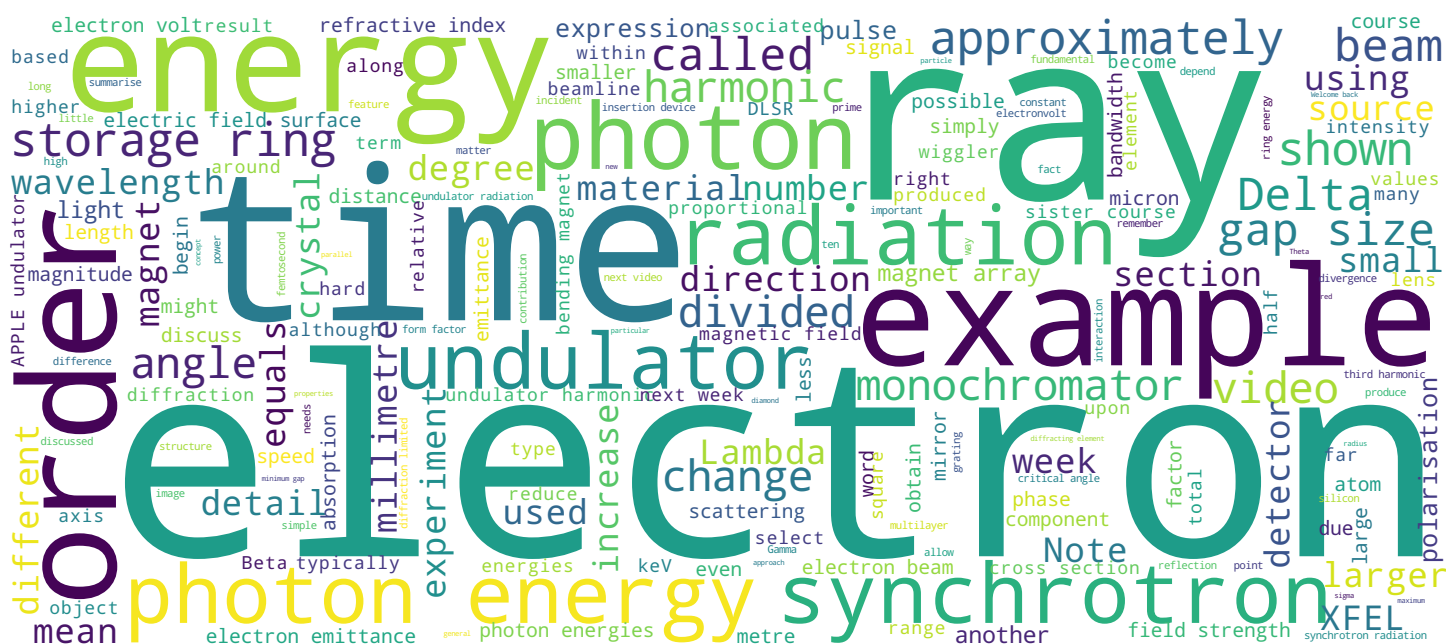


Synchrotrons and x-ray free-electron lasers

Techniques and applications

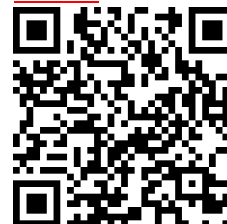
Prof. Philip Willmott



Search MOOC



Video



Contents and objectives of this video



- Undulators
 - Tuning the photon energy
 - Selecting a single harmonic
 - Polarization of undulator radiation

Hello again. In this video, we'll see how one goes about tuning the spectra of undulators, and how we can select a single harmonic. Some experiments depend intimately on being able to vary the polarisation of the radiation, that is, the angle of the electric and magnetic fields relative to some frame of reference, normally, some feature of the sample under investigation, such as its crystal orientation or surface normal direction. We will see how to change these in undulators.

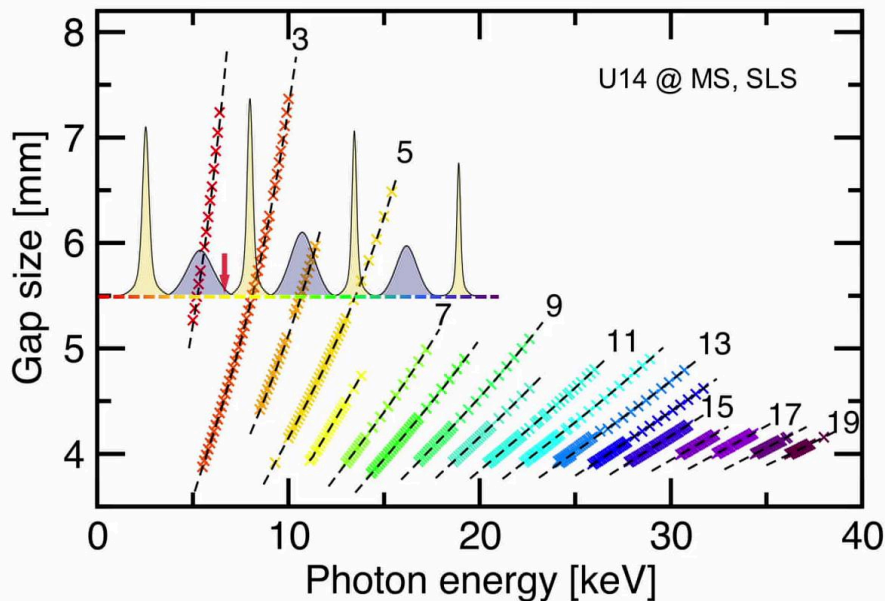
Notes

Summary



0m 05s

Tuning the photon energy for undulators



$$m\lambda_m = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

$$K = 0.934 \lambda_u [\text{cm}] B_0 [\text{T}]$$

$$\Delta E = \frac{2hc\gamma^2}{\lambda_u(1 + K^2/2)}$$

$$\Delta E [\text{eV}] = \frac{949.65}{(1 + K^2/2)} \frac{(\mathcal{E} [\text{GeV}])^2}{\lambda_u [\text{cm}]}$$

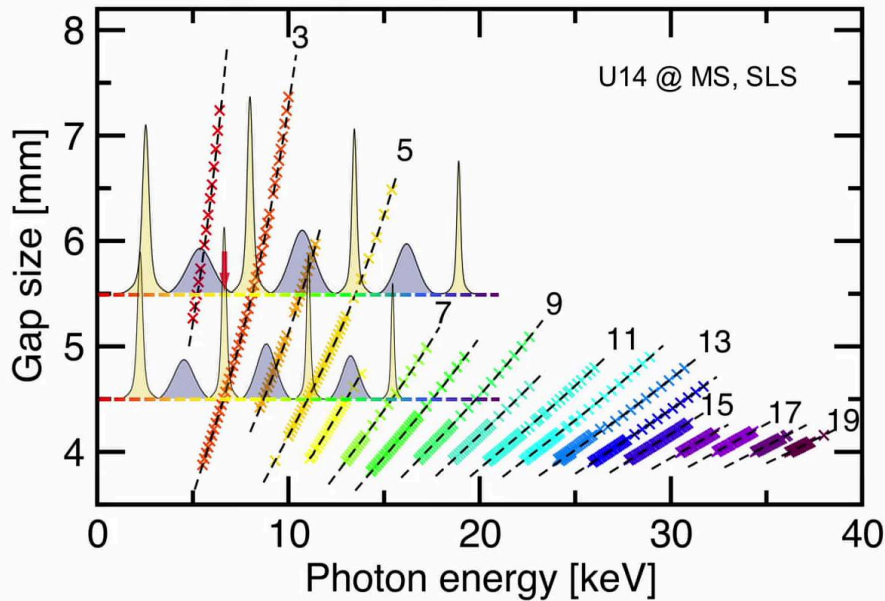
So how do we go about the tuning the photon energy in undulators? Imagine an undulator at a given gap separation between the magnet arrays. Well, take as an example the U14, in-vacuum, cryogenically cooled, permanent-magnet undulator used at the Material Science Beamline at the Swiss Light Source. We set the gap size to be 5.5 millimetres, where this dashed line crosses the experimental data points for the photon energy versus gap size. For the different harmonics, we obtain high intensities. So here, we have the second harmonic at a little above 5 keV, the third at approximately 8 keV, and so on. In steps of about ΔE equals 2.7 keV. Note that for a given undulator periodicity and storage ring energy, ΔE depends only on K and is given by the bottom two basic and practical equations shown on the right. So for a gap size of 5.5 millimetres, we find ΔE equals 2,700 eV, which for the 1.4 centimetre periodicity and 2.4 GeV storage ring energy means K equals 0.946. I'll let you check the mass for yourself. This, in turn, means that B_0 is equal to 0.723 Teslas. But what if I want to do an experiment, for example, close to the K edge of manganese at 6.54 KV.

Notes

Summary



Tuning the photon energy for undulators



$$m\lambda_m = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

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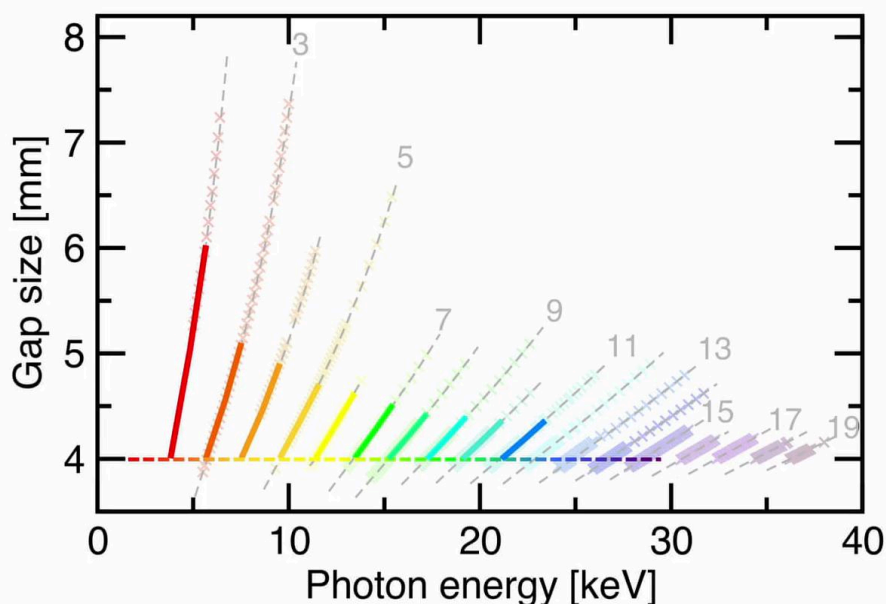
All one needs to do is reduce the gap size. In doing this, we increase the field strength B_0 increase accordingly K , and therefore reduce the energy separations between adjacent harmonics. At the gap site of 4.5 millimetres, ΔE is reduced to 2.18 keV corresponding to a K value of 1.25 and B_0 is equal to 0.953 Tesla. The third harmonic is positioned at the desired photon energy.

Notes

Summary



Tuning the photon energy for undulators



In this manner, all photon energies in the designed range can be accessed. I summarised this here. First, although this more the gap, the higher the field strength and the more intense the radiation, there is a minimum tolerable gap size. If this was set to be too small, the halo around the electron beam would interact too strongly with the undulated magnet array, gradually destroying the magnets and producing unacceptably high background branch travel. In the case of the U14 undulator discussed thus far, this minimum gap lies at approximately four millimetres. If we begin at this minimum gap size, the second harmonic can access between approximately four and 5.5 keV by opening the undulator gap to about six millimetres. Continuing further with the second harmonic, it makes no sense as photon energies above 5.5 keV can be accessed with the next third harmonic with a gap of four millimetres or larger. This procedure of jumping from one harmonic to the next once the latter can access the energy at the minimum gap size continues all the way up to the 19th harmonic at approximately 37 keV, the highest realistic accessible energy for this particular system.

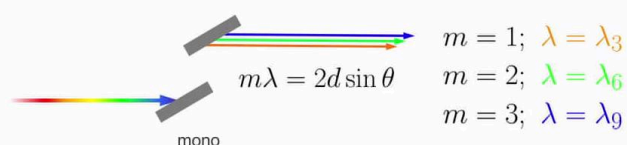
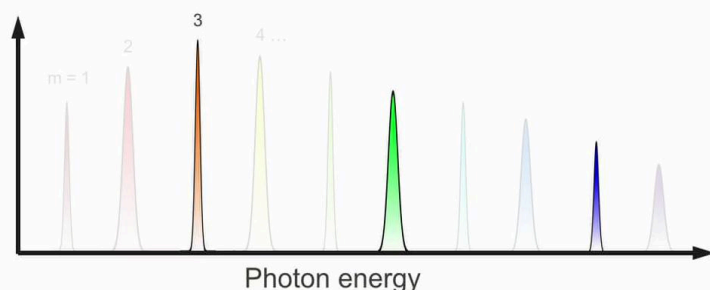
Notes

Summary



2m 59s

Selecting the desired photon energy



- e.g. select $m = 3$ only
 - Monochromator
 - "Systematic absences"
 - Refraction effect in MLs
 - Reflection off mirror(s)
 - Partial detuning
 - Refractive optics
- See videos "Beamlines and Instrumentation"

Now, what you will have surely noticed, however, is that a given gap produces not just one photon energy but a series of harmonics evenly separated by Delta E. In almost all cases, we want to select just one of these. Suppression of the other harmonics is achieved by a combination of methods. We will discuss these in more detail in next week's videos, but I believe this bears repetition, so I'd like to summarise them briefly here too. First, a monochromator, be it a grating, a crystal, or a multilayer device can be adjusted to select one of the undulator harmonics and multiples, thereof. Just a word of warning. For those of you who are new to this, you must distinguish between the undulator harmonics, as shown in the sketch here, and the harmonics are the diffracting element or elements within the monochromator. So, for example, if the monochromator is tuned so that its fundamental or first harmonic selects the third harmonic of the undulator, then only the undulators third, sixth, ninth, and 12th harmonics, etc, will pass through the first, second, fourth, fifth, seventh, etc, are lost after the monochromator.

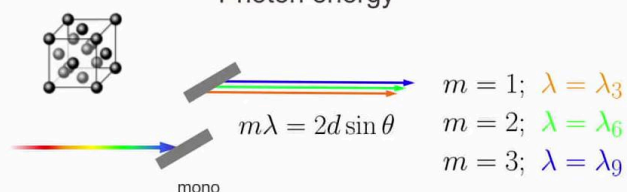
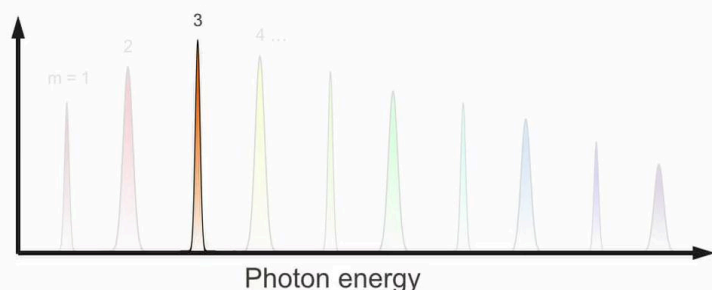
Notes

Summary



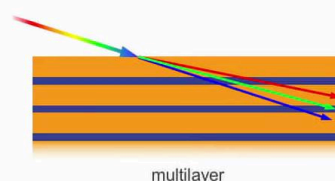
4m 37s

Selecting the desired photon energy



- e.g. select $m = 3$ only
 - Monochromator
 - "Systematic absences"
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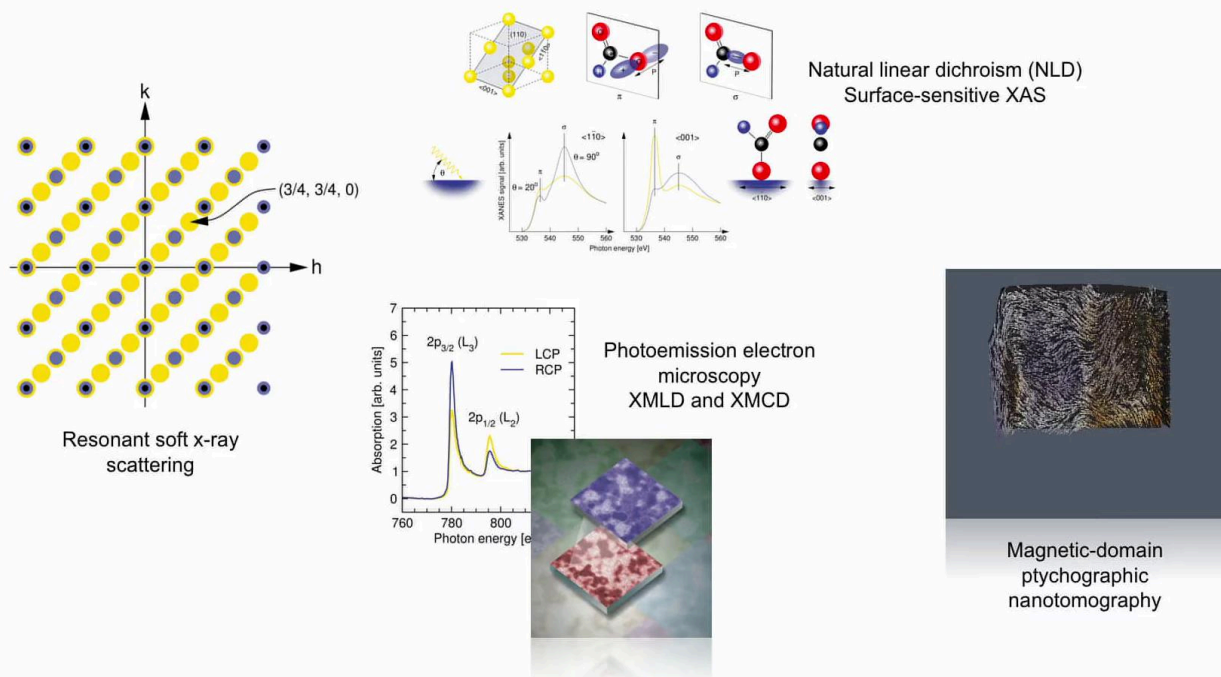
Indeed, crystal and multilayer monos often use diffracting elements that exhibit so-called systematic absences, which filter out yet to more of the undulator harmonics. This is best explained with an example. Silicon (111) crystals, that is silicon with the (111) crystallographic planes parallel to the crystal surface do not allow through all overtones of the fundamental that one might assume by considering only Bragg's law. So although the (111) harmonic is allowed, the second harmonic (222) is forbidden, or at least extremely, strongly suppressed due to the internal arrangement of the atoms within the crystal. We'll discuss this in more detail in the sister course. So in the example above, the undulator sixth harmonic would be suppressed, leaving only the third, ninth, and twelve, etc. Particularly, in the case of multilayer diffracting elements, refraction effects caused the lower harmonics to travel at marginally shallower angles with the multilayer, then the incident angle on the multilayer surface. Hence, the correct angle for the first harmonic of the multilayer will not allow through any of the higher harmonics. Moreover, other approaches can be brought to bear on suppression of undulator harmonics, including reflection of X-ray mirrors, partial detuning of monochromator elements, and reflectively selecting slip prison systems. These we will discuss next week.

Notes

Summary



Varying the polarization – motivations



We finished the first section of this week by discussing control of the polarisation of undulator radiation. Many experiments depend on the polarisation of the incident radiation to provide spatial or orientational information, such as charge, orbital, or spin superstructures, in novel candidate electronic materials, the bonding of molecules to surfaces, or the formation of distinct magnetic domains. We will cover many such examples in the sister course on X-ray experimental techniques.

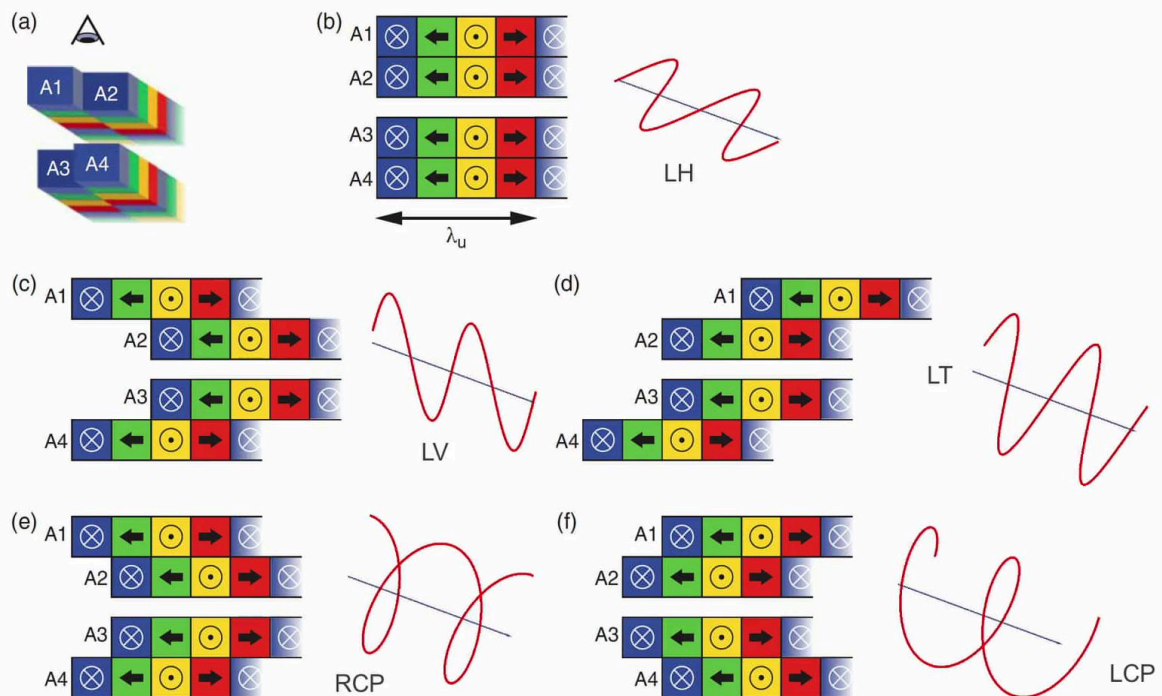
Notes

Summary



8m 04s

Varying the polarization – APPLE undulators



One can control the polarisation using so-called APPLE undulators. APPLE stands for advanced planar polarised light emitter. These special types of undulator have undergone successive refinements, reflected by their generational names of APPLE 1, 2, 3, and X based on the flexibility of movements of their magnet arrays, which we do not date detail here. They are based on their being four arrays of magnets that can shift longitudinally. In other words, along the direction parallel to the electron beam. We label the magnet arrays A1 through A4, according to the schematic shown top-left in part A of the figure. All subsequent parts of the figure show the relative positioning of the magnets as observed from above. So in B, all the arrays are in phase, and we obtain a normal Halbach array. As we discussed in the first video of this week. This produces horizontally polarised undulator radiation by shifting the relative positions of the top and bottom arrays by plus or minus half a period. In other words, arrays 2 and 3 move forward half a period. We generate vertically polarised radiation shown in C by shifting arrays A1 upstream the same amount as are shifting A4 downstream results in tilted linear radiation shown in D. Finally, by moving A1 and A4 a quarter period upstream or downstream produces right or left circularly polarised radiation, respectively, shown in E and F.

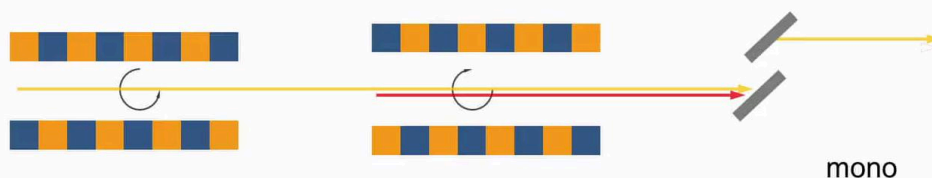
Notes

Summary

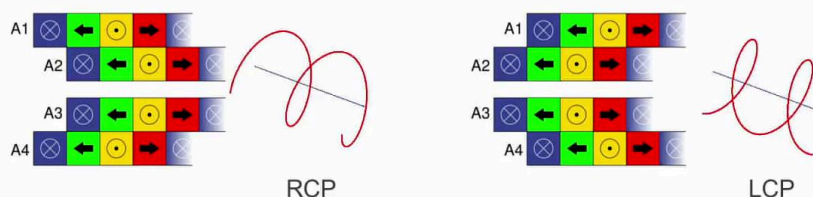


Rapid polarization switching

- Double undulator; gap shift



- Rapid translation of APPLE arrays



In some experiments, particularly in absorption spectroscopy, one wants to rapidly change the polarisation. One approach is to use two undulators with different polarisations and selection using a monochromator. So, for example, the downstream undulator has a gap size that matches the monochromator settings, allowing each radiation to be selected. But if one changes the gap size by a modest amount measured in tenths of a millimetre, the radiation will drift in energy outside the bandwidth of the monochromator. At the same time, one changes the gap of the upstream undulator from a value that produces radiation outside the monos bandwidth to being matched to the mono. Hence, one changes the radiation polarisation within the time required to move the gap size measured in a fraction of a second. This approach is simple and rapid, but does mean that only one undulator is exploited at any one time. An alternative approach is to use one undulator only and make the movement of the APPLE arrays from one polarisation to another very quickly using hydraulic drives.

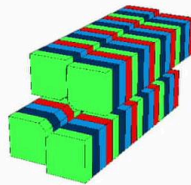
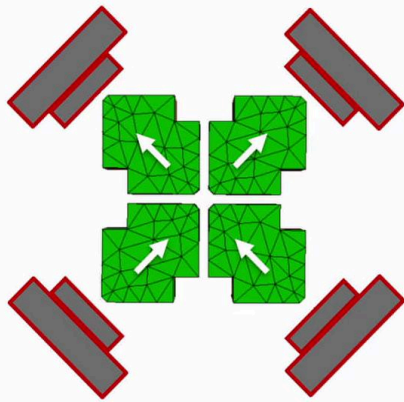
Notes

Summary

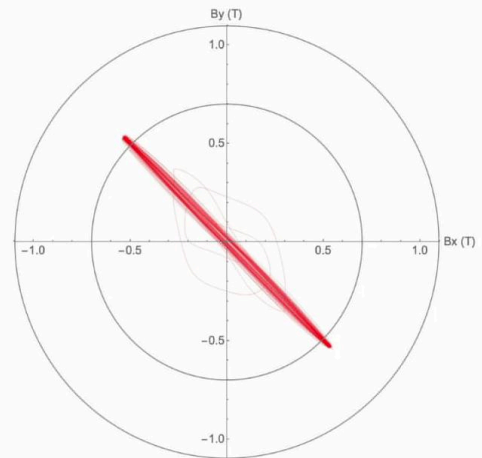


10m 38s

AppleX undulators



Courtesy Marco Calvi,
Undulator group, PSI



Independent motion radially and longitudinally
of each of four jaws of magnet array
⇒ maximum control and flexibility of polarization

See also: <https://www.tandfonline.com/doi/abs/10.1080/08940886.2018.1460174?journalCode=gsm20>

We finished this video with a nice simulation of the most advanced APPLE undulator types, known as the AppleX undulator, in which the jaws are at 45 degrees to the horizontal plane, and all four arrays can be moved independently, both radially and longitudinally. More details of this most sophisticated APPLE undulator type can be found in the link given at the bottom here.

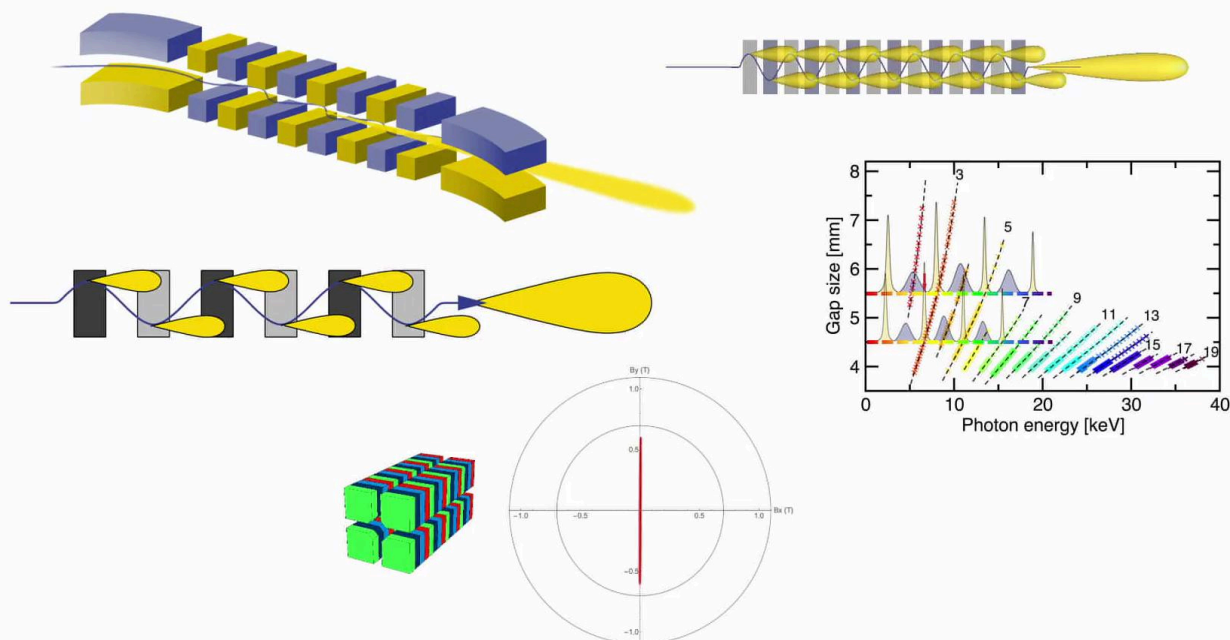
Notes

Summary



12m 05s

Summary of this section



To summarise this first section of week four, we introduced the general aspects of insertion devices, including K , the deviation parameter. IDs with K values well in excess of unity are called wigglers, which act much as a series bond of bending magnets. By reducing K , one transforms a wiggler into an undulator, which produces much more collimated radiation and has two orders of magnitude higher brightness. Its spectrum consists of a set of evenly spaced maxima. One can tune this spacing by varying the gap size between the magnet arrays. Lastly, we saw how it is possible to vary the polarisation of undulator radiation in so-called APPLE undulators by shifting the relative position of four magnet sub arrays. In the most modern manifestation of these, any type of linear, elliptical, or circular polarisation is possible.

Notes

Summary



12m 36s

In the next section...



In the next section, we will look in more detail at the science and technologies associated with the latest generation of synchrotrons, diffraction limited storage rings, including knock on technological and scientific benefits that might not be immediately obvious.

Notes

Summary



13m 52s