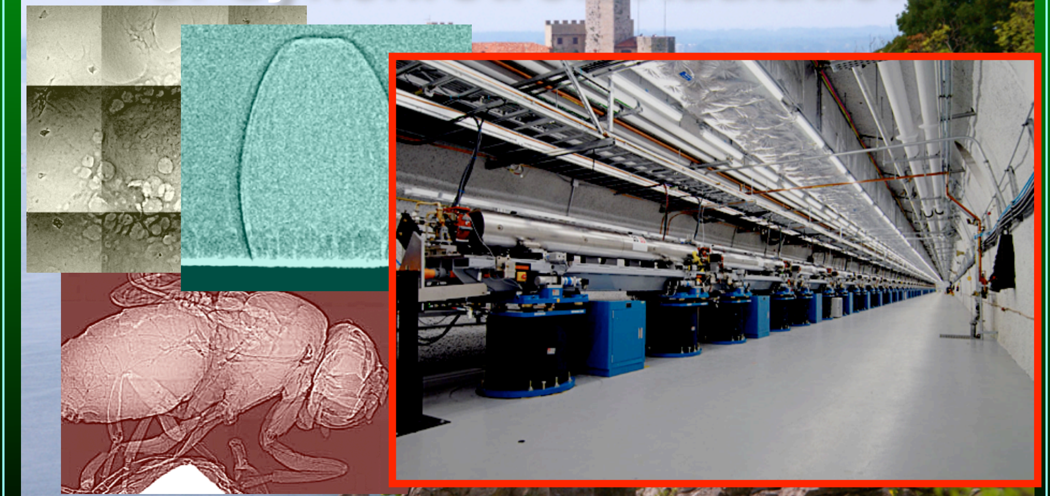
Characteristics and Properties of Synchrotron Radiation

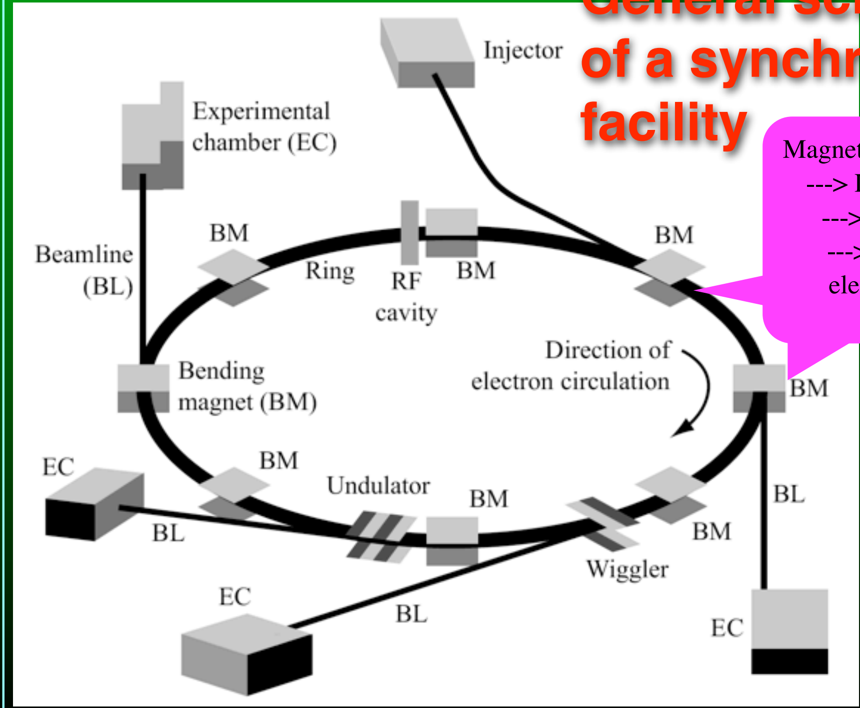


Giorgio Margaritondo
Ecole Polytechnique Fédérale de Lausanne (EPFL)

Outline:

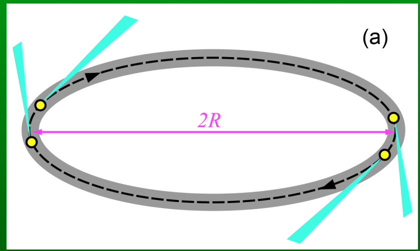
- How to build an excellent x-ray source using Einstein's relativity :
  - Collimation
  - Photon energy range
  - Brightness
  - Polarization
  - Undulators, bending magnets, wigglers
- Coherent x-rays: a revolution in radiology
- From storage rings to free electron lasers

General scheme of a synchrotron facility



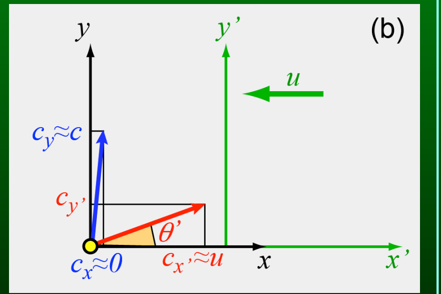
Magnets + electrons
---> Lorentz force
---> acceleration
---> emission of electromagnetic waves

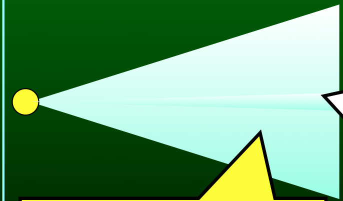
Angular Collimation:



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





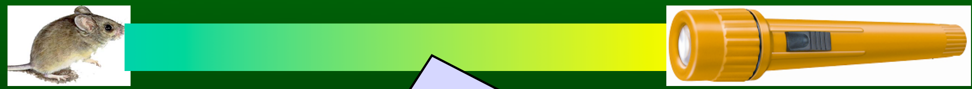
But in the laboratory frame the emission shrinks to a narrow cone

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!!!

Fireplaces and torchlights :

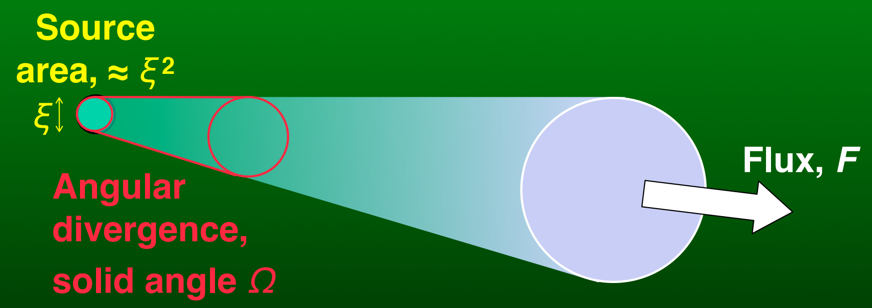
A fireplace is not very effective in "illuminating" a specific target: its emitted power is spread in all directions



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"

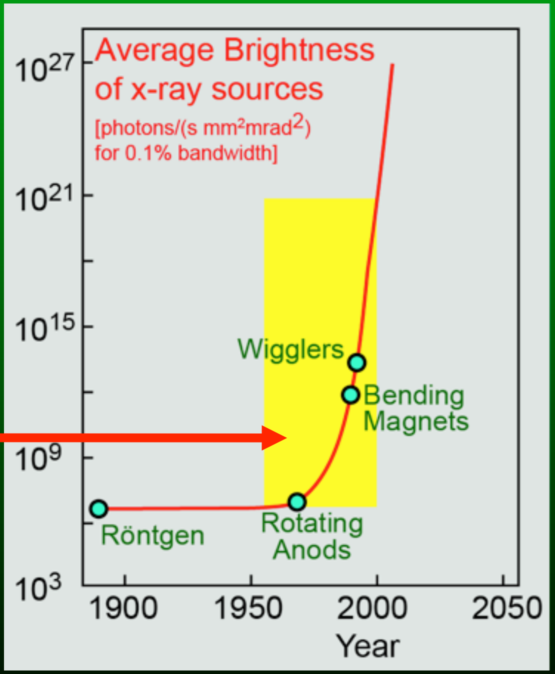
The "brightness" (or brilliance) of a source of light :



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

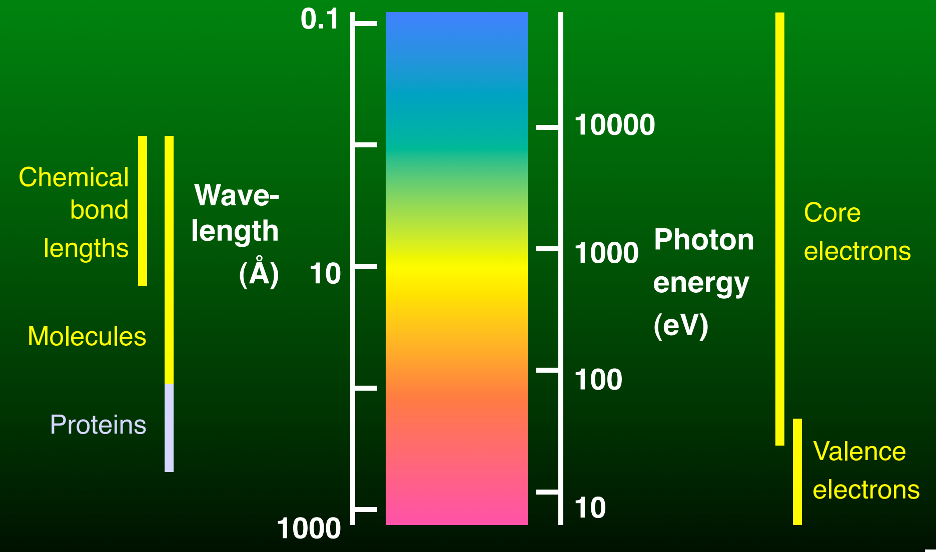
The historical growth in x-ray brightness/brilliance

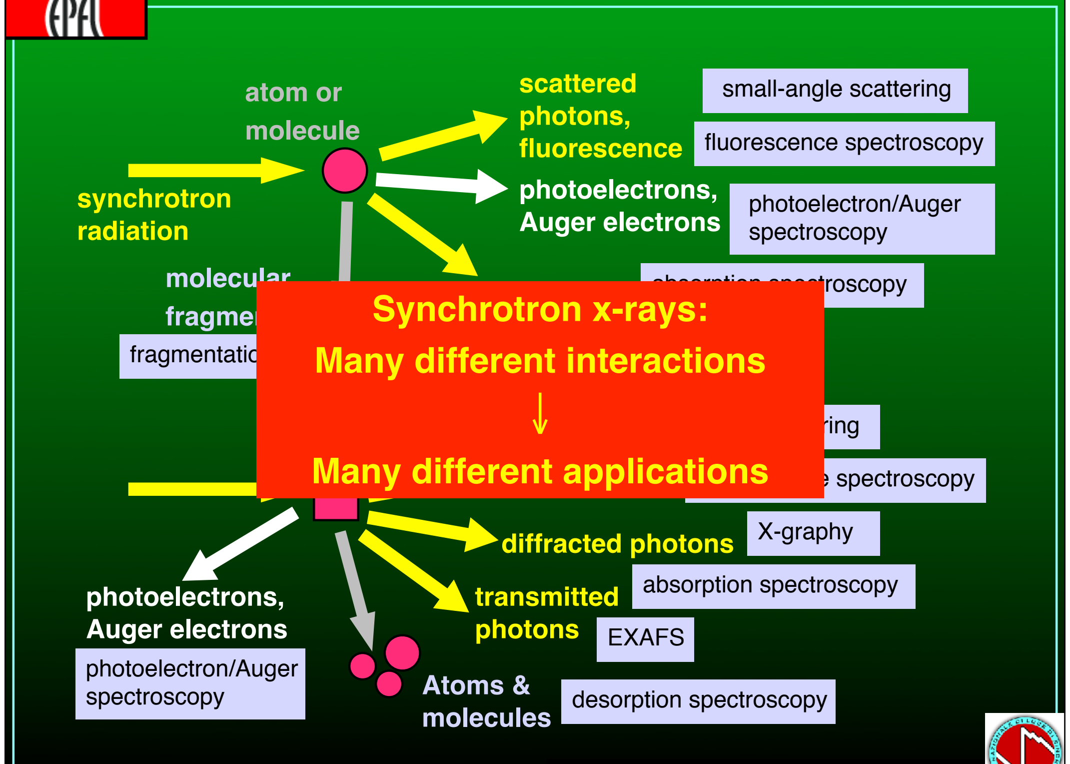
Between 1955 and 2000, the brightness increased by more than 15 orders of magnitude… whereas the top power of computing increased "only" by 6-7 orders of magnitude

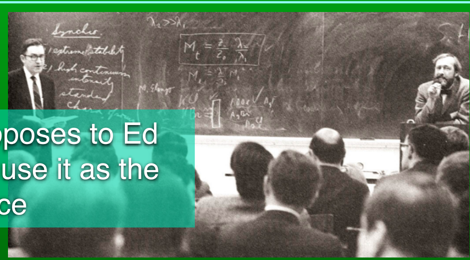


A real synchrotron facility: Diamond (UK)

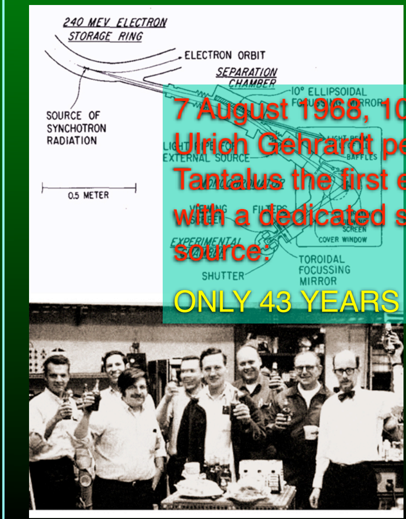
Why x-rays and ultraviolet?




atom or molecule
synchrotron radiation
scattered photons, fluorescence
small-angle scattering
fluorescence spectroscopy
photoelectrons, Auger electrons
photoelectron/Auger spectroscopy
molecular
Synchrotron x-rays:
Many different interactions
↓
Many different applications
spectroscopy
diffracted photons
X-graphy
transmitted photons
absorption spectroscopy
EXAFS
photoelectrons, Auger electrons
photoelectron/Auger spectroscopy
Atoms & molecules
desorption spectroscopy



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 43 YEARS AGO!!!

Synchrotron and Free Electron Laser Facilities in the World (2011):
64 in 27 Countries
(operating or under construction)

Historical Growth:

Worldwide ISI data 1968-2011, Keywords: "synchrotron" or "free electron laser"

1968: 64

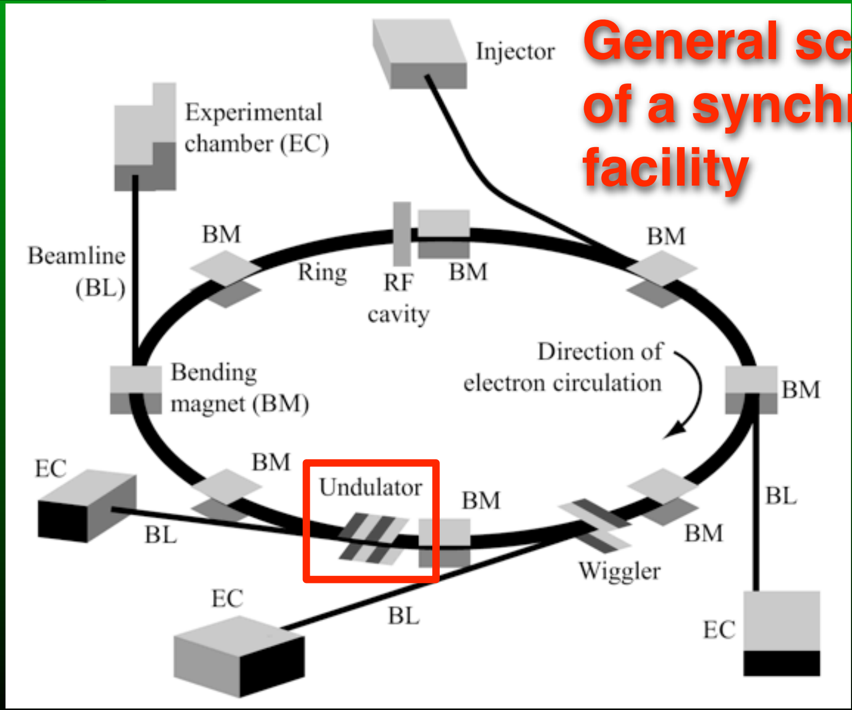
1980: 240

1990: 1,010

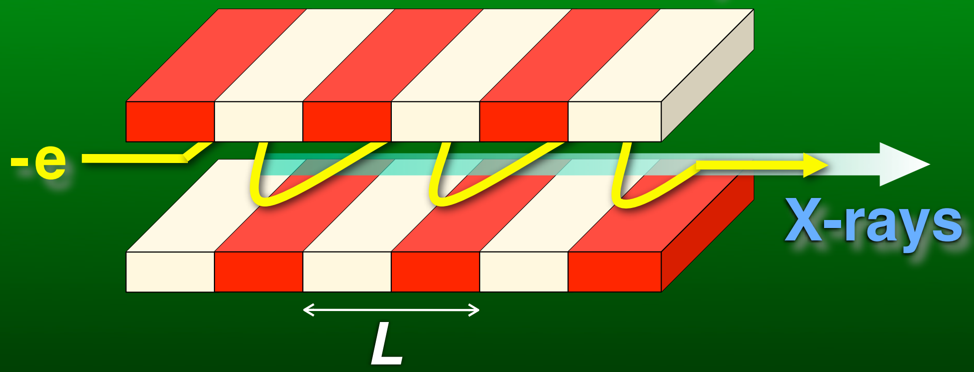
2000: 4,674

2010: 6,763

General scheme of a synchrotron facility



Why do the electrons in an undulator emit x-rays?

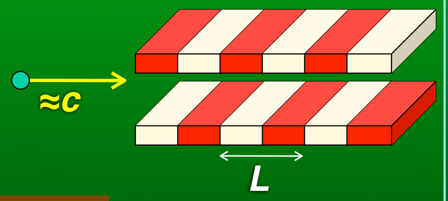


That is a puzzle: the typical undulator period, *L*, is of the order of centimeters -- whereas the x-ray wavelengths are of the order of Angstroms!!!

The key to understand: Einstein's relativity -- with its factor $\gamma = (1 - u^2/c^2)^{-1/2}$ (order of magnitude: 10^3-10^4)

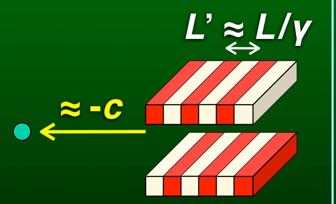
So, why short x-ray wavelengths?

The wiggler point of view: an electron arrives at a speed $u \approx c$



The electron point of view:

- A periodic transverse B-field arrives at speed $\approx -c$
- Its Lorentz transformation is a transverse B-field plus a transverse E-field perpendicular to it.
- The period L is Lorentz-contracted to $L' \approx L/\gamma$
- Thus, the electron "sees" the wiggler like a photon wave with wavelength $\approx L/\gamma$



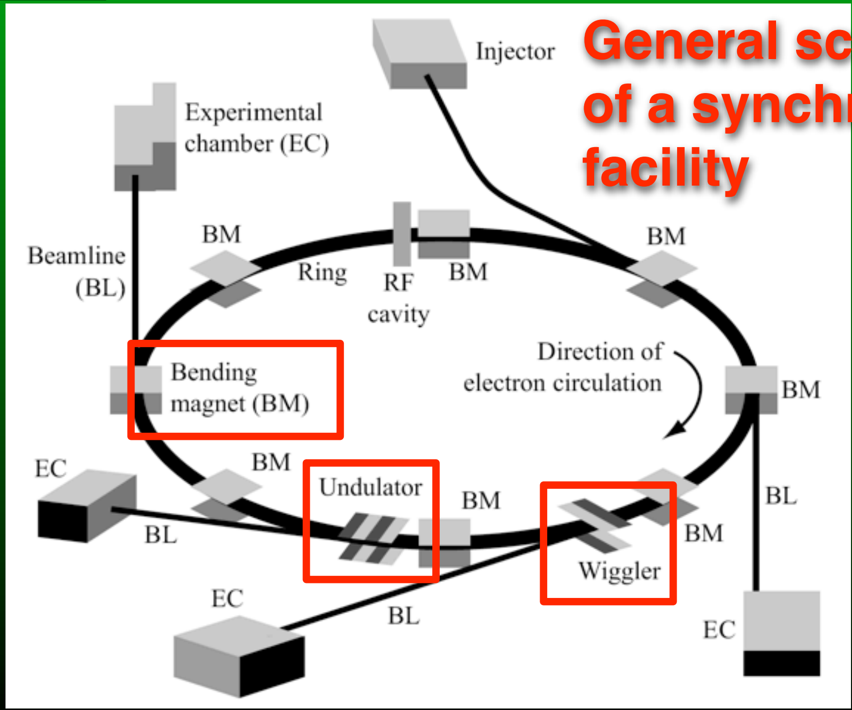
- The electron scatters this "wave": this is the cause of its photon emission.
- The wavelength in the laboratory frame is Doppler-shifted by $\approx 2\gamma$, becoming $\lambda \approx L/2\gamma^2$
- Since γ is very large, λ corresponds to x-rays!

In summary, what produces the high brightness of a real synchrotron source?

- Free electrons can emit more power than bound electrons --> high flux
- The control of the electron beam trajectories in the storage ring is very sophisticated: small transverse beam cross section --> small photon source size
- Relativity drastically reduces the angular divergence of the emitted synchrotron radiation

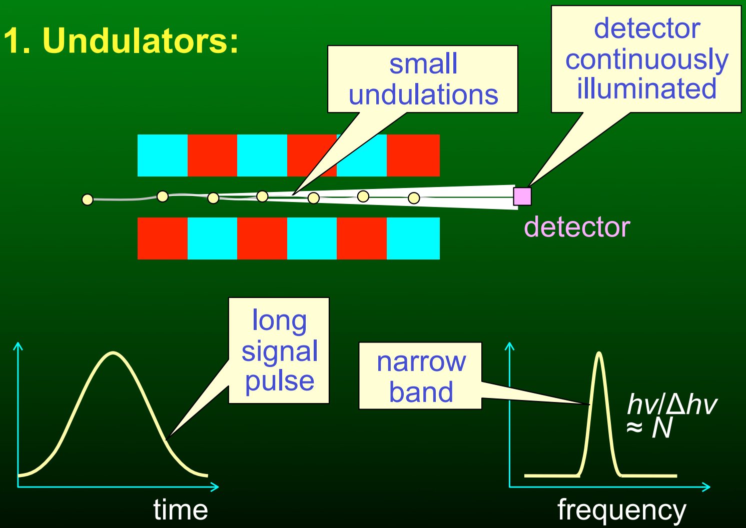

...and now,
can we all
go to the
beach?
...sorry again folks, later... (maybe)

General scheme of a synchrotron facility



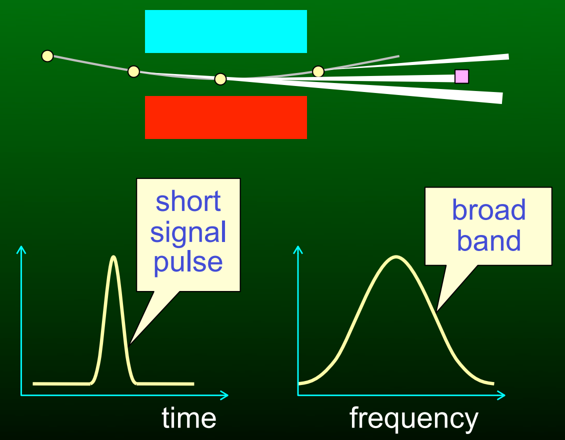
3 types of sources:

1. Undulators:



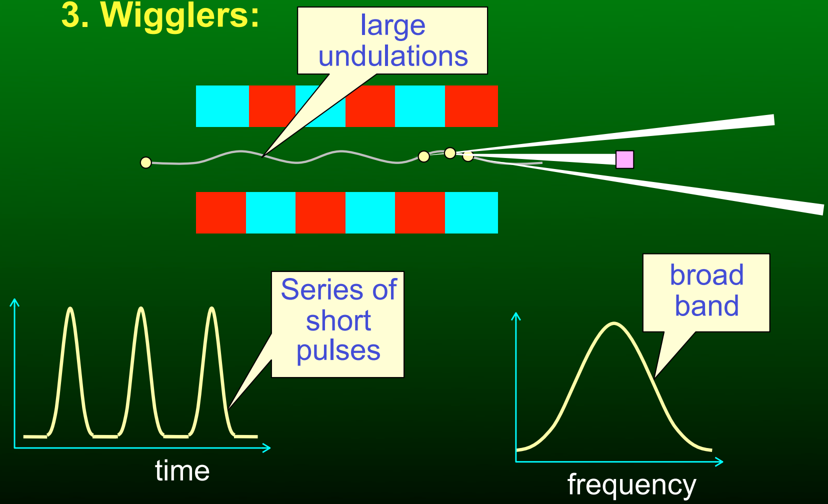
3 types of sources:

2. Bending magnets:

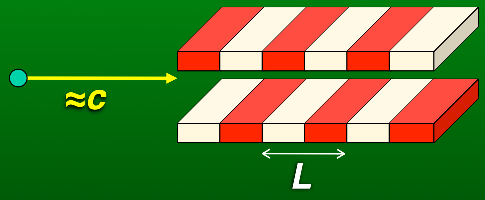


3 types of sources:

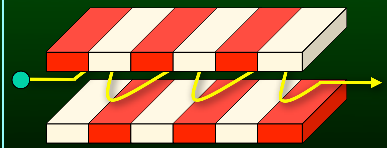
3. Wigglers:



Controlling the undulator wavelength:

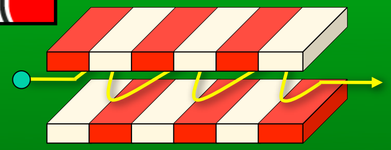


Starting point: we have seen that $\lambda \approx \lambda_o = L/2\gamma^2$, so λ could be changed by changing γ (i.e., the electron energy)



Plus: the electron oscillations and the transverse velocity are proportional to the wiggler *B*-field. The Lorentz force does no work so the kinetic energy is constant: as the transverse velocity increases, the longitudinal velocity *u* decreases.

This effectively changes $\gamma = (1-u^2/c^2)^{-1/2}$, so that λ can be modified by tuning *B*.



Controlling the x-ray wavelength (continues):

In detail:

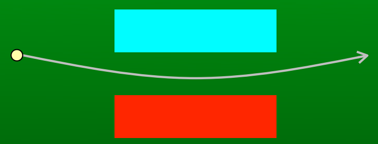
- The transverse velocity v_T is proportional to the B-field strength B
- The kinetic energy stays constant, so the longitudinal speed squared changes from u^2 to $(u^2 - v_T^2)$
- This effectively changes $1/\gamma^2$ from $(1-u^2/c^2)$ to $(1 - u^2/c^2 - v_T^2/c^2)$
- And λ changes from $\lambda_o \approx (L/2)(1 - u^2/c^2)$ to $\lambda \approx \lambda_o(1 - K^2/2)$, where K^2 is proportional to B^2

Note: this is the "central" emitted wavelength -- there is a wavelength band $\Delta\lambda$ around it

In fact:

- An electron going through an undulatorr with N_W periods emits a train of N_u wavelengths, with length $N_W\lambda$ and duration $\Delta t = N_W\lambda/c$
- Fourier transform (frequency): $\Delta\nu = c/N_W\lambda = \nu/N_W$
- $\Delta\lambda/\lambda = \Delta\nu/\nu = 1/N_W$

Bending magnet emission spectrum:

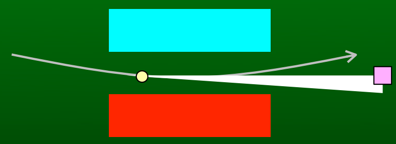


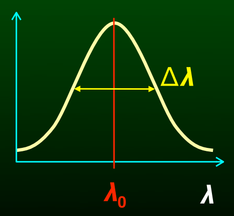
The (relativistic) rotation frequency of the electron determines the (Doppler-shifted) central wavelength:

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

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

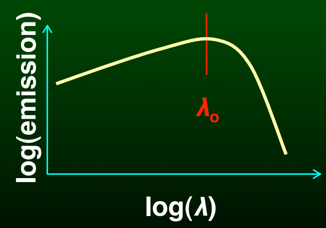
$\Delta\lambda / \lambda_o = 1$





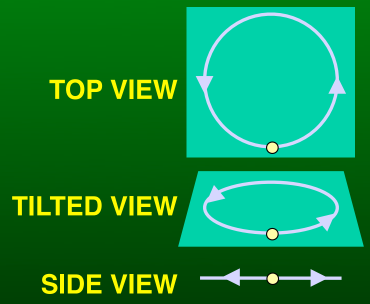
A peak centered at λ_c with width $\Delta\lambda$: is this really the well-known synchrotron spectrum?

YES -- see the log-log plot:



Synchrotron light polarization:

Electron in a storage ring:



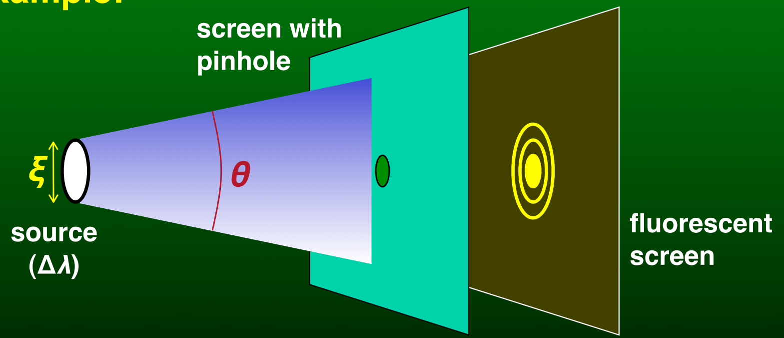
Polarization:

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

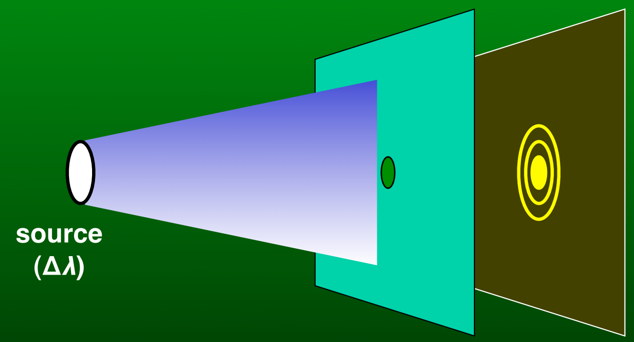
Coherence: "the property that enables a wave to produce visible diffraction and interference effects"

Example:



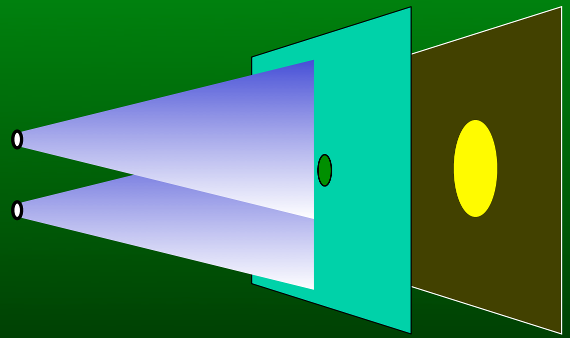
The diffraction pattern may or may not be visible on the fluorescent screen depending on the source size ξ, on its angular divergence *θ* and on its wavelength bandwidth Δ*λ*

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:

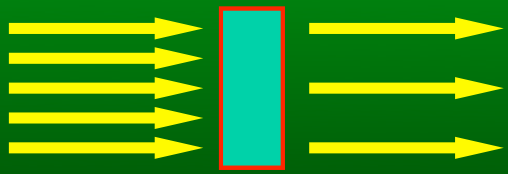


- Two point sources produce overlapping patterns: diffraction effects may no longer be visible.
- However, if the two source are close to each other an overall diffraction pattern may still be visible: the condition is to have a **large "coherent power" $\approx(\lambda/\xi\theta)^2$**

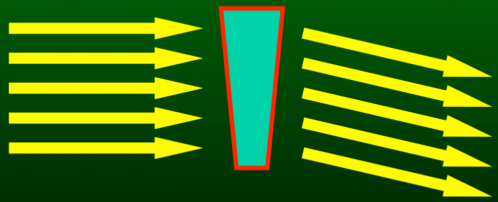
Coherence — summary:

- Coherence in general requires a large coherence volume $L^2\lambda^4/(\xi^2\Delta\lambda) = L_c\,(L^2\lambda^2/\xi^2)$
- Longitudinal coherence: requires a large coherence length $L_c = \lambda^2/\Delta\lambda$
- Lateral coherence: requires a large coherent power $\approx (\lambda/\xi\theta)^2$
- Both difficult to achieve for small wavelengths (x-rays)
- The geometric conditions for large $(\lambda/\xi\theta)^2$ are the same as for high brightness

Light-matter Interactions in Radiology:



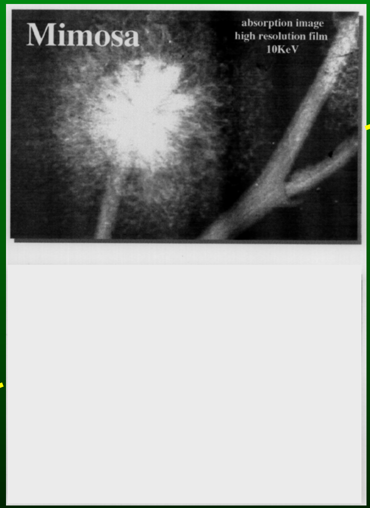
Absorption -- described by the absorption coefficient *α*



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

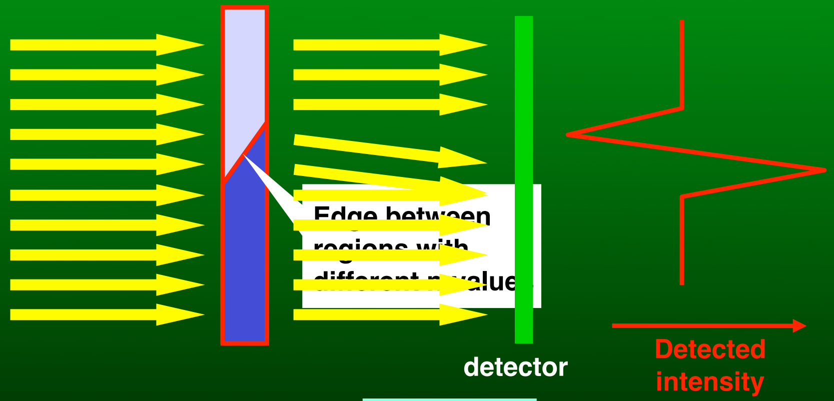
For over one century, radiology was based on absorption: why not on refraction /diffraction?

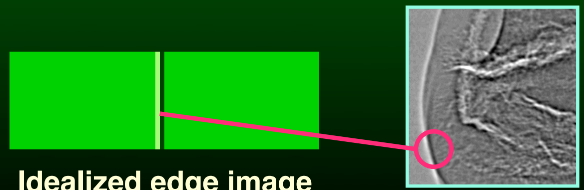
Conventional radiology



Refractive-index radiology (Giuliana Tromba)

“Refraction” x-ray imaging:

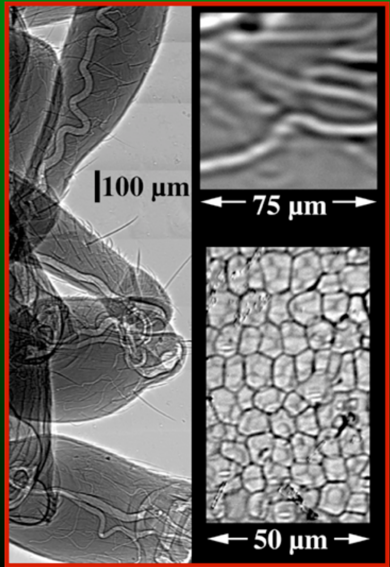


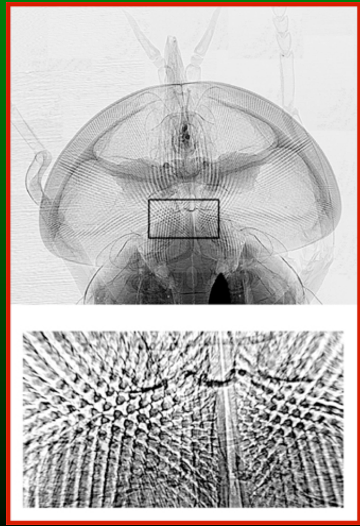


Idealized edge image

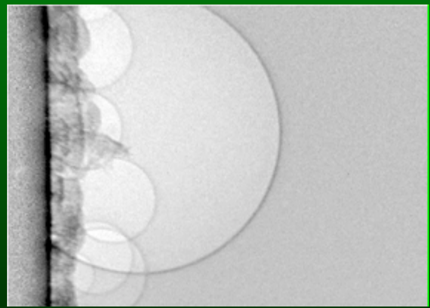
Real example (frog egg)

Examples of "refraction" radiology:

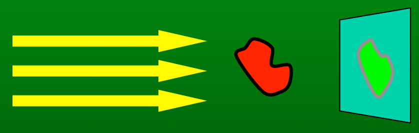




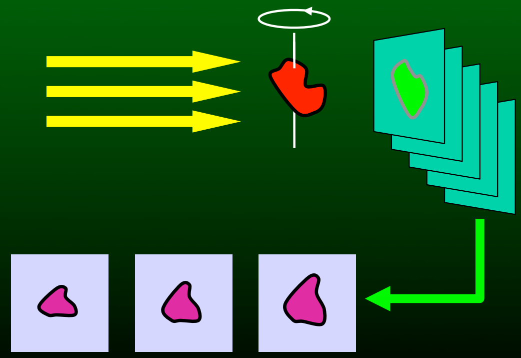
Building on bubbles (zinc electrodeposition):



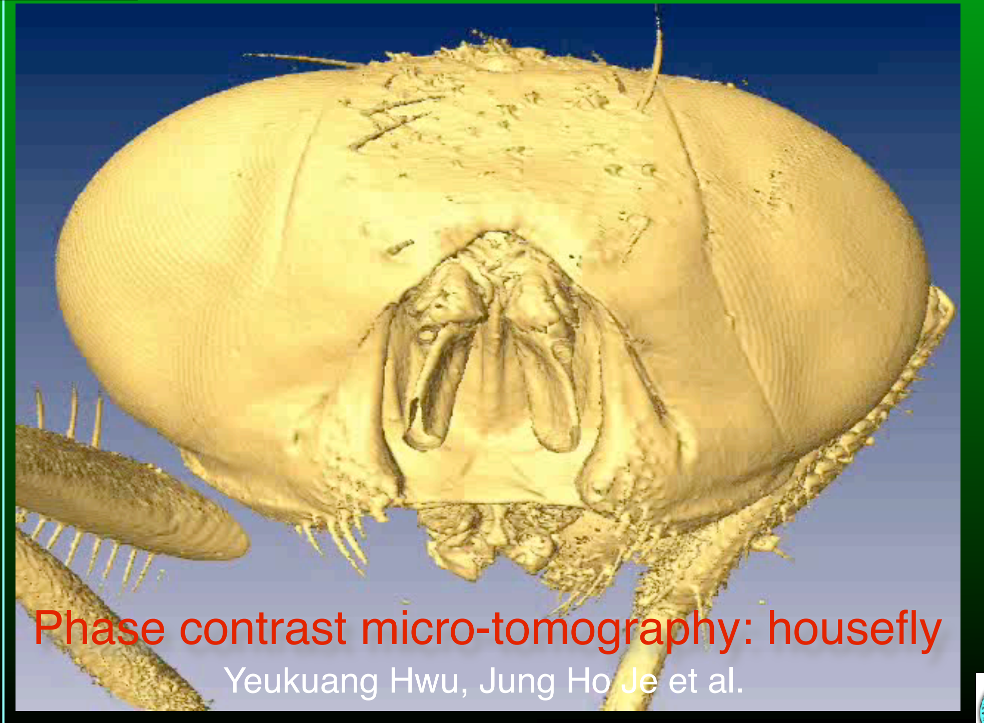
X-ray (micro)tomography:



A single (projection) x-ray image does not deliver three-dimensional information

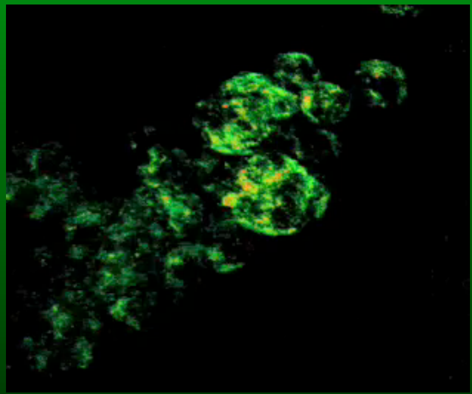


In tomography, many x-ray images taken at different angles are processed to obtain different views of the object in three dimensions -- for examples “slices”


Phase contrast micro-tomography: housefly
Yeukuang Hwu, Jung Ho Je et al.

From detection to treatment?

Y. S. Chu, J. M. Yi, F. De Carlo, Q. Shen, W.-K-Lee, H. J. Wu, C. L. Wang, J. Y. Wang, C. J. Liu, C. H. Wang, S. R. Wu, C. C. Chien, Y. Hwu, A. Tkachuk, W. Yun, M. Feser, K. S. Liang, C. S. Yang, J. H. Je, G. Margaritondo



Agglomerated Au nanoparticles attached to cancer cells

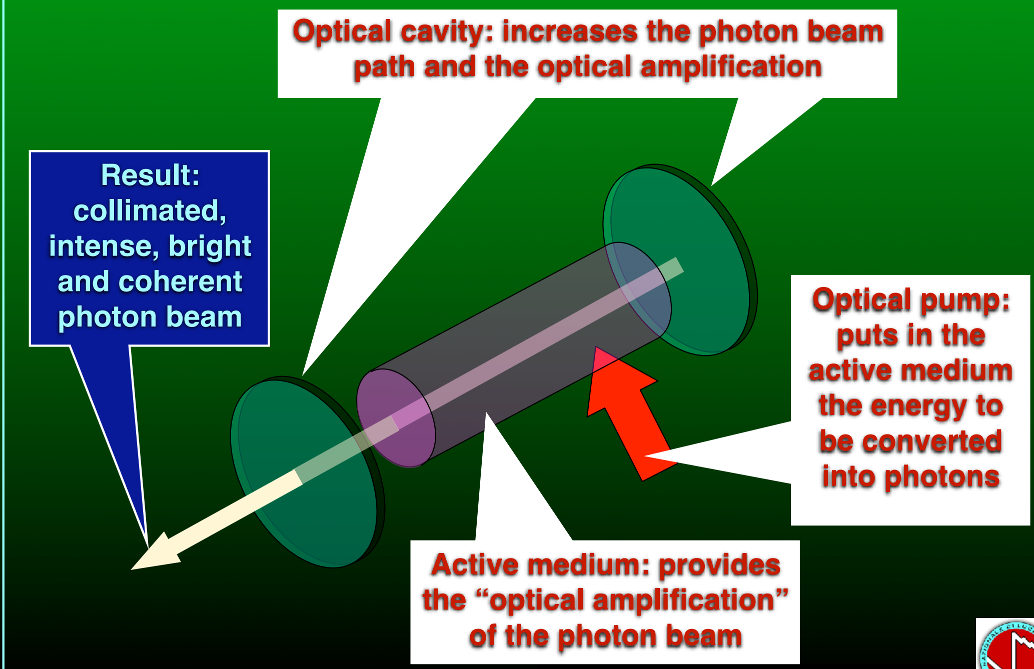
New types of sources:

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

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

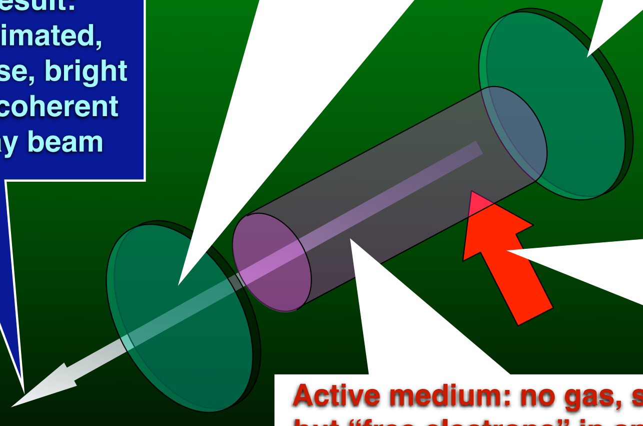
The ingredients of a normal lasers:



Normal lasers ---> x-ray laser:

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

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

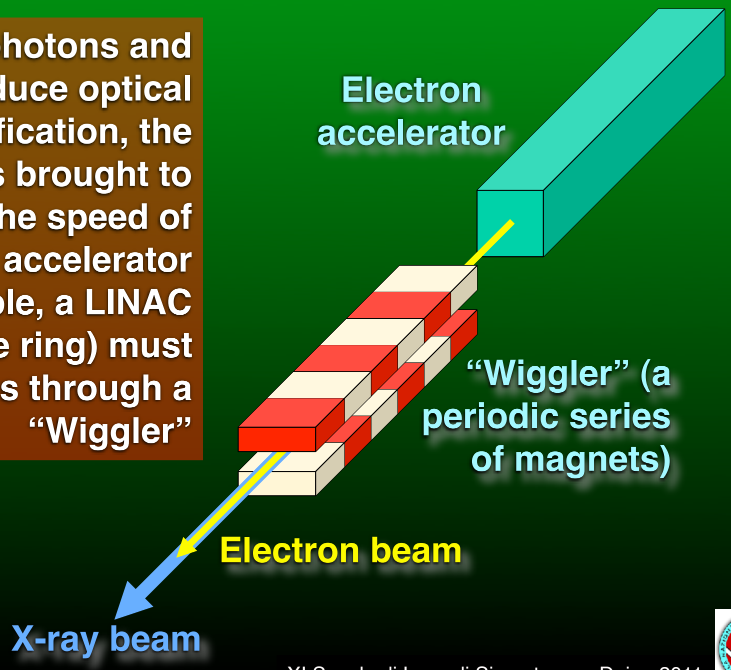


Optical pump: the free electrons provide the energy and transfer it to the photons

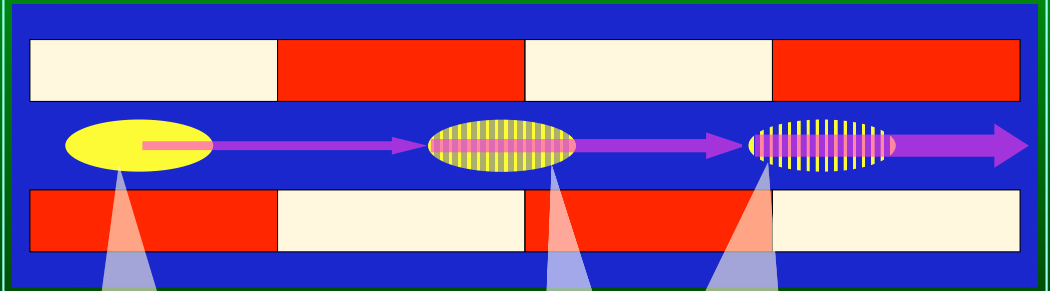
Active medium: no gas, solid or liquid but "free electrons" in an accelerator: hight power possible without damage

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:

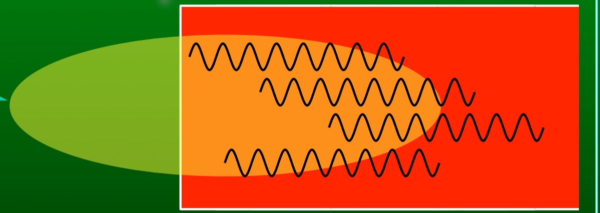


A bunch of electrons enters the wiggler: some of them stochastically start emitting waves

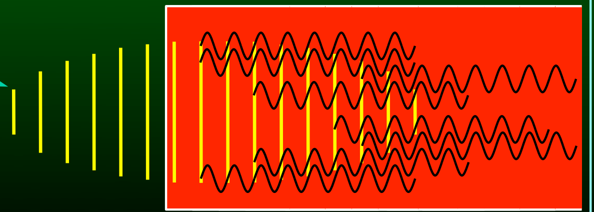
The combined wiggler+wave action progressively microbunches the electrons. The emission of microbunched electrons enhances the previously emitted waves

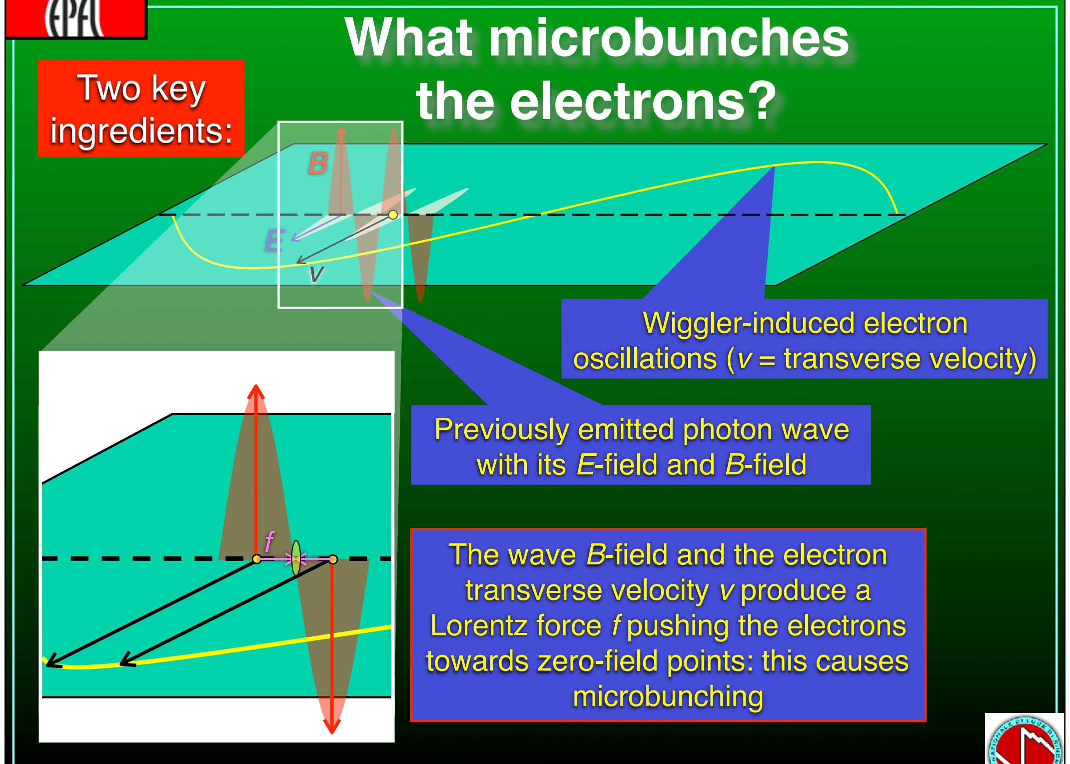
Microbunching makes the difference: this is what happens from the electron point of view:

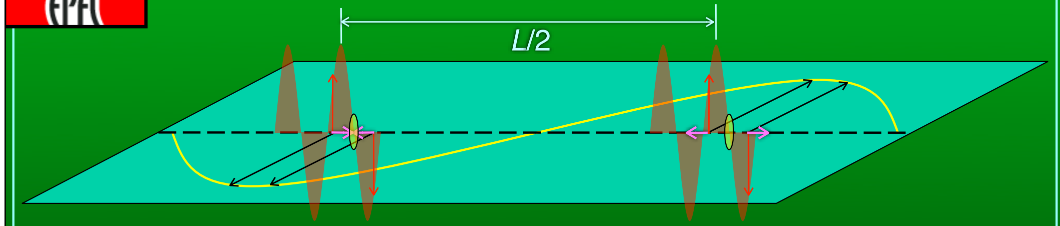
With no microbunching, as electrons enter the **wiggler**, they emit in an uncorrelated way



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

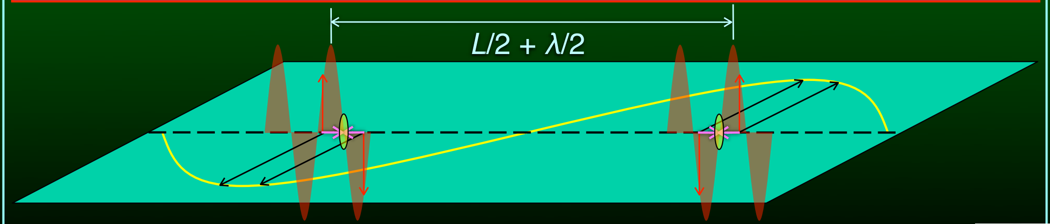



What microbunches the electrons?
Two key ingredients:
B
E
v
Wiggler-induced electron oscillations (v = transverse velocity)
Previously emitted photon wave with its E-field and B-field
f
The wave B-field and the electron transverse velocity v produce a Lorentz force f pushing the electrons towards zero-field points: this causes microbunching



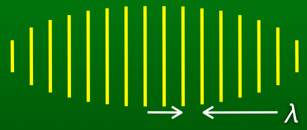
…but something seems wrong: after 1/2 wiggler period, the electron transverse velocity is reversed. If the wave travels together with the electron, the *B*-field stays the same. Are the forces and the microbunching reversed?

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



the forces are not reversed, microbunching continues

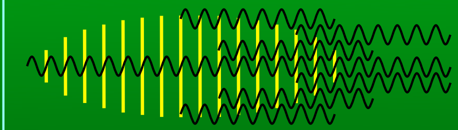
Why is microbunching (and lasing) more difficult for x-rays than for longer wavelengths?



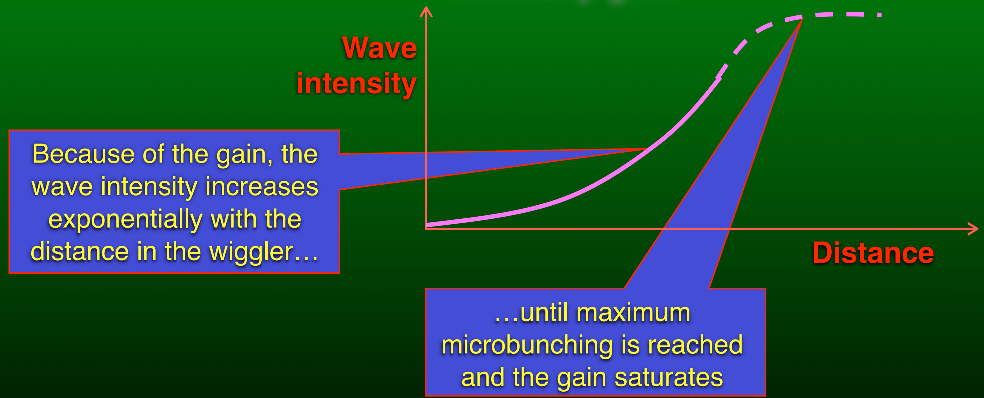
On one hand, at short wavelengths the microbunches are closer to each other and this facilitates microbunching

But:

- **Short 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 proportional to the square of the number of electrons, and a wave intensity gain

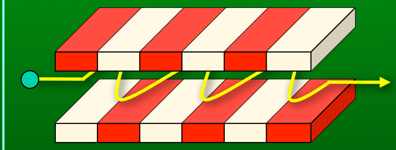


For an x-ray FEL (no 2-mirror cavity), gain saturation must be reached before the end of the (very long) wiggler, in a single pass

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*

An FEL emits very short pulses:



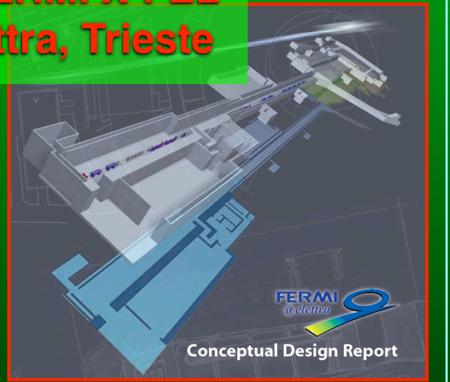
The basic physics -- we have seen that:

- **One electron emits a wave train of length $N_w\lambda$**
- **The duration of this train is $N_w\lambda/c$**

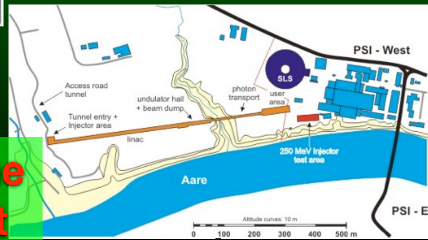
Take for example $N_w = 3\text{x}10^3$ and $\lambda = 10$ angstrom: the duration is 10^{-16} s = 0.1 femtoseconds

- **The real pulse duration and time structure are determined by the length and shape of the electron bunches and by other factors in the wave emission process**
- **But the real pulse duration can still reach the femtosecond range**

The FERMI X-FEL at Elettra, Trieste



The European X-FEL project underway at DESY, Hamburg

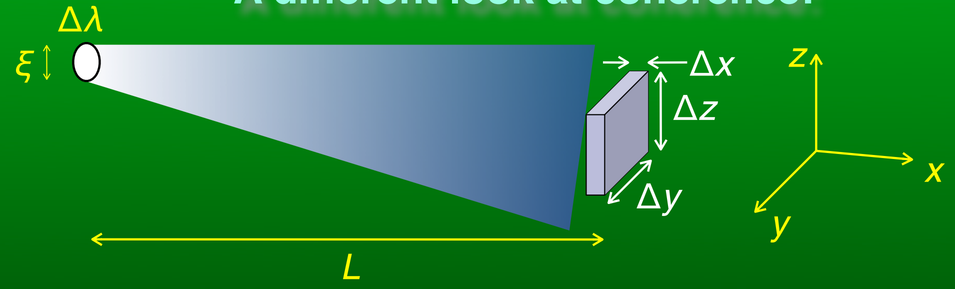


The Swiss X-FEL at the Paul-Scherrer Institut

Thanks to:

- 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).
- The POSTECH colleagues (group of Jung Ho Je).
- The Academia Sinica Taiwan colleagues (group of Yeukuang Hwu).
- The Vanderbilt colleagues (group of Norman Tolk).
- The ISM-Frascati colleagues (group of Antonio Cricenti and Paolo Perfetti)
- The facilities: PAL-Korea, Elettra-Trieste, Vanderbilt FEL, SRRC-Taiwan, APS-Argonne, SLS-Villigen, LURE-Orsay

A different look at coherence:



A source of size ξ and bandwidth $\Delta\lambda$ can illuminate coherently a volume $\Delta x\Delta y\Delta z$ at the distance L. Let us see what is this coherence volume.

Along x : if two waves of wavelength λ and $\lambda + \Delta\lambda$ are in phase ar a certain time, they will be out of phase after Δt such that $\Delta\omega\Delta t = 2\pi$ or $\Delta t = 2\pi/\Delta\omega = \lambda^2/(c\Delta\lambda)$.

Thus, $\Delta x = c\Delta t = \lambda^2/\Delta\lambda = L_c$.

Along y : the spread in k-vector is $\Delta k = k\xi/L = 2\pi\xi/(L\lambda)$.

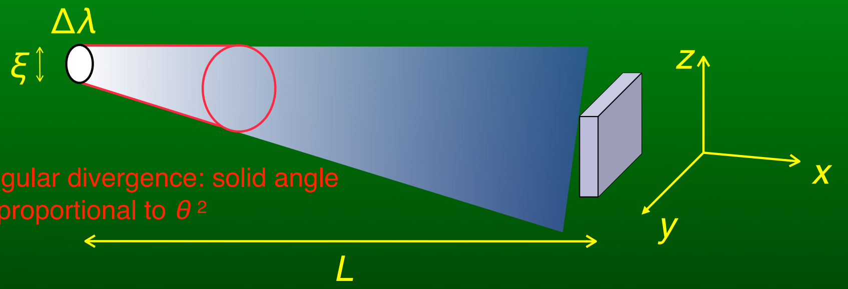
If two waves with k-vectors 0 and Δk along y are in phase at a certain point, they will be out of phase at a distance Δy such that $\Delta k\Delta y = 2\pi$ or $\Delta y = L\lambda/\xi$.

Along z: same as along y.

Coherence volume: $\Delta x\Delta y\Delta z = L^2\lambda^4/(\xi^2\Delta\lambda)$

Behind this: Heisenberg! Photons in the coherence volume cannot be distinguished from each other

This also explains the notion of "coherent power":



The solid angle corresponding to the area $\Delta y \Delta z$ is $\Delta y \Delta z / L^2$.

If the solid angle of the emitted light is $\approx \theta^2$, then only a portion $(\Delta y \Delta z / L^2)/\theta^2$ of the total emitted power illuminates the coherence volume.

This is the coherent power.

Since $\Delta y \Delta z = (L\lambda/\xi)^2$, the coherent power equals $\approx (\lambda/\xi\theta)^2$.