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1936-1

Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

7 - 25 April 2008

Fundamentals of Synchrotron Radiation

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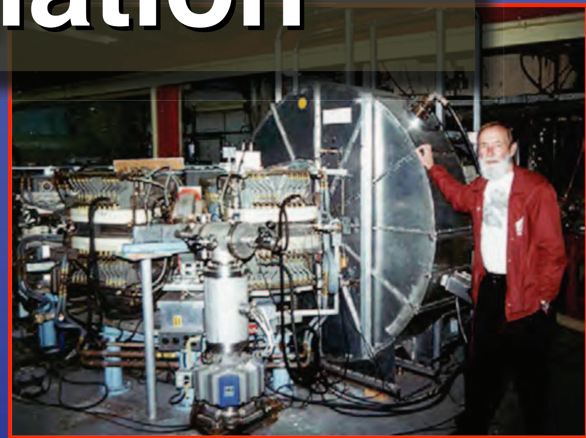
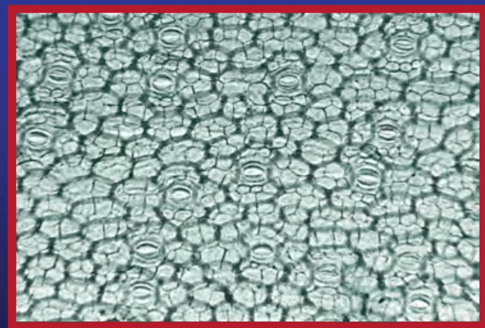
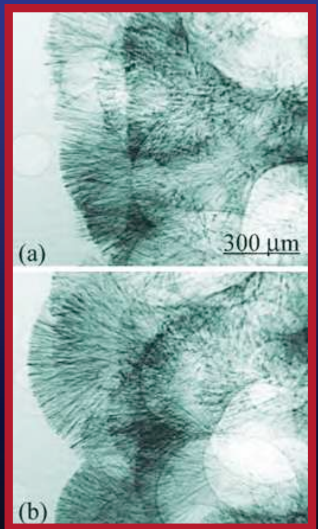
Fundamentals of Synchrotron Radiation







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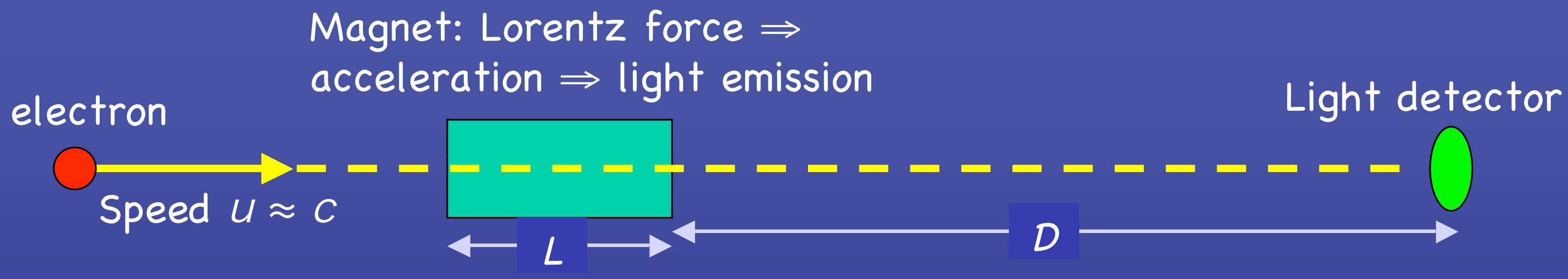
Ecole Polytechnique Fédérale de Lausanne (EPFL)

Advanced School on Synchrotron and FEL Sources and their Multidisciplinary Applications - Trieste, ICTP 2008

Program:

- How to build an excellent x-ray source using Einstein's relativity
- Some examples of applications
- Coherence: a revolution in radiology
- History and future: from synchrotrons to storage rings and to free electron lasers

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



Light pulse starts at $(L+D)/c$, ends at $D/c + L/u$, therefore

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

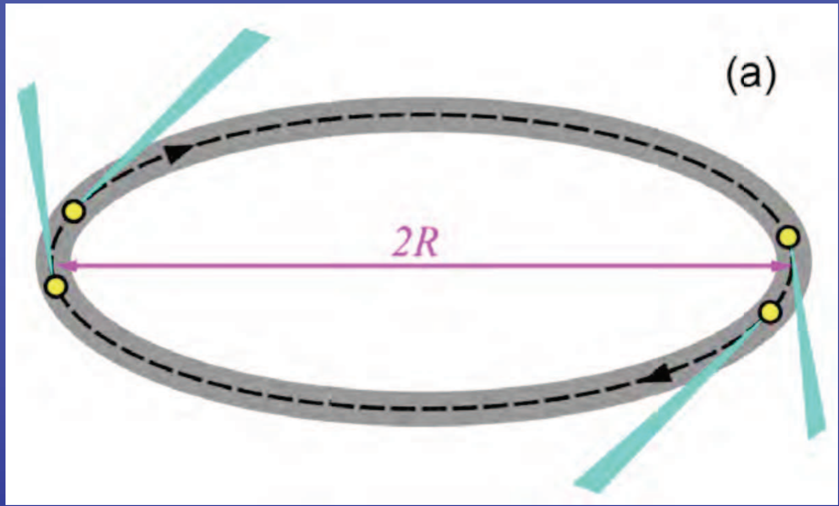
For $u \approx c$, $u(1+u/c) \approx 2c$ and $\Delta t \approx (L/2c)(1-u^2/c^2) = L/(2c\gamma^2)$

Characteristic frequency $\nu = 1/\Delta t \approx 2c\gamma^2/L \Rightarrow$ wavelength $= c/\nu \approx L/(2\gamma^2)$

For $L = 0.1$ m and $\gamma = 4000$, the wavelength is ≈ 30 angstroms: x-rays!

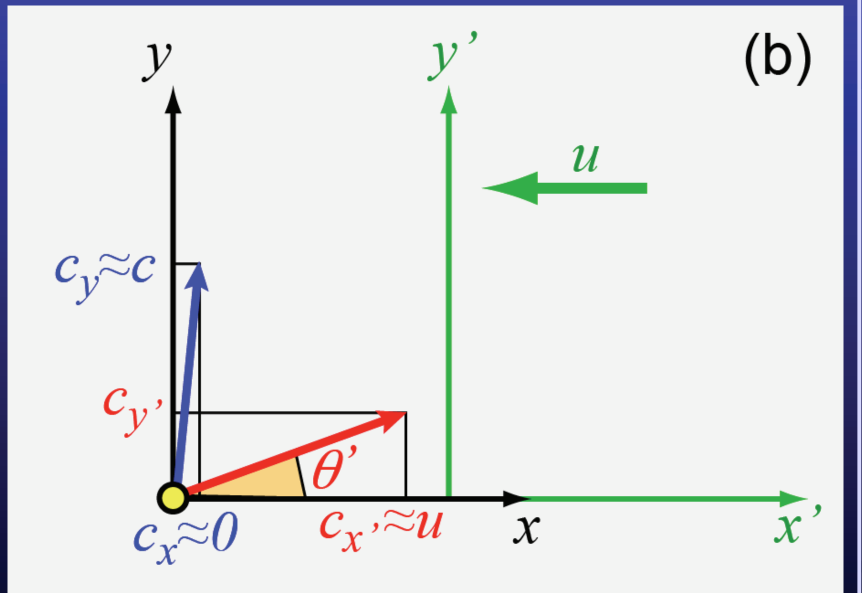
...and: in its reference frame, the electron emits in all directions, but the Lorentz transform squeezes the transverse photon velocity component by γ. The light emission angle with respect to the electron trajectory is thus squeezed to $\approx 1/\gamma$ or <1 milliradian: almost an x-ray laser!

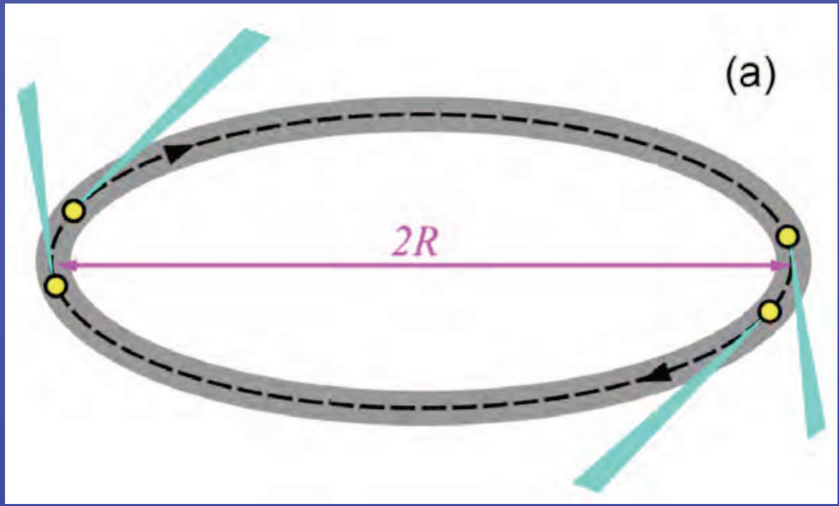
Synchrotron light in 9.5 minutes for (not entirely) lazy students (and teachers):



The electrons going around at a speed $\approx c$ in a storage ring emit synchrotron light like a "flashlight", in a narrow angular cone: why?

Answer: relativity (Lorentz transforms)! Take a photon (blue arrow) emitted almost in the transverse direction in the electron reference frame (black). Its velocity components are $c_x \approx 0$ and $c_y \approx c$. In the laboratory frame (green) its direction (red arrow) changes. The velocity components are $c_y' \approx u$ and $c_y' \approx (c^2 - u^2)^{1/2} = c/\gamma$. The angle θ' is therefore $\approx c_y'/c = 1/\gamma$ -- very narrow!!!





Seen from the side, each electron looks like an oscillating charhe in an antenna, emitting electromagnetic waves with a characteristic frequency 2πR/c -- in the radio wave range.

What shifts the emission to the x-rays?

Answer: relativity again!!! Going around the ring, the torchlight-electron illuminates a small-area detector only once per turn during a short time Δt. This is the time required for the electron to travel along a trajectory arc $L \approx R(1/\gamma)$. The time Δt starts at $(L+D)/c$ and ends at $D/c + L/u$, therefore

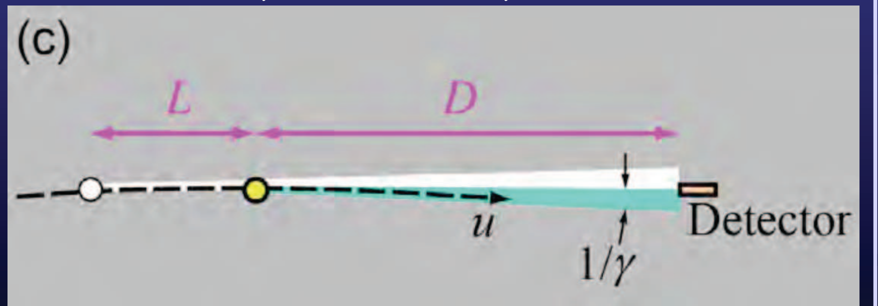
$\Delta t = L/u - L/c = (L/u)(1-u/c) = (L/u(1+u/c)](1-u^2/c^2)$

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

Characteristic frequency $\nu = 1/\Delta t \approx 2c\gamma^3/R$

$\Rightarrow$ wavelength $\approx R/(2\gamma^3)$

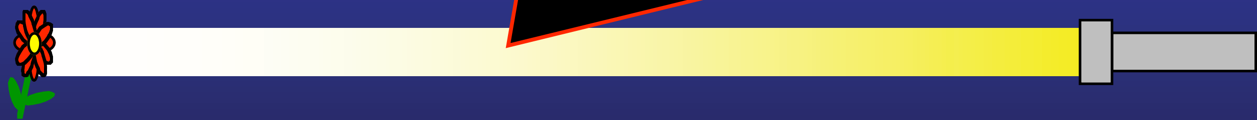
For L = 10 m and γ = 4000, the wavelength is ≈ 0.8 angstroms: again, x-rays!



From ancient fires to synchrotrons and FEL's, the same problems:

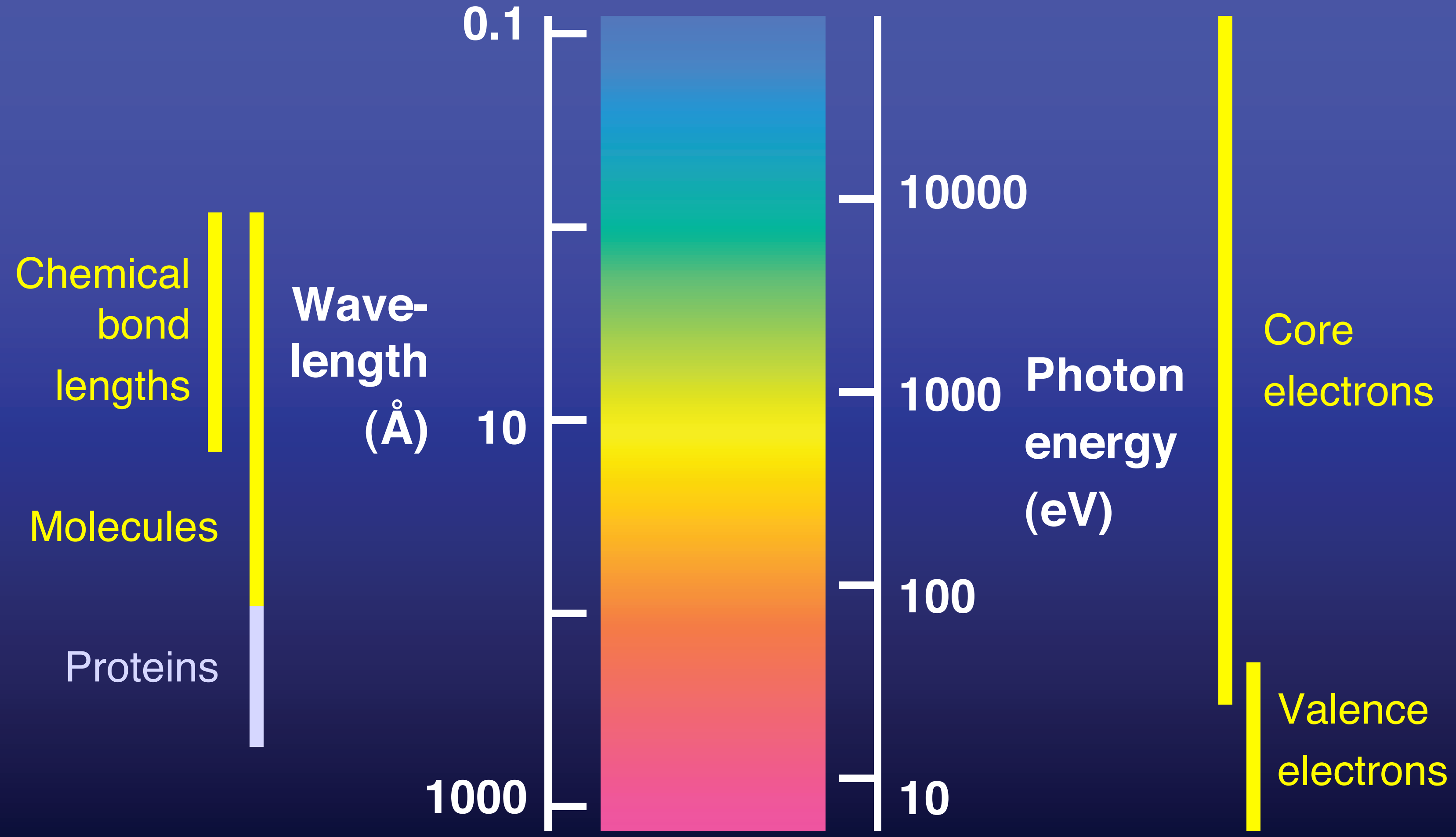
A fire is not very effective in "illuminating" a specific target: its emitted power is spread in all directions

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



Likewise, we would like to use "bright" sources for x-rays (and ultraviolet light)

Why x-rays and ultraviolet?

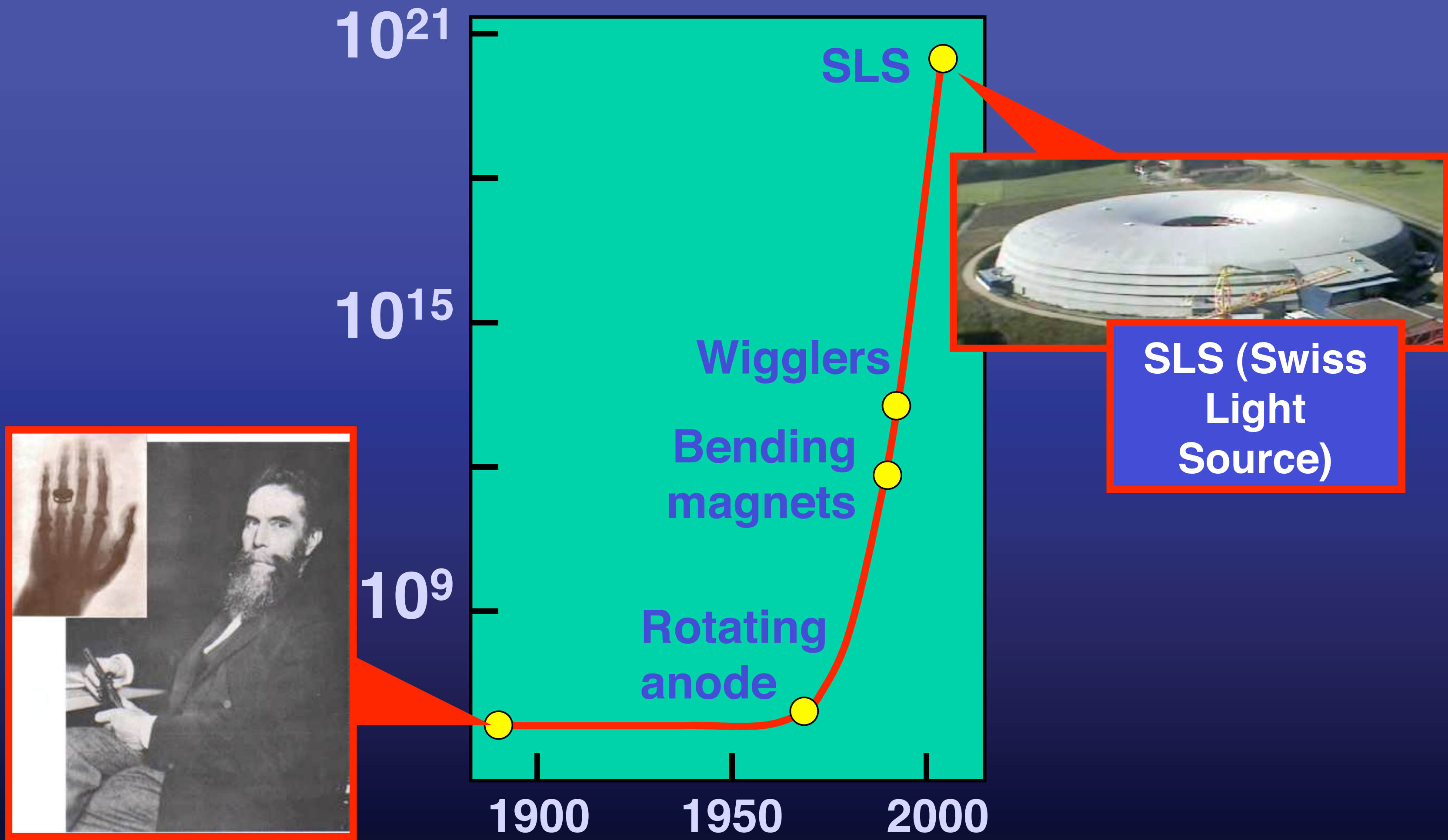


The "brightness" of a light source:

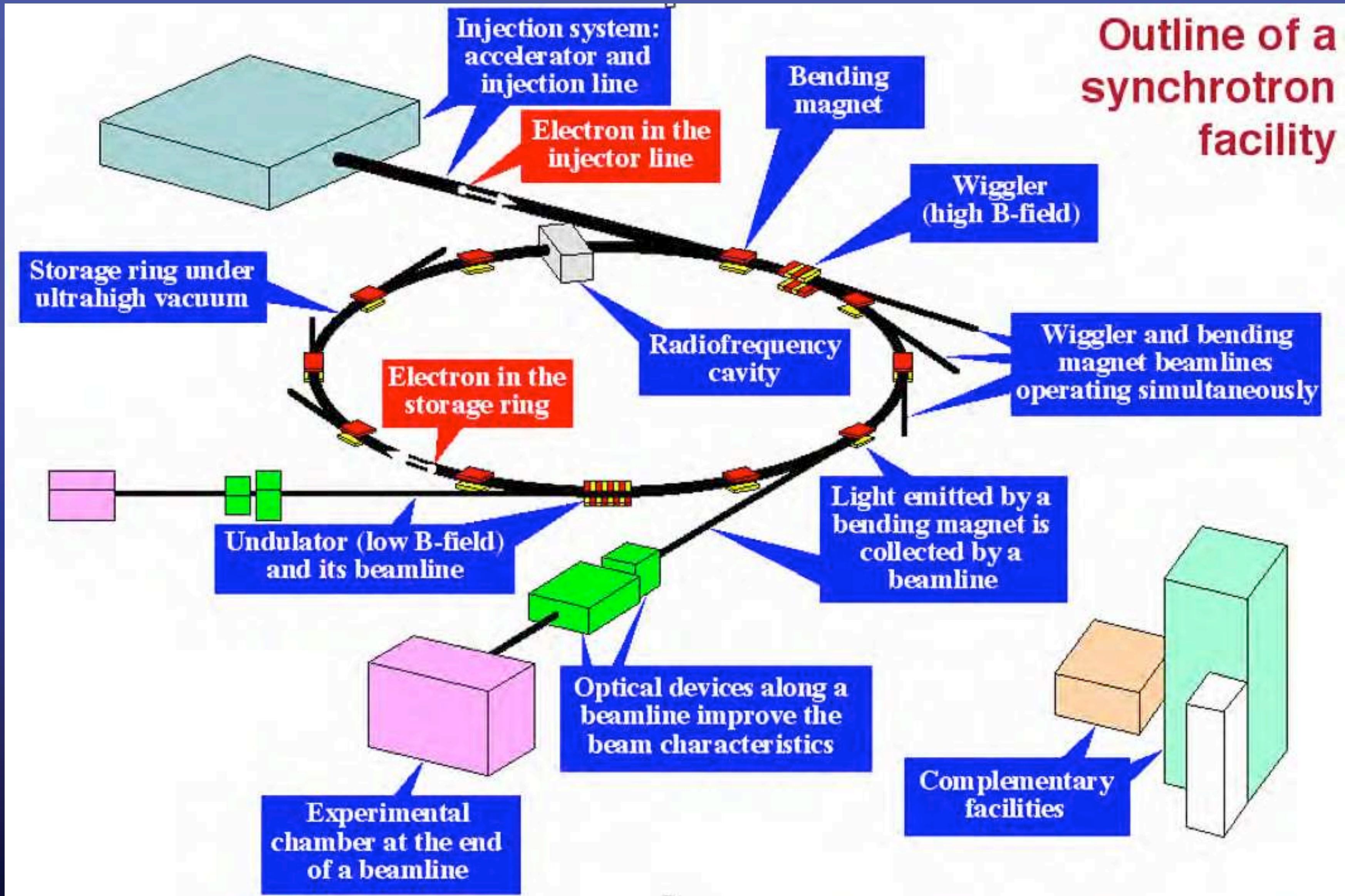
$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

The historical growth in brightness/brilliance

(units: photons/mm^2/s/$mrad^2$, 0.1% bandwidth)

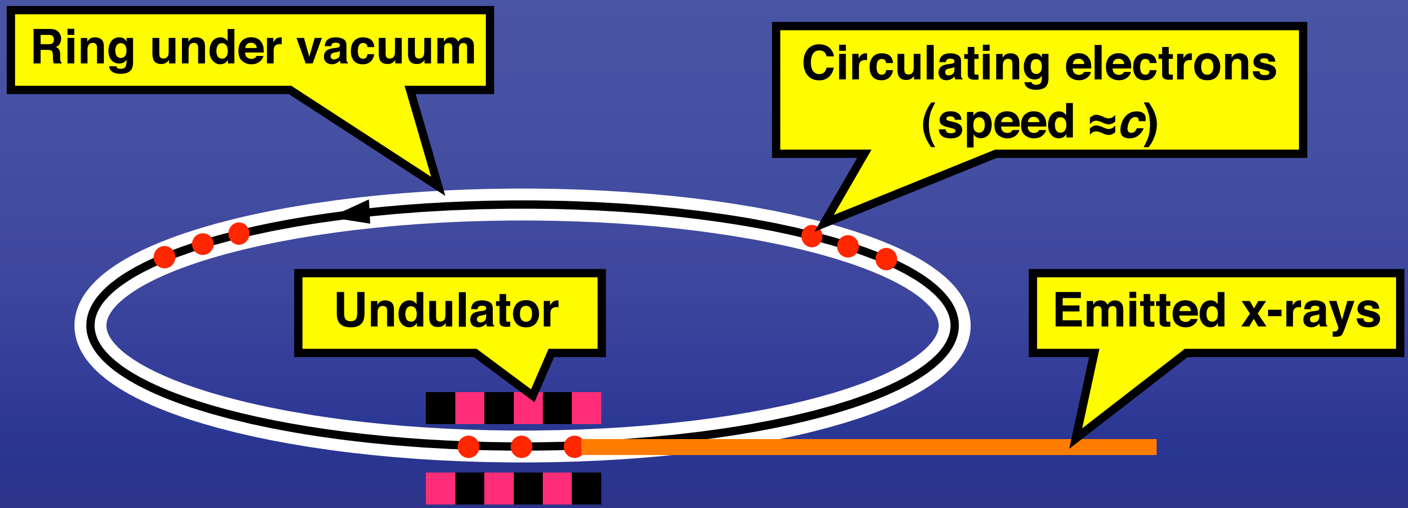


A real synchrotron facility: Swiss Light Source (SLS)


Outline of a synchrotron facility
Injection system: accelerator and injection line
Electron in the injector line
Bending magnet
Wiggler (high B-field)
Storage ring under ultrahigh vacuum
Radiofrequency cavity
Electron in the storage ring
Wiggler and bending magnet beamlines operating simultaneously
Undulator (low B-field) and its beamline
Light emitted by a bending magnet is collected by a beamline
Optical devices along a beamline improve the beam characteristics
Experimental chamber at the end of a beamline
Complementary facilities

Objective: building a very bright x-ray source.

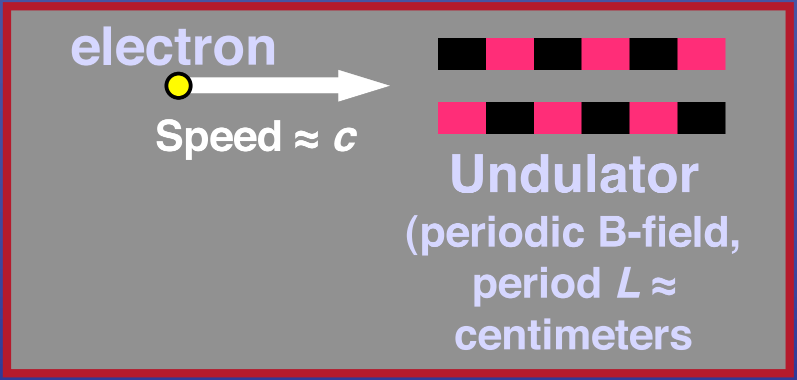
Solution: relativity!!



- 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

Details of the solution:



In the electron reference frame:

- Periodic B-field → periodic B & E-fields moving at speed ≈*c*, similar to electromagnetic wave
- Lorentz contraction: $L \rightarrow L/\gamma$
- Undulation of electron trajectory → emission of waves with wavelength L/γ

In the laboratory frame:

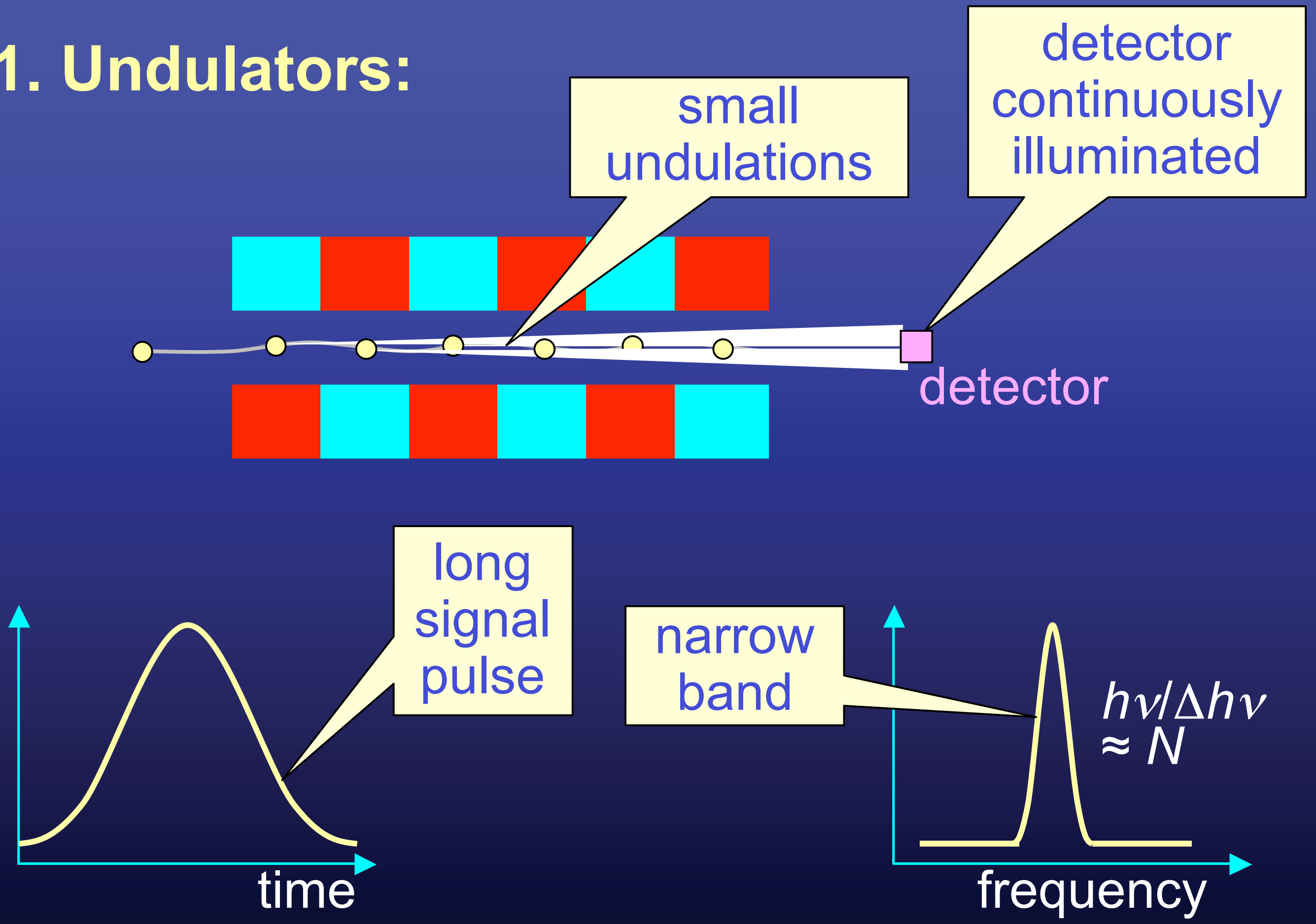
- Doppler effect → wavelength further reduced by a factor of ≈2γ, changing from L/γ to $L/2\gamma^2$

Overall: $L \rightarrow L/2\gamma^2$

Centimeters → 0.1-1,000 Å (x-rays, UV)

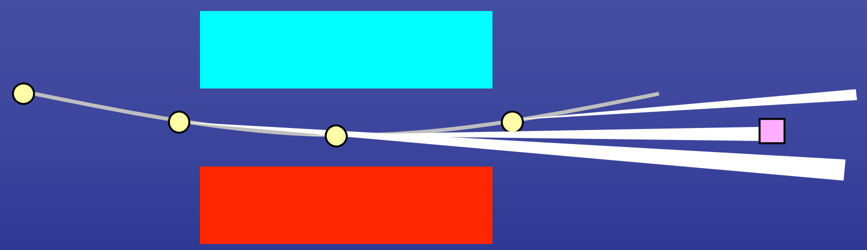
3 types of sources:

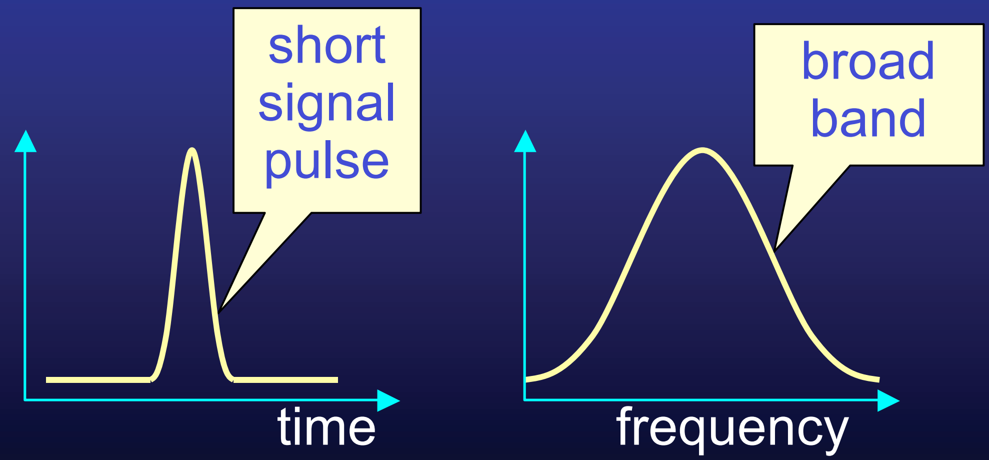
1. Undulators:



3 types of sources:

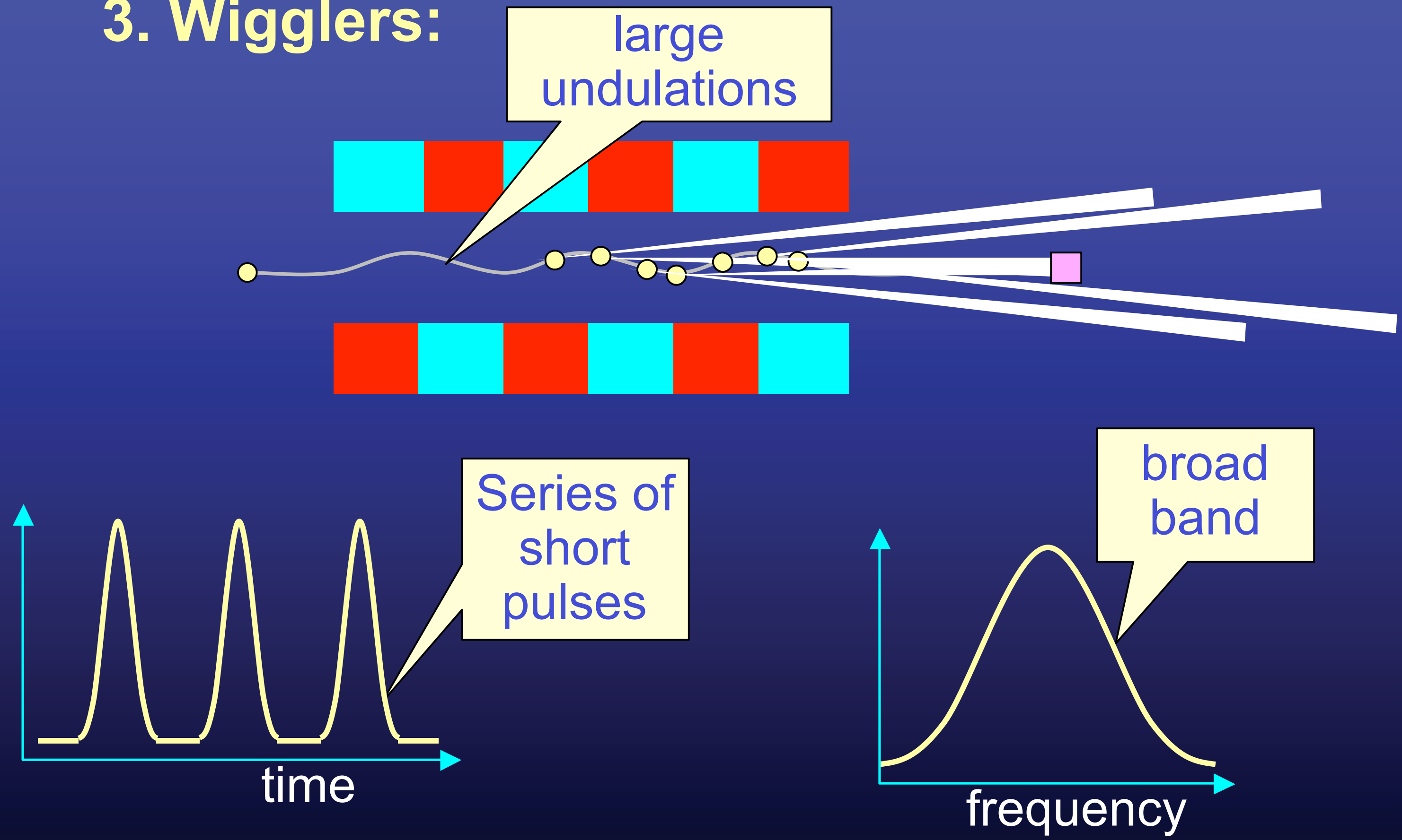
2. Bending magnets:





3 types of sources:

3. Wigglers:

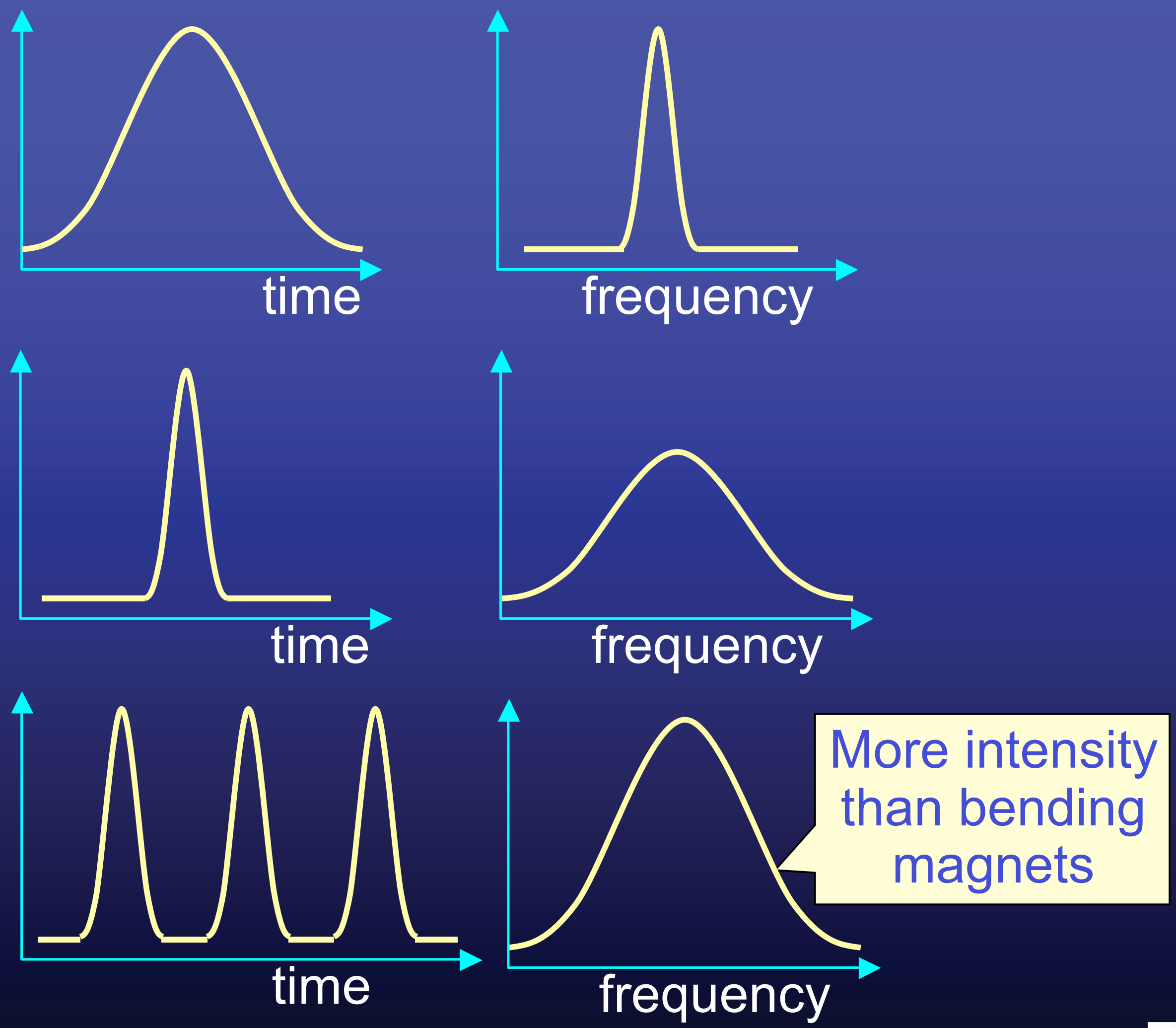


3 types of sources - summary:

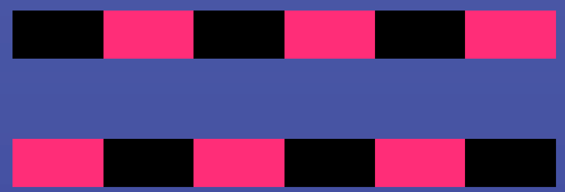
Undulators:

Bending magnets:

Wigglers:



Undulator emission spectrum:

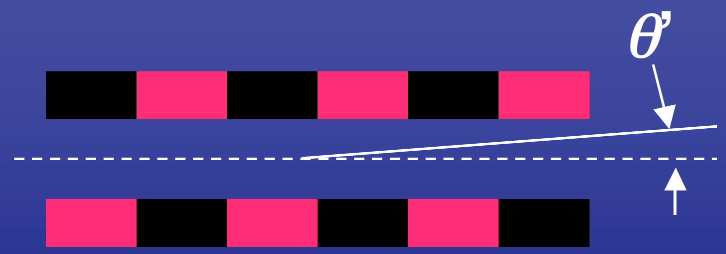


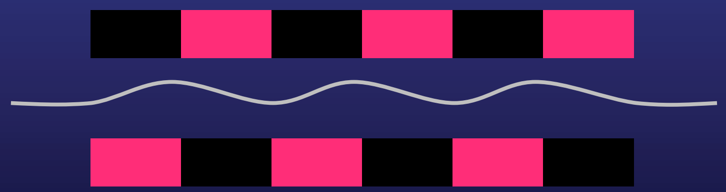
L = period

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

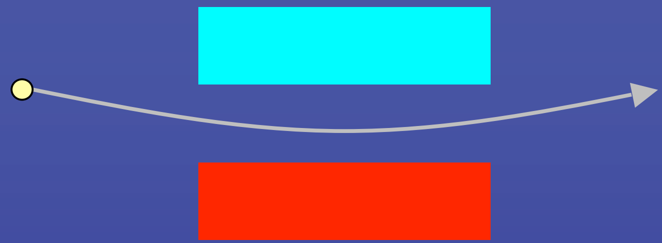




Second correction: higher B-field means stronger undulations and less on-axis electron speed. This changes γ so that:

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

Bending magnet emission spectrum:

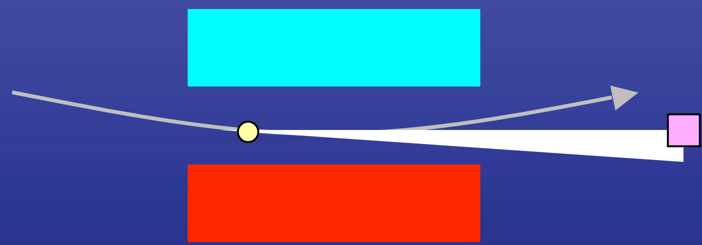


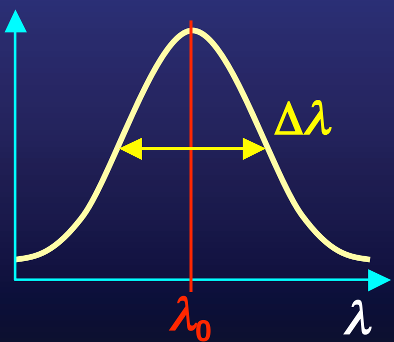
The (relativistic) rotation frequency of the electron determines the (Doppler-shifted) central wavelength:

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

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

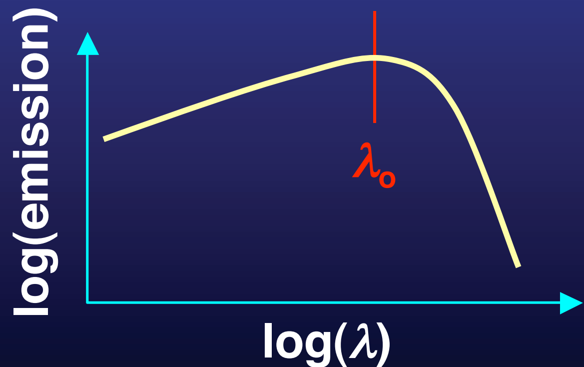
$\Delta\lambda / \lambda_o = 1$





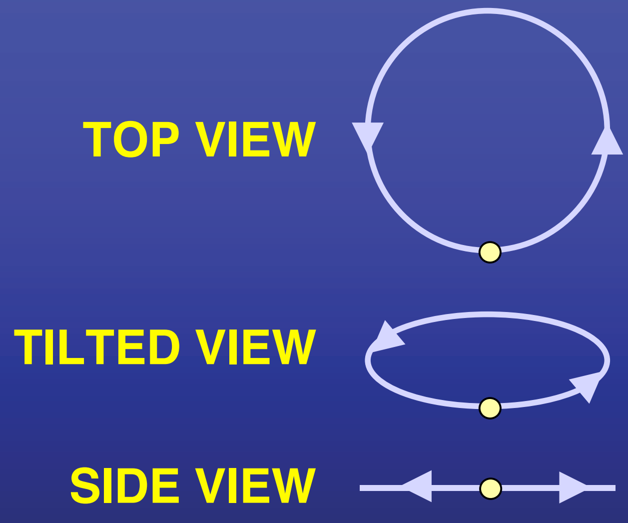
A peak centered at λ_c with width $\Delta\lambda$: is this really the well-known synchrotron spectrum?

YES -- see the log-log plot:



Synchrotron light polarization:

Electron in a storage ring:

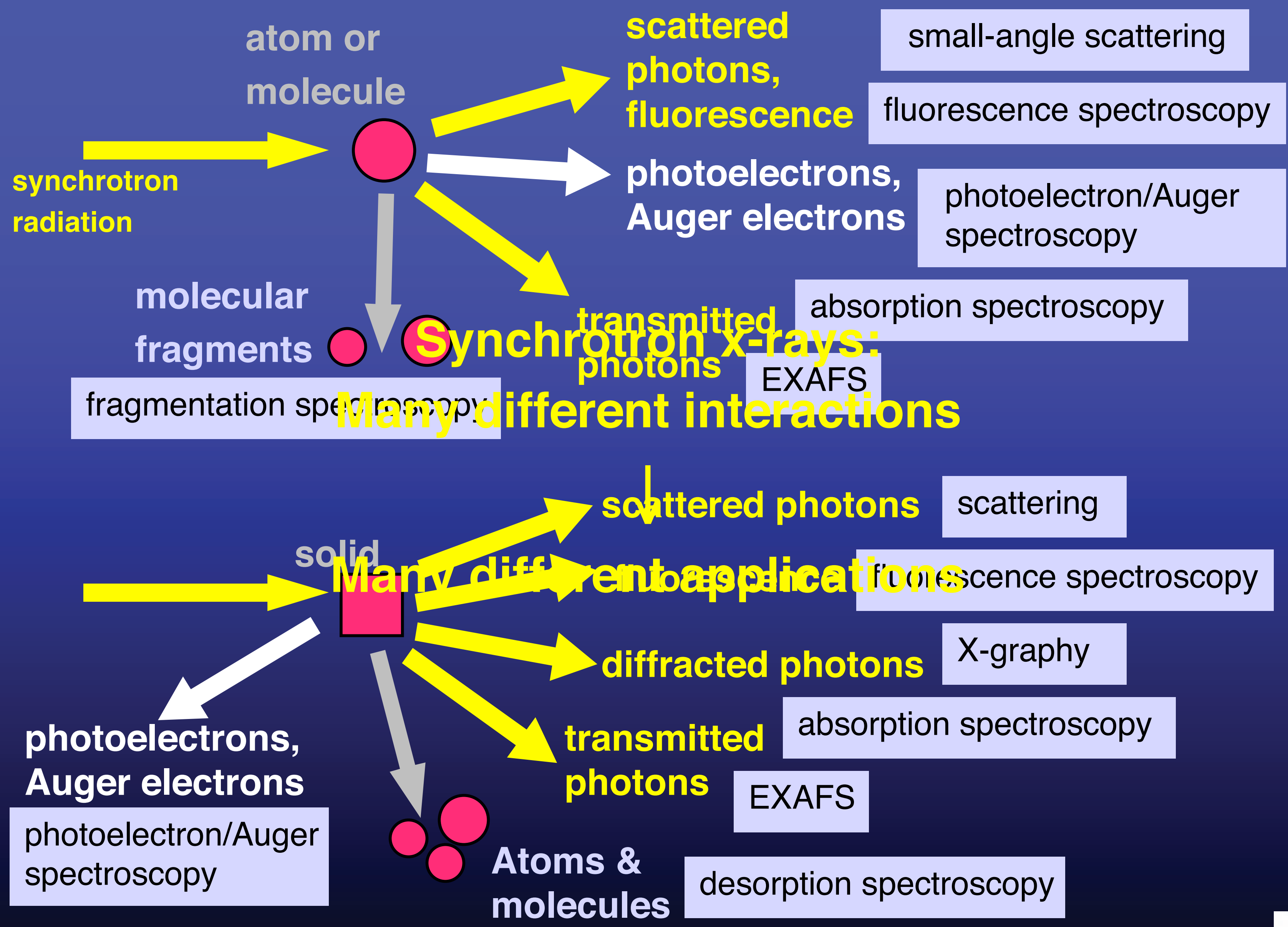


Polarization:

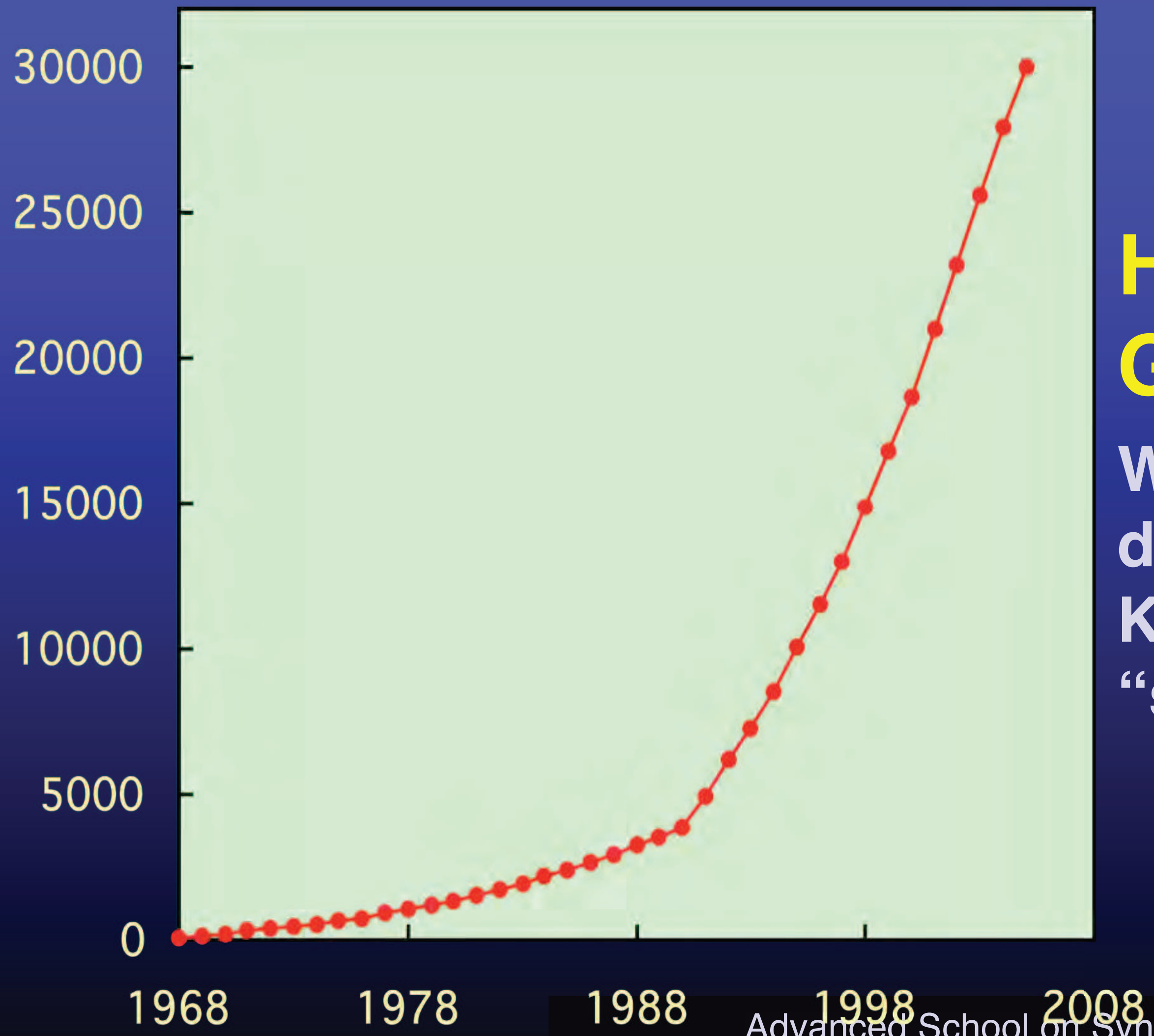
Linear in the plane of the ring, elliptical out of the plane

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

Synchrotron x-rays: Many different interactions
↓
Many different applications



Synchrotron Facilities in the World (2007):
69 in 25 Countries
(operating or under construction)

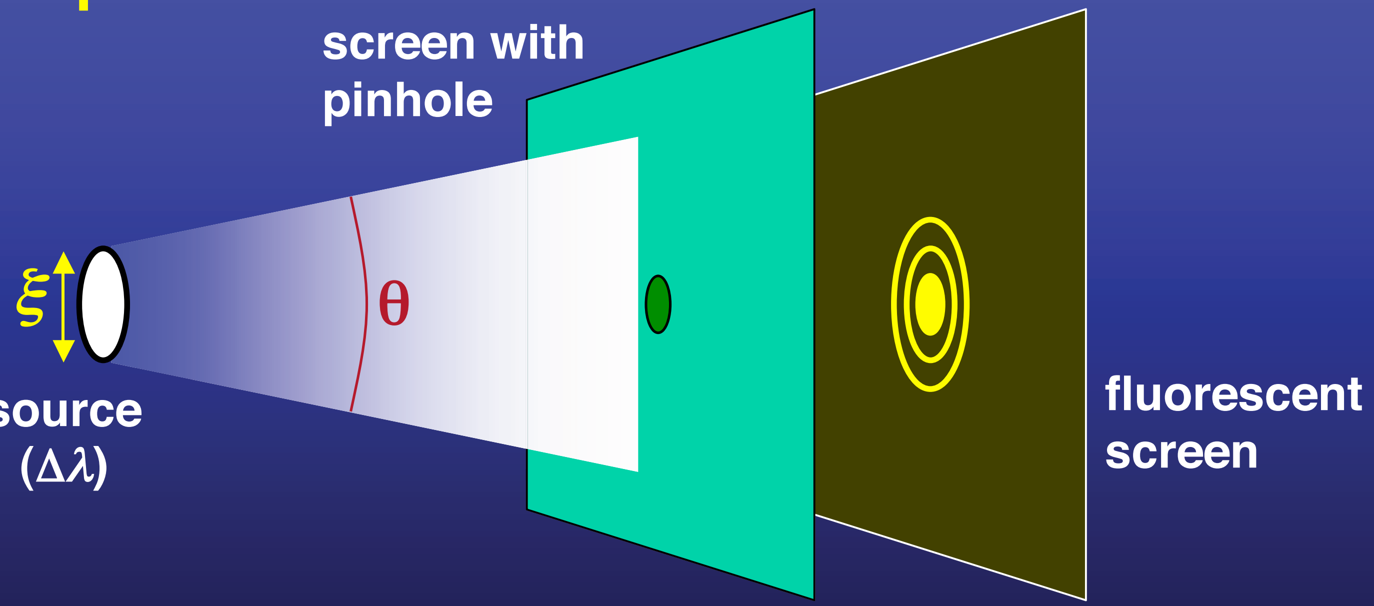


Historical Growth:

Worldwide ISI data 1968-2006, Keyword: "synchrotron"

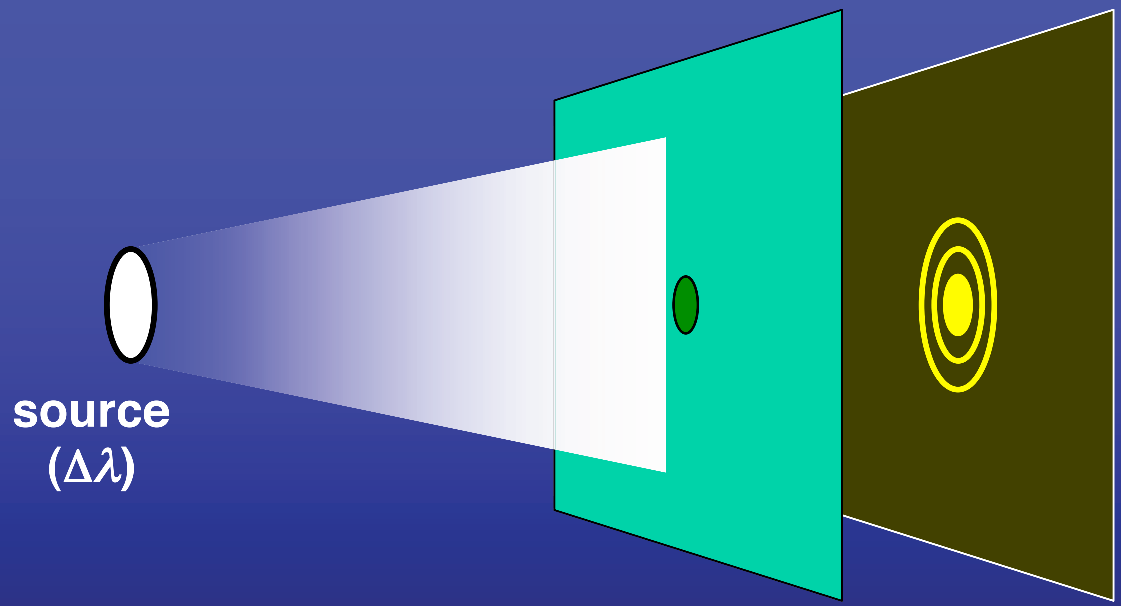
Coherence: "the property that enables a wave to produce visible diffraction and interference effects"

Example:



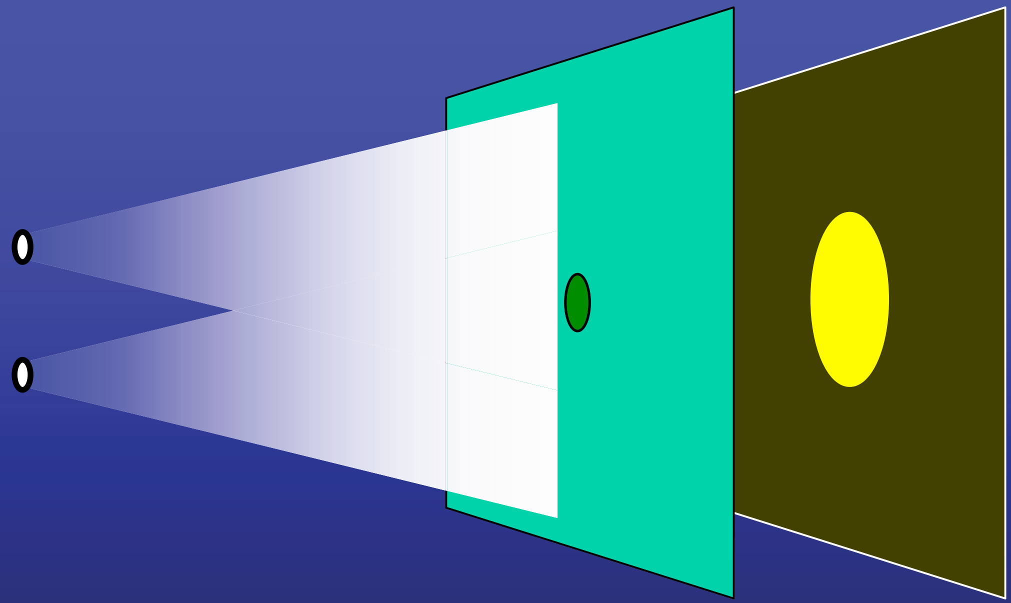
The diffraction pattern may or may not be visible on the fluorescent screen depending on the source size ξ, on its angular divergence θ and on its wavelength bandwidth $\Delta\lambda$

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:

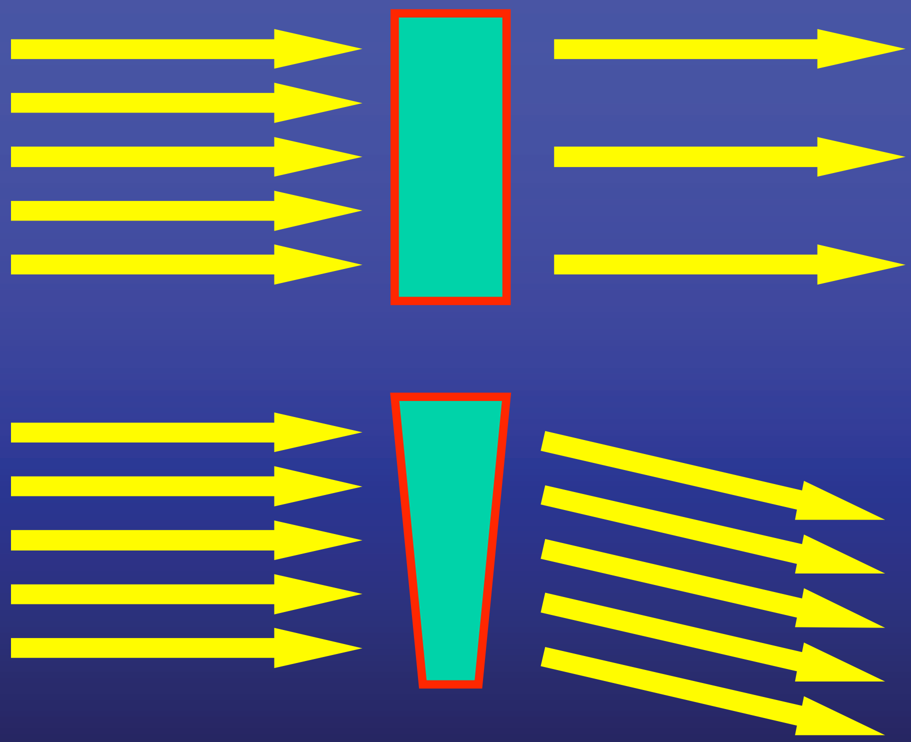


- Two point sources produce overlapping patterns: diffraction effects are no longer visible.
- However, if the two source are close to each other an overall diffraction pattern may still be visible: the condition is to have a **large "coherent power" $(2\lambda/\xi\theta)^2$**

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:

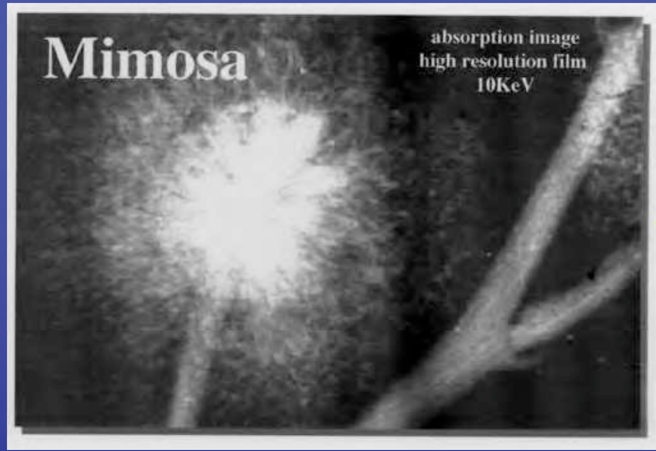


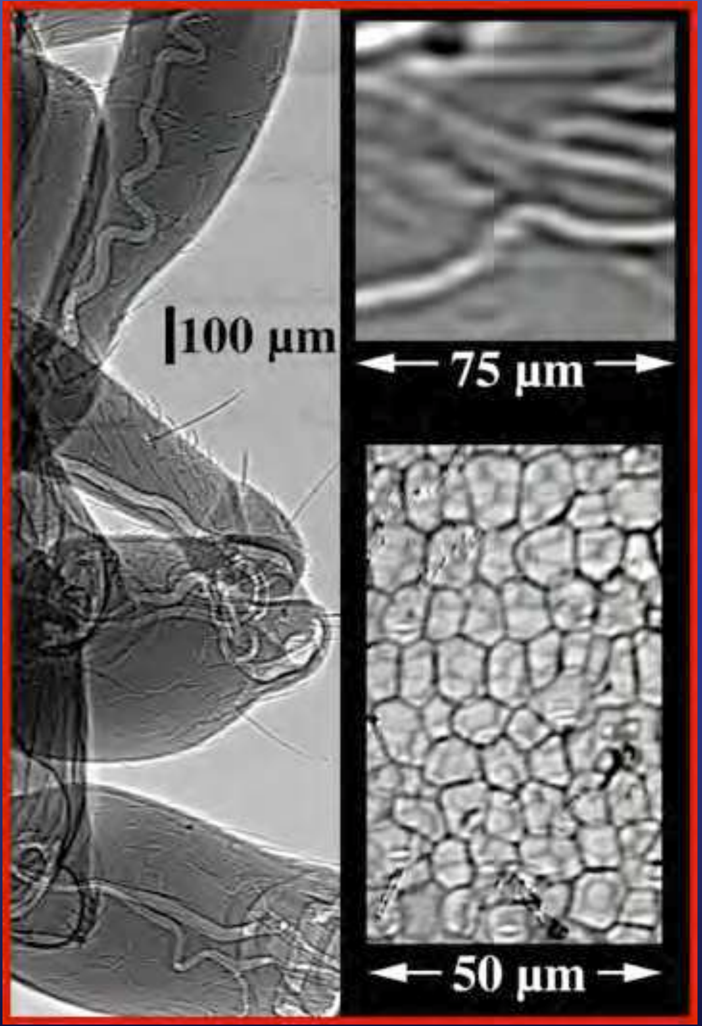
Absorption -- described by the absorption coefficient α

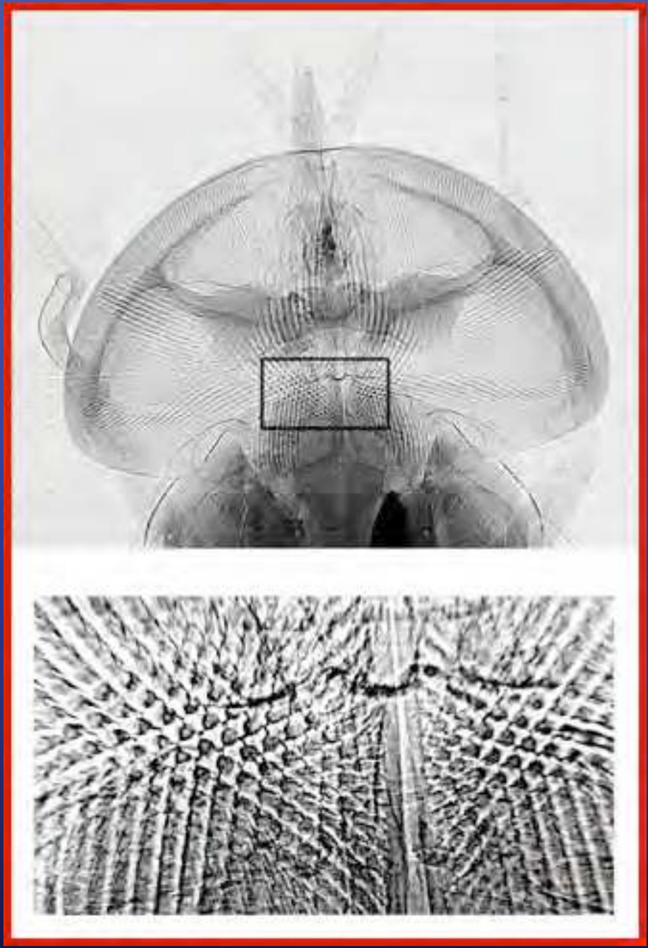
Refraction (and diffraction/interference) -- described by the refractive index n

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

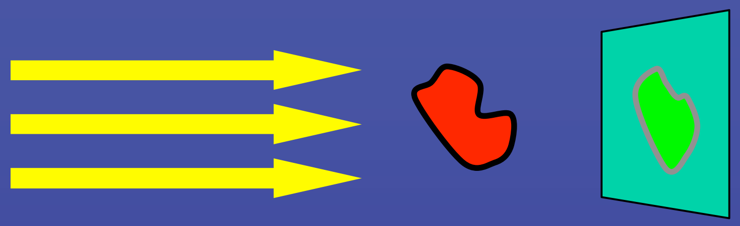
Conventional radiology



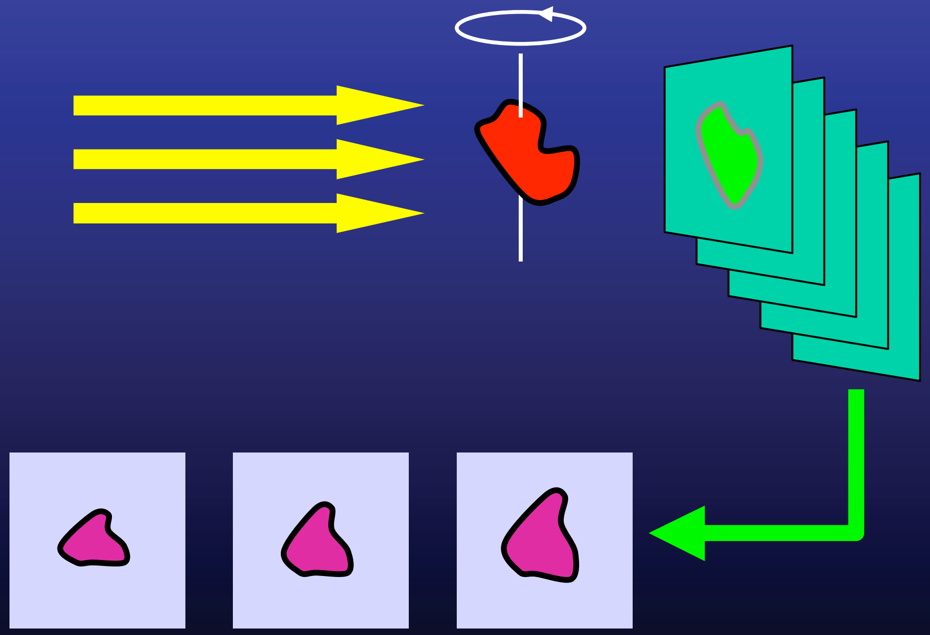

100 µm
75 µm
50 µm



X-ray (micro)tomography:

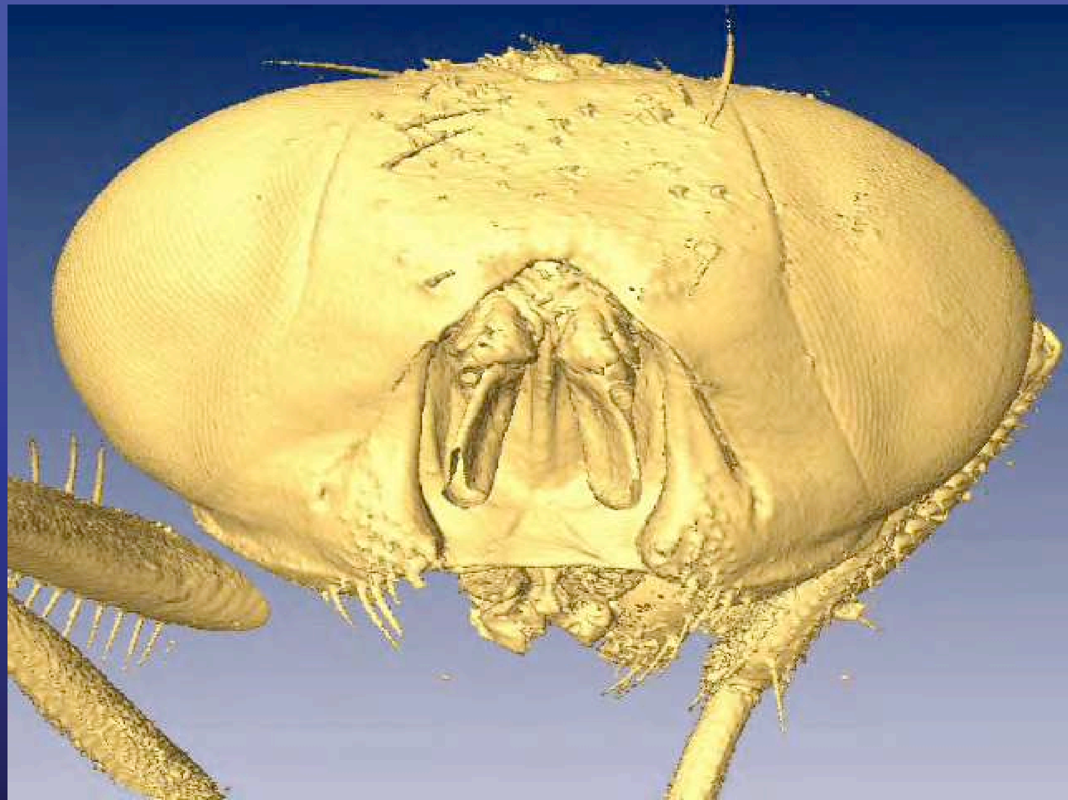


A single (projection) x-ray image does not deliver three-dimensional information



Many x-ray images taken at different angles can be computer-reconstructed in three dimensions -- and can even give movies

Phase contrast micro-tomography: housefly



Yeukuang Hwu, Jung Ho Je et al.

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

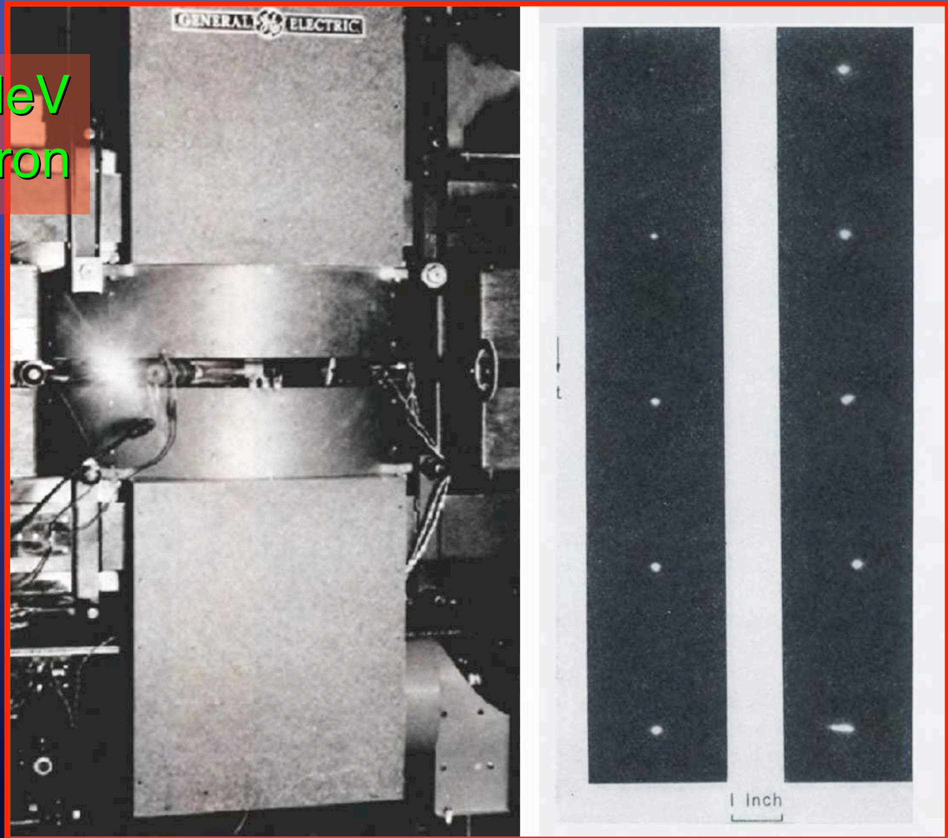
$$\delta E = \frac{4\pi}{3}\frac{e^2}{R}\left(\frac{E}{mc^2}\right)^4$$

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

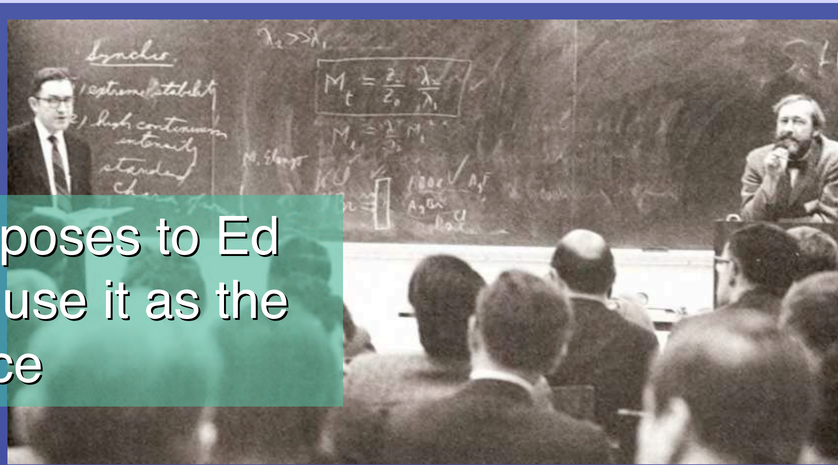
1940s: Isaak Pomeranchuk, Dmitri Ivanenko and Julian Schwinger develop a full theory

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

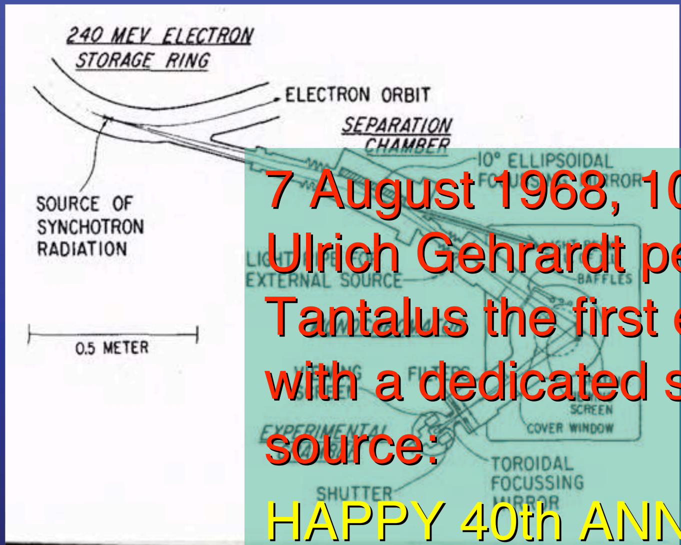
The GE 70 MeV synchrotron



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

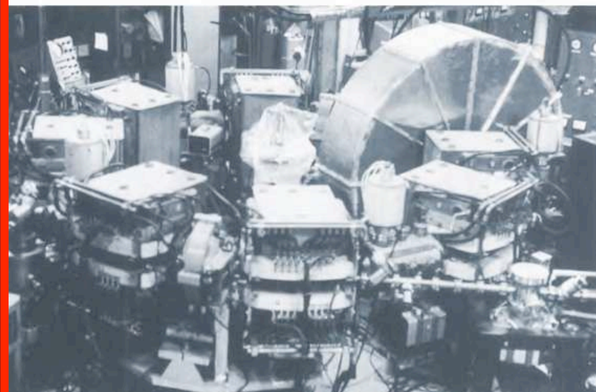


1966: Fred Brown (Urbana) proposes to Ed Rowe, the father of Tantalus, to use it as the first dedicated synchrotron source



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

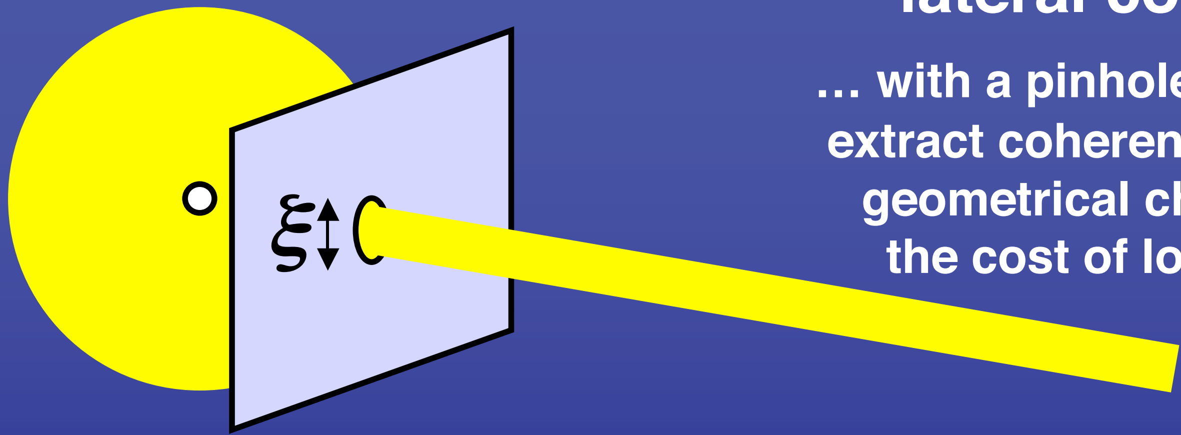
HAPPY 40th ANNIVERSARY!!!



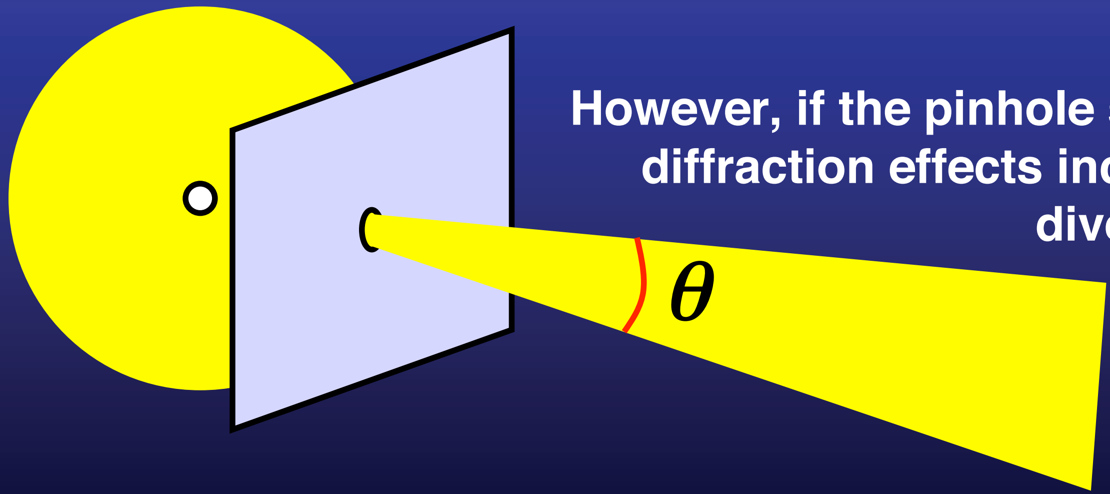
New types of sources:

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

Take a standard photon source with limited brightness and no lateral coherence …



… with a pinhole (size ξ), we can extract coherent light with good geometrical characteristics (at the cost of losing most of the emission)

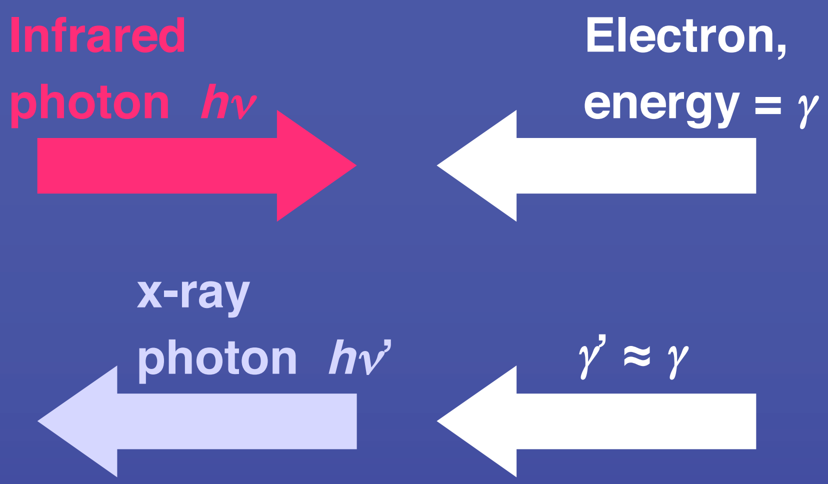


However, if the pinhole size is too small diffraction effects increase the beam divergence so that:

$$\xi\theta > \lambda$$

No source geometry beats this diffraction limit

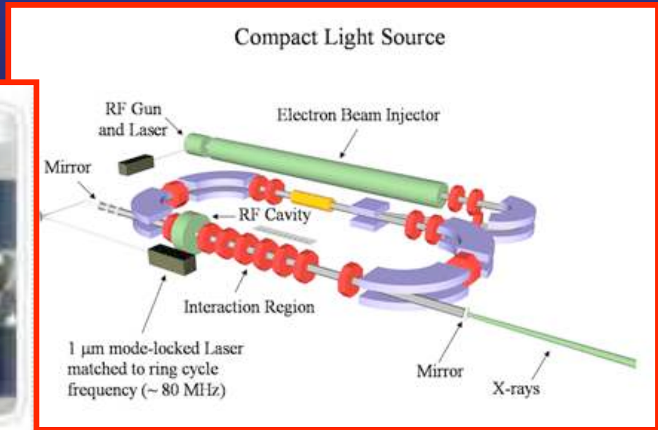
The Magic of Compton Backscattering



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:

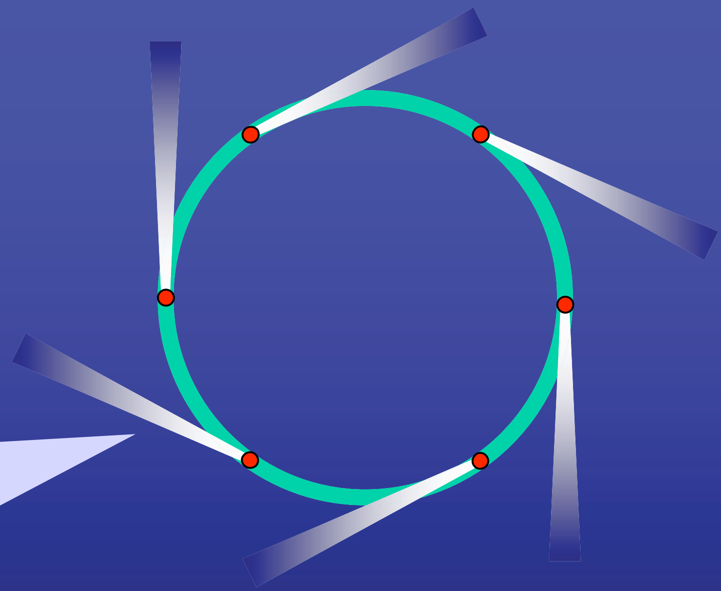
$$h\nu' \approx 4\gamma^2\ h\nu$$



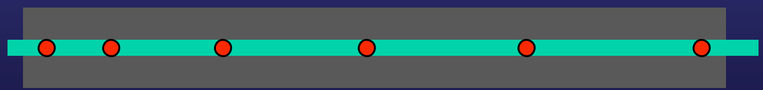
lyncean TECHNOLOGIES, INC.

Energy-recovery LINAC sources

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

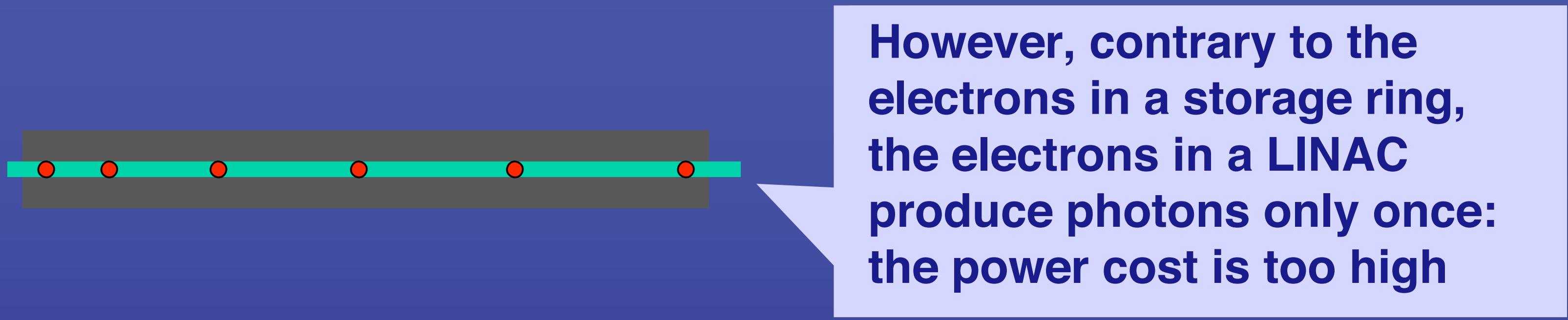


In a storage ring, the electrons continuously emit photons. This "warms up" the electron beam and negatively affects its geometry

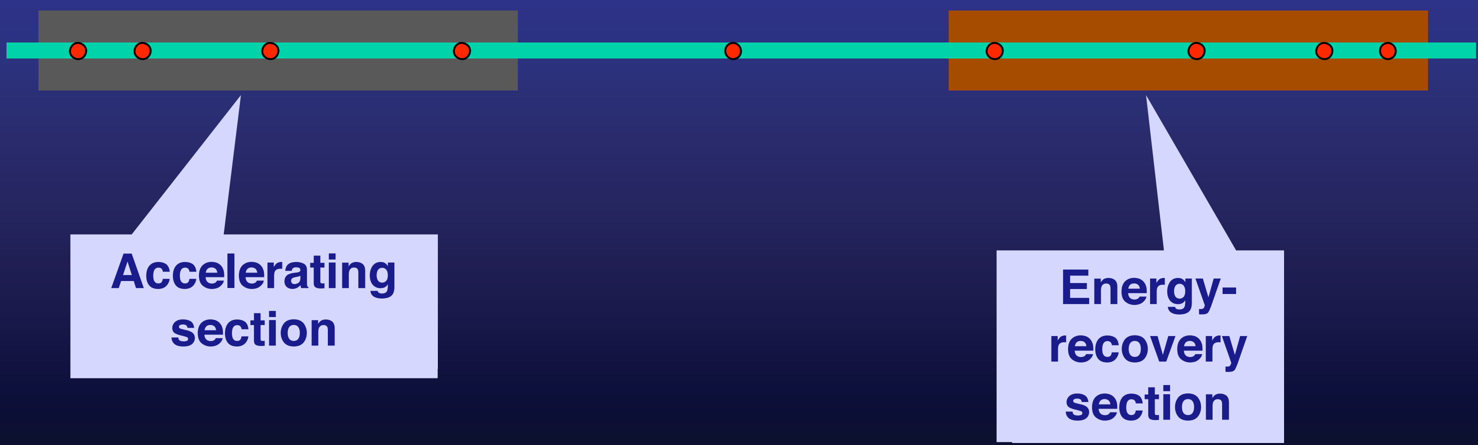


Controlling the electron beam geometry is much easier in a linear accelerator (LINAC). Thus, LINAC sources can reach higher brightness levels

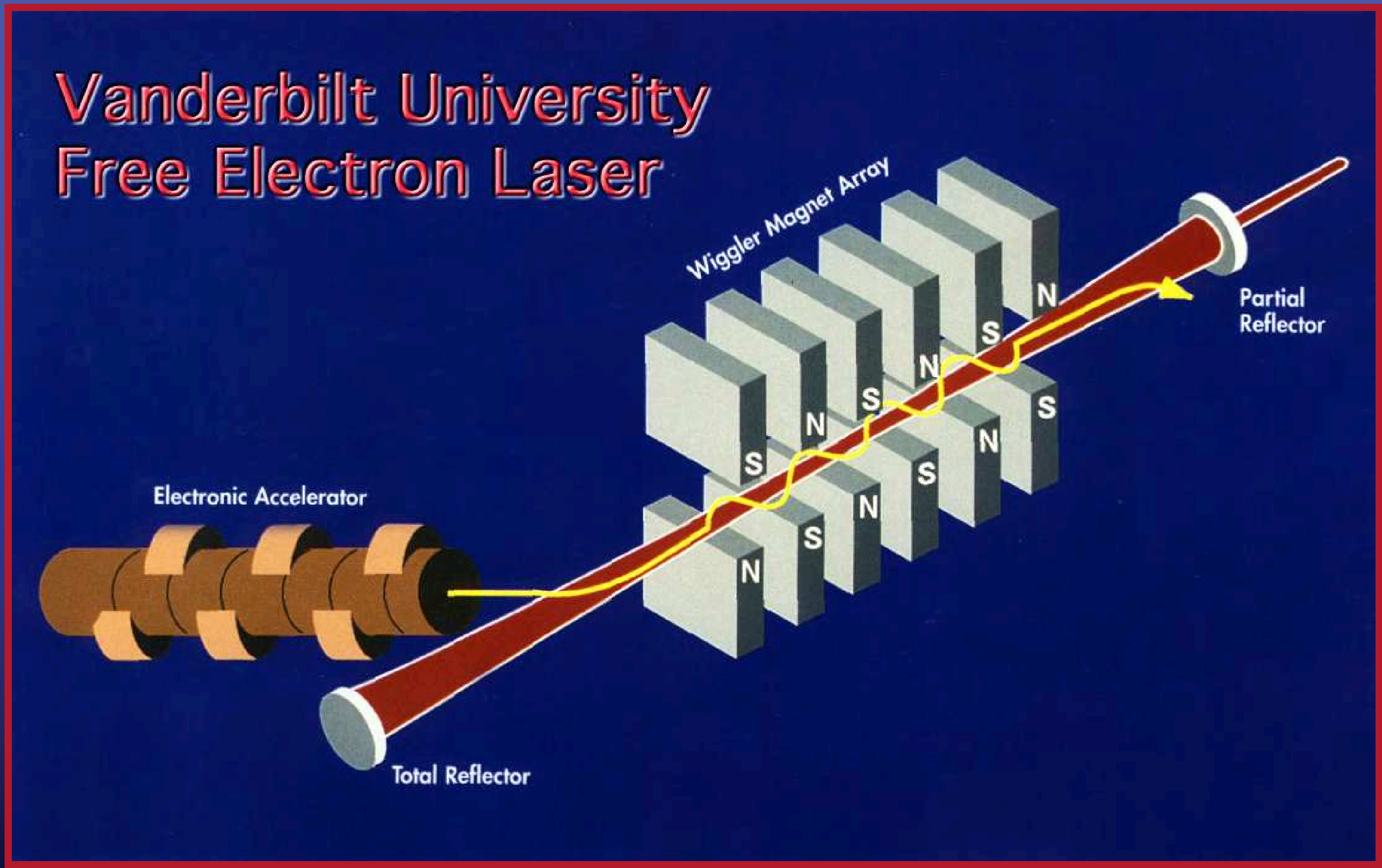
Energy-recovery LINAC sources



Solution: recovering energy



Free-electron lasers:

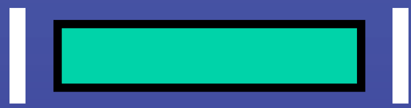


Self-amplified spontaneous emission x-ray free-electron lasers (SASE X-FEL's)

Normal (visible, IR, UV) lasers:

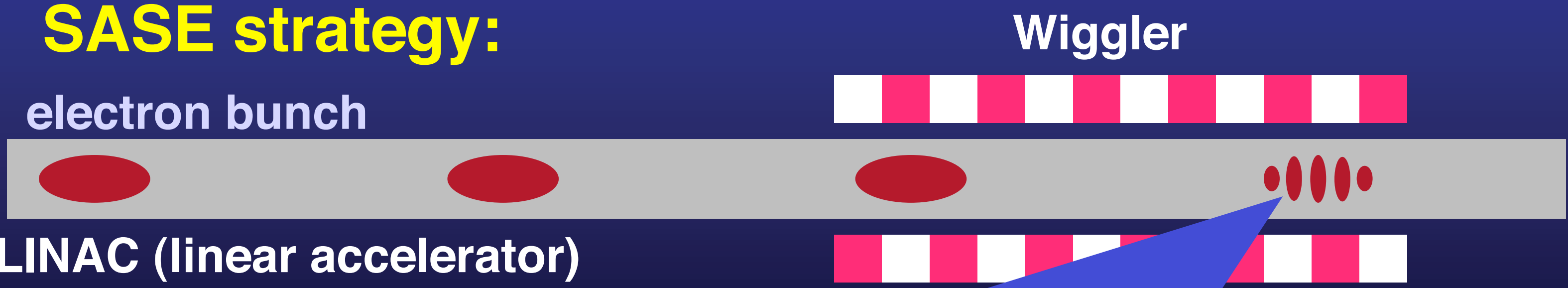
optical amplification in amplifying medium

plus optical cavity (two mirrors)



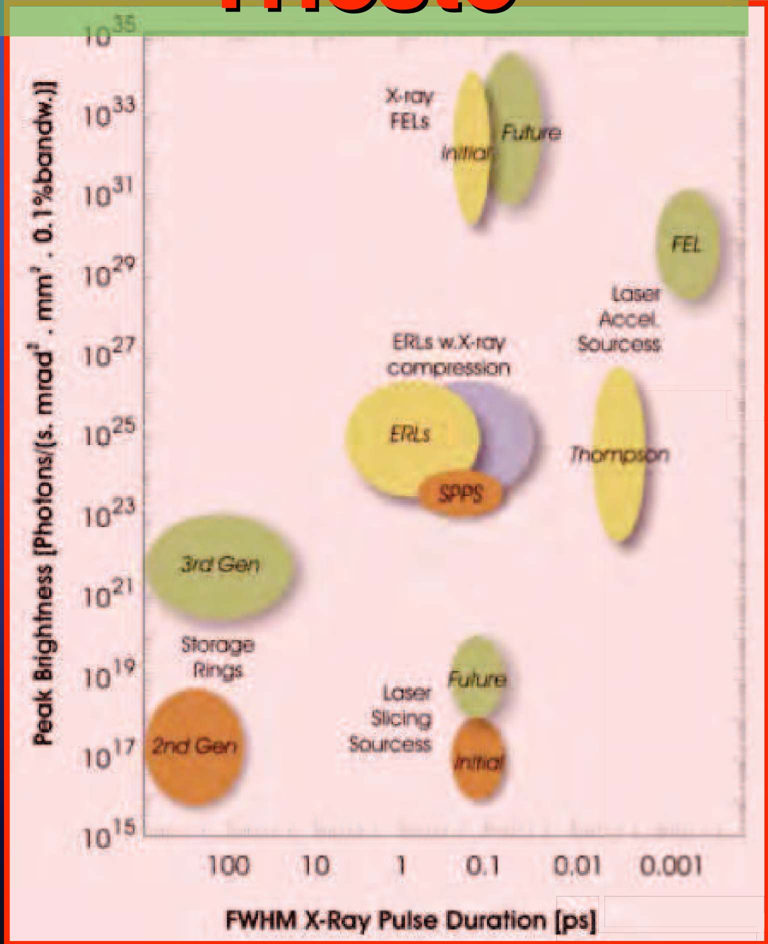
X-ray lasers: no mirrors → no optical cavity → need for one-pass high optical amplification

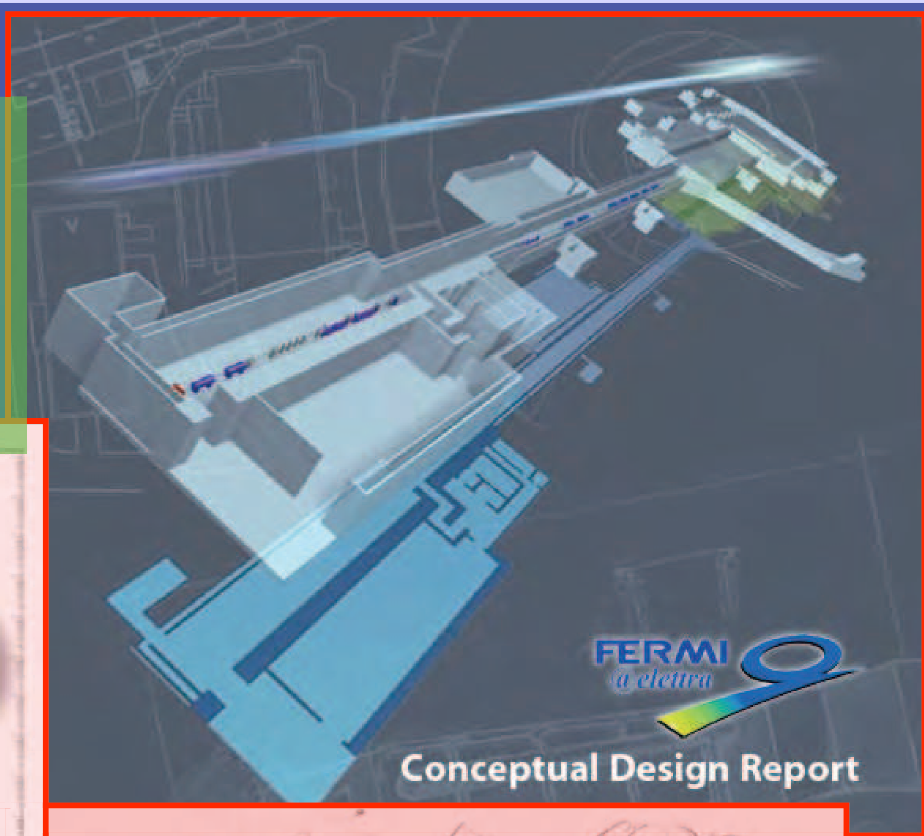
SASE strategy:



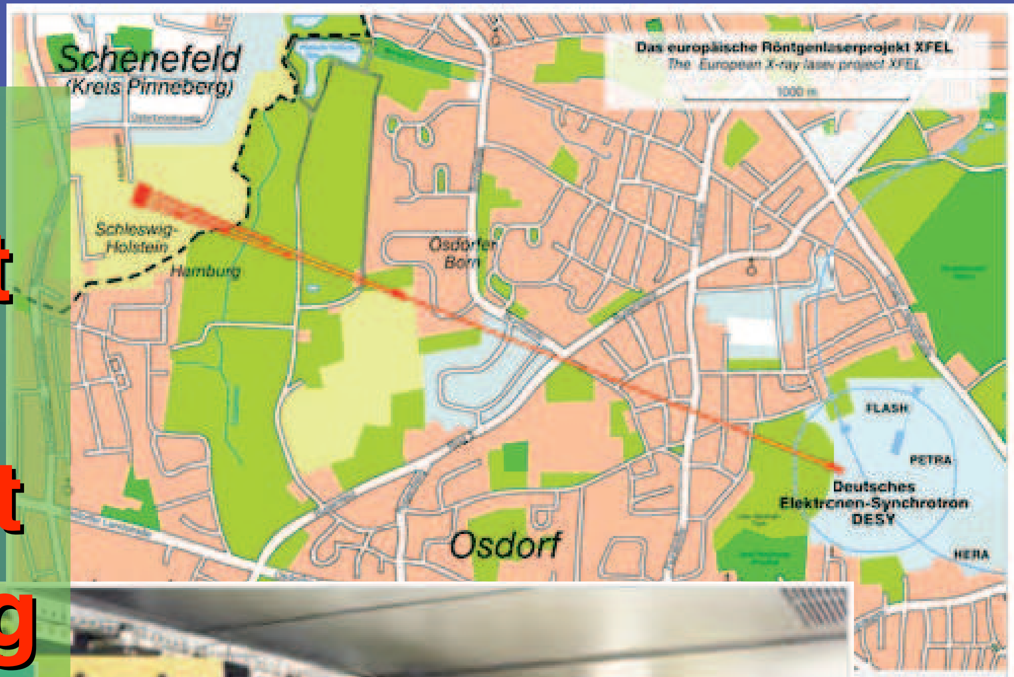
The microbunching increases the electron density and the amplification and creates very short pulses

The FERMI X-FELs at Elettra, Trieste





The European X-FELs Project under development at DESY, Hamburg



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