The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2332-1

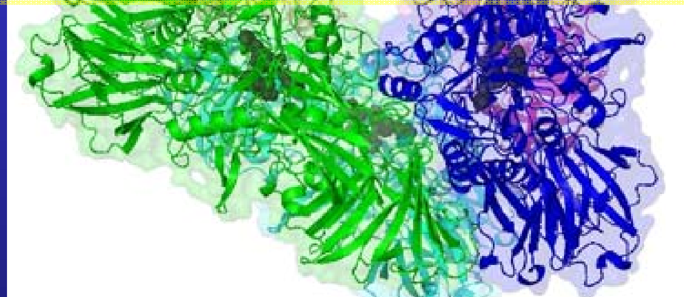
School on Synchrotron and FEL Based Methods and their Multi-Disciplinary Applications

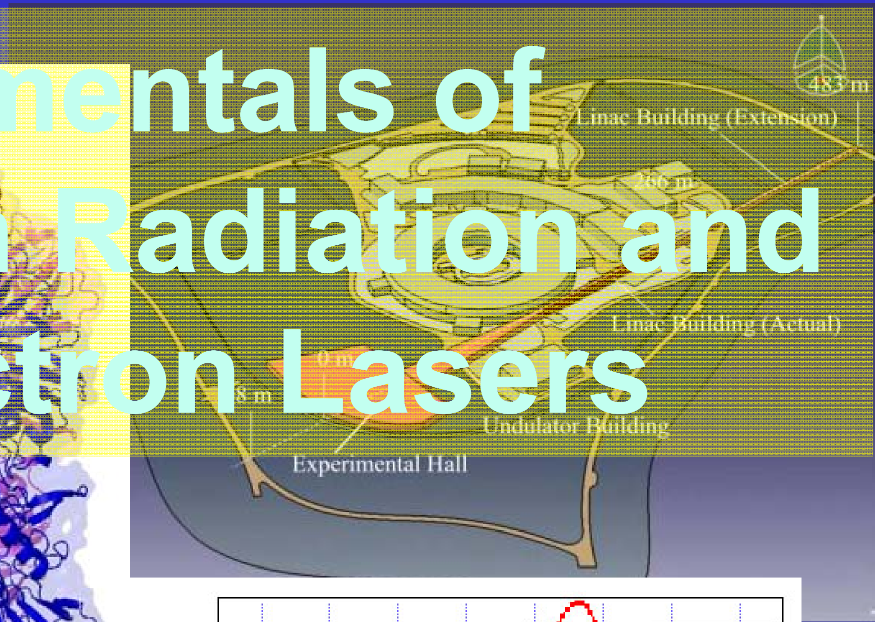
19 - 30 March 2012

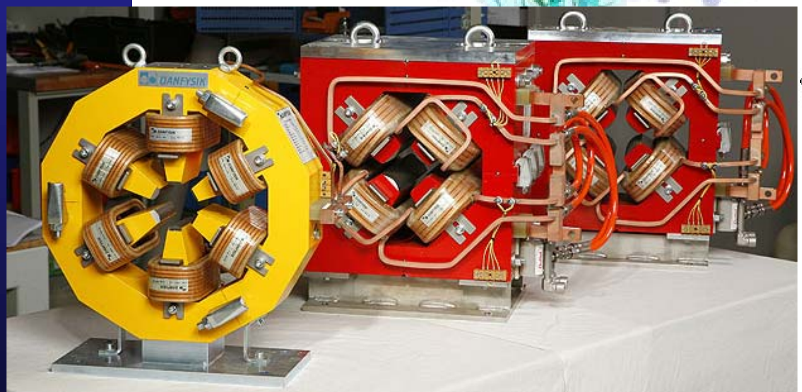
Fundamentals of Synchrotron Radiation and Free Electron Lasers

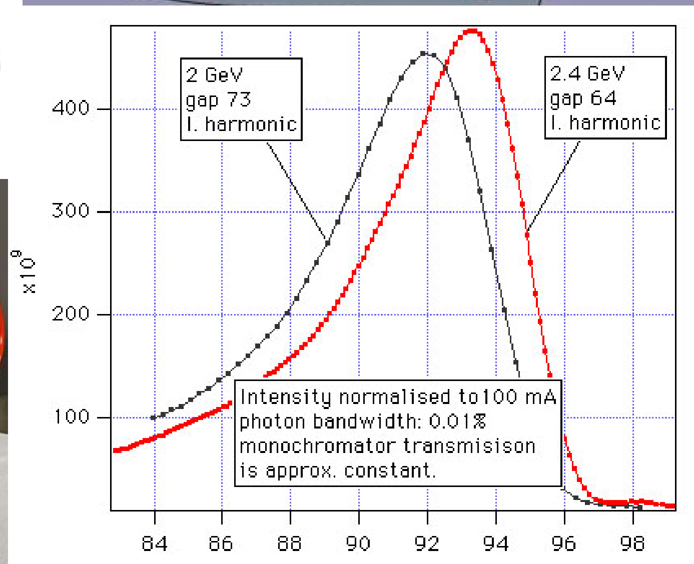
Giorgio Margaritondo
Ecole Polytechnique Fédérale de Lausanne (EPFL)

Fundamentals of Synchrotron Radiation and Free Electron Lasers









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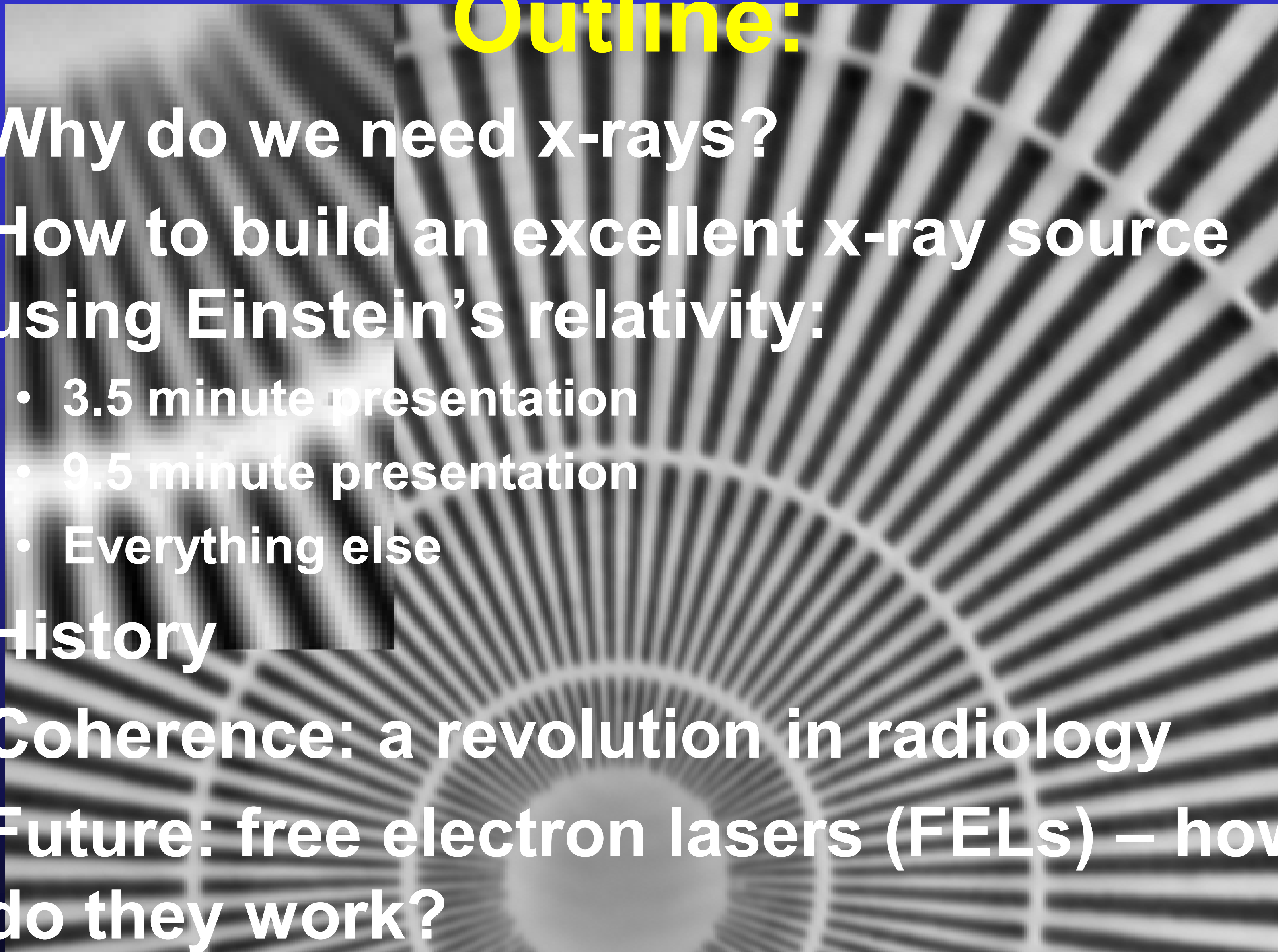
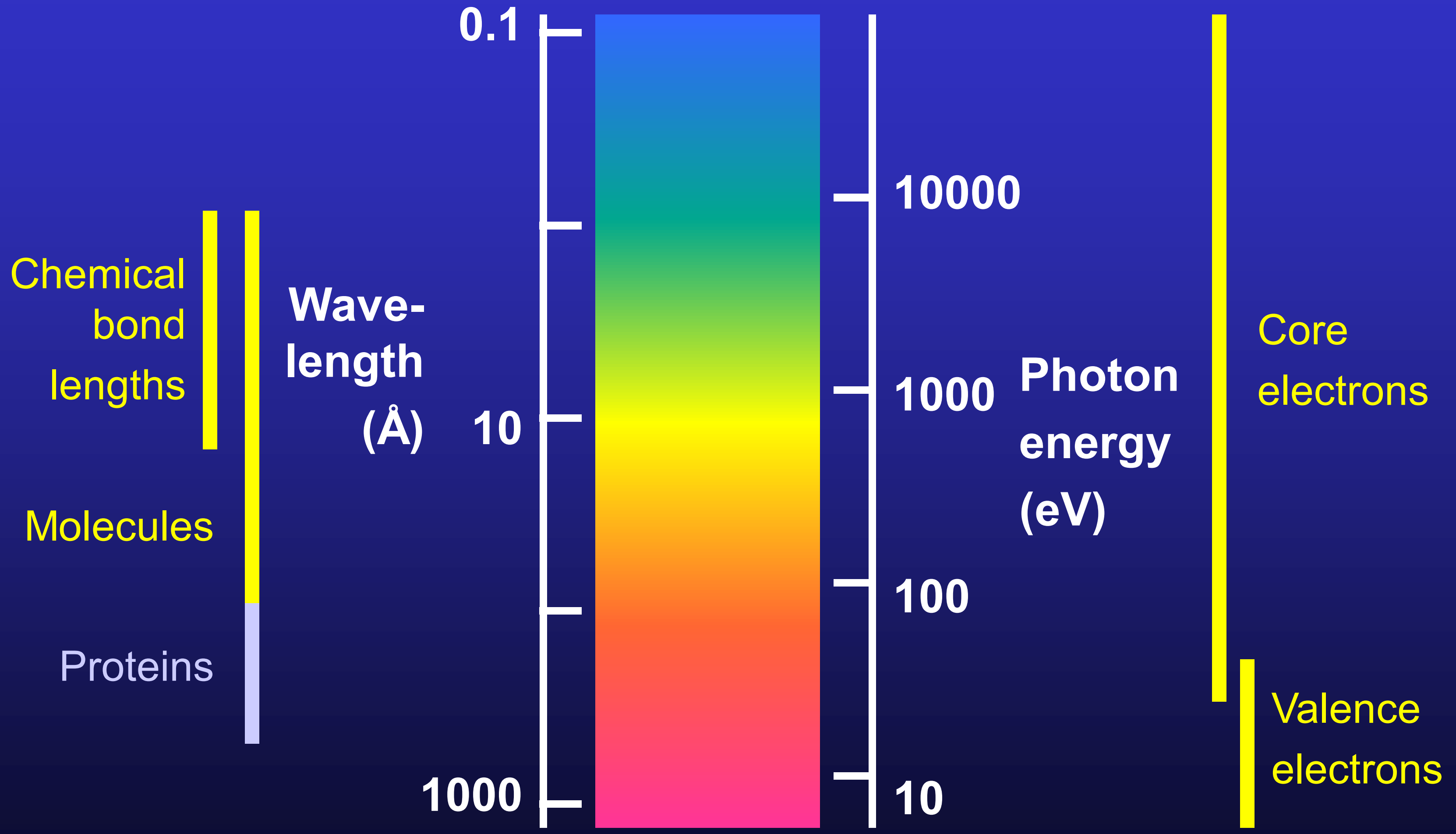
Outline:



- 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: free electron lasers (FELs) – how do they work?

Why x-rays and ultraviolet?

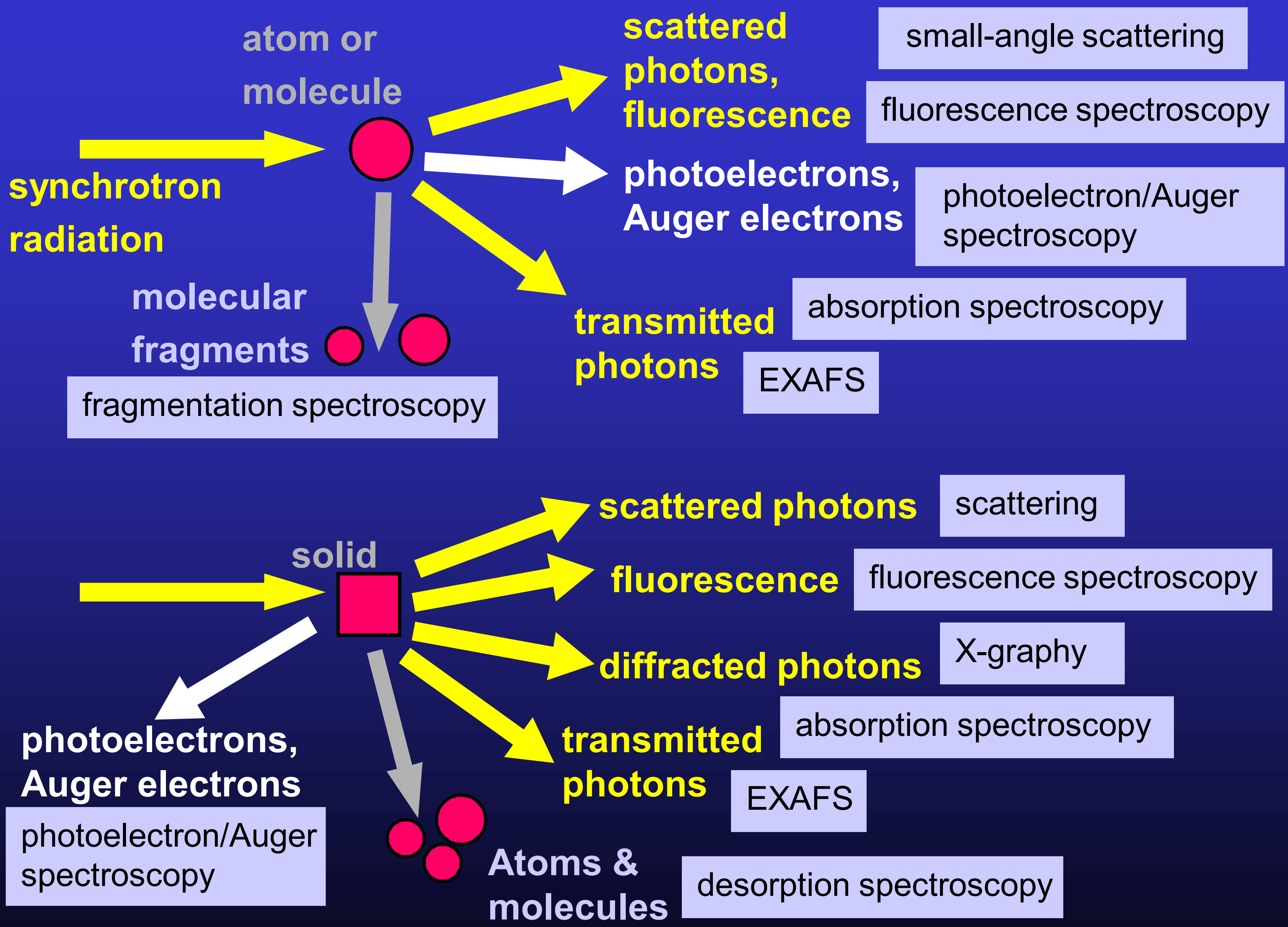


Synchrotron x-rays:

Many different interactions

↓

Many different applications


atom or molecule
synchrotron radiation
scattered photons, fluorescence
small-angle scattering
fluorescence spectroscopy
photoelectrons, 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?

START! THE "RELAXATION PROGRAM":

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

AFTER STEP A -- OPTIONS: (1) relax 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?

AFTER STEP B -- OPTIONS: (1) relax for the day, or (2) go to step C

STEP C (the rest of the time… maybe more): (almost) everything about synchrotrons and FELs

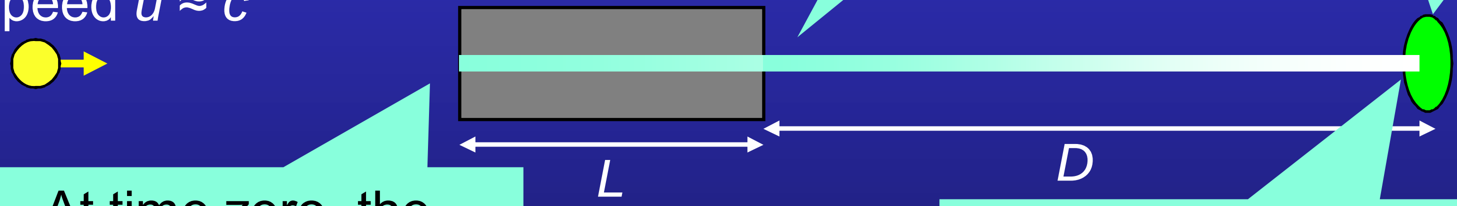
Synchrotron light in 3.5 minutes for lazy students (and teachers):

Electron:
Speed $u \approx c$

Magnet:
Lorentz force $\Rightarrow$ acceleration $\Rightarrow$ photon emission

At the time L/u, the electron leaves the magnet

The last photons arrive at the time $L/u + D/c$



Photon detector

At time zero, the electron enters the magnet, is accelerated and emits photons

The first photons arrive at the detector at the time $(L + D)/c$

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

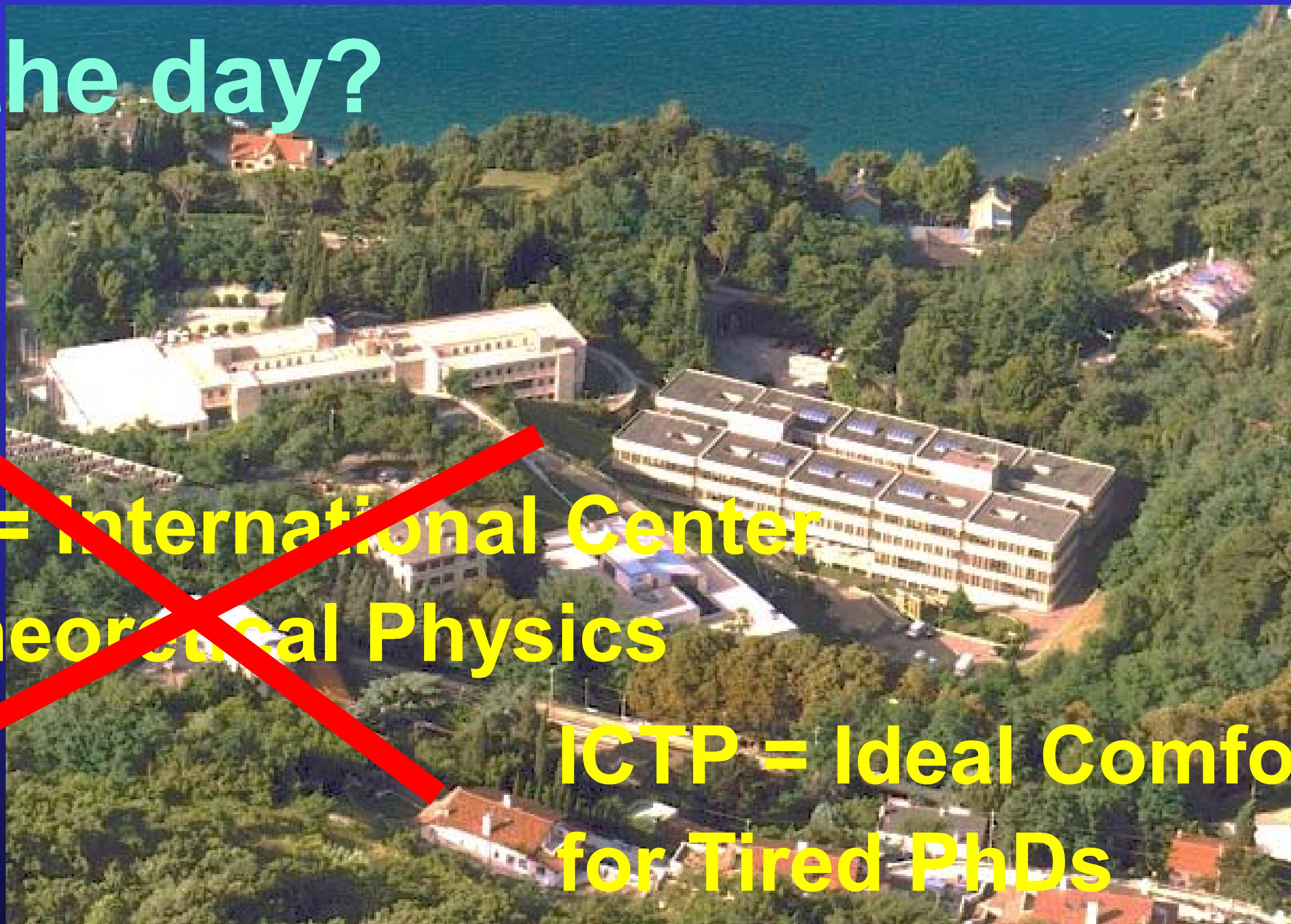
Characteristic frequency: $\nu = 1/\Delta t = u/[L(1-u/c)] = u\,\gamma^2\,(1+u/c)/L$

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

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

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

And now, can we all relax for the day?

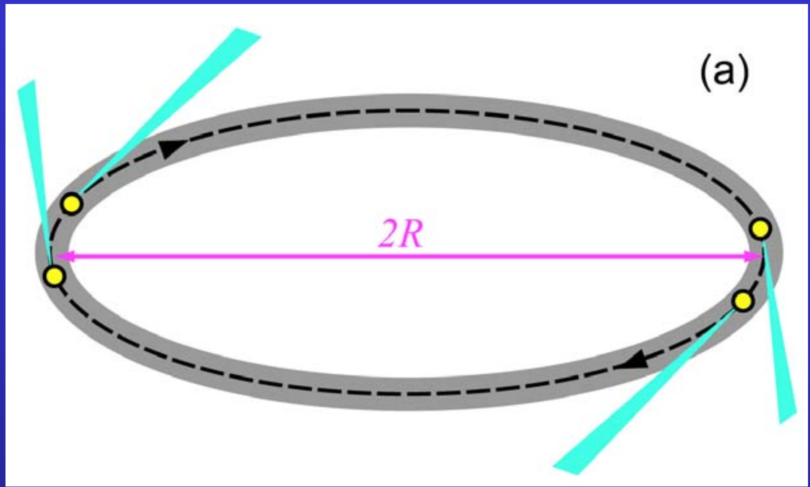


~~ICTP = International Center for Theoretical Physics~~

ICTP = Ideal Comfort for Tired PhDs

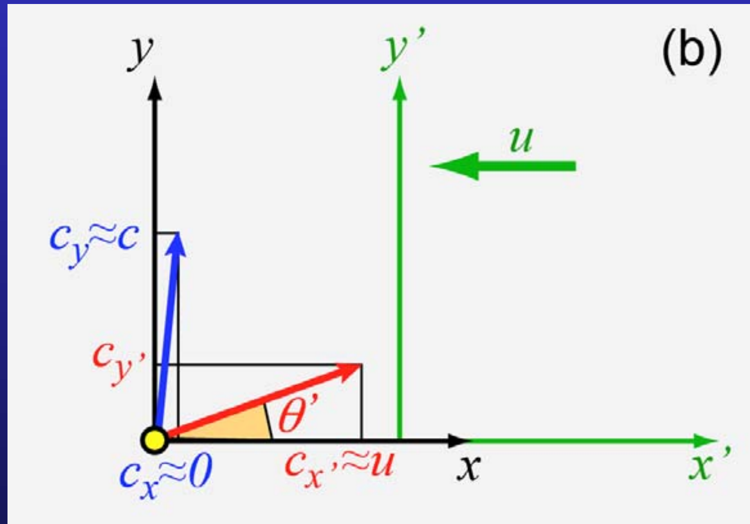
…Well, not really, (sorry)!!!

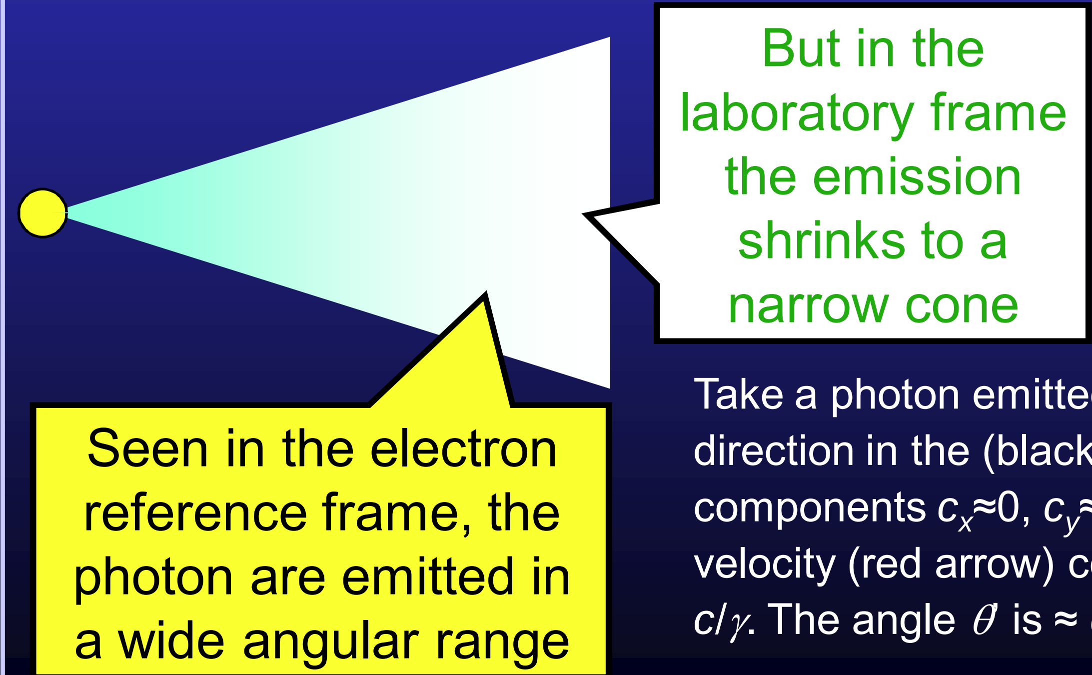
Synchrotron light in 9.5 minutes for (not entirely) lazy students (and teachers):



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

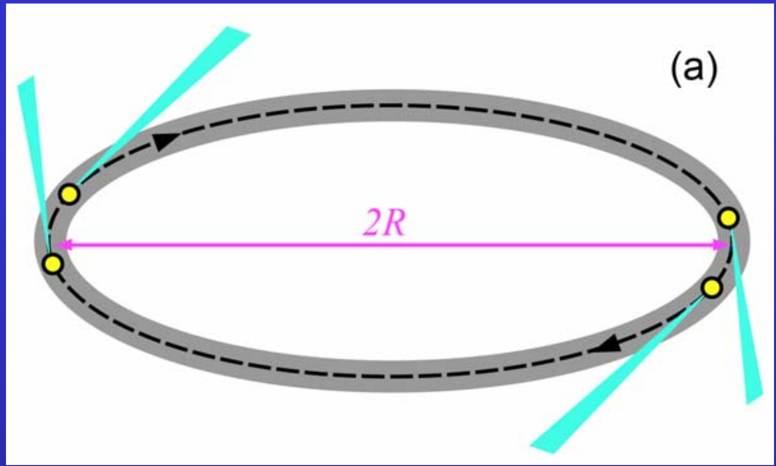
Answer: RELATIVITY





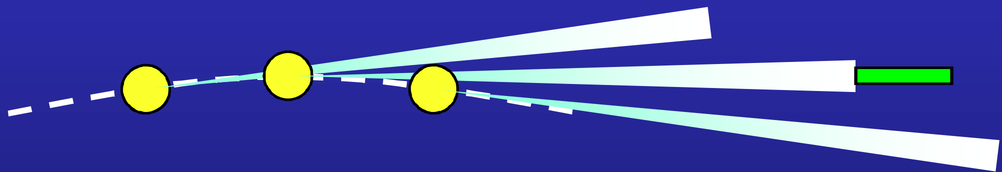
Take a photon emitted (blue arrow) in a near-trasverse direction in the (black) electron frame, with velocity components $c_x \approx 0$, $c_y \approx c$. In the (green) laboratory frame the velocity (red arrow) components become $c_x' \approx u$, $c_y' \approx (c^2 - u^2)^{1/2} = c/\gamma$. The angle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

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

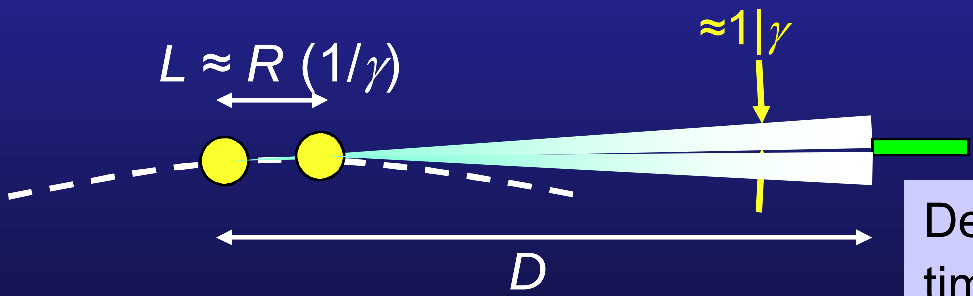


Seen from the side of the ring, each electron looks like an oscillating charge in an antenna, emitting photons with a frequency $2\pi R/c$ -- in the radio wave range.

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 $L/u + (D - L)/c$

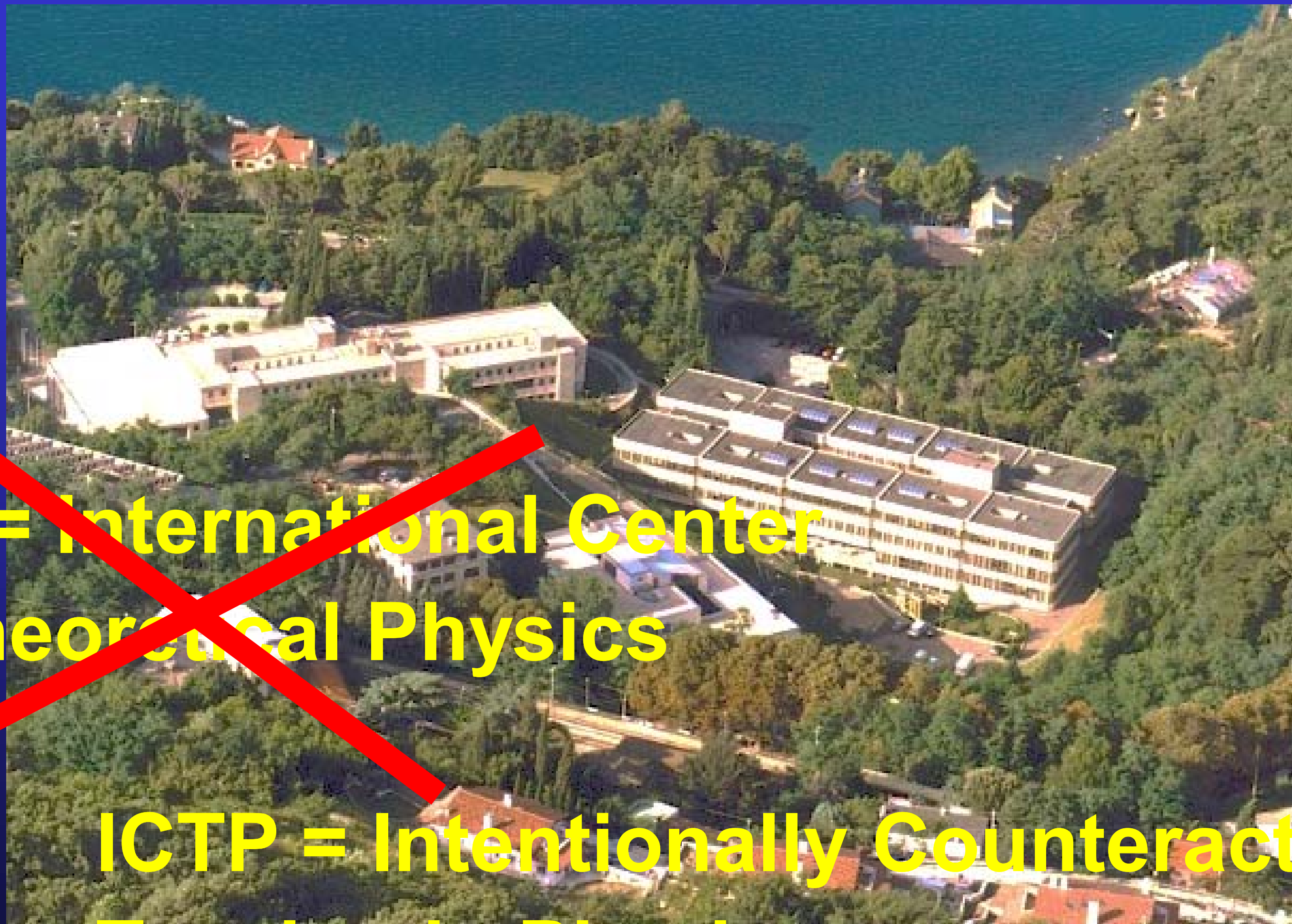
Photon pulse duration:

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

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, relax maybe?



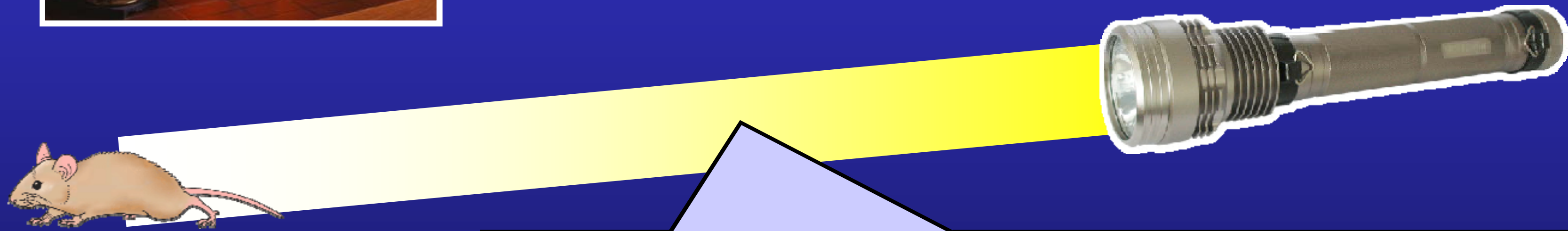
~~ICTP = International Center for Theoretical Physics~~

ICTP = Intentionally Counteracting Tension in Physics

…Sorry again, 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 :

Source area, ≈ ξ^2

ξ ↕

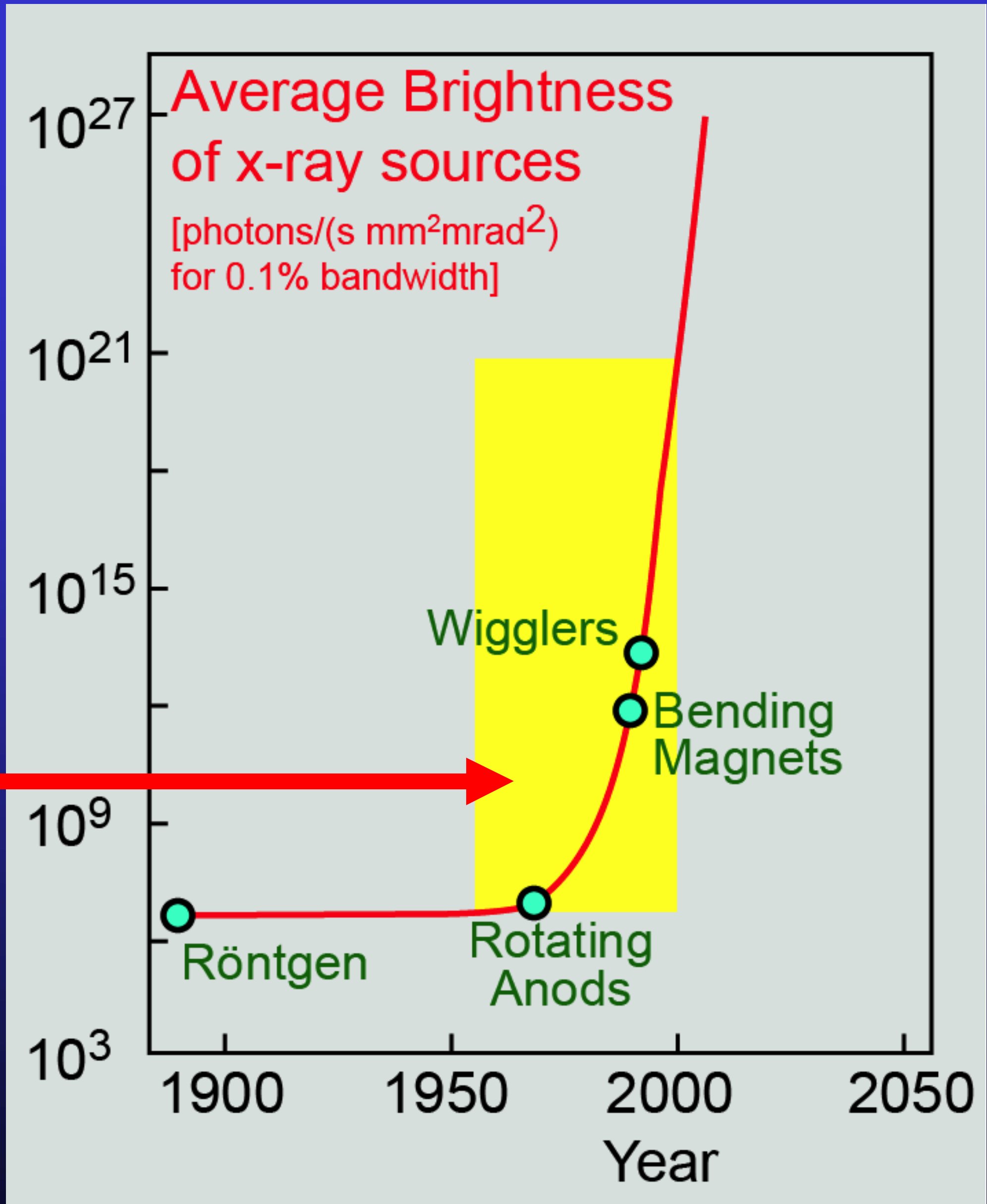
Flux, F

Angular divergence, solid angle Ω

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

The historical growth in x-ray brightness/brilliance

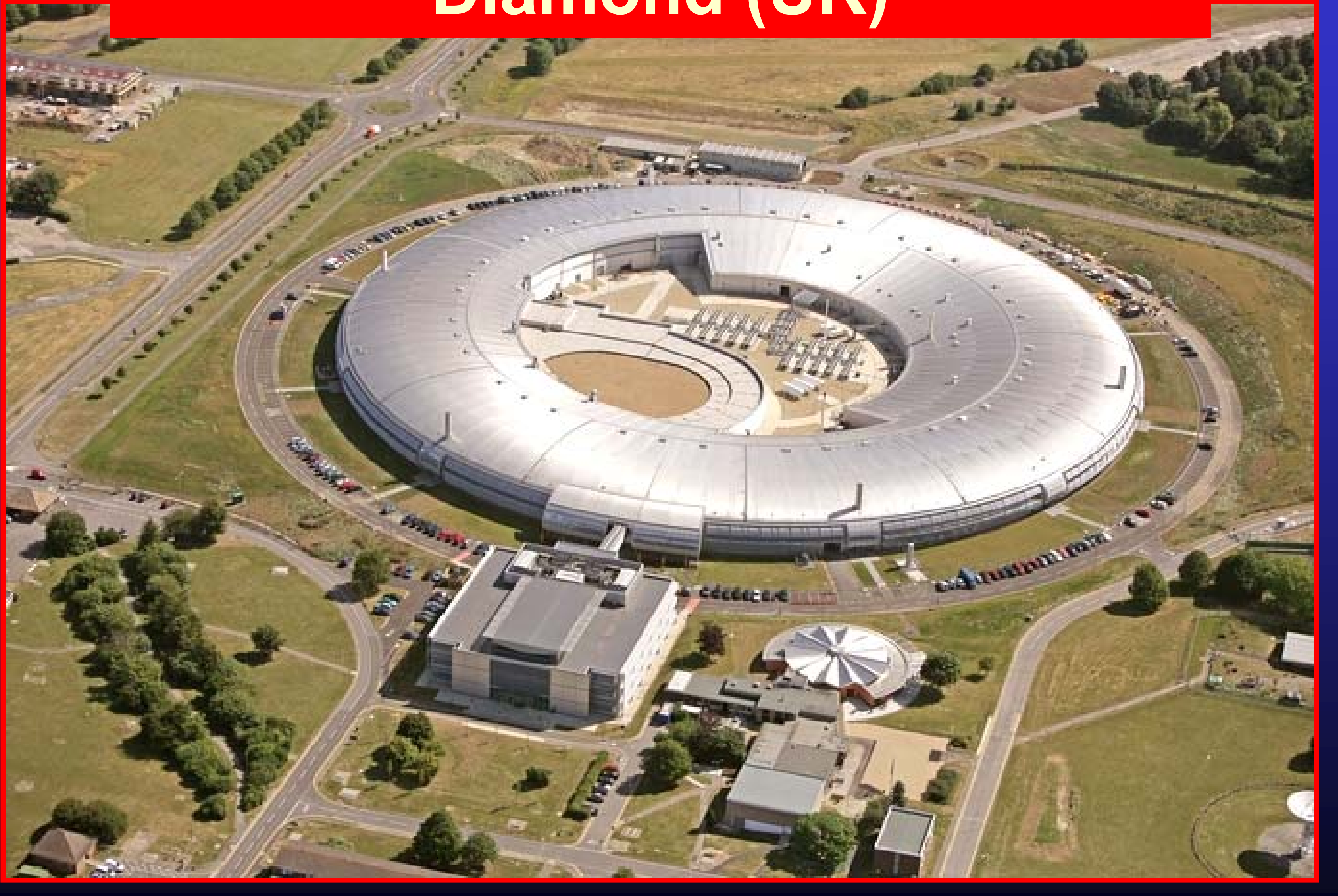
Between 1955 and 2000, the brightness increased by more than 15 orders of magnitude… whereas the top power of computing increased "only" by 6-7 orders of magnitude



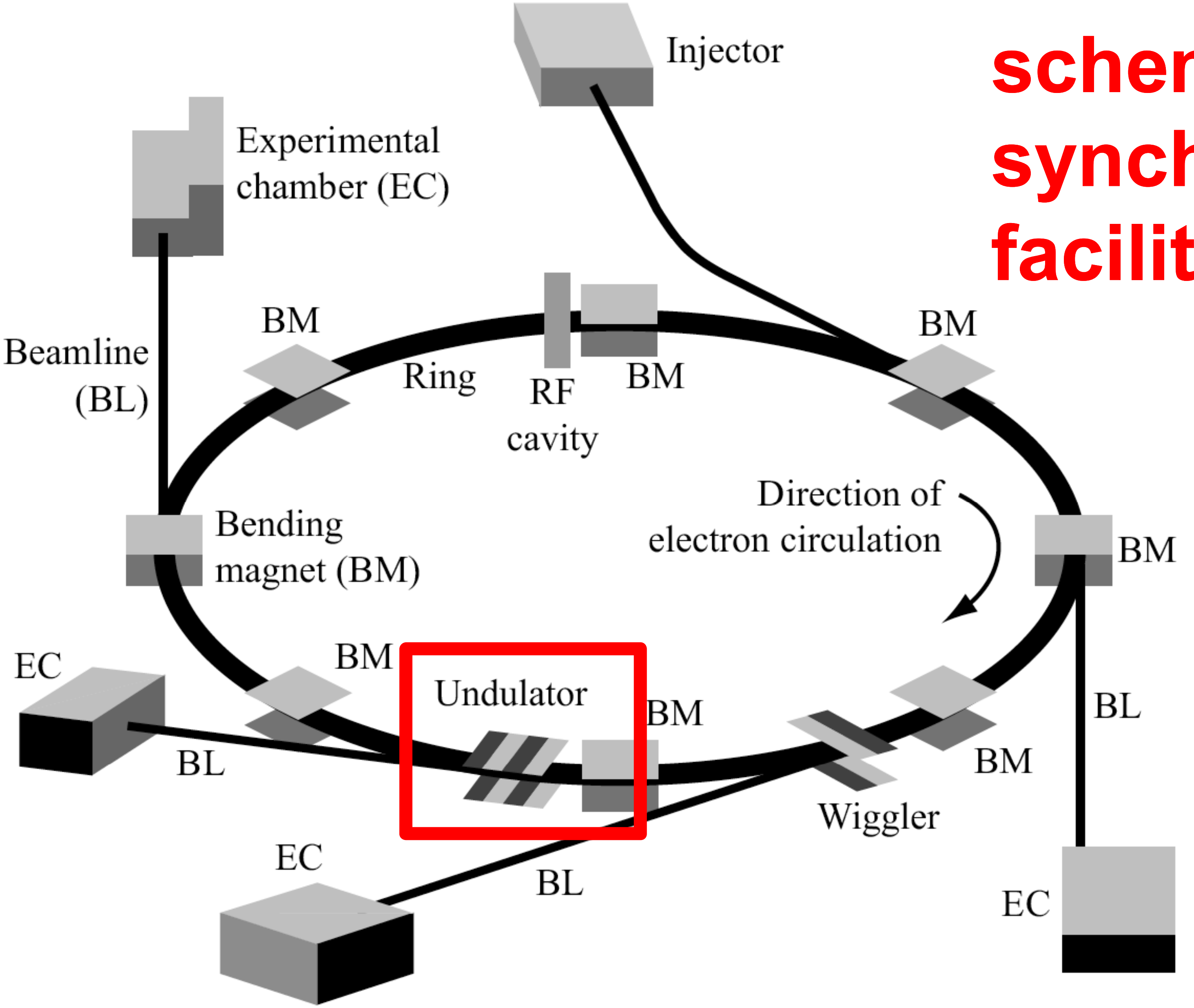
What produces the high brightness of a synchrotron source?

- Free electrons can emit more power than electrons bound in a solid because the power does not damage their environment $\Rightarrow$ 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 $\Rightarrow$ small photon source size
- Relativity drastically reduces the angular divergence of the emitted synchrotron radiation

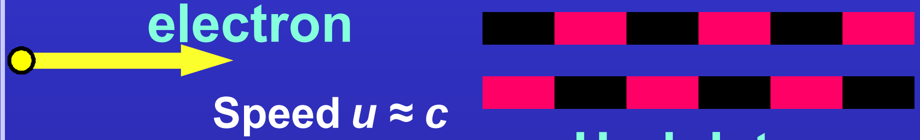
A real synchrotron facility: Diamond (UK)



General scheme of a synchrotron facility



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

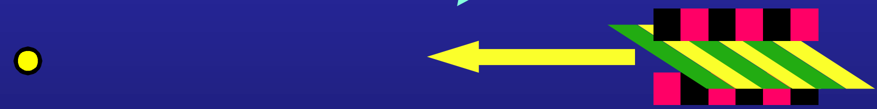


Undulator
(periodic B-field, period $L \approx$ centimeters)

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:

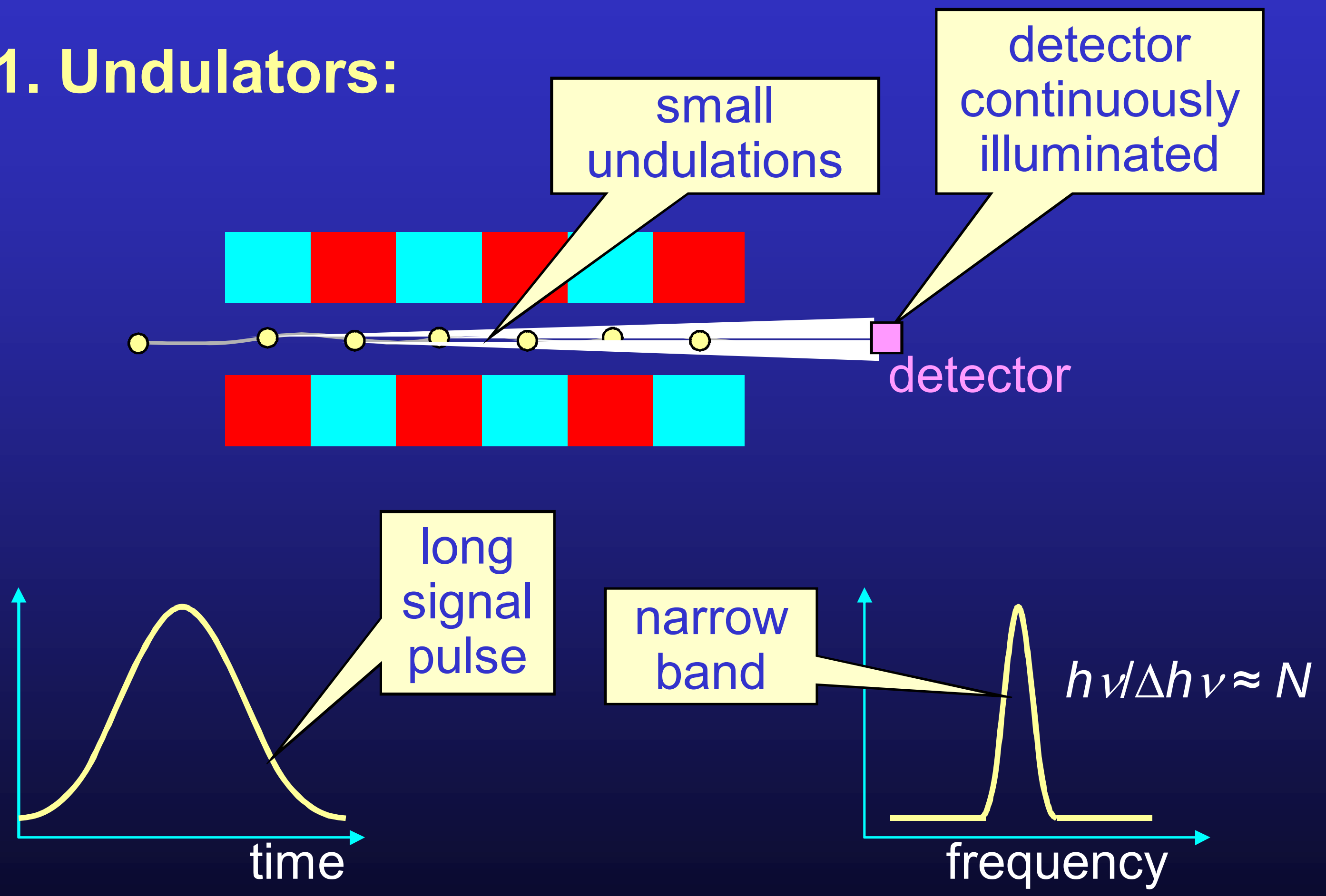


The periodic B-field is accompanied by a perpendicular periodic E-field. Moving at a speed ≈c towards the electron, the undulator looks like an electromagnetic wave with wavelength L/γ. Synchrotron radiation is produced by the elastic scattering of this wave by the electron.

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!

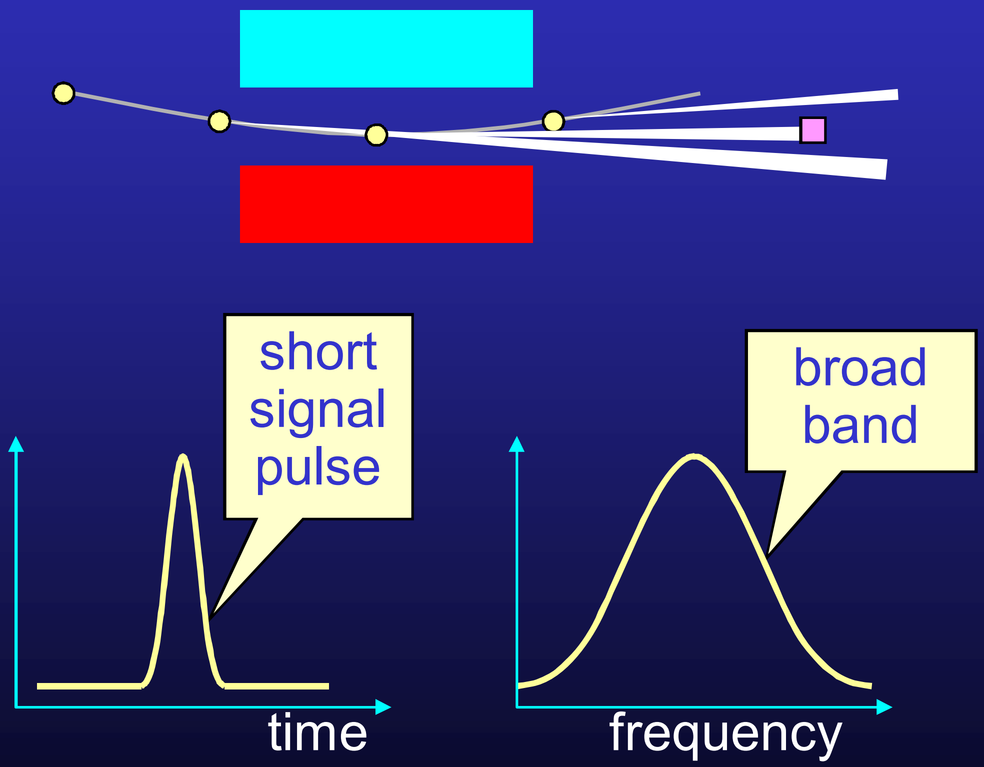
3 types of sources:

1. Undulators:



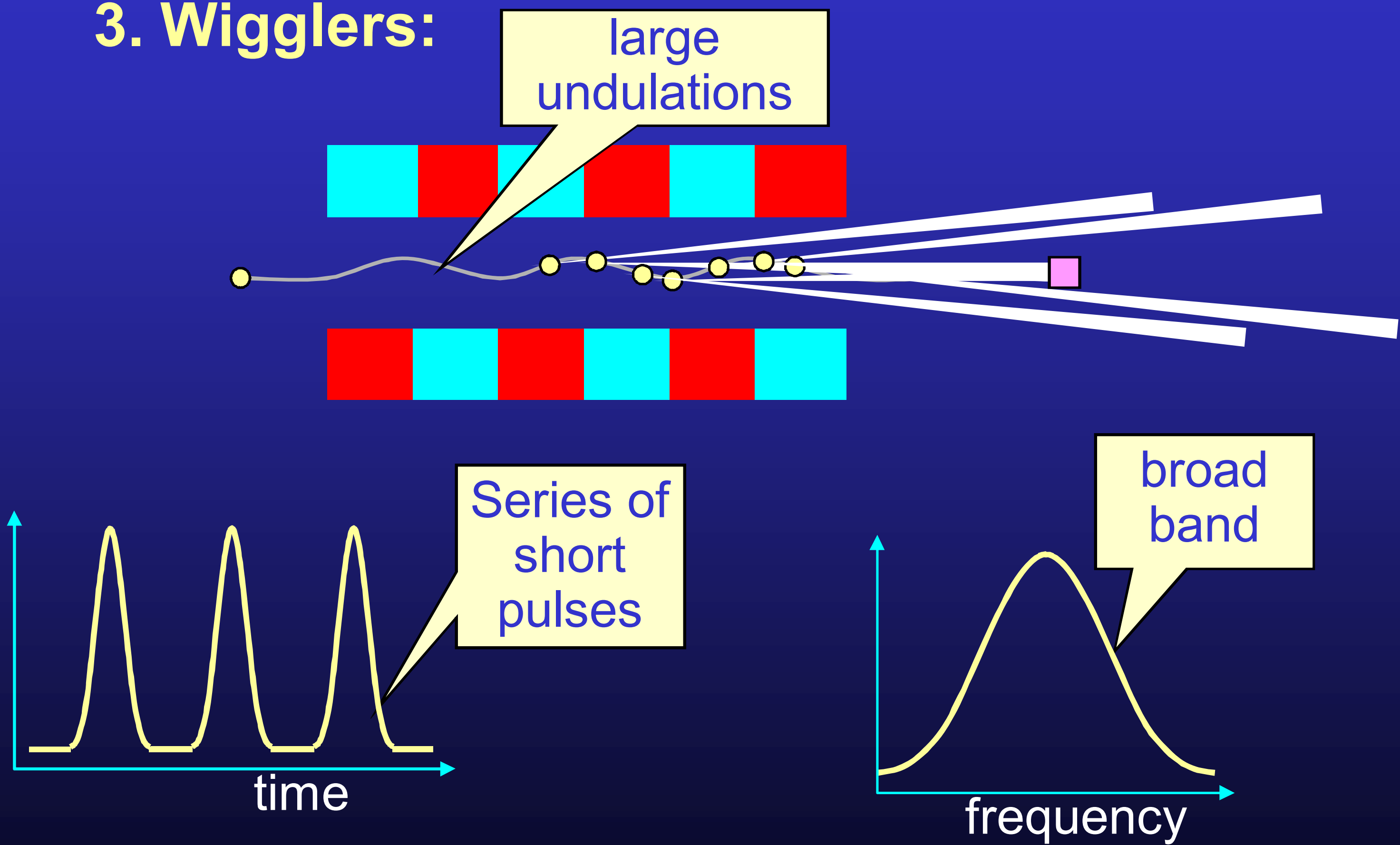
3 types of sources:

2. Bending magnets:



3 types of sources:

3. Wigglers:

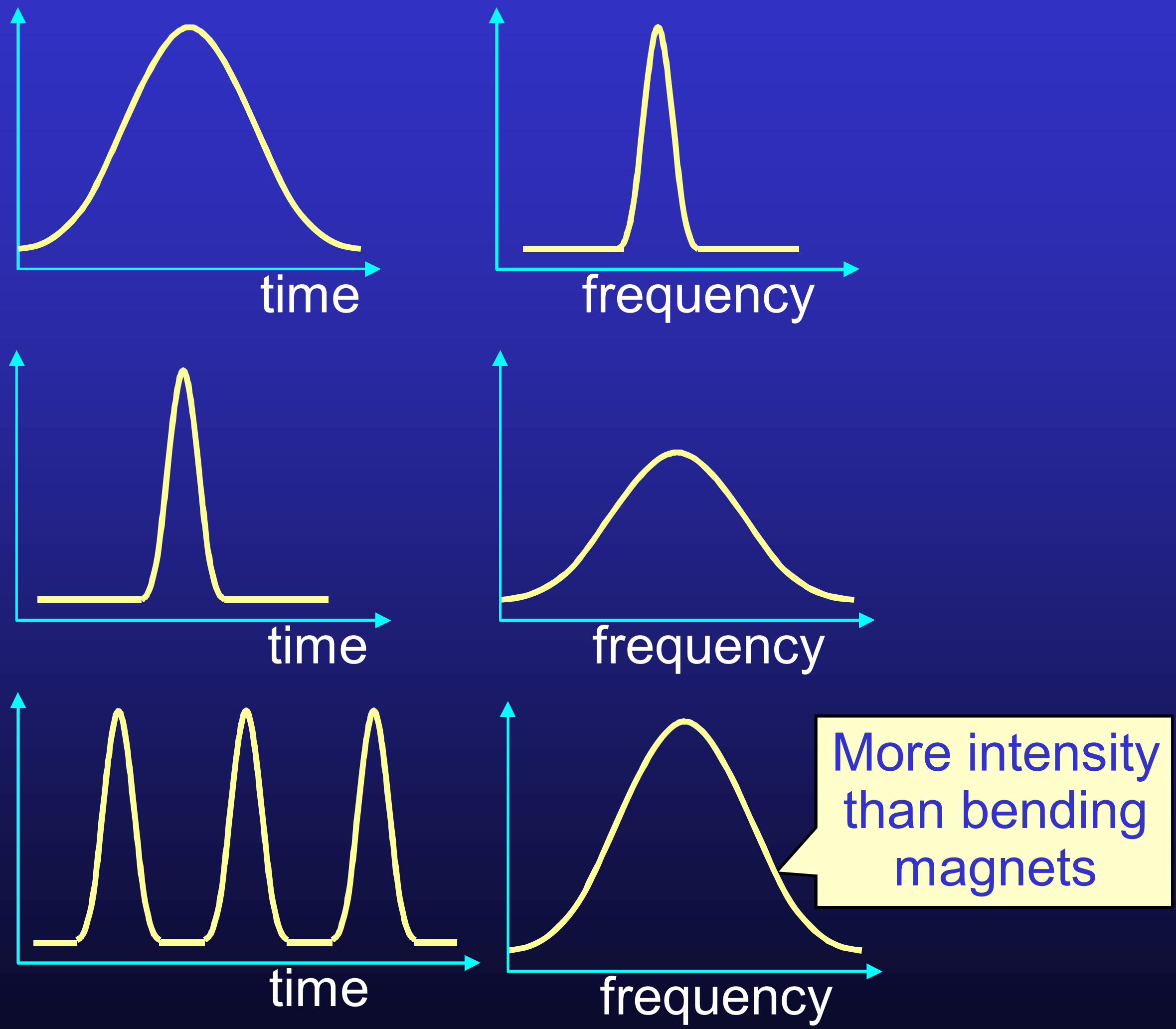


3 types of sources - summary:

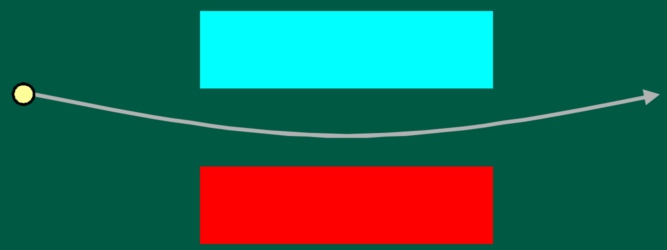
Undulators:

Bending magnets:

Wigglers:



Bending magnet emission spectrum:

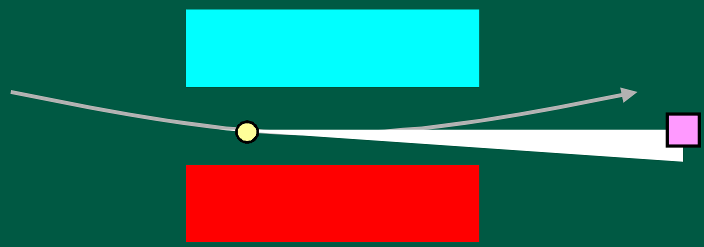


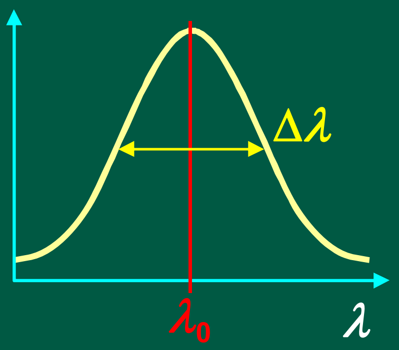
The (relativistic) rotation frequency of the electron determines the (Doppler-shifted) central wavelength:

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

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

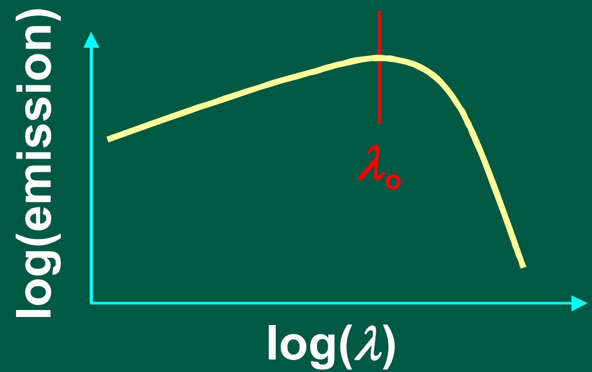
$\Delta\lambda / \lambda_o = 1$



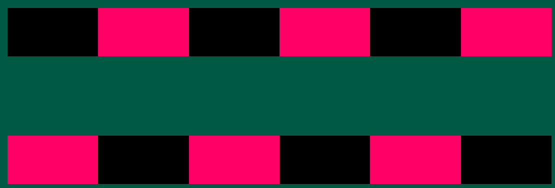


A peak centered at λ_c with width $\Delta\lambda$: is this really the well-known synchrotron spectrum?

YES -- see the log-log plot:



Undulator emission spectrum:

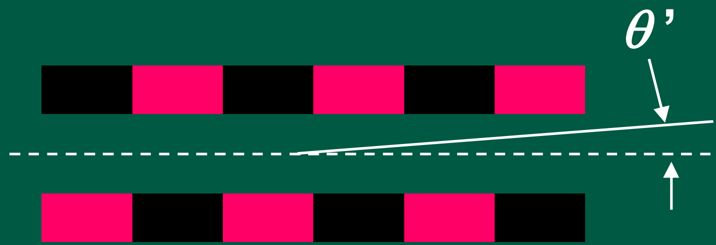


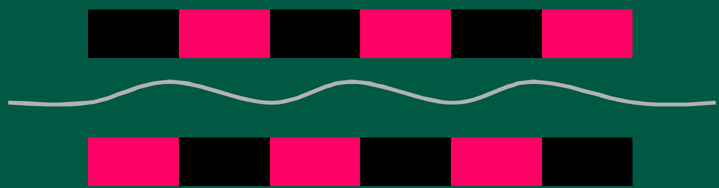
L = period

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



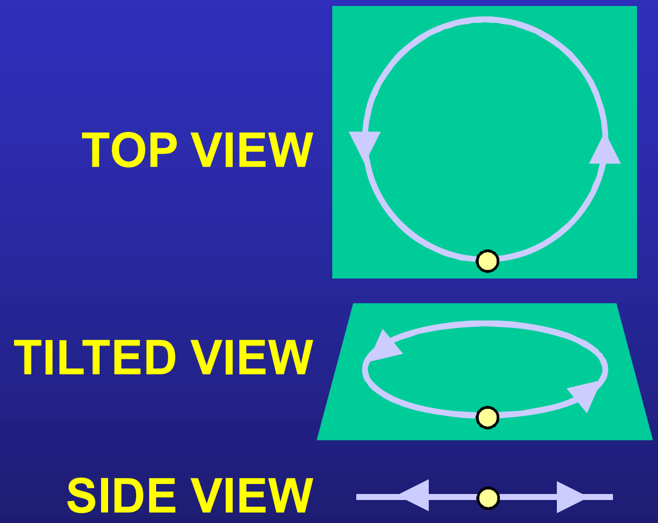


Second correction: stronger B-field means stronger undulations and less on-axis electron speed. This changes γ so that:

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

Synchrotron light polarization:

Electron in a storage ring:



Polarization:

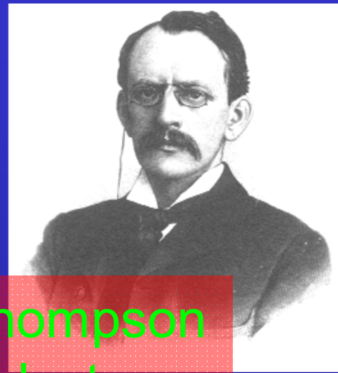
Linear in the plane of the ring, **elliptical** out of the plane

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

An interesting history, a bright future:

The origins:

1898 -- Alfréd Lienard conceives synchrotron light

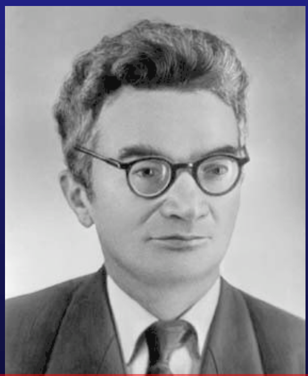


1897 -- J. J. Thompson discovers the electron

A8. Electron Radiation in High Energy Accelerators. JULIAN SCHWINGER, *Harvard University.**—The only fundamental limitation to the attainment of very high energy electrons in devices such as the betatron and synchrotron is the radiative energy loss accompanying the circular motion. For an electron of energy $E \gg mc^2$, moving in a circular path of radius R, the energy radiated per revolution is

$$\delta E = \frac{4\pi}{3}\frac{e^2}{R}\left(\frac{E}{mc^2}\right)^4$$

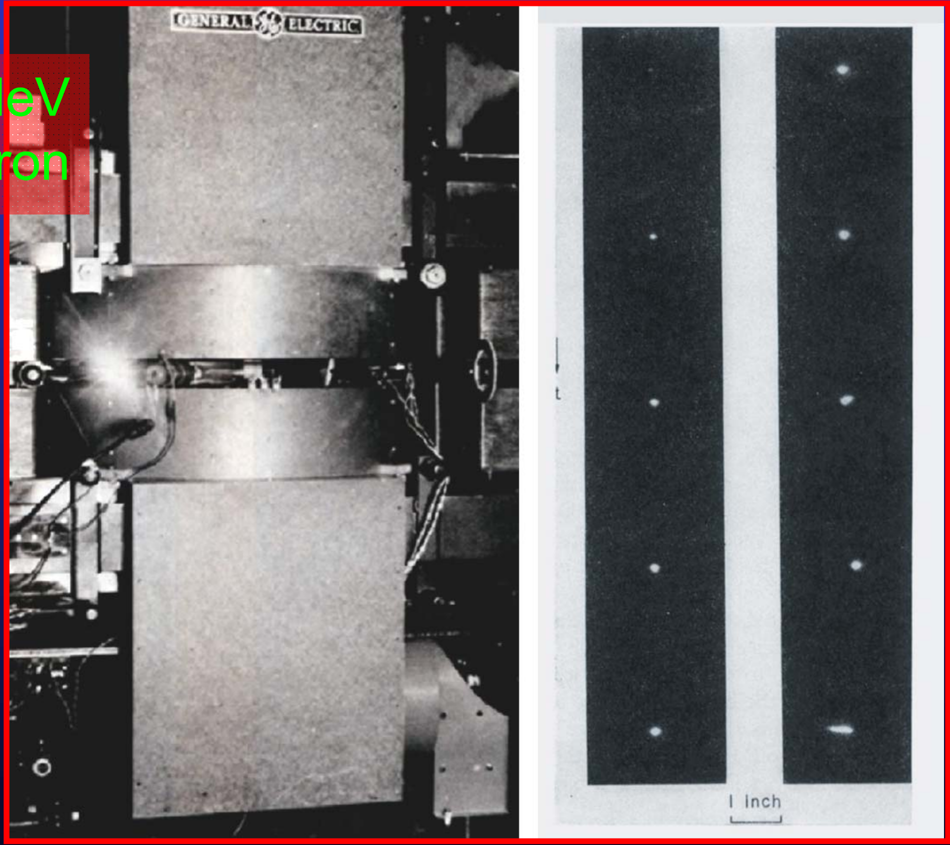
which amounts to roughly 30 kev for an electron of 1 Bev in a magnetic field of 10^4 gauss. The radiation spectrum consists of harmonics of the rotation angular frequency



1940s: Isaak Pomeranchuk, Dmitri Ivanenko and Julian Schwinger develop a full theory

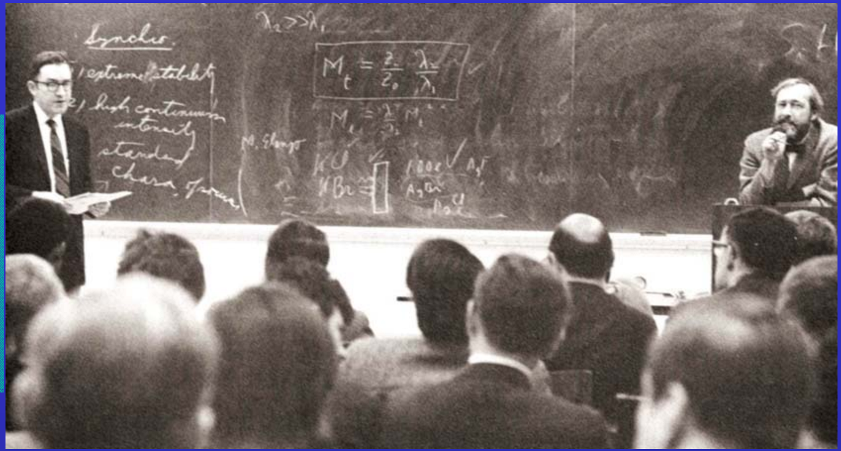
24 April 1947: at General Electrics in Schenectady, Herb Pollock, Robert Langmuir, Frank Elder and Anatole Gurewitsch see synchrotron light for the first time:

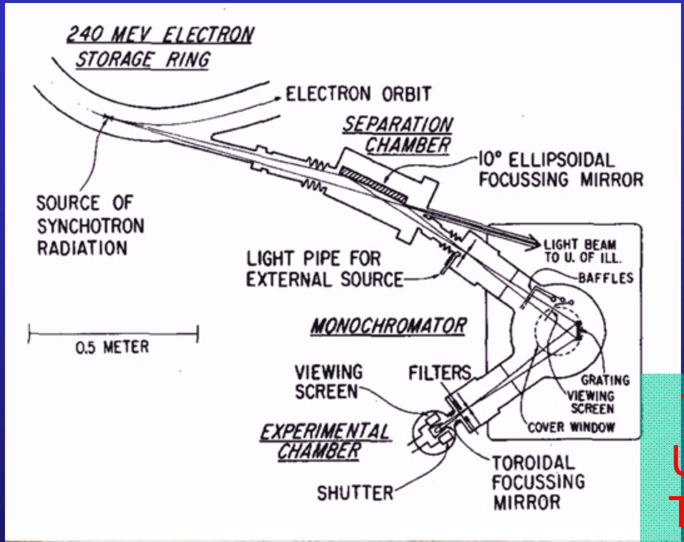
The GE 70 MeV synchrotron



"a trivial design change and … a conscious disregard for the rules of radiation safety"

1966: Fred Brown (Urbana) proposes to Ed Rowe, the father of Tantalus, to use it as the first dedicated synchrotron source





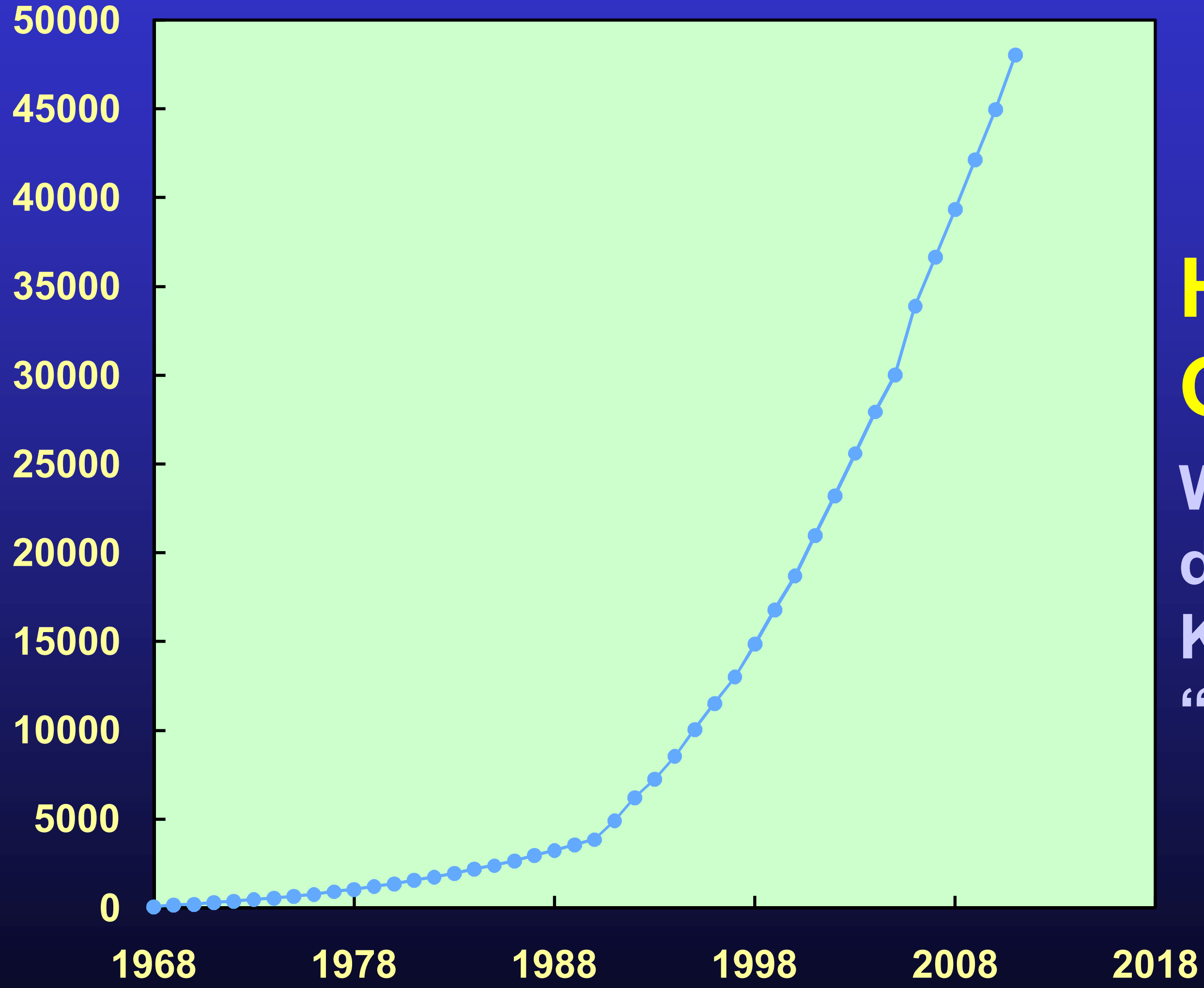
7 August 1968, 10:40 a.m.: Ulrich Gehrardt performs on Tantalus the first experiment with a dedicated synchrotron source:

ONLY 44 YEARS AGO!!!

Synchrotron Facilities in the World (2010):

69 in 25 Countries

(operating or under construction)



Historical Growth:

Worldwide ISI data 1968-2006, Keyword: “synchrotron”

… but, for a broader picture:

Hits from a 2012 Google search:

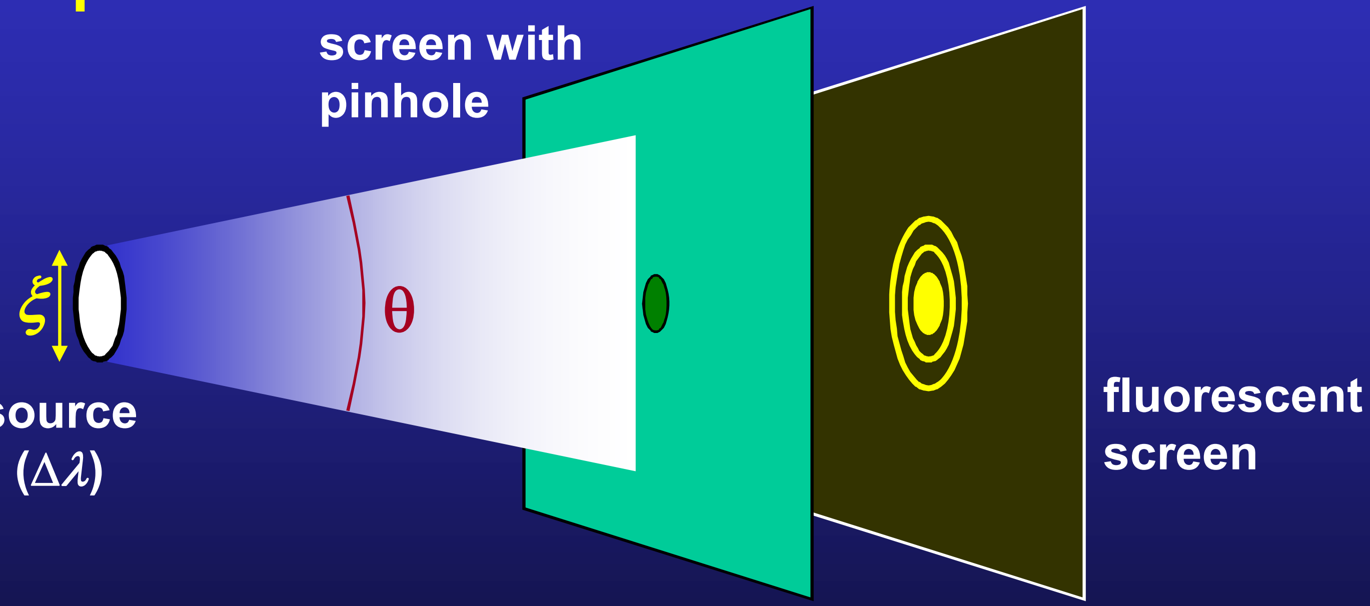
"Synchrotron"	4,830,000
"Free electron laser"	1,910,000
"LINAC"	1,330,000
"Hadron collider"	5,770,000

"Protein crystallography"	2,350,000
"Synchrotron photoemission"	435,000

"Margaritondo"	158,000
"Berlusconi"	91,100,000
"Pamela Anderson"	82,000,000

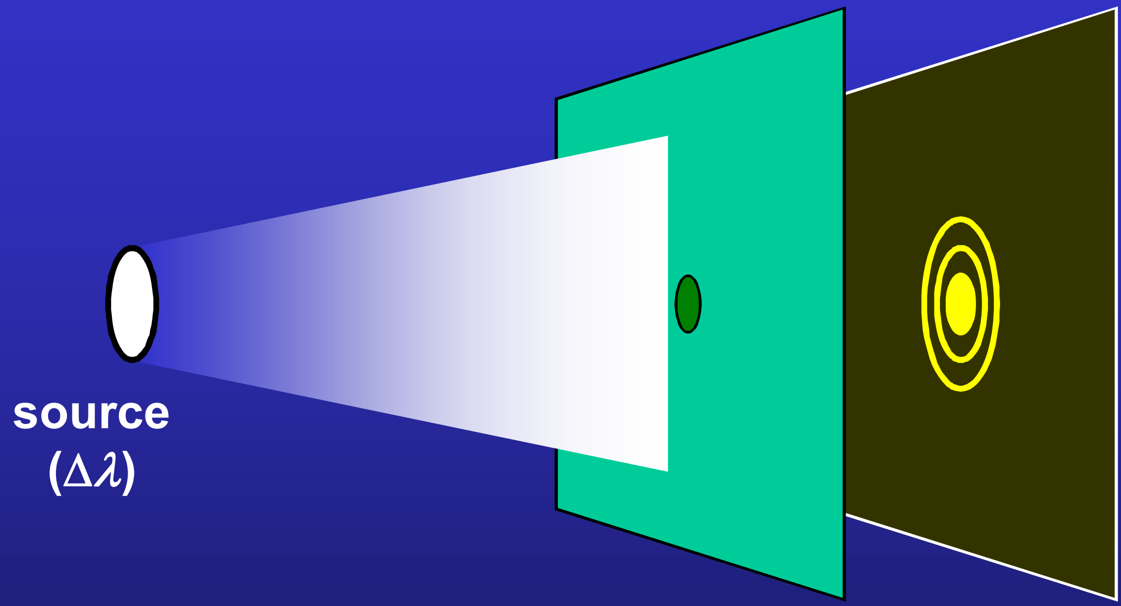
Coherence: "the property that enables a wave to produce visible diffraction and interference effects"

Example:



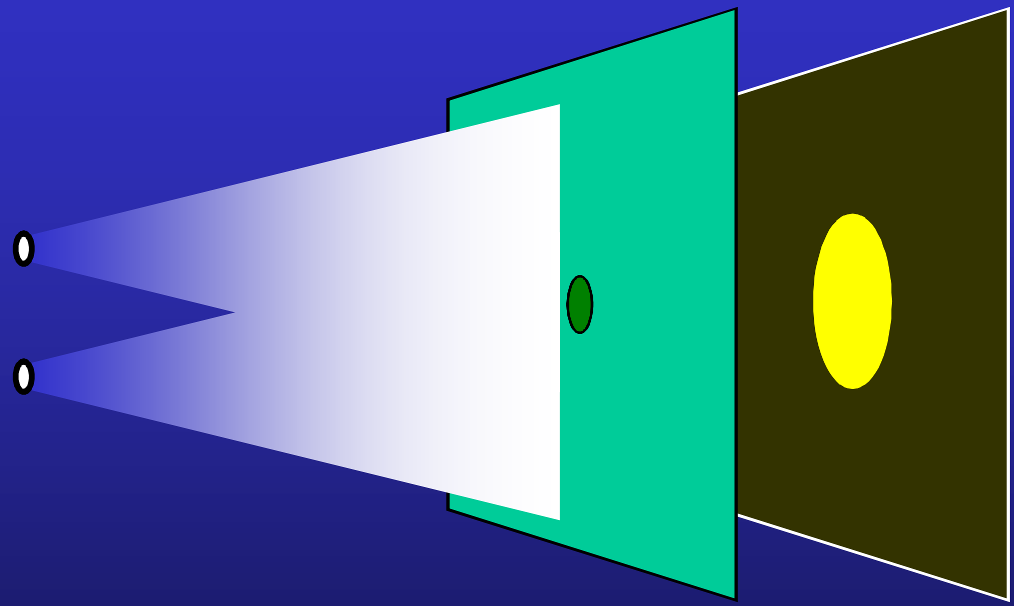
The diffraction pattern may or may not be visible on the fluorescent screen depending on the source size ξ, on its angular divergence θ and on its wavelength bandwidth $\Delta\lambda$

Longitudinal (time) coherence:



- Condition to see the pattern: $\Delta\lambda/\lambda < 1$
- Parameter characterizing the longitudinal coherence: "<u>coherence length</u>": $L_c = \lambda^2/\Delta\lambda$
- Condition of longitudinal coherence: $L_c > \lambda$

Lateral (space) coherence — analyzed with a source formed by <u>two point sources</u>:

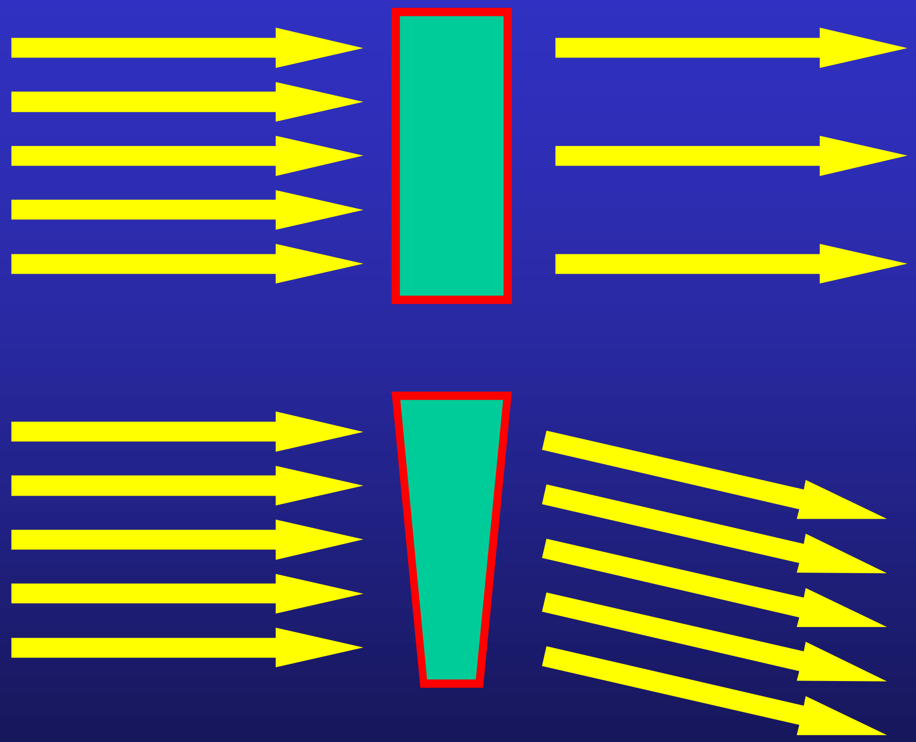


- Two point sources produce overlapping patterns: diffraction effects are no longer visible.
- However, if the two source are close to each other an overall diffraction pattern may still be visible: the condition is to have a **large "coherent power" $(2\lambda/\xi\theta)^2$**

Coherence — summary:

- Large coherence length $L_c = \lambda^2/\Delta\lambda$
- Large coherent power $(2\lambda/\xi\theta)^2$
- **Both difficult to achieve for small wavelengths (x-rays)**
- **The conditions for large coherent power are equivalent to the geometric conditions for high brightness**

Light-matter interactions in radiology:



Absorption -- described by the absorption coefficient α

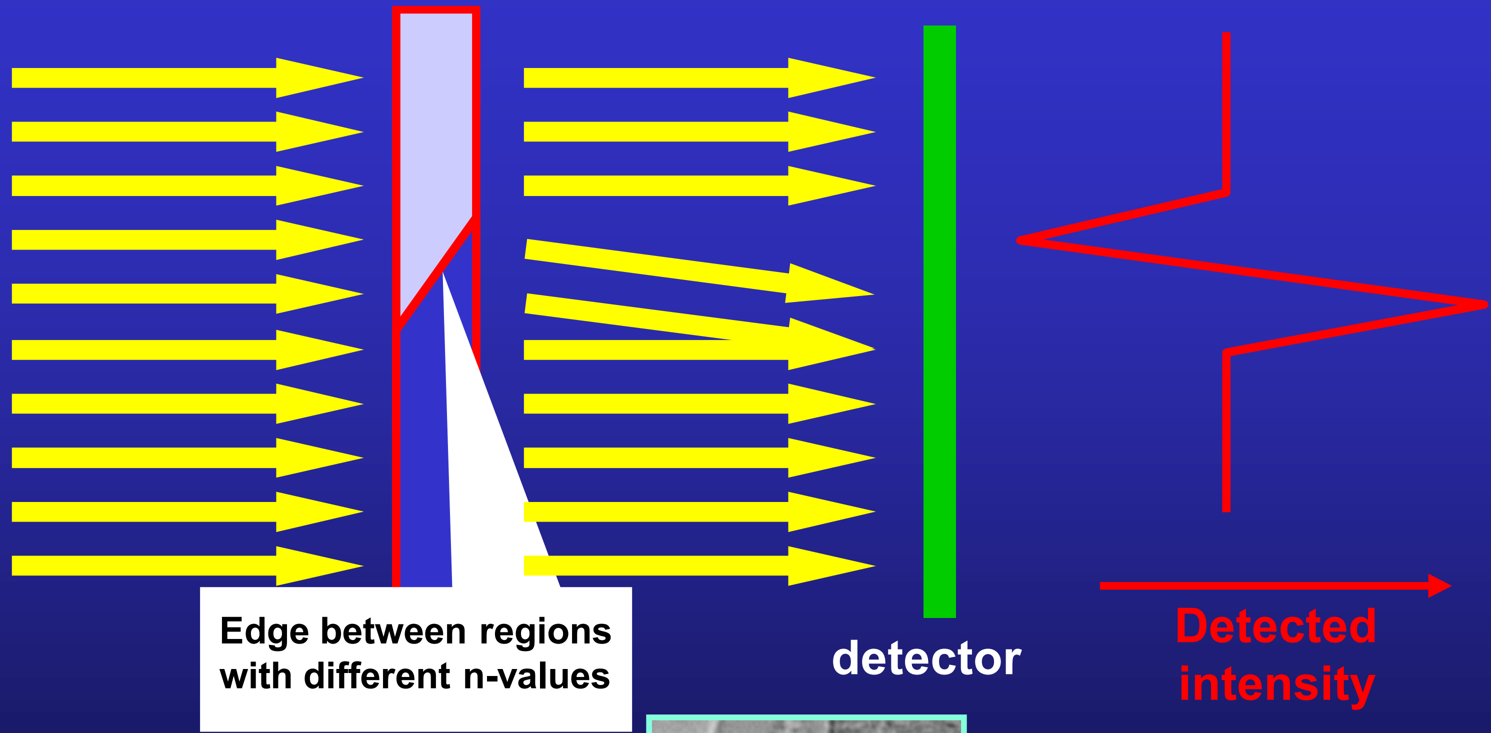
Refraction (and diffraction/interference) -- described by the refractive index n

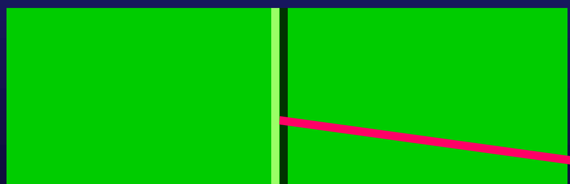
For over one century, radiology was based on absorption: why not on refraction /diffraction?

Conventional radiology

Refractive-index radiology (Giuliana Tromba)

“Refraction” x-ray imaging:





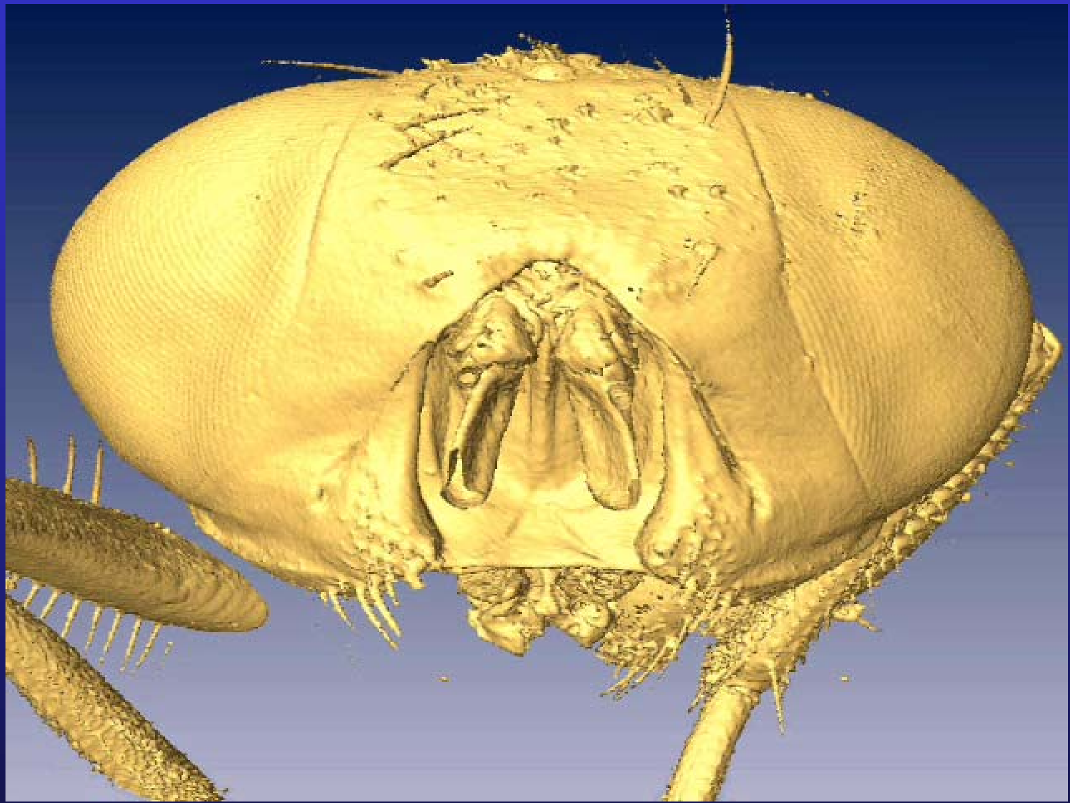
Idealized edge image

Real
example
(frog egg)

Microradiology study of mutant drosophila fly evolution

[Charron, Vassalli et al.]

Phase contrast micro-tomography: housefly

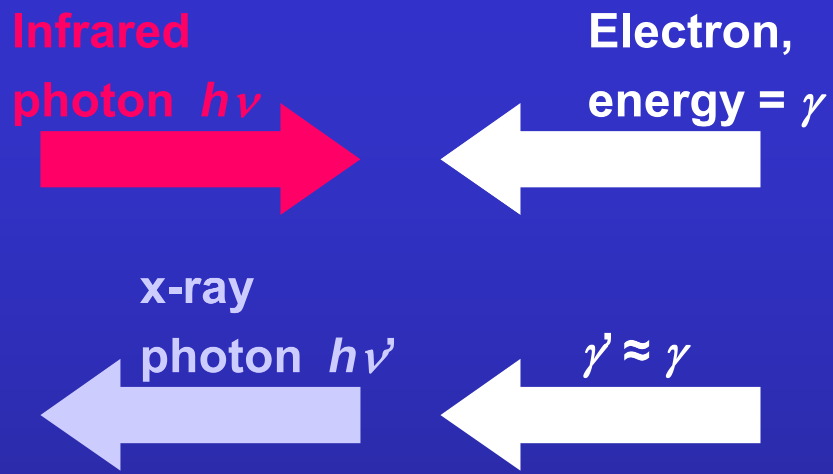


Yeukuang Hwu, Jung Ho Je et al.

New types of sources:

- Ultrabright storage rings (SLS, new Grenoble project) approaching the diffraction limit
- X-ray free electron lasers
- VUV FEL's (such as CLIO)
- Energy-recovery machines
- Inverse-Compton-scattering table-top sources

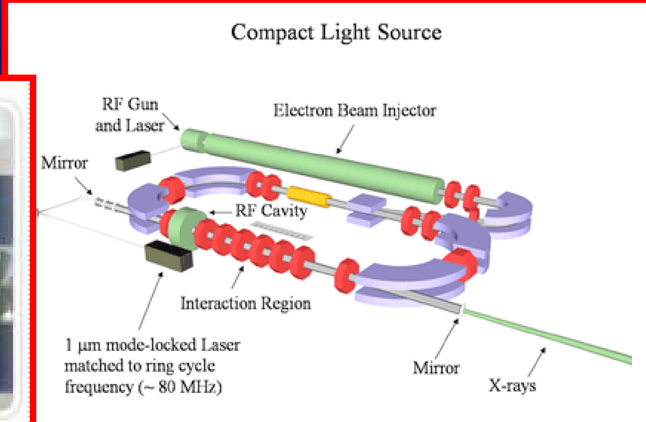
The magic of Compton backscattering: changing infrared into x-rays



Doppler effect: in the electron beam frame, the photon energy ≈ $2\gamma h\nu$. This is also the energy of the backscattered photon in the electron-beam frame.

In the laboratory frame, there is again a Doppler shift with a 2γ factor, thus:

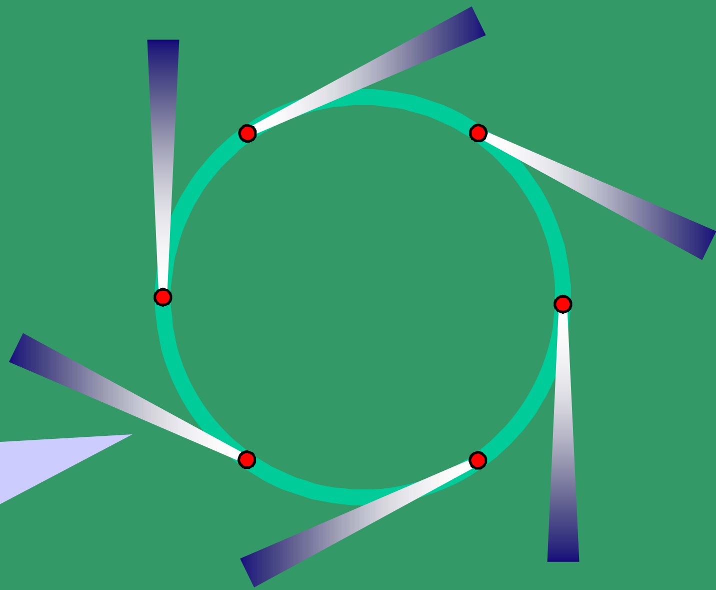
$$H\nu' \approx 4\gamma^2 h\nu$$

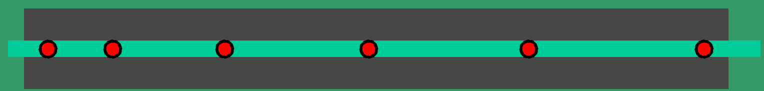


Energy-recovery LINAC sources

The brightness depends on the geometry of the source, i.e., of the electron beam

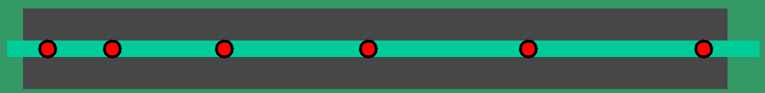
In a storage ring, the electrons continuously emit photons. This “warms up” the electron beam and negatively affects its geometry





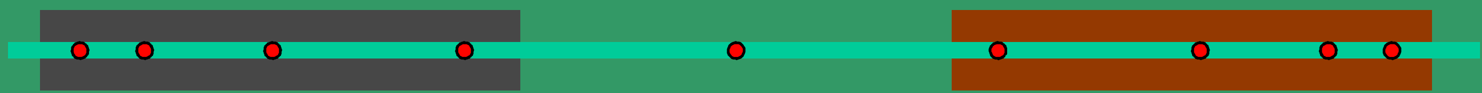
Controlling the electron beam geometry is much easier in a linear accelerator (LINAC). Thus, LINAC sources can reach higher brightness levels

Energy-recovery LINAC sources



However, contrary to the electrons in a storage ring, the electrons in a LINAC produce photons only once: the power cost is too high

Solution: recovering energy



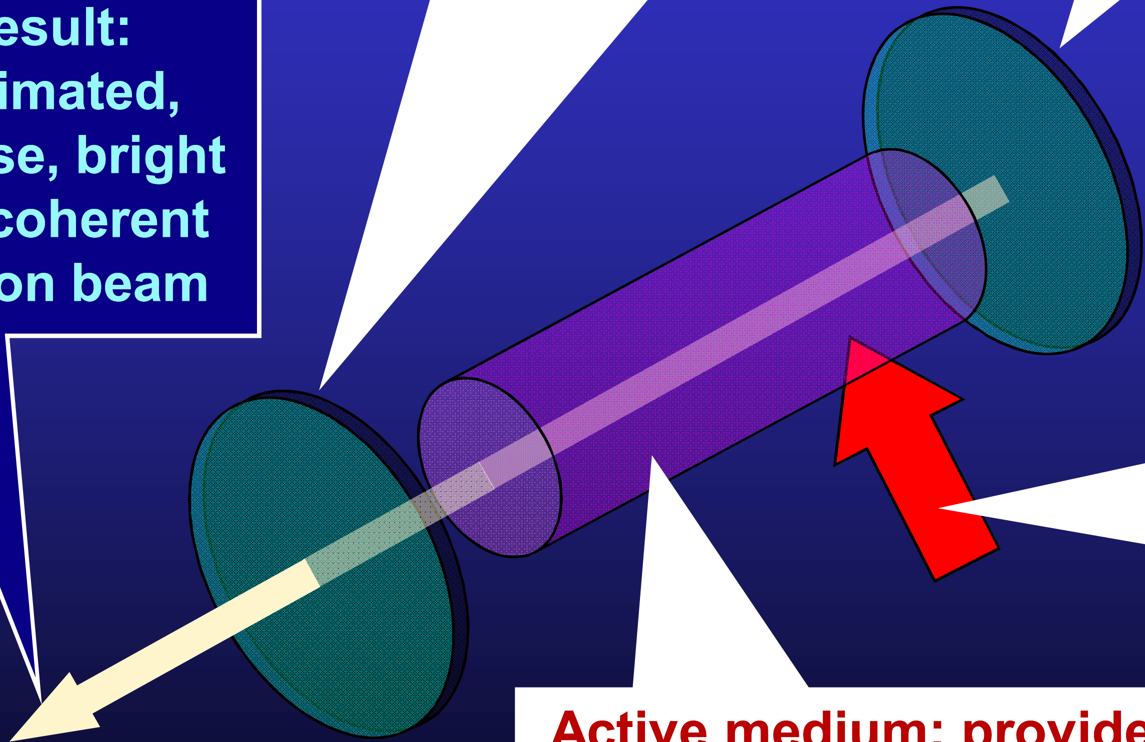
Accelerating section

Energy-recovery section

The ingredients of a normal lasers:

Optical cavity: increases the photon beam path and the optical amplification

Result: collimated, intense, bright and coherent photon beam



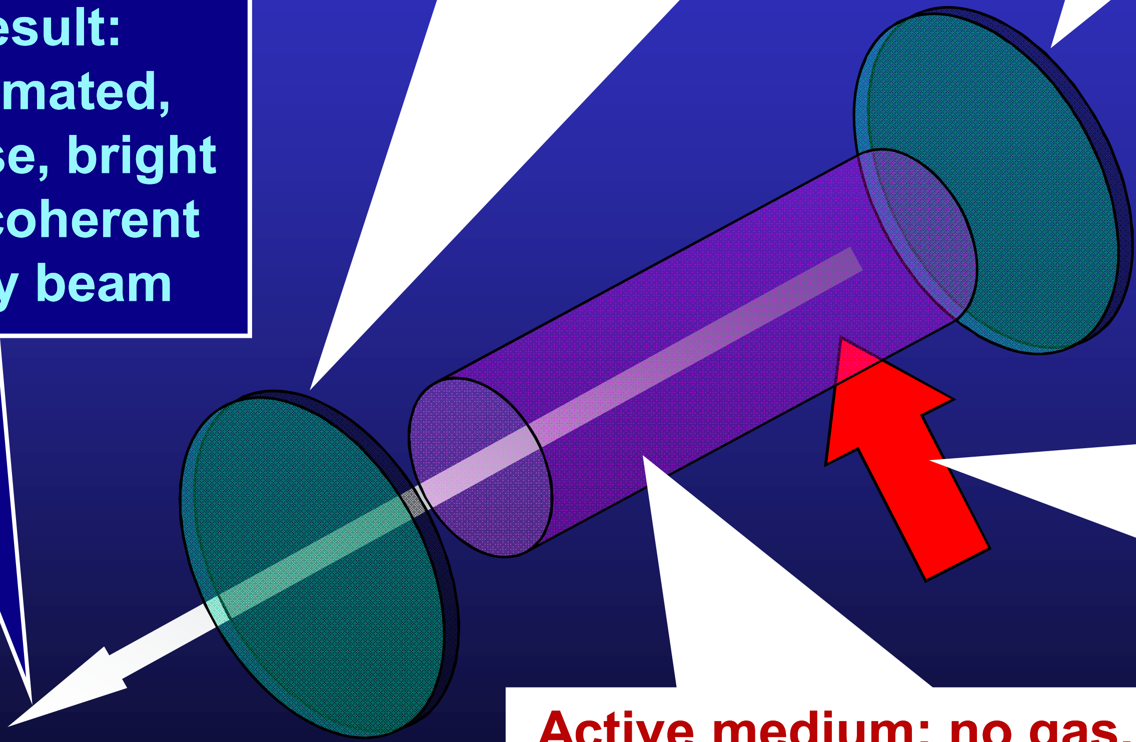
Optical pump: puts in the active medium the energy to be converted into photons

Active medium: provides the “optical amplification” of the photon beam

Normal lasers ⇒ x-ray laser:

No x-ray mirrors ⇒ no optical cavity ⇒ enough amplification needed for <u>one-pass</u> lasing

Result: collimated, intense, bright and coherent x-ray beam

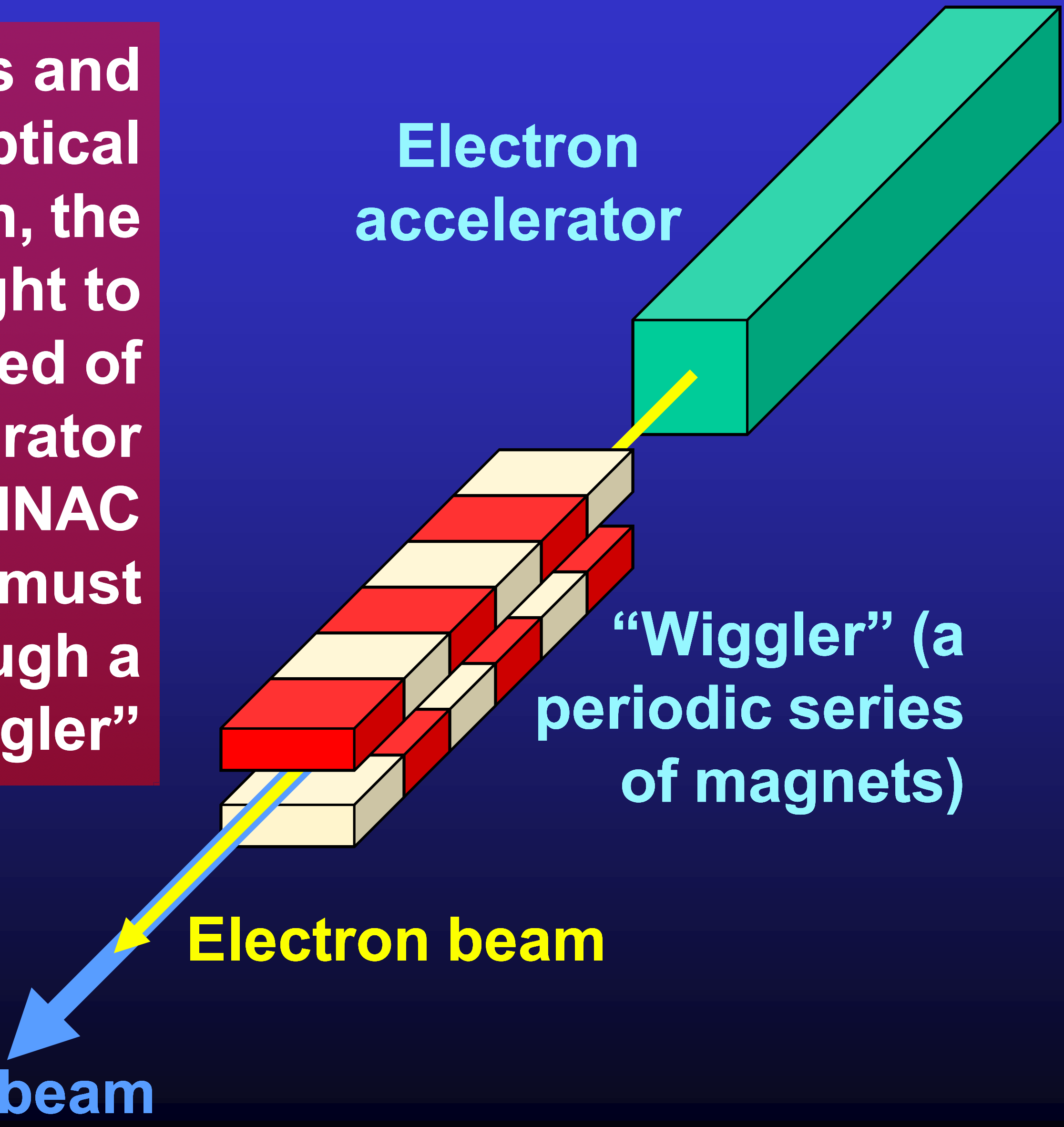


Optical pump: the free electrons provide the energy and transfer it to the photons

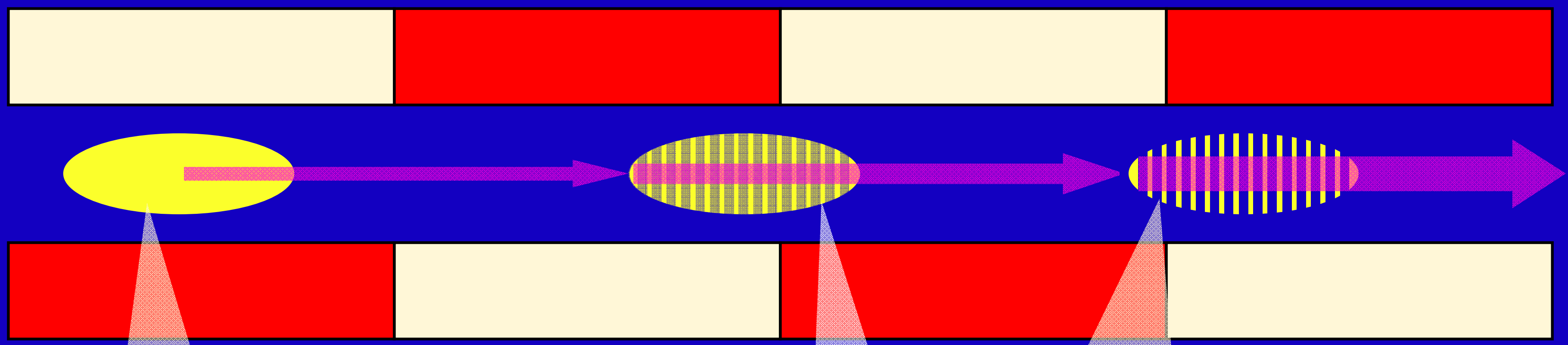
Active medium: no gas, solid or liquid but "free electrons" in an accelerator: hight power possible without damage

Free-electron lasers (FEL's):

To emit photons and produce optical amplification, the electrons brought to (almost) the speed of light by an accelerator (for example, a LINAC or a storage ring) must pass through a "Wiggler"



This is what happens in detail:

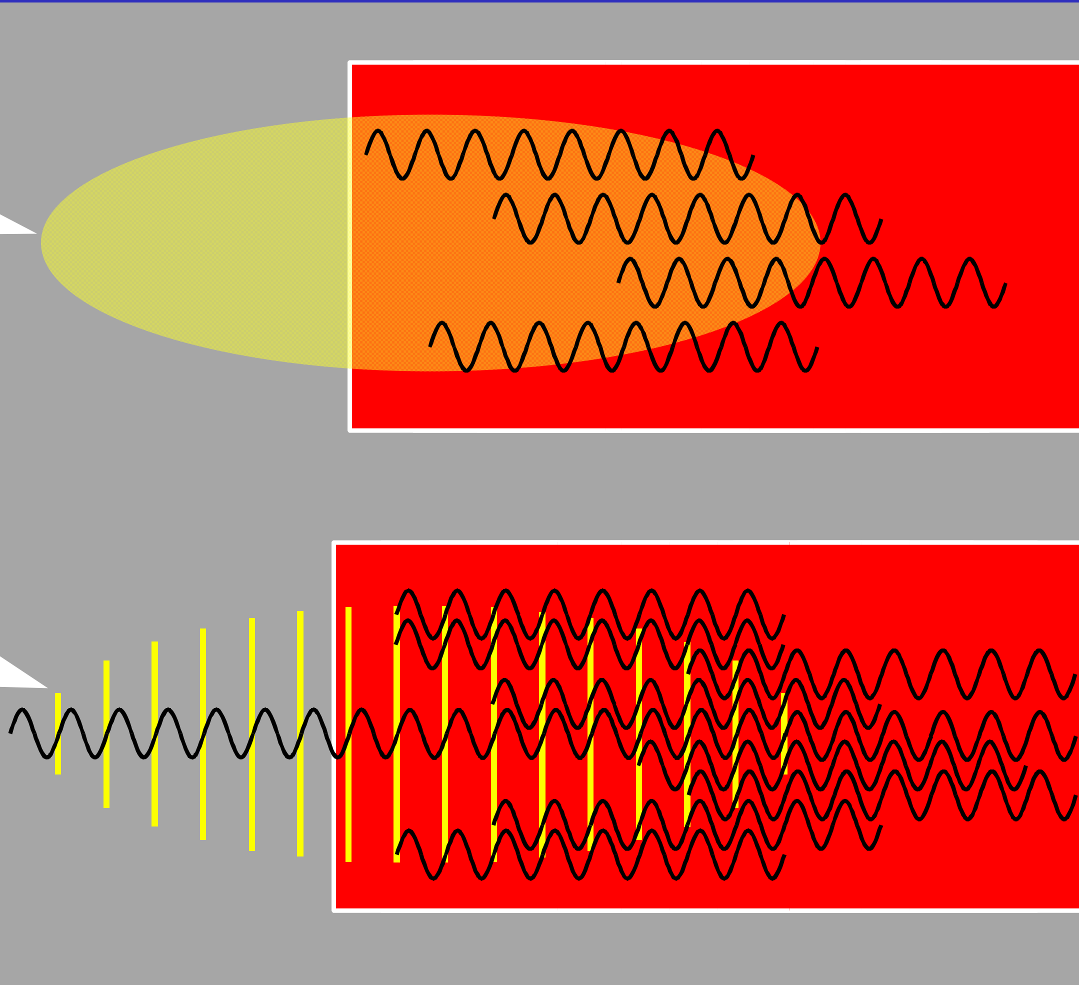


A bunch of electrons enters the wiggler: some of them stochastically start emitting waves

The combined wiggler+wave action progressively microbunches the electrons. The emission of microbunched electrons enhances the previously emitted waves

Microbunching makes the difference: this is what happens from the electron point of view:

With no microbunching, as electrons enter the **wiggler**, they emit in an uncorrelated way



Instead, the electrons in the wiggler-induced microbunches emit in a correlated way, enhancing previously emitted waves

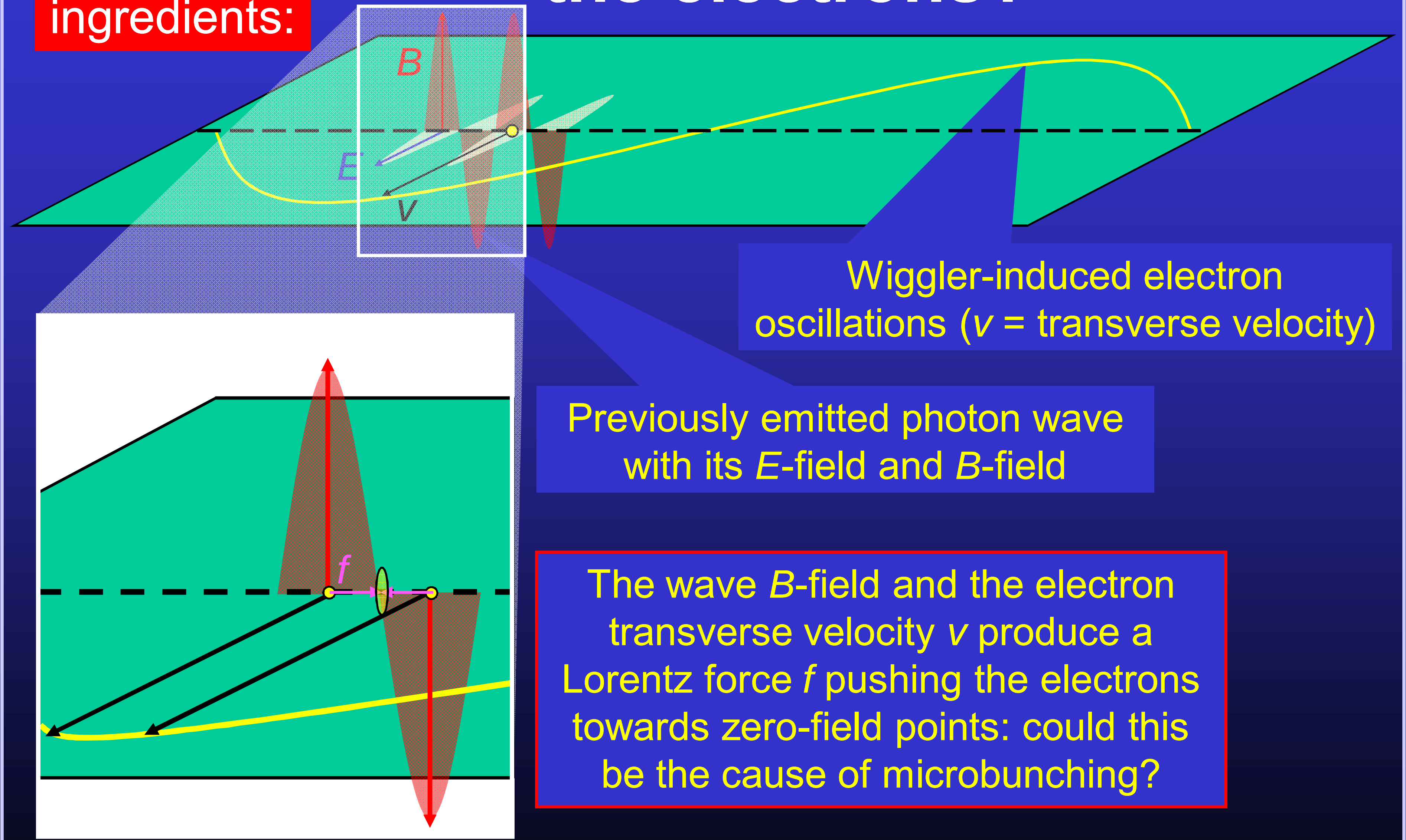
In summary, the wiggler induces transverse electron oscillations that:

1. Accelerate the electron charges enabling them to emit photon waves
2. Cooperate with previously emitted waves in microbunching the electrons

Note: without microbunching, the wave intensity is proportional to the number of electrons, N. With microbunching, the electrons in each microbunch emit in a correlated way: the wave amplitude is proportional to N. The wave intensity is proportional to the square of the amplitude and therefore proportional to N^2.

What microbunches the electrons?

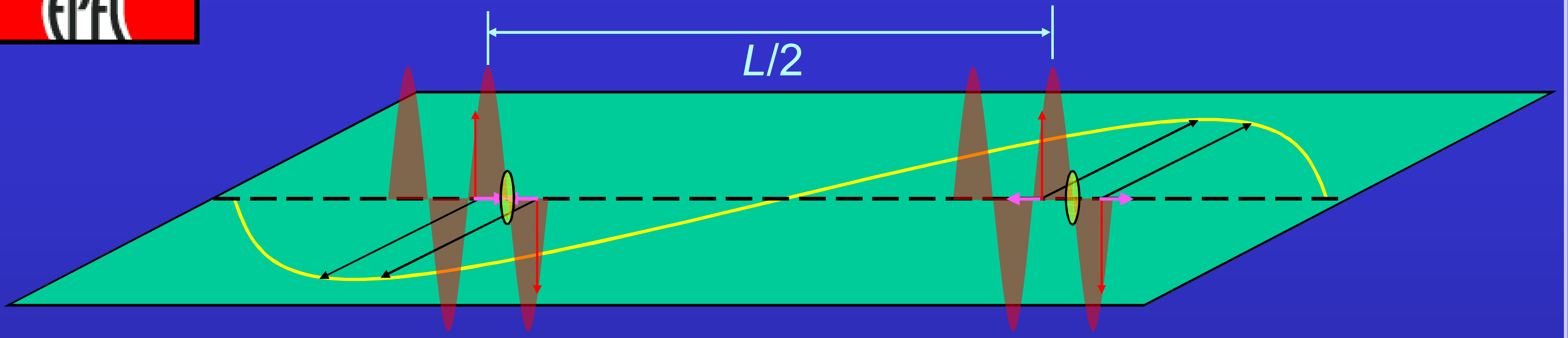
Two key ingredients:



Wiggler-induced electron oscillations (*v* = transverse velocity)

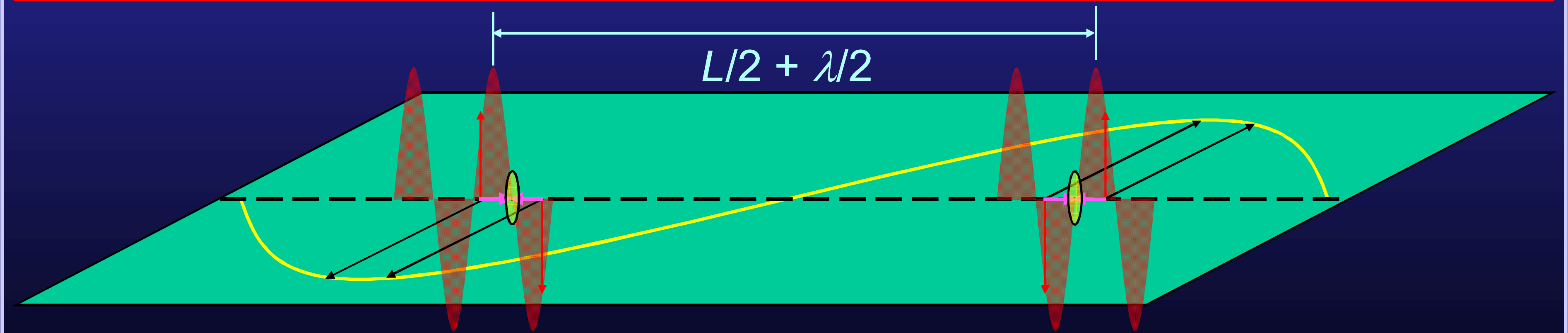
Previously emitted photon wave with its *E*-field and *B*-field

The wave *B*-field and the electron transverse velocity *v* produce a Lorentz force *f* pushing the electrons towards zero-field points: could this be the cause of microbunching?



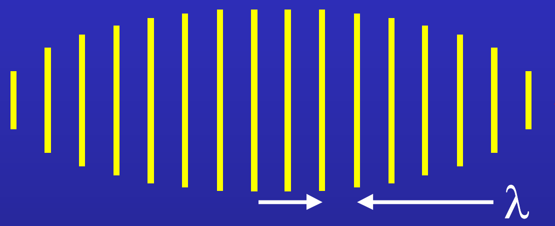
…but something seems wrong: after 1/2 wiggler period, the electron transverse velocity is reversed. If the wave travels together with the electron, the *B*-field stays the same. Are the forces and the microbunching reversed?

No! Electron and wave <u>do not</u> travel together: the electron speed is $u < c$. As the electron travels over $L/2$ in a time $L/(2u)$, the wave travels over $[L/(2u)]c$. The difference is $(L/2)(c/u - 1) \approx L/(4\gamma^2)$ = <u>half wavelength</u>



B-fields, velocities are reversed: the forces are not, and keep microbunching

Why is microbunching (and lasing) more difficut for x-rays than for longer wavelengths?

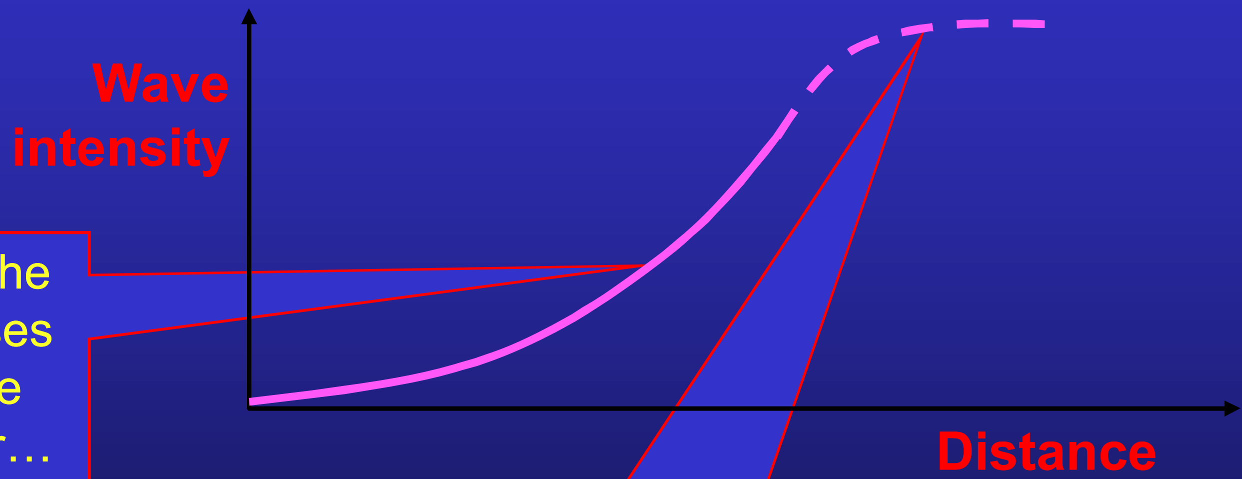


On one hand, at short wavelengths the microbunches are closer to each other and this facilitates microbunching

But:

- **Short x-ray wavelengths require a high electron energy corresponding to a large γ - factor**
- **The large γ makes the electrons "heavy" and therefore difficult to move towards microbunches: their transverse relativistic mass is γm_o and the longitudinal relativistic mass (directly active in the microbunching mechanism) is $\gamma^3 m_o$**
- **This offsets the advantage of closer microbunches, making microbunching difficult**

Microbunching produces correlated emission and gain in the wave intensity



Because of the gain, the wave intensity increases exponentially with the distance in the wiggler…

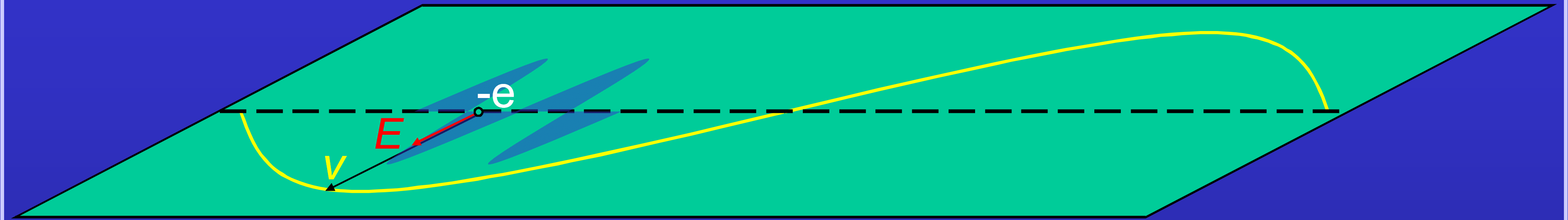
…until maximum microbunching is reached and the gain saturates

For an x-ray FEL (no 2-mirror cavity), gain saturation must be reached before the end of the (very long) wiggler, in a single pass

Why the exponential intensity increase?

- The total energy transfer rate from the electron beam to a pre-existing wave of intensity *I* is determined by two factors: (1) the transfer rate for each single electron (2) the effects of microbunchig
- The one-electron transfer rate is given by the (negative work) proportional to *E v* , where *E* = the wave (transverse) E-field and *v* = the electron transverse velocity.
- But *E* is proportional to $I^{1/2}$ so the energy transfer rate for one electron is proportional to $I^{1/2}$
- The effects of microbunching are proportional to the Lorentz force that causes it, which is produced by v_T and by the B-field *B* of the pre-existing wave. Since B is proportional to $I^{1/2}$, they give another factor $I^{1/2}$
- Overall, dI/dt is proportional to $I^{1/2} I^{1/2} = I$
- This corresponds to an exponential increase as a function of *t* and therefore also of the distance = *ut*

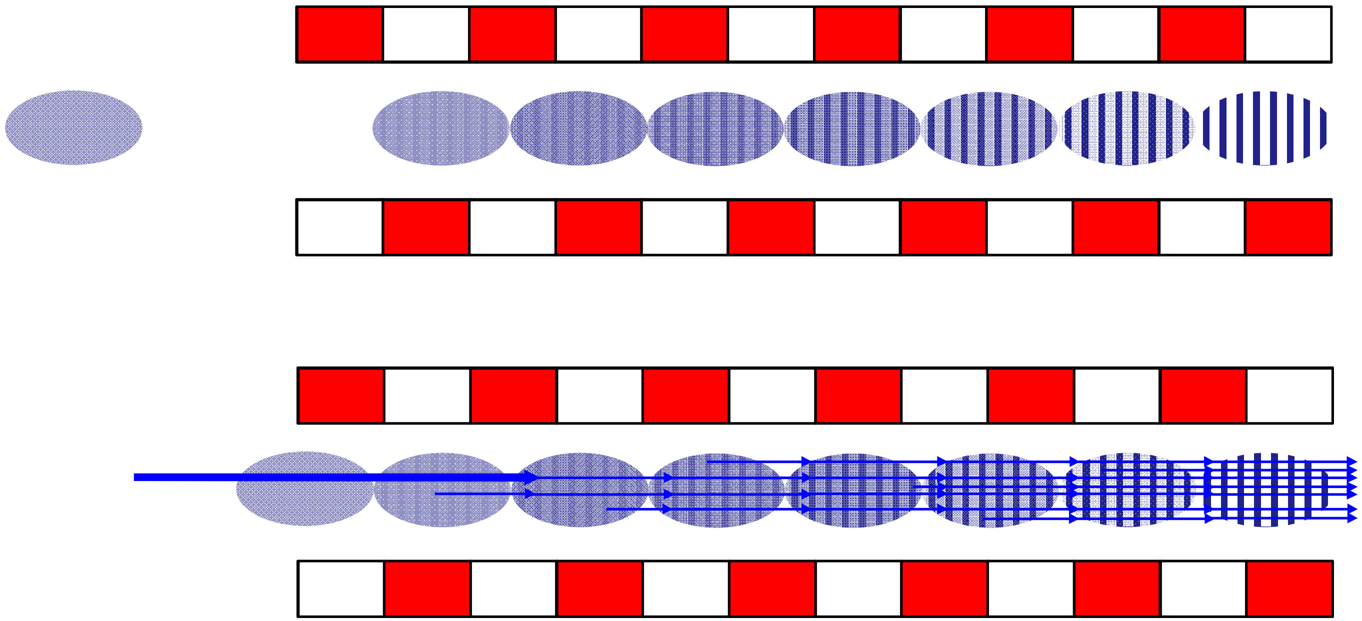
Why does the intensity increase saturate?



For the electron→wave energy transfer, the directions of the electron transverse velocity and of the wave E-field must produce negative work. In this case, the electron-wave phase differences fullfil that condition

- **But as the electron gives energy to the wave, it slows down and its phase changes.**
- **Eventually, the conditions are reversed leading to wave→ electron energy transfer**
- **This accelerates the electrons until the conditions are restored for electron→wave energy transfer**
- **The mechanism goes on and on, producing an energy oscillation between electrons and wave rather than a continuing increase of the wave intensity: hence, saturation**

FELs: summary view



An alternate strategy: seeding the FEL with a wave rather than relying only on the first emitted waves [in self-amplified spontaneous emission (SASE) FELs)]

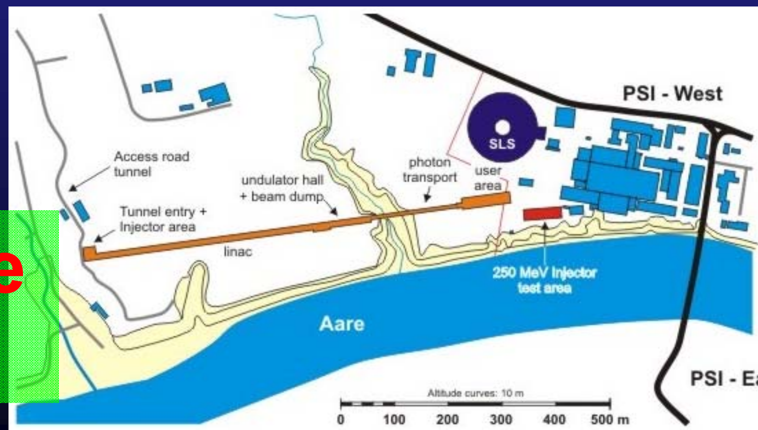
April 21, 2009 - New Era of Research Begins as World's First Hard X-ray Laser Achieves "First Light"

X-ray laser pulses of unprecedented energy and brilliance produced at SLAC

The FERMI X-FEL at Elettra, Trieste

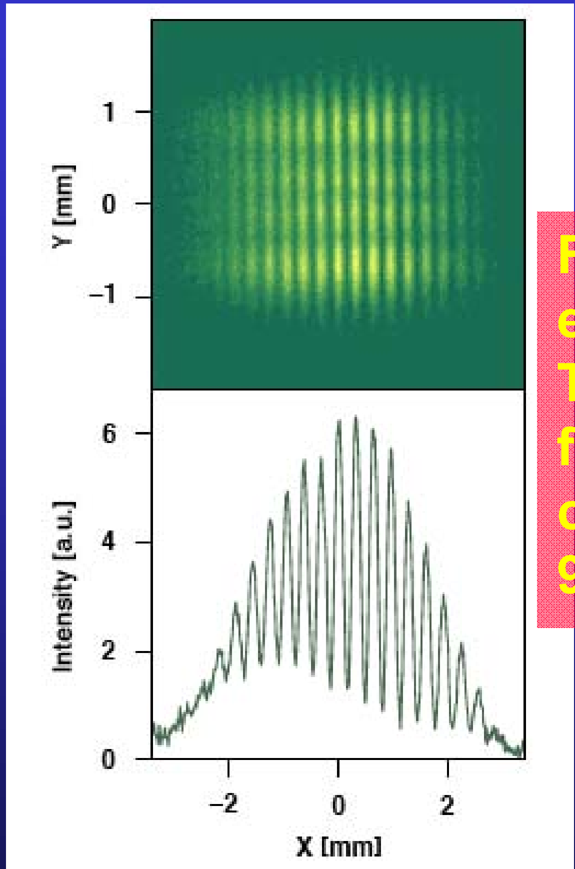
The European X-FEL project underway at DESY, Hamburg

The Swiss X-FEL at the Paul-Scherrer Institut



SASE-FEL coherence:

Full lateral (space) coherence all the way to the hard x-rays



First coherence experiments on the Tesla Test Facility: full lateral coherence at λ = 95 nm

Longitudinal (time) coherence: determined by the bandwidth/pulse structure -- can be improved, e.g., by seeding

Thanks:

- The EPFL colleagues (Marco Grioni, Davor Pavuna, Mike Abrecht, Amela Groso, Luca Perfetti, Eva Stefanekova, Slobodan Mitrovic, Dusan Vobornik, Helmuth Berger, Daniel Ariosa, Johanna Generosi, Vinko Gajdosic, Primoz Rebernik).
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- The Academia Sinica Taiwan colleagues (group of Yeukuang Hwu).
- The Vanderbilt colleagues (group of Norman Tolk).
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