The Abdus Salam
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Educational, Scientific and
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School on Synchrotron and Free-Electron-Laser Sources and their Multidisciplinary Applications

26 April - 7 May, 2010

Fundamentals of Synchrotron Radiation

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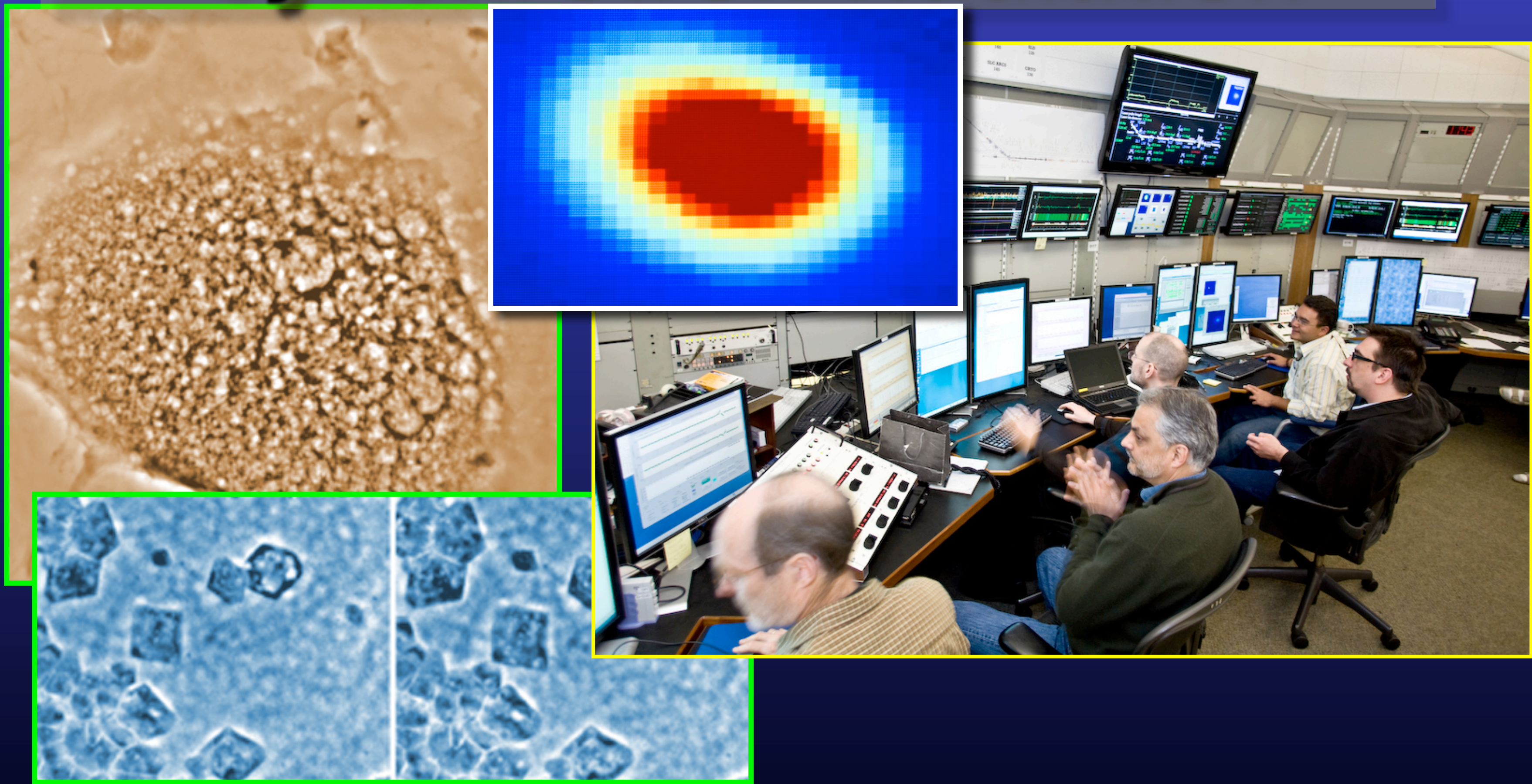
Fundamentals of Synchrotron Radiation



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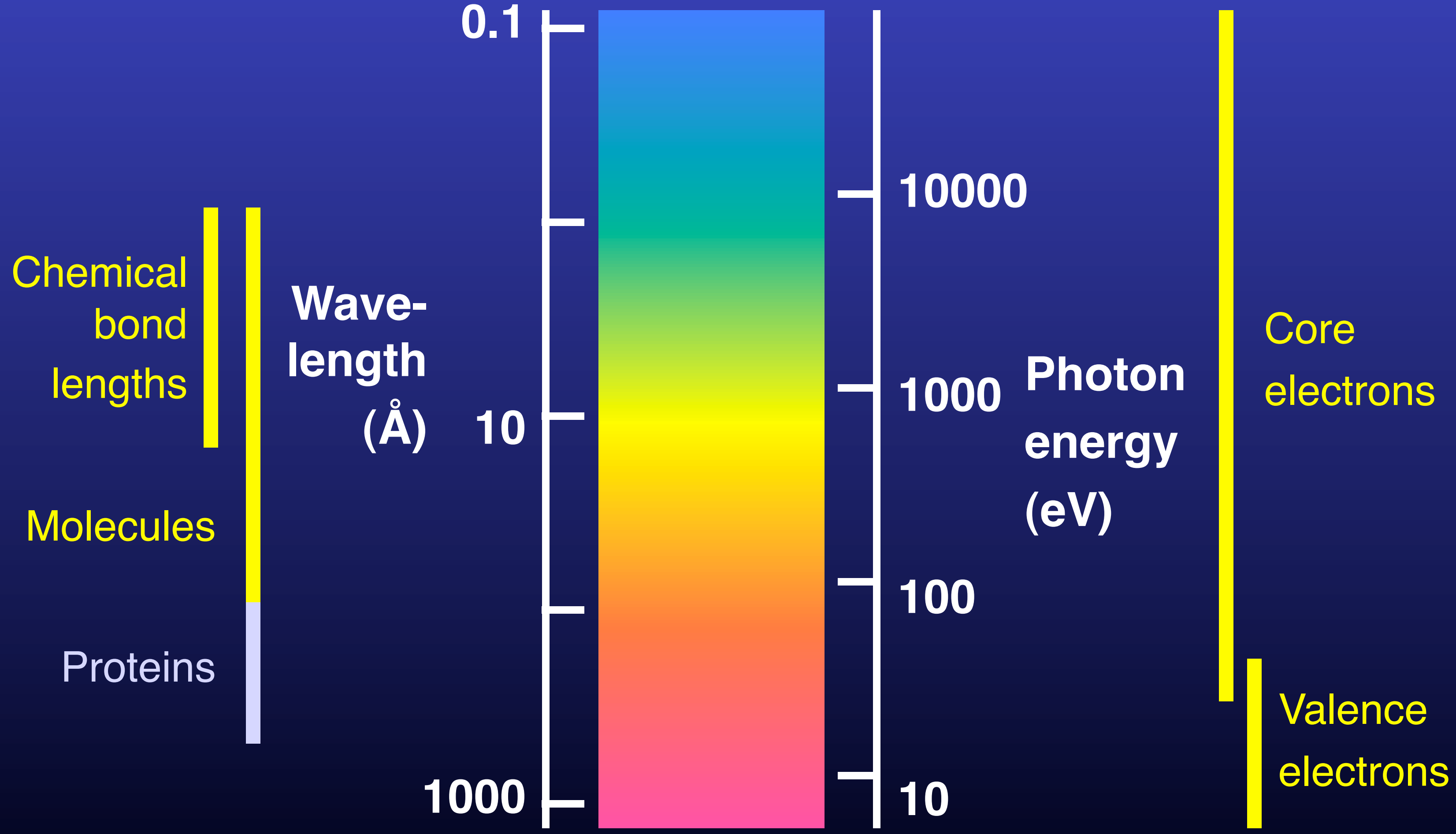
Outline:

- Why do we need x-rays?
- How to build an excellent x-ray source using Einstein's relativity:
  - 3.5 minute presentation
  - 9.5 minute presentation
  - Everything else
- History
- Coherence: a revolution in radiology
- Future: from storage rings to free electron lasers

Why x-rays and ultraviolet?

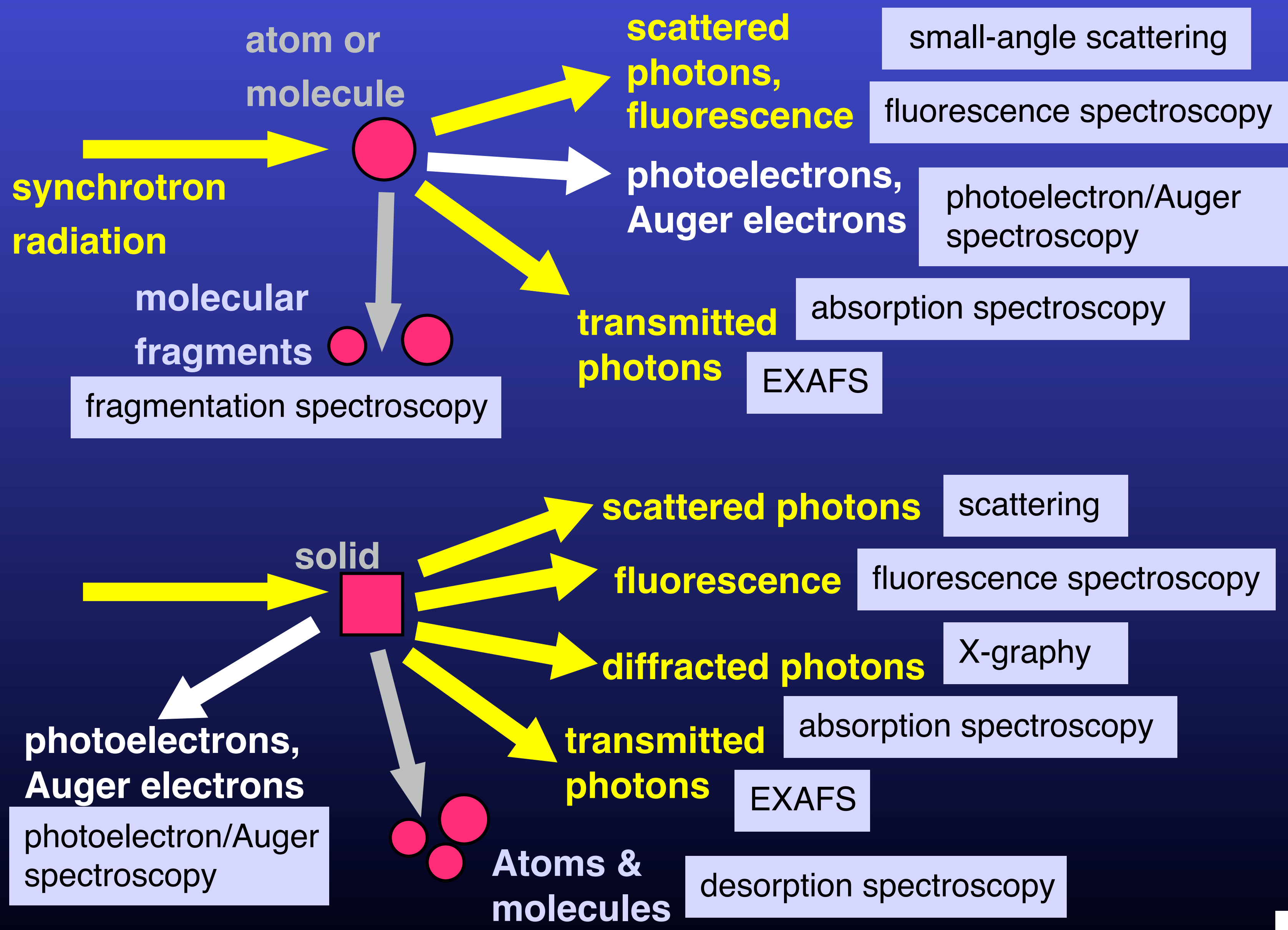


Synchrotron x-rays:

Many different interactions

↓

Many different applications


atom or
molecule
synchrotron
radiation
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Auger electrons
photoelectron/Auger
spectroscopy
molecular
fragments
fragmentation spectroscopy
transmitted
photons
absorption spectroscopy
EXAFS
solid
scattered photons
scattering
fluorescence
fluorescence spectroscopy
diffracted photons
X-graphy
transmitted
photons
absorption spectroscopy
EXAFS
photoelectrons,
Auger electrons
photoelectron/Auger
spectroscopy
Atoms &
molecules
desorption spectroscopy

SO, WE DO NEED SYNCHROTRONS: BUT HOW DO THEY WORK?

THE "BEACH OPTION PROGRAM":

START!

STEP A (3.5 minutes): how are x-ray produced?

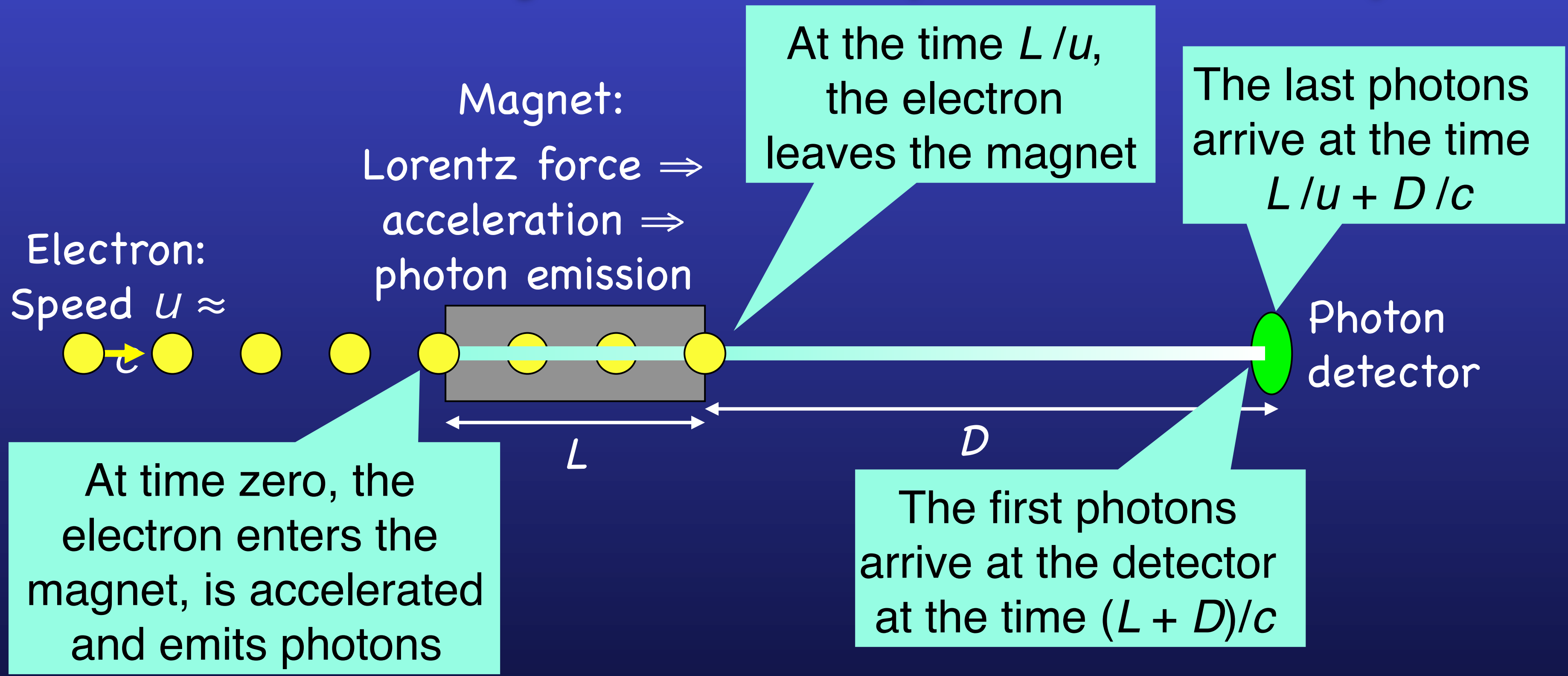
NEXT OPTIONS: (1) go to the beach for the day, or (2) go to step B

STEP B (9.5 minutes): how to get collimation? And, again, how are x-ray produced?

NEXT OPTIONS: (1) go to the beach for the day, or (2) go to step C

STEP C (the rest of the time... maybe more): (almost) everything else about synchrotrons

Synchrotron light in 3.5 minutes for lazy students (and teachers):



Photon pulse duration: $\Delta t = L/u - L/c = (L/u)\,(1-u/c)$

Characteristic frequency: $\nu = 1/\Delta t = u/[L(1-u/c)] = u\,\gamma^2\,(1+u/c)/L$

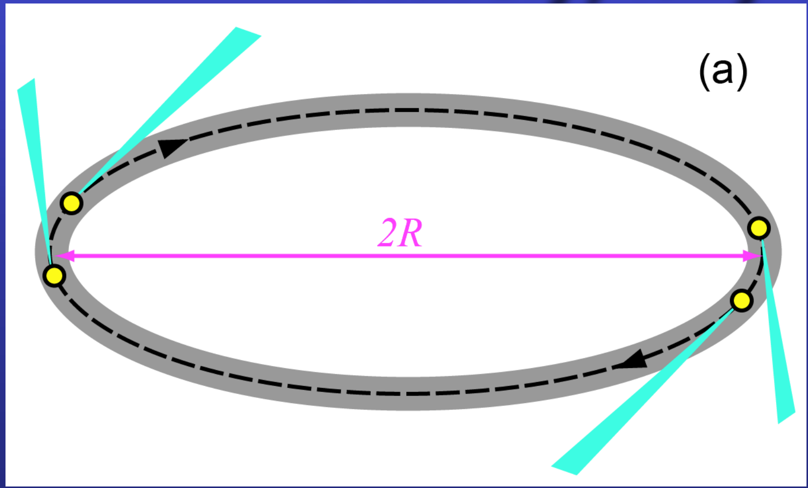
$\gamma^2 = 1/(1-u^2/c^2)$

For $u \approx c$, $(1+u/c) \approx 2$ and $\nu \approx 2c\gamma^2/L$

For L = 0.1 m and γ = 4000, $\nu \approx 10^{17}\ s^{-1}$ -- x-rays!

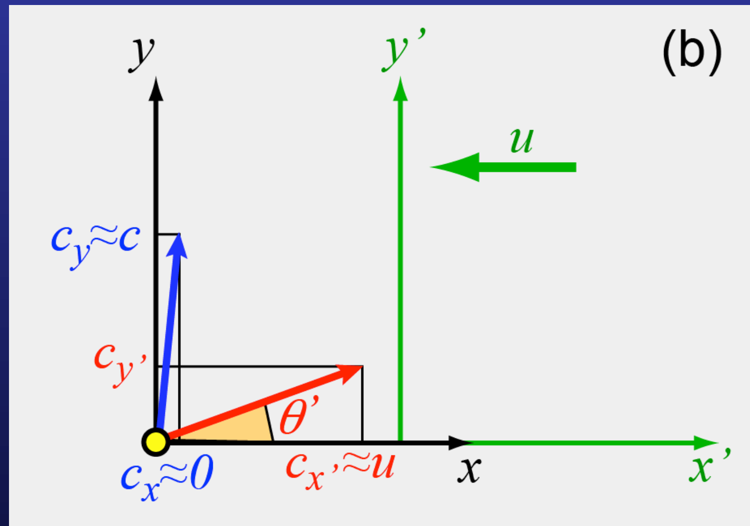
...Well, not really, Maya (sorry)!!!

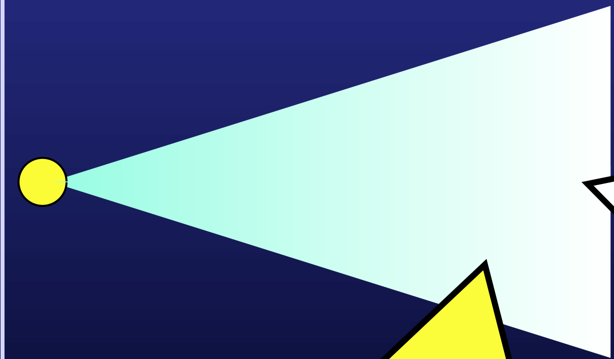
Synchrotron light in 9.5 minutes for (not entirely) lazy students (and teachers):



Electrons circulating at a speed $u \approx c$ in a storage ring emit photons in a narrow angular cone, like a "flashlight": why?

Answer: RELATIVITY



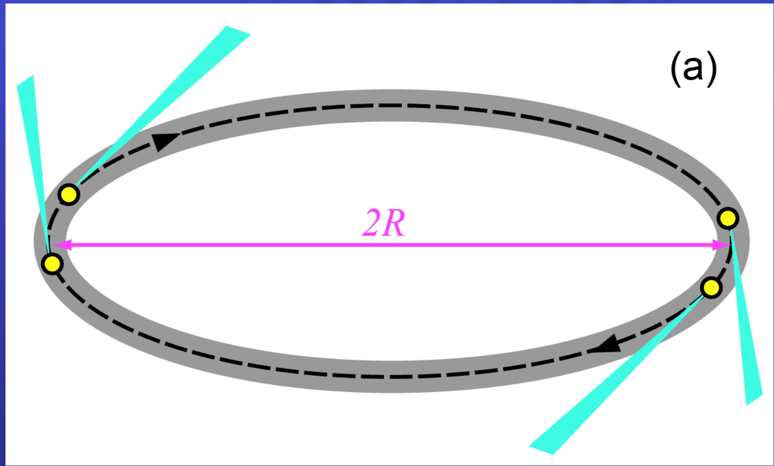


But in the laboratory frame the emission shrinks to a narrow cone

Seen in the electron reference frame, the photon are emitted in a wide angular range

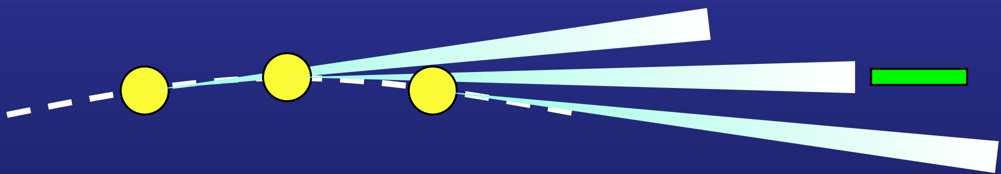
Take a photon emitted (blue arrow) in a near-trasverse direction in the (black) electron frame, with velocity components $c_x \approx 0$, $c_y \approx c$. In the (green) laboratory frame the velocity (red arrow) components become $c_x' \approx u$, $c_y' \approx (c^2 - u^2)^{1/2} = c/\gamma$. The angle θ' is $\approx c_y'/c = 1/\gamma$ -- very narrow!!!

A second look -- the emission is x-rays: why?

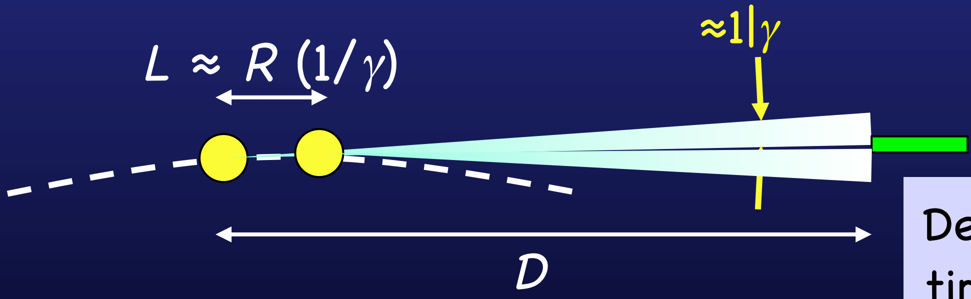


Seen from the side of the ring, each electron looks like an oscillating charge in an antenna, emitting photons with a frequency $2\pi R/c$ -- in the radio wave range.

What shifts the emission to the x-ray range? RELATIVITY AGAIN!



A torchlight-electron illuminates a small-area detector once per turn around the ring for a short time Δt



Photons start to be detected at the time D/c

Detection ends at the time $L/u + (D - L)/c$

Photon pulse duration:

$\Delta t = L/u + (D - L)/c - D/c = L/u - L/c = (L/u)\,(1-u/c) = (L/u)\gamma^2/(1+u/c)$

For $u \approx c$, $(1+u/c) \approx 2$ and $\Delta t \approx L/(2c\gamma^2) \approx R/(2c\gamma^3)$.

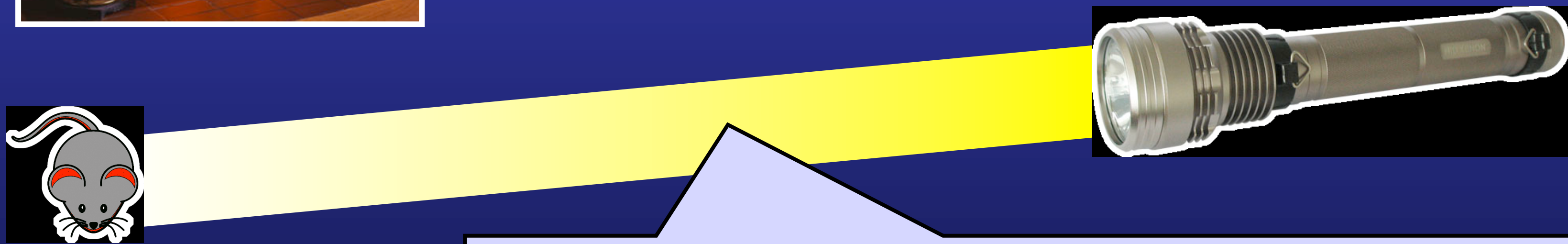
Characteristic frequency $\nu = 1/\Delta t \approx 2c\gamma^3/R$ -- again, x-rays

And now, we can really go to the beach!

Sorry again, Maya & Nadia, not yet!!!

Fireplaces and torchlights :

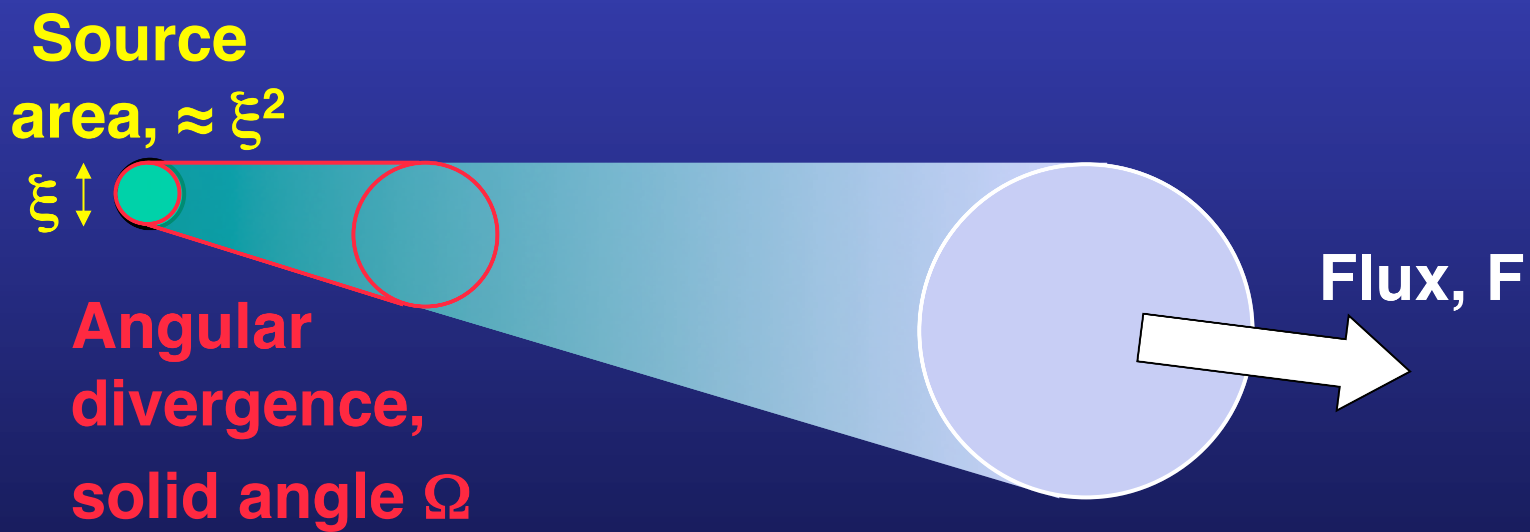
A fireplace is not very effective in "illuminating" a specific target: its emitted power is spread in all directions



A torchlight is much more effective: it is a small-size source with emission concentrated within a narrow angular spread

This can be expressed using the “brightness”

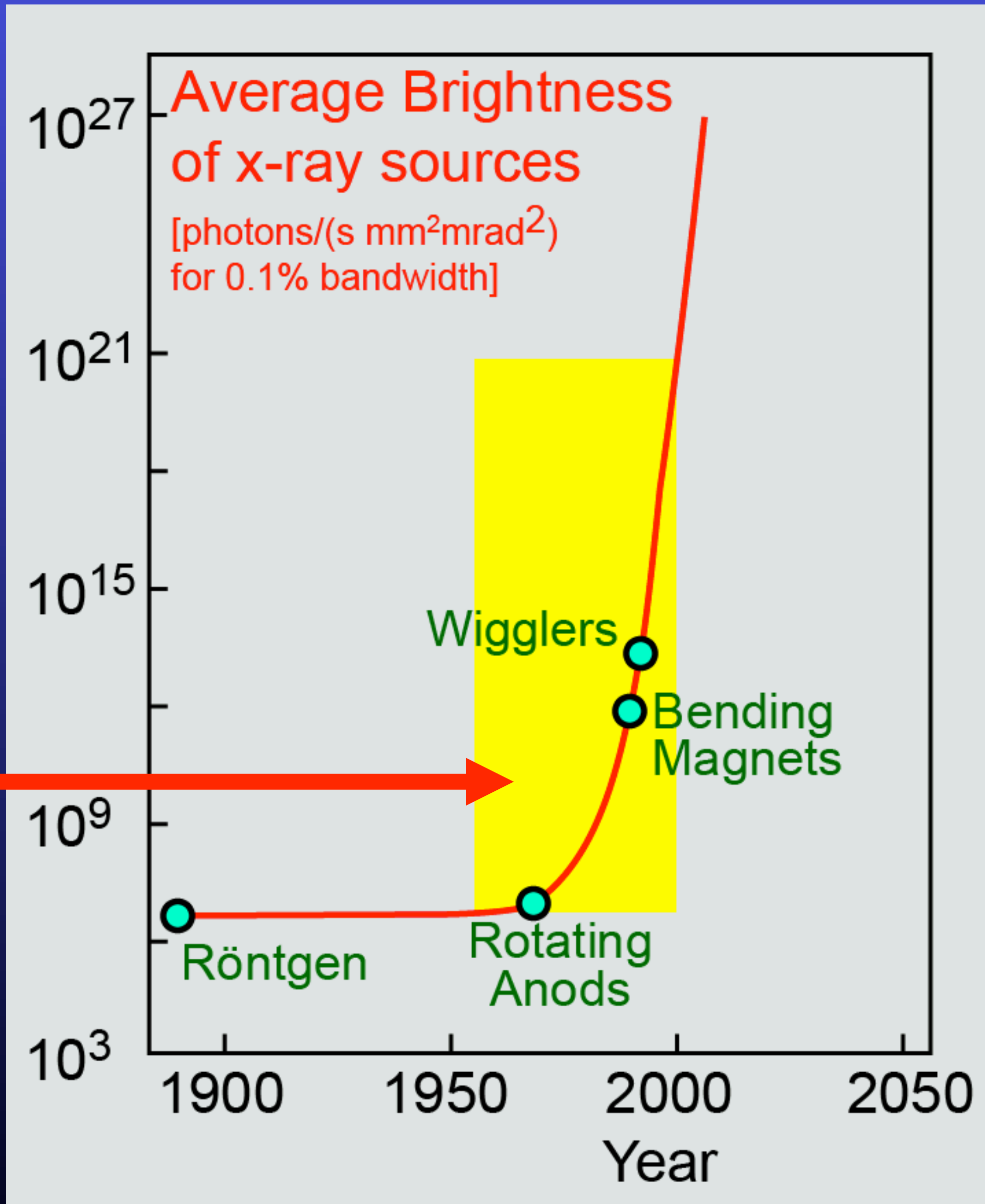
The "brightness" (or brilliance) of a source of light :



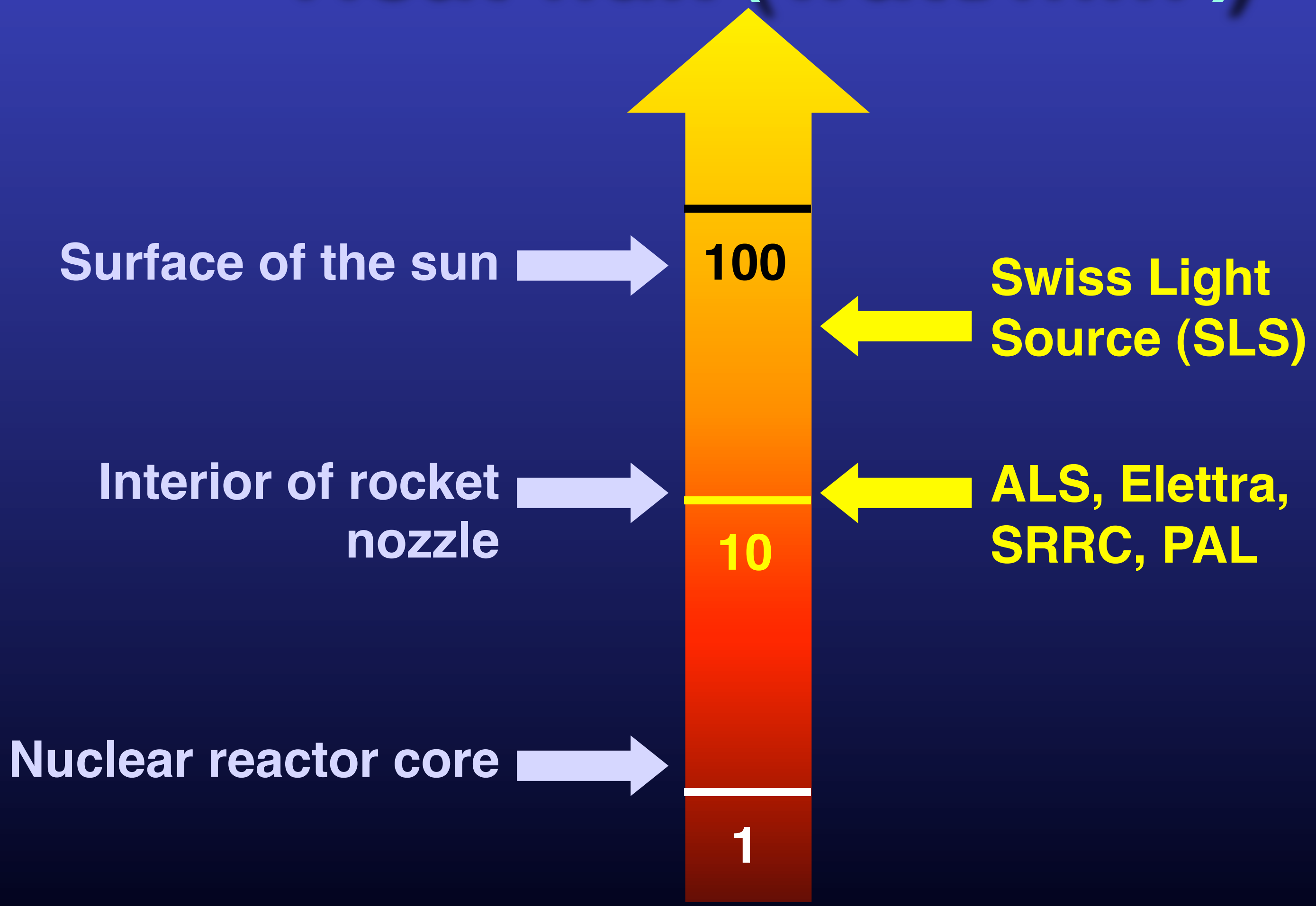
$$\text{Brightness} = \text{constant}\ \frac{F}{\xi^2\ \Omega}$$

The historical growth in x-ray brightness/brilliance

Between 1955 and 2000, the brightness increased by more than 15 orders of magnitude… whereas the top power of computing increased “only” by 6-7 orders of magnitude



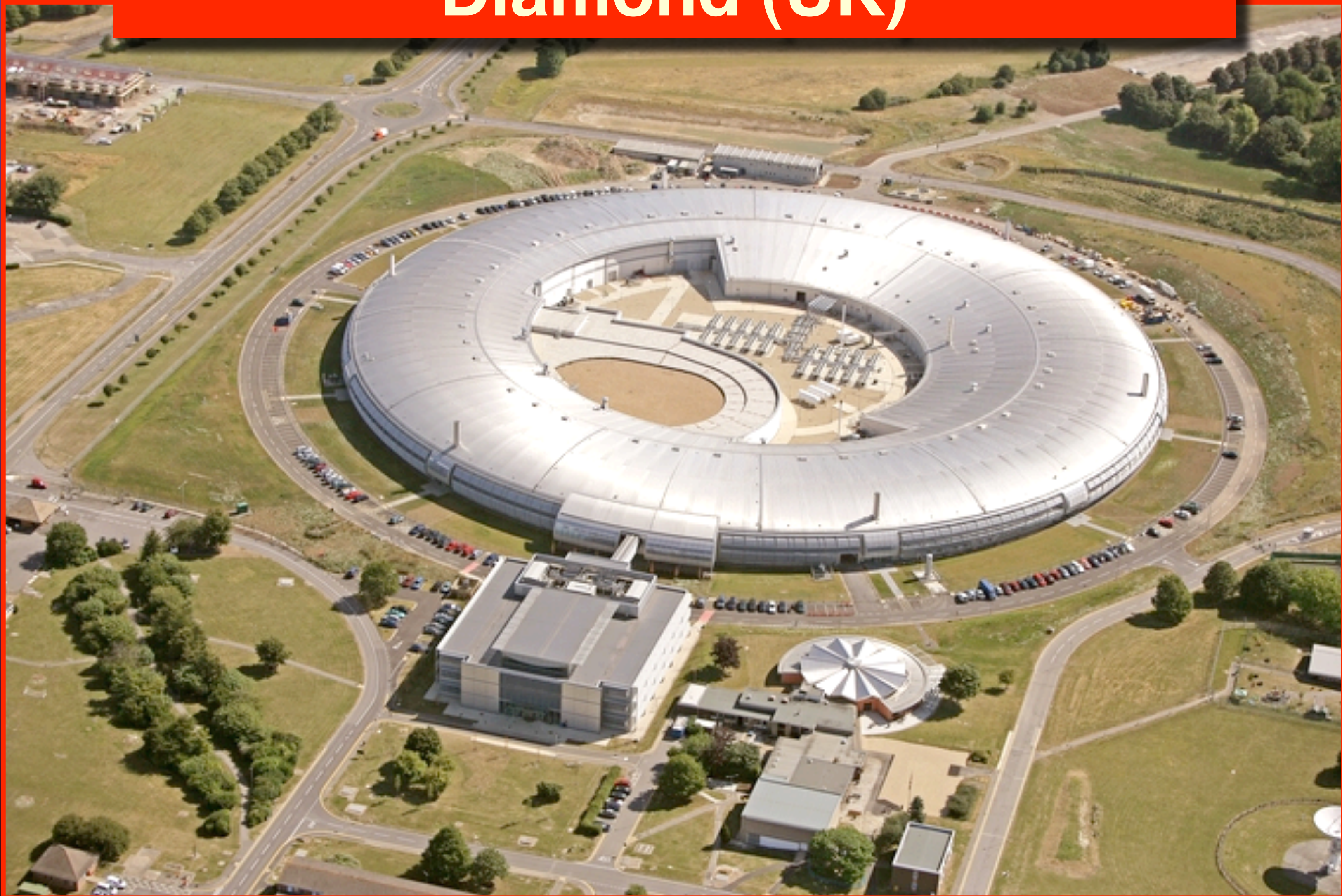
Heat flux (watt/mm²)



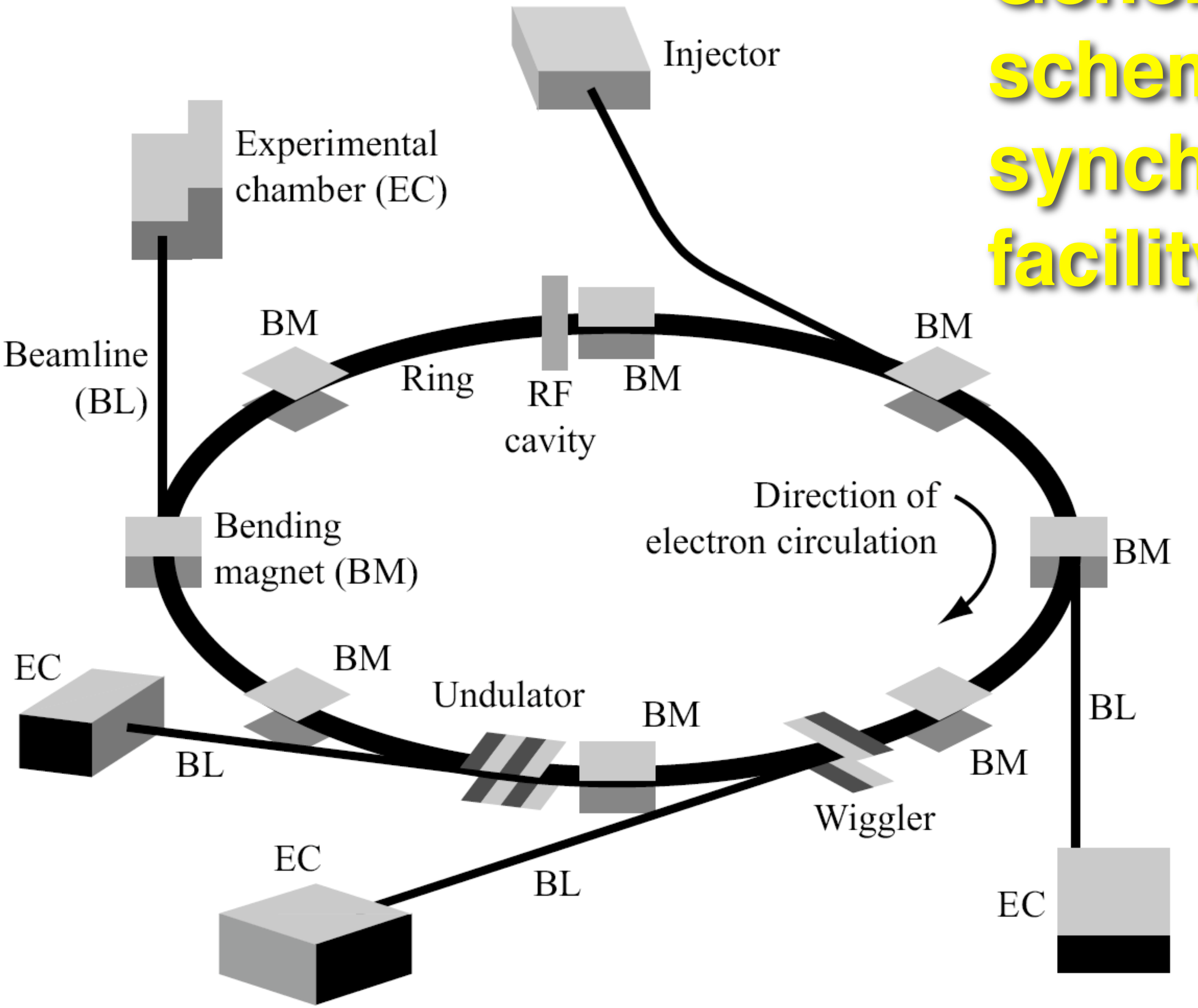
What produces the high brightness of a synchrotron source?

- Free electrons can emit more power than electrons bound in a solid because the power does not damage their environment ⇒ high flux
- The control of the electron beam trajectories in a synchrotron source (storage ring) is very sophisticated, producing a small transverse beam cross section ⇒ small photon source size
- Relativity drastically reduces the angular divergence of the emitted synchrotron radiation

A real synchrotron facility: Diamond (UK)

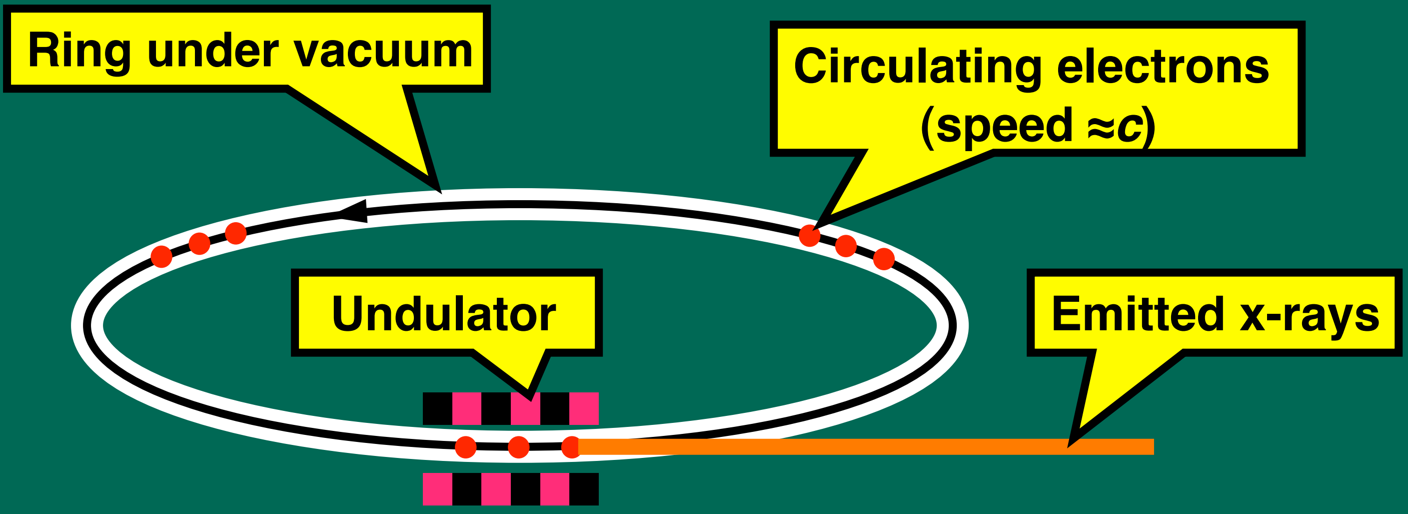


General scheme of a synchrotron facility



Objective: building a very bright x-ray source.

Solution: relativity!!



- The undulator (periodic magnet array) period determines the emitted wavelength. This period is shortened by the relativistic "Lorentz contraction" giving x-ray wavelengths
- The emitted x-rays are "projected ahead" by the motion of their sources (the electrons), and therefore collimated. Relativity enhances the effect

Objective: building a very bright x-ray source using an "undulator" and relativity

Undulator
(periodic B-field, period $L \approx$ centimeters)

In the undulator (laboratory) frame, the electron moves at speed ≈c

The period L is Lorentz-contracted becoming $\approx L/\gamma$

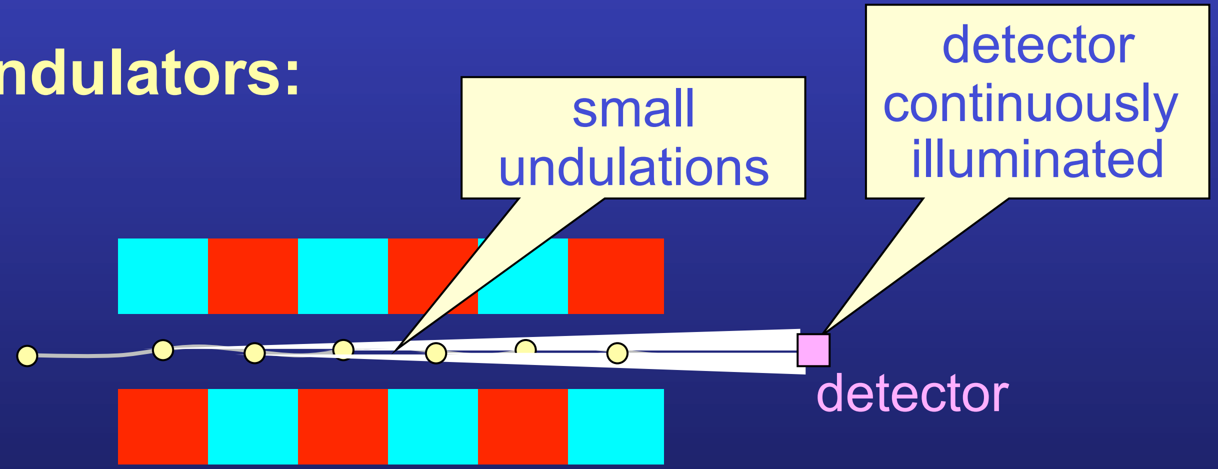
In the electron frame:

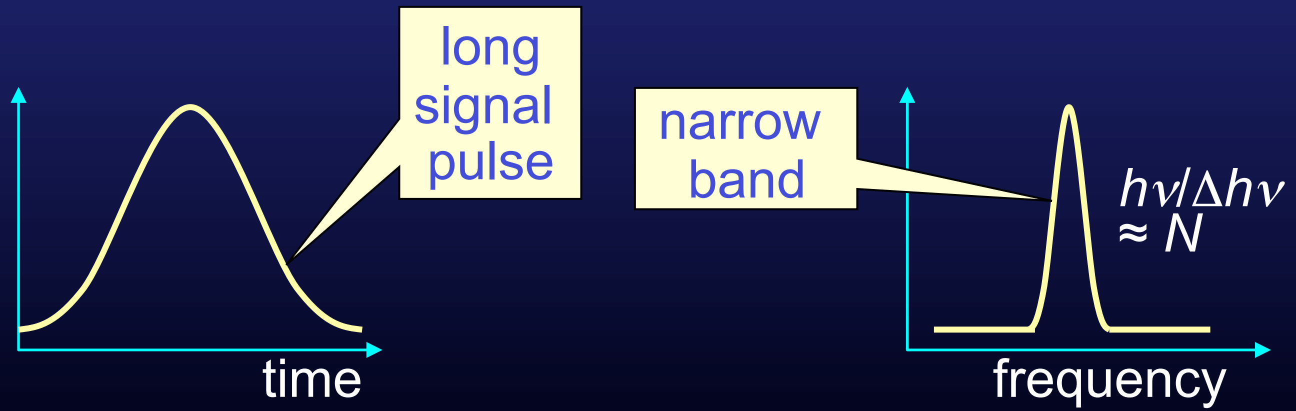
The periodic B-field is accompanied by a perpendicular periodic E-field. Moving at a speed ≈c towards the electron, the undulator looks like an electromagnetic wave with wavelength L/γ. Synchrotron radiation is produced by the elastic scattering of this wave by the electron.

Back to the laboratory frame, the wavelength L/γ emitted by the moving electron is Doppler-shifted by a factor $\approx 2\gamma$, becoming $L/2\gamma^2$. The "macroscopic" undulator period is transformed into x-ray wavelengths!

3 types of sources:

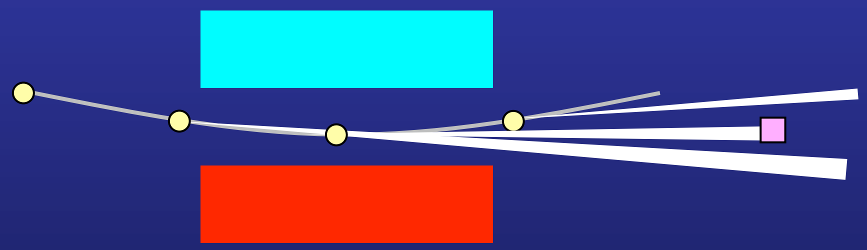
1. Undulators:

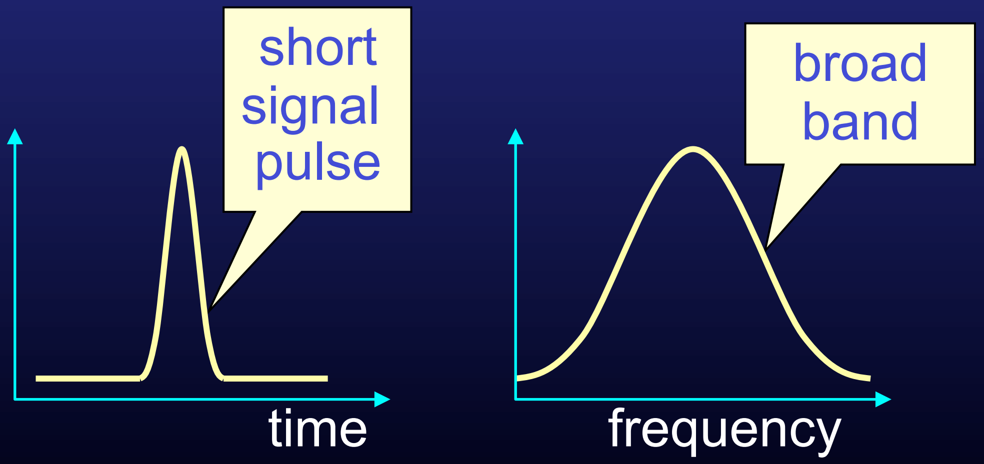




3 types of sources:

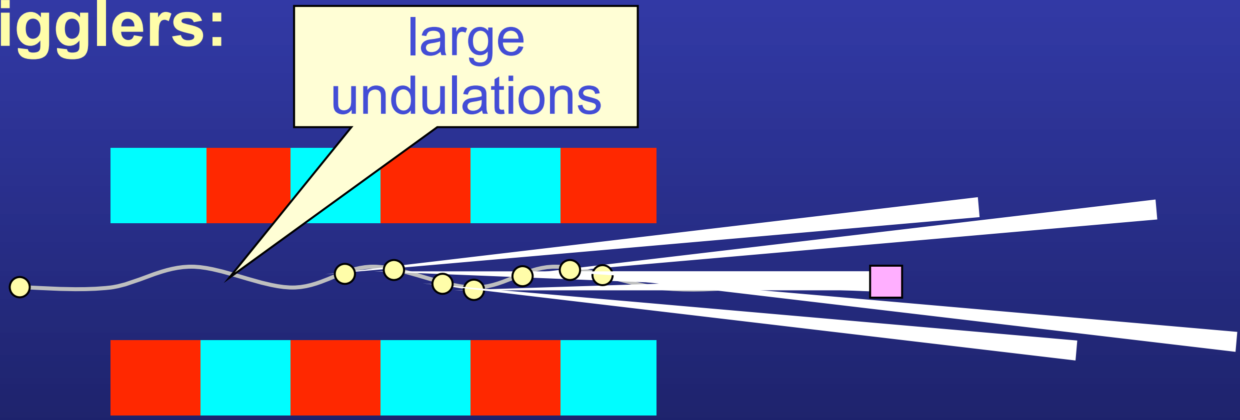
2. Bending magnets:

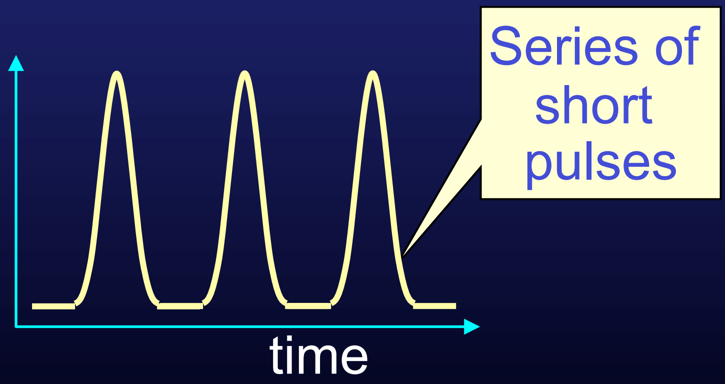


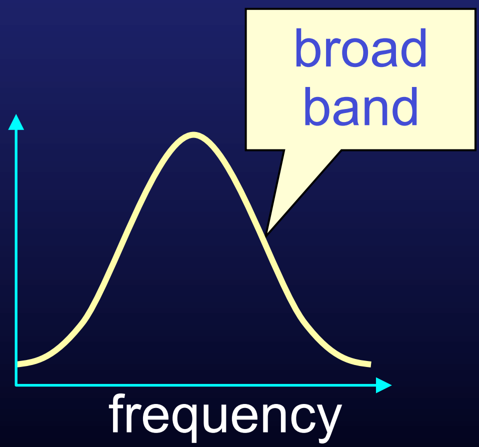


3 types of sources:

3. Wigglers:





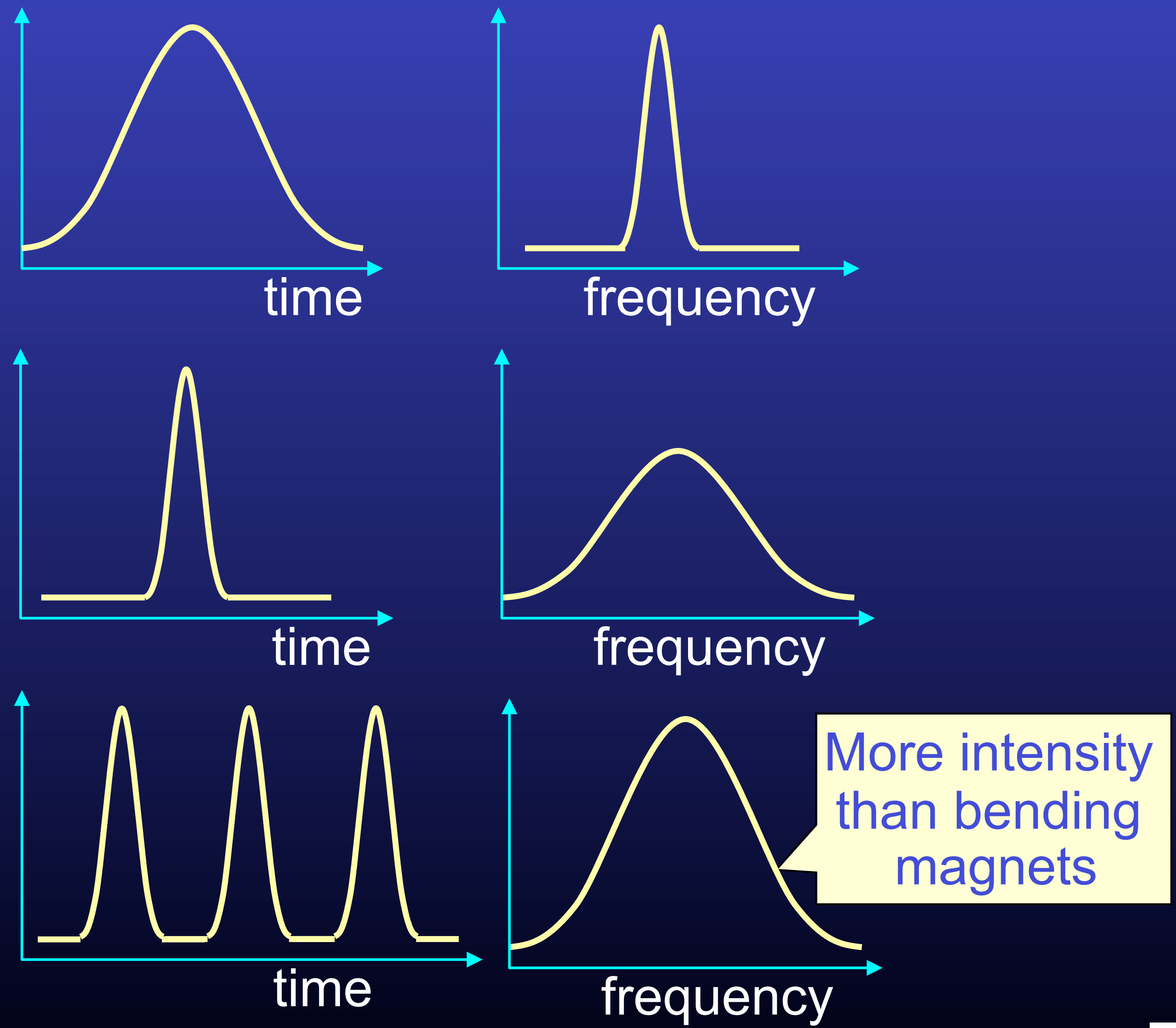


3 types of sources - summary:

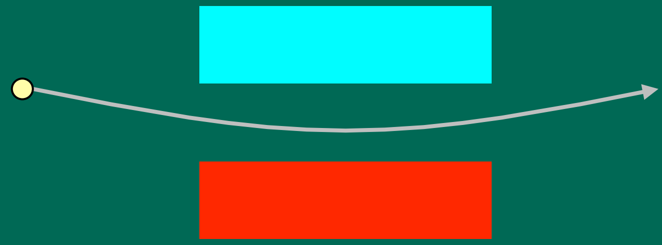
Undulators:

Bending magnets:

Wigglers:



Bending magnet emission spectrum:

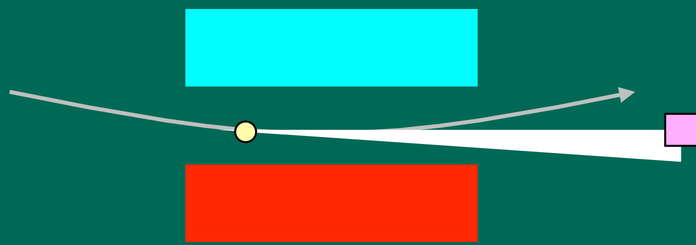


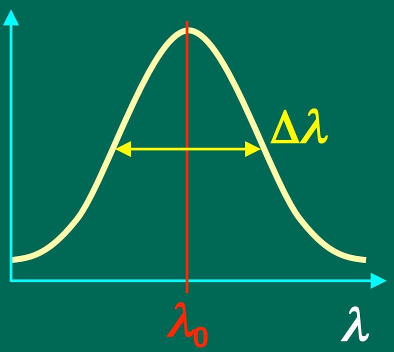
The (relativistic) rotation frequency of the electron determines the (Doppler-shifted) central wavelength:

$\lambda_o = (1/2\gamma^2)(2\pi c m_o/e)(1/B)$

The "sweep time" δt of the emitted light cone determines the frequency spread $\delta \nu$ and the wavelength bandwidth:

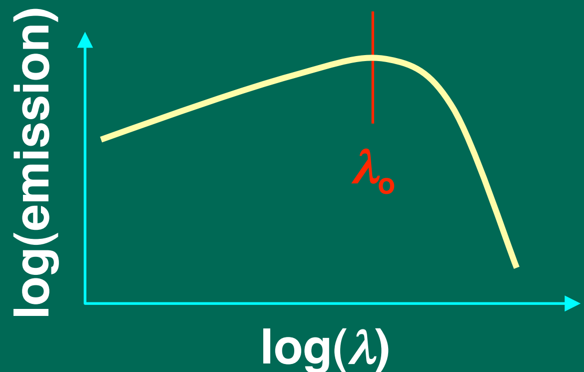
$\Delta\lambda / \lambda_o = 1$



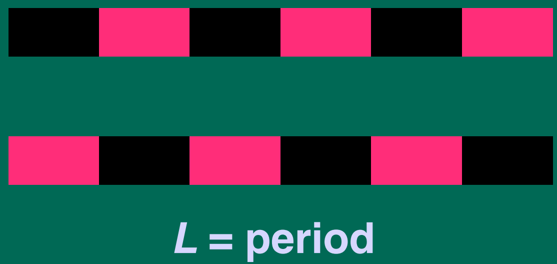


A peak centered at λ_c with width $\Delta\lambda$: is this really the well-known synchrotron spectrum?

YES -- see the log-log plot:



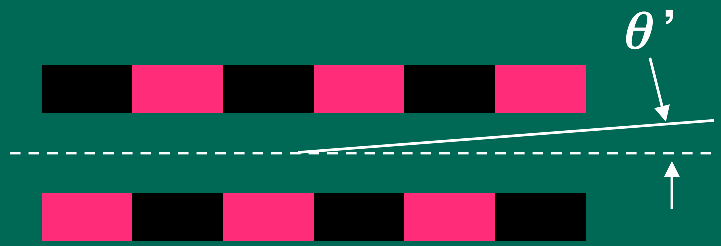
Undulator emission spectrum:

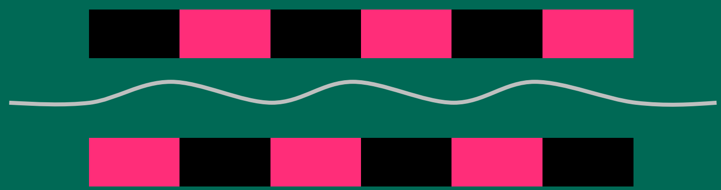


Central wavelength: $L/2\gamma^2$

First correction: out of axis, the Doppler factor is not $2\gamma^2$ but changes with θ'

Central wavelength: $(L/2\gamma^2)/(1+2\gamma^2\theta'^2)$



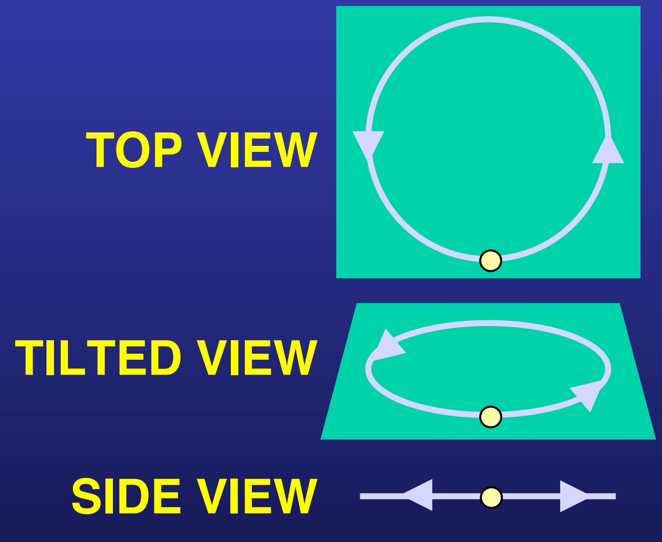


Second correction: stronger B-field means stronger undulations and less on-axis electron speed. This changes γ so that:

Central wavelength: $(L/2\gamma^2)/(1+aB^2)$

Synchrotron light polarization:

Electron in a storage ring:



Polarization:

Linear in the plane of the ring, **elliptical** out of the plane

Special (elliptical) wigglers and undulators can provide ellipticaly polarized light with high intensity