2139-11

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

26 April - 7 May, 2010

Properties of Synchrotron Radiation

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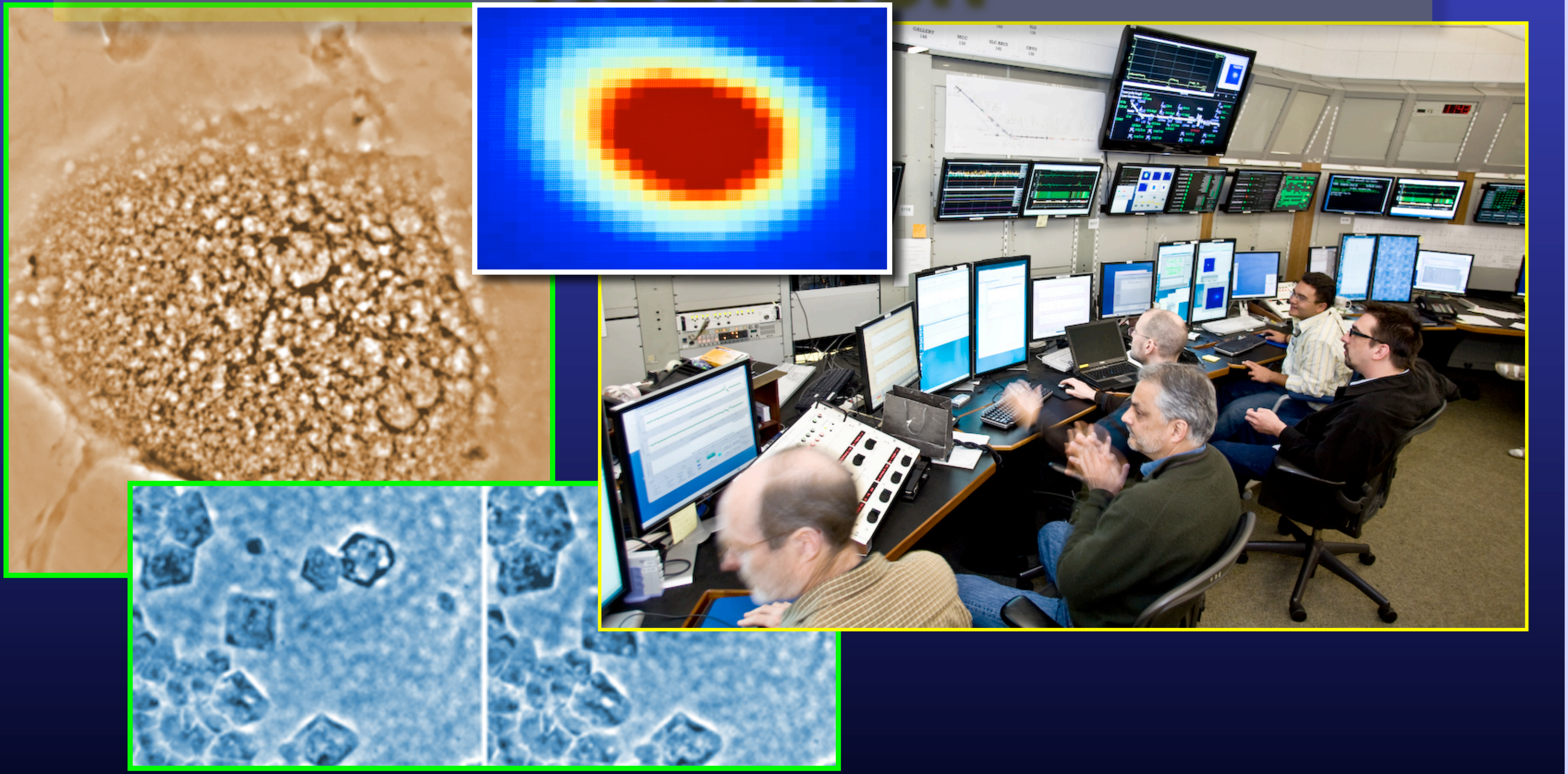


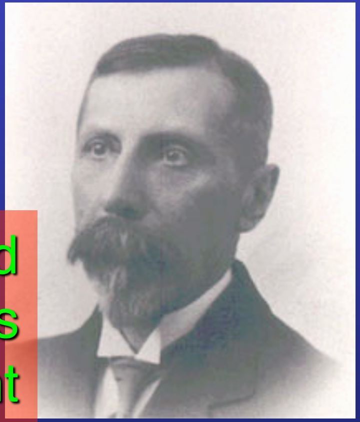
Giorgio Margaritondo

Ecole Polytechnique Fédérale de Lausanne (EPFL)

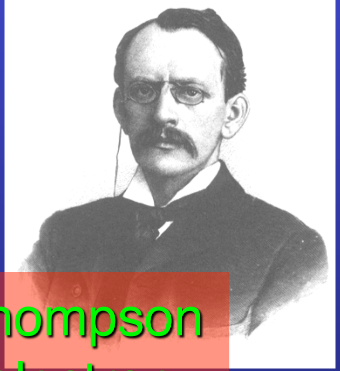
Synchrotron and FEL Sources and their Multidisciplinary Applications - Trieste, ICTP 2010

An interesting history, a bright future:

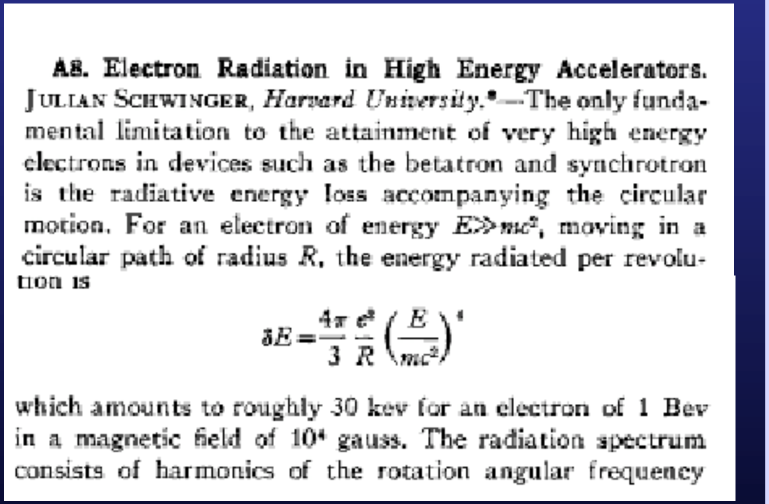
The origins:



1898 -- Alfréd Lienard conceives synchrotron light



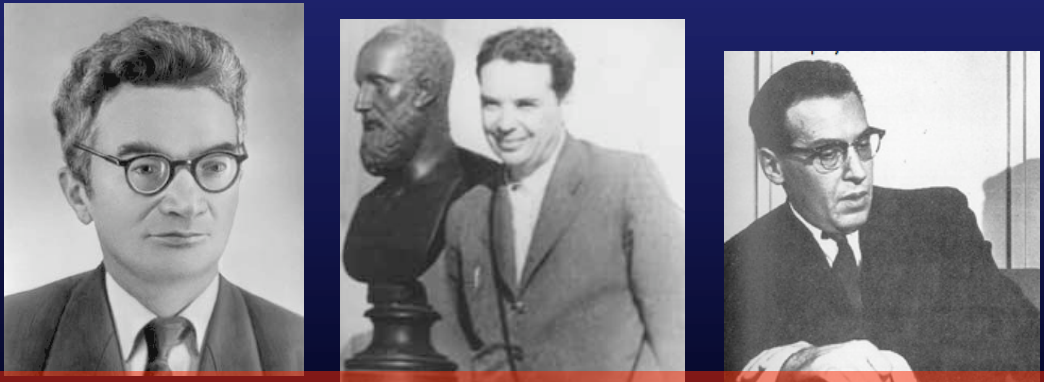
1897 -- J. J. Thompson discovers the electron



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

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

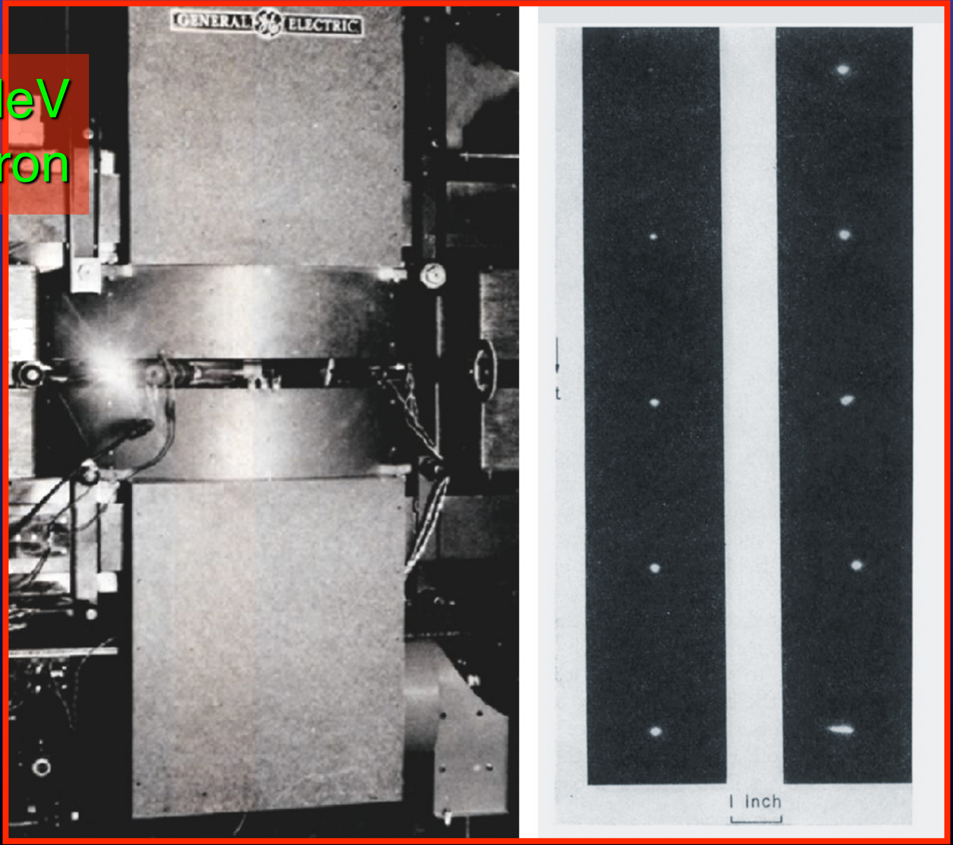
which amounts to roughly 30 kev for an electron of 1 Bev in a magnetic field of 10^4 gauss. The radiation spectrum consists of harmonics of the rotation angular frequency



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

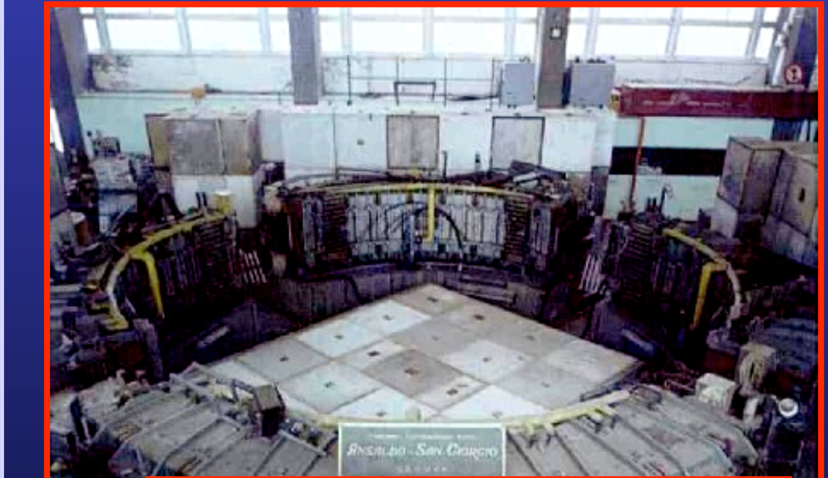
24 April 1947: at General Electrics in Schenectady, Herb Pollock, Robert Langmuir, Frank Elder and Anatole Gurewitsch see synchrotron light for the first time:

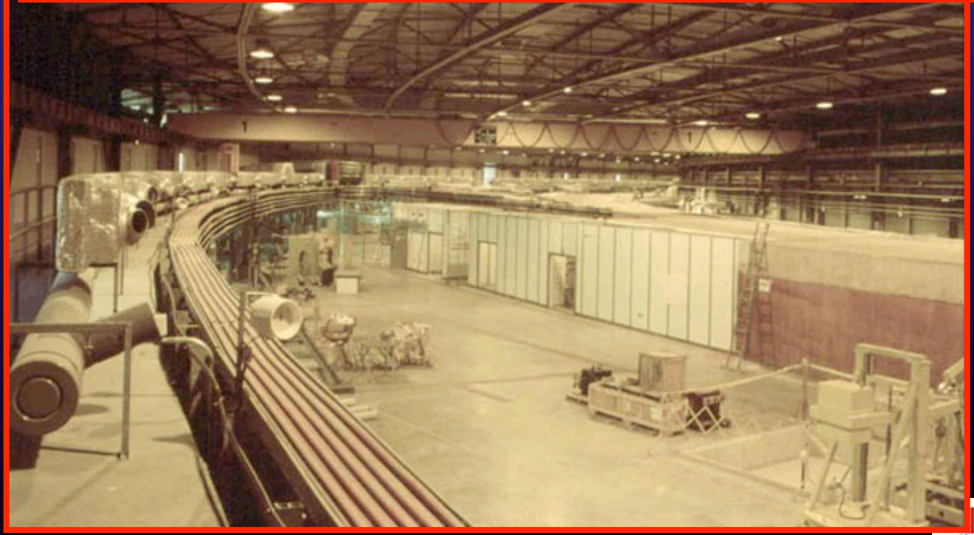
The GE 70 MeV synchrotron



> *“a trivial design change and … a conscious disregard for the rules of radiation safety”*

From the mid-1960s: Pioneering tests at the Frascati Electron Synchrotron (and then ADONE) and the PULS (Progetto Utilizzazione Luce di Sincrotrone)





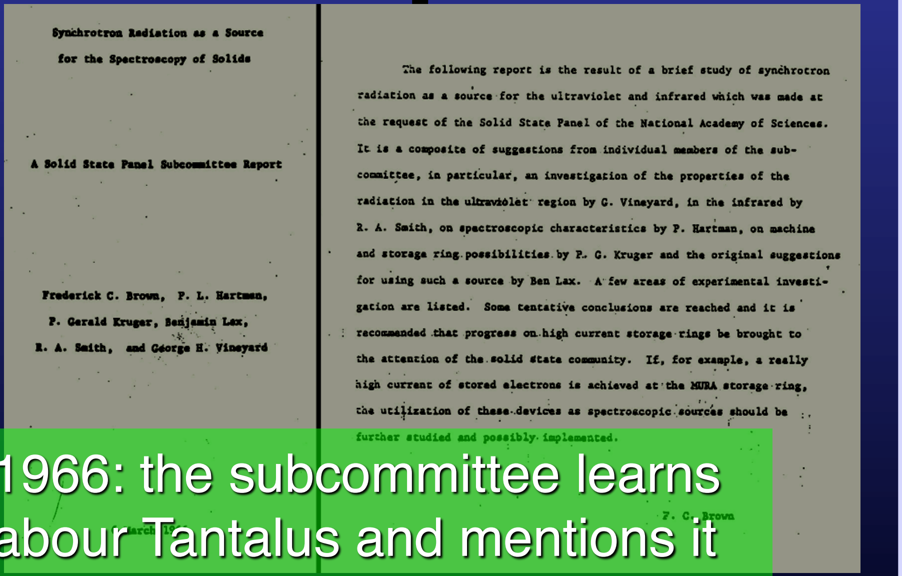
A parallel series of lucky coincidences:

1953: 15 institutions form MURA (Midwest Universities Research Association) to bid for the future Fermilab

1963: The Batavia site obtains Fermilab, MURA dies in 1967

In the meantime (1965) MURA started in Stoughton, Wisconsin, the construction of the 240 MeV storage ring Tantalus, that no longer had a mission

1965: a subcommittee of the National Research Council starts exploring the use of synchrotron light



Synchrotron Radiation as a Source
for the Spectroscopy of Solids

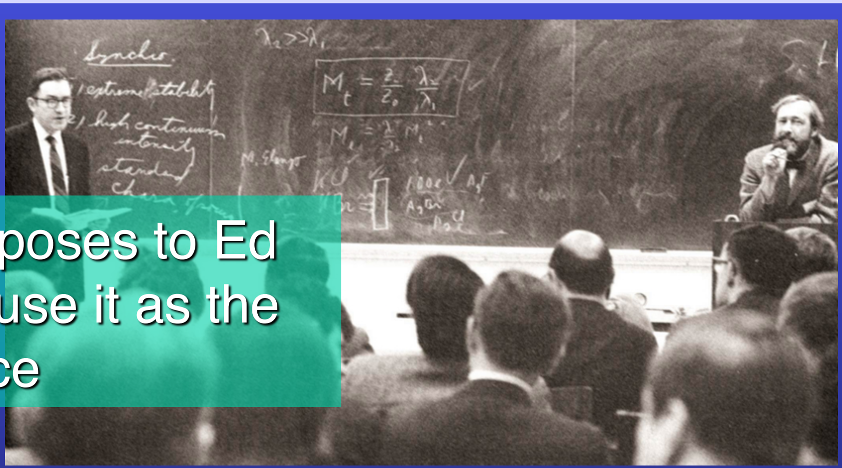
A Solid State Panel Subcommittee Report

Frederick C. Brown, P. L. Hartman,
P. Gerald Kruger, Benjamin Lax,
R. A. Smith, and George H. Vineyard

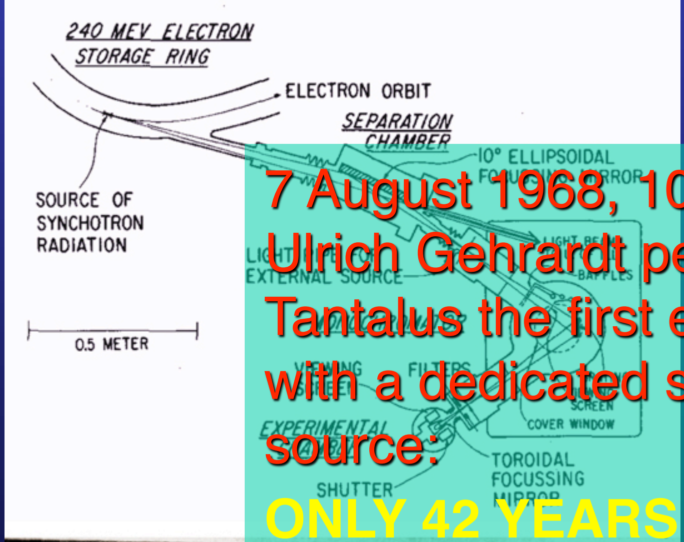
The following report is the result of a brief study of synchrotron radiation as a source for the ultraviolet and infrared which was made at the request of the Solid State Panel of the National Academy of Sciences. It is a composite of suggestions from individual members of the sub-committee, in particular, an investigation of the properties of the radiation in the ultraviolet region by G. Vineyard, in the infrared by R. A. Smith, on spectroscopic characteristics by P. Hartman, on machine and storage ring possibilities by P. G. Kruger and the original suggestions for using such a source by Ben Lax. A few areas of experimental investigation are listed. Some tentative conclusions are reached and it is recommended that progress on high current storage rings be brought to the attention of the solid state community. If, for example, a really high current of stored electrons is achieved at the MURA storage ring, the utilization of these devices as spectroscopic sources should be further studied and possibly implemented.

F. C. Brown

1966: the subcommittee learns abour Tantalus and mentions it in its final report



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



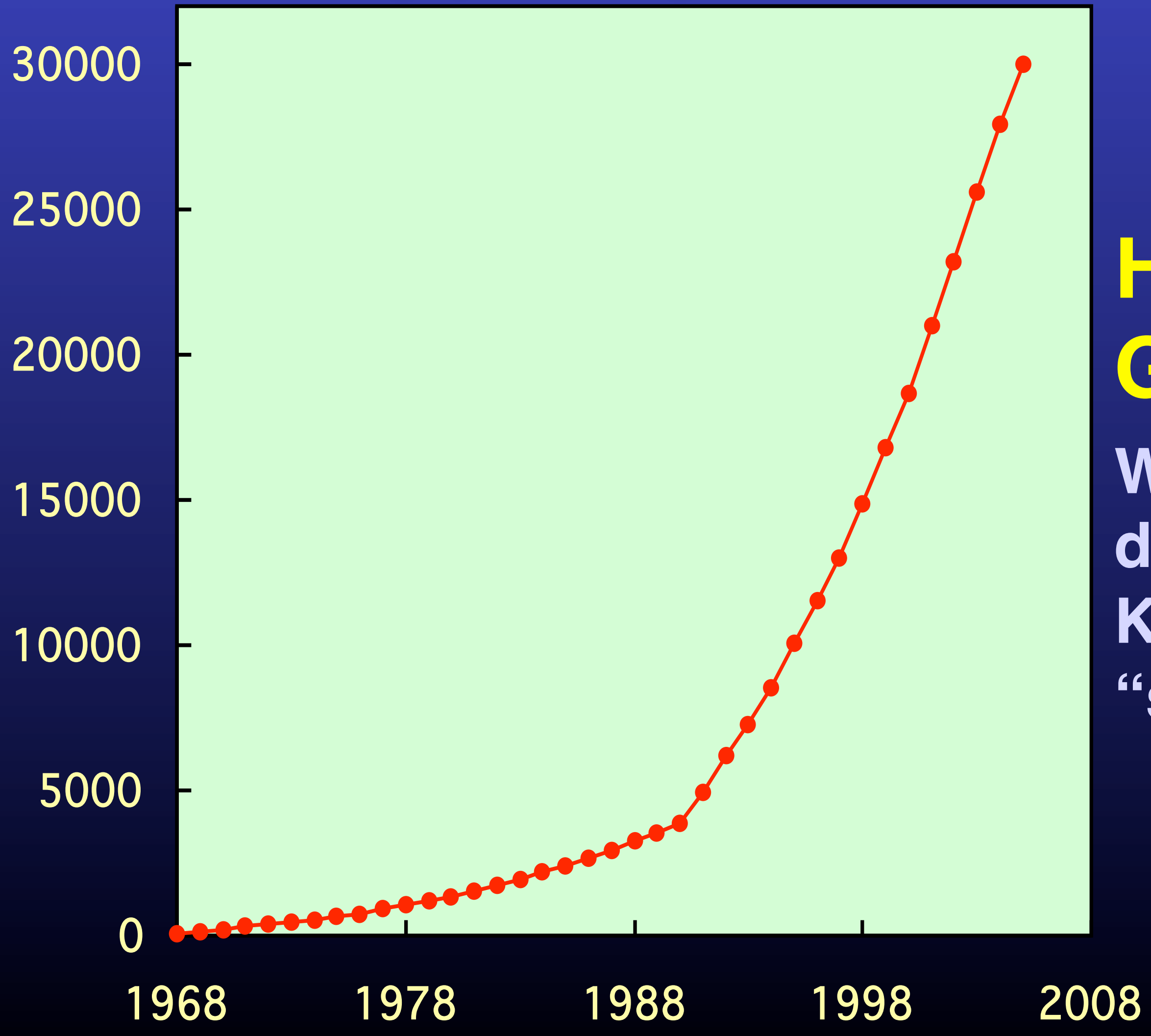
7 August 1968, 10:40 a.m.: Ulrich Gehrardt performs on Tantalus the first experiment with a dedicated synchrotron source:

ONLY 42 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”

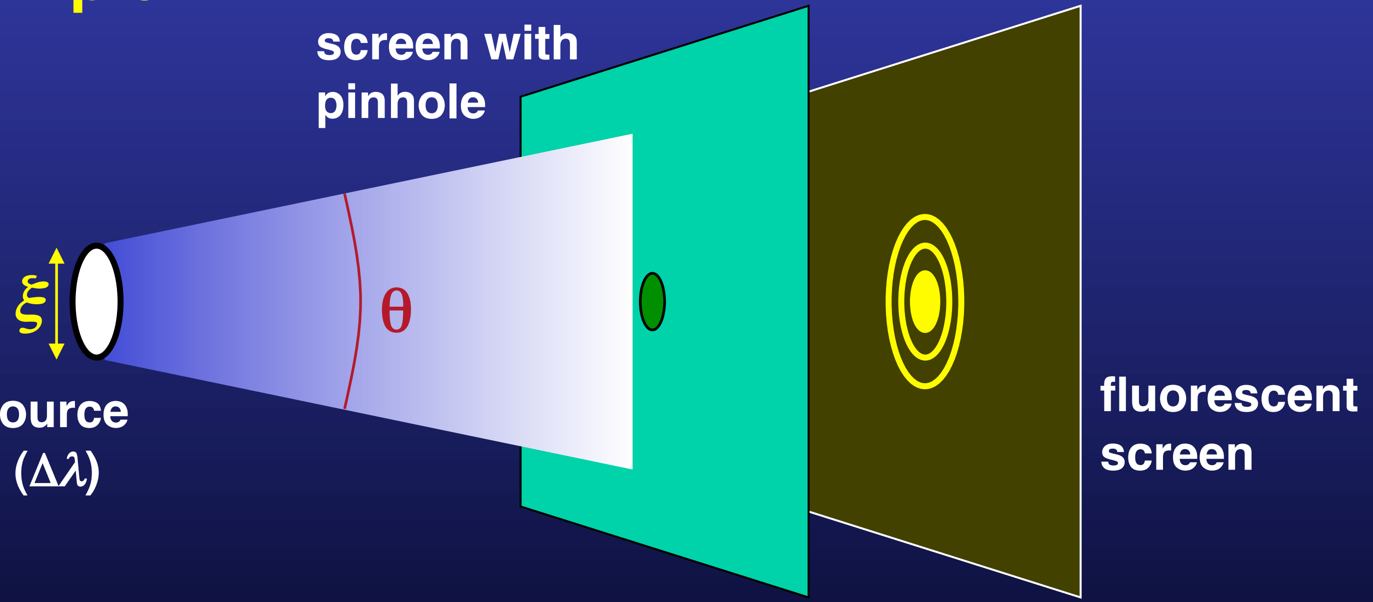
… but, for a broader picture:

Hits from a 2010 Google search:

"Synchrotron"	2,090,000
"Free electron laser"	2,070,000
"LINAC"	431,000
"Hadron collider"	1,370,000
"Protein crystallography"	469,000
"Synchrotron photoemission"	186,000
"Margaritondo"	64,800
"Pamela Anderson"	21,300,000
"Viagra"	53,700,000

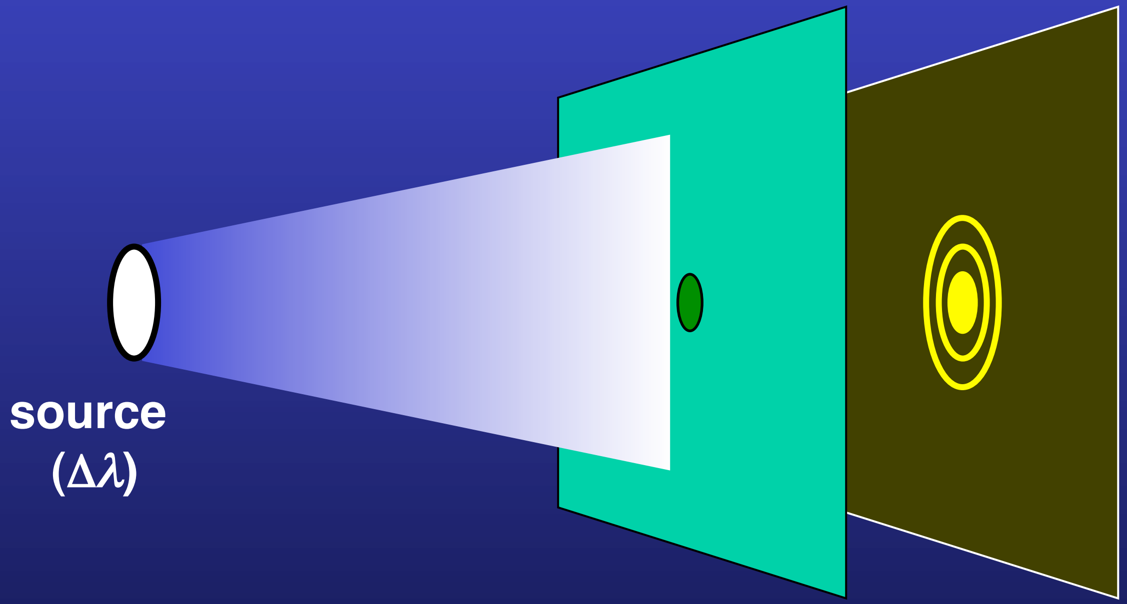
Coherence: "the property that enables a wave to produce visible diffraction and interference effects"

Example:



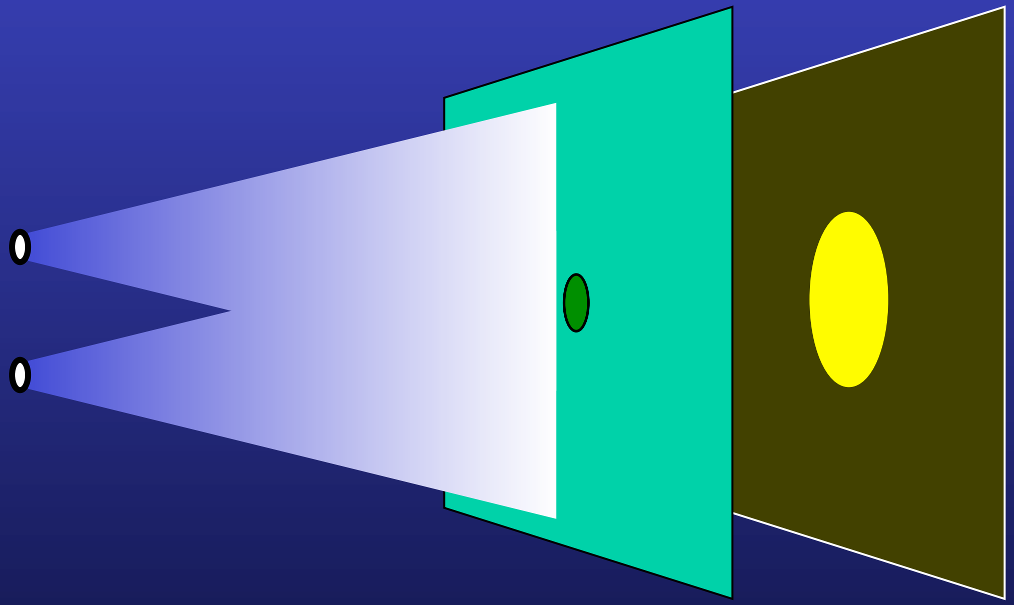
The diffraction pattern may or may not be visible on the fluorescent screen depending on the source size ξ, on its angular divergence θ and on its wavelength bandwidth $\Delta\lambda$

Longitudinal (time) coherence:



- Condition to see the pattern: $\Delta\lambda/\lambda < 1$
- Parameter characterizing the longitudinal coherence: "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:

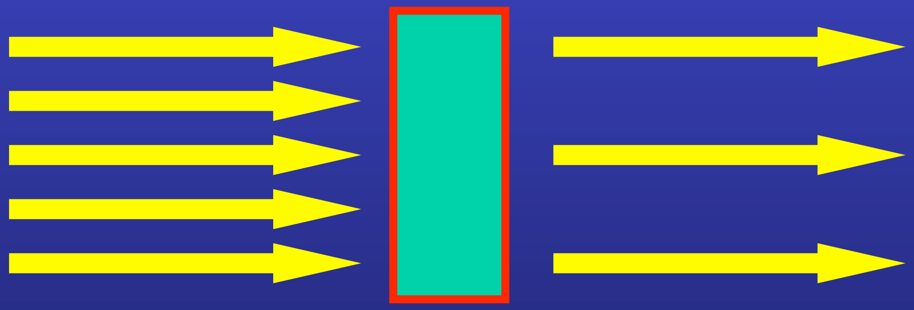


- **Two point sources produce overlapping patterns: diffraction effects are no longer visible.**
- **However, if the two source are close to each other an overall diffraction pattern may still be visible: the condition is to have a large "coherent power" $(2\lambda/\xi\theta)^2$**

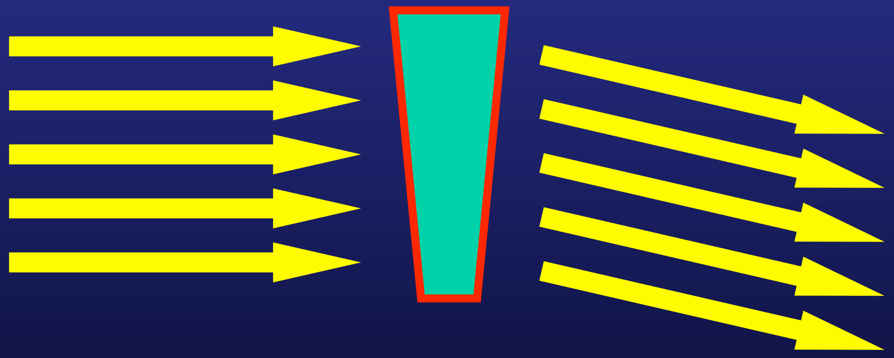
Coherence — summary:

- 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:



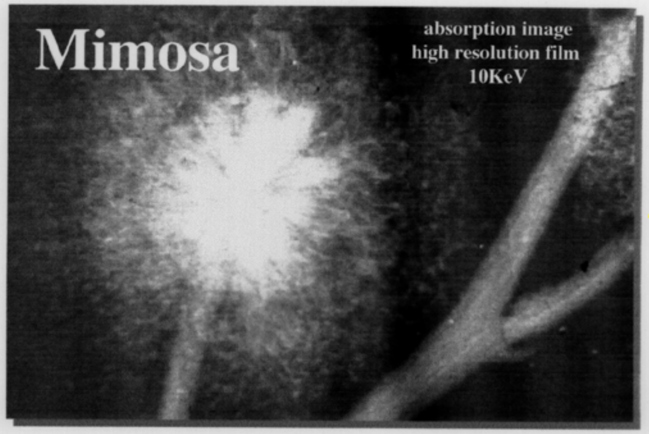
Absorption -- described by the absorption coefficient α



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

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

Conventional radiology

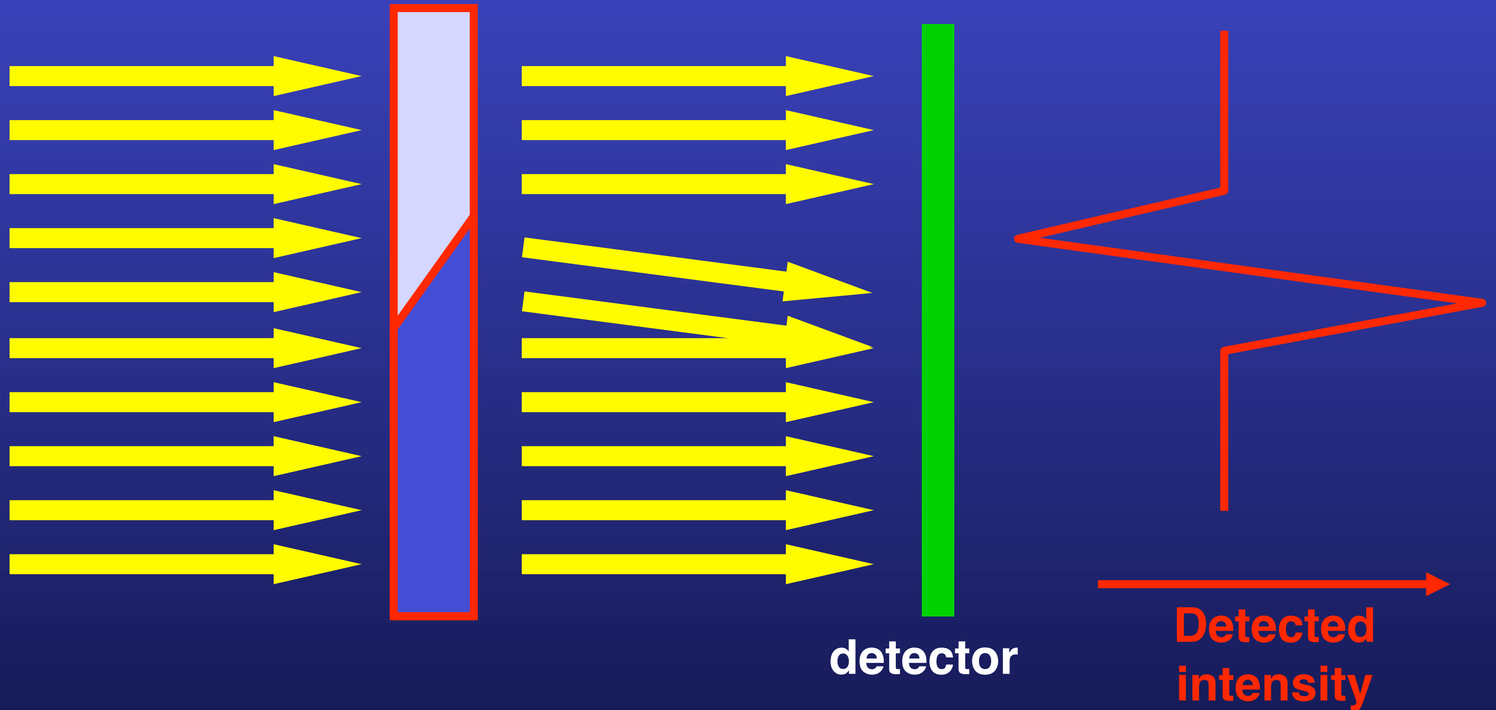


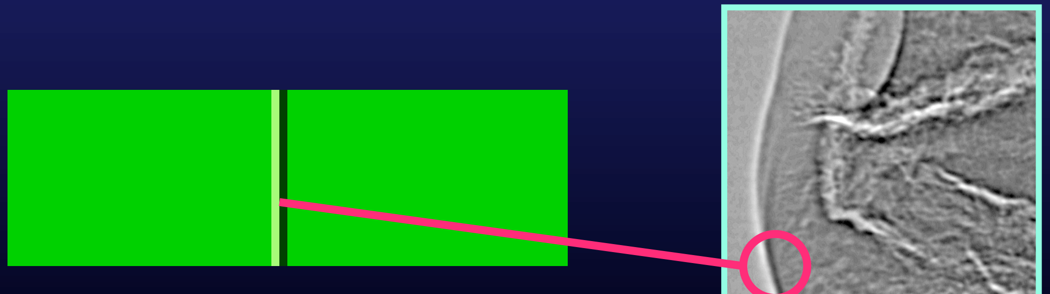
Refractive-index radiology (Giuliana Tromba)

“Refraction” x-ray imaging:

Edge between regions with different n-values

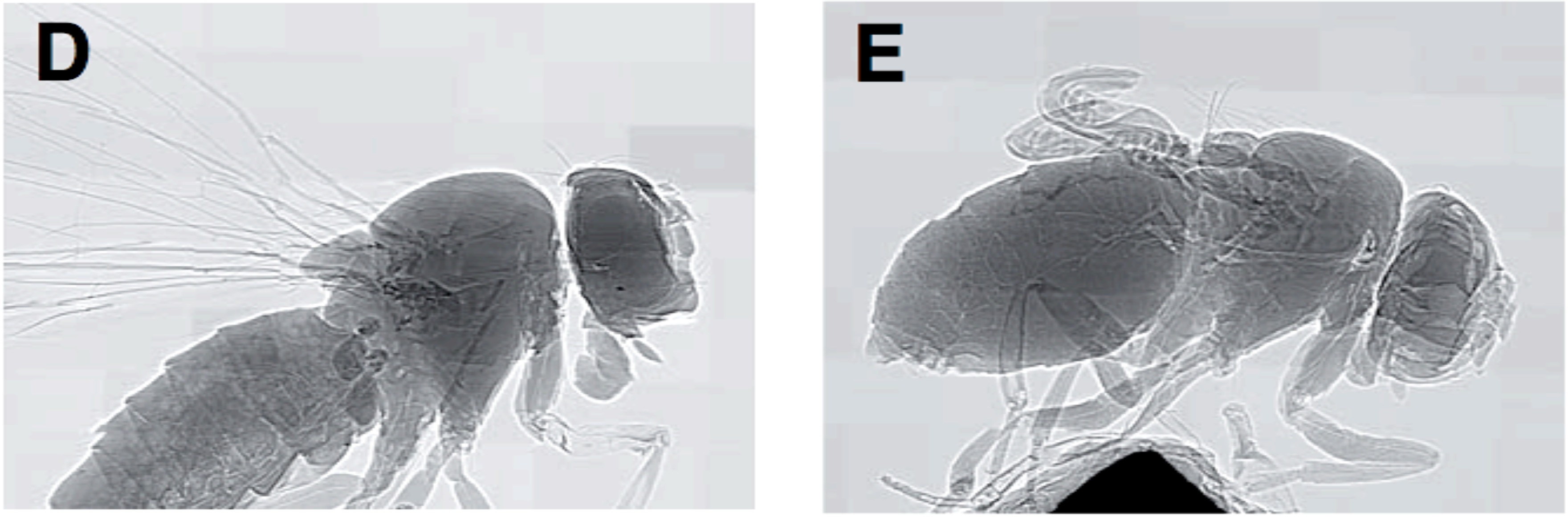
“Refraction” x-ray imaging:





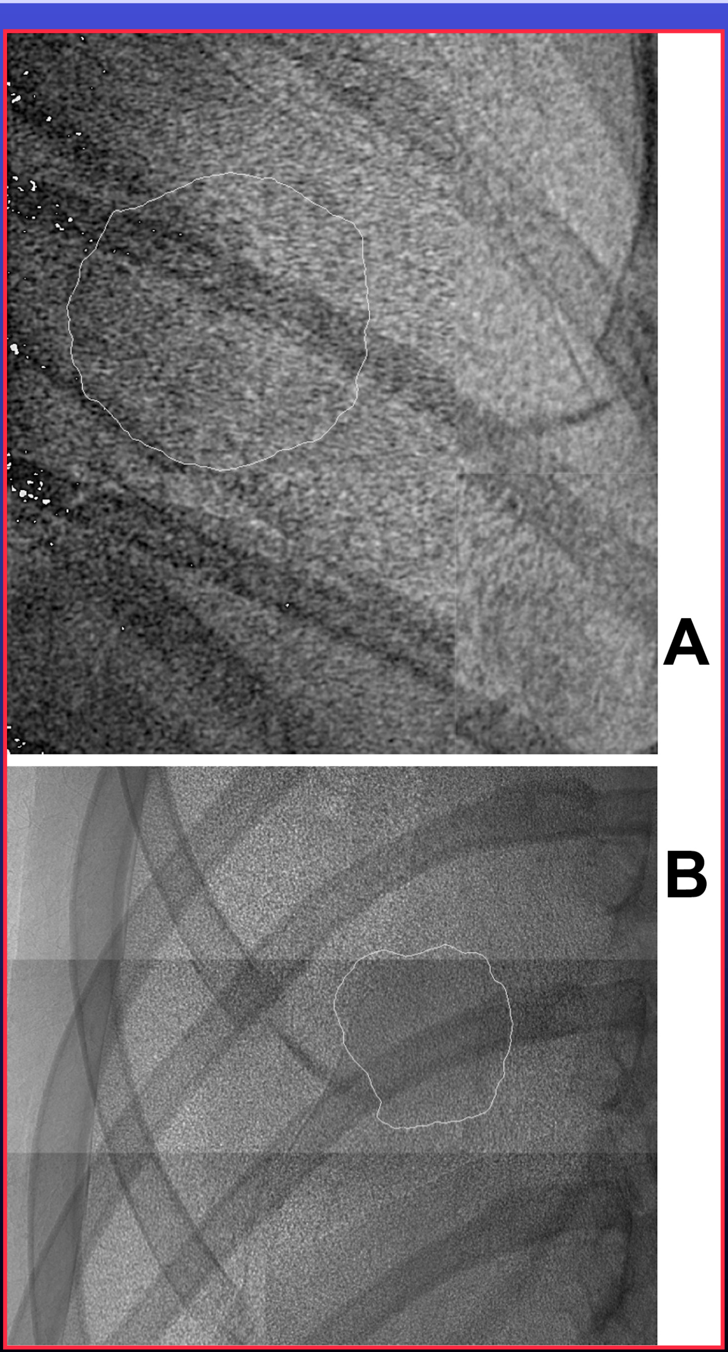
Microradiology study of mutant drosophila fly evolution

[Charron, Vassalli et al.]

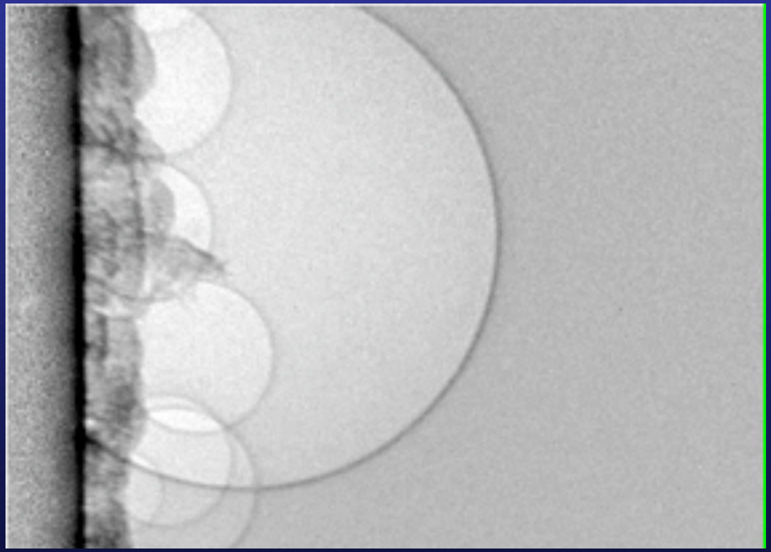


Very Early Detection of Lung Cancer in Mouse Models

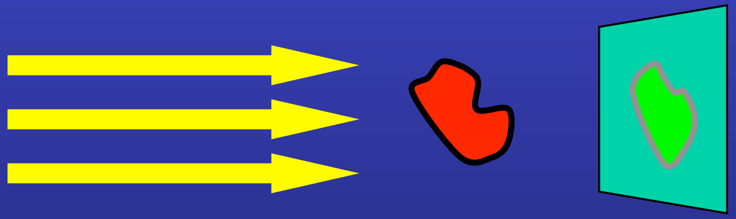
Guilin Zhang, Chia-Chi Chien, Ping Liu, Weisheng Yue, Jiangi Sun, Yan Li, Hong-Jie Xue, Xuemin Xu, Chang Hai Wang, Y. Hwu, Nanyow Chen, Chien Hung Lu, Ting-Kuo Lee, M. Hsiao, Yuh-Cheng Yang, Yen-Ta Lu, Yu-Tai Ching, P. C. Yang, J. H. Je, G. Margaritondo



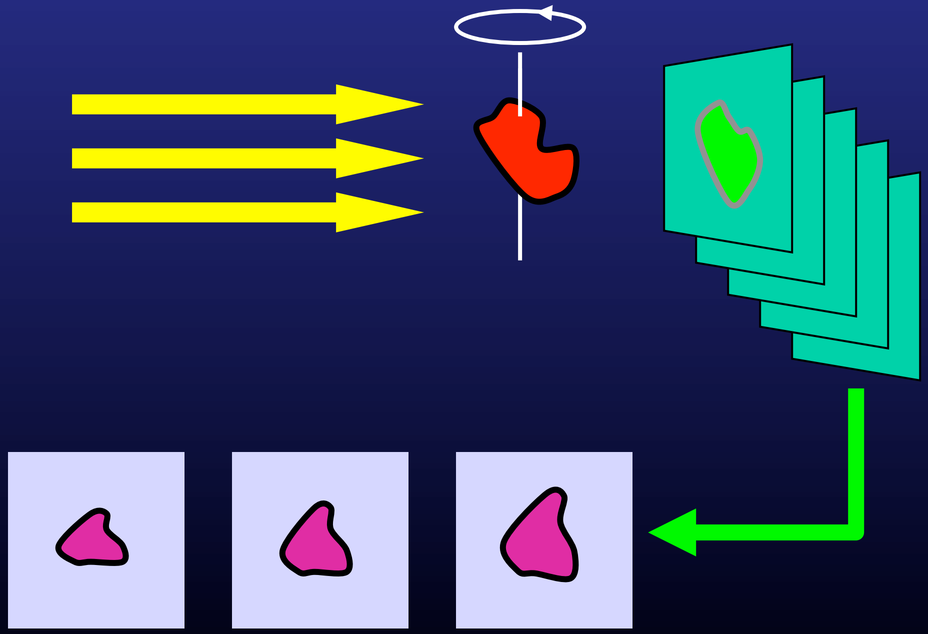
Building on bubbles (zinc electrodeposition):



X-ray (micro)tomography:

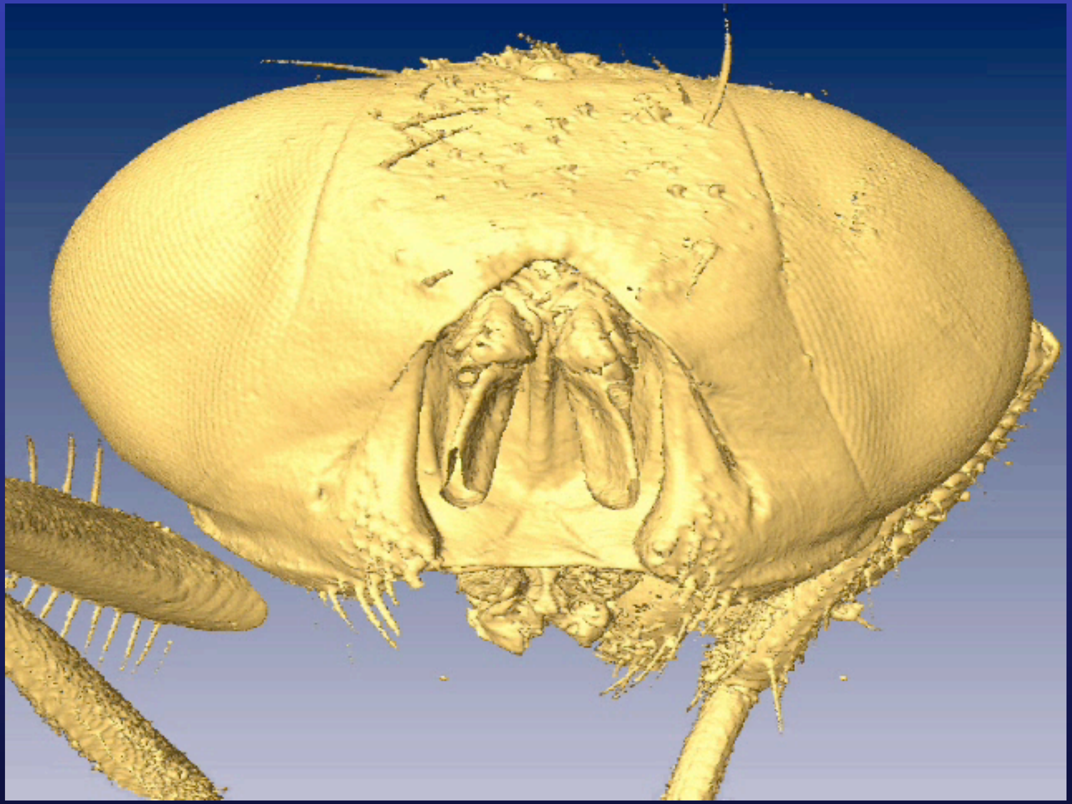


A single (projection) x-ray image does not deliver three-dimensional information



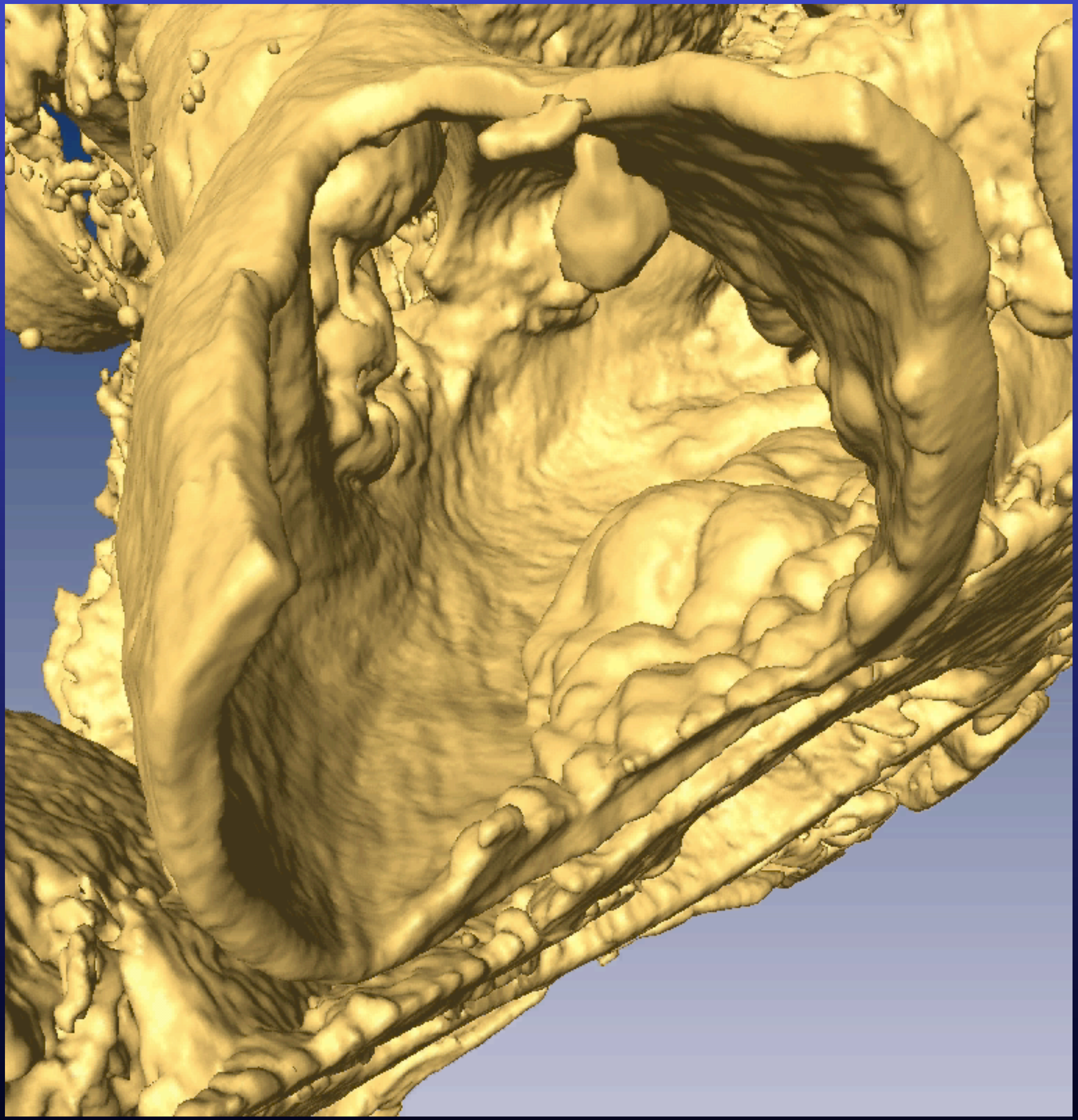
Many x-ray images taken at different angles can be computer-reconstructed in three dimensions -- and can even give movies

Phase contrast micro-tomography: housefly



Yeukuang
Hwu, Jung
Ho Je et al.

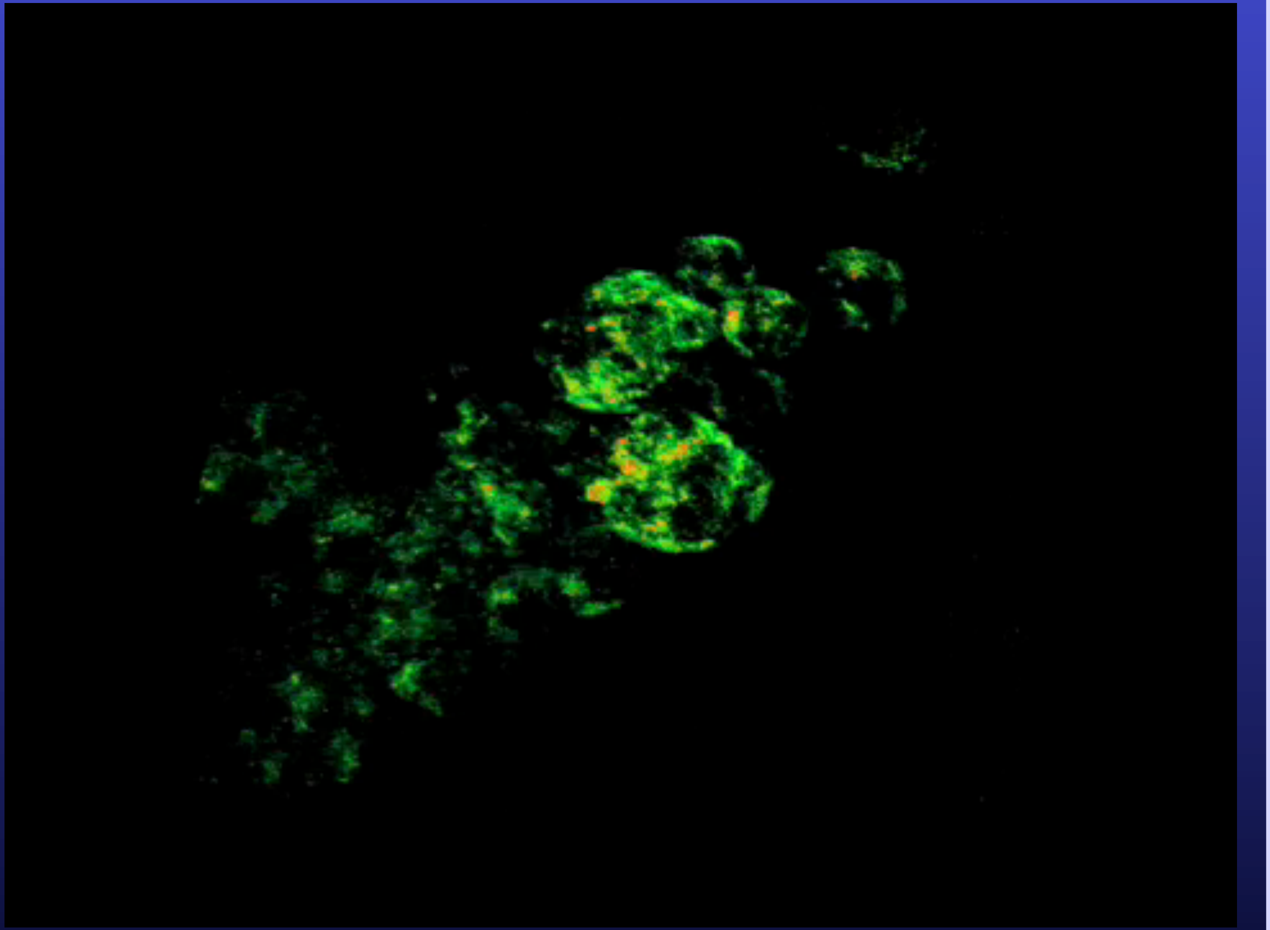
Phase contrast micro-tomography: navigating inside micro-vessels



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

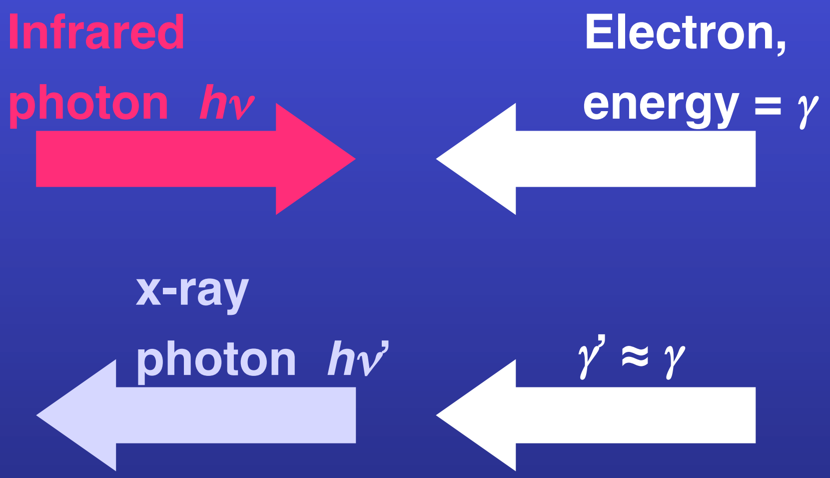


Agglomerated Au nanoparticles attached to cancer cells

New types of sources:

- Ultrabright storage rings (SLS, new Grenoble project) approaching the diffraction limit
- 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

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



Infrared photon $h\nu$

Electron, energy = γ

x-ray photon $h\nu'$

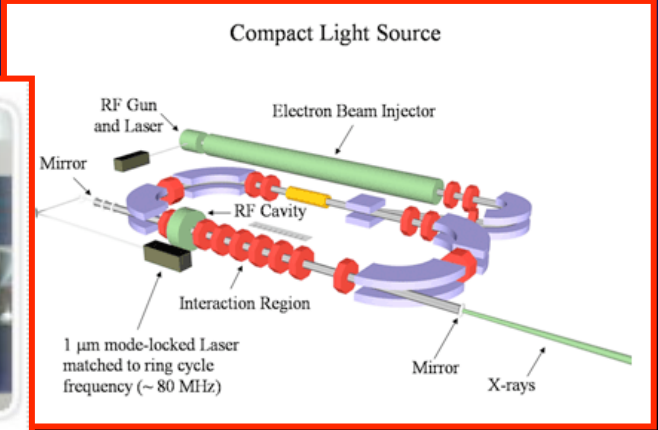
$\gamma' \approx \gamma$

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:

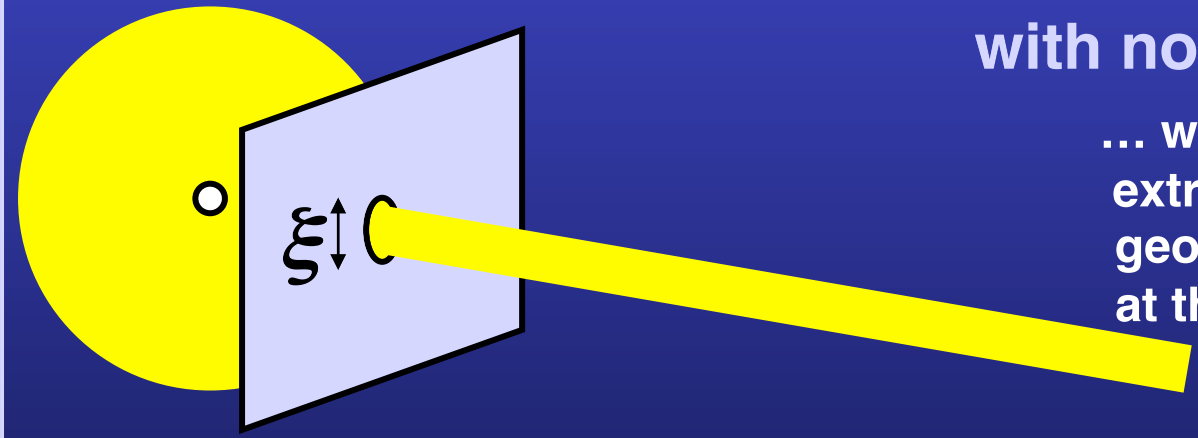
$$h\nu' \approx 4\gamma^2\, h\nu$$

lyncean TECHNOLOGIES, INC.

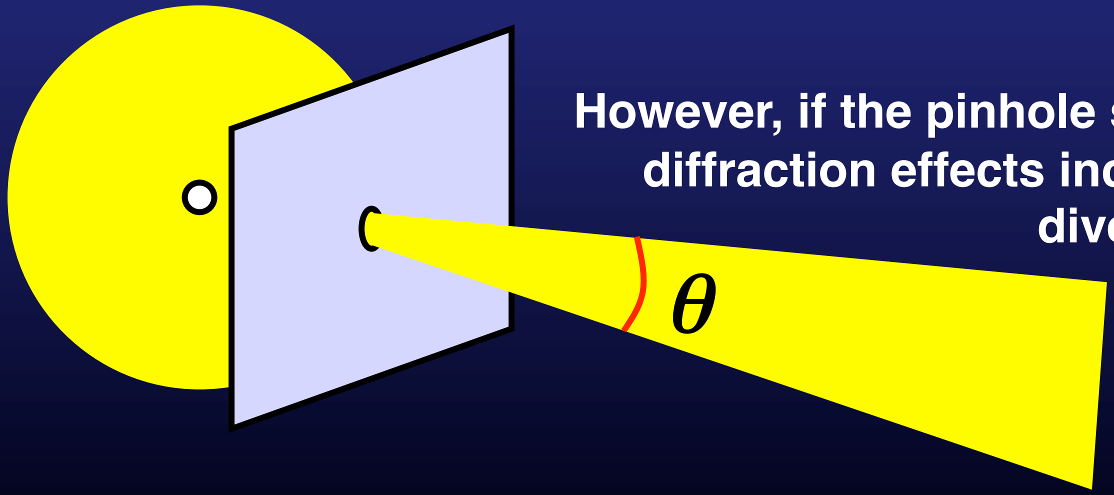


The absolute limit for coherence -- and brightness

Take a standard photon source with no lateral coherence …



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



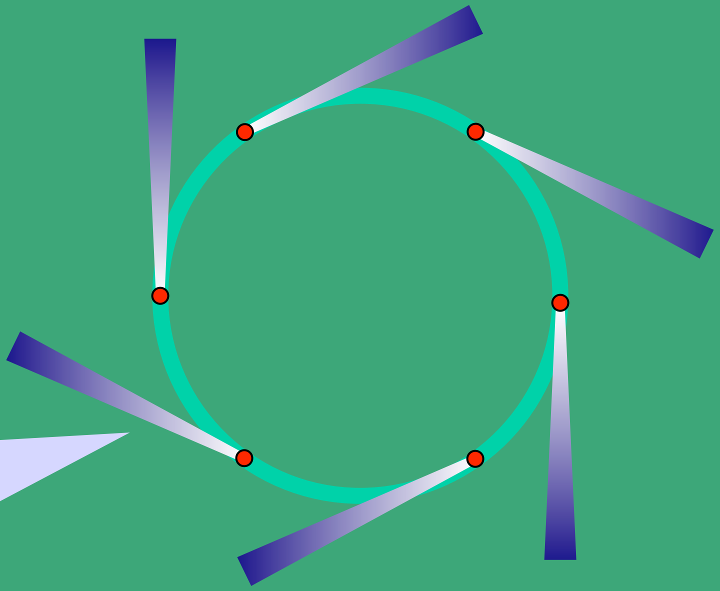
However, if the pinhole size is too small diffraction effects increase the beam divergence so that:

$$\xi\theta > \lambda$$

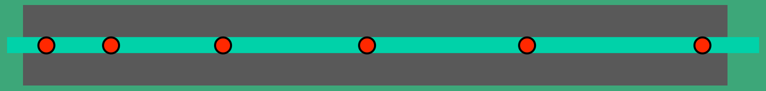
No source geometry beats this diffraction limit

Energy-recovery LINAC sources

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

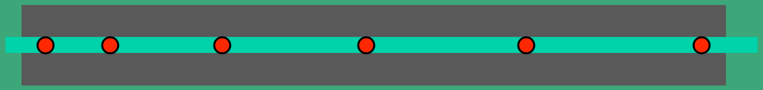


In a storage ring, the electrons continuously emit photons. This “warms up” the electron beam and negatively affects its geometry



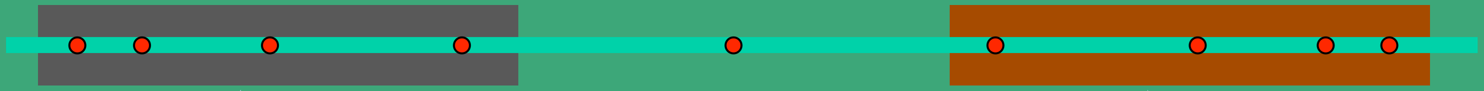
Controlling the electron beam geometry is much easier in a linear accelerator (LINAC). Thus, LINAC sources can reach higher brightness levels

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

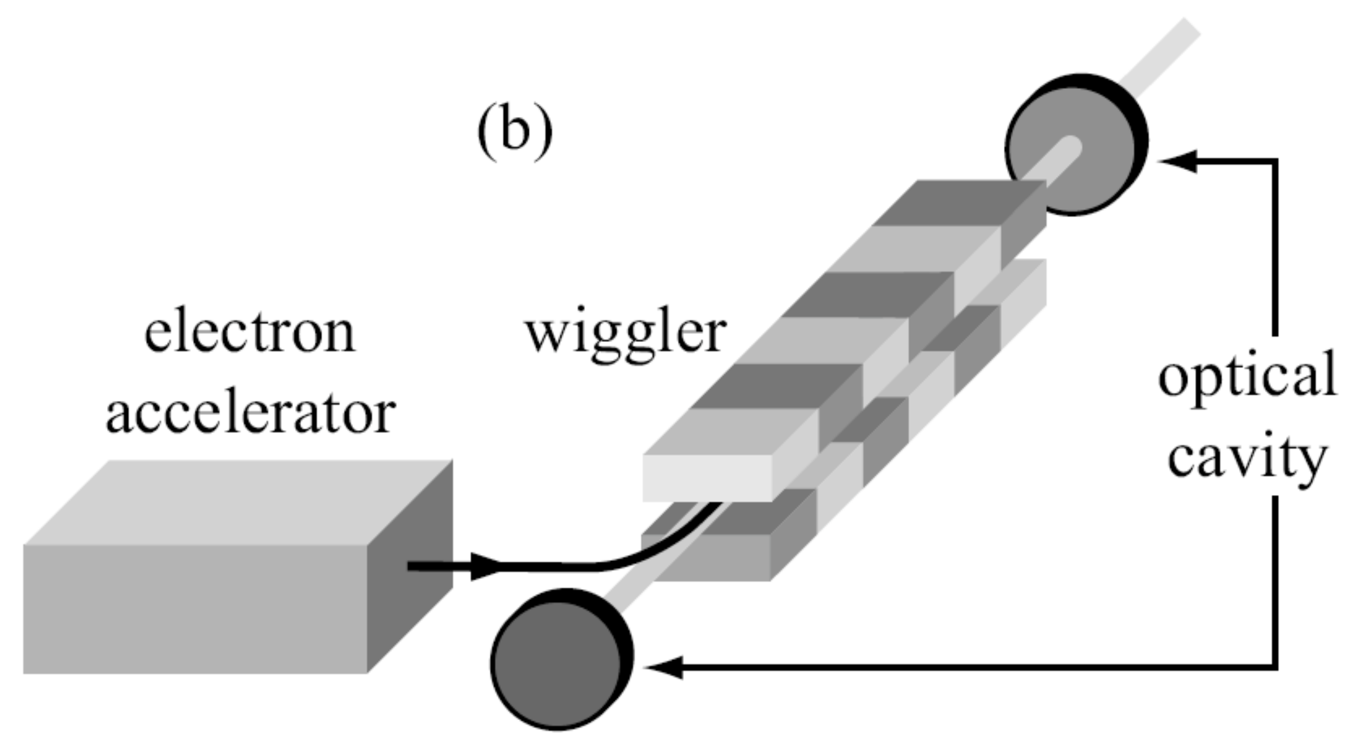
Solution: recovering energy



Accelerating section

Energy-recovery section

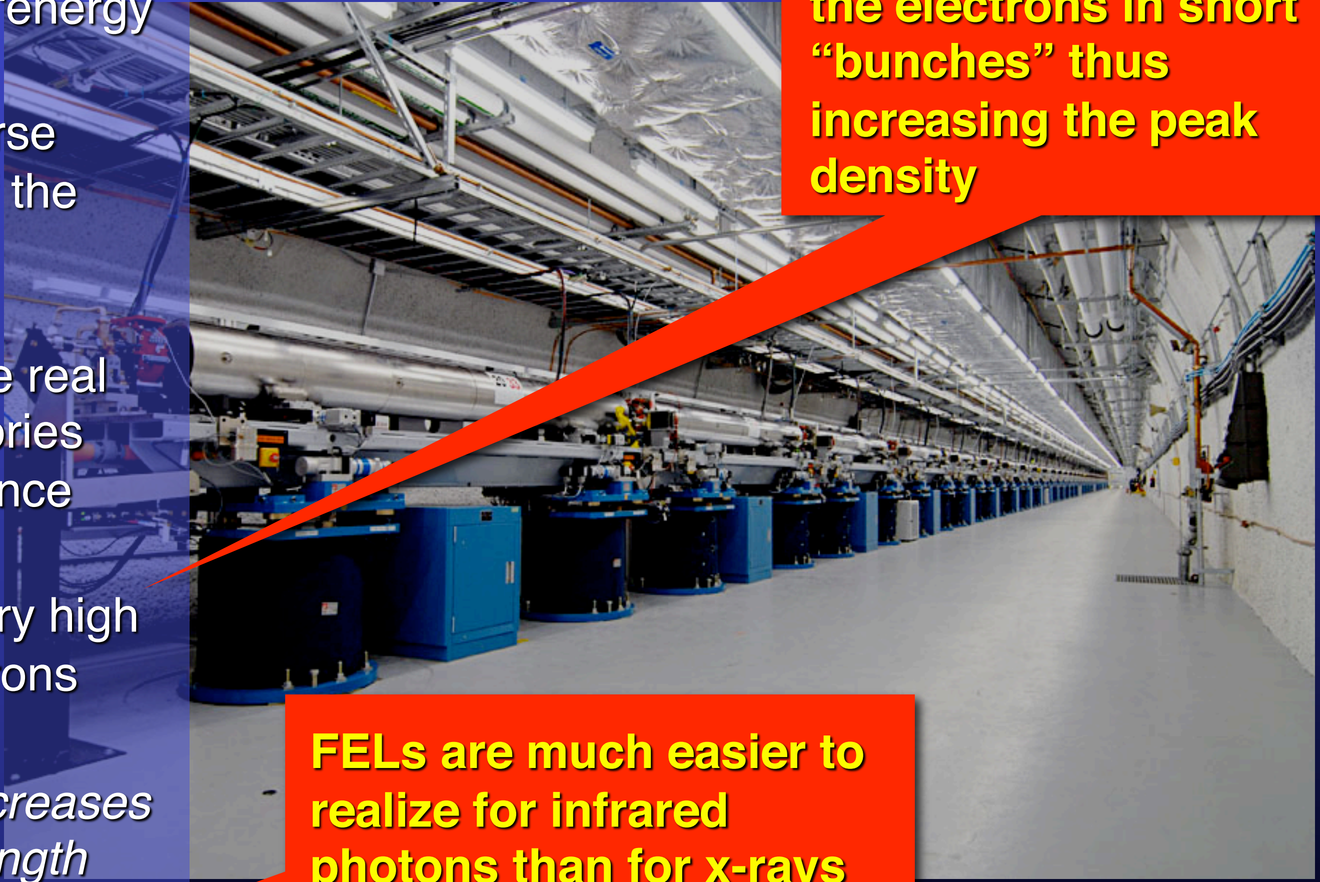
Free-electron lasers (FEL's):



A lasing mechanism requires optical amplification in an optically active medium.

In an FEL, the medium is an electron bunch passing through a wiggler or undulator; its interaction with previously emitted photons causes the amplification

FEL’s: main requirements for strong optical amplification



1. A well-defined electron energy: limited “energy spread”
2. A small transverse cross section of the electron beam.
3. Small angular deviations of the real electron trajectories from the “reference path”
4. In general, a very high density of electrons
5. The optical amplification *increases with the wavelength*

It is better to close-pack the electrons in short “bunches” thus increasing the peak density

FELs are much easier to realize for infrared photons than for x-rays

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

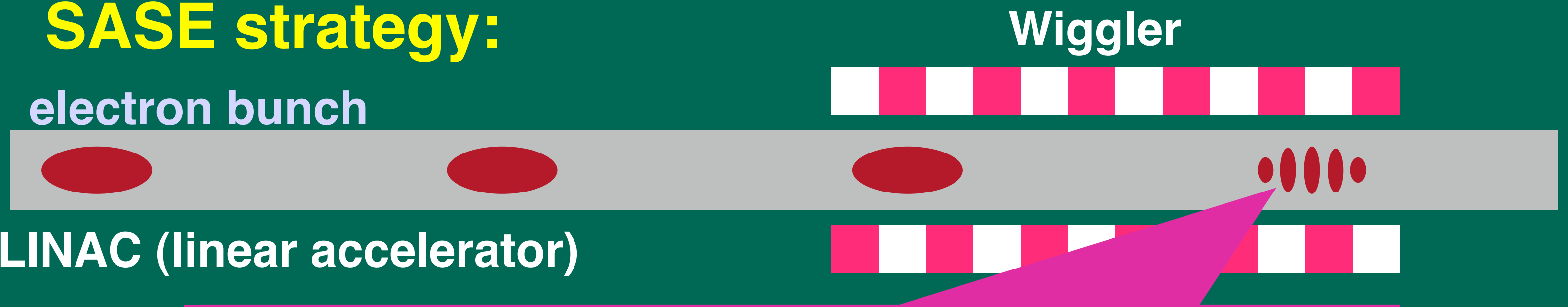
Normal (visible, IR, UV) lasers:

optical amplification in amplifying medium

plus optical cavity (two mirrors)

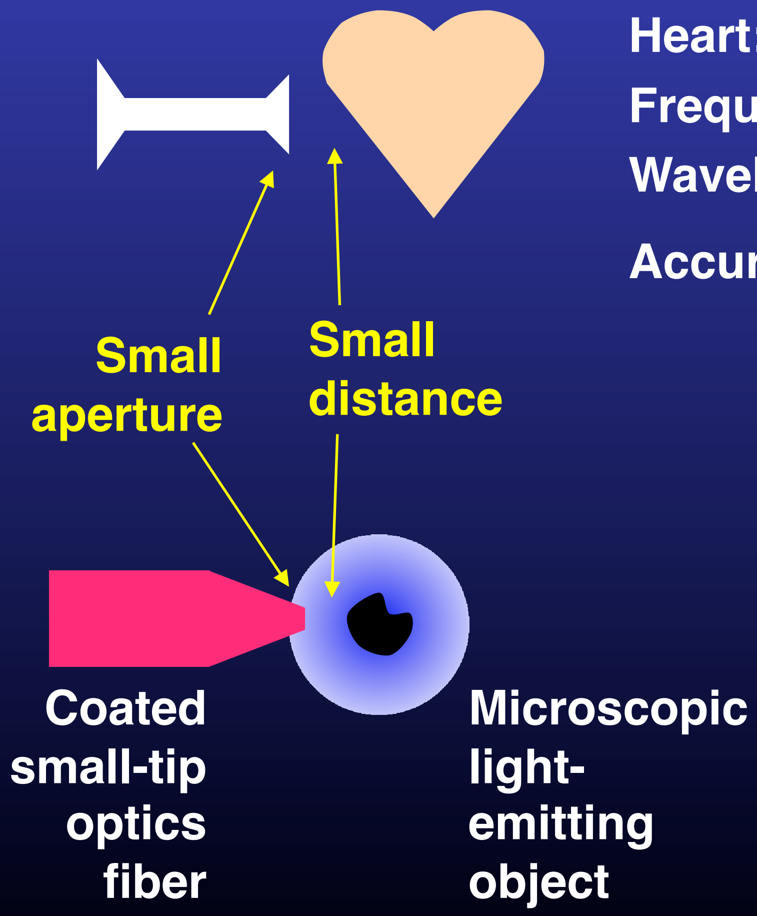
X-ray lasers: no mirrors → no optical cavity → need for one-pass high optical amplification

SASE strategy:



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

Use of infrared FEL's: The scanning near-field optical microscope (SNOM) -- like a "stethoscope"



Heart:

Frequency ≈ 30-100 Hz

Wavelength $\lambda \approx 102$ m

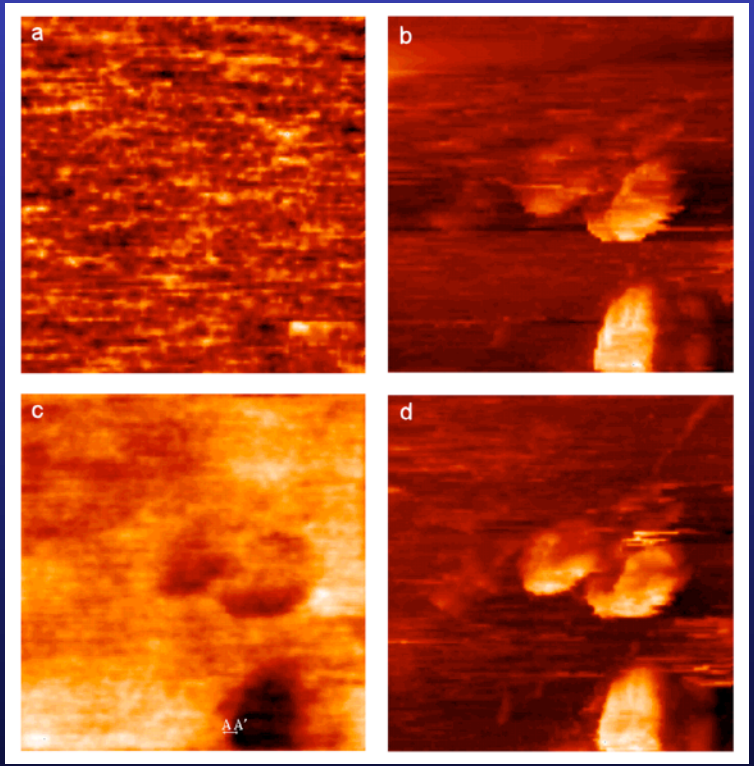
Accuracy in localization ≈ 10 cm ≈ $\lambda/1000$

SNOM resolution: well below the "diffraction limit" of standard microscopy (≈ λ)

20x20 μm^2 SNOM image of growth medium (A. Cricenti et al.):

λ = 6.6 μm

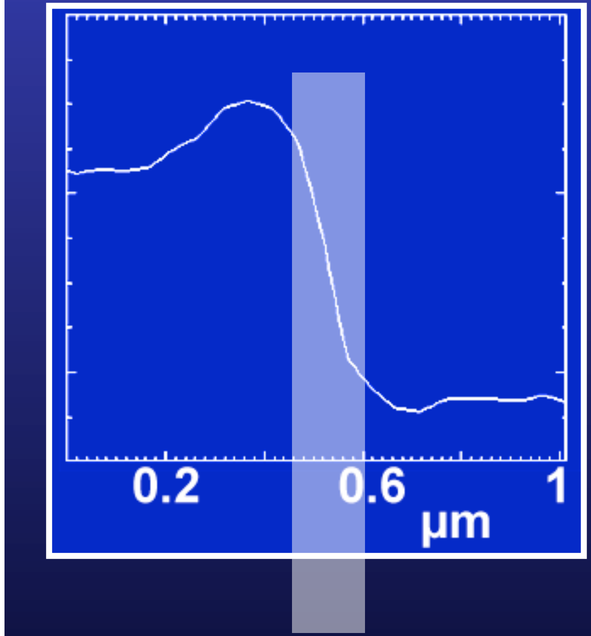
S-O & N-O vibrations (λ = 6.95 μm)



SNOM

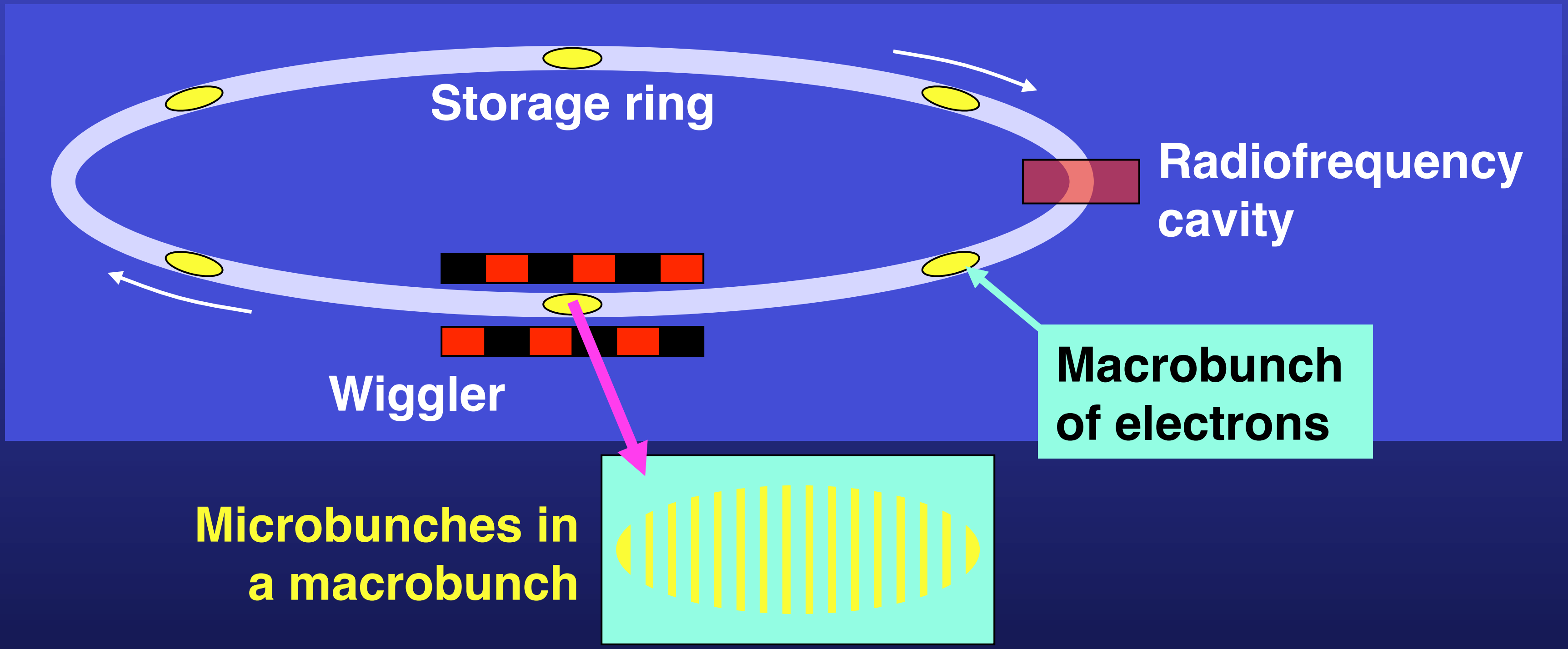
topography

Intensity line scan



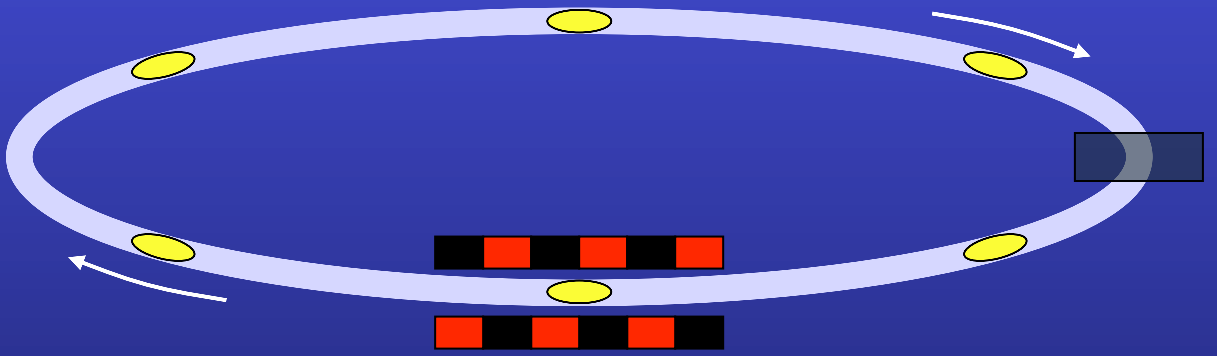
Resolution ≈ 0.15 μm << λ

Electron bunches in an FEL

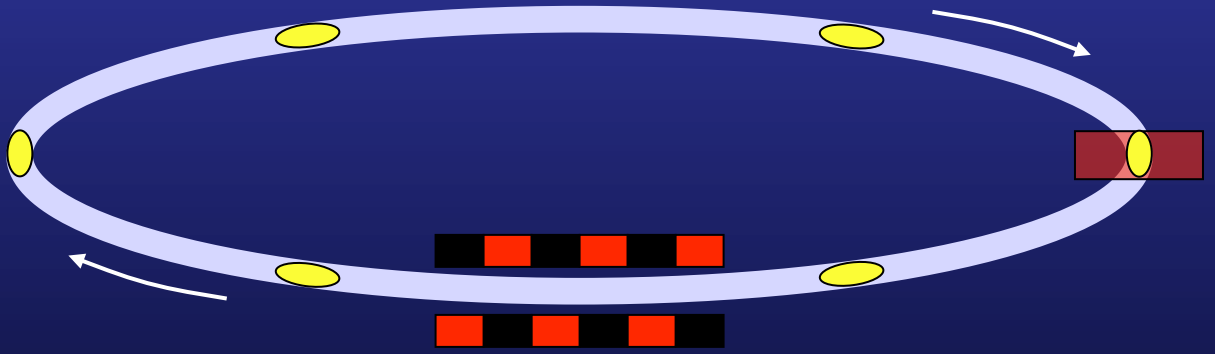


The electrons passing through a wiggler in a storage ring are concentrated in “macrobunches”; within each macrobunch, the electrons are further concentrated in a series of “microbuches”

What causes the macrobunches?



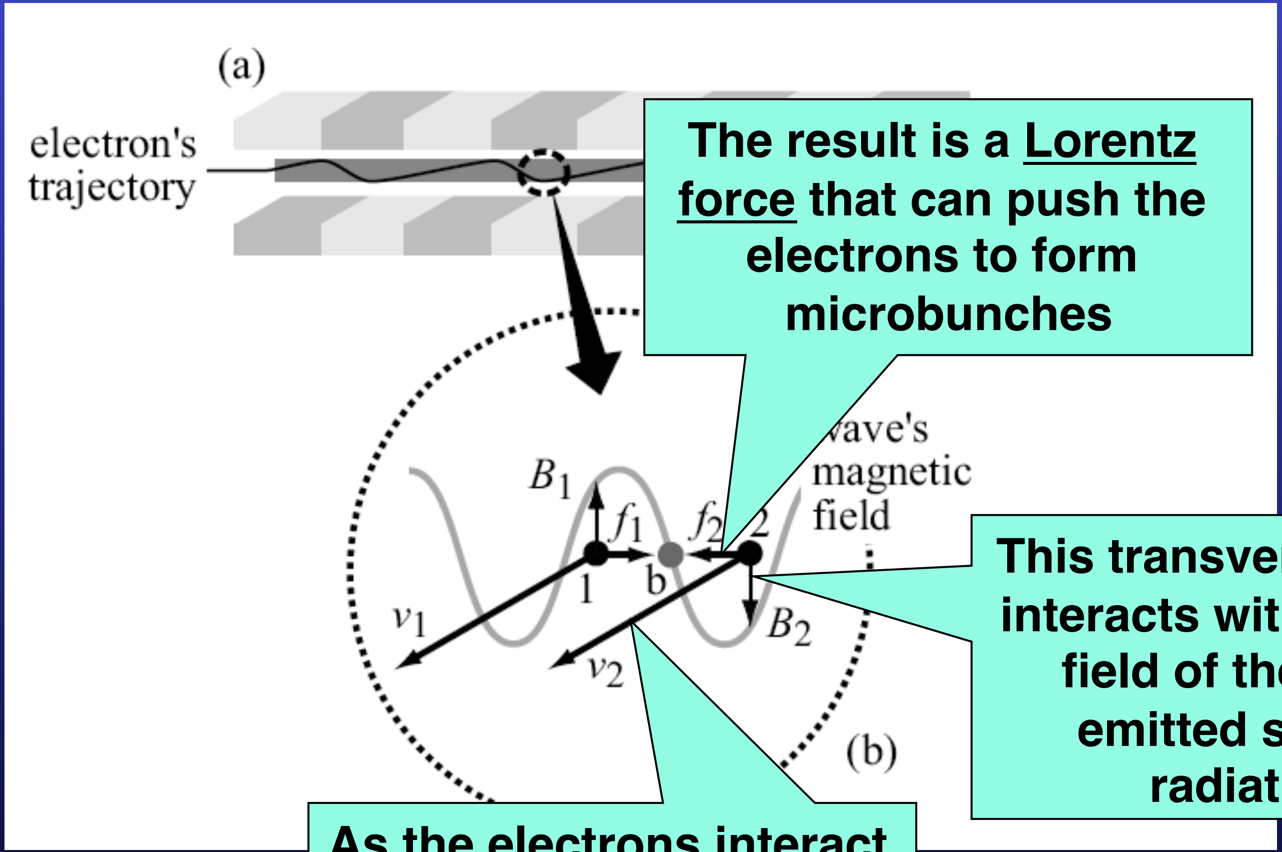
Radiofrequency cavity: field OFF



Radiofrequency cavity: field ON

The circulating electrons lose energy by emitting synchrotron radiation. This energy is given back to them by a radiofrequency cavity that produces an accelerating electric field. But this only works for electrons that pass through the cavity at the right time: only the electrons in the corresponding macrobunches can steadily circulate -- the others decay

What causes the microbunches?

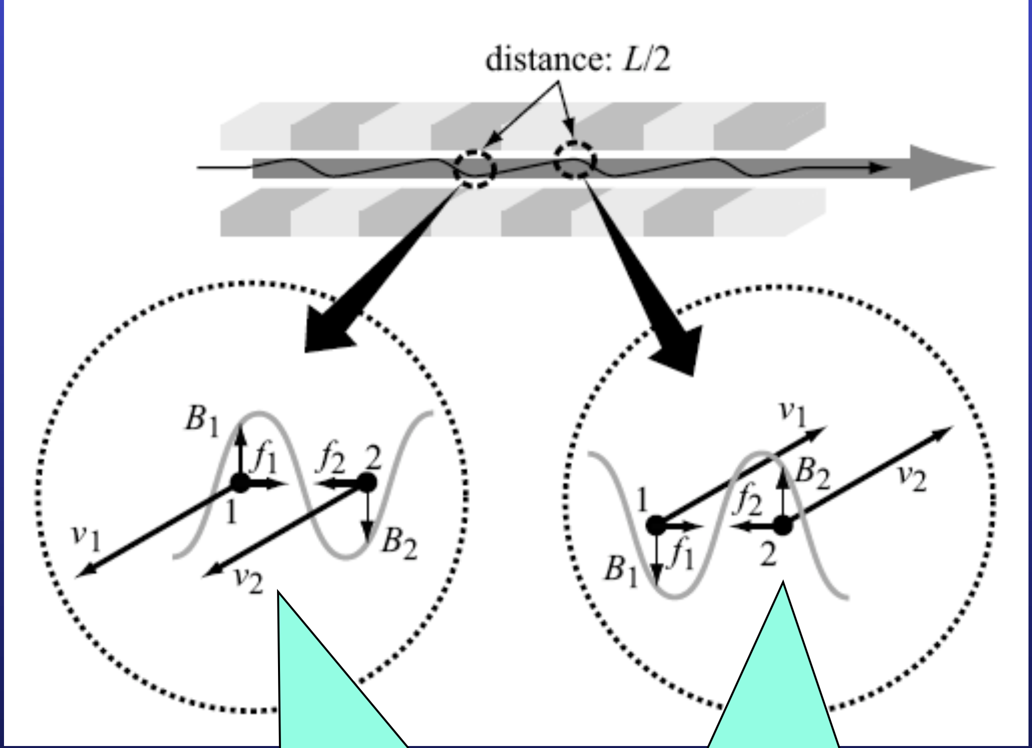


As the electrons interact with the wiggler, they get a <u>transverse component</u> of the velocity

This transverse component interacts with the magnetic field of the previously emitted synchrotron radiation wave

The result is a <u>Lorentz force</u> that can push the electrons to form microbunches

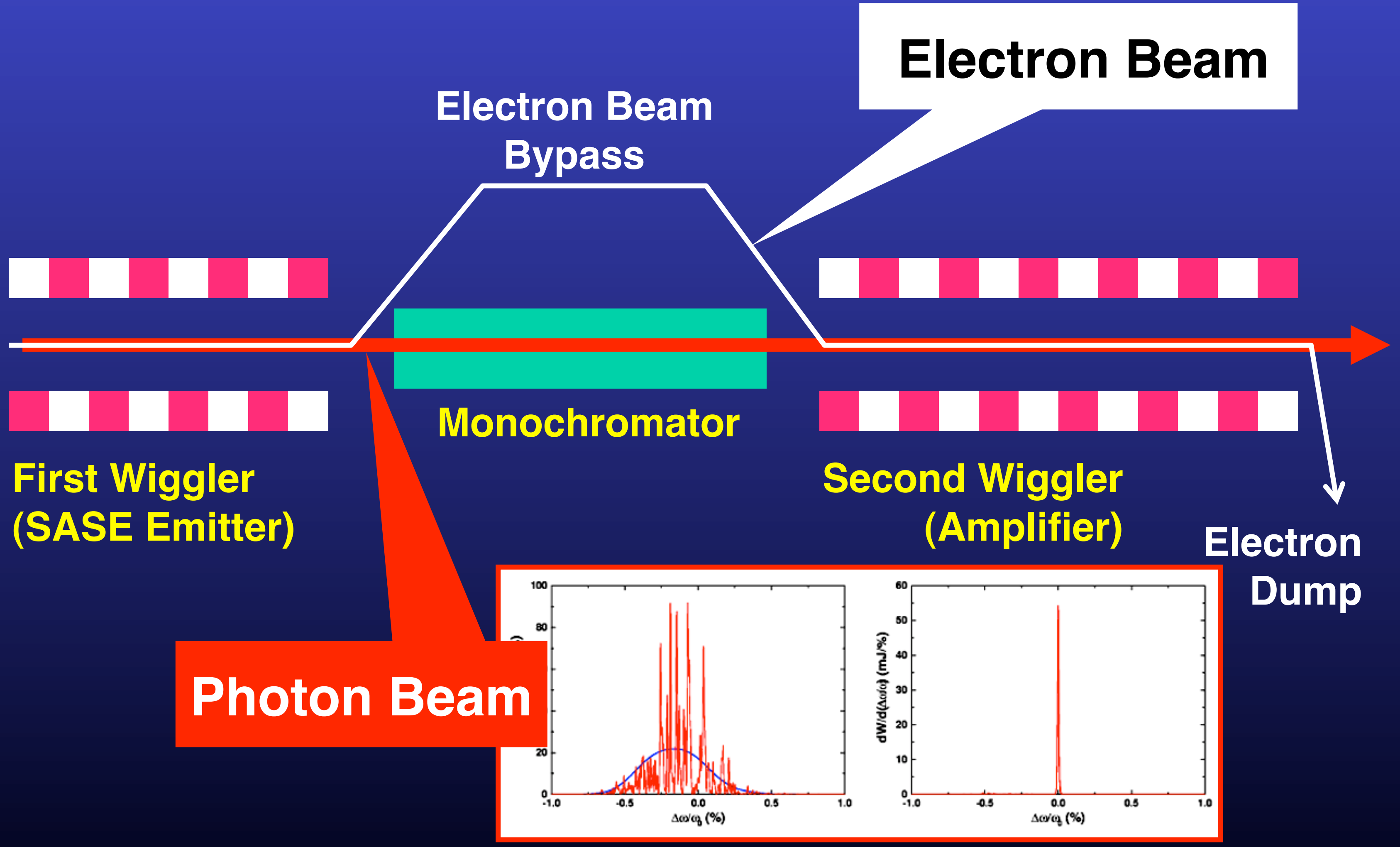
The right conditions for microbunching:



Specifically, within 1/2 of the wiggler period, the electrons shift by 1/2 wavelength with respect to the wave, which is just right for microbunching

Microbunching could not occur if the Lorentz forces were not continuously pushing the electrons towards the microbunches. This is made possible by the shift in space between the electrons and the photon wave caused within one wiggler period by the difference between the speed of light *c* and that of the electrons, *u*

Seeding-Amplifier X-FELs



Electron Beam

Electron Beam Bypass

Monochromator

First Wiggler (SASE Emitter)

Second Wiggler (Amplifier)

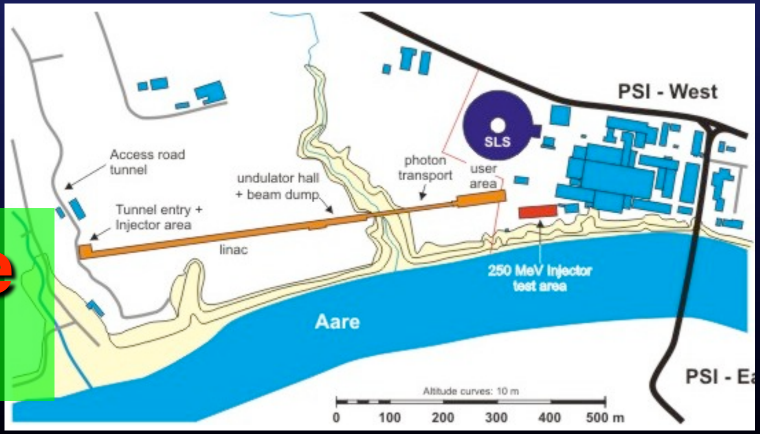
Electron Dump

Photon Beam

The FERMI X-FEL at Elettra, Trieste

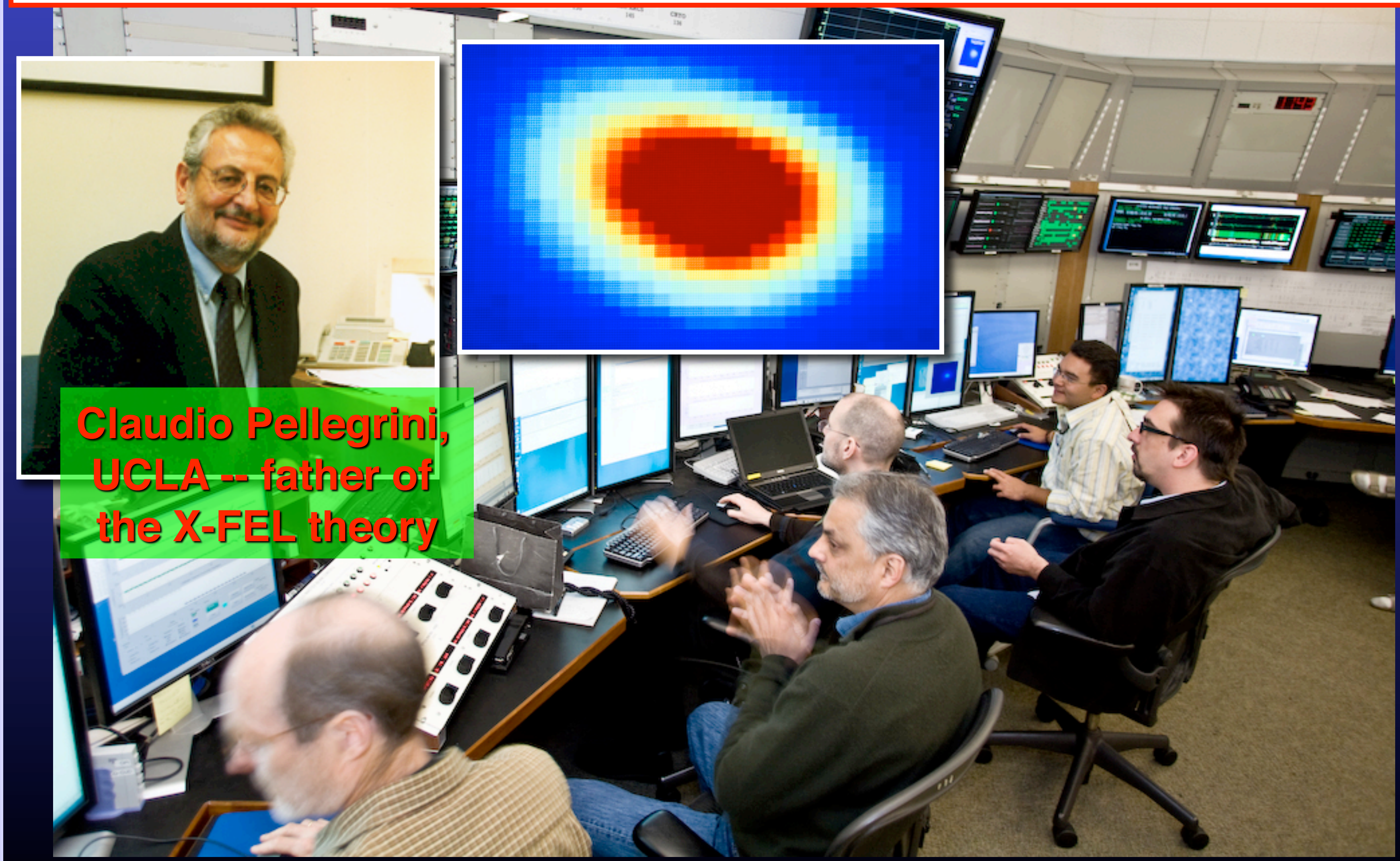
The European X-FEL project underway at DESY, Hamburg

The Swiss X-FEL at the Paul-Scherrer Institut



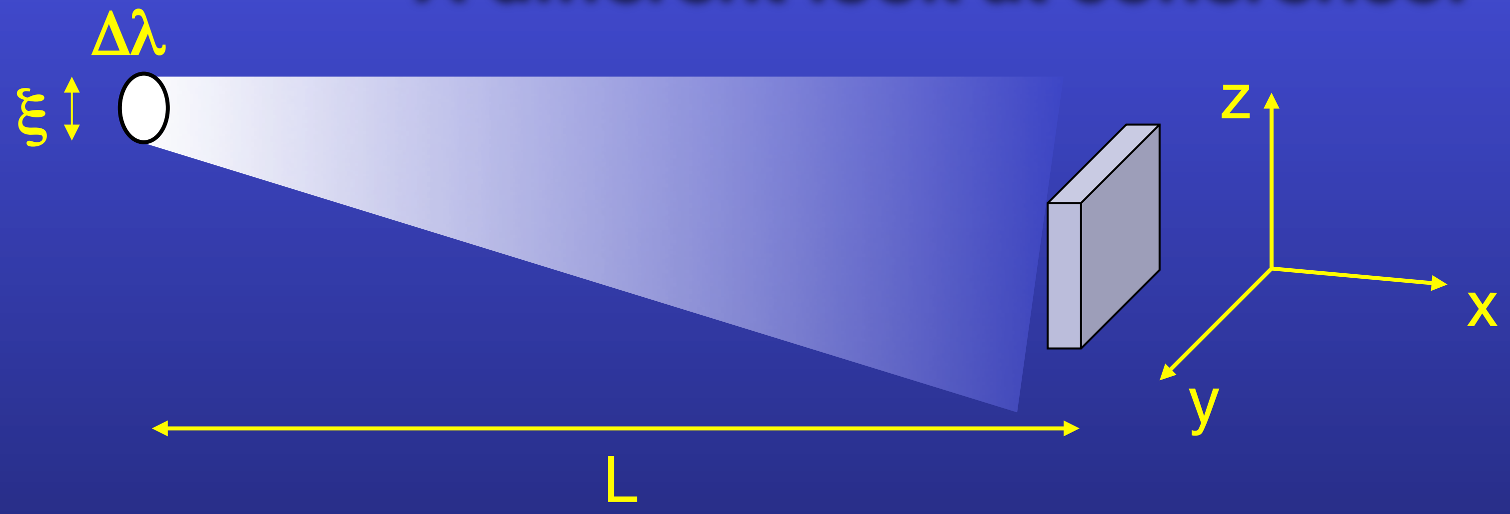
April 21, 2009 - New Era of Research Begins as World's First Hard X-ray Laser Achieves "First Light"

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



Claudio Pellegrini, UCLA -- father of the X-FEL theory

A different look at coherence:



A source of size ξ and bandwidth $\Delta\lambda$ can illuminate coherenty a volume $\Delta x \Delta y \Delta z$.

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

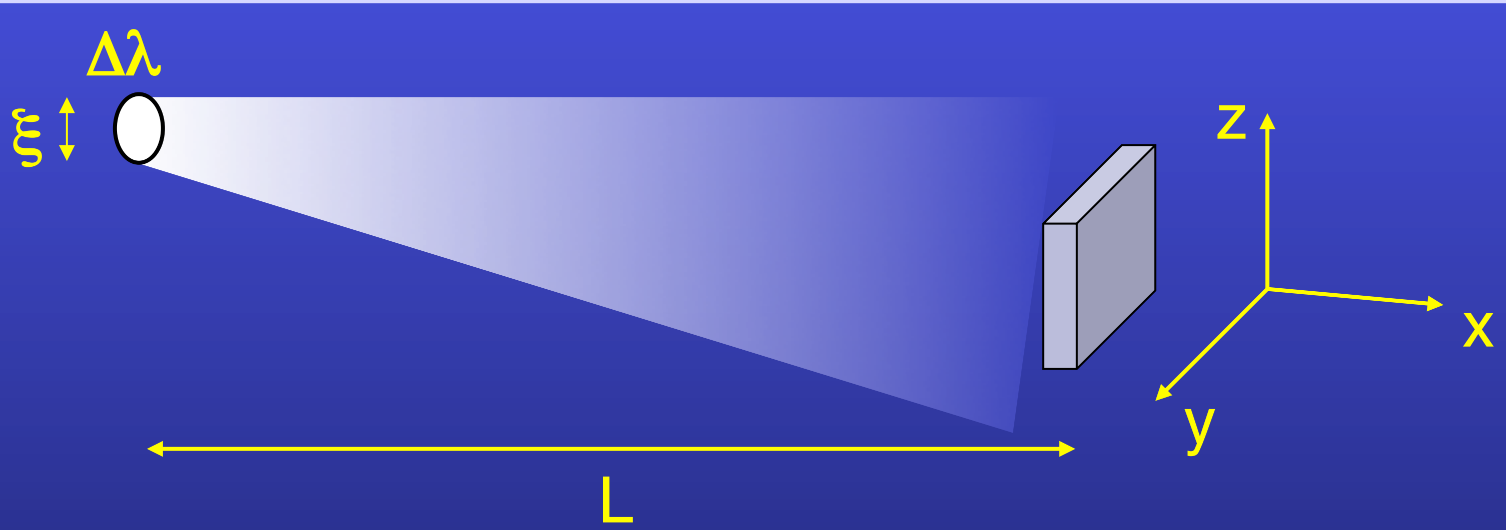
Along y: the spread in k-vector is $\Delta k = k\xi/L = 2\pi\xi/(L\lambda)$.

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

Behind all this: Heisenberg!



Heisenberg: photons are indistinguishable from each other - and therefore coherent - within a transverse length Δy such that $\Delta y \Delta p_y = [h/(2\pi)]$.

But $\Delta p_y = |p|(\xi/L) = [h/(2\pi\lambda)](\xi/L)$, thus $\Delta y = \lambda L/\xi$

Likewise, Δx and Δz can be derived from Heisenberg's principle obtaining the coherence volume $V_c = \lambda^4 L^2/(\Delta\lambda\xi^2)$

Due to the laser action and high brightness, for a SASE-FEL the number of photons in the "coherence volume" is > 9 orders of magnitude larger than for a synchrotron

What is the number n_c of photons in the "coherence volume" for a SASE-FEL with full transverse coherence?

Full transverse coherence means that all the emitted photons are within the "coherence volume". Thus, their number n_c is given by the flux F times $L_c/c = \lambda^2/(c\Delta\lambda)$.

The brightness B is proportional to $F/(\xi\theta)$; for full transverse coherence, $F/(\xi\theta) \approx F/(\lambda^2)$ and F is proportional to $\lambda^2 B$.

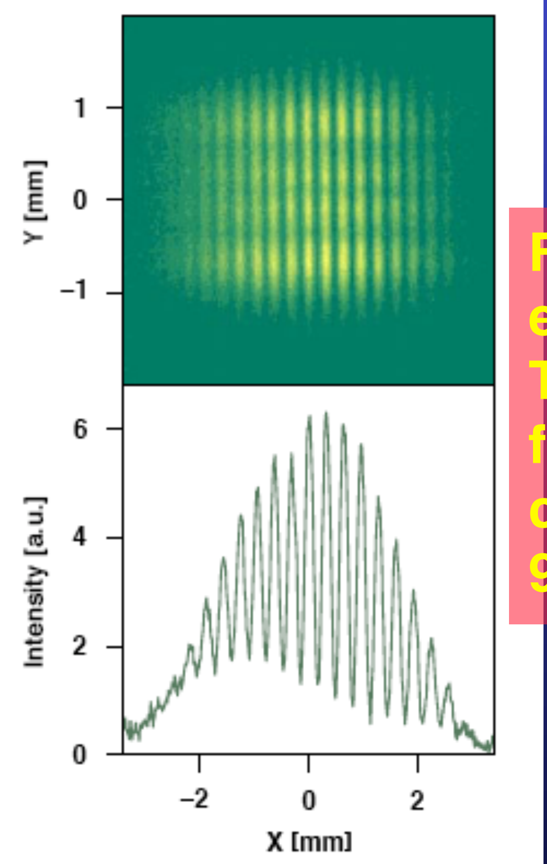
The F-B proportionality factor contains the relative bandwidth $\Delta\lambda/\lambda$.

Thus, $n_c = F\lambda^2/(c\Delta\lambda)$ is proportional to $(\lambda^2 B)[\lambda^2/(c\Delta\lambda)](\Delta\lambda/\lambda)$:

Overall, the number of photons in the "coherence volume" is proportional to $B\lambda^3$: high brightness helps, but short wavelengths are a problem!

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

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- 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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