Introduction to Synchrotron Radiation: History and Machine

Giorgio Margaritondo

Ecole Polytechnique Fédérale de Lausanne (EPFL)

This is how it started:

$$P(\nu) = \frac{\sqrt{3} e^3 B \sin\alpha}{mc^2} \left(\frac{\nu}{\nu_c}\right) \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta) d\eta$$

$$\nu_c = \frac{3}{2} \gamma^2 \nu_G \sin\alpha$$

Must synchrotron light be so mathematically complicated?

J. Synchrotron Rad. (1995). 2, 148–154

A Primer in Synchrotron Radiation: Everything You Wanted to Know about SEX (Synchrotron Emission of X-rays) but Were Afraid to Ask

G. Margaritondo

NO!!!
What matters is the underlying physics

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A simplified description of X-ray free-electron lasers

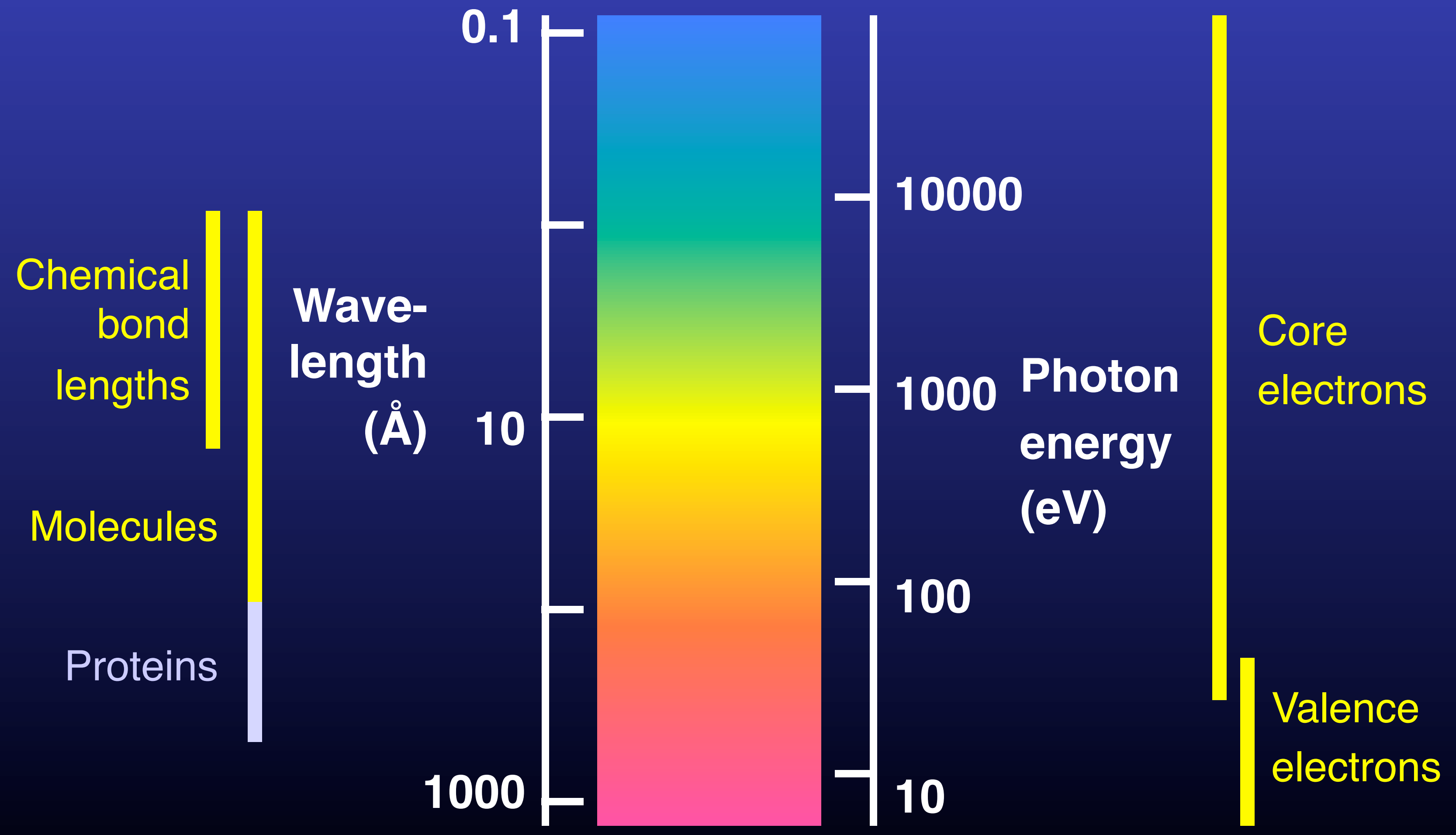
G. Margaritondo[a,*] and Primoz Rebernik Ribic[a]

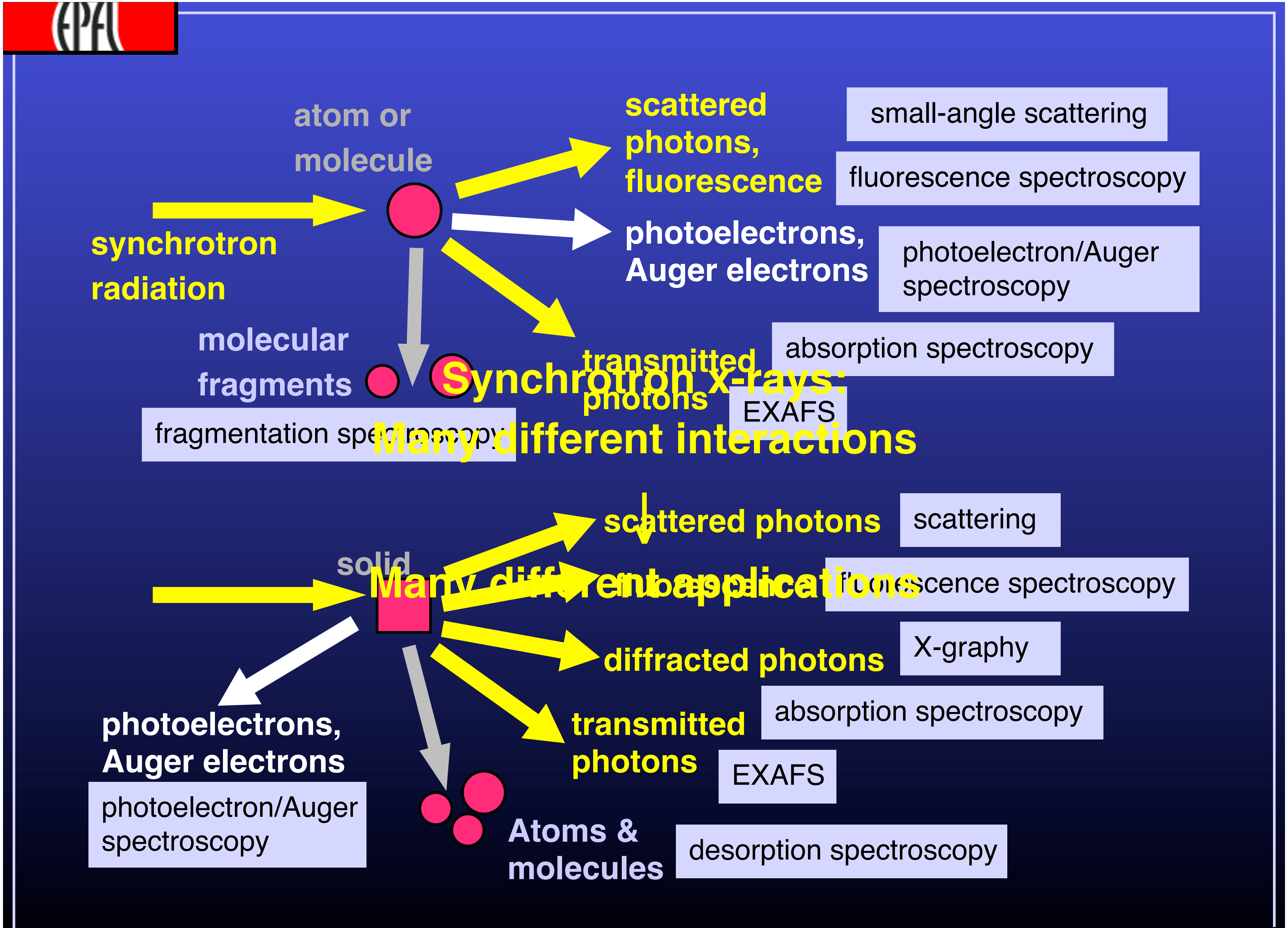
Outline:

- Motivation: why do we need x-rays?
- Building an excellent x-ray source :
  - 3.5 minute presentation
  - 9.5 minute presentation
- A short history of this field
- A more detailed description of synchrotron light
- Coherence: a revolution
- Free electron lasers and other new sources

Why x-rays and ultraviolet light?

To study something, it is better to use a probe with similar magnitude (size and energy)




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

SO, WE NEED X-RAYS AND SYNCHROTRONS GIVE THEM TO US: BUT HOW DO THEY WORK?

THE "RELAXATION PROGRAM":

START!

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

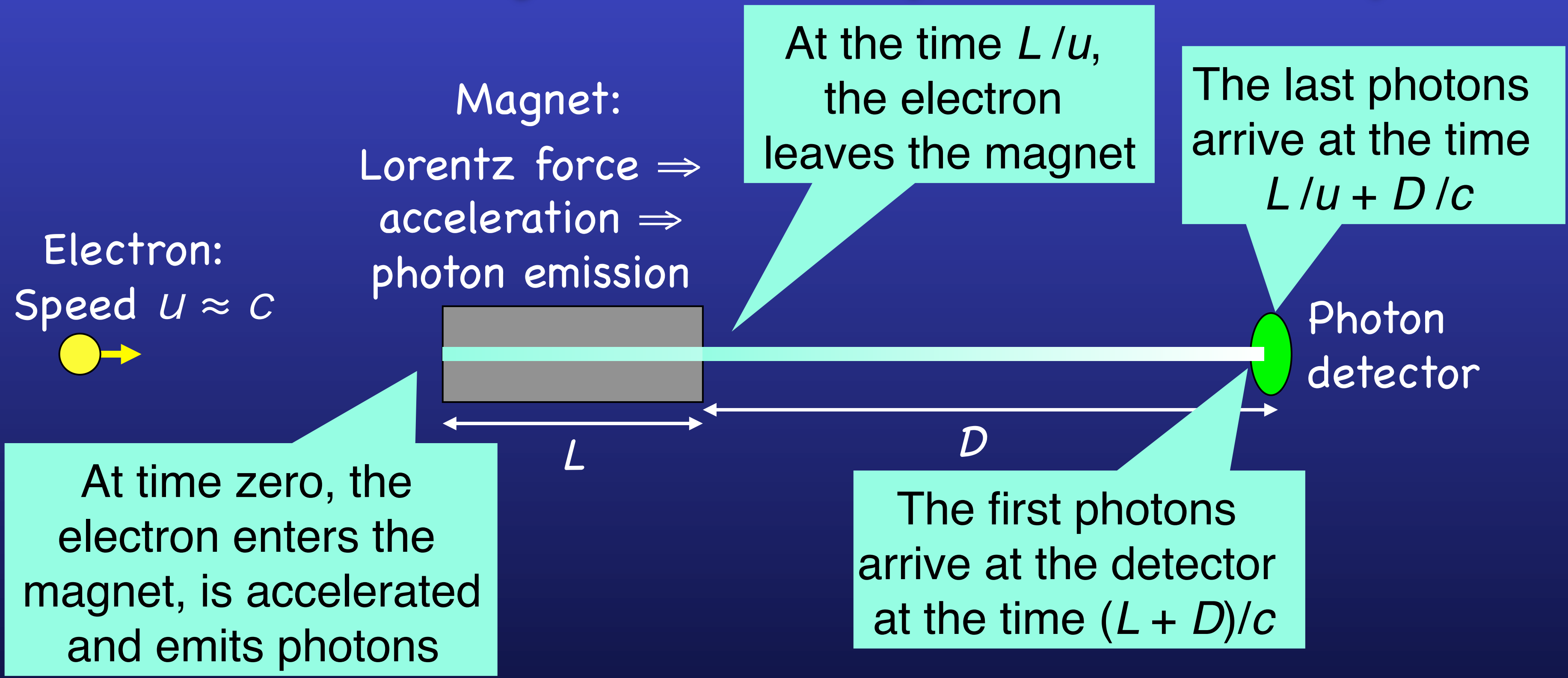
AFTER STEP A -- OPTIONS: (1) relax for the rest of the day, or (2) go to step B

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

AFTER STEP B -- OPTIONS: (1) relax for the rest of 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):



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

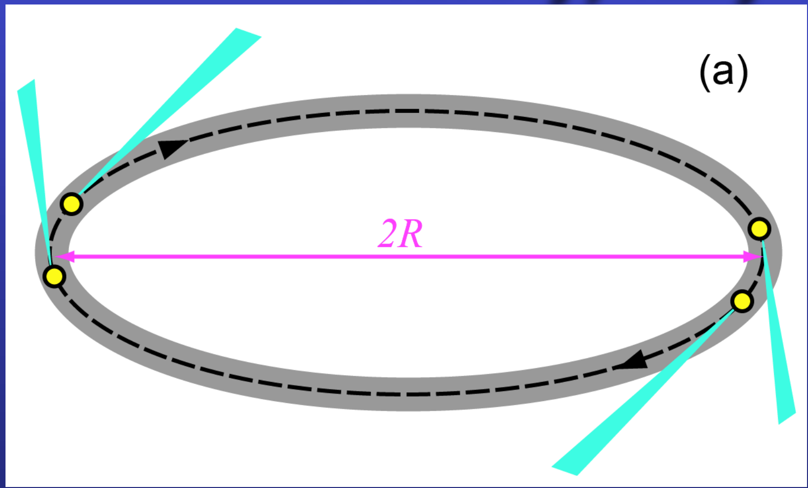
Characteristic frequency: $\nu = 1/\Delta t = u/[L(1 - u/c)] = u\,\gamma^2\,(1 + u/c)/L$

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!

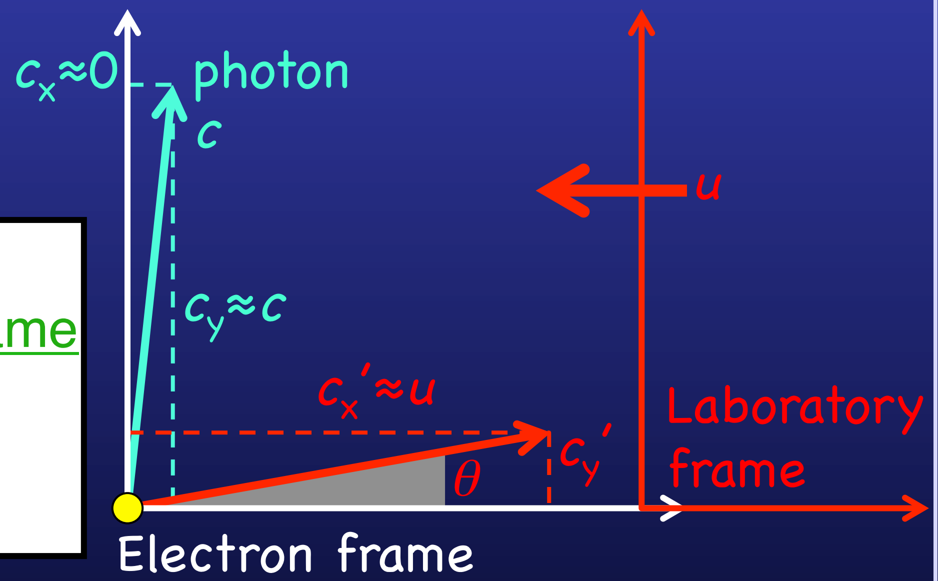
$\gamma^2 = 1/(1 - u^2/c^2)$

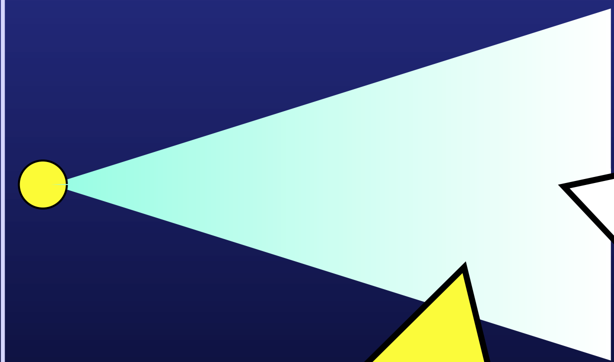
Synchrotron light in 9.5 minutes for (not entirely) lazy students (and teachers):



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





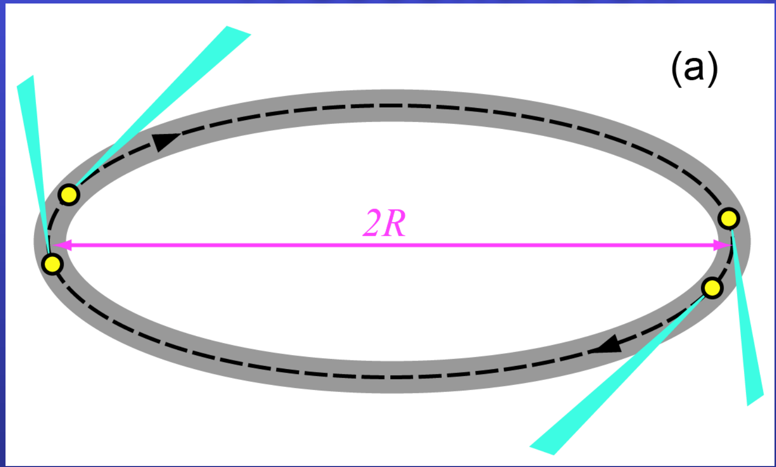
But in the laboratory frame the emission shrinks to a narrow cone

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

Take a photon emitted in a near-transverse direction in the electron frame. In the (green) laboratory frame its velocity components become $c_x' \approx u$ and c_y'. But c, the speed of light, cannot change, so $c_y' \approx (c^2 - u^2)^{1/2} = c\,(1 - u^2/c^2)^{1/2} = c/\gamma$.

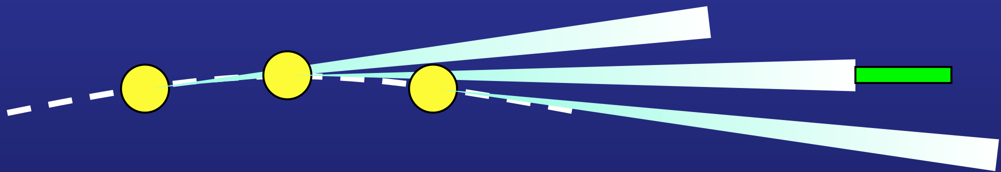
The angle θ' is $\approx c_y'/c = 1/\gamma$ -- very narrow!!!

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

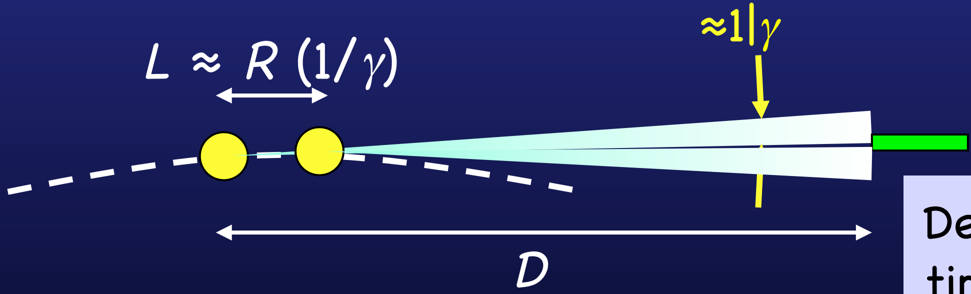


Seen from the side of the ring, each electron looks like an oscillating charge in an antenna, emitting photons with a frequency $2\pi R/c$ -- in the radio wave range.

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:

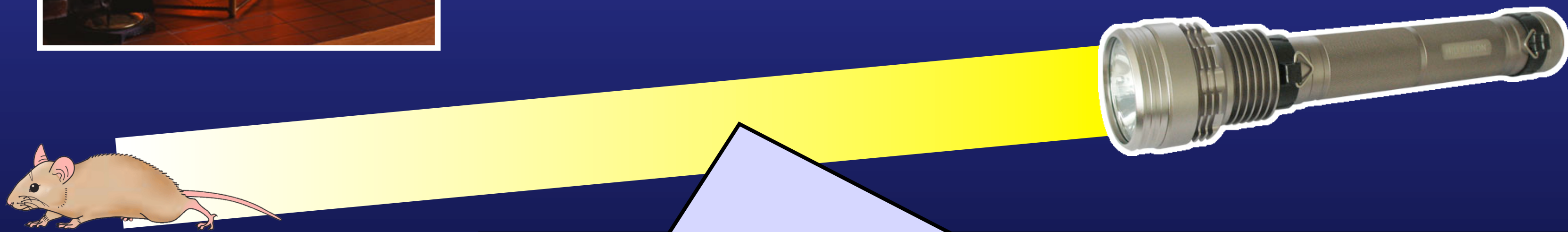
$\Delta t = L/u + (D - L)/c - D/c = L/u - L/c = (L/u)\,(1-u/c) = (L/u)\gamma^2/(1+u/c)$

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

So, synchrotrons emit x-rays: but why is this interesting? Consider fireplaces and torchlights:

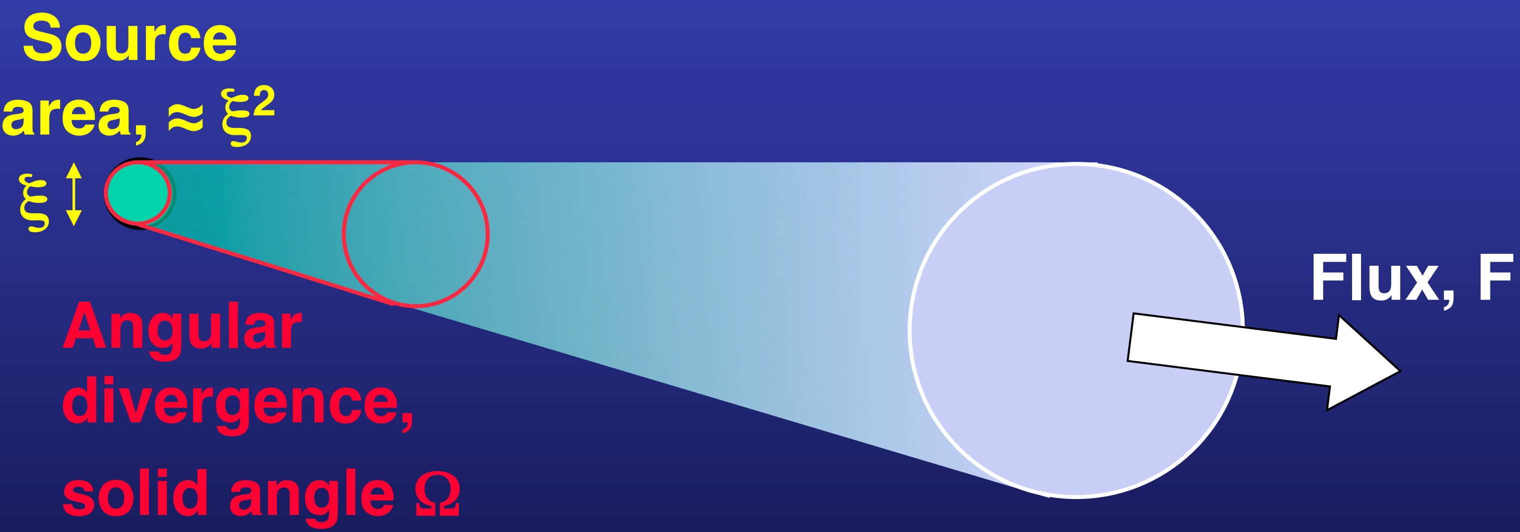
A fireplace is not very effective in "illuminating" a specific target: its emitted power is spread in all directions



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”

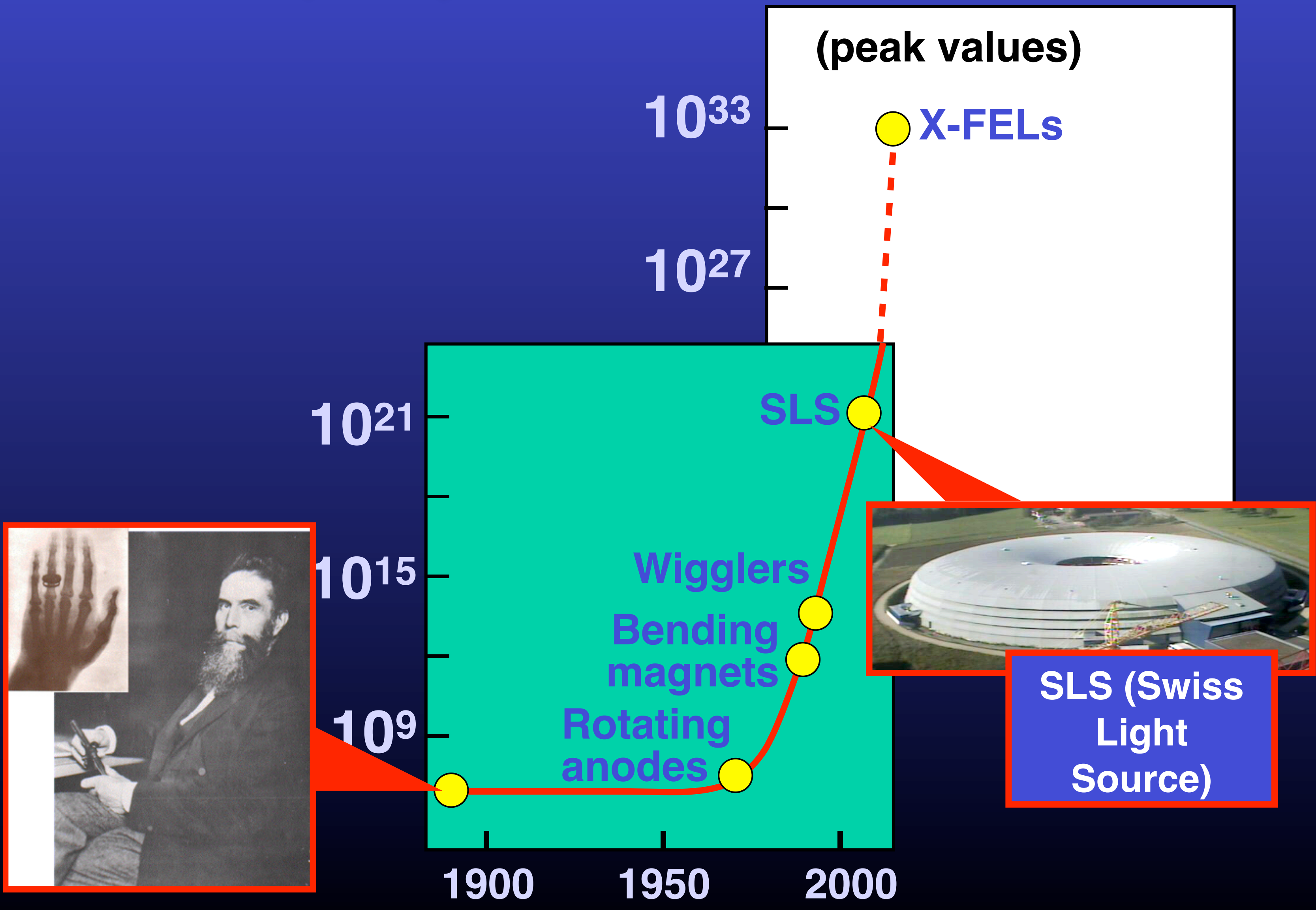
The "brightness" (or brilliance) of a source of light :



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

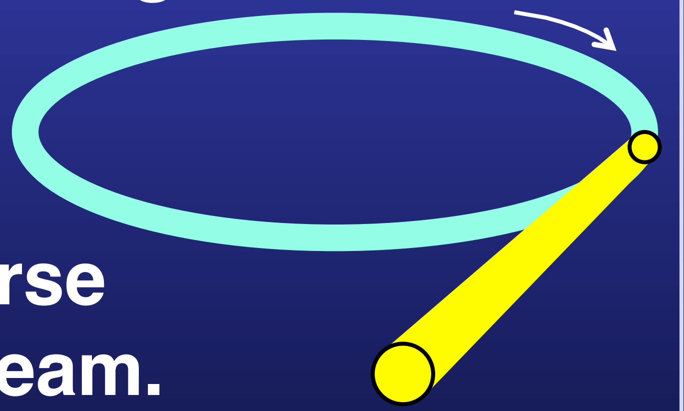
Historical growth in X-ray brightness

(units: photons/mm2/s/mrad2, 0.1% bandwidth)



What causes the high brightness of a synchrotron source? Three factors:

1. Electrons in vacuum can emit more power than electrons in a solid because the power does not damage their environment ⇒ high flux

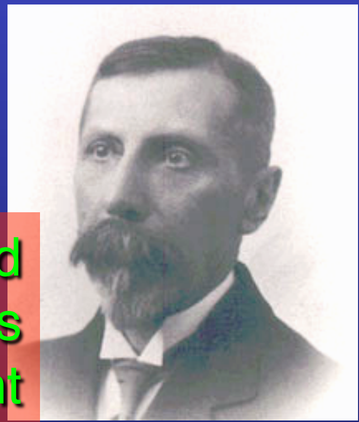


2. The source size is not that of a single electron but the transverse cross section of the electron beam. The sophisticated trajectory control system makes it very small

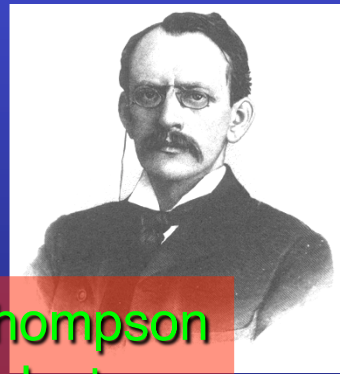
3. Relativity drastically reduces the angular divergence of the emission

An interesting history, a bright future:

The origins:



1898 -- Alfréd Lienard conceives synchrotron light

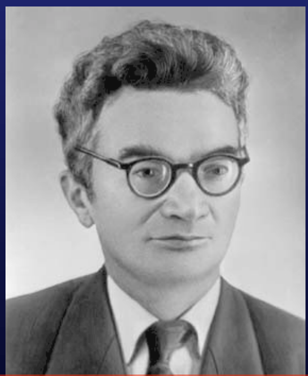


1897 -- J. J. Thompson discovers the electron

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

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

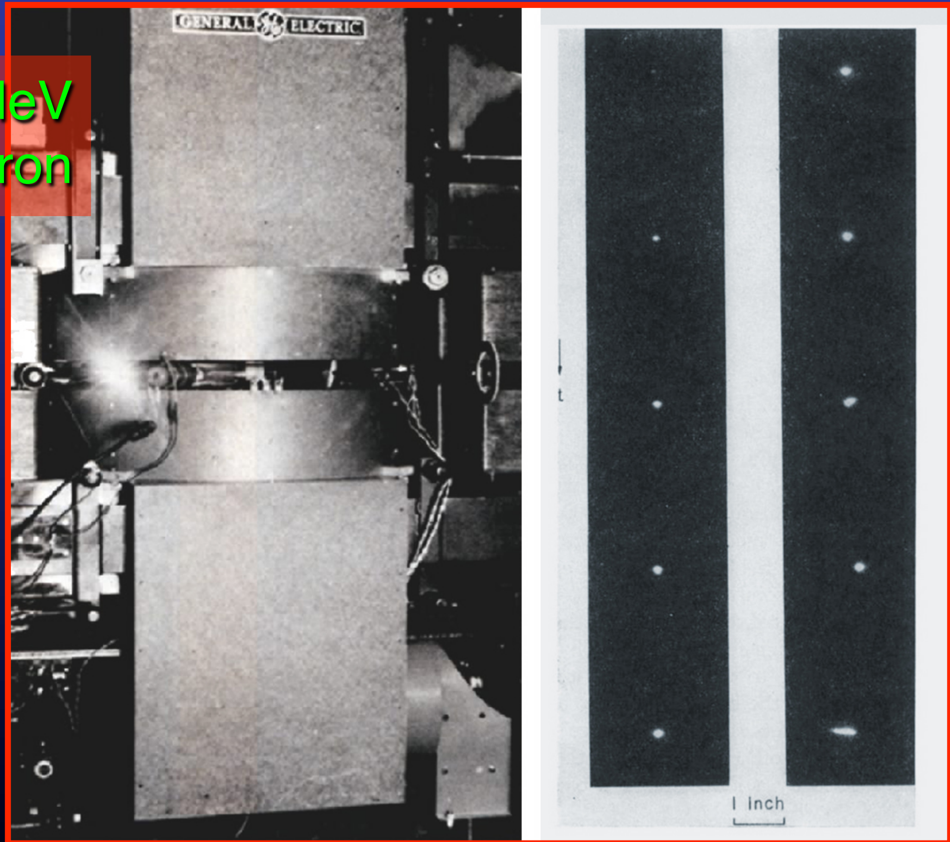
which amounts to roughly 30 kev for an electron of 1 Bev in a magnetic field of 10^4 gauss. The radiation spectrum consists of harmonics of the rotation angular frequency



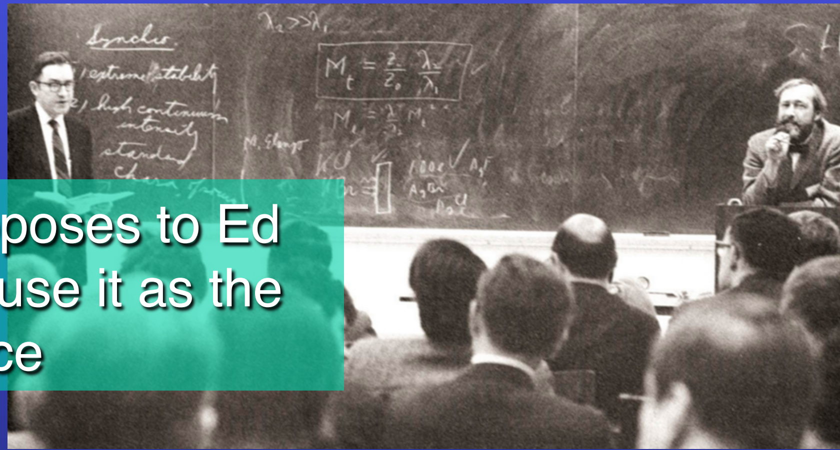
1940s: Isaak Pomeranchuk, Dmitri Ivanenko and Julian Schwinger develop a full theory

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

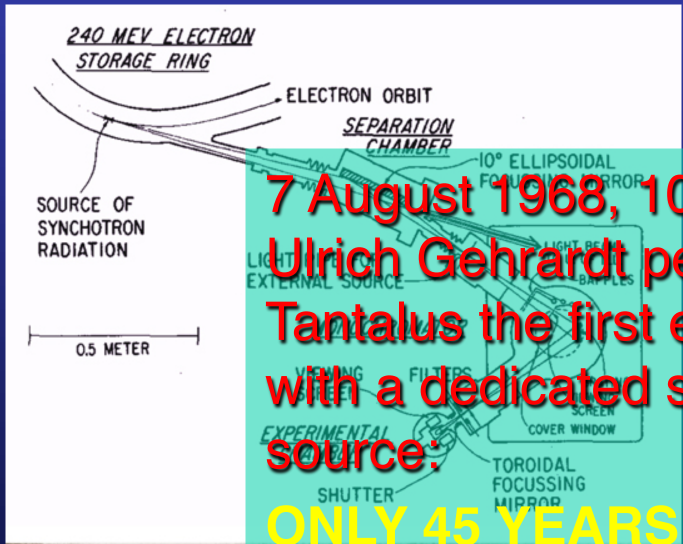
The GE 70 MeV synchrotron



"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 45 YEARS AGO!!!

Synchrotron Facilities in the World (2010):

67 in 25 Countries

(operating or under construction)

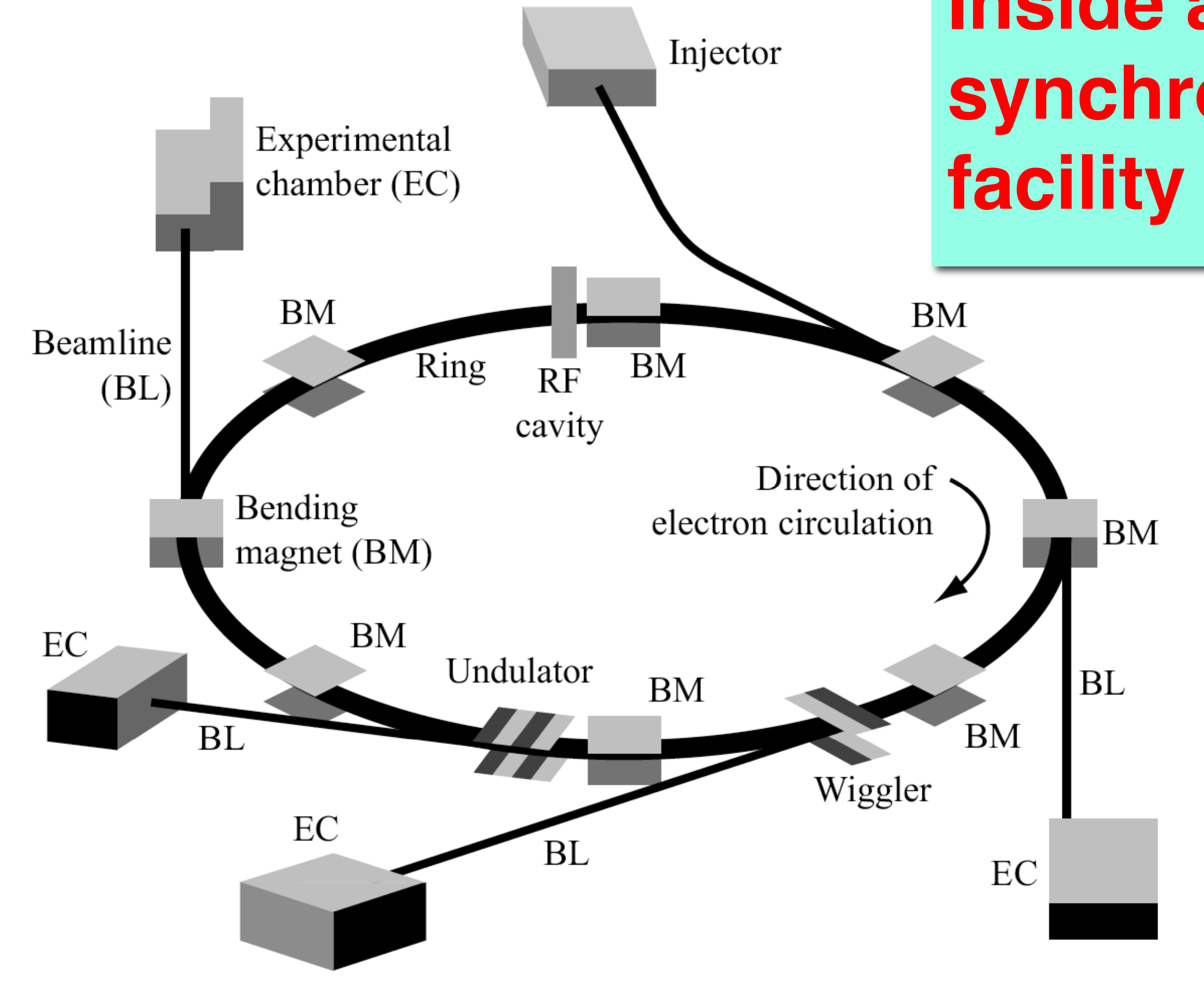
Historical Growth:

Worldwide ISI data 1970-2011, Keyword: “synchrotron”

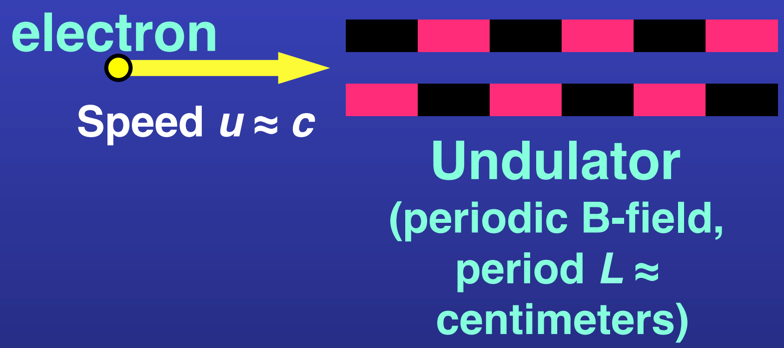
1970:	62 items
2000:	4,455 items
2011:	7,190 items
Overall:	108,096 items

Let's discover synchrotron light: this is a real facility -- Diamond (UK)

Inside a synchrotron facility



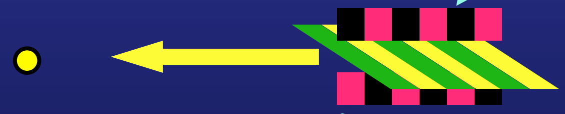
Objective: building a very bright x-ray source using an "undulator" and relativity



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:

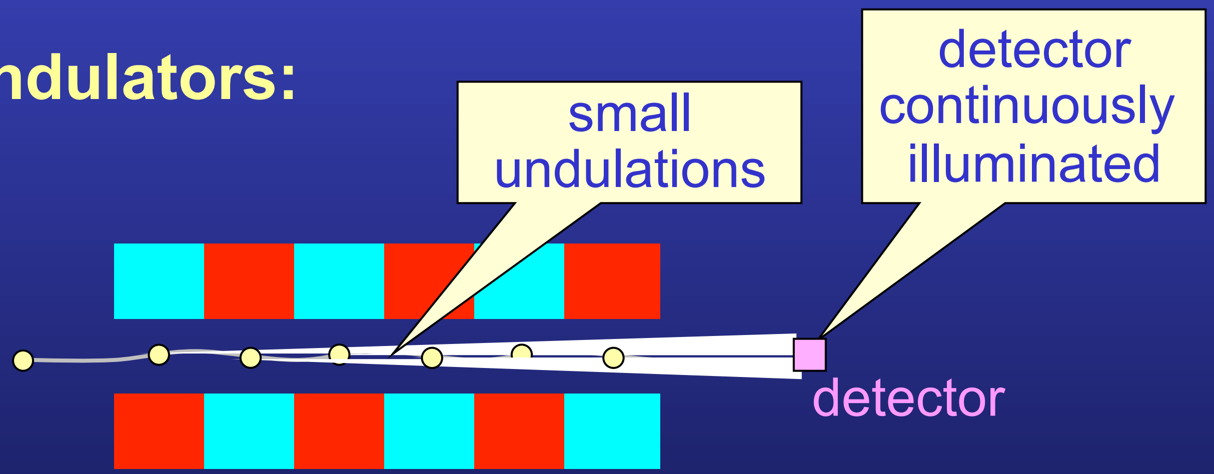


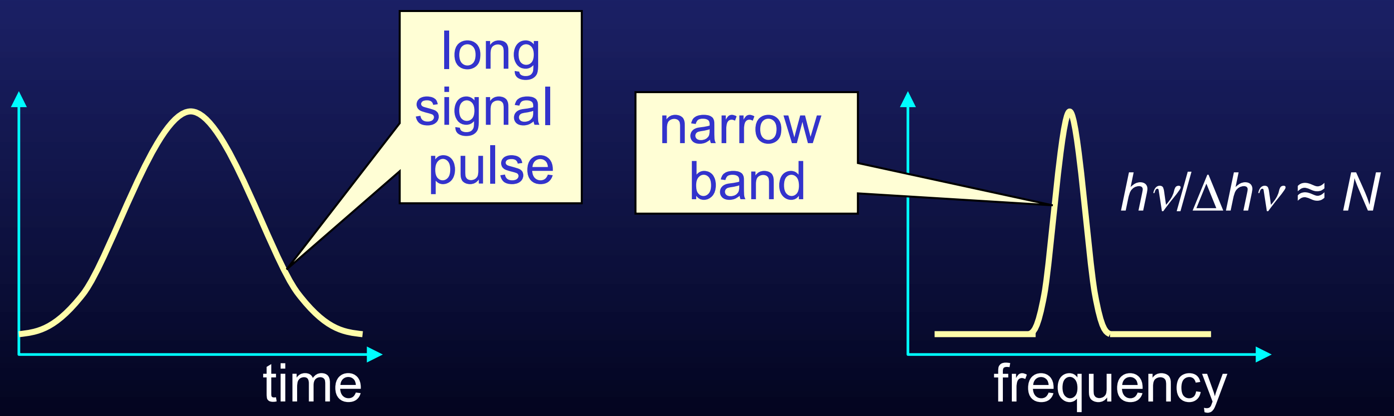
The periodic B-field is accompanied by a perpendicular periodic E-field. Moving at a speed ≈c towards the electron, the undulator looks like an electromagnetic wave with wavelength L/γ. <u>Synchrotron radiation is produced by the elastic scattering of this wave by the electron.</u>

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:

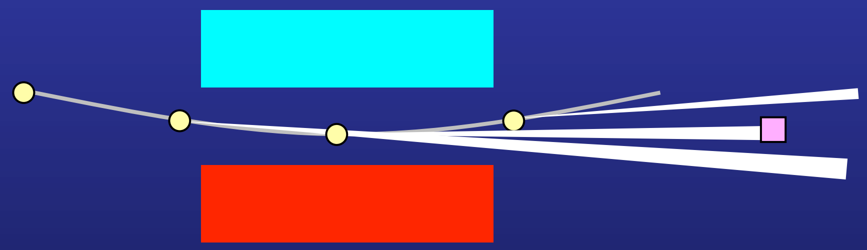
1. Undulators:

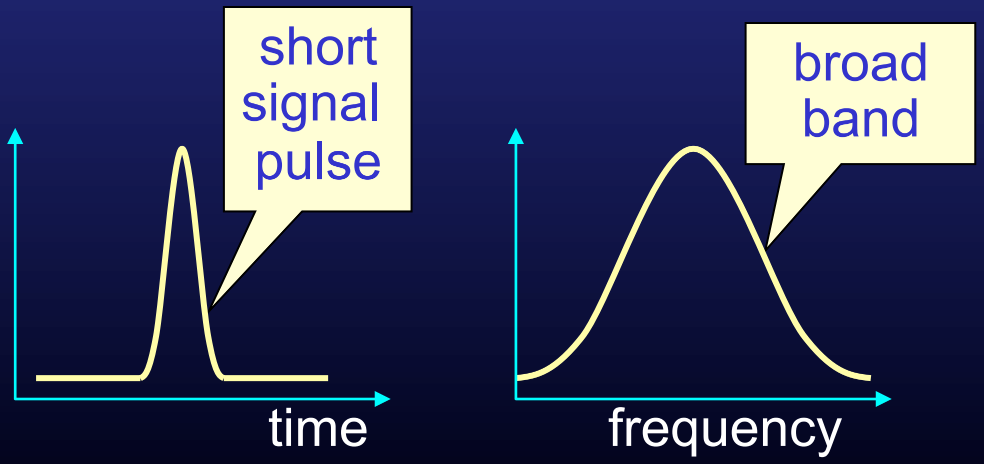




3 types of sources:

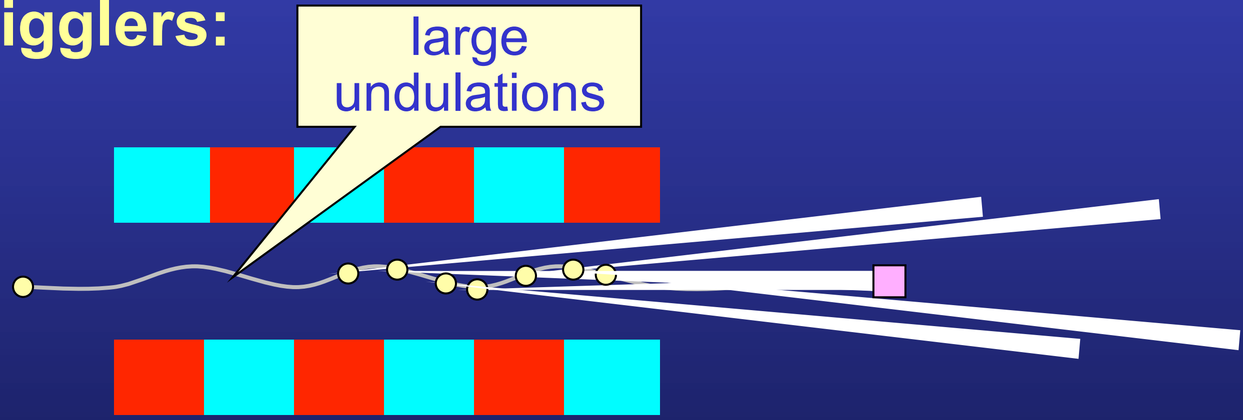
2. Bending magnets:

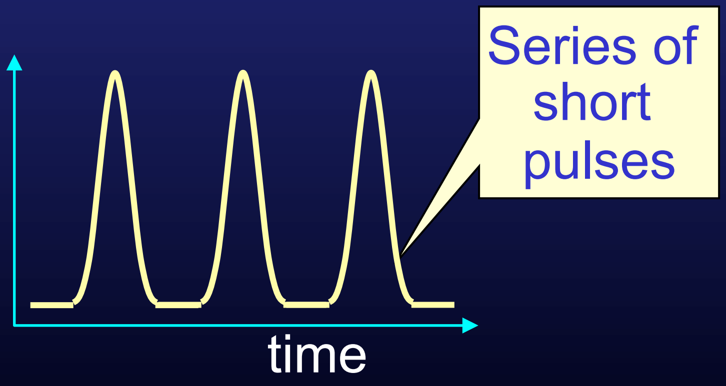


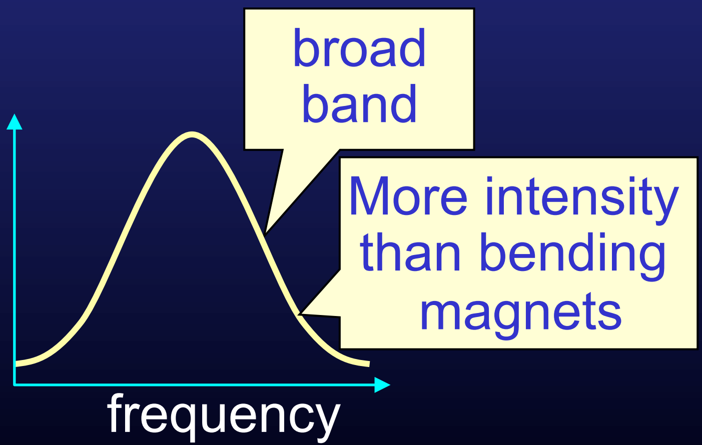


3 types of sources:

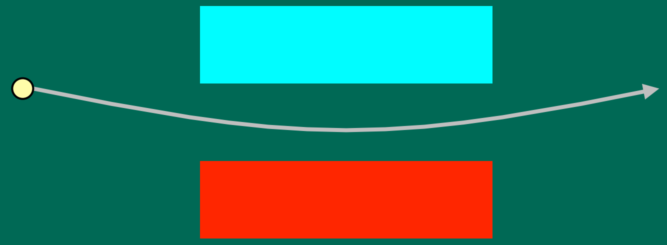
3. Wigglers:







Bending magnet emission spectrum:

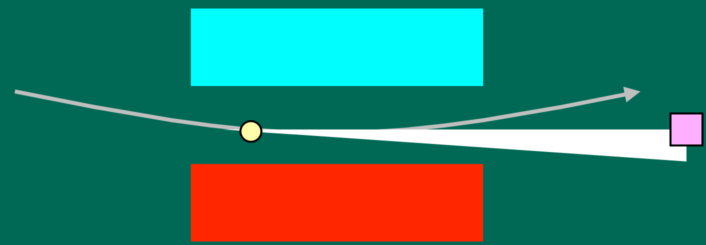


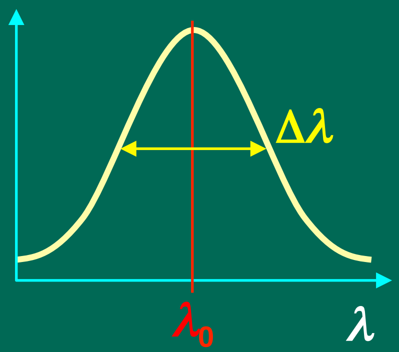
The (relativistic) rotation frequency of the electron determines the (Doppler-shifted) central wavelength:

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

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

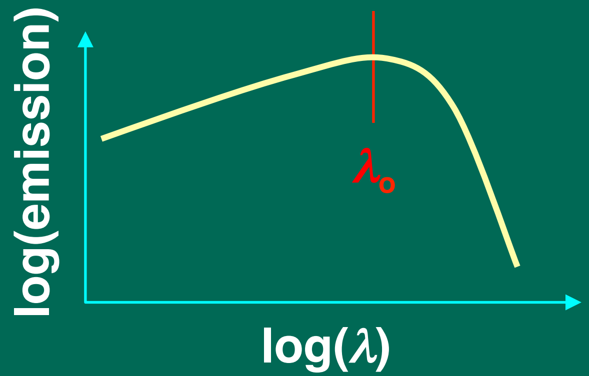
$\Delta\lambda / \lambda_o = 1$



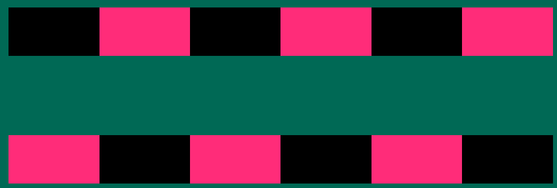


A peak centered at λ_c with width $\Delta\lambda$: is this really the well-known synchrotron spectrum?

YES -- see the log-log plot:



Undulator emission spectrum:

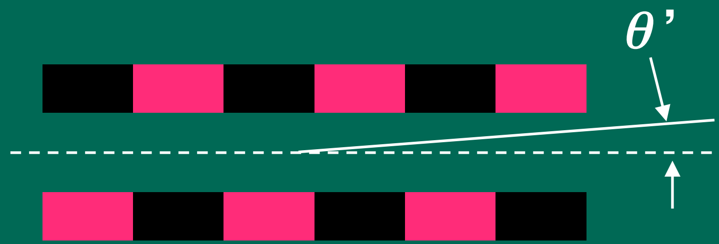


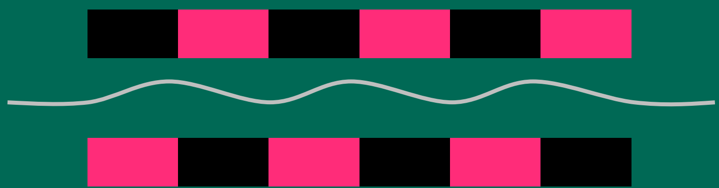
L = period

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



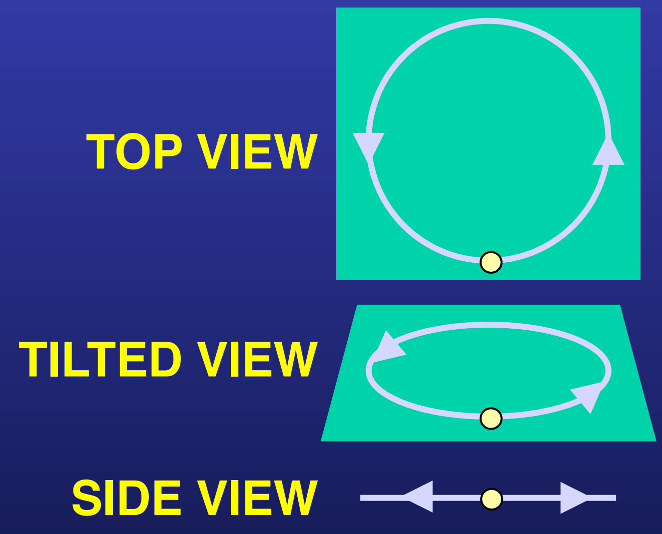


Second correction: stronger B-field means stronger undulations and less on-axis electron speed. This changes γ so that:

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

Synchrotron light polarization:

Electron in a storage ring:



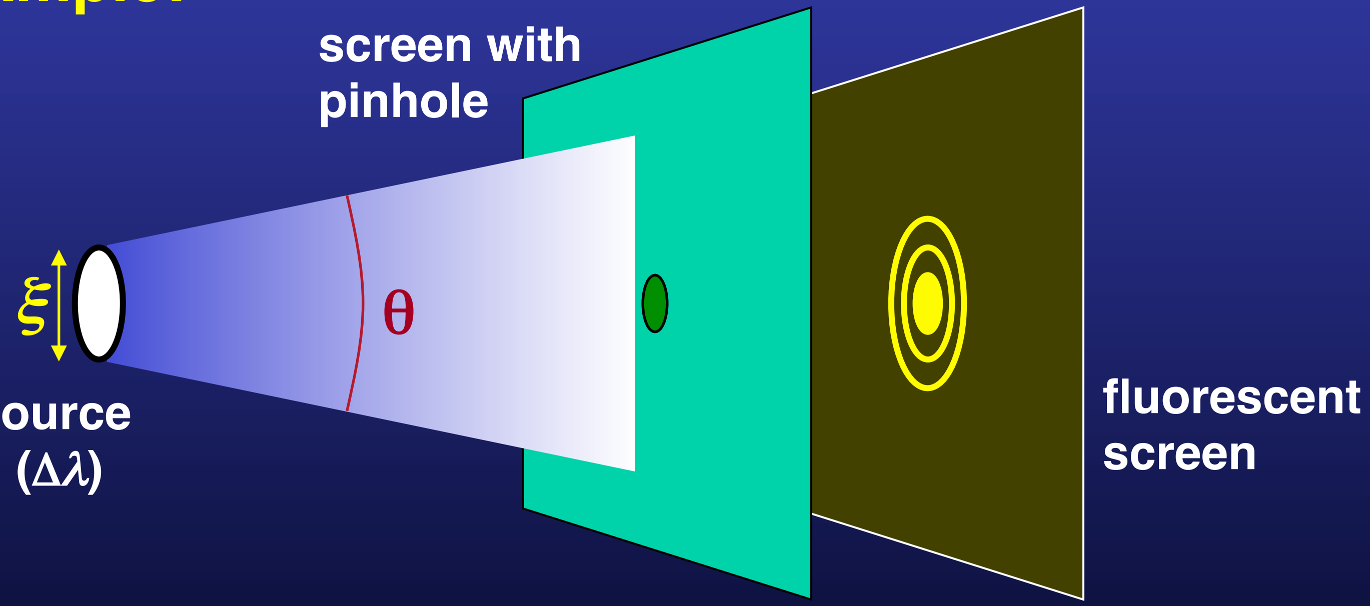
Polarization:

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

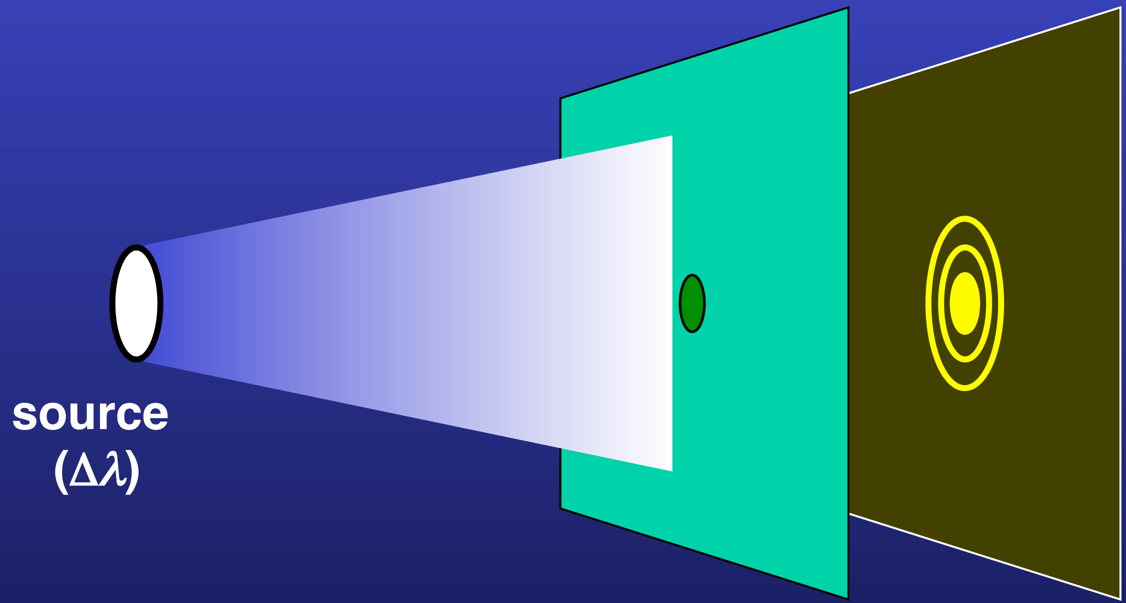
Coherence: "the property that enables a wave to produce visible diffraction and interference effects"

Example:



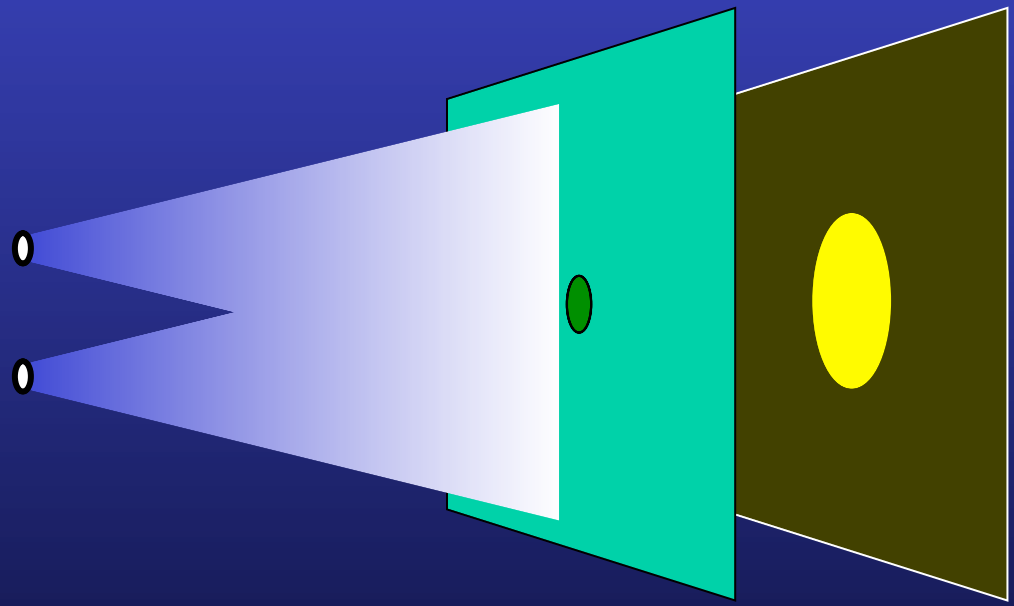
The diffraction pattern may or may not be visible on the fluorescent screen depending on the source size ξ, on its angular divergence θ and on its wavelength bandwidth $\Delta\lambda$

Longitudinal (time) coherence:



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

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

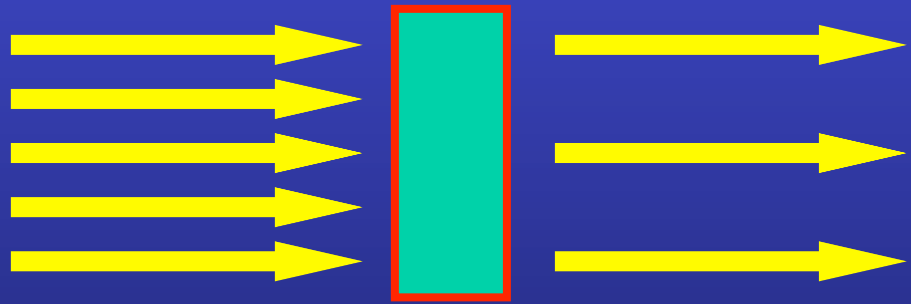


- **Two point sources produce overlapping patterns: diffraction effects are no longer visible.**
- **However, if the two source are close to each other an overall diffraction pattern may still be visible: the condition is to have a large "coherent power" $(2\lambda/\xi\theta)^2$**

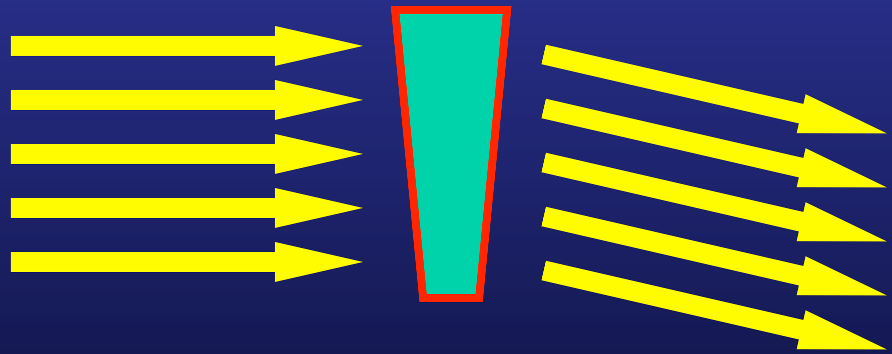
Coherence — summary:

- 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

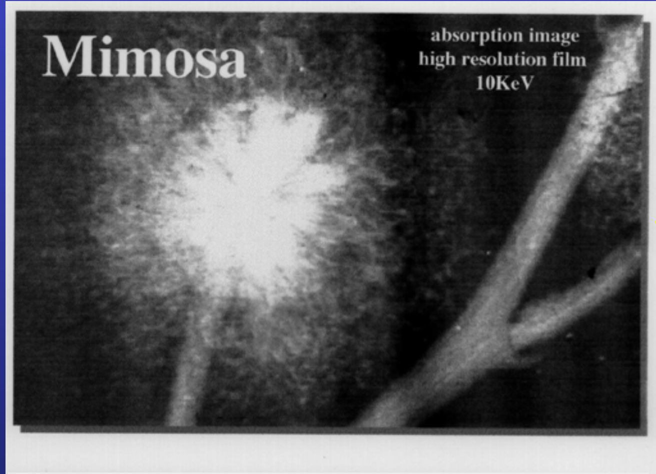


Refraction (and diffraction/interference) -- described by the refractive index n

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

Condition: the effects depend on the direction – to exploit them one needs a spatially coherent source

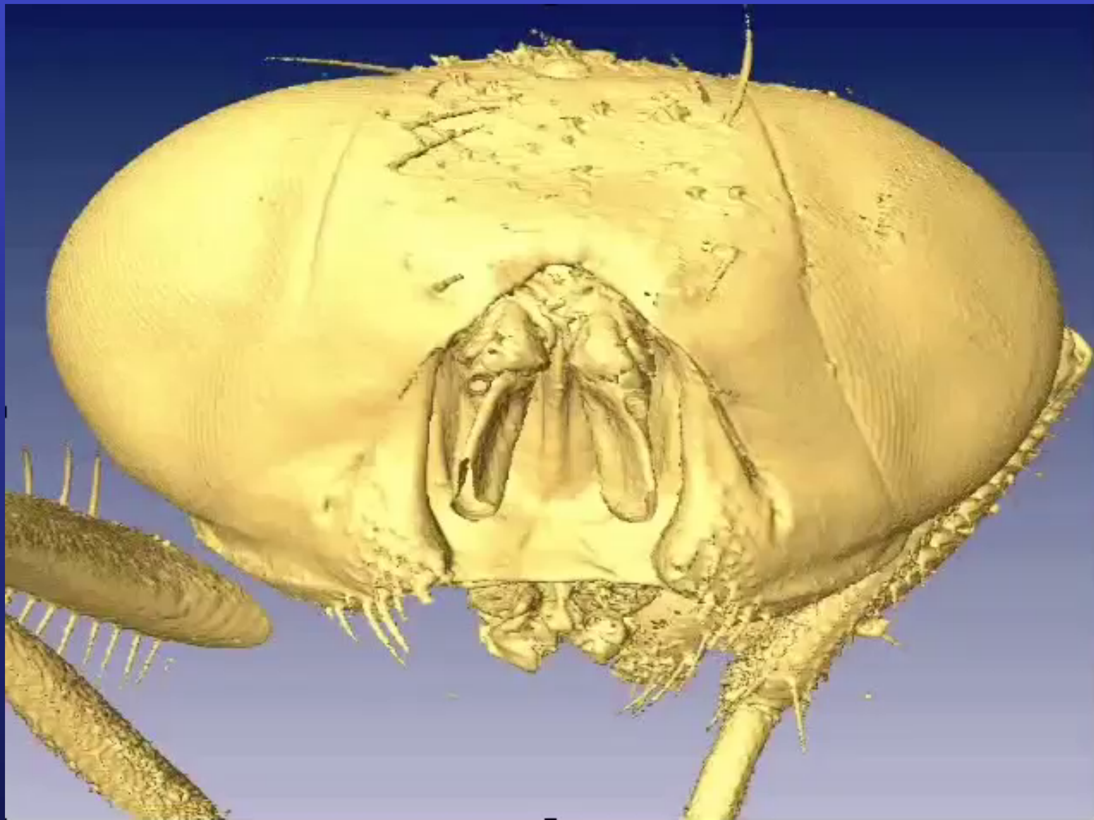
Conventional radiology



Refractive-index radiology (Giuliana Tromba)

Phase contrast micro-tomography: housefly

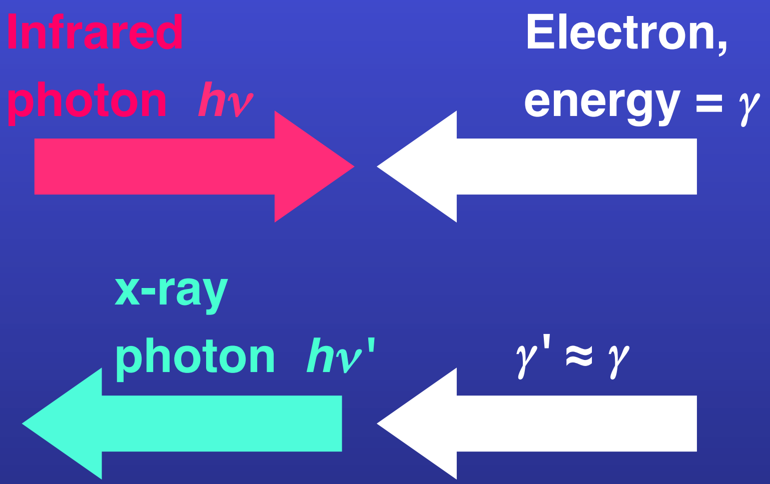
Yeukuang Hwu, Jung Ho Je et al.



New types of sources:

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

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

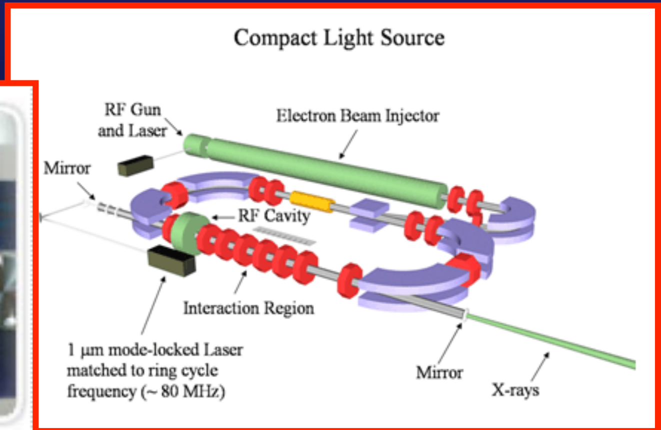


Doppler effect: in the electron frame, the photon energy ≈ $2\gamma\ h\nu$. This is also the energy of the backscattered photon in the electron frame.

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

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

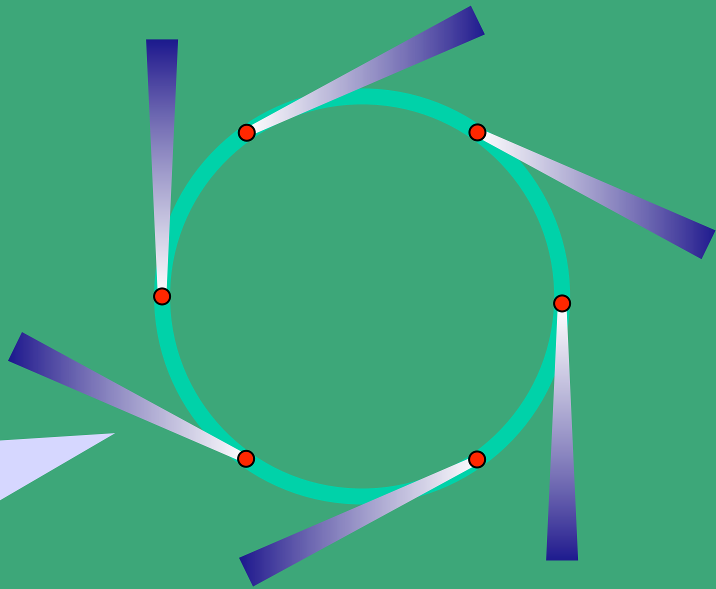
Lyncean Technologies, Inc.

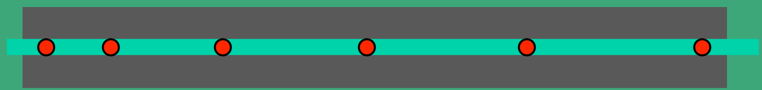


Energy-recovery LINAC sources

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

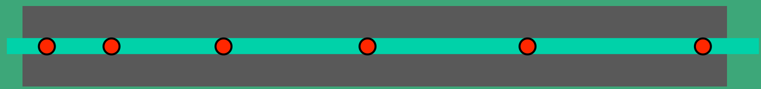
In a storage ring, the electrons continuously emit photons. This “warms up” the electron beam and increases its cross section





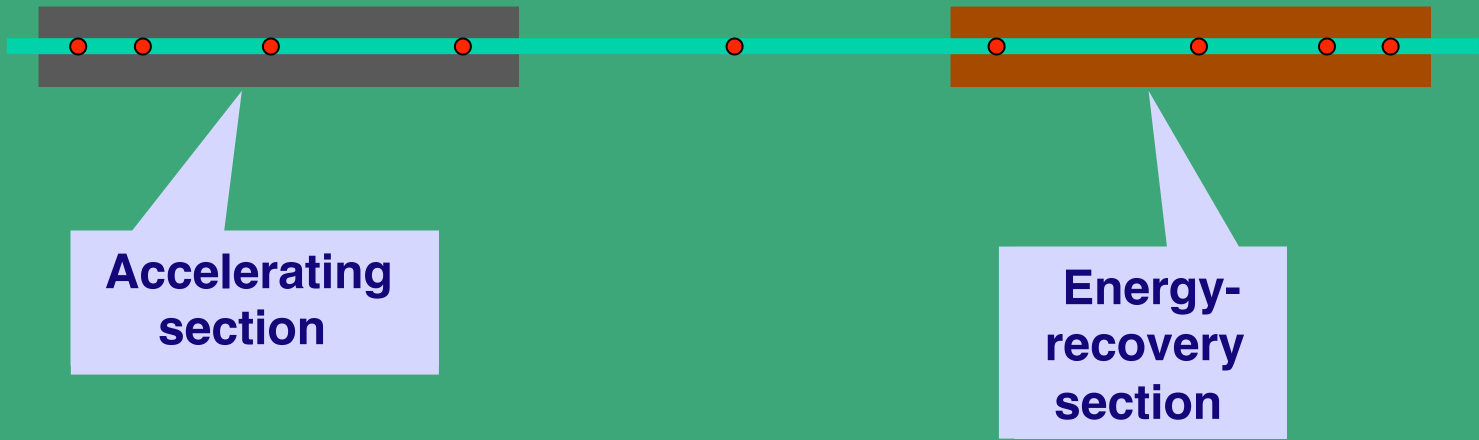
Controlling the electron beam geometry is much easier in a linear accelerator (LINAC). Thus, LINAC sources can reach higher brightness levels

Energy-recovery LINAC sources

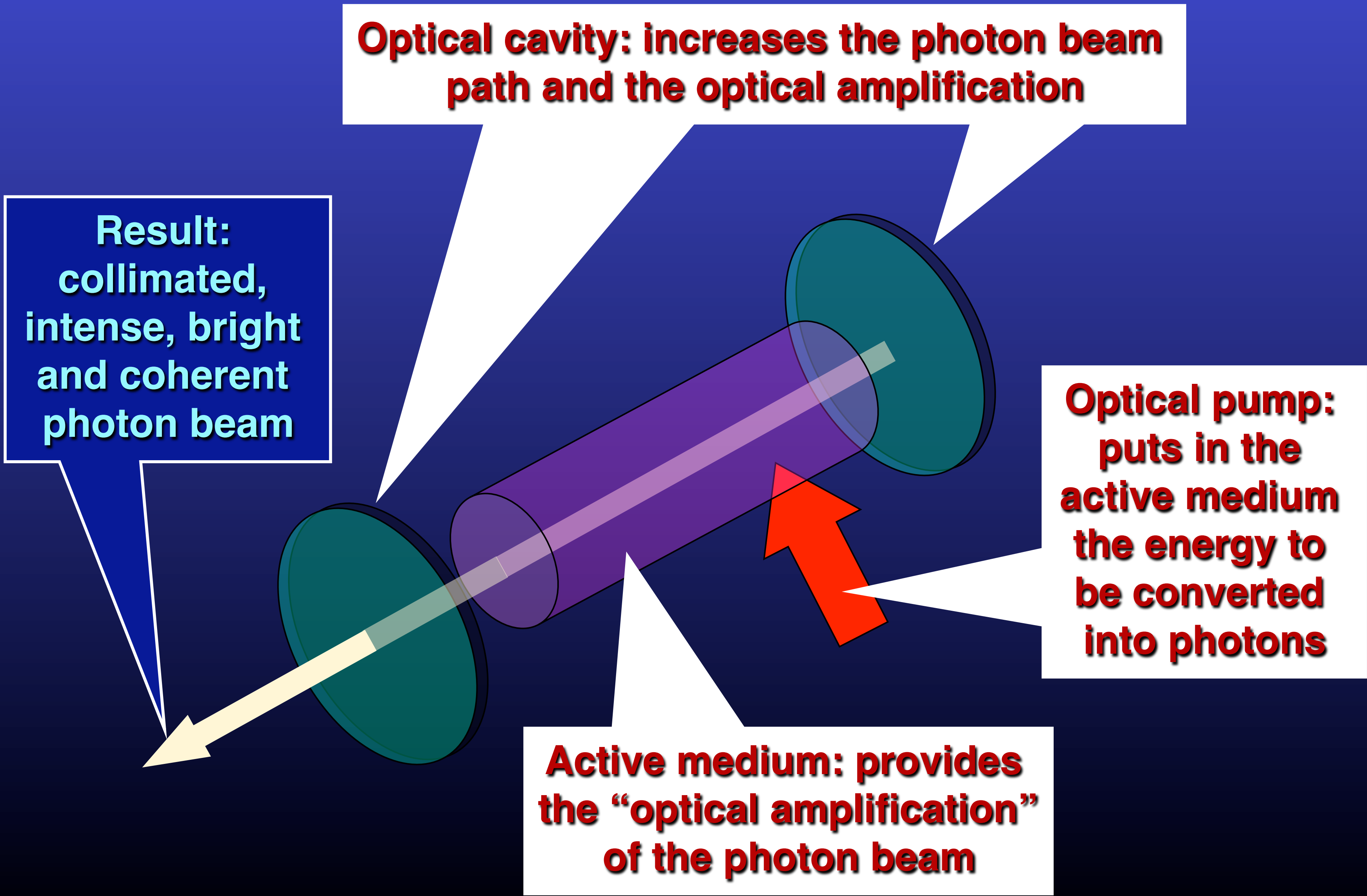


However, contrary to the electrons in a storage ring, the electrons in a LINAC produce photons only once: the power cost is too high

Solution: recovering energy



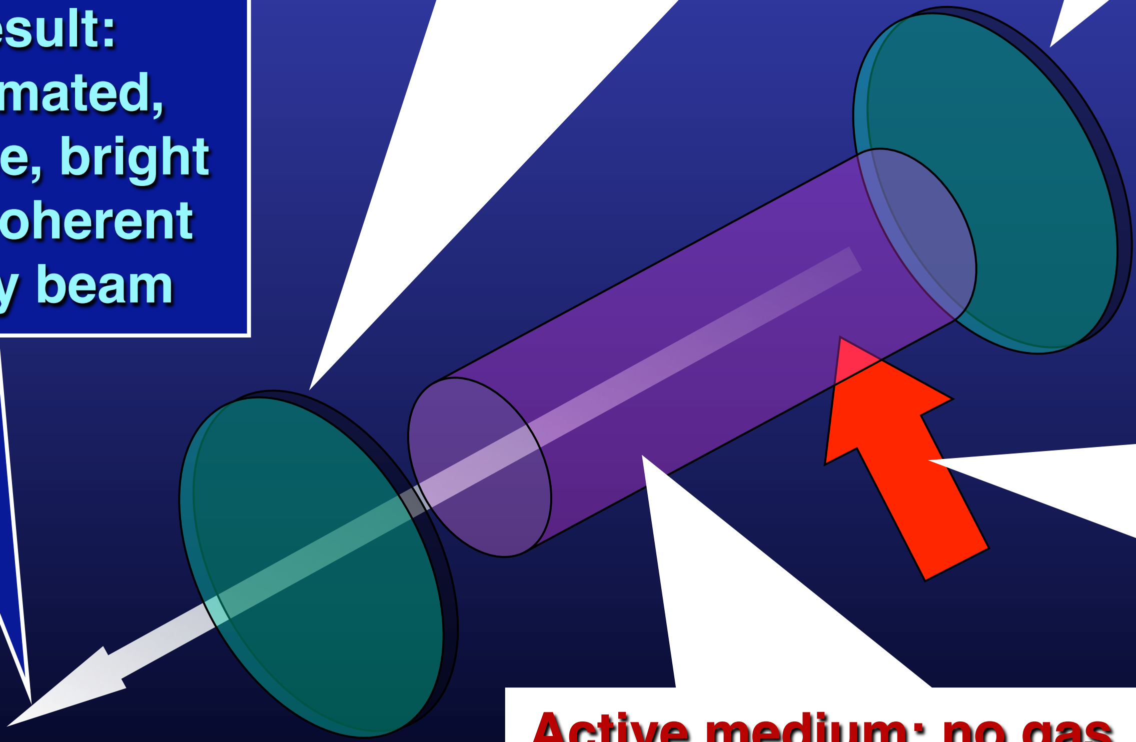
Towards FEL's -- a normal laser:



Normal laser ⇒ x-ray FEL:

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

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

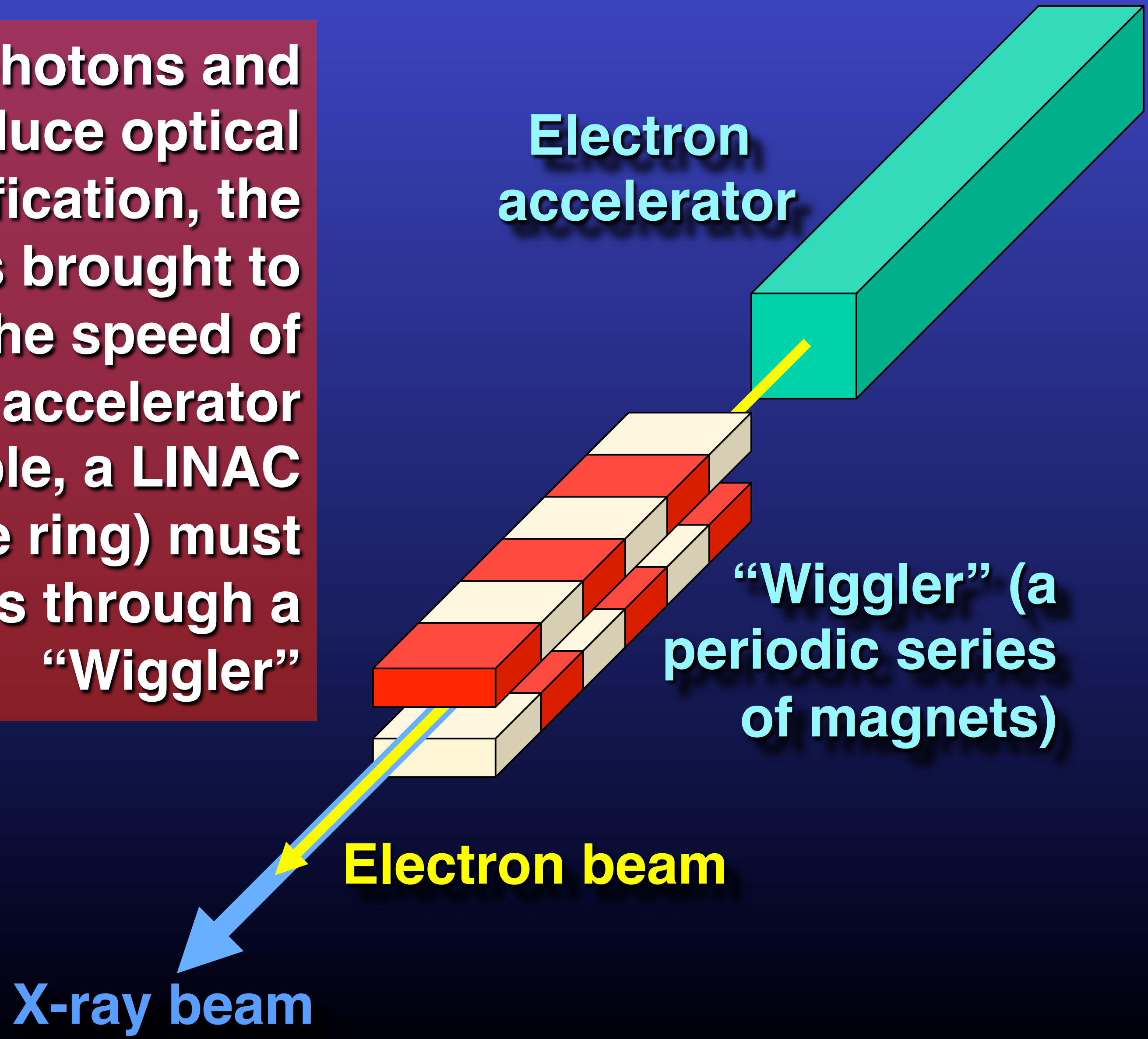


Optical pump: the free electrons provide the energy and transfer it to the photons

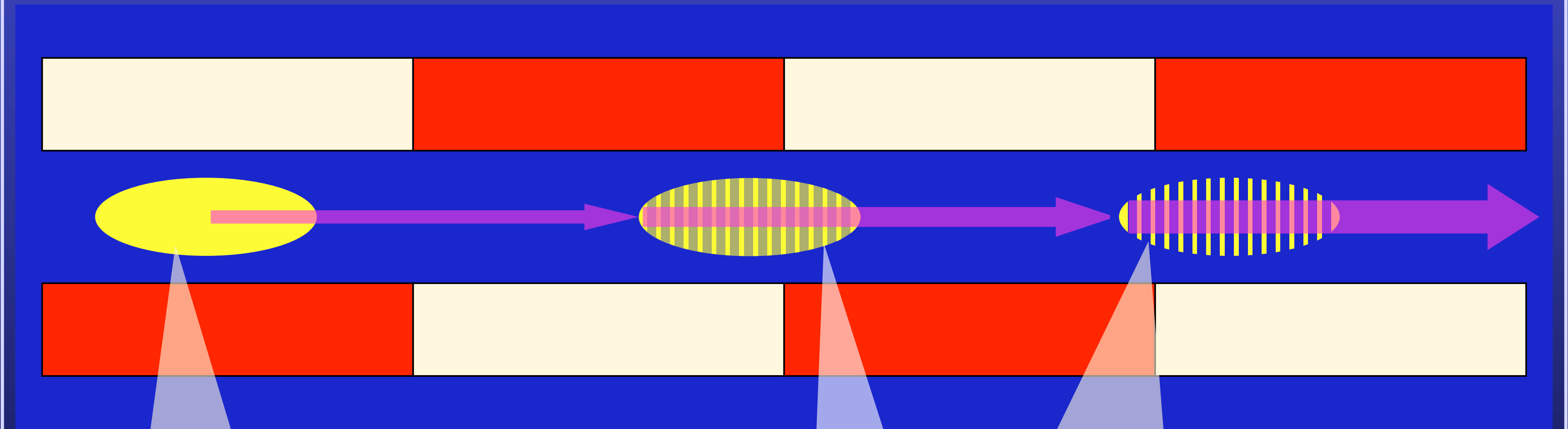
Active medium: no gas, solid or liquid but "free electrons" in an accelerator: hight power possible without damage

FEL's: general scheme

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:

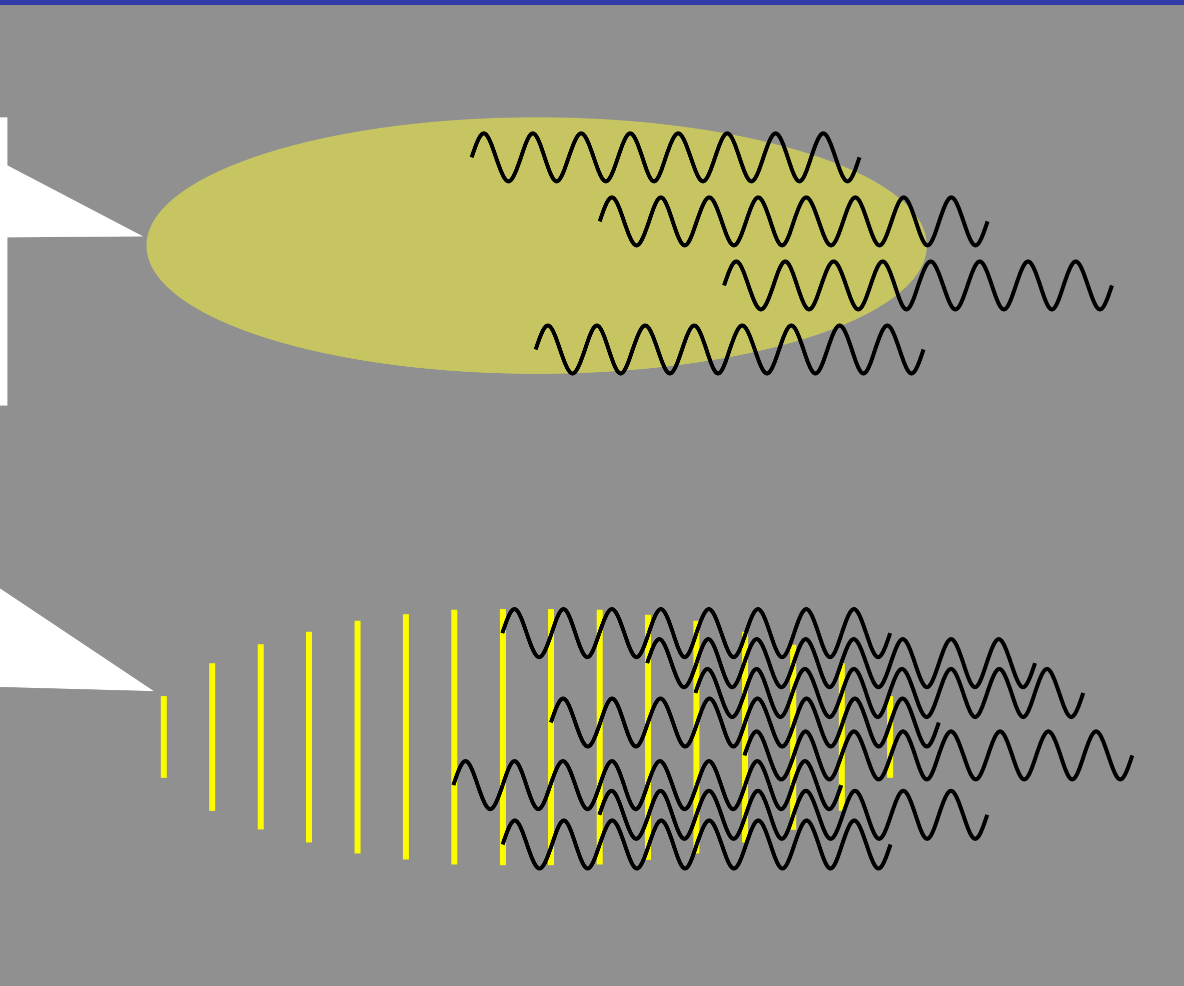


A bunch of electrons enters the wiggler: some of them stochastically start emitting waves

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

Emission from microbunched electrons:

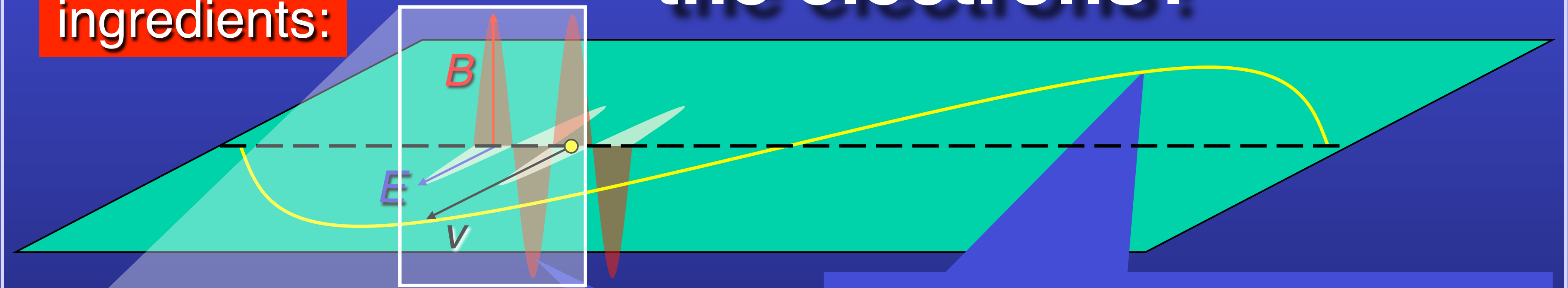
With no microbunching, as electrons enter the **wiggler**, they emit in an uncorrelated way



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

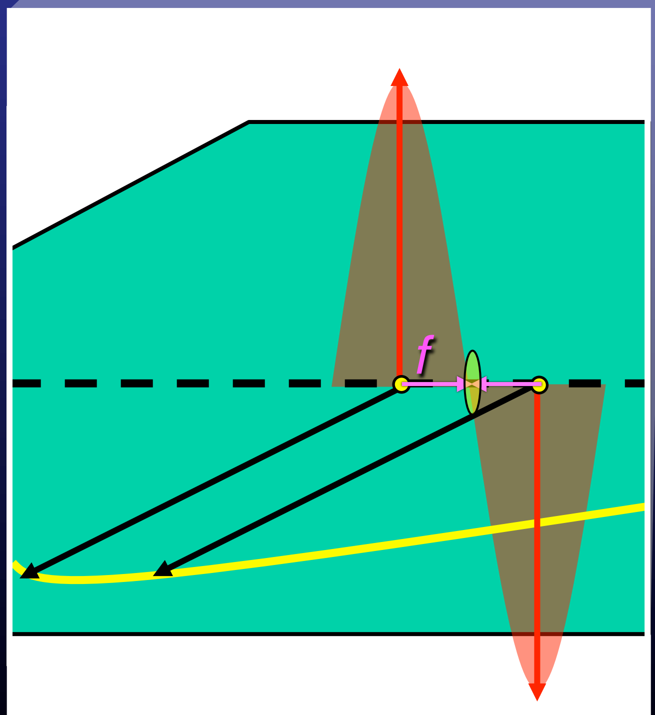
But what microbunches the electrons?

Two key ingredients:

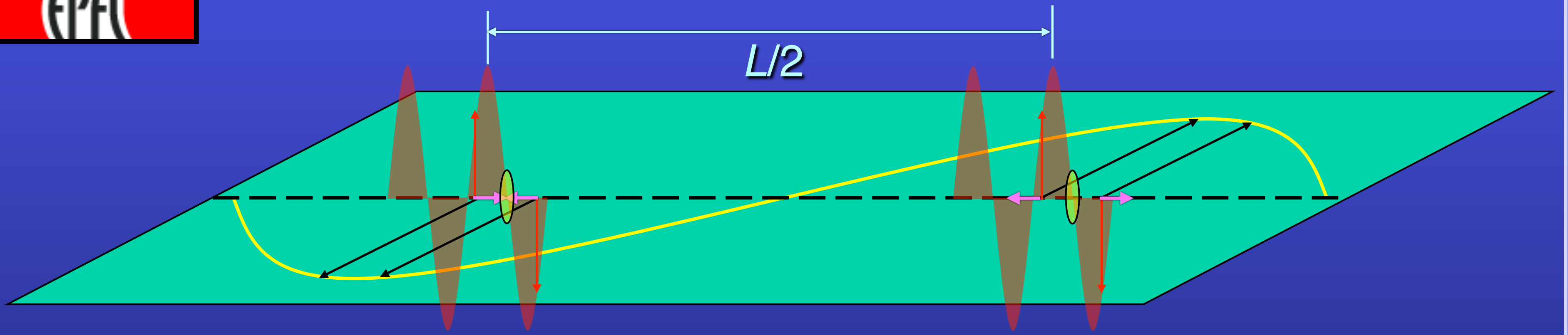


Wiggler-induced electron oscillations (*v* = transverse velocity)

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

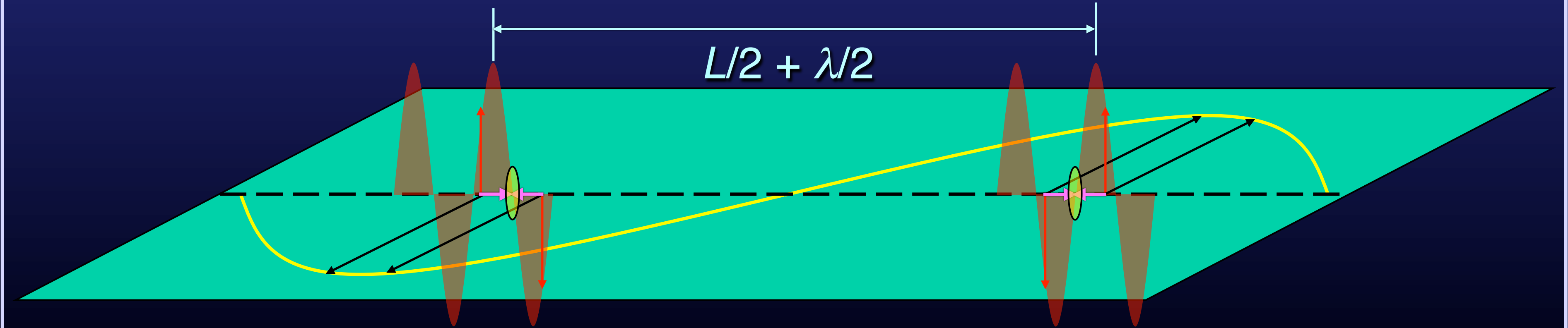


The wave *B*-field and the electron transverse velocity *v* produce a Lorentz force *f* pushing the electrons towards zero-field points: could this be the cause of microbunching?



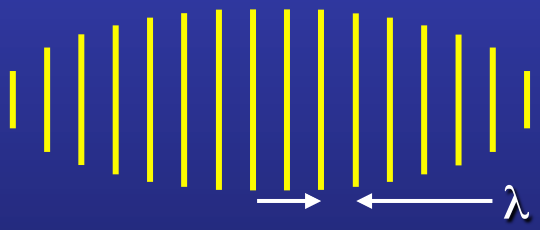
…but something seems wrong: after 1/2 wiggler period, the electron transverse velocity is reversed. If the wave travels together with the electron, the *B*-field stays the same. Are the forces and the microbunching reversed?

No! Electron and wave do not 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 $(L/2)(c/u - 1) \approx L/(4\gamma^2)$ = half wavelength



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

Why is microbunching (and lasing) more difficut for x-rays than for infrared photon?

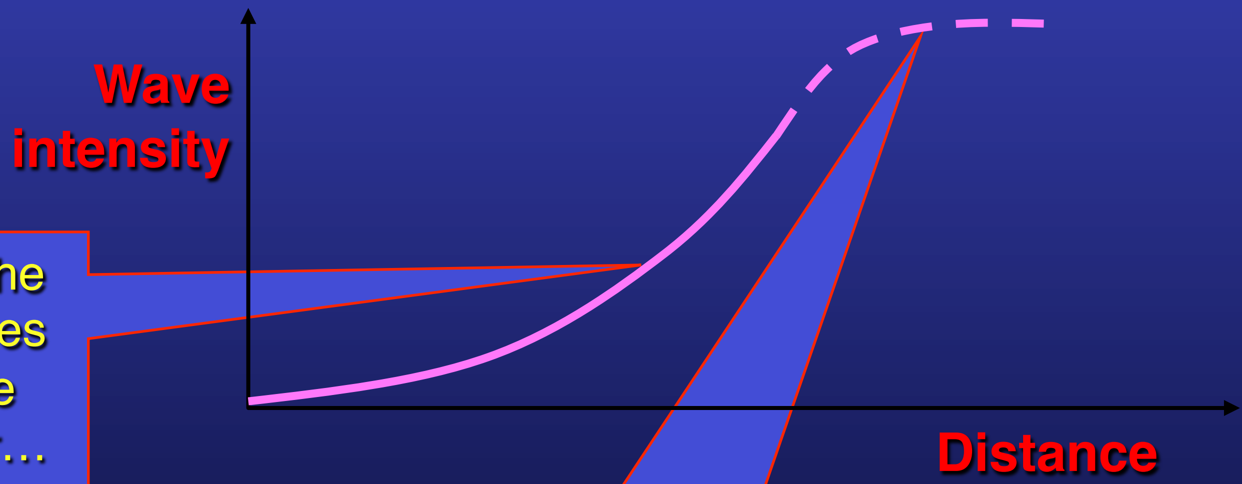


On one hand, at short wavelengths the microbunches are closer to each other and this facilitates microbunching

But:

- **Short 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 a progressive gain in the wave intensity



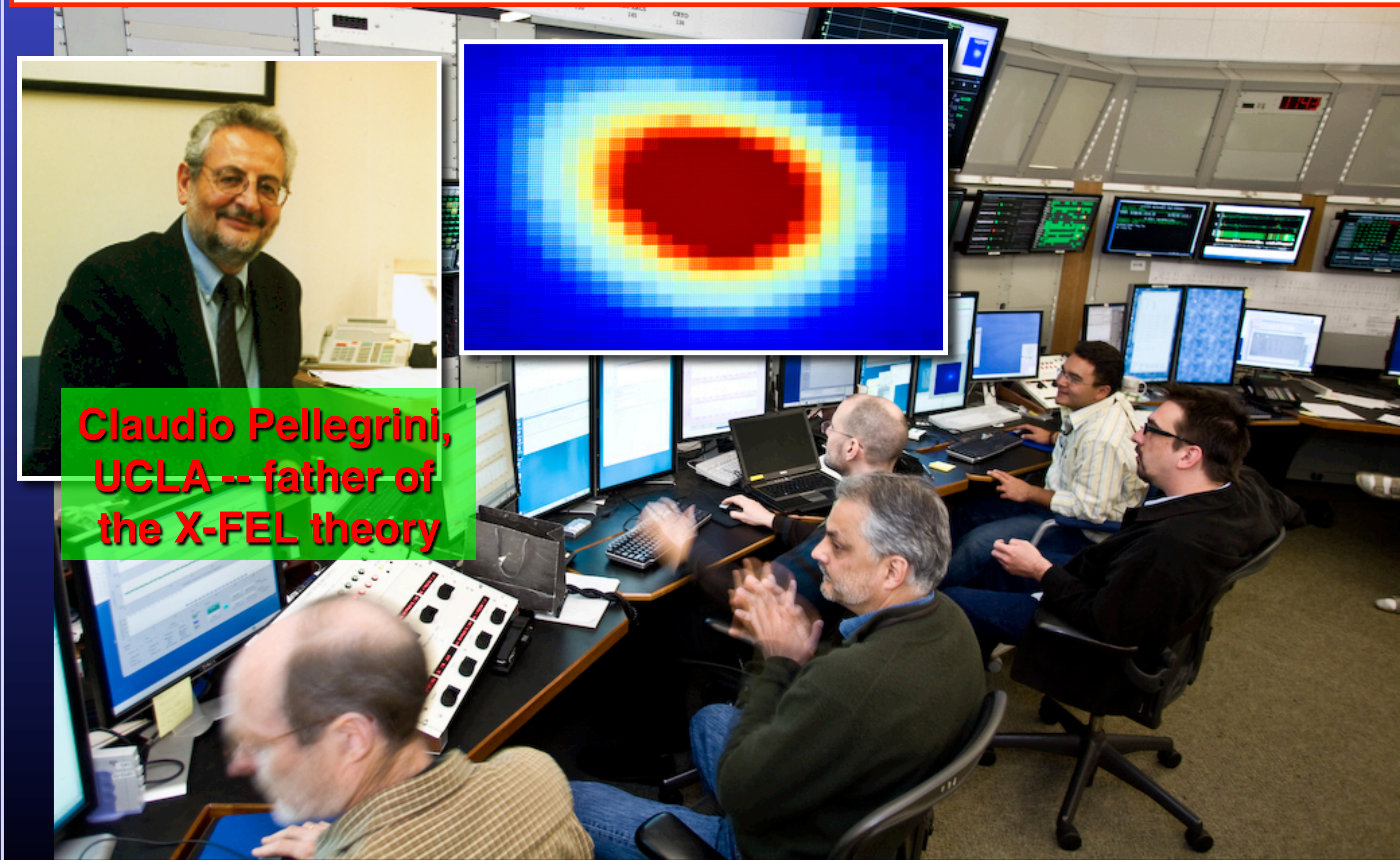
Because of the gain, the wave intensity increases exponentially with the distance in the wiggler…

…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

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

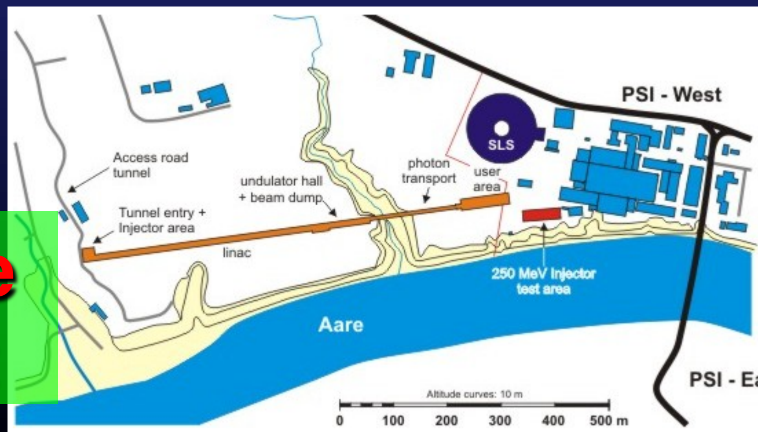
X-ray laser pulses of unprecedented energy and brilliance produced at SLAC



The FERMI X-FEL at Elettra, Trieste

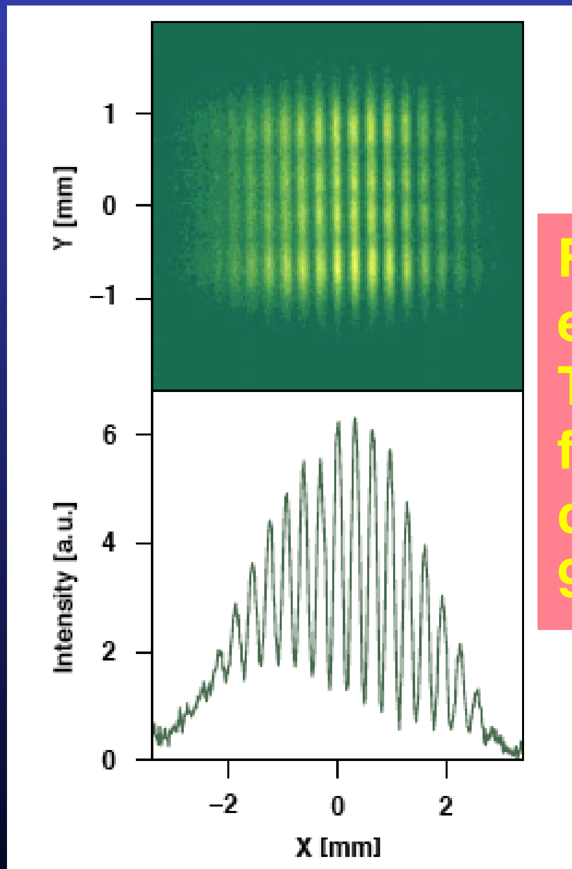
The European X-FEL project underway at DESY, Hamburg

The Swiss X-FEL at the Paul-Scherrer Institut



X-ray FEL coherence:

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

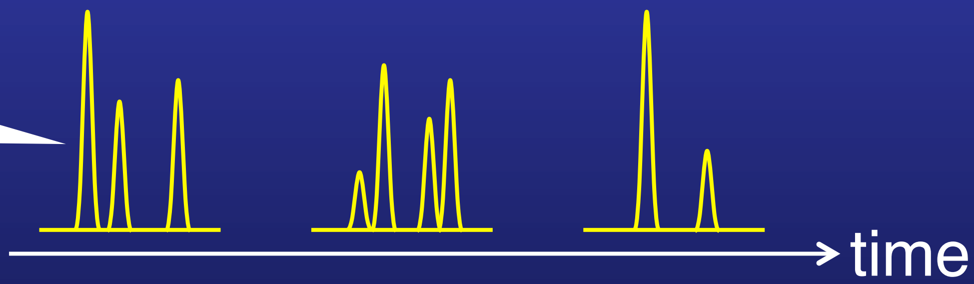


First coherence experiments on the Tesla Test Facility: full lateral coherence at λ = 95 nm

For longitudinal (time) coherence, a critical problem:

Amplification starts with the first waves <u>stochastically</u> emitted when the electron bunch enters the wiggler

The pulse time structure changes with each bunch, limiting the time coherence



Solution: “seeding” – the process is triggered by an artificially injected wave

A complicated technology, recently implemented in the FERMI FEL at Elettra.

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).
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