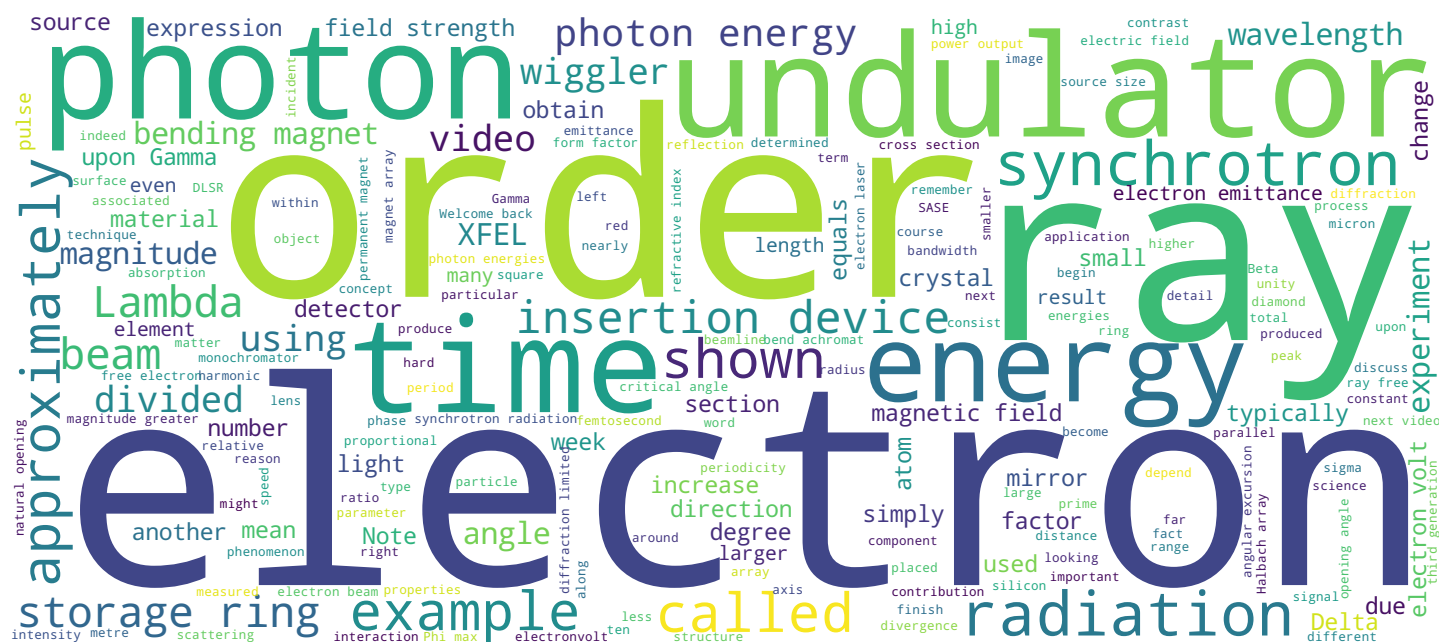


Synchrotrons and x-ray free-electron lasers

Techniques and applications

Prof. Philip Willmott



Search MOOC



Video



Contents and objectives of this video



- Insertion devices
 - General features
 - The K-parameter
 - The Halbach array

Hello, and welcome back to week four of this course, synchrotrons and x-ray free-electron lasers, techniques and applications. This week we will tackle three major themes. First, we will take a closer look at insertion devices, the sources placed in the straight sections between the achromat arcs of the synchrotrons, focusing particularly on the properties and functionality of undulators. We'll then return to the topic of the multi-bend achromats, and the characteristics of diffraction-limited storage rings, and how this latest technology impacts other technological developments and scientific endeavours in photon science. In the final section of this week, we will review the architecture of high-gain x-ray free-electron lasers, and consider the phenomenon of self-amplified spontaneous emission, or SASE, the process which is responsible for the generation of x-ray pulses with transient brightnesses up to 10 orders of magnitude greater than those produced at synchrotrons. We'll finish by presenting a small selection of recent scientific successes using x-ray radiation. Now, in this video we'll consider the general features of insertion devices, in particular, the dimensionless K-parameter. We will finish by looking at the Halbach array of magnet configuration, that optimises the magnetic field strengths where they are most needed.

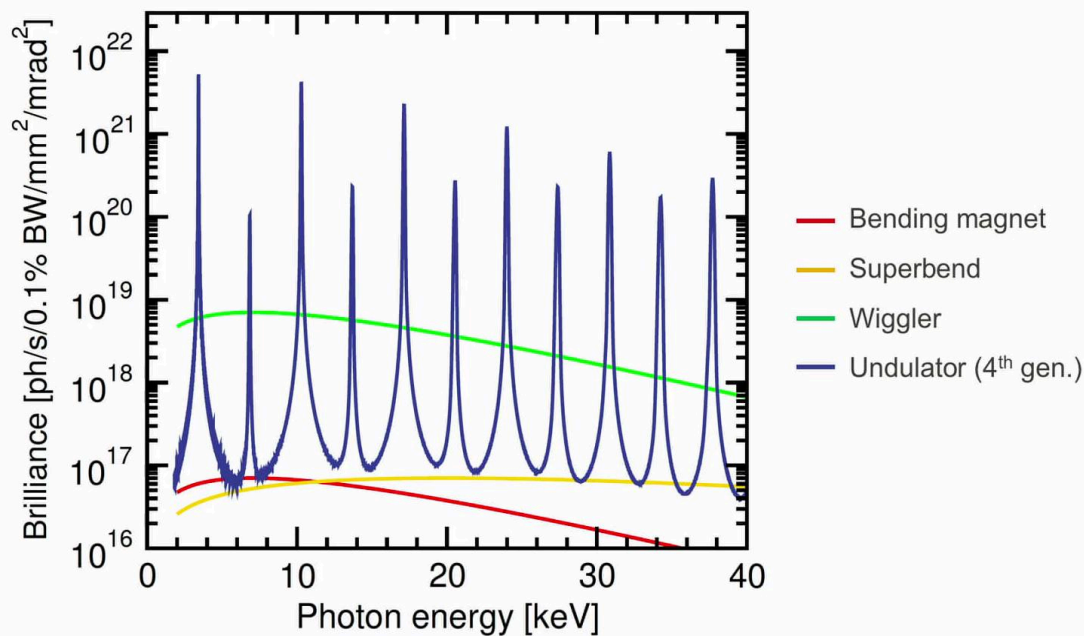
Notes

Summary



0m 04s

Comparison of different source types



So let's begin by looking at the spectral features of the four commonly-used sources at synchrotrons, namely, bending magnets, superbends, wigglers, and undulators. As we've already discovered, bending magnets and superbends are dipole magnet devices placed in the arc sectors of the magnet lattice. They deliver broadband radiation, as one can see here, and, for synchrotrons, have relatively modest brightnesses, of the order of the magnitude of 10 to the 16 to 10 to the 17 photons per second, per square milliradian, per square millimetre at 0.1% bandwidth. Their integrated optical power output is of the order of a few hundred watts, although the average power on the sample after monochromatization is measured in milliwatts. Their efficiency is thus of the order of ten to the minus five. As we will see in the following video, one can consider wigglers to be simply a series bank of bending magnets. Their brightnesses and integrated power output are typically up to two orders of magnitude greater than those for bending magnets, and can be an order of magnitude greater still, in the case of damping wigglers. Their efficiencies are light-bending magnets of the order of 10 to the minus five.

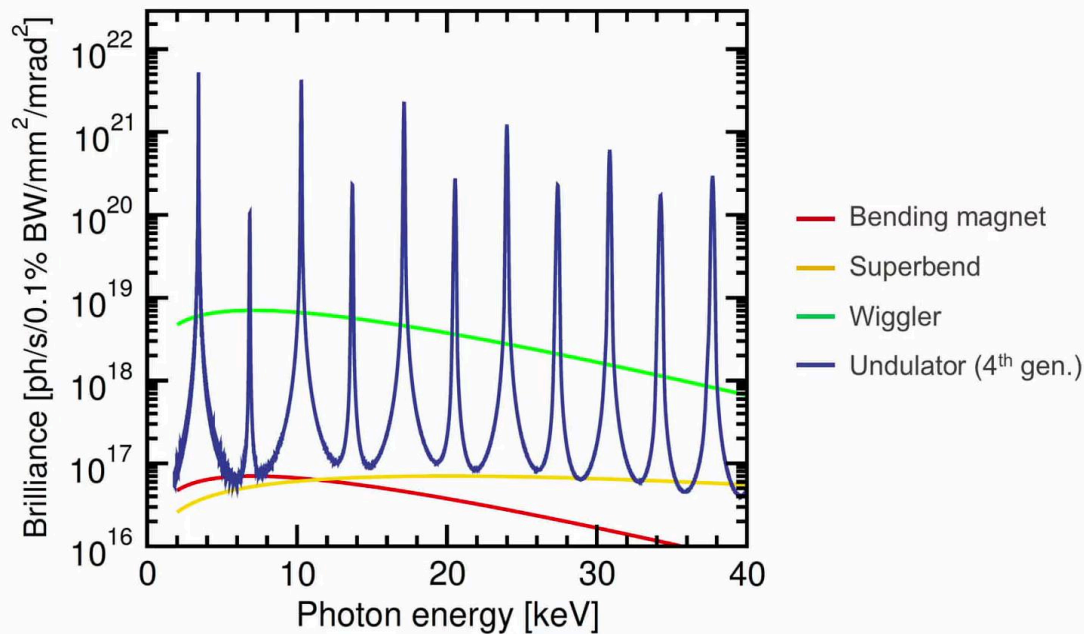
Notes

Summary

1m 53s



Comparison of different source types



The introduction of undulators at synchrotrons defined the third generation of storage rings. The first immediately apparent feature of undulators is that their spectra look very different indeed to those of bending magnets and wigglers. They consist of a comb-like array of evenly separated narrow peaks, with only weak intensity in between. Their brightnesses at the peaks are two to three orders of magnitude greater than those for wigglers. This is due to a greater flux, by approximately an order of magnitude, and a smaller source size and divergence. In other words, emittance, by around two orders of magnitude. In addition, their total optical power output is up to an order of magnitude smaller than that of wigglers, and their efficiency, at approximately 10^{-3} to 10^{-4} , is up to two orders of magnitude superior to that of wigglers. Undulators are, for the majority, but not all experiments at synchrotrons, therefore, the first choice.

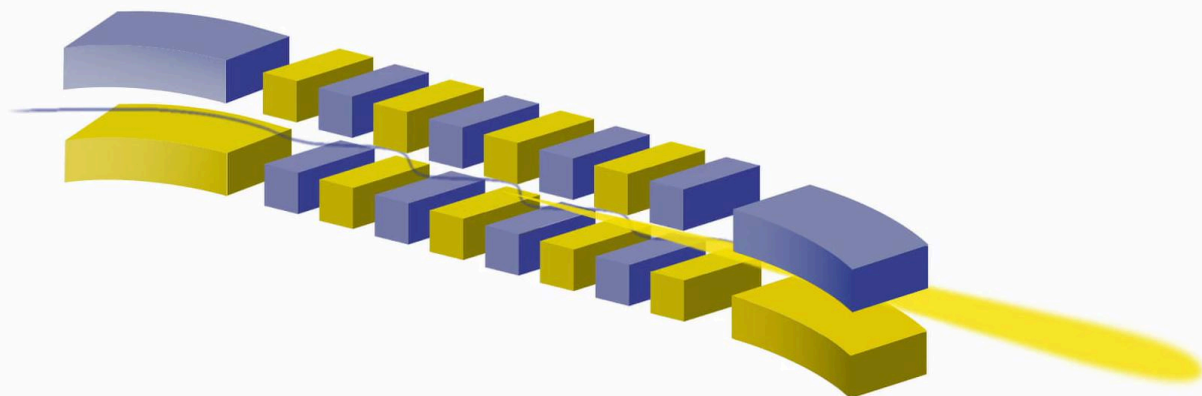
Notes

Summary

3m 31s



Insertion devices



Both wigglers and undulators are sorts of insertion devices, which means they are placed in the straight sections in between the arc sectors.

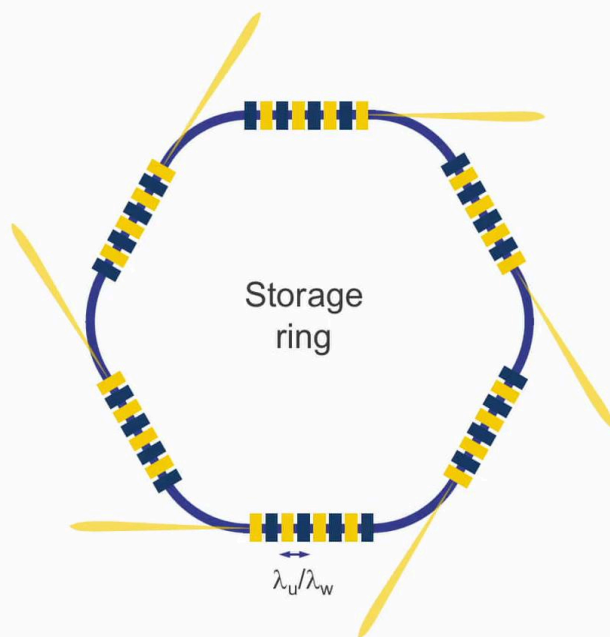
Notes

Summary



4m 44s

General features of IDs



- Placed in straight sectors around ring
- IDs defined 3rd generation synchrotrons
- Typically 1 – 10 m long (L)
- Set of alternating N-S, S-N poles
 - Electrons execute a “slalom” path
 - N-S pair periodicity = λ_u or λ_w
 - N periods \Rightarrow 2N poles
 - $L = N\lambda_{u,w}$

They consist of a series of north-south, south-north dipole pairs which cause the electron beam to execute a slalom path as it travels down the length of the insertion device, which is typically one to 10 metres long. The periodicity of the insertion device, or ID, for short, is given by the repeat length of the magnet array. This is called Lambda u for undulators and Lambda w for wigglers. Clearly, if there are N periods, there are 2N pole pairs, and the total length is L is equal to N times Lambda u or Lambda w.

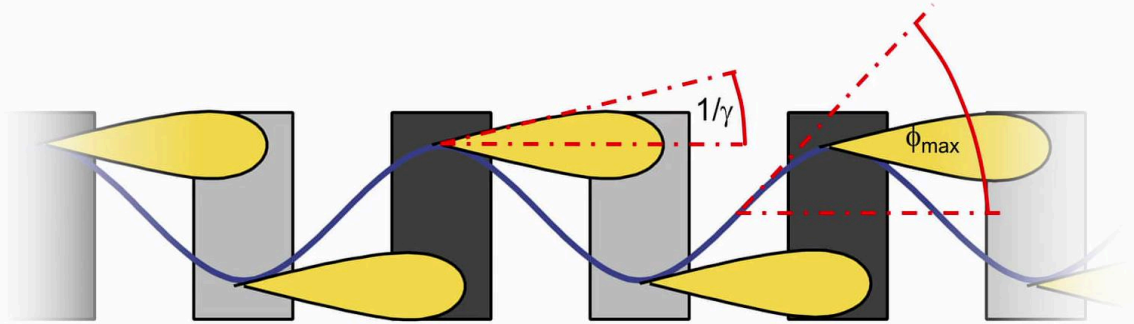
Notes

Summary



4m 55s

The K-parameter



Now, what distinguishes a wiggler from an undulator? We've already discovered last week that the natural opening angle of the cone of synchrotron radiation in the forward direction has a half angle of one upon Gamma, as we see here, due to relativistic effects. Now remember, Gamma is of the order of several thousand. So one upon Gamma is well below a milliradian. But the electron path also has angular excursions, due to the magnet array of the insertion device. We label the maximum excursion Φ_{\max} . Now, the so-called deviation parameter, or K-parameter, is simply the ratio of these two angles, Φ_{\max} divided by one upon Gamma, or Φ_{\max} multiplied by Gamma. The maximum angular excursion, Φ_{\max} , is determined by the periodicity of the ID and the maximum magnetic field strength, B_0 .

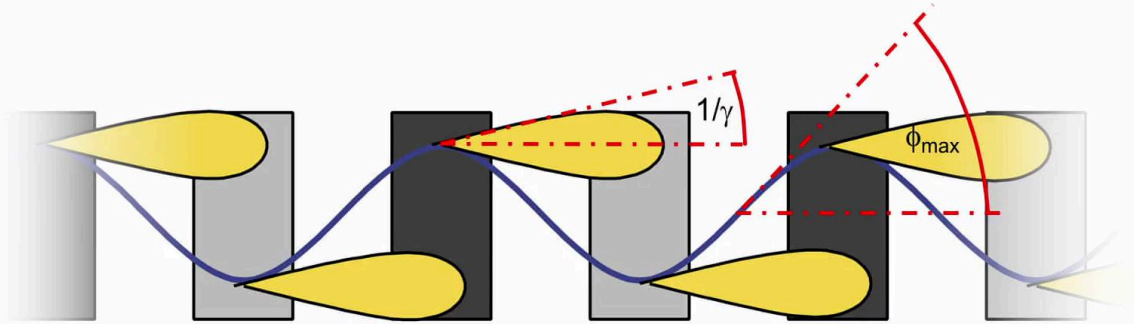
Notes

Summary



5m 40s

The K-parameter



$$K = \phi_{\max} \gamma = \frac{eB_0}{mc k_{u,w}} = 0.934 \lambda_{u,w} [\text{cm}] B_0 [\text{T}]$$

$$k_{u,w} = 2\pi / \lambda_{u,w}$$

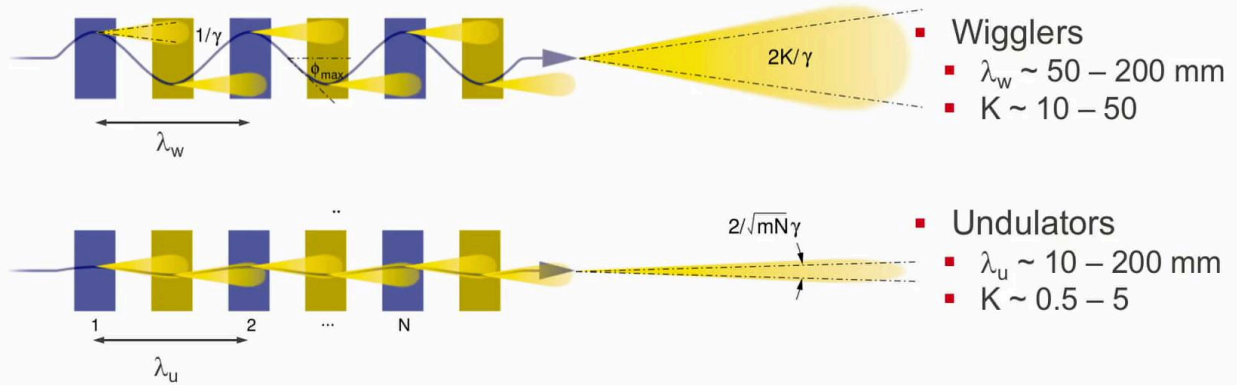
It can be relatively easily demonstrated that K is equal to eB_0 divided by $mc k_u$ or k_w , where k_u or k_w is equal to 2π divided by λ_u or λ_w . In practical units, we obtain K is equal to 0.934 multiplied by λ_u or λ_w in centimetres, multiplied by B_0 in Tesla.

Notes

Summary



The K-parameter



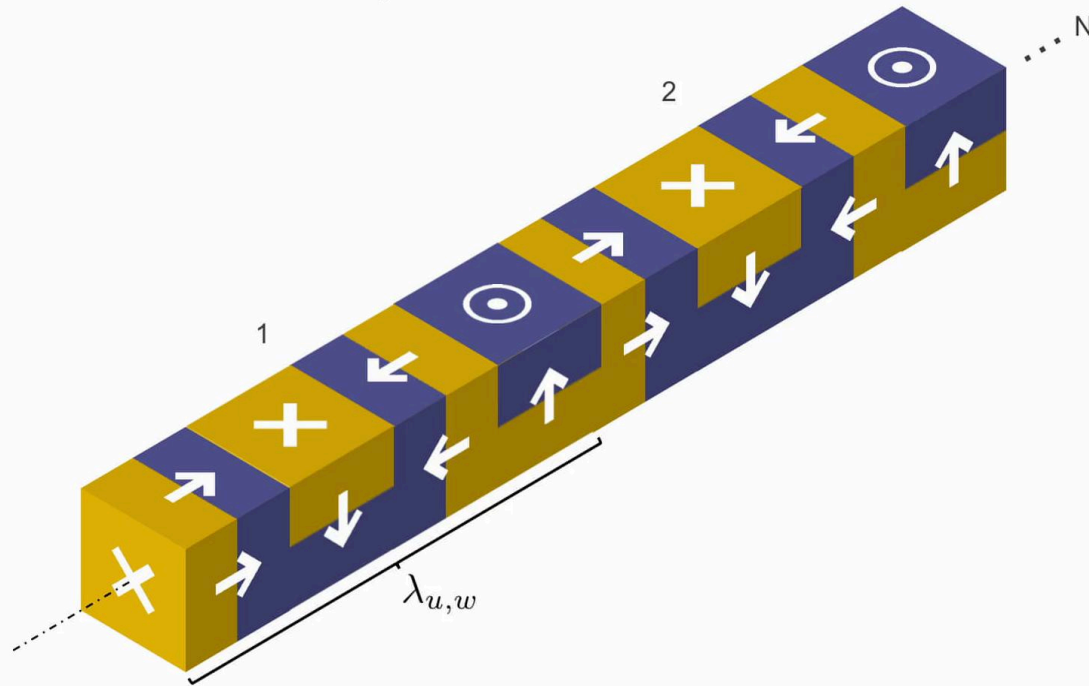
It is K that distinguishes wigglers from undulators. K values substantially larger than unity, that is, for large angular excursions, compared to the natural opening angle one upon Γ , result in wigglers. Undulators have K values close to unity. Why this seemingly prosaic difference results in fundamentally different spectral outputs will be explained directly. It's also noted that the fan of radiation in the central plane, parallel to the magnet faces for wigglers reflects the large angular excursions of the electron slalom path in the individual dipole pairs, and is equal to $2K$ divided by Γ , or several milliradians. In contrast, the radiation cone emitted by an undulator is normally substantially narrower than one divided by Γ , the natural radiation cone opening half angle. The reason for this has its origins in the same phenomenon that results in the very different spectral features, namely, interference.

Notes

Summary



The Halbach array



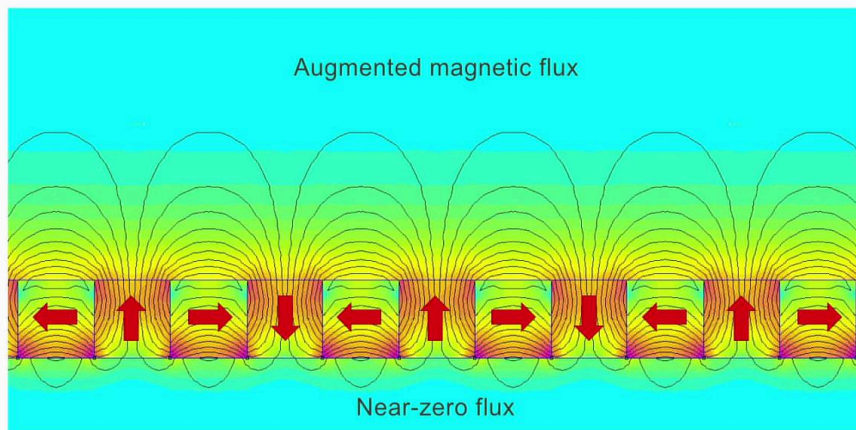
In our schematic cartoons of insertion devices so far, we have simply shown alternating north-south and south-north dipoles, in order to keep the description simple. We finish this video by briefly describing reality, which are Halbach arrays used commonly in permanent magnet insertion devices. A Halbach array is a particular arrangement of permanent magnets that results in one side of the array having an enhanced magnetic field strength while the field on the opposite side is almost cancelled out to be nearly zero. This is achieved in the following manner. Consider a magnet with its magnetic field pointing as shown here along the dot-dashed axis. Next to this is placed an identical magnet with its field pointing down, i.e. rotated by 90 degrees. Next, is added another magnet, but now rotated by a further 90 degrees, so that its field points anti-parallel to that of the first magnet. Lastly, a fourth magnet is added with a further 90-degree rotation of its orientation. This completes one period. The insertion device array is constructed by adding N such periods as desired.

Notes

Summary



The Halbach array



K. Halbach, Nucl. Instrum. Methods **169** 1 (1980). doi:10.1016/0029-554X(80)90094-4

Image adapted from contributor "Teapeat", Wikimedia Commons: https://en.wikipedia.org/wiki/Halbach_array#/media/File:Halbach_array_field.jpg

If one then looks at how the magnetic fields of adjacent magnets couple to one another, we see that on one side, the field strength is considerably enhanced by nearly a factor of two, while on the opposite side, it almost cancels out, leaving only a very weak residual field. Using two such arrays so that the strong sides face one another is the basis for permanent magnet ID technology.

Notes

Summary



9m 55s

In the next video...



In this video we have been introduced to insertion devices and, in particular, the so-called K-parameter, describing the extent of angular oscillations of the electrons in terms of the natural opening angle of synchrotron radiation, one upon Gamma. In the next short video, we look at wigglers, once a commonly-installed insertion device source, but now becoming increasingly rare, as both undulator and lattice technologies progress.

Notes

Summary



10m 26s