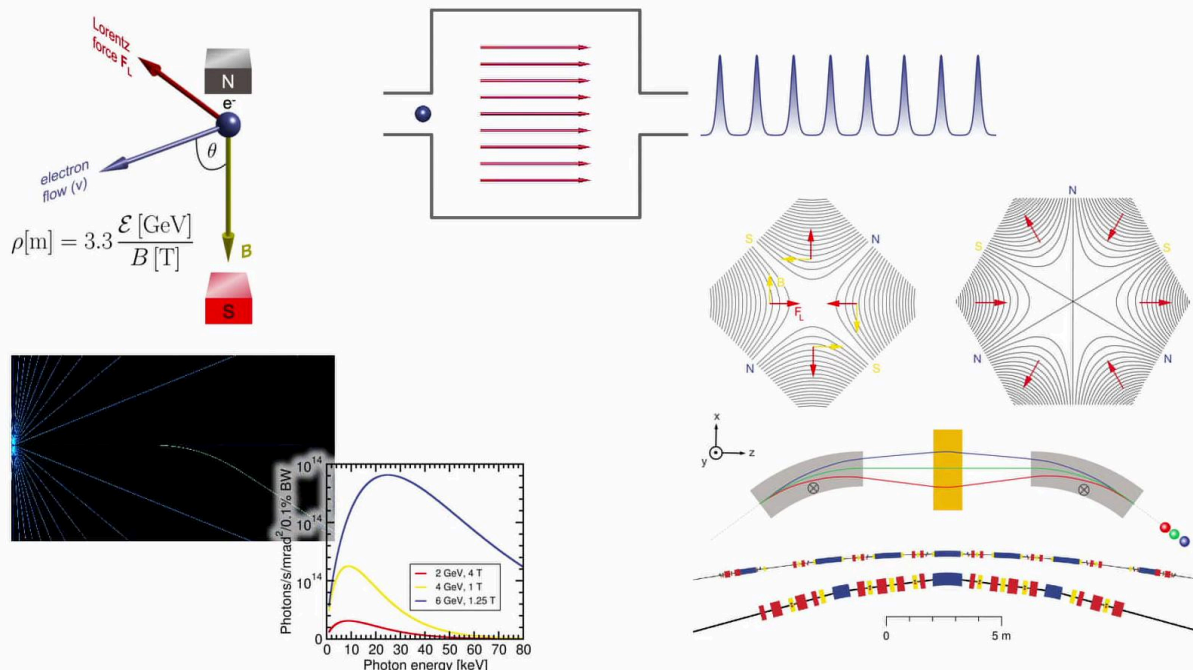
Notes

Summary



11m 20s

Summary of this section



Summarising this section, we first looked at the forces and magnetic field strengths required to produce bending radii of the order of metres. The centripetal acceleration exerted on the electrons by bending magnet dipoles causes the electric field lines to shift laterally, producing broadband radiation that depends on the field strength and the electron energy. Radiation emission by the electrons causes them to lose energy, which must be replaced. This is achieved with one or more RF cavities, the beating heart of any synchrotron. The limited range within the RF cycle that accelerates the electrons by the correct amount results in the electron current being divided into bunches with durations measured in tens of picoseconds and separated from one another by a few nanoseconds, given by the RF temporal periodicity. We then looked at quadrupoles and sextupoles, which combined can produce end achromats. Subsequently, we looked at how the electron emittance improves with a number of dipoles within an achromat, and how this has led to the borrow time shift of fourth generation diffraction limited storage rings.

Notes

Summary



12m 44s

Next week



Next week we will look at the equipment installed in the straight sections of storage rings in between the arc sectors, namely insertion devices and in particular undulators. We will see that the small electron emittances of DLSRs have a fundamental impact on the radiation produced by insertion devices, and how this has unexpected further scientific and technological benefits. We will finish week four with an overview of the architecture of XFELs and the physics of self amplified spontaneous emission, or SASE and a brief review of different scientific disciplines using XFEL radiation.

Notes

Summary



14m 14s