Introduction to Synchrotron Radiation

Antonella Balerna

DAΦNE-Light Facility
INFN – Frascati National Laboratory

XIII School on Synchrotron Radiation: Fundamentals, Methods and Applications
14-25 September 2015 Grado - Italy

2015 - International year of light

INTERNATIONAL
YEAR OF LIGHT
2015

United Nations designated ***2015 as the International Year of Light and Light-based Technologies.***

2015 marks many anniversaries:

- ***1015*** - ***first scientific accounts of optics published*** by the Islamic scholar Ibn al-Haytham
- ***1815*** - August Fresnel's proposal that ***light is a wave***
- ***1865*** - James Clerk Maxwell's ***electromagnetic theory of light***
- ***1915*** - Albert Einstein's ***general theory of relativity***
- ***1965*** - ***discovery of the cosmic microwave background radiation*** and the ***development of optical fibers*** for communication
- ***2014 (!) -*** *Nobel Prize in Physics was awarded jointly to I. Akasaki, H. Amano and S. Nakamura* ***"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"***

Introduction to Synchrotron Radiation

Outline

- Light, light sources, brightness and x-rays
- Synchrotron light
- Main properties
- Sources of Synchrotron Radiation
- Short history
- Present and future
- Some applications

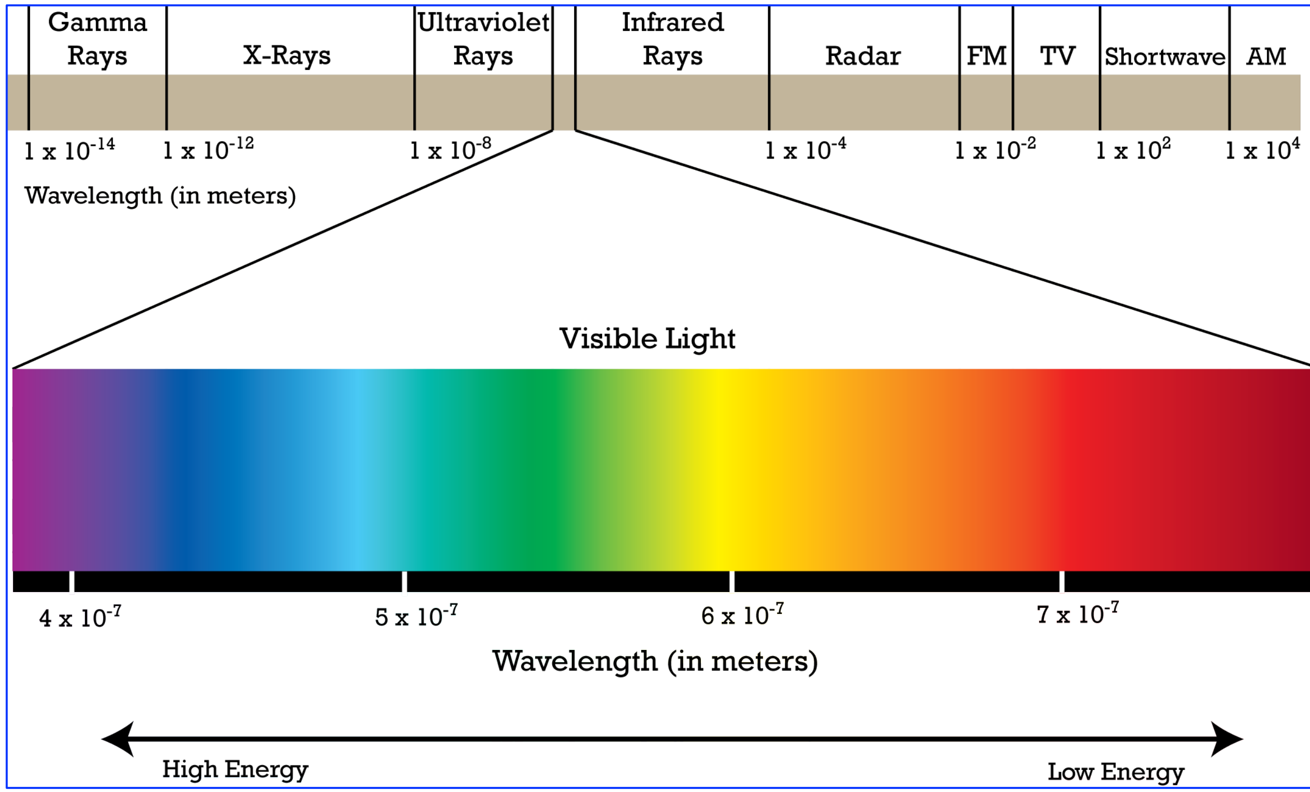
Light

Progress in science goes in parallel with the technical progress in producing and using light at different wavelengths to explore the physical world.

Light

Visible light is only a ***tiny slice of the electromagnetic spectrum***. The entire electromagnetic spectrum of light is huge, spanning from ***gamma rays on one end to radio waves***.

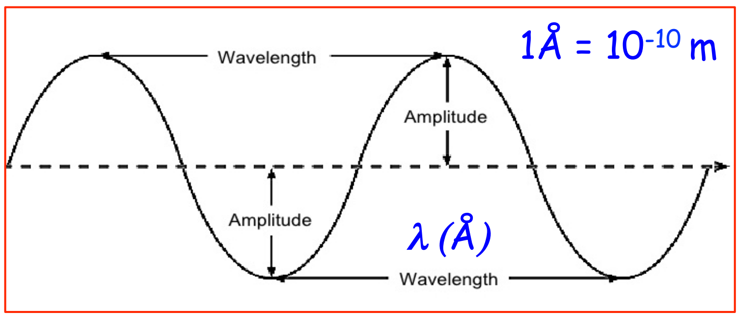
Visible Light is the light we can see using our eyes. This tiny human spectrum encompasses a very specific range of wavelengths from about ***380 nm to 780 nm***.

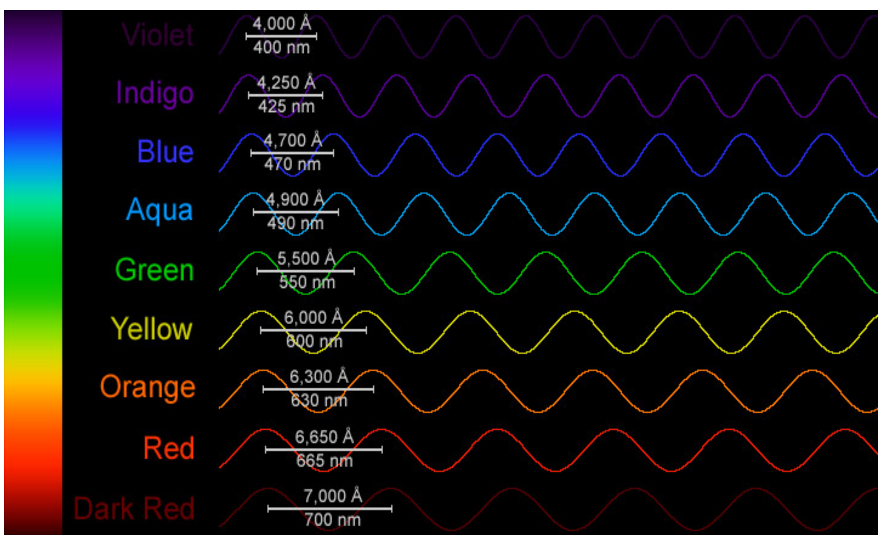


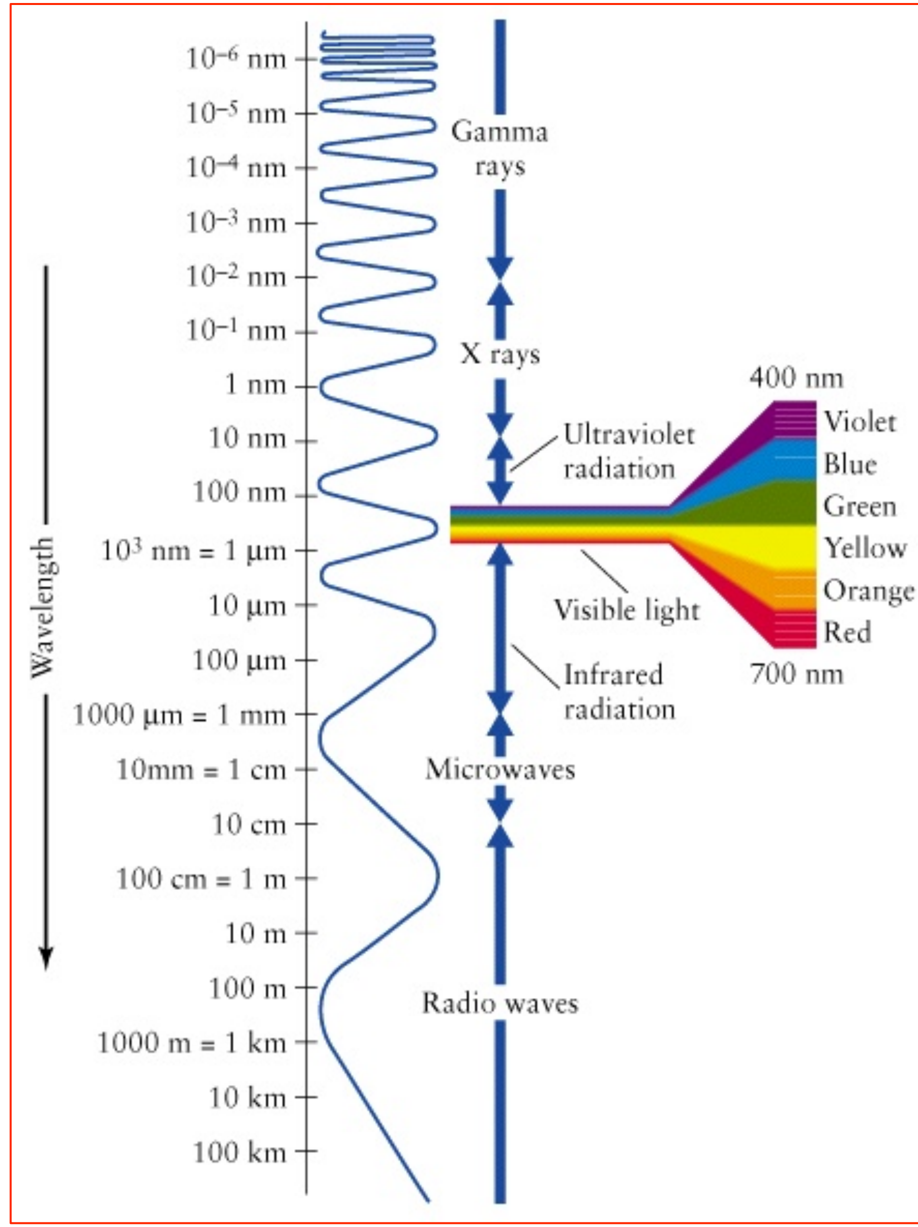
Physiologically we see these frequencies because the photoreceptors in our retinas are sensitive to them. When photons of light hit the photoreceptors this creates an electrochemical signal which is the first step in a fascinating process which ultimately results in us seeing colors.

Light and waves

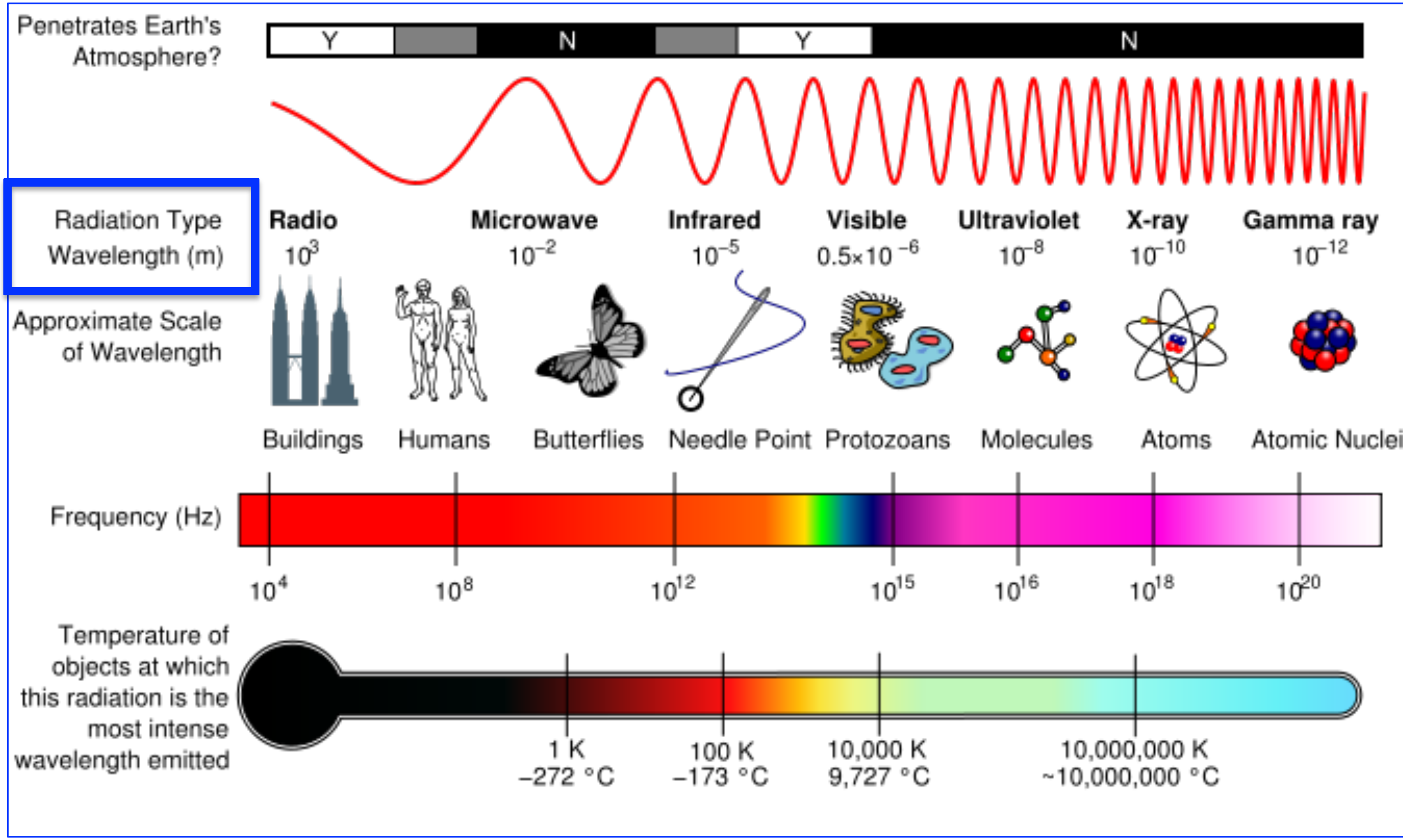
Light travels as waves of energy. Waves of light have different ***wavelengths*** (the distance between the top of one wave and the top of the next). ***Different colors of visible light have different wavelengths.***







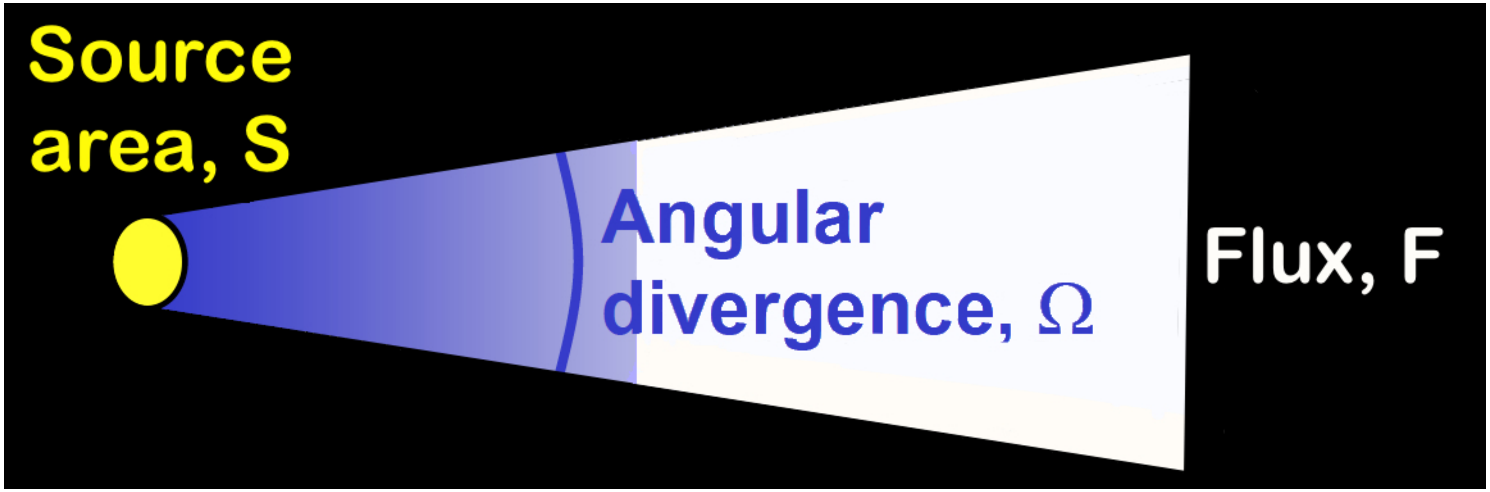
Electromagnetic Spectrum



The *wavelength* (λ) and *frequency* (ν) *of light are strictly related*: ***the higher the frequency the shorter the wavelength***! This is because *all light waves move through vacuum at the same speed* (c = speed of light) and the equation that relates wavelength and frequency for electromagnetic waves is: $\lambda\nu = c$

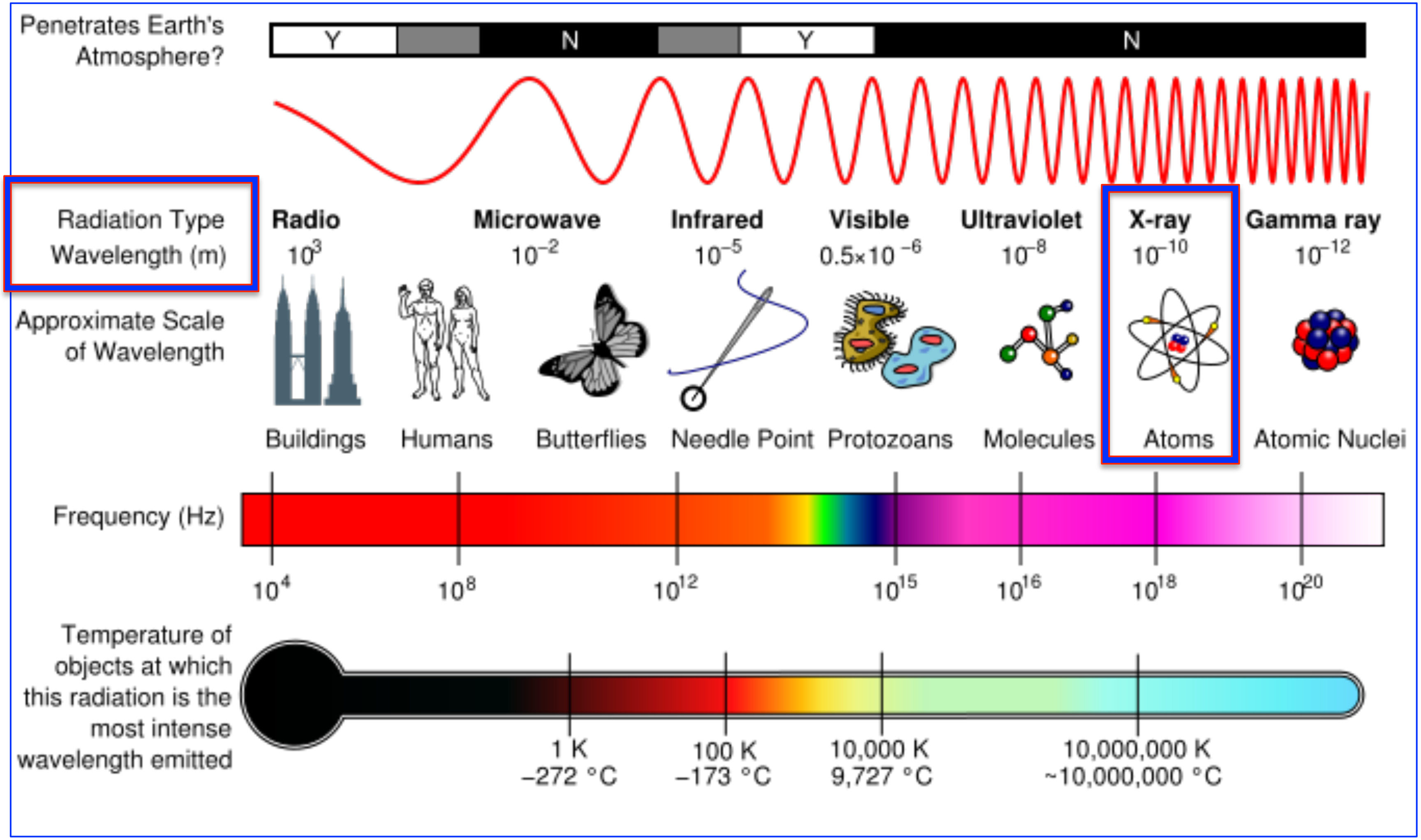
Light sources and brightness

A ***bright source*** is the one ***very effective in illuminating a specific target***. If the specific target is small a ***bright source*** is ***a small size source with emission concentrated within a narrow angular spread.***



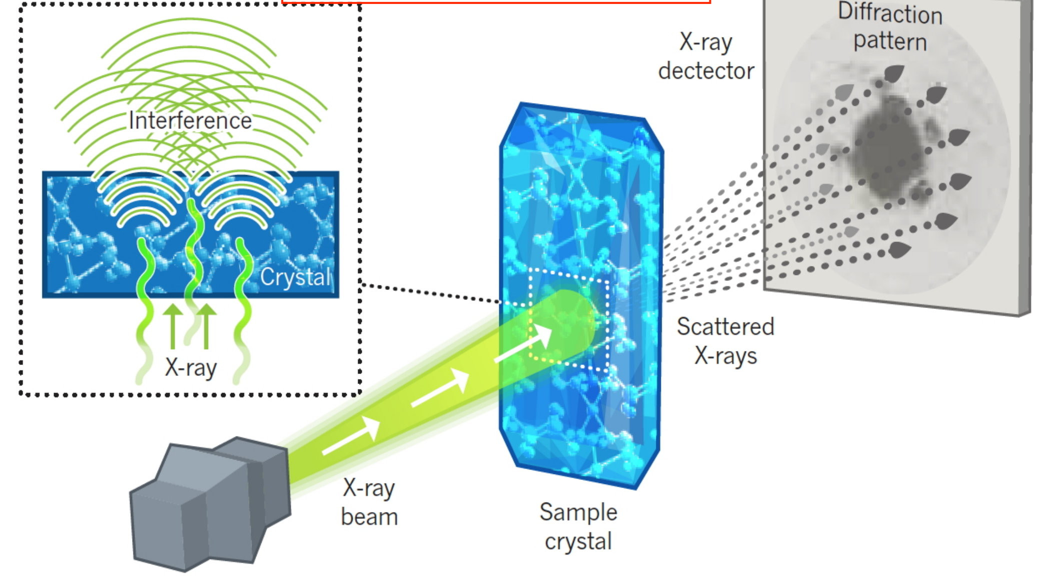
$$Brightness = constant \; \frac{F}{S \times \Omega}$$

Electromagnetic Spectrum and X-rays



X-rays and atoms

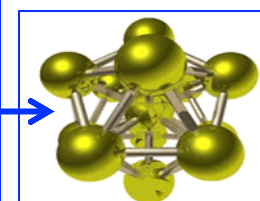
N. Jones, Nature 505, 602 (2014)



With X-rays we can study atoms because wavelengths are of the order of 10^{-10} m or 0.1 nm or 1Å

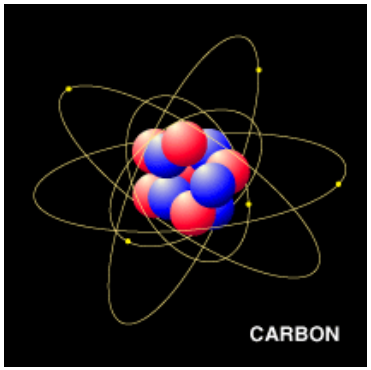
Matter is composed of atoms!

Using X-rays we can study the atomic structure of materials! The atomic structure primarily affects the chemical, physical, thermal, electrical, magnetic, and optical properties.



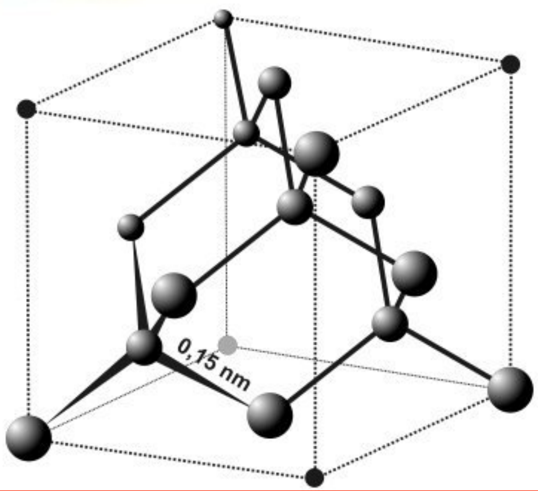
Why is this important?

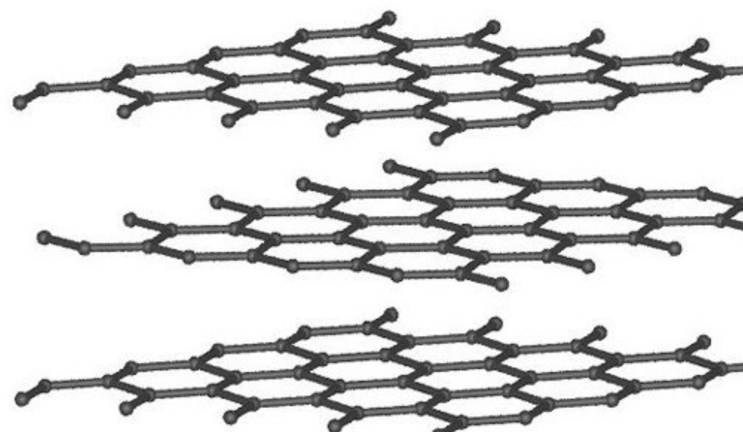
X-rays and Atoms



Both diamond and graphite are made entirely out of carbon!

Using x-rays to reveal the atomic structure of materials

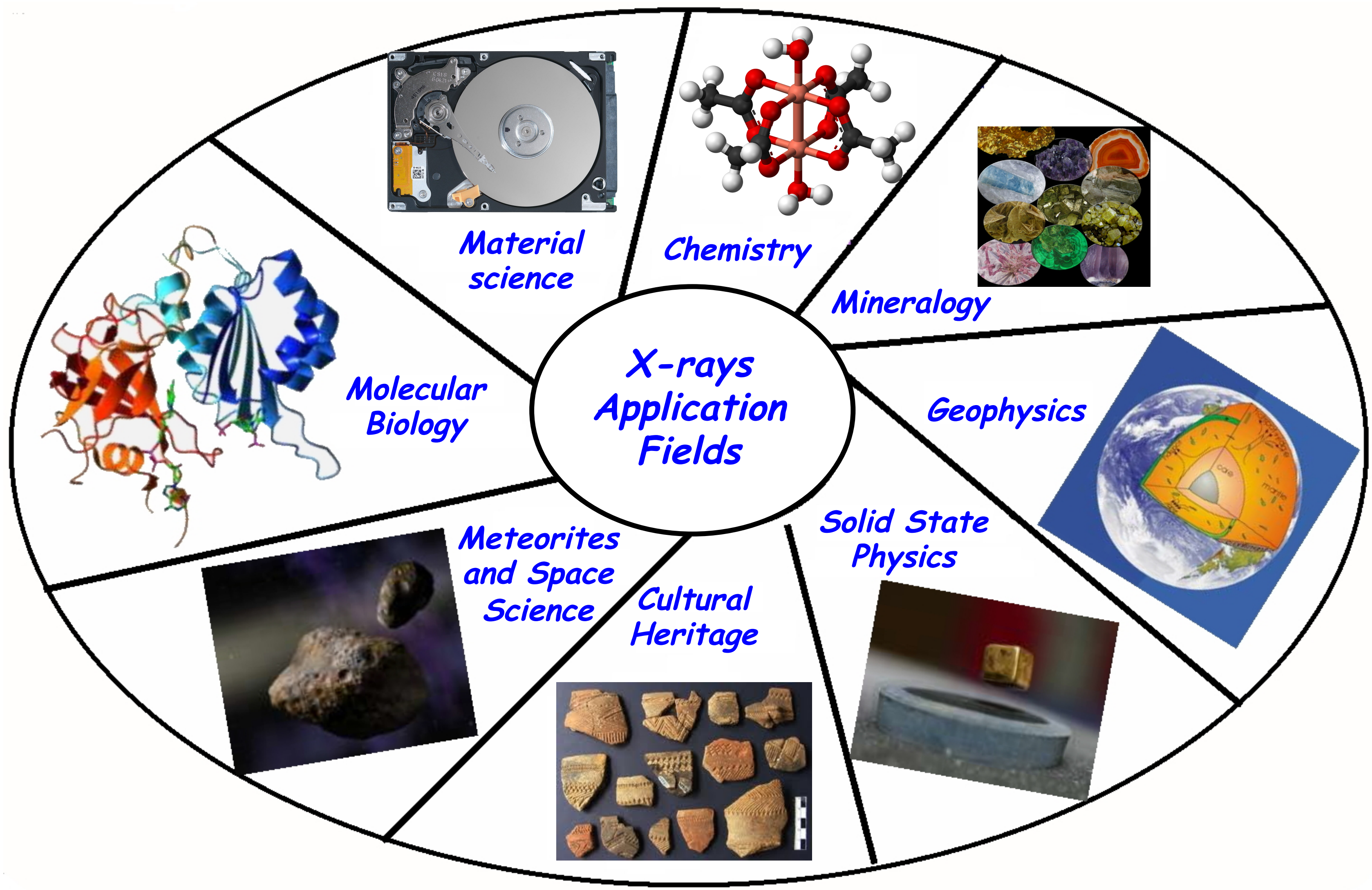




Graphite is opaque and metallic- to earthy-looking, while diamonds are transparent and brilliant.

The different properties of graphite and diamond arise from their distinct crystal structures.

X-rays application fields



Bright light sources?

HE particle accelerators

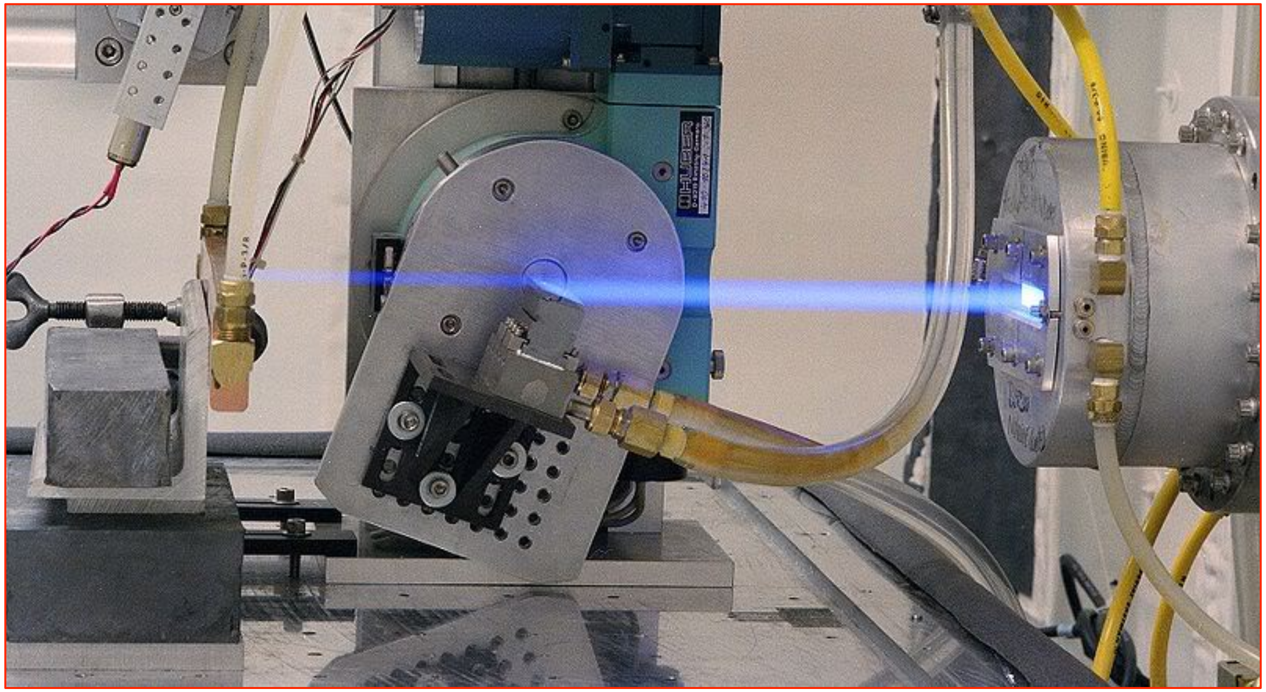
↓

Relativistic effects

↓

Synchrotron light

Synchrotron radiation and light sources



Synchrotron radiation opened a new era of accelerator-based light sources that have evolved rapidly over four generations:

- *the first three-generations based on storage rings*

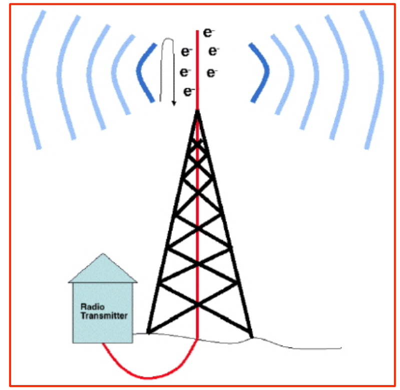
-the forth and fifth generation light sources based on FELs.

A dramatic improvement of brightness and coherence over about 70 years.

Synchrotron radiation

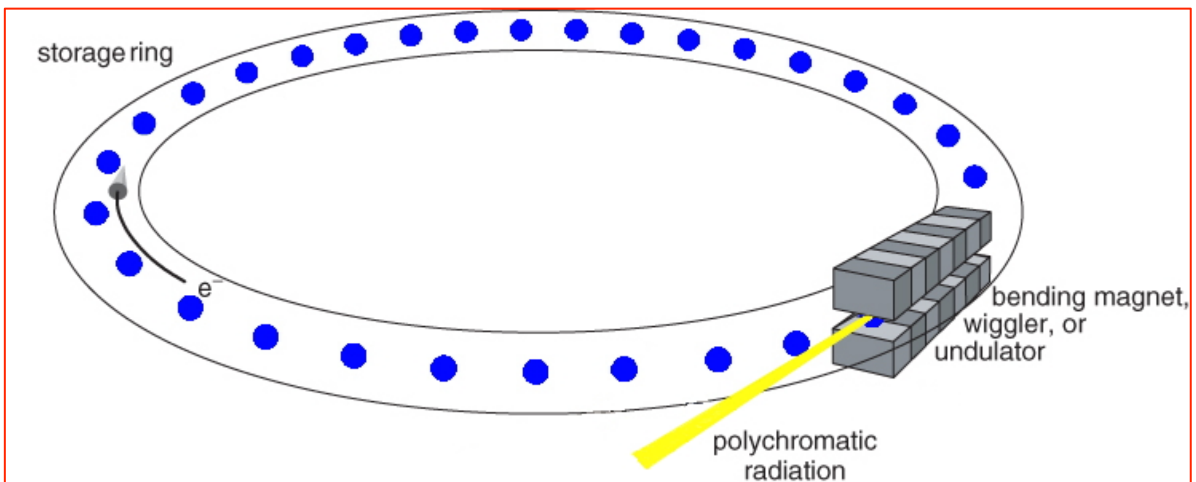
Synchrotron radiation

Accelerated charged particle, e^+, e^- and ions, emit electromagnetic radiation like electric charges forced to oscillate along an antenna.



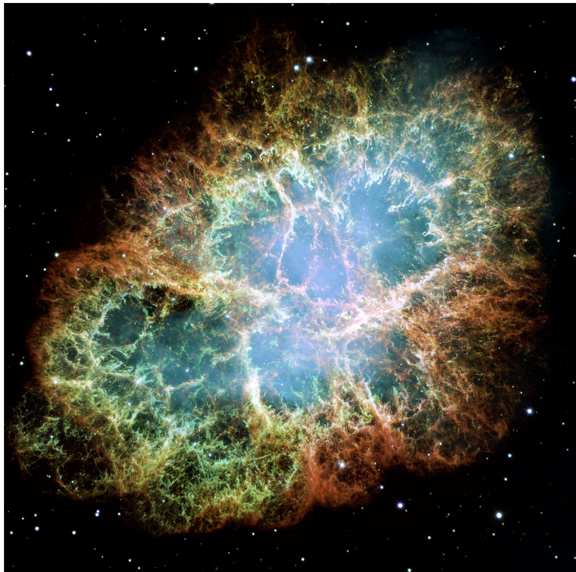
$v \ll c$ or $\beta = v/c \ll 1$

*When **charged particles, moving at relativistic speeds** ($v \approx c$), are forced **(Lorentz force)** to **change the direction of their motion (acceleration)**, under the effect of **magnetic fields**, in **circular particle accelerators, like synchrotrons**, the radiation produced is called **synchrotron radiation**.*

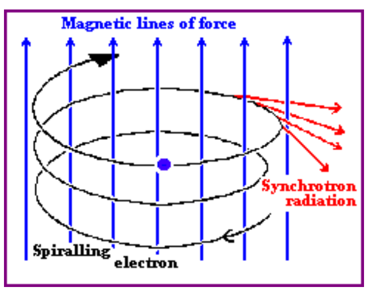


$v \approx c$ or $\beta = v/c \approx 1$

Synchrotron light is present in nature!



NASA Hubble Space Telescope image of the Crab Nebula (NASA, ESA and Allison Loll/Jeff Hester (Arizona State University)).



Synchrotron radiation is a very important emission process in astrophysics!

Crab Nebula: remnant of a supernova explosion seen on earth by Chinese astronomers in 1054, at about 6500 light years from Earth in the constellation Taurus !

SR emission is produced by high energy electrons whirling around the magnetic fields lines originating from a Pulsar

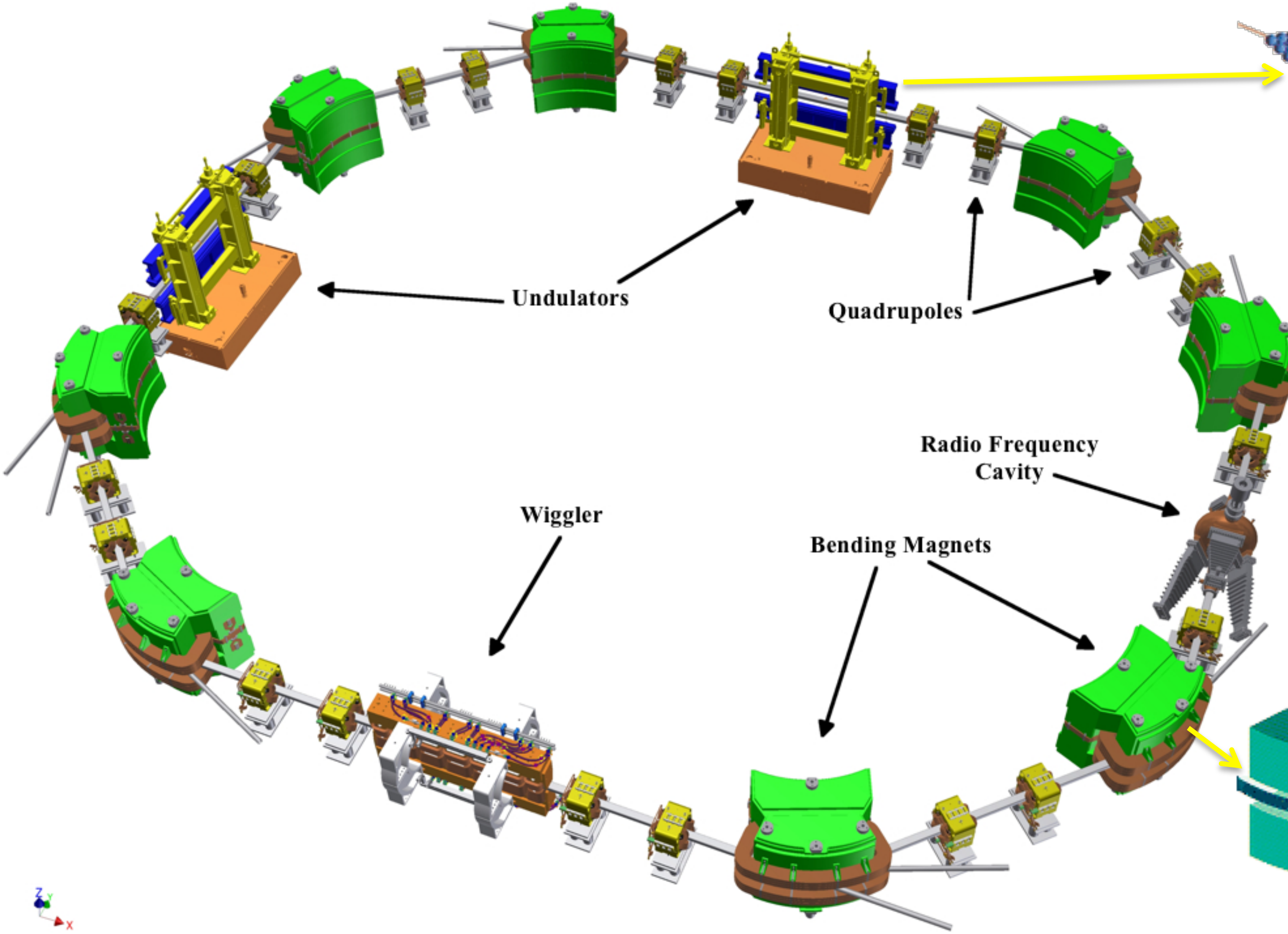
The heart of the nebula is a rapidly-spinning neutron star, a pulsar, that powers the strongly polarised bluish 'synchrotron' nebula.

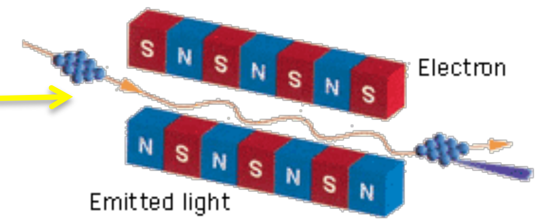
NASA's Great Observatories' View of the Crab Nebula X-Ray-blue: NASA/CXC/J.Hester (ASU); Optical-red and yellow: NASA/ESA/J.Hester & A.Loll (ASU); Infrared-purple: NASA/JPL-Caltech/R.Gehrz (Univ. Minn.)

The ***Crab pulsar*** is ***slowing at the rate of about 10^{-8} sec per day***, and the ***corresponding energy loss agrees well with the energy needed to keep the nebula luminous***. Some of this luminosity takes the form of ***synchrotron radiation, requiring a source of energy for accelerating charged particles***.

*Composite image data from **three of NASA's Great Observatories**. The **Chandra X-ray Observatory image** is shown in blue, the **Hubble Space Telescope optical image** is in red and yellow, and the **Spitzer Space Telescope's infrared** image is in purple. The X-ray image is smaller than the others because extremely energetic electrons emitting X-rays radiate away their energy more quickly than the lower-energy electrons emitting optical and infrared light. **The Crab Nebula is one of the most studied objects in the sky, truly making it a cosmic icon**.*

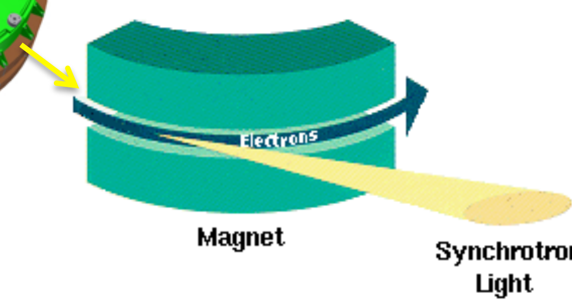
Synchrotron light is artificially produced by relativistic particles accelerated in circular orbits.



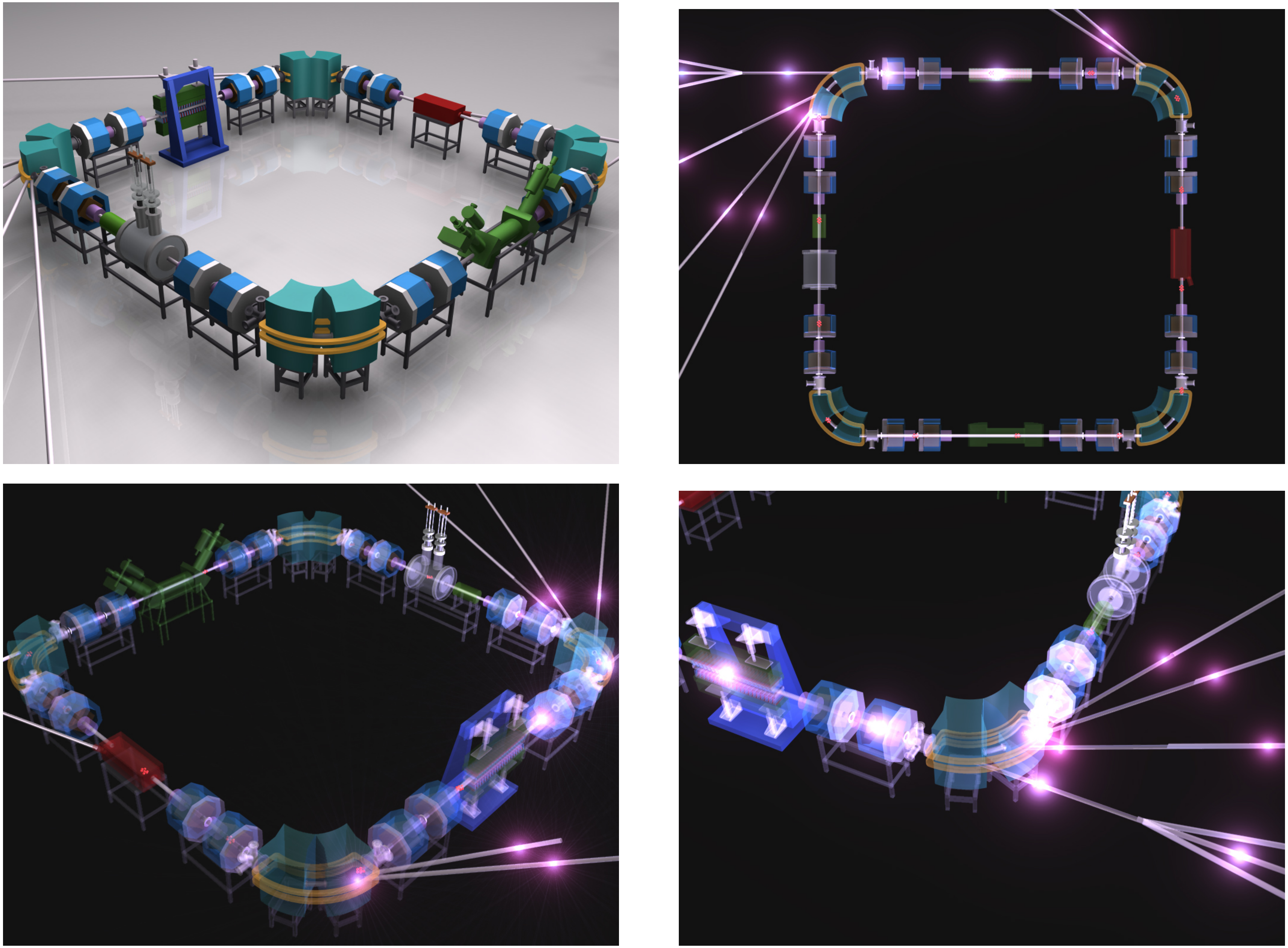


Insertion Device

Bending Magnet



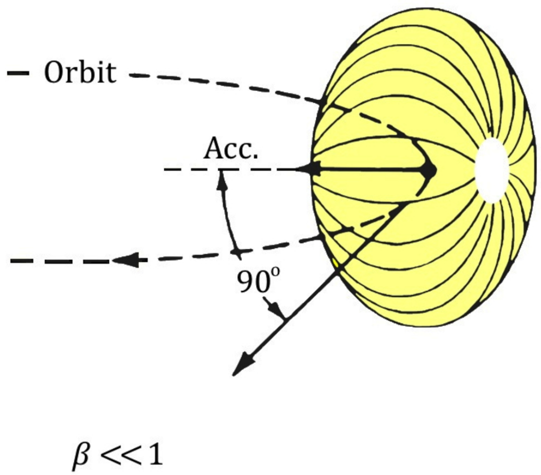
… and synchrotron radiation is also the coherent radiation emitted by the undulators of Free Electron Lasers.

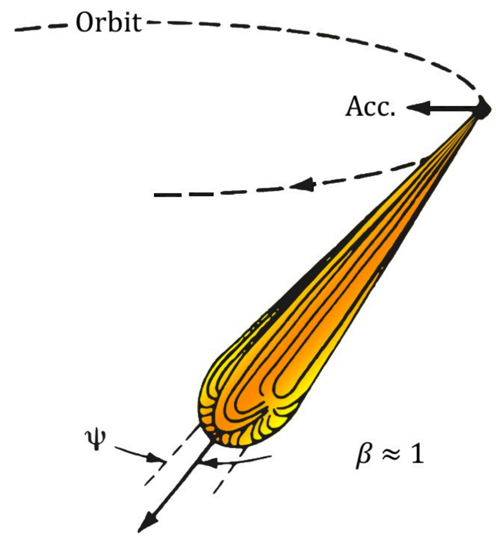


ASTRID (Aarhus - Denmark) http://www.isa.au.dk/animations/pictures/pic-index.asp

http://www.isa.au.dk/animations/Finalmovie/astrid_total_v2.mov

Synchrotron radiation: physics





v << c or β = v/c << 1

$$P = 2\, e^2\, a^2 / (3c^3) \quad [W]$$

P = total emitted power, *a* = acceleration

At low electron velocity (non-relativistic) the radiation is emitted in a ***classical dipole pattern***.

1897 ***Lamor***: calculates power radiated by an accelerated charged particle.
1898 ***Liénard***: extends the theory to particles in a circular path *conceiving synchrotron light*.

v ≈ c or β = v/c ≈ 1

For a ***relativistic effect***, when the speed of the emitting electrons increases to relativistic values (v ≈ c) the radiation pattern is compressed into a ***narrow cone in the direction of motion, resulting into an emission tangential to the particle orbit***.

The vertical half-opening angle, ψ , is given by:

$$\psi \approx m_0c^2/E \approx \gamma^{-1} .$$

ESRF E = 6 GeV, m_0c^2 = 511KeV

$\psi \approx 9x10^{-5}$ **mrad** $\gamma = E/m_0c^2 = 1957\, E\,(GeV)$

Synchrotron radiation: physics

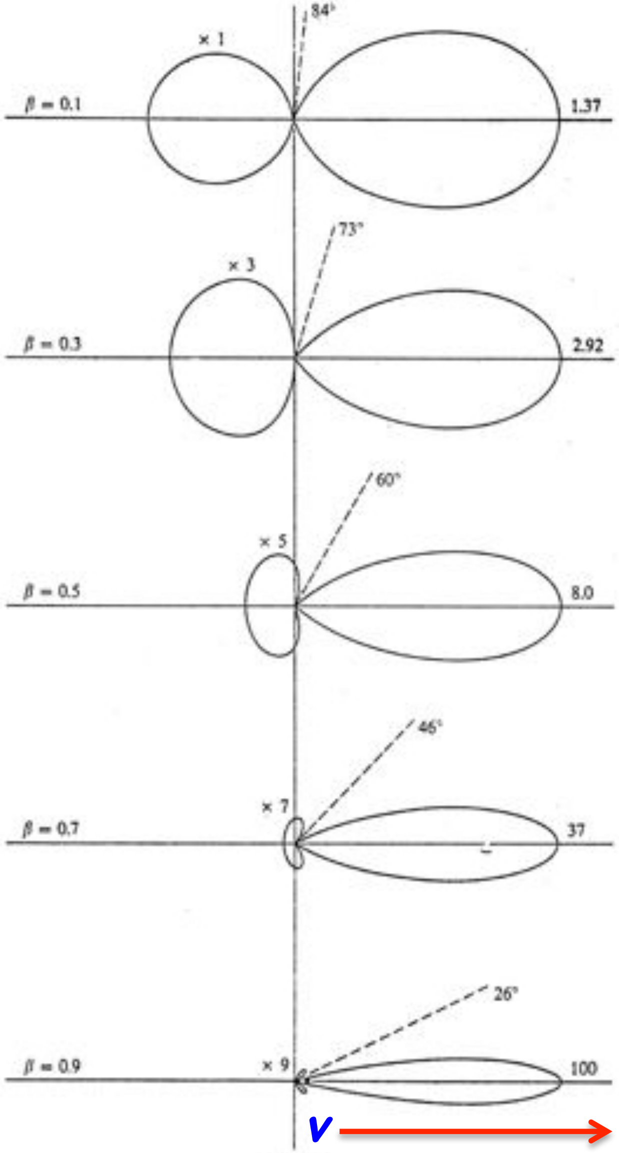


FIG. 7-7

$v \ll c$ or $\beta = v/c \ll 1$

As β approaches 1:

1. *the shape of the radiation pattern changes: it is more in the forward direction!*
2. *the relativistic Lorentz transformation of angles gives a decrease by a factor of γ, γ being the ratio between the total energy of the particle and the rest mass energy*
3. *the node at $\theta' = 90°$ (in the frame of the radiating particle $v \perp a$) transforms to:*

$$\tan\theta_{lab} = \frac{\sin\theta'}{\gamma(\cos\theta' + \beta)} = \frac{1}{\gamma\beta} \approx \frac{1}{\gamma}$$

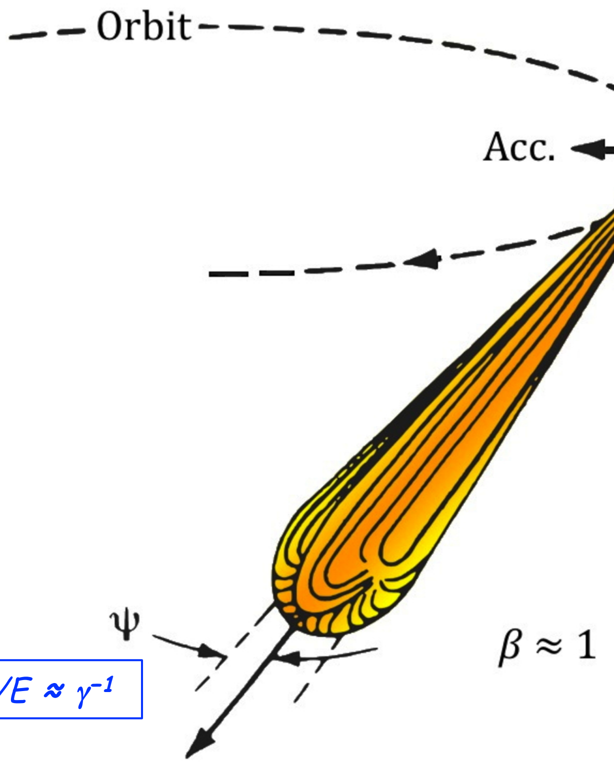
For electron energies in storage rings between 1-5 GeV, γ is between 2000 and 10000. The angle of emission is lower than a mrad.

$\gamma = (1-\beta^2)^{-1/2}$ *Lorentz factor*

$v \approx c$ or $\beta = v/c \approx 1$

Synchrotron radiation: physics

Relativistic focusing of Synchrotron Radiation



$\psi \approx m_0c^2/E \approx \gamma^{-1}$

$v \approx c$ or $\beta = v/c \approx 1$

The vertical half-opening angle:

$$\psi \approx \frac{m_0 c^2}{E} \approx \frac{1}{\gamma}$$

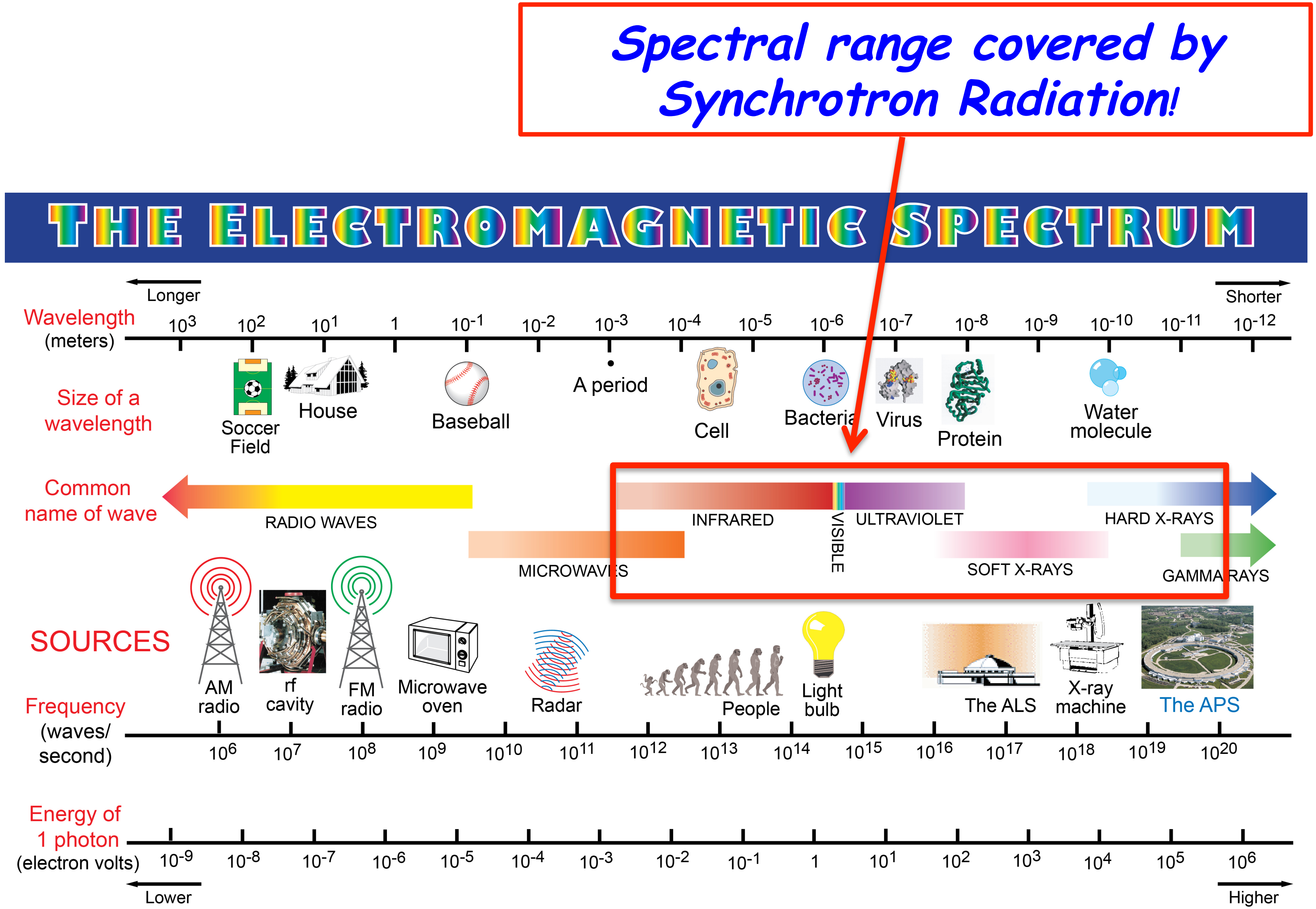
Total radiated power:

$$P_{rad} = \frac{2}{3}\frac{Q^2 c}{R^2}\left[\frac{E}{m_0 c^2}\right]^4$$

E = particle energy, m_0 = rest mass, R = radius of curvature

1949 Schwinger: classical theory of radiation from accelerated relativistic electrons

Tomboulian, D. H. and Hartman, P.L., Spectral and Angular Distribution of Ultraviolet Radiation from the 300-Mev Cornell Synchrotron. Phys. Rev. 102, 1423–1447 (1956)
J. Schwinger, On the Classical Radiation of Accelerated Electrons, Phys. Rev. 75, 1912 (1949)
J. Schwinger, On Radiation by Electrons in a Betatron, (1945) [LBNL-39088]
D. Iwanenko and I. Pomeranchuk, On the Maximal Energy Attainable in a Betatron, Phys. Rev. 65,343 (1944)

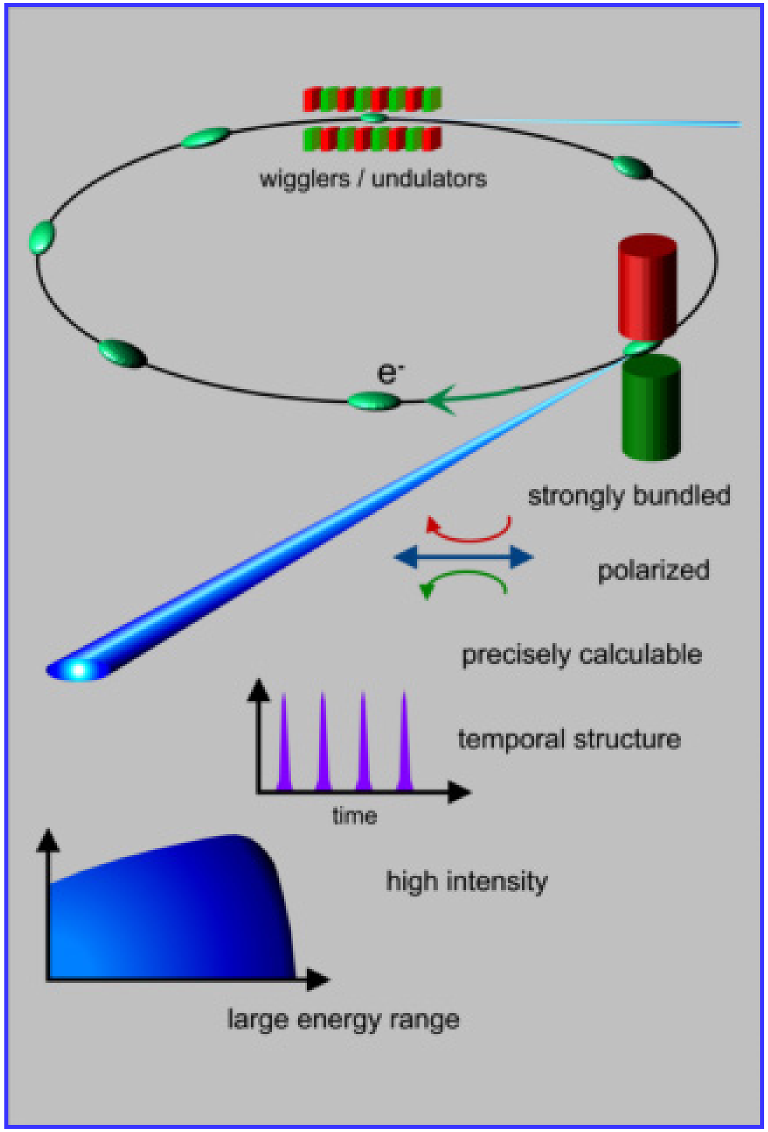


Spectral range covered by Synchrotron Radiation!
THE ELECTROMAGNETIC SPECTRUM
Longer
Shorter
Wavelength (meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
Size of a wavelength
Soccer Field
House
Baseball
A period
Cell
Bacteria
Virus
Protein
Water molecule
Common name of wave
RADIO WAVES
MICROWAVES
INFRARED
VISIBLE
ULTRAVIOLET
SOFT X-RAYS
HARD X-RAYS
GAMMA RAYS
SOURCES
AM radio
rf cavity
FM radio
Microwave oven
Radar
People
Light bulb
The ALS
X-ray machine
The APS
Frequency (waves/ second)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy of 1 photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
Lower
Higher

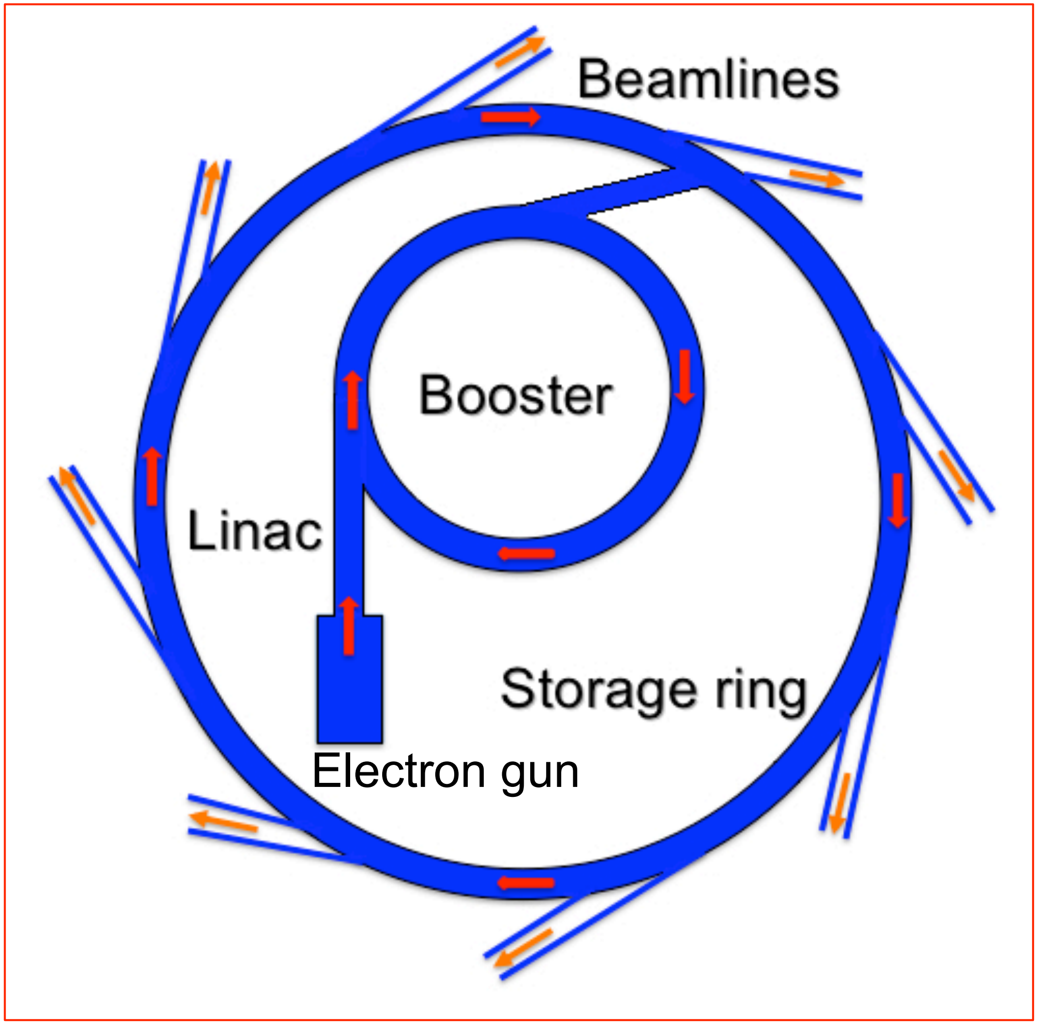
Synchrotron Radiation Properties

What makes synchrotron radiation interesting, powerful and unique?

- ***Continuum source from IR to X-rays*** ***(tunability)*** which covers from **microwaves to hard X-rays**: the user can select the wavelength required for experiment- **continuous** *(Bending Magnet/Wiggler)* - **quasi-monochromatic** *(Undulator)*
- ***Source in a clean UHV environment***
- ***Very high flux and brightness (with undulators)*** highly **collimated photon beams** generated by a ***small divergence*** and **small size sources** .
- ***Highly Polarized***
- ***Pulsed time structure*** **-** pulsed length down to tens of picoseconds allows the resolution of processes on the same time scale
- ***High stability*** **(submicron source stability)**

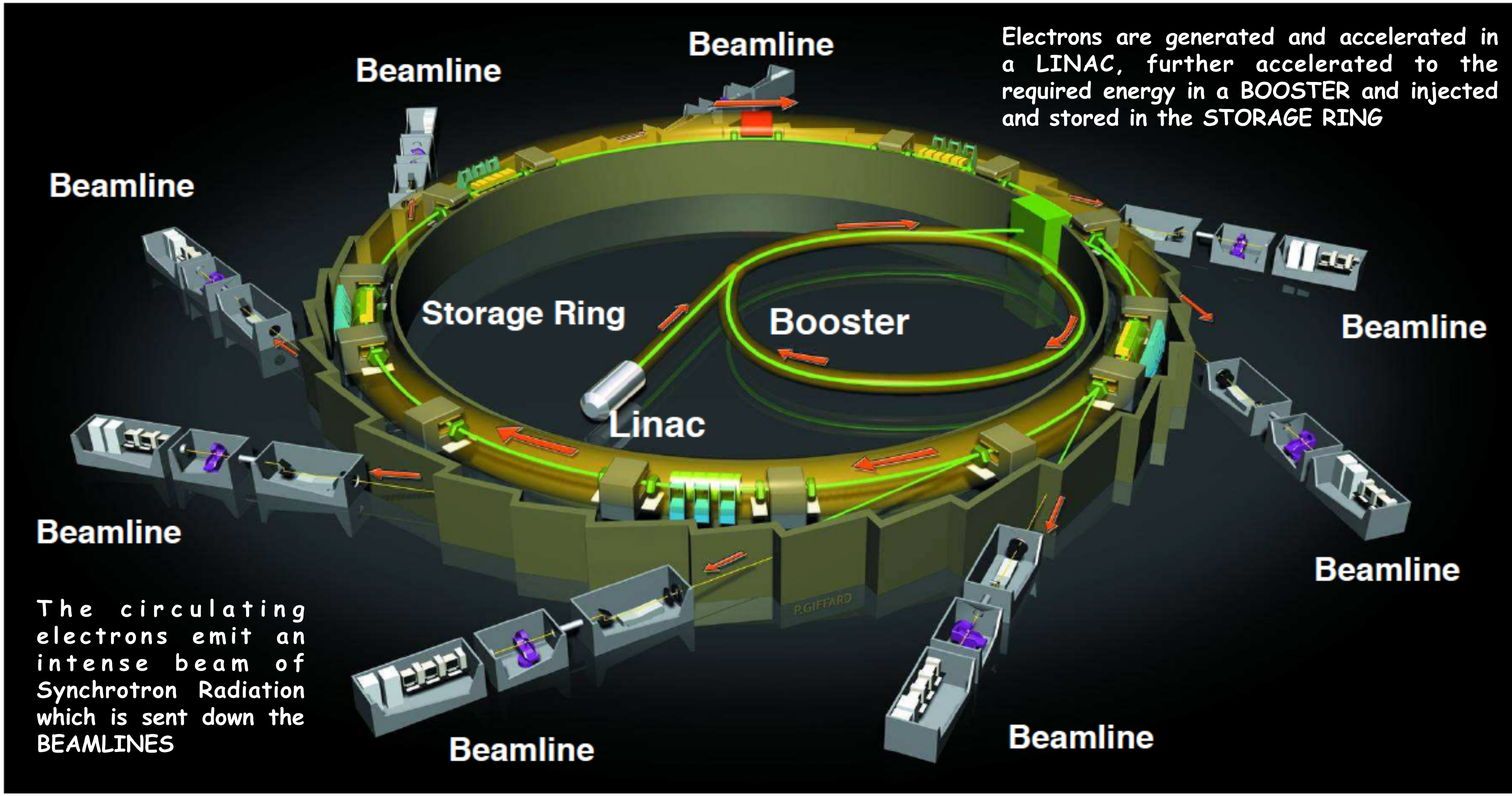


Modern synchrotron radiation sources



- ***Electron gun***: e^- source (thermionic emission from a hot filament)
- ***LINAC***: linear accelerator where electrons are accelerated up to several millions of electron volts (MeV)
- ***Booster ring***: electrons are boosted in energy from millions to billions or giga electron volts (GeV)
- ***Storage ring***: consist of an array of magnets for focusing and bending the beam, connected by straight linear sections where RF cavities or insertion devices are installed.
- ***Beamlines*** : collect radiation running off tangentially to the storage ring, along the axes of the insertion devices and tangentially at bending magnets

Schematic view of a Synchrotron Radiation facility



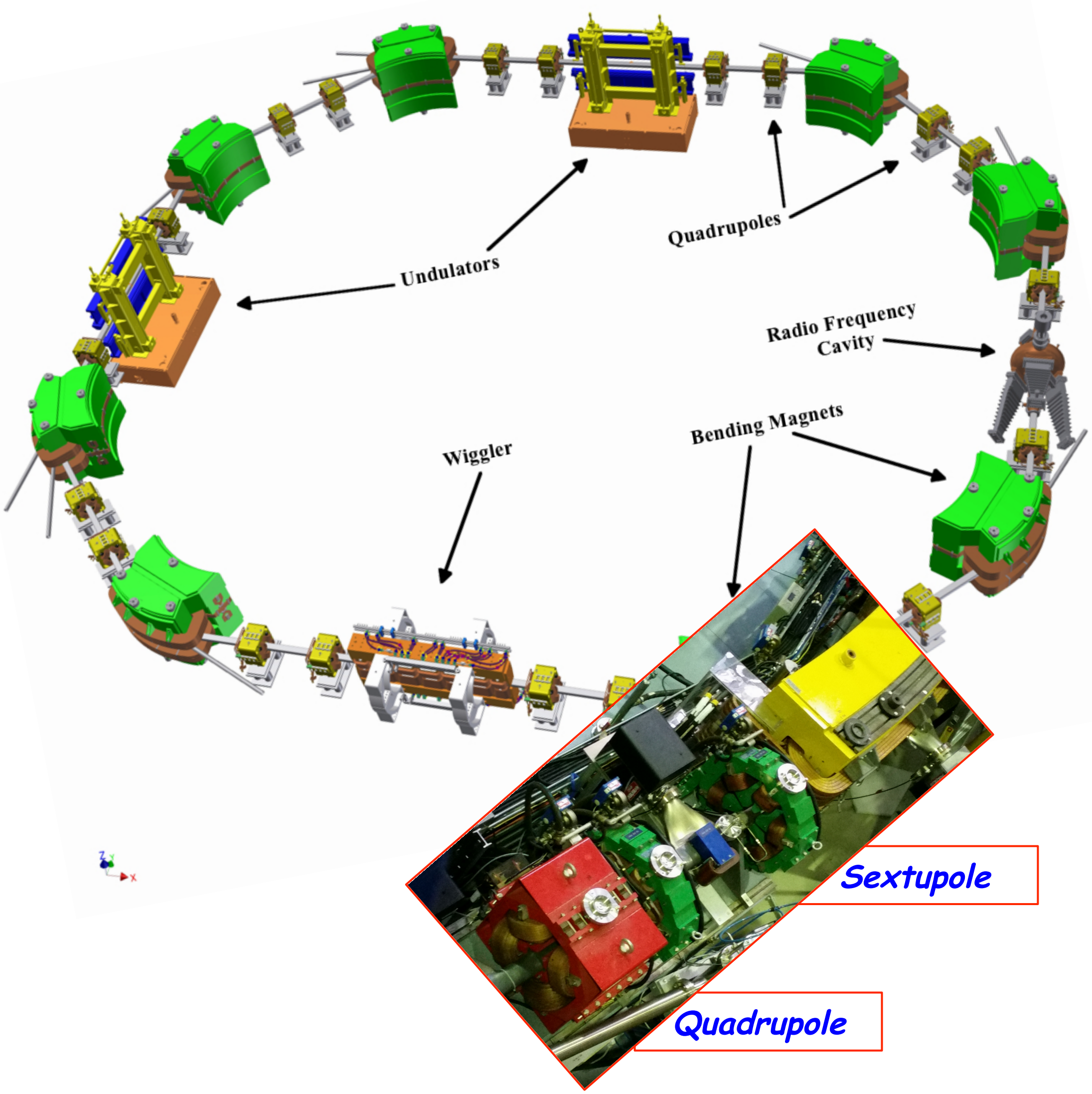
As a function of the energy range to be used each beamline must be optimized for a particular field of research.

Beamline schematic composition:

- *Front end*
- *Optical hutch*
- *Experimental hutch*
- *Control and computing*

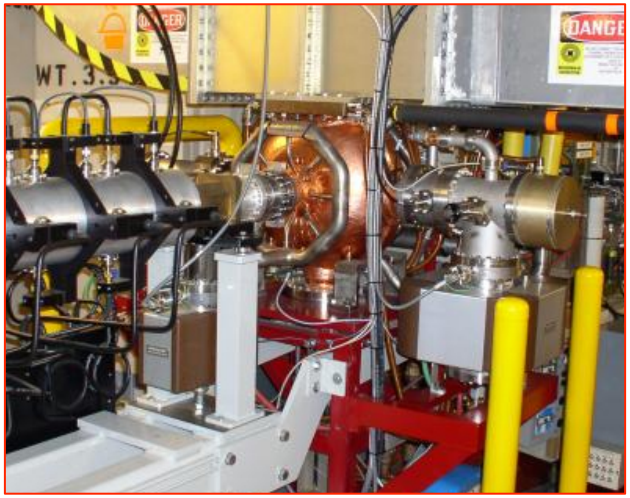
The ***front end*** isolates the beamline vacuum from the storage ring vacuum; **defines the angular acceptance of the synchrotron radiation** via an aperture; blocks(beam shutter) when required, the x-ray and Bremsstrahlung radiation during access to the other hutches.

Schematic view of a storage ring



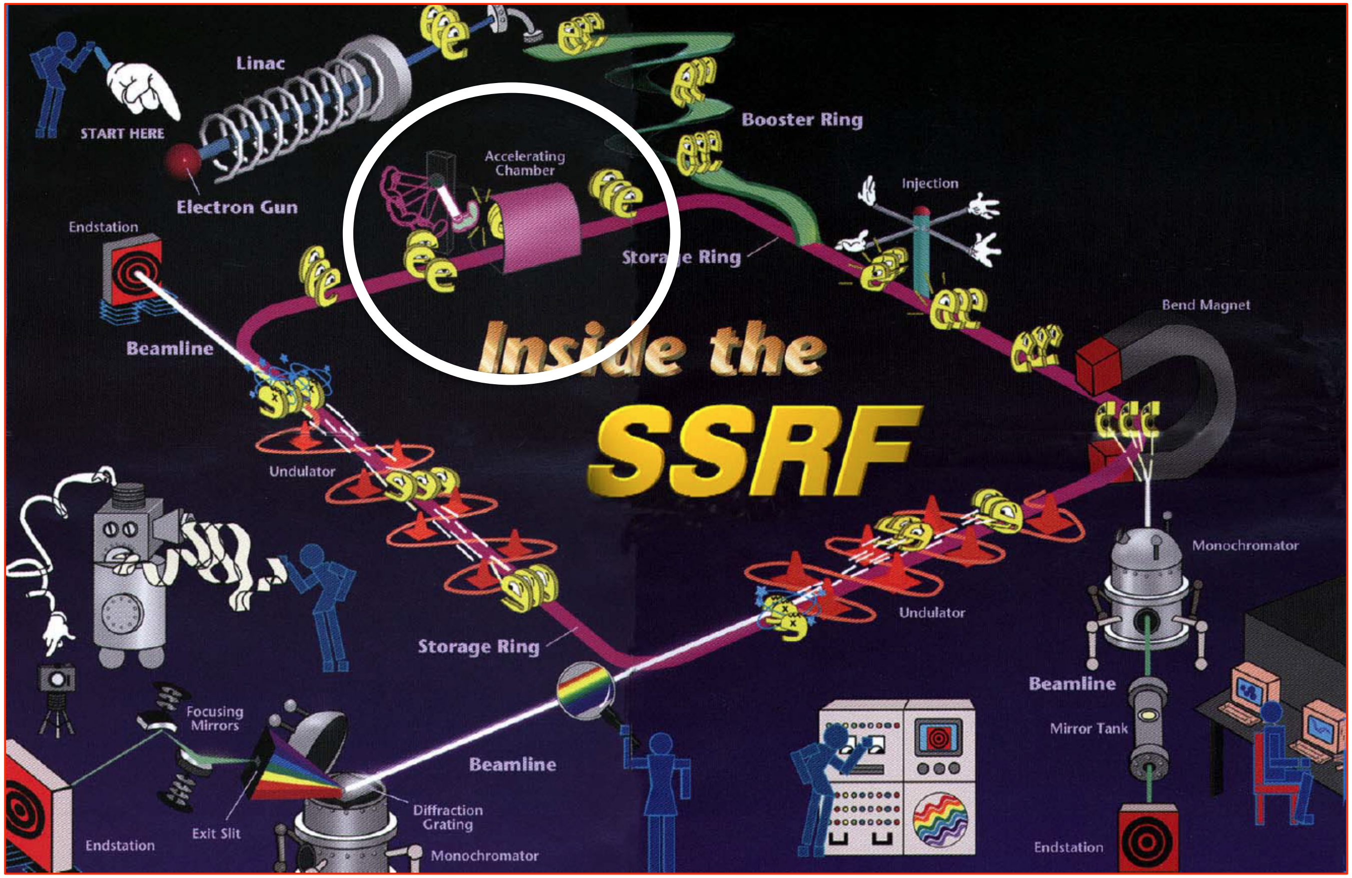
- ***Storage rings*** contain the electrons and maintain them on a closed path by the use of an array of magnets or '***magnet lattice***'.
- ***The magnet lattice*** is most commonly contains three types of magnets: ***dipoles - or bending magnets*** cause the electrons to change their path and thereby follow a closed path; ***quadrupole magnets*** are used to focus the electron beam and compensate for Coulomb repulsion between the electrons; and ***sextupole magnets*** correct for chromatic aberrations that arise from the focusing by the quadrupoles.
- ***RF cavities*** supply the energy lost by electrons emitting synchrotron radiation.
- ***Insertion devices (ID)*** while the arced sections contain bending magnets, the straight sections are used for insertion devices (***wigglers*** and ***undulators***), that generate the most intense synchrotron radiation

Radio Frequency cavities



ALS 1.9 GeV storage ring: the electrons lose up to 300 keV per revolution from radiative losses. In the storage ring a pair of RF cavities, with a peak voltage of 1.5 Megavolts, operating at 500 MHz are used.

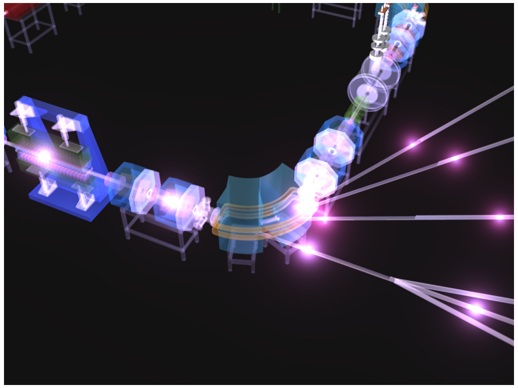
RF cavities and time structure



Z. Zhao – RF System For Electron Storage Rings – The 4th OCPA Accelerator School Yangzhou, Jul. 17-Aug.5, 2006.
SSRF: Shanghai Synchrotron Radiation Facility

As the electrons circulate around the storage ring they pass through the bending magnets and insertion devices, radiating energy in the form of synchrotron light. On each rotation the electron beam passes through a cavity containing electromagnetic fields oscillating at radio frequencies. This provides an energy boost which compensates for the energy losses, and allows the beam to maintain a fixed orbit around the storage ring.

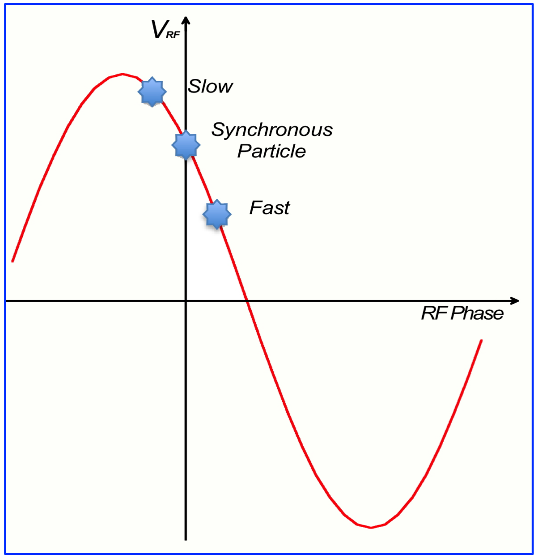
Radio Frequency (RF) cavities and time structure

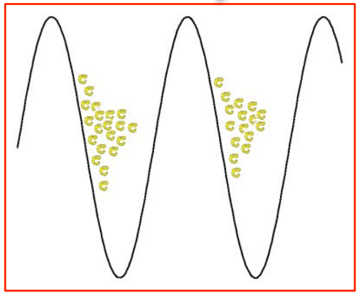


To restore the radiated power and keep the electrons at a constant energy, ***radio frequency (RF) cavities*** are used with ***longitudinal electric fields that accelerate the electrons.***

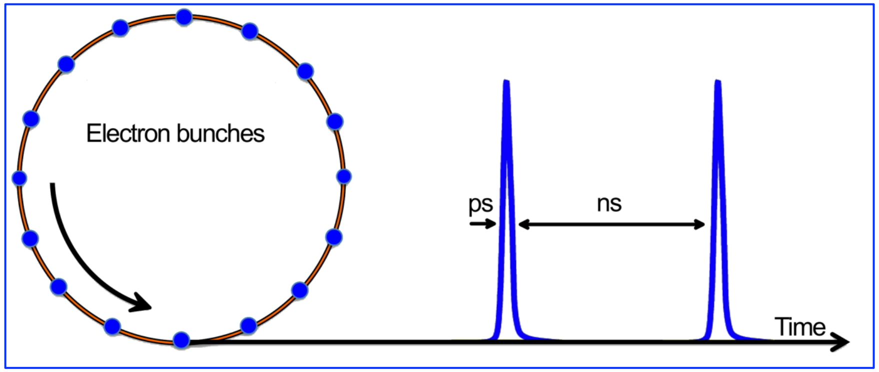
$$P_{rad} = \frac{2}{3}\frac{Q^2 c}{R^2}\left[\frac{E}{mc^2}\right]^4$$

The RF fields have ***an accelerating effect only during one half of their period***. ***Only 5% - 10% of the RF period is effective in restoring the electron energy*** so electrons, passing through the RF, not in phase are lost.





As a consequence the RF acceleration induces a distribution of the electrons in bunches with time lengths that are typically 5% - 10% of the RF period.
Radiation appears in pulses with the same time duration and separation. The ***time interval between them is an integer multiple of the RF period*** (called harmonic number of the ring). The ***maximum separation between two pulses is obtained in the single bunch mode***, i.e. when only one bunch in the full ring is present. In this case the ***time interval is equal to the period of revolution***, ***typically of the order of microseconds***. When more bunches are present the time interval is lower; ***the minimum possible time interval between bunches is equal to the RF period***.



EXAMPLES

ESRF : E = 6GeV, *C* = 844 m, ν_{RF} = 355 MHz, V = 9 MV and Imax = 200mA.

- **Single bunch mode**: I = 20mA

$$T_0 = C/c = 2.81\mu s$$

T_0 represents the **maximum time separation between bunches** achievable only in **single bunch mode**; **bunch length** is normally of the order of **mm** corresponding to tens of **picoseconds** and in single bunch mode is of the order of **73 ps** .

- **Uniform bunch mode**: **Imax** = 200mA

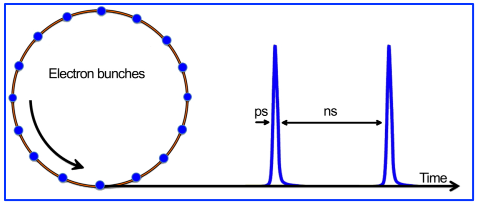
$$T_{RF} = 1/\nu_{RF} = 2.82 \text{ ns}$$

T_{RF} represents the **minimum time separation between bunches** achievable only in uniform bunch mode (corresponding to a separation of about 86 cm between them).

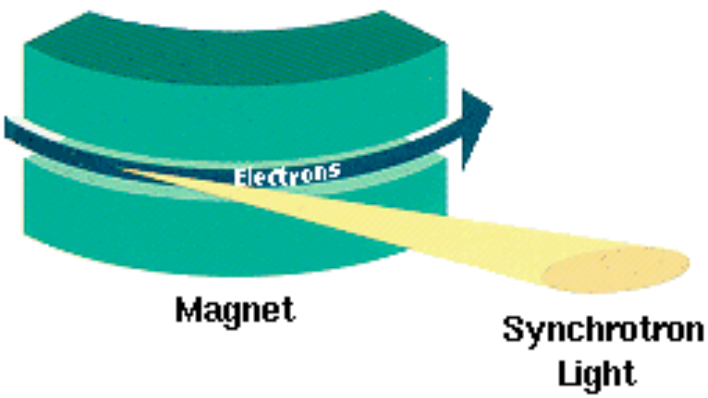
The maximum number of bunches that can be stored depends on ν_{RF} and on $\nu_0 = (1/T_0)$:

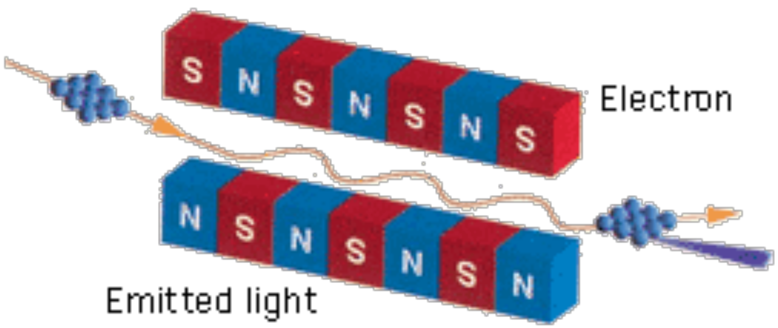
$$N_{max} = \nu_{RF}/\nu_0 = 992.$$

In uniform bunch mode the bunch length is of the order of **20 ps**.



Radiation sources

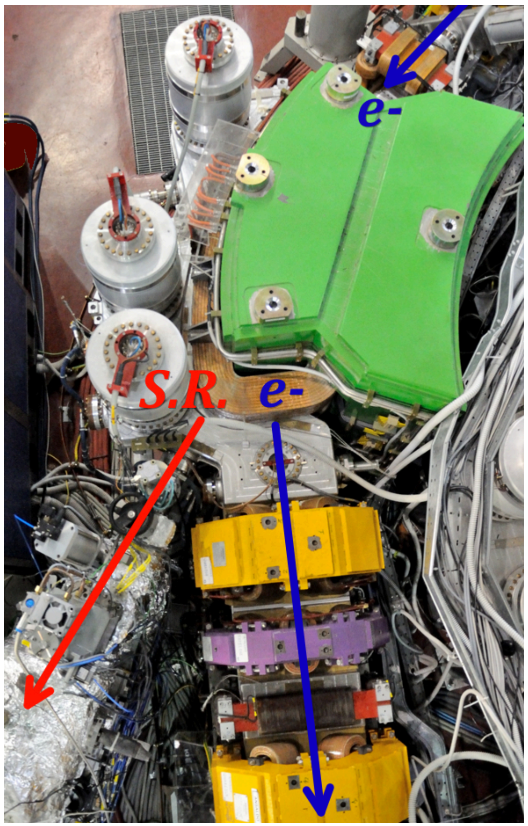




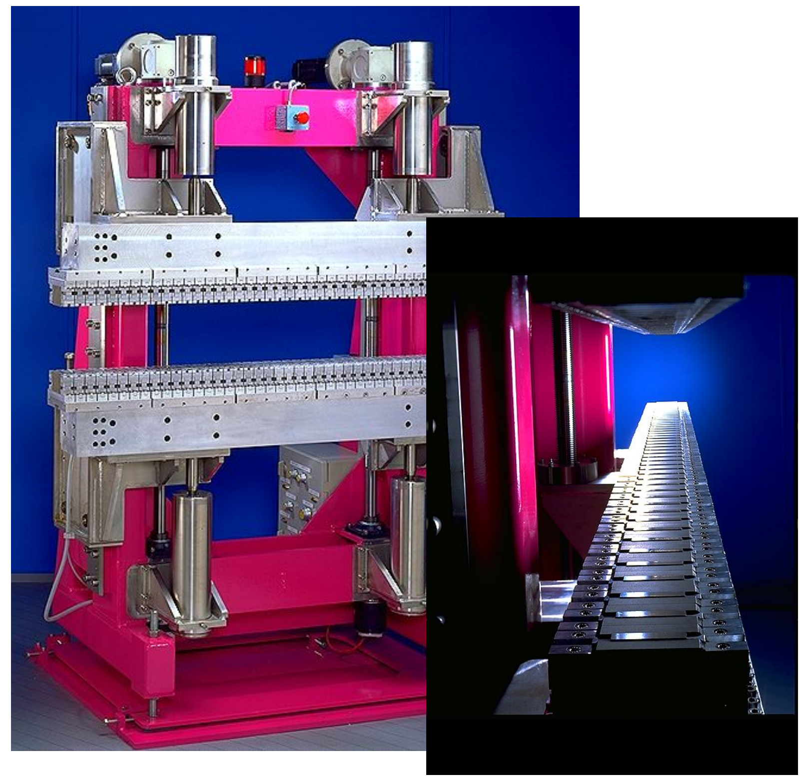
Radiation Sources

There are two different sources of radiation in a storage ring:

- *bending magnets (BMs)*
- *insertion devices (IDs) or periodic arrays of magnets inserted between the BMs (wigglers and undulators)*



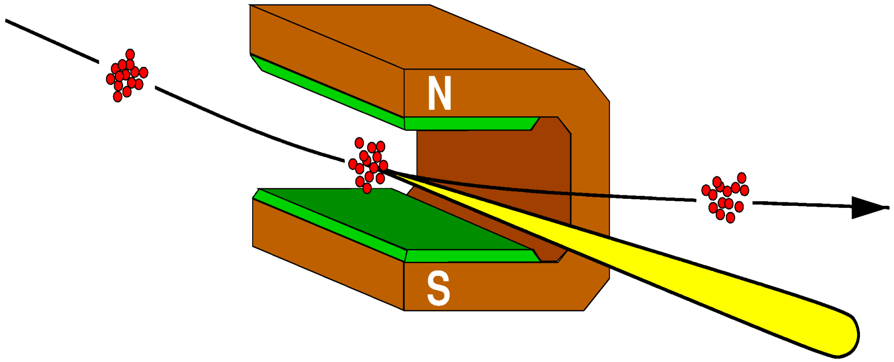
DAΦNE bending magnet (BM)



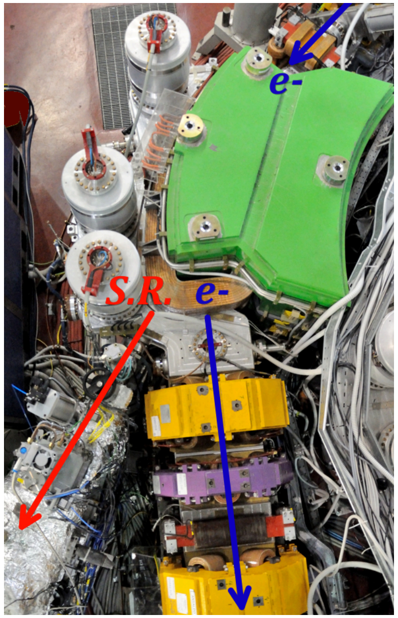
ESRF Insertion Device (ID) - Undulator

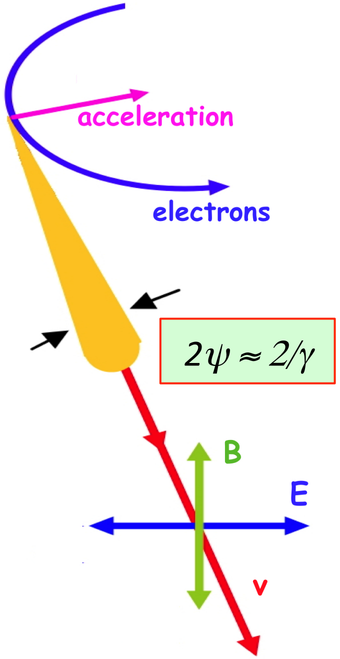
BM and ID have different characteristics concerning, spectral distribution, flux, brightness and polarization.

Bending magnets



Bending magnets





The acceleration of high energy (relativistic) particles moving in a closed trajectory under the action of dipole bending magnets is given by the ***Lorentz equation*** ***F = ma = dp/dt***

$$\frac{d\vec{p}}{dt} = \vec{f} \Rightarrow m_0 \frac{d}{dt}(\gamma\vec{v}) = q\left(\vec{E} + \vec{v} \wedge \vec{B}\right)$$

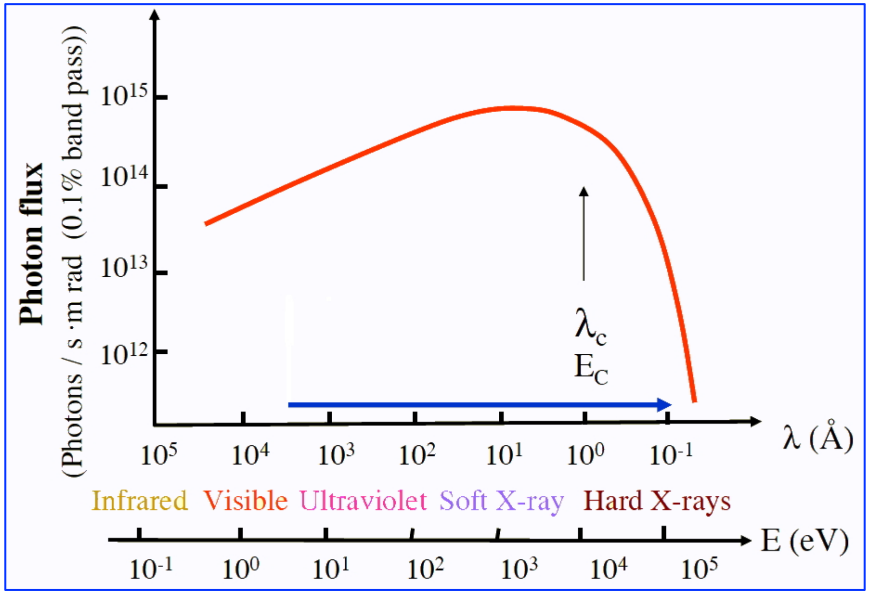
Schwinger in 1949 found that the spectral distribution of the radiation emitted from accelerated relativistic charged particles, under the effect of a constant magnetic field is a smoothly varying function of photon energy whose continuous spectrum is characterized by a critical energy, E_c, that scales as γ^3.

$$\varepsilon_c = \hbar\omega_c = \frac{3}{2}\frac{\hbar c}{R}\gamma^3$$

$$\varepsilon_c[keV] = 2.218\frac{E[GeV]^3}{R[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T]$$

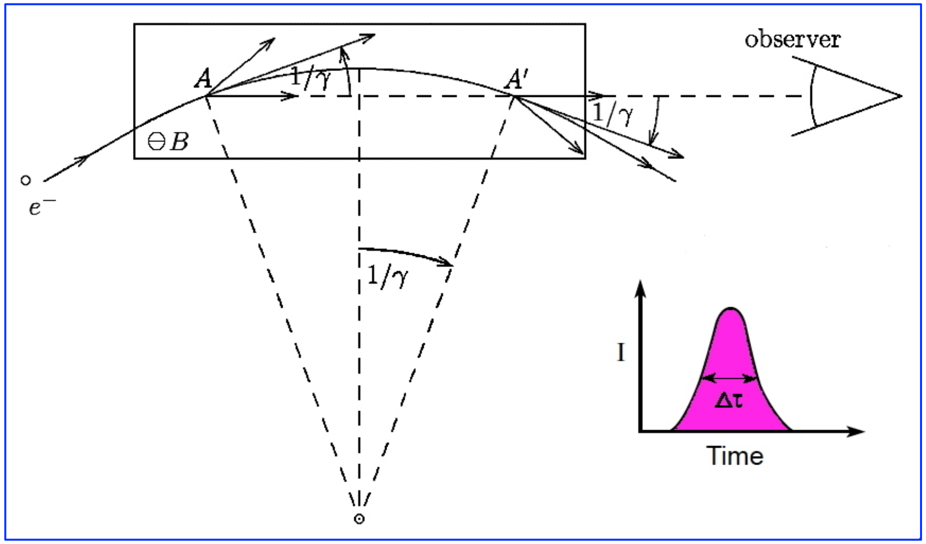
B(T) = 3.336 E(GeV)/R(m)

The critical energy, ε_c , divides the spectrum into two parts of equal radiated power: 50% of the total power is radiated at energies lower than ε_c and 50% at energies higher than ε_c .



J.D. Jackson, "Classical Electrodynamics", 1999

Origin of the broad spectral distribution



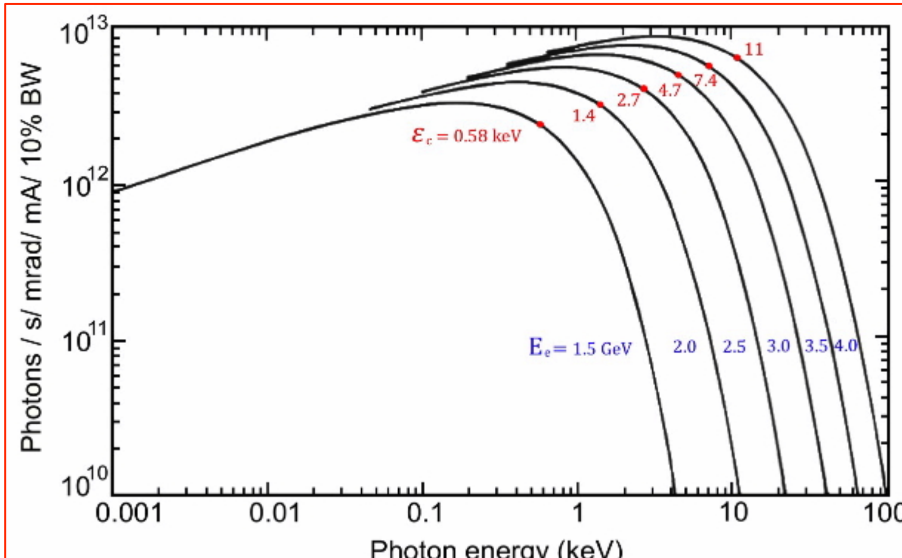
The time duration of the radiation pulse seen by **the observer** is the difference between **the time for the electron to travel along the arc** ($2/\gamma$) and the time for **light to travel along the chord subtended by this arc.**

$$\Delta\tau = \frac{R}{c}\left[\frac{1}{\gamma\beta} - 2\sin\left(\frac{1}{2\gamma}\right)\right] \simeq \frac{R}{c\gamma^3}$$

A light pulse of this duration has frequency components up to about:

$$\omega_{cutoff} \approx \Delta\tau^{-1} \approx \frac{c\gamma^3}{R}$$

Synchrotron radiation from ***one electron consists of a discrete spectrum of closely spaced lines up to*** ω_{cutoff}. In practice, the ***spectral distribution coming from many electrons is continuous*** due to the statistical oscillations of the electrons around the main orbit, to the fluctuations of their kinetic energy and to the statistical nature of the emission itself: all ***effects that lead to a line broadening of each harmonic***. This results in the continuous broad spectrum with the cutoff at **E > ε_c**.



Angular distribution

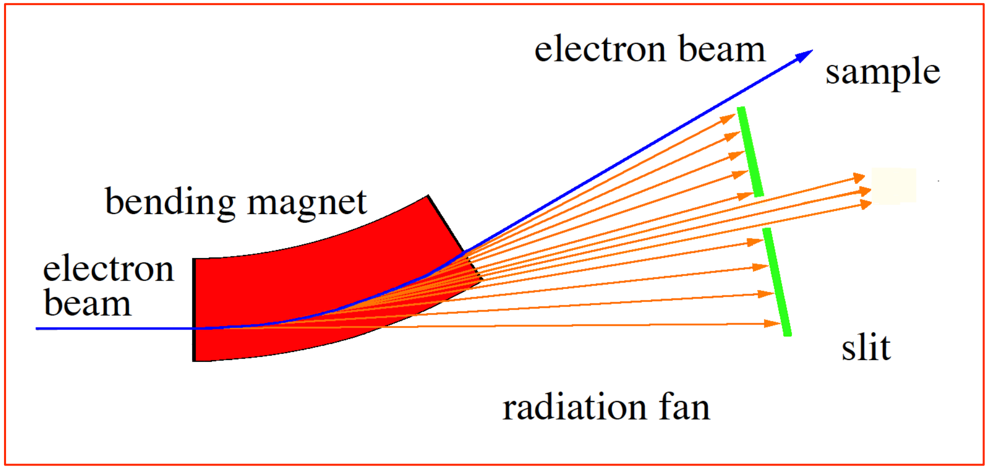
Vertical angular distribution: radiation pattern is compressed into a narrow cone in the direction of motion, resulting into an emission tangential to the particle orbit with a vertical opening angle,
$\Psi = 2\psi \approx 2mc^2/E \approx 2/\gamma$.

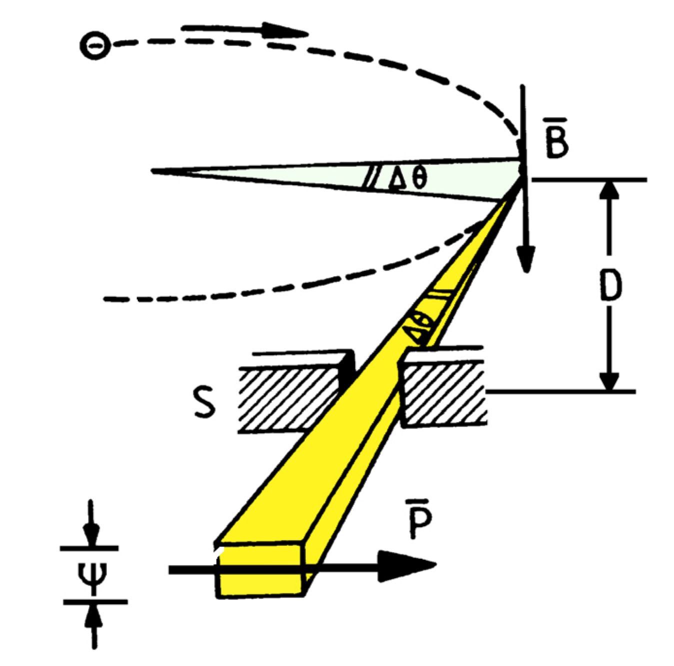
For E= 1 GeV,

$1/\gamma \approx 0.511$ mrad (29×10^{-3})°

1 deg = 17.45 mrad; 1 mrad = (57×10^{-3})°

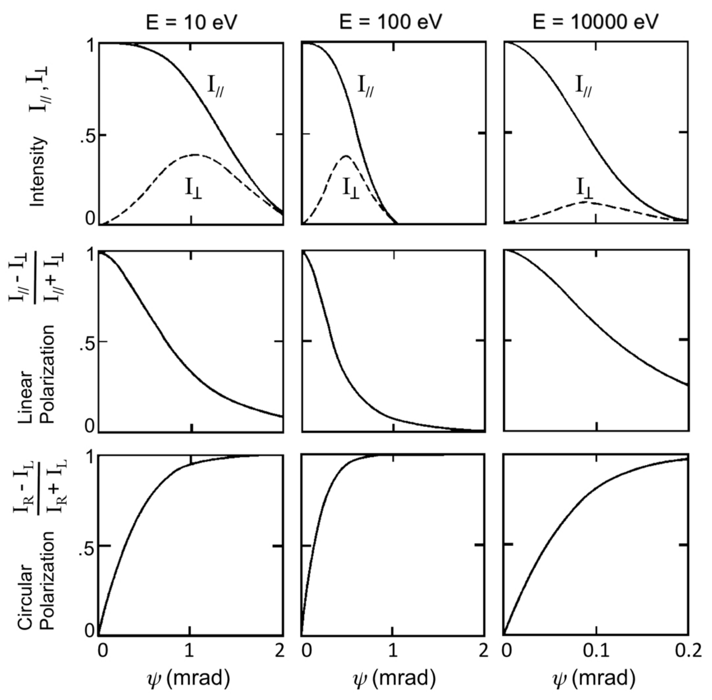
Horizontal angular distribution: in a bending magnet the horizontal collimation is lost because the electrons move along a circular orbit emitting the radiation along the tangent. The radiation is collected, for experiments, through a horizontal slit (S) of width, **w** , at a distance, **D** , from the electron orbit; this corresponds to an angular collection angle, $\Delta\theta = w/D >> \Psi$.





Polarization

The radiation emitted by a bending magnet is mostly ***linearly polarized.*** When observed in the horizontal plane, the ***electric field is parallel to the plane*** of the electron orbit (horizontal). Observing the radiation above and below this plane at finite vertical angles, a ***polarization component perpendicular to the plane*** of the electron orbit is present.



$$P_{Linear} = \frac{I_{//} - I_{\perp}}{I_{//} + I_{\perp}}$$

Degree of linear polarization

Integrating over all energies:

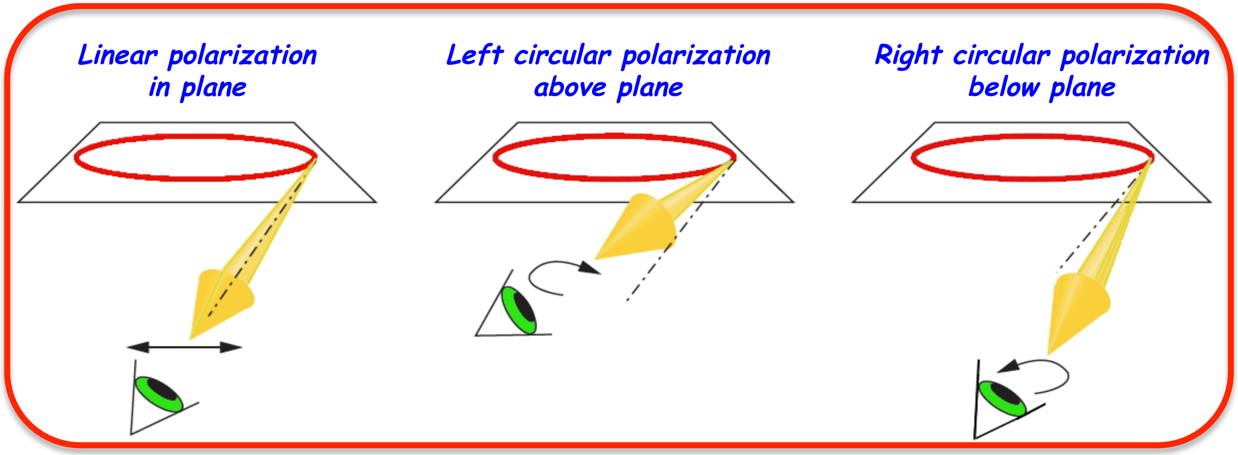
$$I_{//} = (7/8) I_{total} \quad I_{\perp} = (1/8) I_{total}$$

that means a linear polarization degree of about 75%.

Above and below the plane there is a constant phase difference of +π/2 and -π/2 between the parallel and perpendicular components of the electric field.

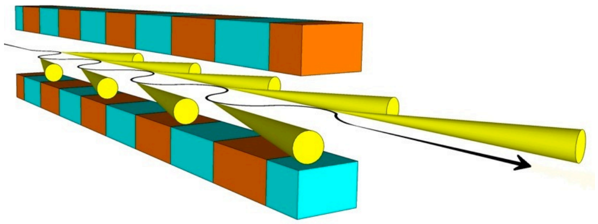
$$P_C = \frac{I_R - I_L}{I_R + I_L} = \frac{\pm 2\sqrt{(I_{//} I_{\perp})}}{I_{//} + I_{\perp}}$$

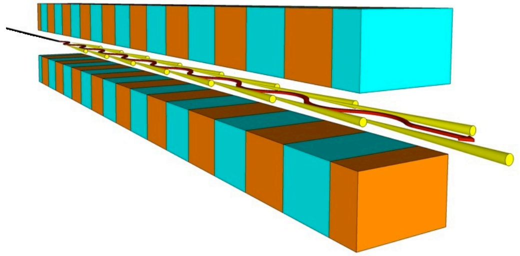
Degree of circular polarization



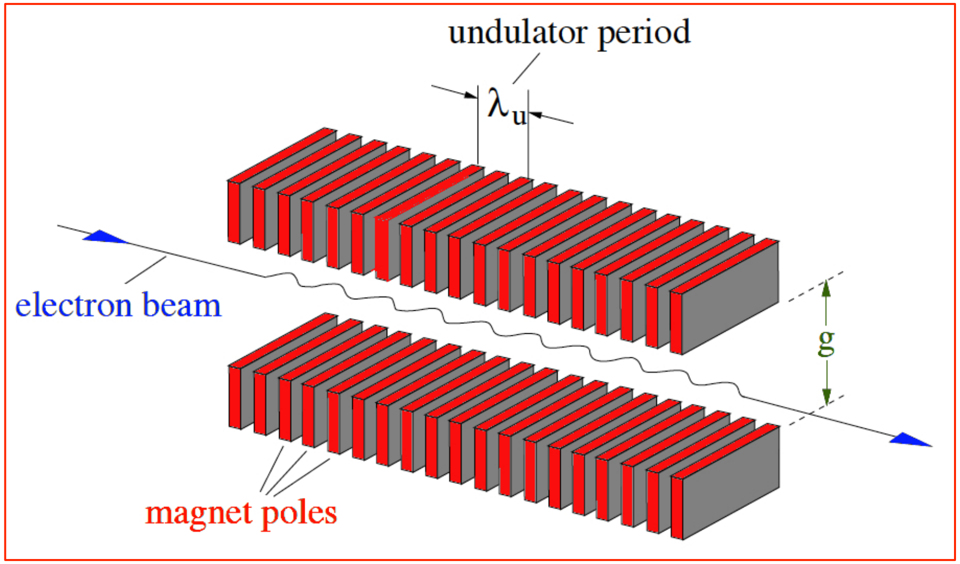
Circularly polarized light is fundamental in techniques like **Magnetic Circular Dichroism (MCD).**

Insertion devices (ID):
wigglers and undulators



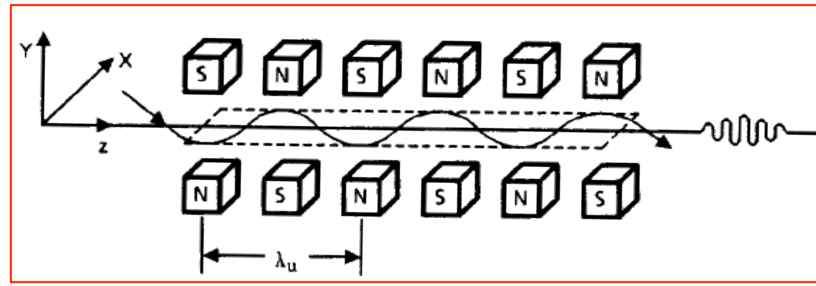


Insertion Devices



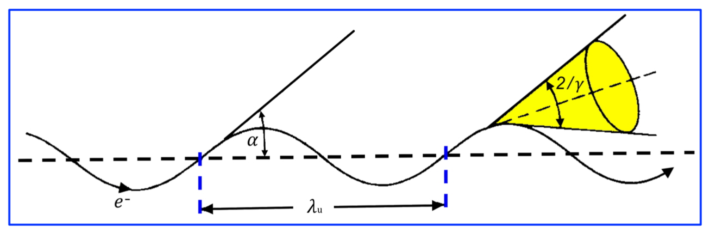
Insertion devices (ID) are ***periodic arrays of magnetic poles*** with alternating field directions installed, in the straight sections of storage rings that force the particles to oscillate passing through the device.

Overall length: $L=N\lambda_u$



IDs are characterized by the so called 'deflection parameter', K.

$$K = \alpha\gamma$$



α = wiggling angle

$2/\gamma$ = SR natural angular aperture

$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36 B_0 \lambda_u$$

In a simplified approximation:

- If ***$K \approx 1$***, α is comparable to $1/\gamma$, so the ***radiation from each pole overlaps causing interference effects on the spectral distribution*** – **undulator**.
- If **$K >> 1$**, α is bigger than $1/\gamma$, **so the radiation spectrum looks like dealing with 2N dipole sources**– ***wiggler.***

Calculation of K

Using the equation of motion for a relativistic charged particle in a magnetic field.

$$F_x = ma_x = \gamma m_0 \dot{v}_x = e\vec{v} \times \vec{B} = ecB_0 \sin\left(\frac{2\pi z}{\lambda_{ID}}\right)$$

$$\dot{v}_x = \frac{ecB_0}{\gamma m_0} \sin\left(\frac{2\pi z}{\lambda_{ID}}\right) \qquad z = ct$$

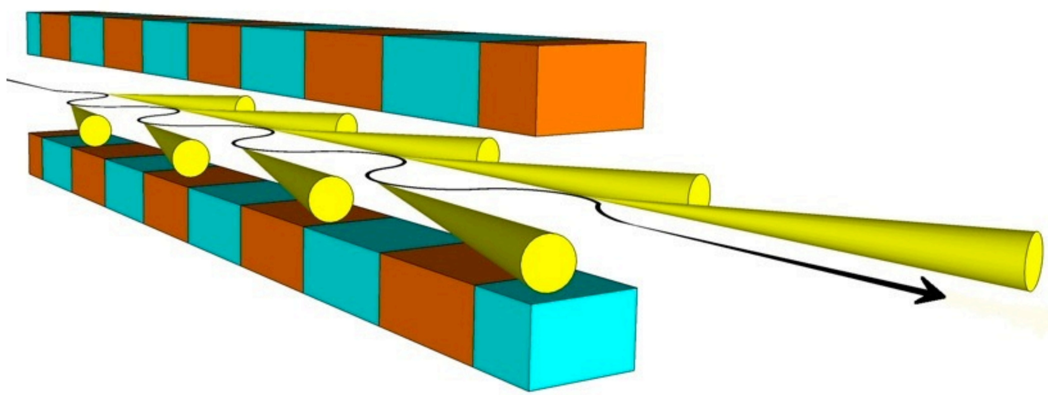
$$v_x = -\frac{ecB_0}{\gamma m_0}\frac{\lambda_{ID}}{2\pi c} \cos\left(\frac{2\pi ct}{\lambda_{ID}}\right) = -\frac{eB_0}{\gamma m_0}\frac{\lambda_{ID}}{2\pi} \cos\left(\frac{2\pi ct}{\lambda_{ID}}\right)$$

$$x = \frac{eB_0}{\gamma m_0 c}\left[\frac{\lambda_{ID}}{2\pi}\right]^2 \sin\left(\frac{2\pi ct}{\lambda_{ID}}\right) = \left[\frac{eB_0}{m_0}\frac{\lambda_{ID}}{2\pi c}\right]\frac{1}{\gamma}\left[\frac{\lambda_{ID}}{2\pi}\right] \sin\left(\frac{2\pi z}{\lambda_{ID}}\right) = K\frac{1}{\gamma}\left[\frac{\lambda_{ID}}{2\pi}\right] \sin\left(\frac{2\pi z}{\lambda_{ID}}\right)$$

$$x_{\max} = K\frac{1}{\gamma}\left[\frac{\lambda_{ID}}{2\pi}\right] \quad \textit{and} \quad \left[\frac{dx}{dz}\right]_{\max} = \frac{K}{\gamma} \quad \textit{where} \quad \boxed{K = \left[\frac{eB_0}{2\pi}\frac{\lambda_{ID}}{m_0 c}\right]}$$

D. M. Mills, Synchrotron Radiation: Properties and Production, 2011

Wigglers



Wigglers

*A **wiggler*** is a ***multipole magnet (MPW)*** made up of a periodic series of magnets. ***Electrons are forced to follow a sinusoidal trajectory*** with a ***smaller local radius of curvature*** with respect to the one of the dipole-bending magnet, because in a wiggler, a ***magnetic field higher than in a bending magnet can be used.***

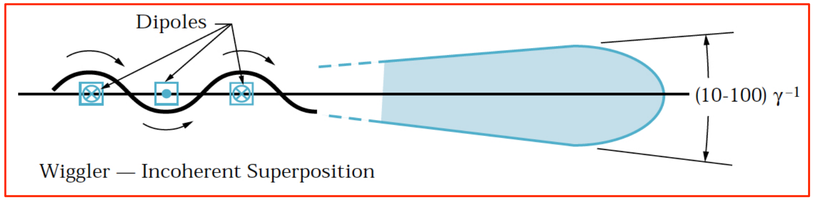
$\rho(m)=3.336\, E(GeV)/B(T)$

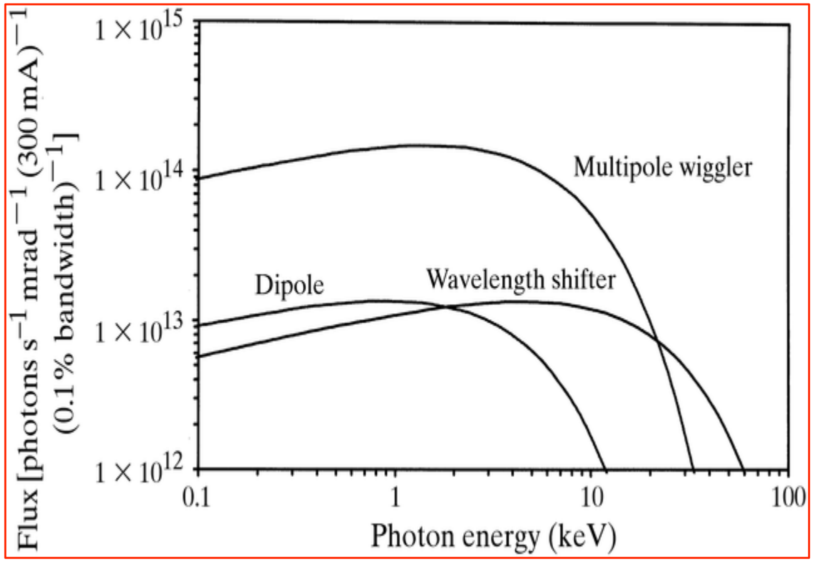
$$\varepsilon_c[keV] = 2.218\frac{E[GeV]^3}{\rho[m]} = 0.665\cdot E[GeV]^2\cdot B[T]$$

- A MPW can be considered a ***series of dipoles***, one after the other.
- There are ***two source points per period***
- The flux is simply the ***product of the number of source points and the dipole flux*** for that critical energy

The MPW has two clear advantages:

1. the ***critical energy can be set to suit the science need;***
2. the ***flux is enhanced by twice number of periods.***



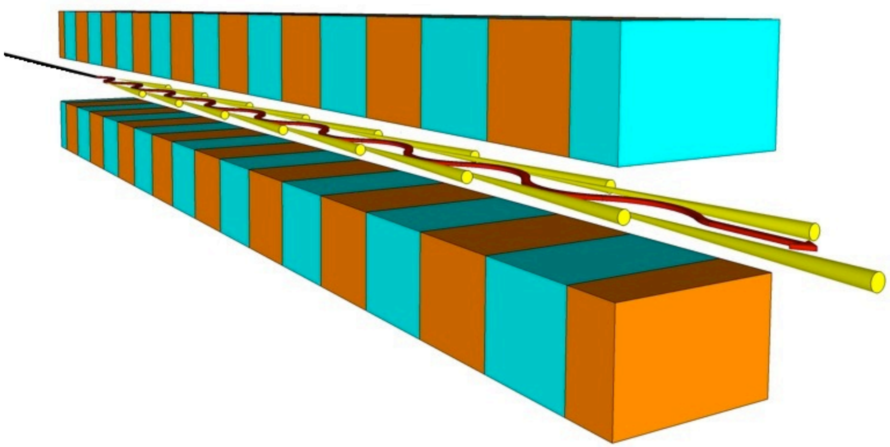


Comparison of the flux from a 1.2 T Bending Magnet, 6.0 T Wavelength Shifter and 2.0 T multipole wiggler

Wavelength shifter wiggler 2N = 1 (1 period= 2 poles in particular: 1pole and 2 half poles.

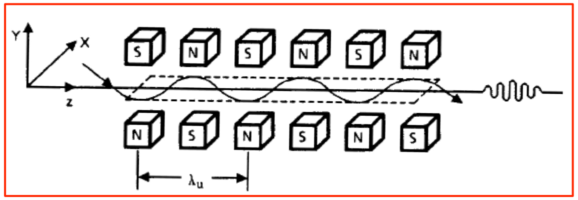
If 2N> 1 it gives also a 2N increase of the emitted flux.

Undulators: very bright radiation sources



Undulators

In an ***undulator K ≈ 1***, so the ***wiggling angle*** α ***is smaller than, or close to, the photon natural emission angle*** $1/\gamma$ and in this case ***constructive interference***, at ***specific wavelengths*** *occurs between* ***the radiation emitted by electrons at different poles along the trajectory***.



$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \approx \frac{\lambda_u}{n\gamma^2}$$

n is the harmonic number

Overall ondulator length: $L = N\lambda_u$

$\lambda_u = L/N$

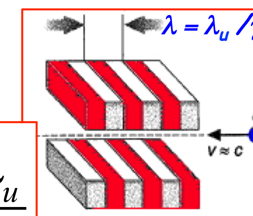
From cm to nm ?

$$\lambda_n \approx \frac{\lambda_u}{n\gamma^2}$$

Two relativistic effects :

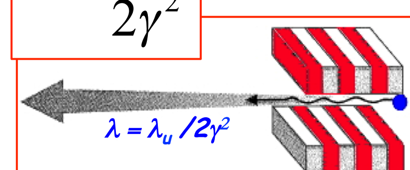
- ***Lorentz contraction*** **-** a relativistic charged particle is travelling through a periodic magnetic field; in the particles rest frame it sees a magnetic field rushing towards it. If in lab rest frame the magnet period is λ_u then because of **Lorentz contraction** the electron sees it as:

$$\lambda \approx \frac{\lambda_u}{\gamma}$$

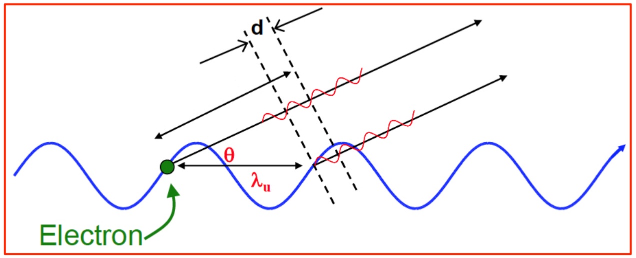


- ***Doppler shift*** **–** Due to the fact that the electron is moving towards us, the radiation emitted by the electron is ***Doppler shifted to higher frequencies*** or ***shorter wavelengths being further reduced by a factor 2γ***.

$$\lambda \approx \frac{\lambda_u}{2\gamma^2}$$



Undulators



$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

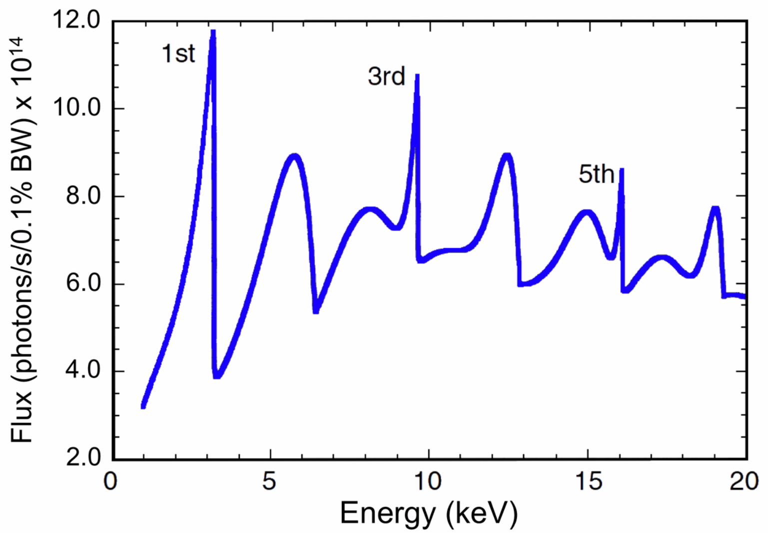
$$K = 93.36 B_0 \lambda_u$$

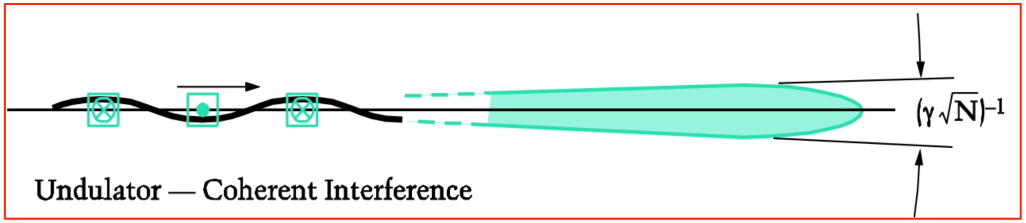
The wavelength changes with θ^2, so it always gets longer moving away from the axis: an important consequence is that the beamline aperture choice is important because it alters the radiation characteristics reaching the observer.

As B increases (and so K), the output wavelength increases (photon energy decreases).

Undulators produce ***quasi-monochromatic spectra*** with peaks at lower energy than a wiggler.

The ***very narrow angular distribution*** together with the ***N²*** dependence ***of the intensity radiated in the 'undulator' regime*** can explain why the ***spectral brightness achievable with undulators exceeds by several order of magnitude that of bending magnets and of wigglers.***



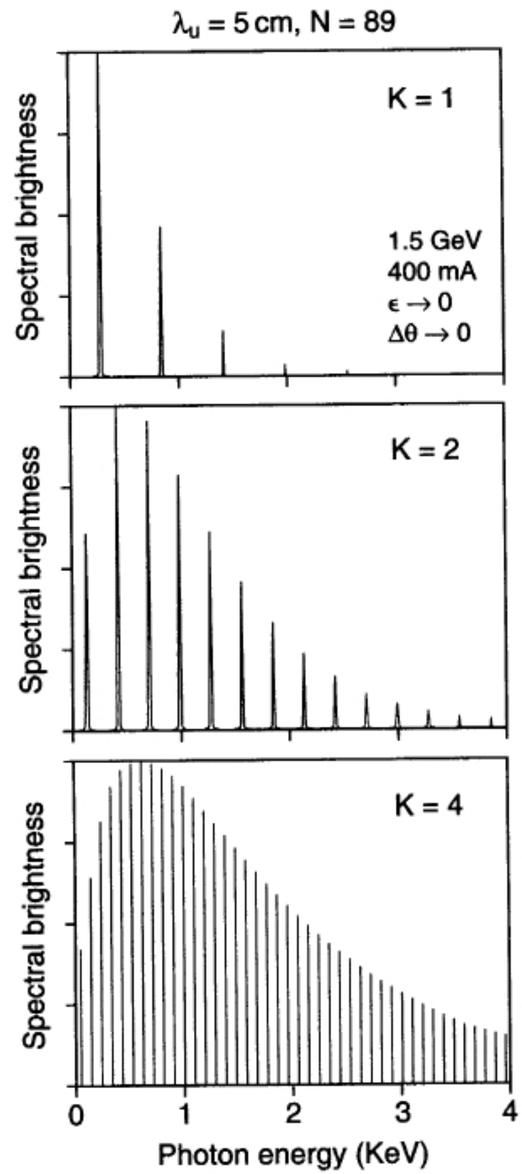


$$\theta_{cen} \approx \frac{1}{\gamma\sqrt{N}}$$

For on-axis radiation (θ = 0), θ_{cen} ***or central radiation cone*** is defined as containing radiation of relative spectral bandwidth, $\Delta\lambda/\lambda$ = **1/N**.

Undulator equation and wiggler limit

$$E_n(eV) = 9.496 \frac{nE[GeV]^2}{\lambda_u[m]\left(1 + \frac{K^2}{2}\right)}$$



Undulator radiation ($K \lesssim 1$)

- Narrow spectral lines
- High spectral brightness
- Partial coherence

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \frac{eB_o\lambda_u}{2\pi mc}$$

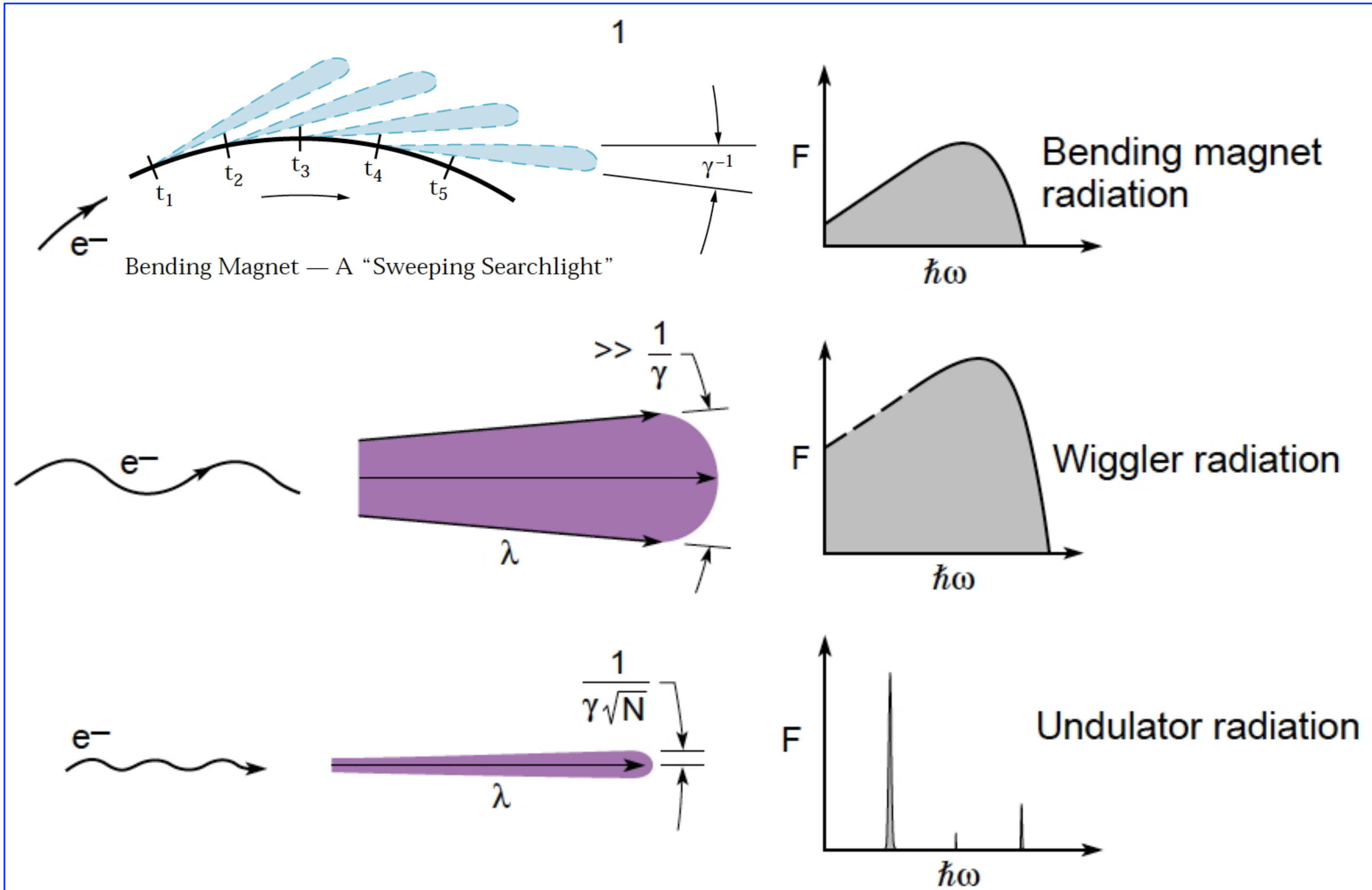
Wiggler radiation ($K >> 1$)

- Higher photon energies
- Spectral continuum
- Higher photon flux (2N)

$$\hbar\omega_c = \frac{3}{2}\frac{\hbar\gamma^2 eB_o}{m}$$

$$n_c = \frac{3K}{4}\left(1 + \frac{K^2}{2}\right)$$

Just to summarize!

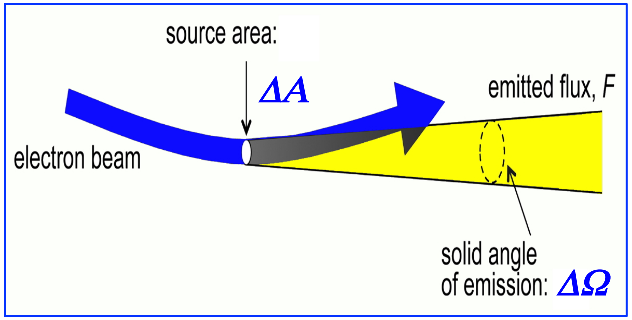


D. Attwood, Intro Synchrotron Radiation, Bending Magnet Radiation - http://ast.coe.berkeley.edu/srms/2007/Lec08.pdf

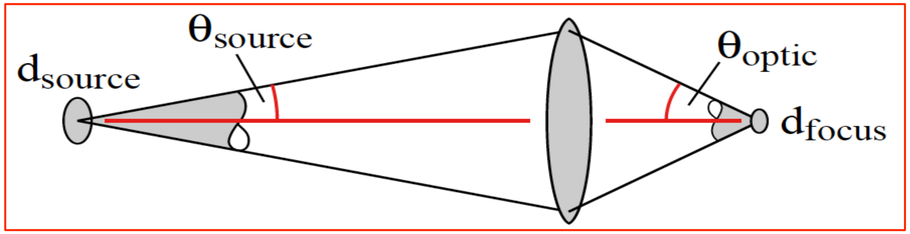
Brightness

Brightness

Brightness (flux density in phase space) is an invariant and depends on the ***size of the source (ΔA)*** (electron beam) and on ***the angular divergence of the radiation ($\Delta\Omega$)***, given by the ***convolution of the angular distribution of synchrotron radiation with the angular divergence of the electron beam***.

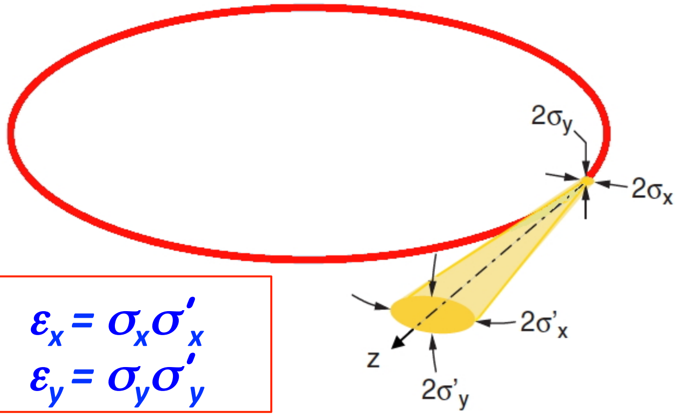


As well known due to ***Liouville's theorem***, ***focusing preserves brightness***, i.e. ***the brightness of the source is equal to the brightness of the beam when focused on the sample.***



$$d_{source} \cdot \theta_{source} = d_{focus} \cdot \theta_{optic}$$

In a storage ring the ***product of the electron beam transverse size and angular divergence is a constant along the ring*** and is called ***emittance***. There is a horizontal and a vertical emittance. The ***horizontal emittance (ε_x) is measured in nanometer-radians*** (nm-rad). The ***vertical emittance (ε_y)*** is normally a ***few percent of the horizontal one***.

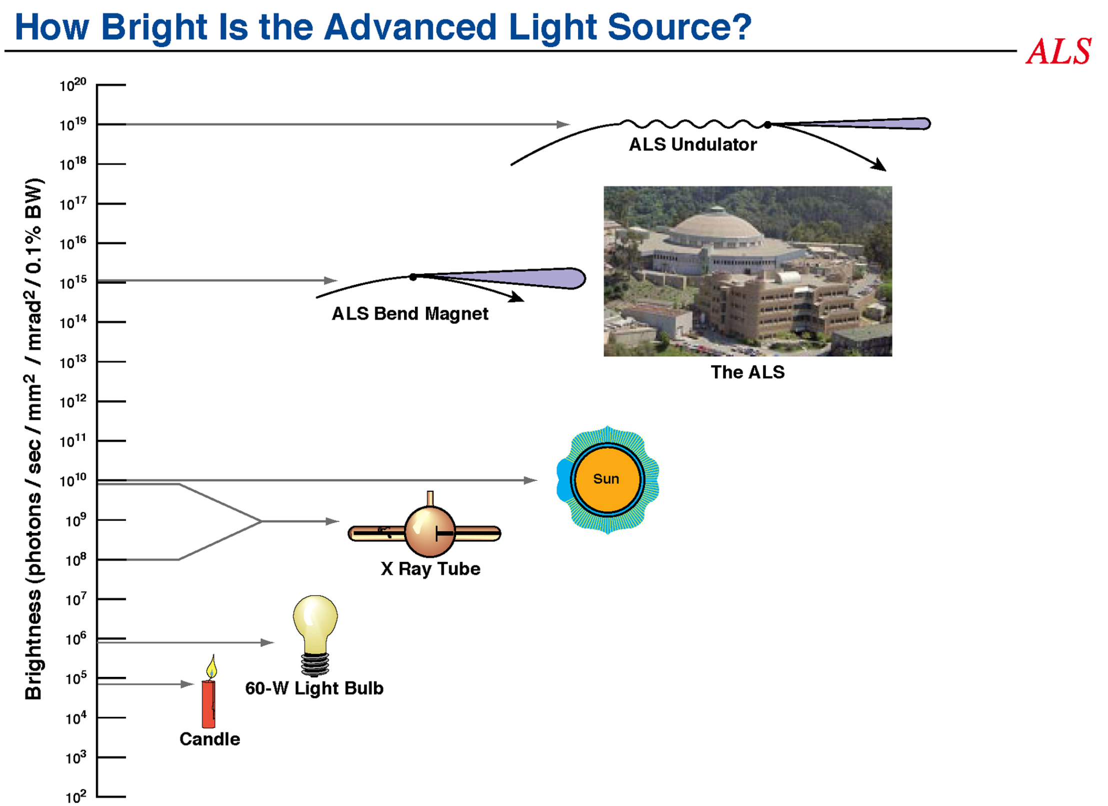


Brightness is a conserved quantity in perfect optical systems, and thus is useful in designing beamlines and synchrotron radiation experiments which involve focusing to small areas.

$$\varepsilon_x = \sigma_x \sigma'_x$$
$$\varepsilon_y = \sigma_y \sigma'_y$$

Brightness

Synchrotron radiation sources have very high brightness.

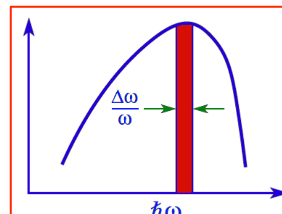


Brightness is defined as radiated flux per unit area and per unit solid angle at the source.

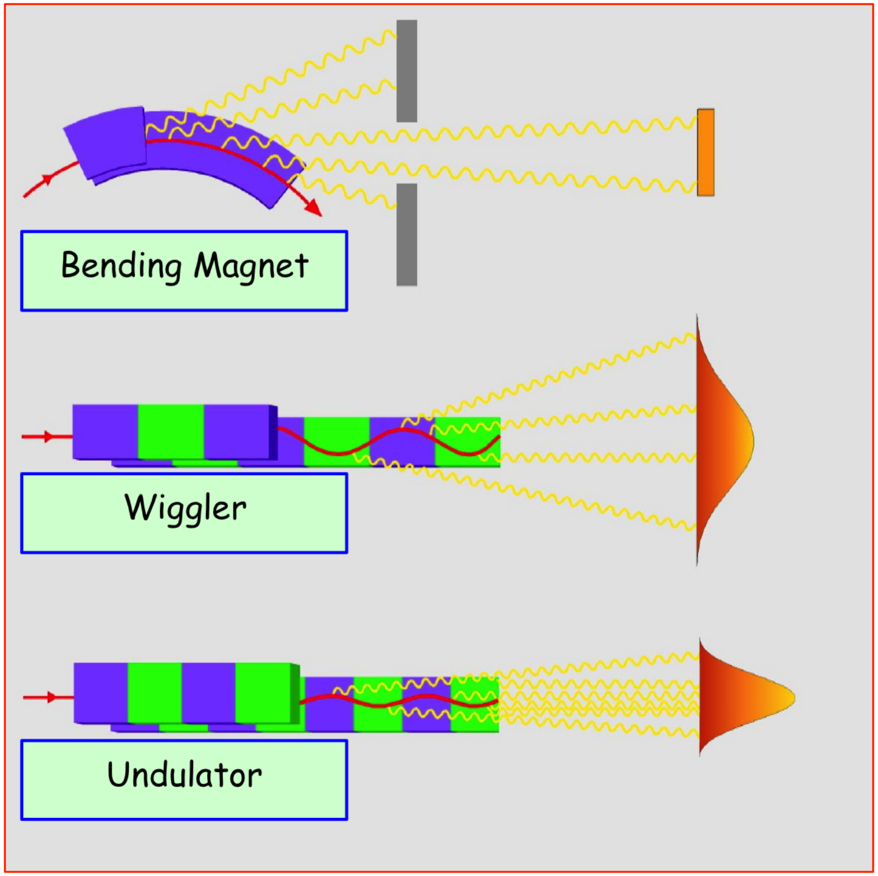
- ***Electrons in vacuum*** *can emit more power than electrons in a solid because the power does not damage their environment ⇒* ***high flux.***
- *The* ***source size*** *is not that of a single electron but the transverse cross section of the electron beam. The sophisticated trajectory control system makes it* ***very small.***
- *Relativity induces* ***drastically reduced angular divergence*** *of the emission.*

Spectral brightness is that portion of the brightness lying within a ***relative spectral bandwidth*** $\Delta\omega/\omega$:

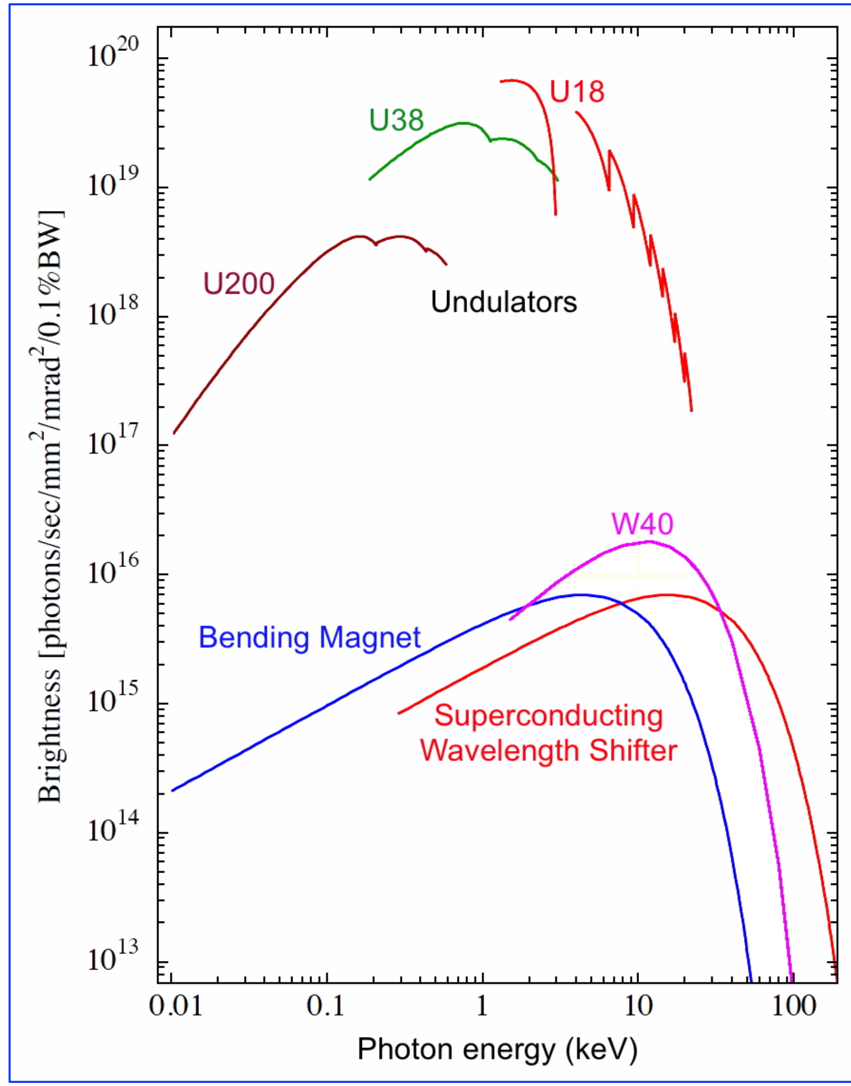
$$\text{Spectral Brightness} = \frac{photons}{second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW}$$



Comparing the achievable brightness



Courtesy DESY



Calculated brightness of beams emitted by undulators (200 mm (L= 10 m), 38 mm (L= 4 m) and 18 mm (L= 2 m) periods), wigglers (wavelength shifter and 40 mm (L= 2 m) period) and bending magnets for a 2.4 GeV storage ring with 400 mA circulating current (**M. Boge** http://accelconf.web.cern.ch/Accelconf/e98/PAPERS/MOP28G.PDF)

Short history of synchrotron radiation

... from particle physics "parasite" to fundamental tool !!!

Synchrotron Light Short History and Name

5th gen. – Very compact XFELs

4th gen. - LINAC based accelerators FELs

3rd* gen. ultimate storage rings like MAX IV (Sweden) near future

3rd gen. dedicated storage ring ESRF (France) 1994

Brightness increase

Accelerators built to optimize SR - ID

First accelerators built for SR - BM

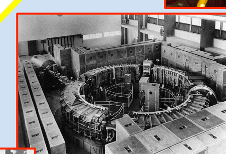
2nd gen. dedicated storage ring SRS (UK) 1981

1st gen. dedicated ring Tantalus I (USA) 1968

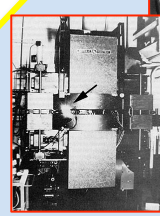
Using accelerators built for HE physics

Storage rings development 1960s

ADA - B. Touschek - LNF

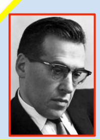


Parasitic use of electro-synchrotrons 1961



General Electric Res. Lab. - 70 MeV Electro-Synchrotron (N.Y. USA)

First observation of synchrotron radiation 1947

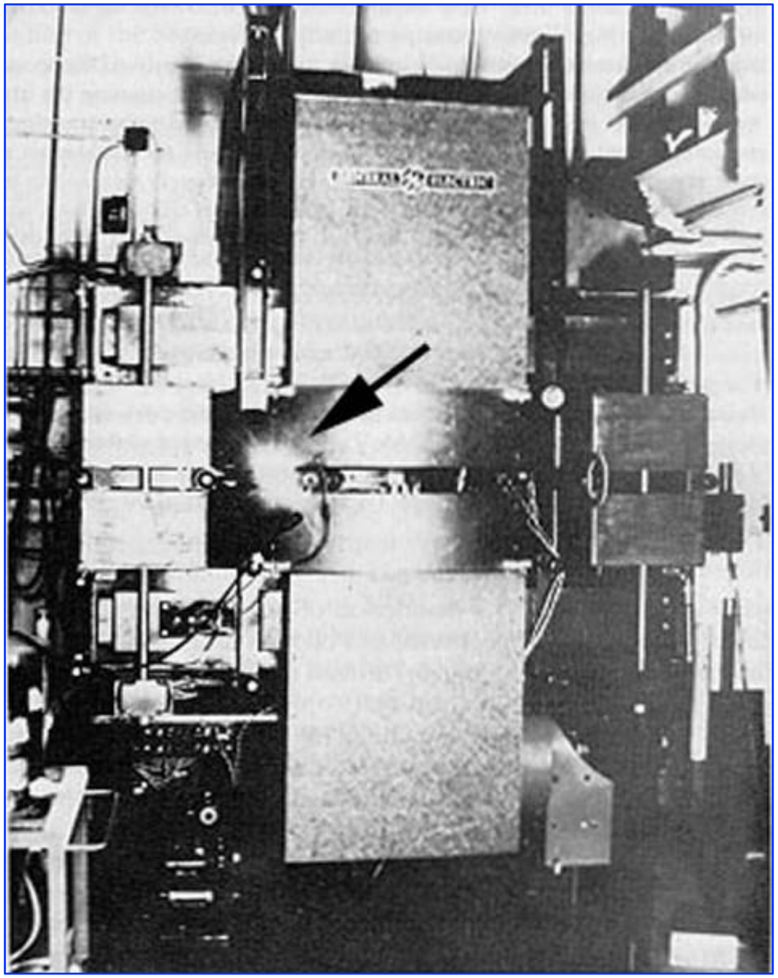


J. Schwinger Nobel Prize 1965 Classical Relativistic quantum field theory

Proof of concepts, tests of theories 1897-1946

Synchrotron radiation: history

First generation: parasitic operation and storage rings



1947 *General Electric Res. Lab.* - 70 MeV Electron Synchrotron – N.Y. USA

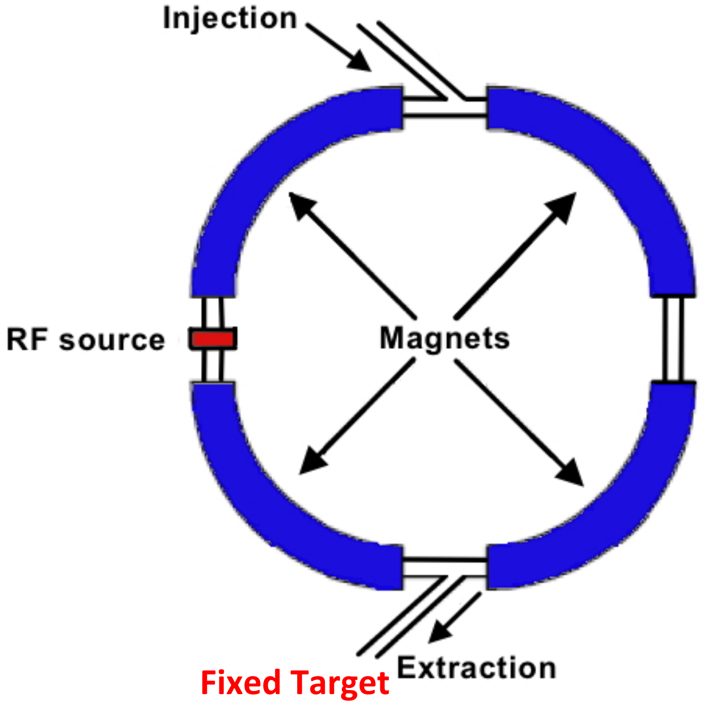
Starting point: Proof of concepts, tests of theories!

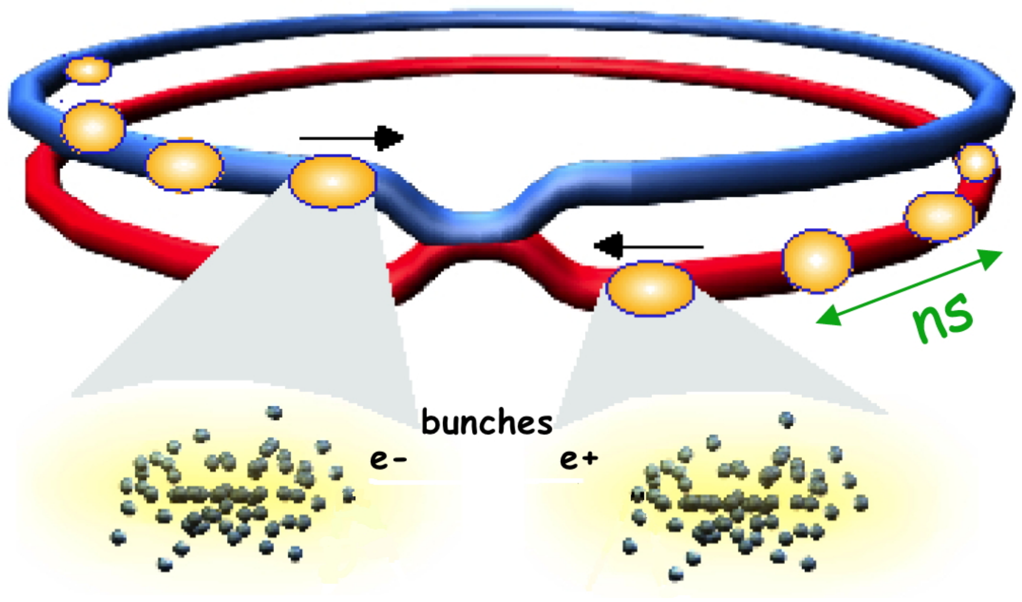
- In the 50s and 60s machines built for High Energy Physics: synchrotrons (*1947 First 'visual observation of synchrotron radiation*).
- Synchrotron radiation was considered a ***nuisance by particle physicists***: ***unwanted but unavoidable loss of energy***!
- 1961 US National Bureau of Standards (now NIST) modified their electron synchrotron : ***access to the synchrotron radiation users***.
- Synchrotron radiation scientists became ***parasites*** of nuclear physics experiments. (*1961 Frascati – CNEN Electrosynchrotron – (0.4-1.1) GeV*)
- 1968 ***First storage ring dedicated*** to synchrotron radiation research: ***Tantalus*** (University of Wisconsin) only ***bending magnets.***

F.R. Elder, A.M. Gurewitsch, R.V. Langmuir, and H.C. Pollock, Radiation from Electrons in a Synchrotron, Phys. Rev. 71, 829 (1947)

G. C. Baldwin and D.W. Kerst, Origin of Synchrotron Radiation, Physics Today, **28**, 9 (*1975*)

Synchrotrons and Storage Rings





Synchrotron

Particle beam on fixed target

$E_{CM} = (mE)^{1/2}$

Storage rings

Colliding particle beams

$E_{CM} = 2E$

Colliding beams more efficient

E= particle energy >> mc^2; E_{CM}= centre-of-mass energy

Comparing synchrotrons and storage rings

Synchrotrons

- *Cyclic* - the guiding magnetic field used to bend the particles into a closed path, is time-dependent, being *synchronized* to a particle beam of increasing kinetic energy.
- ***Emitted photon spectrum varies*** as e^- energy changes during each cycle.
- ***Photon intensity varies*** as e^- energy changes during each cycle (also cycle to cycle variations).
- ***Source position varies*** during the acceleration cycle.
- ***High Energy Radiation Background*** (Bremsstrahlung + e^-): ***high***, due to loss of all particles on each cycle.

Storage rings

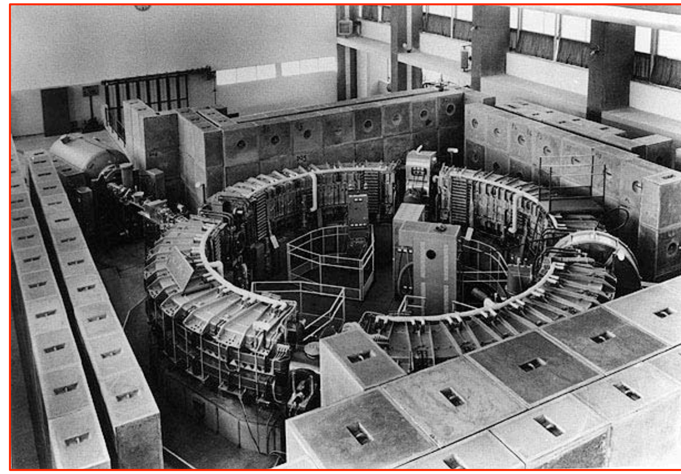
- ***Constant***: as special type of synchrotron in which the kinetic energy of the particles is kept constant.
- ***Emitted photon spectrum constant.***
- ***Photon intensity decays slowly*** over many hours.
- ***Source position constant***- submicron source stability.
- ***High Energy Radiation Background:*** ***low*** because same particles are stored for many hours.

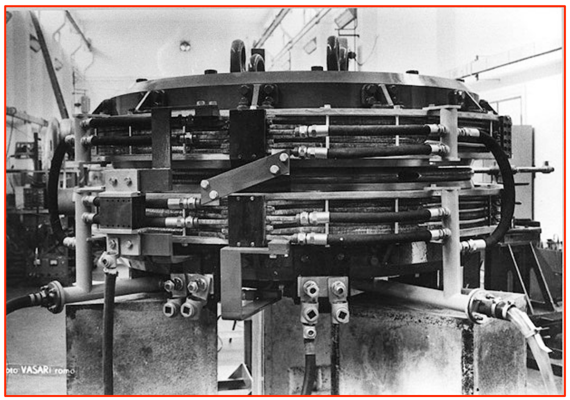
H. Winick, ***From Röntgen to X-ray Free-electron Lasers***, http://indico.cern.ch/event/145296/contribution/47/material/slides/1.pdf, *2012*

Synchrotron radiation: short history

Frascati: ElettroSynchrotron, ADA and ADONE

Frascati - CNEN (Comitato Nazionale Energia Nucleare) Laboratory ElettroSincrotrone – (0.4-1.1) GeV, C= 28 m (1959-1975)





LNF ADA (Anello Di Accumulazione) – first electron-positron storage ring (proposed by B. Touschek) 0.25 GeV, C= 5 m (1961-1964)

LNF ADONE (big ADA) electron-positron storage ring 1.5 GeV per beam, C = 105 m (1969-1993)

1976-1993 LNF ADONE 1.5 GeV parasitic/dedicated use for SR experiments after its use for HE experiments.

Synchrotron radiation: history

Second generation: dedicated sources

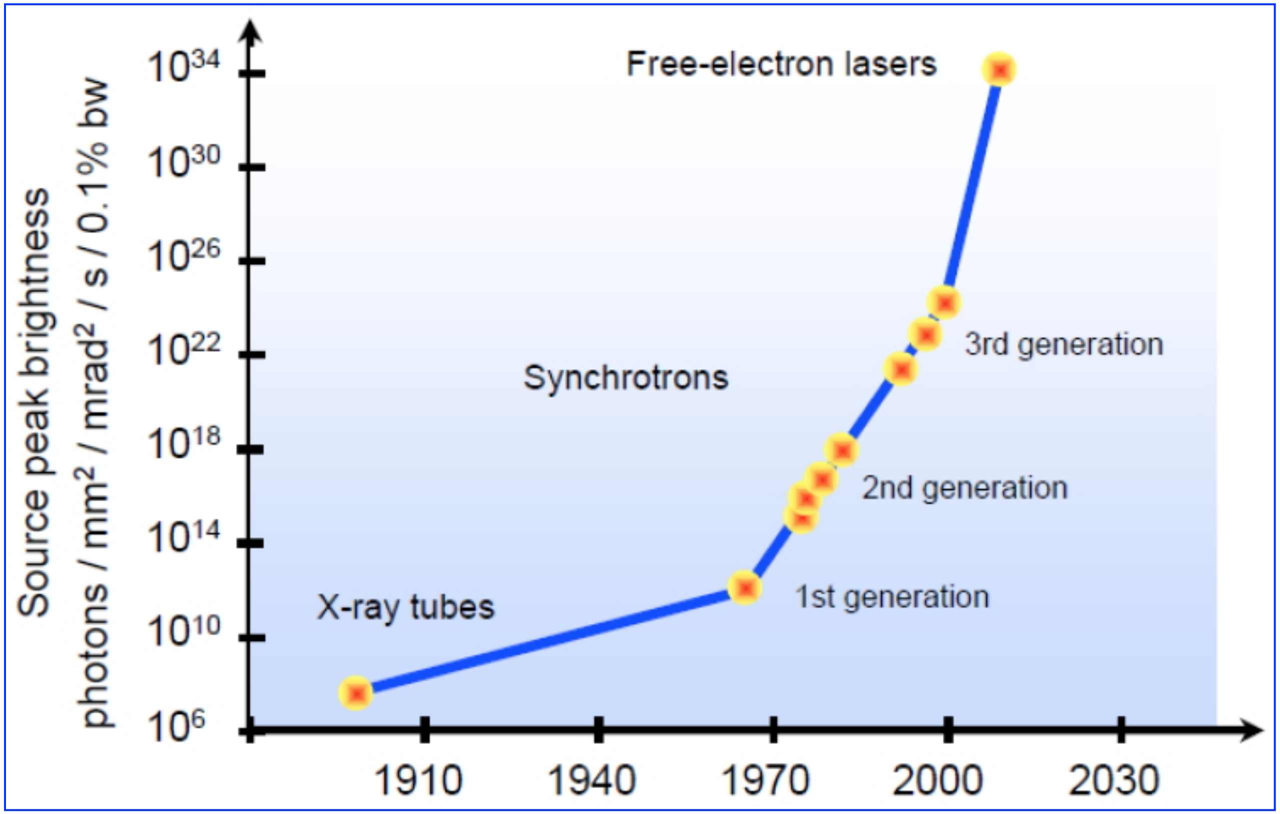
Development of new techniques, and better sources!

SRS storage ring at Daresbury (UK)

- First purpose built synchrotron light sources!
- SRS (2 GeV) at Daresbury (UK) was the first dedicated machine (1981 – 2008)
- First insertion devices (wigglers, undulators) although many were added later
- 1981 2.5 GeV NSLS, Brookhaven, USA
- 1982 2.5 GeV 'Photon Factory' KEK, Tsukuba, Japan
- 1982 0.8 GeV BESSY, Berlin, Germany
- 1984 0.8 GeV 'SuperACO' ring LURE, Orsay, France

Increasing brightness

Brightness is the main figure of merit of synchrotron radiation sources and its huge increase, was obtained designing low emittance machines, minimizing the source size and the beam divergence.



Increase of a factor 1000 every 10 years!!!

Synchrotron radiation: short history

Third generation: optimized sources

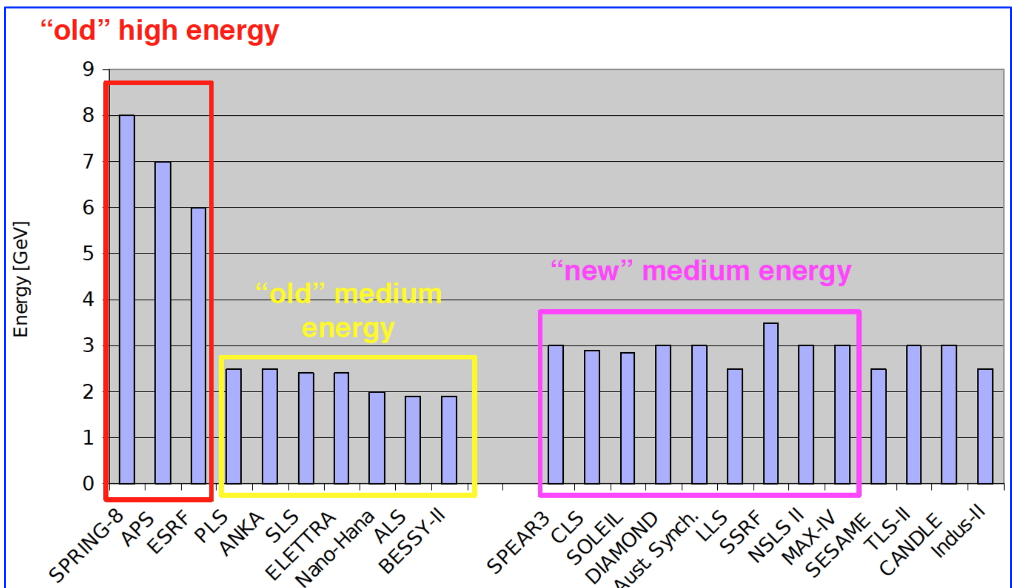
Synchrotron light is now a unique tool for science!

ESRF, Grenoble - France 6 GeV, C = 844 m
opened to users in 1994

- Sources designed specifically for high brightness or low emittance.
- Emphasis on research with insertion devices like undulators!
- High-energy machines able to generate hard x-rays
- Larger facilities to support rapidly growing user community, many beamlines high number of users.

Synchrotron radiation facilities

18 in America
25 in Asia
25 in Europe
1 in Oceania
including facilities under design and FELS



wayforlight
the european lightsources single entry point

Info on European Synchrotron Radiation Facilities: www.wayforlight.eu
About 67 operational Synchrotron Radiation Facilities Around the World information on: www.lightsources.org

Ultimate Storage Rings

… toward Diffraction Limited Light Sources

Diffraction limit and Emittance

Electron beam provides "diffraction-limited" radiation when:

$$\epsilon_{x,y} \le \frac{1}{2}\epsilon_r \approx \frac{\lambda}{4\pi}$$

where ε_r the emittance given by the angular divergence and the effective radiation source size is :

$$\epsilon_r = \sigma_r \sigma_{r'} \approx \frac{\lambda}{2\pi}$$

and in this case, the coherent fraction can be quite high:

$$f_c = \frac{\epsilon_r^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \gtrsim 44\%$$

For 1 Å radiation, the diffraction-limited photon-beam emittance is about 8 pmrad.

Typically 3rd-generation rings have:

ε_y = 1 - 40 pmrad and ε_x = 1- 5 nmrad

ESRF Grenoble

ε_y = 4 pmrad

ε_x = 4 nmrad

Several orders of magnitude away from diffraction-limited performance in horizontal

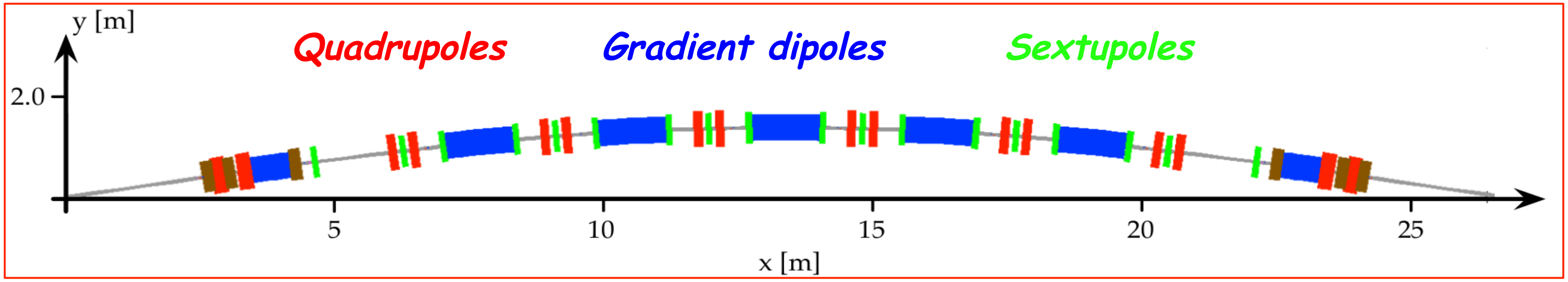
M. Borland, The diffraction-limited storage ring frontier, July 2015, Varenna, Italy

Emittance and Multibend Achromat Lattice

$$\varepsilon_{x_0,min} \propto \frac{E^2}{N_B^3}$$

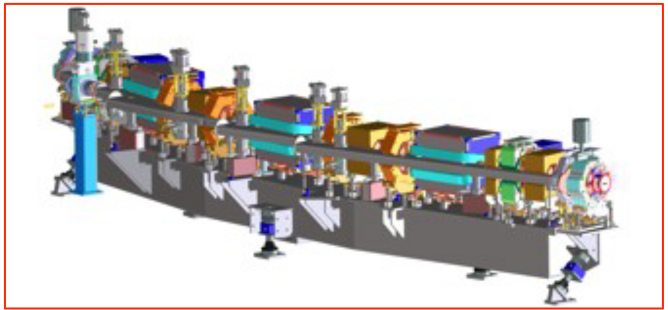
Emittance is governed by energy, E, and number of bending magnets, N_B.

- *Emittance is driven by randomness of photon emission in presence of dispersive (energy-dependent) orbits;*
- *Breaking up dipoles and putting focusing (quadrupoles) between the parts allows tightly controlling the magnitude of dispersive orbits*

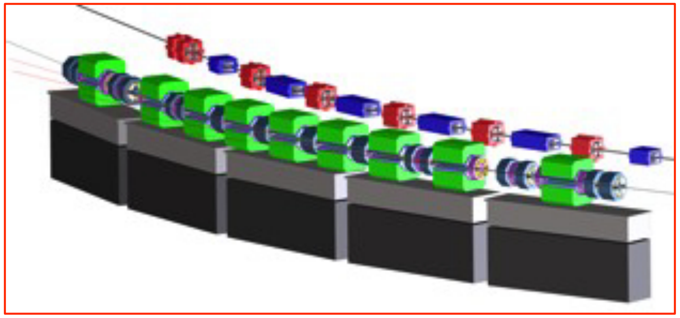


Multi-Bend Achromat Lattices enable small electron emittance and high brightness

P.F. Tavares, *The MAX IV storage ring project*, **J. Synch. Rad.** , (2014). 21, 862-877



ALS today triple-bend achromat (TBA)
ε_x = 2000 pmrad



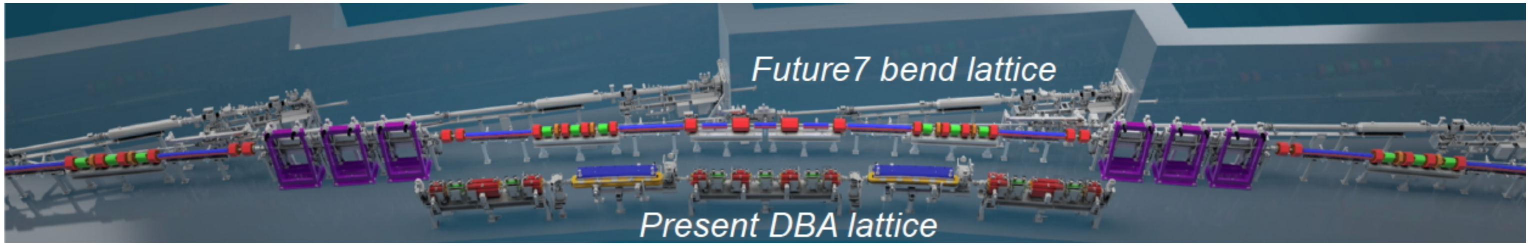
ALS multi-bend achromat (9BA)
ε_x = 52 pmrad

C. Steier, ALS SAC

Synchrotron radiation: history

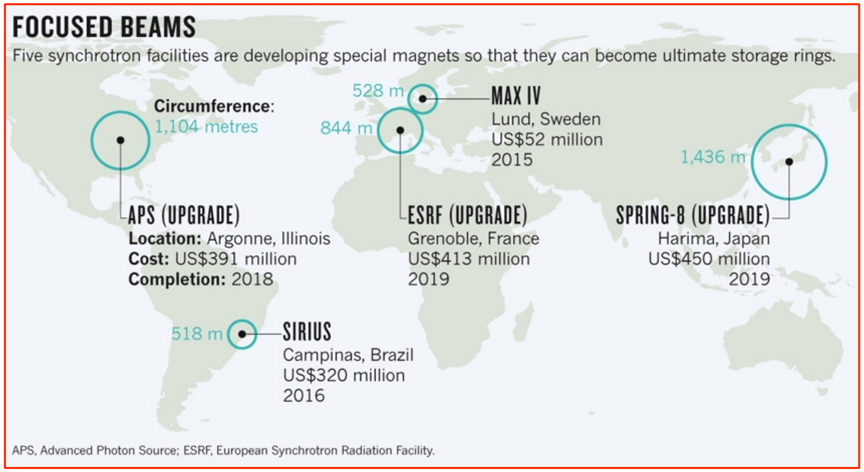
Future : Ultimate Storage Rings

Brightness and transverse coherence increase in the X-ray range with implementation of ***low emittance lattices*** *(multi-bend achromat schemes).*

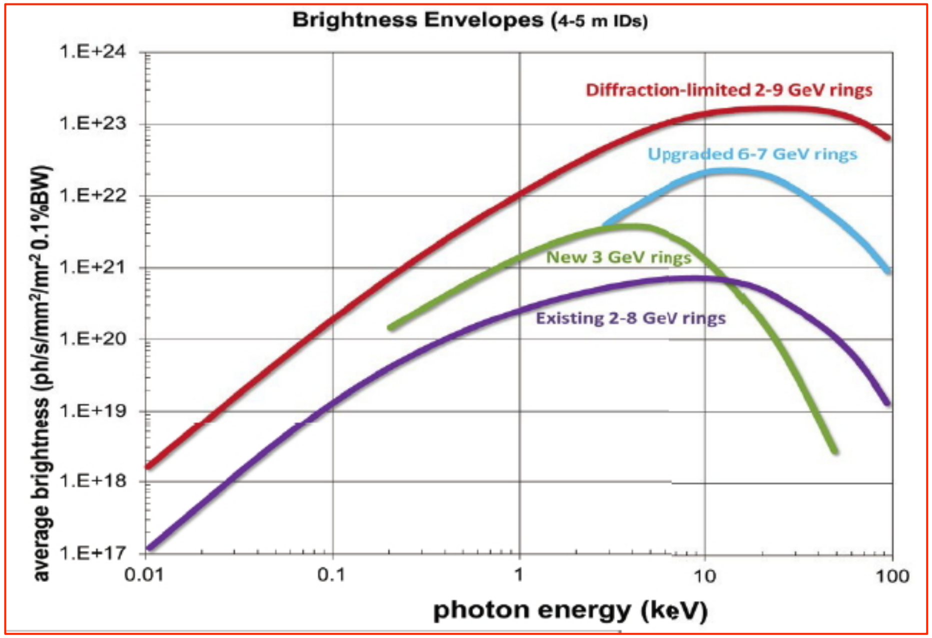


J.Jacob, Status of the ESRF operation & upgrade, 2013

ESRF ε_x= 4 nm; ε_x= 5 pm in the future ε_x= 0.16 nm

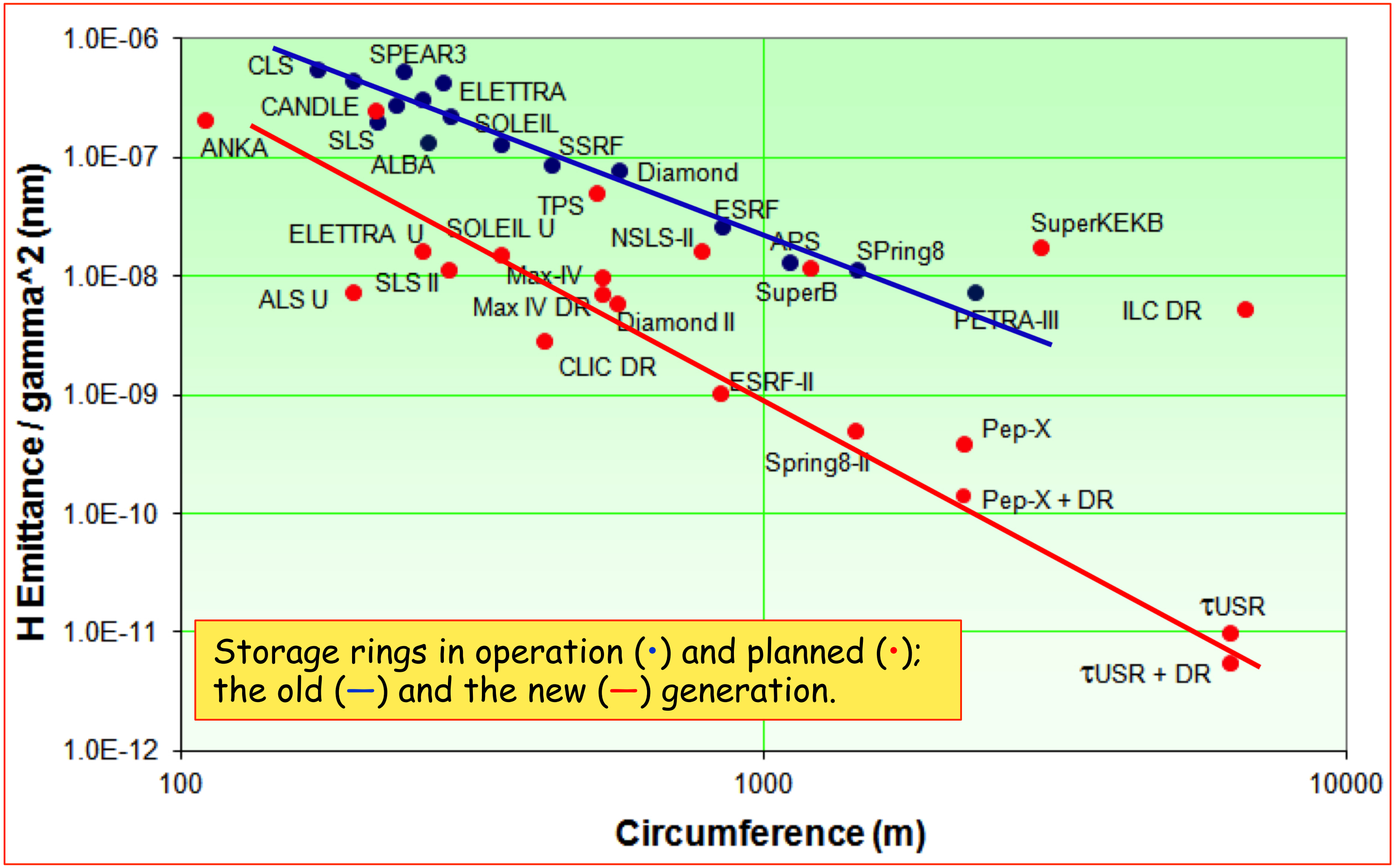


E.S. Reich, Ultimate upgrade for US synchrotron, Nature, 2013



H. Owen – Univ. of Manchester (UK)

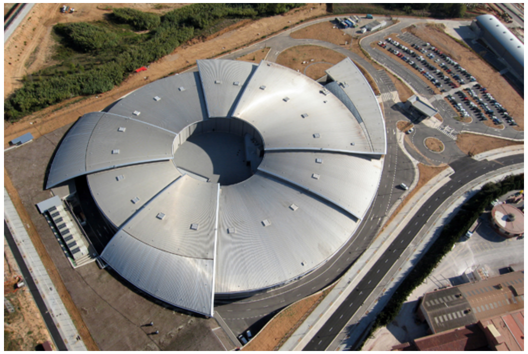
Storage rings generational change



3rd Generation Light Sources

ESRF - France

DIAMOND - UK

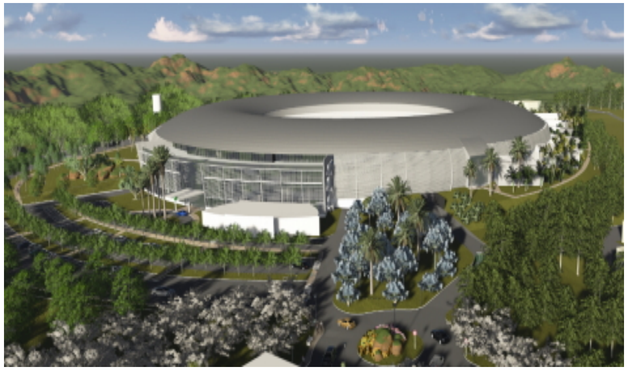


ALBA - Spain

Brightness is the main figure of merit of synchrotron radiation sources and its huge increase, was obtained designing low emittance machines, minimizing the source size and the beam divergence.

Under construction – Ultimate SR facilities

Lund - Sweden



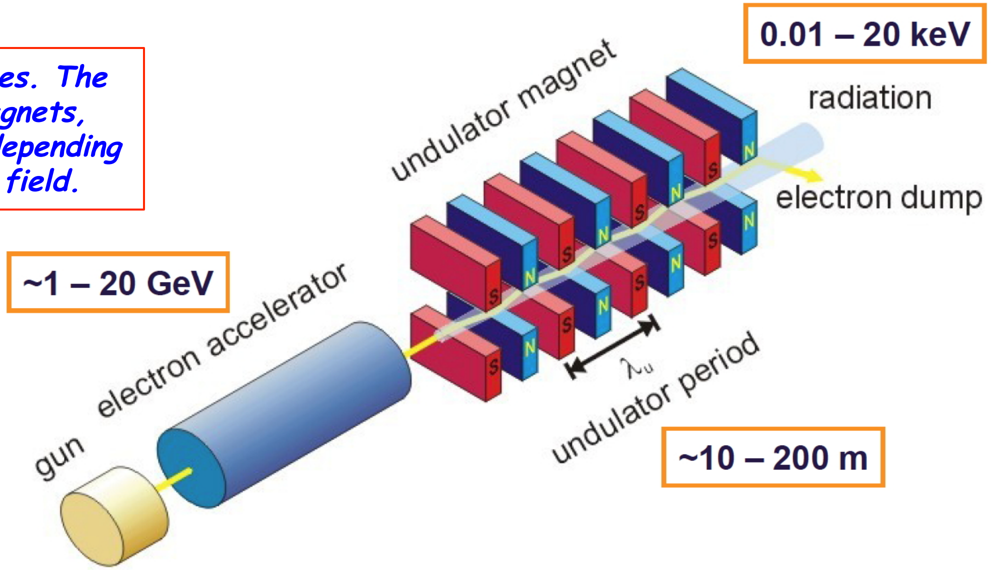
Sirius - Brazil

Shanghai -China

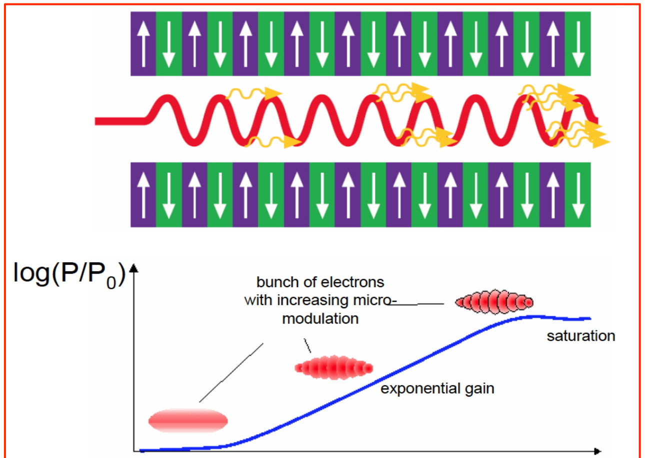
FELs or Free Electron Lasers

Fourth generation: LINAC based sources and Free Electron Lasers

Electrons in a FEL are not bound to atoms or molecules. The "free" electrons traverse a series of alternating magnets, called "undulators," and radiate light at wavelengths depending on electrons energy, undulator period and magnetic field.



SASE FEL – Self Amplified Stimulated Emission



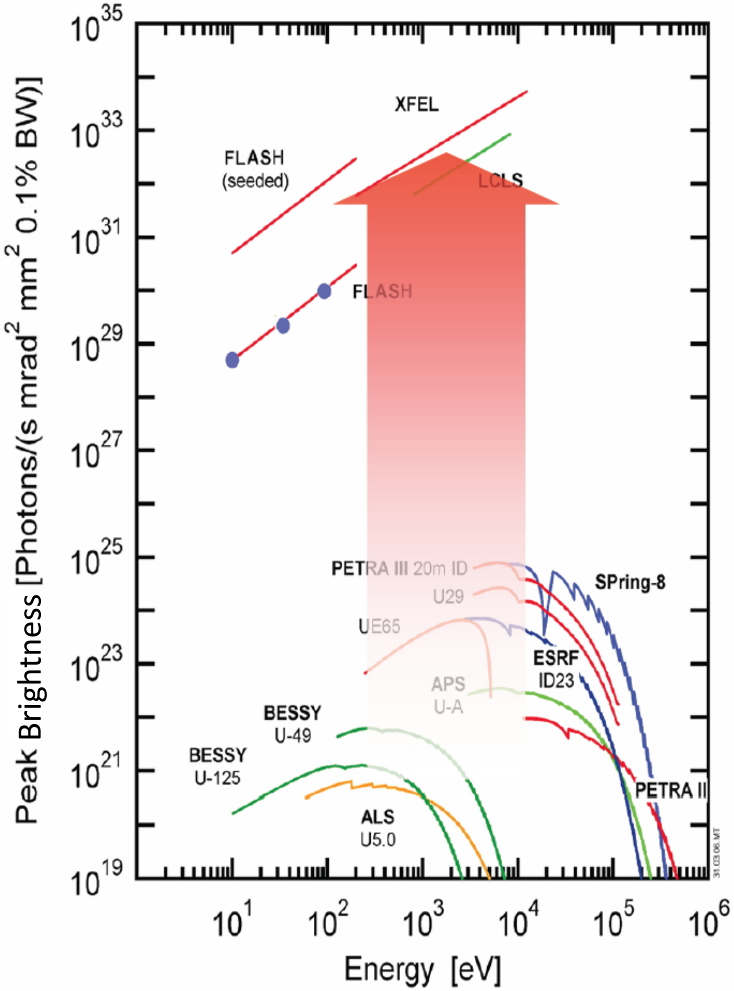
Letargy Spontaneous Emission Low Gain Random electron phase	***Exponential Growth*** Stimulated emission High Gain ***Electron bunched at radiation wavelength***	***Saturation*** Absorption No Gain Debunching

- The undulator induces **transverse sinusoidal velocity in electrons**
- **Energy exchange** occurs between the transverse **electron current** and **transverse electric field of a co-propagating light beam**
- Depending on the phase of the light beam with the electrons' wiggling motion, **some electrons gain energy while others lose energy → energy modulation →bunching of electrons** along the axial direction into micro-bunches with period equal to an optical wavelength
- **Micro-bunched electron beams radiate coherently** at higher power → amplification of the co-propagating light beam.

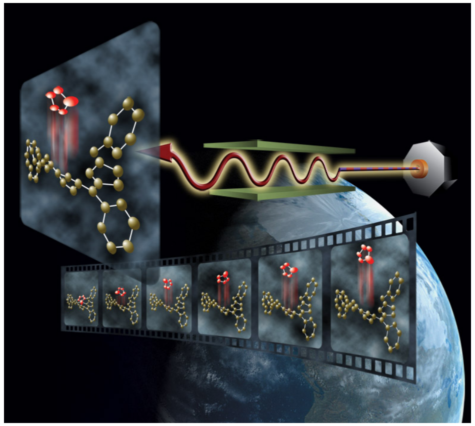
D. Nguyen, S. Russell and N. Moody, Theory and Practice of Free-Electron Lasers, 2009
T. Tschentscher, Free-electron lasers as sources of extremely brilliant x-ray radiation, 2011

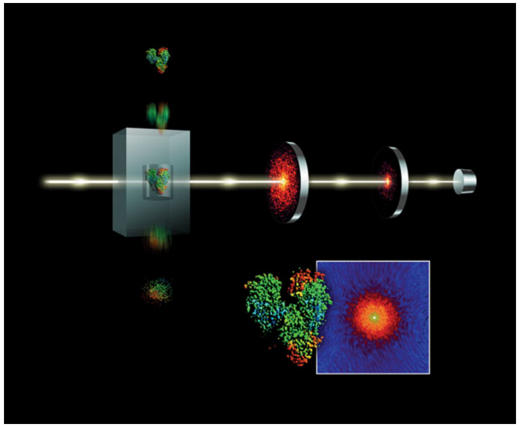
Synchrotron radiation: history

Fourth generation: LINAC based sources and Free Electron Lasers



- *Extremely bright and coherent sources*
- *Ultrafast pulses*
- *Already working in IR to UV and X-ray (first XFEL - LCLS April 2009) ranges*
- *European XFEL being built*
- *Filming chemical reactions as they occur*
- *Protein crystallography no longer needed – image molecules directly*

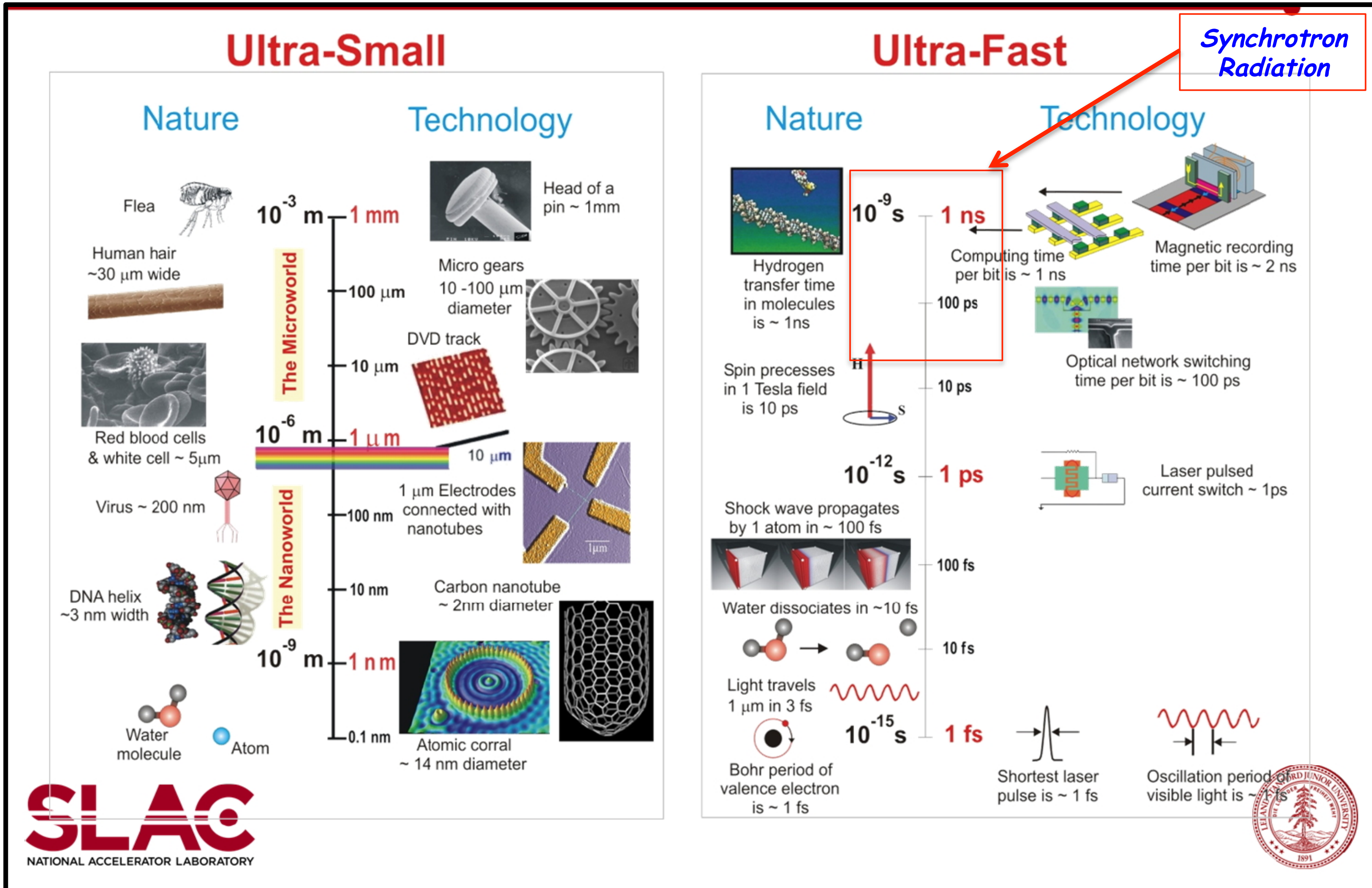




LCLS http://www-public.slac.stanford.edu/lcls/aboutlcls.aspx

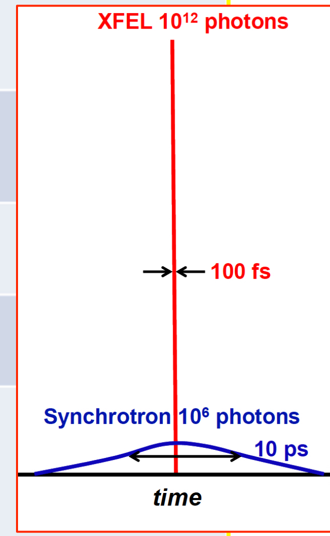
Synchrotron radiation: history

Fourth generation: free electron lasers



Comparing ultimate storage rings and FELs- future

Parameter	Storage Rings	FEL
Wavelength Range	2-3 decades typically	1-2 decades (multiple undulators)
Peak Brightness (ph/s/mr^2/ mm^2/0.1%BW)	$10^{24} - 10^{26}$ (x 100 increase but still modest compared to FEL)	$10^{31} - 10^{33}$
Average Brightness (ph/s/mr^2/ mm^2/0.1%BW)	$10^{21} - 10^{23}$ (x 100 increase)	$10^{23} - 10^{25}$ (x 1000 increase)
Minimum Pulse Width (fs)	~1000	Below ~1 fs
Coherence	High spatial coherence	Full coherence
Energy Position Time	<.01% (with ~0.1% energy spread) < 0.1 σ (~0.3 μm H, V) < 0.1 σ (~0.5 ps)	< 0.1 eV (seeded) ~0.1 σ ~10 fs
Number of Beamlines	Large (~30-60)	Limited (~3-6 endstations per undulator), multiple undulators per facility



P. S. Drell, Status of International Light Sources: Today and in the Near Future, BESAC 2013
http://science.energy.gov/bes/besac/meetings/meeting-presentations/)

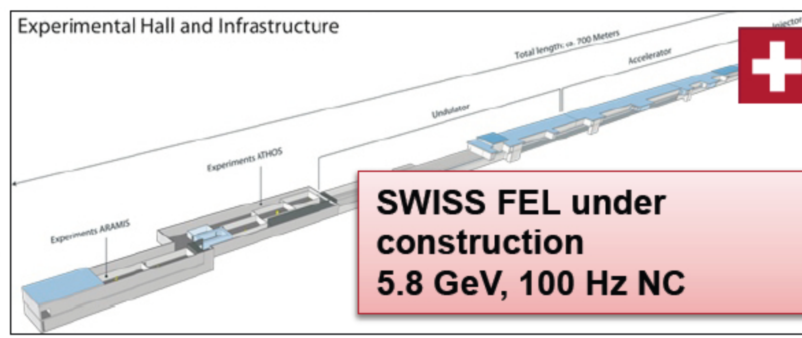
XFELs present and near future

LCLS-I, II 2009, 2019
14.5 GeV, 120 Hz NC

SACLA 2011
8.5 GeV, 60 Hz NC

PAL XFEL under construction
10 GeV, 100 Hz NC

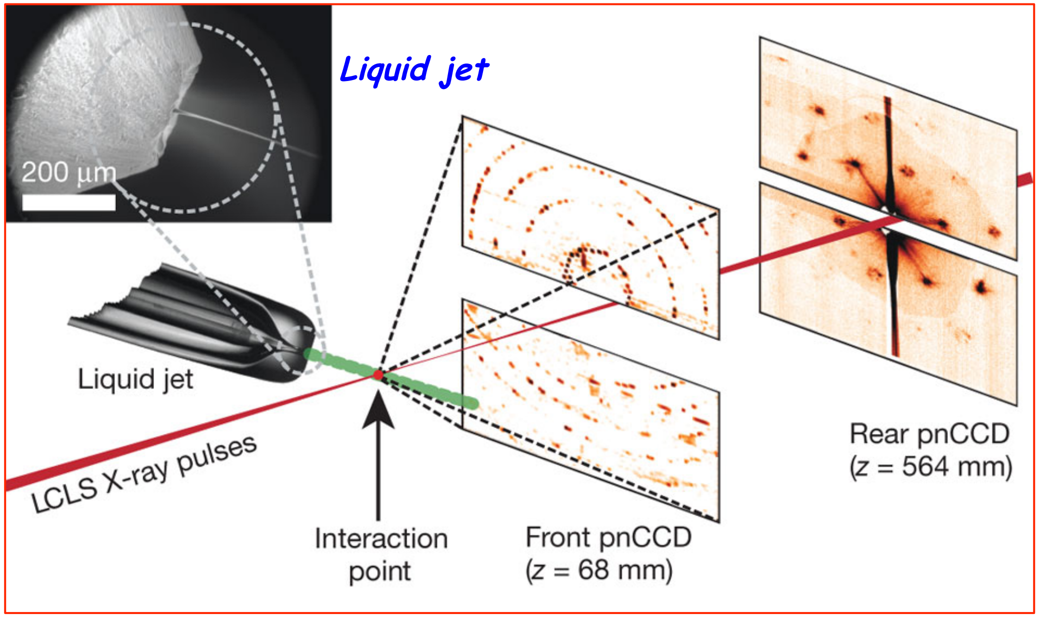
XFEL under construction
17.5 GeV, 2700 x 10 Hz SC



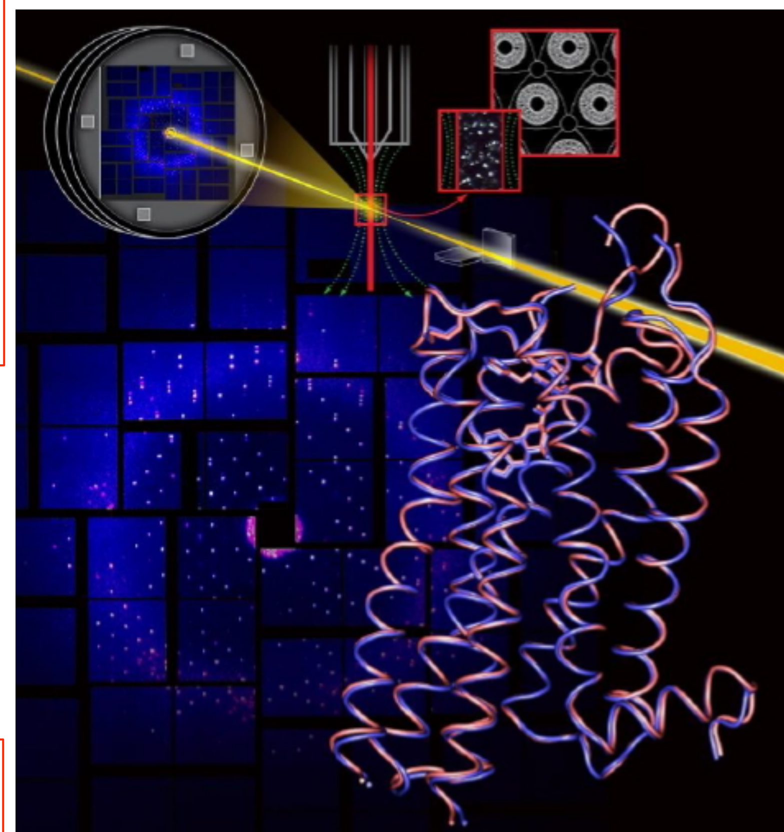
SWISS FEL under construction
5.8 GeV, 100 Hz NC

NC: normal conducting acceleration, SC: super conducting acceleration

Serial femtosecond crystallography experiments at LCLS



H.N.Chapman et al. *Femtosecond X-ray protein nanocrystallography,* ***Nature 470 (2011)***

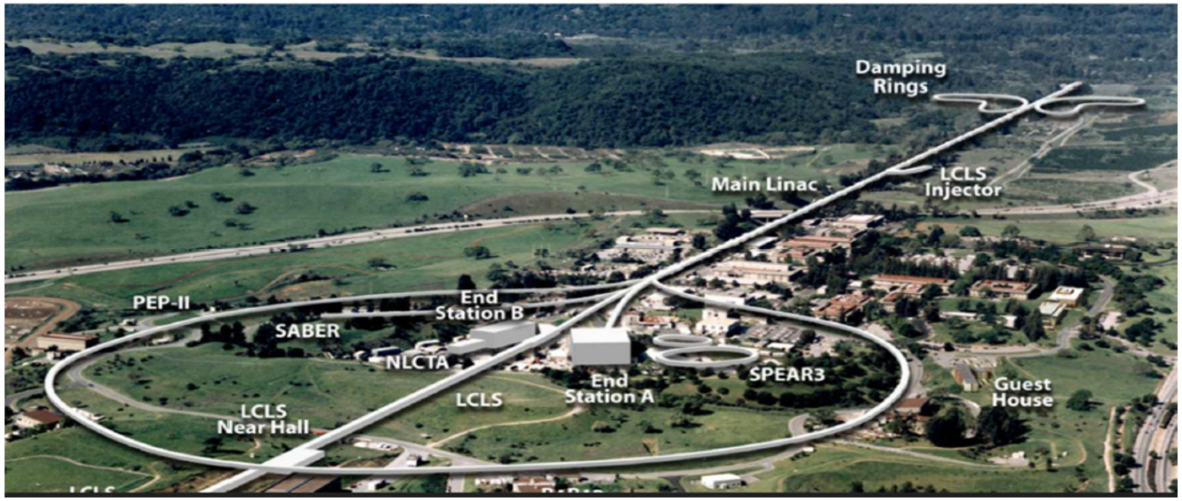


W. Liu et al. *Serial Femtosecond Crystallography of G Protein-Coupled Receptors,* ***Science 342 (2013)***

Fifth Generation Light Sources

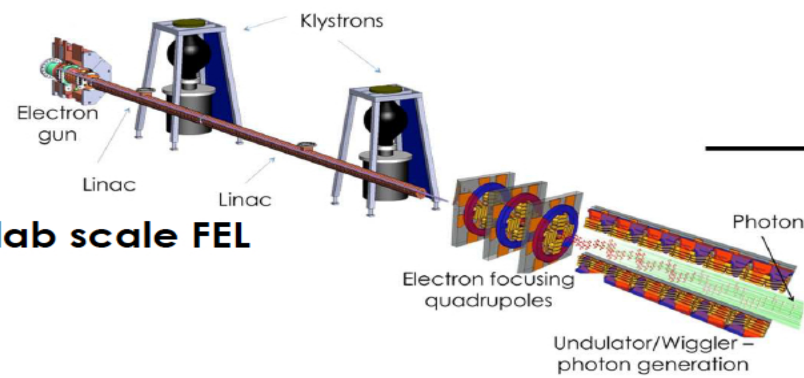
… re-invent XFEL to fit in campus laboratory.

The X-ray FEL is enormous. Challenge is to fit this…



1 km

Into this…



5 m

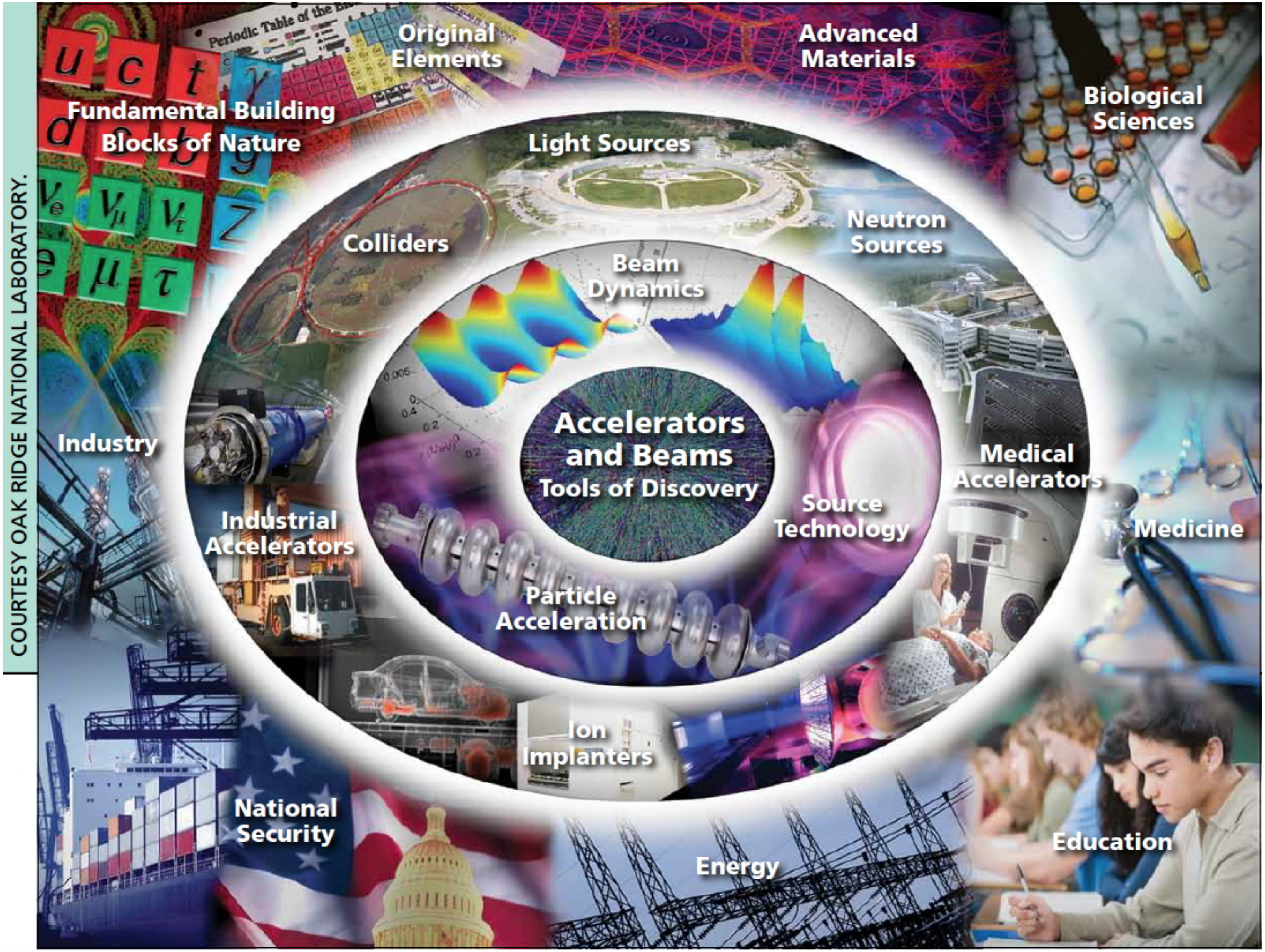
The university lab scale FEL

J. Rosenzweig, UCLA - Fifth Generation Light Sources X-ray FELs Based on New Accelerator and Undulators - 2014

Ongoing research on laser/plasma/wakefield accelerators, high frequency, high repetition rate linacs and electron beam injectors can lead in the future to very compact, university scale, X-ray FELs.

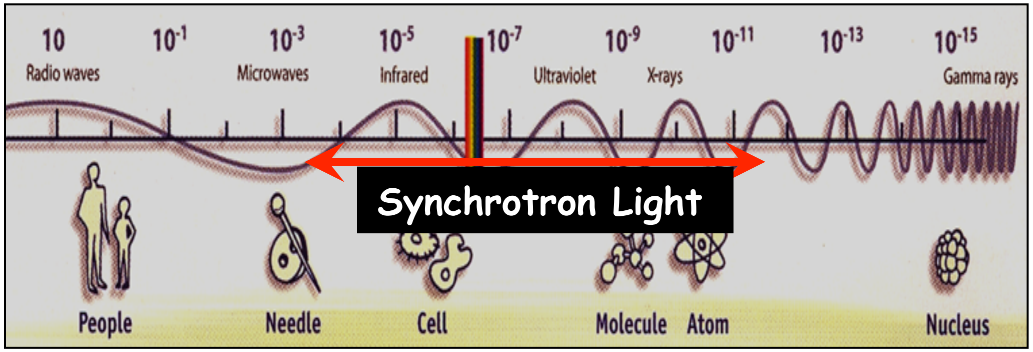
C. Pellegrini, UCLA - 5th Generation light sources - 2011

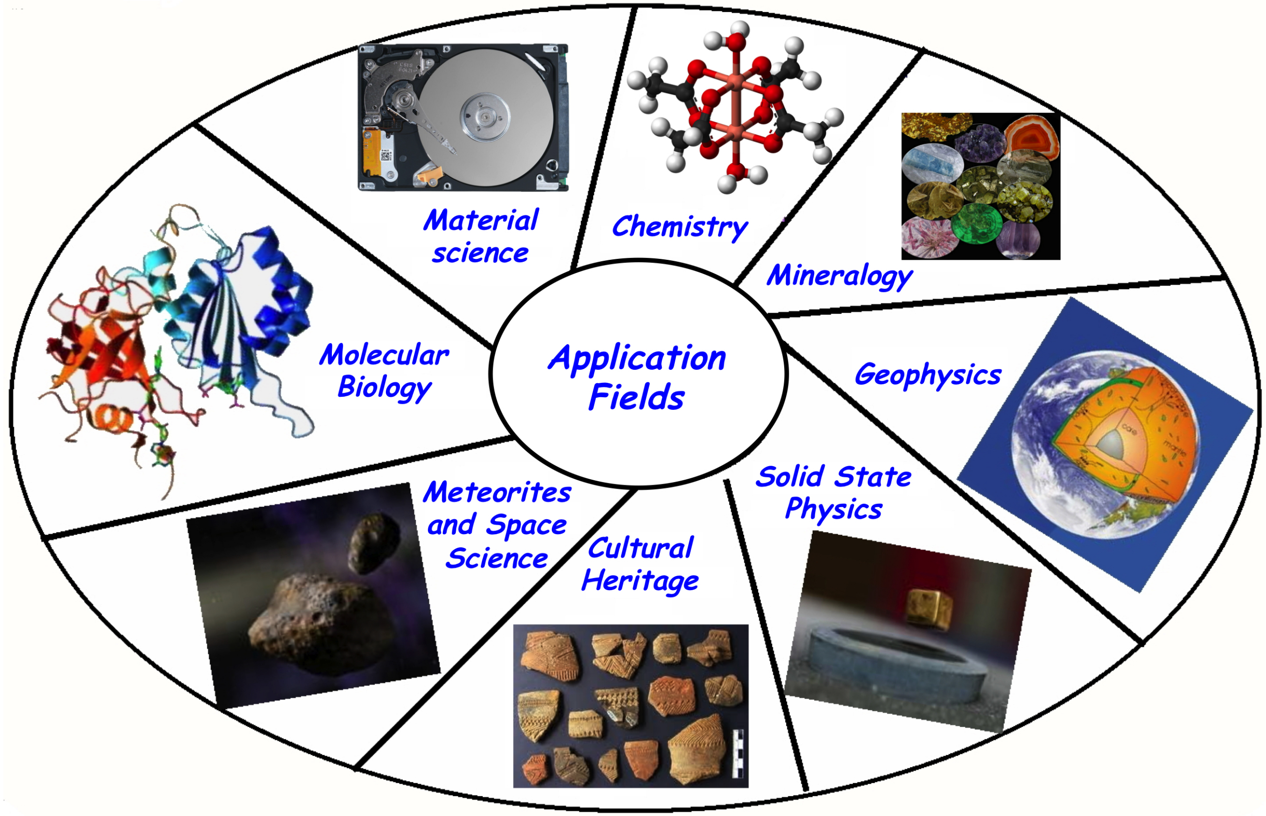
From accelerators to applications



E. Malamud *Ed.*, ***Accelerators and Beams tools of discovery and innovation*** (http://www.aps.org/units/dpb/news/edition4th.cfm) ***2013***

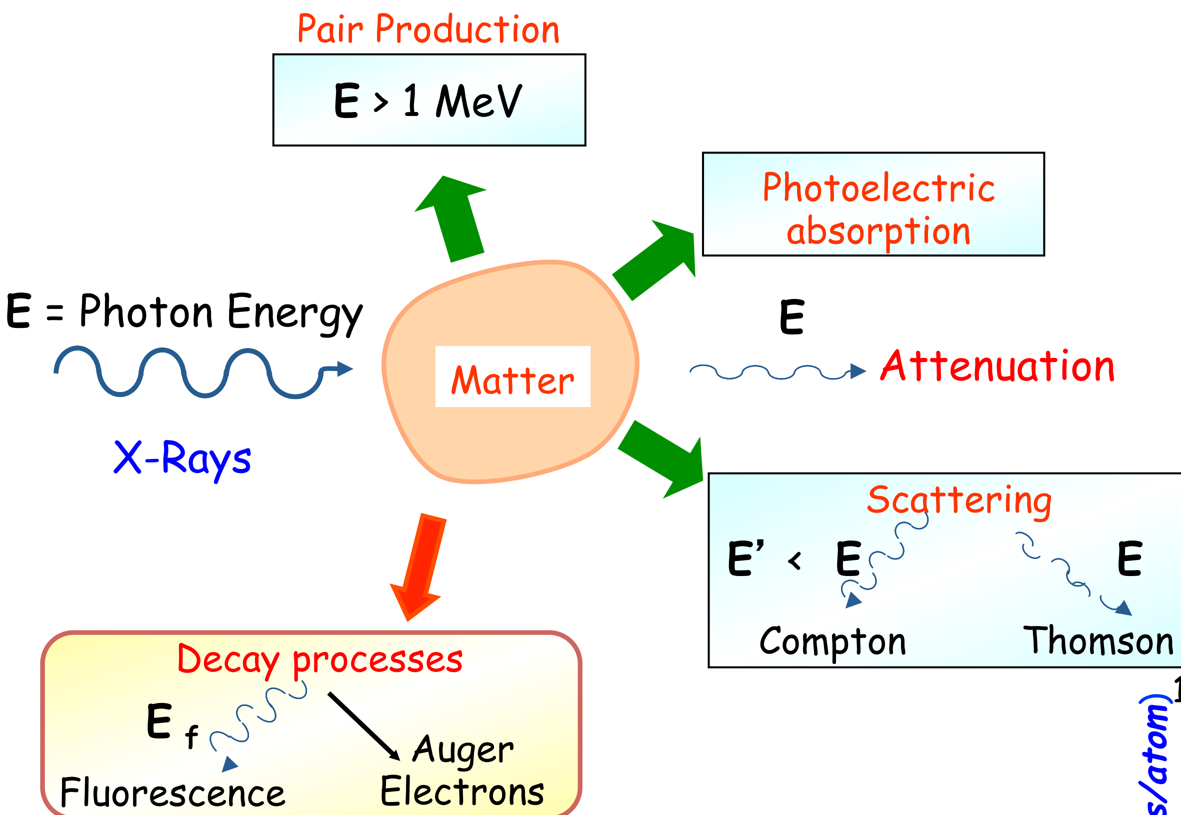
Synchrotron radiation applications

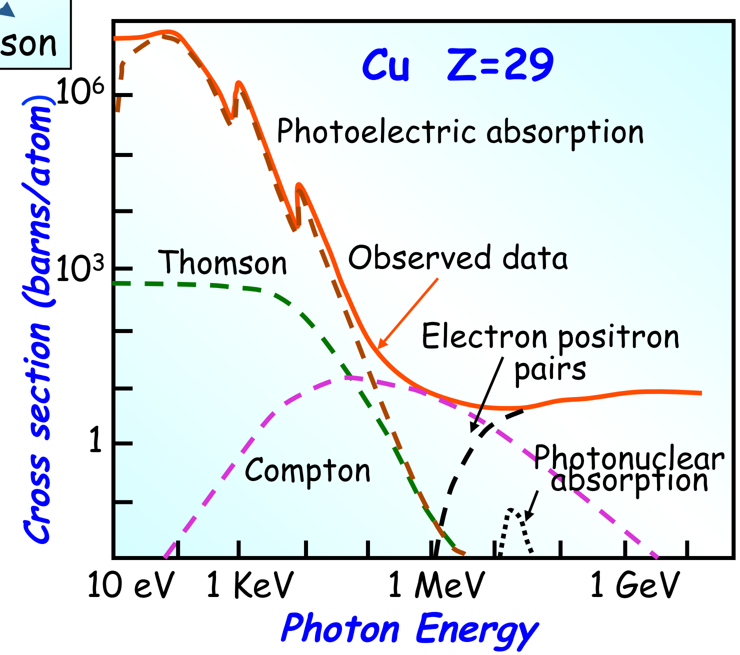




Some applications using X-rays

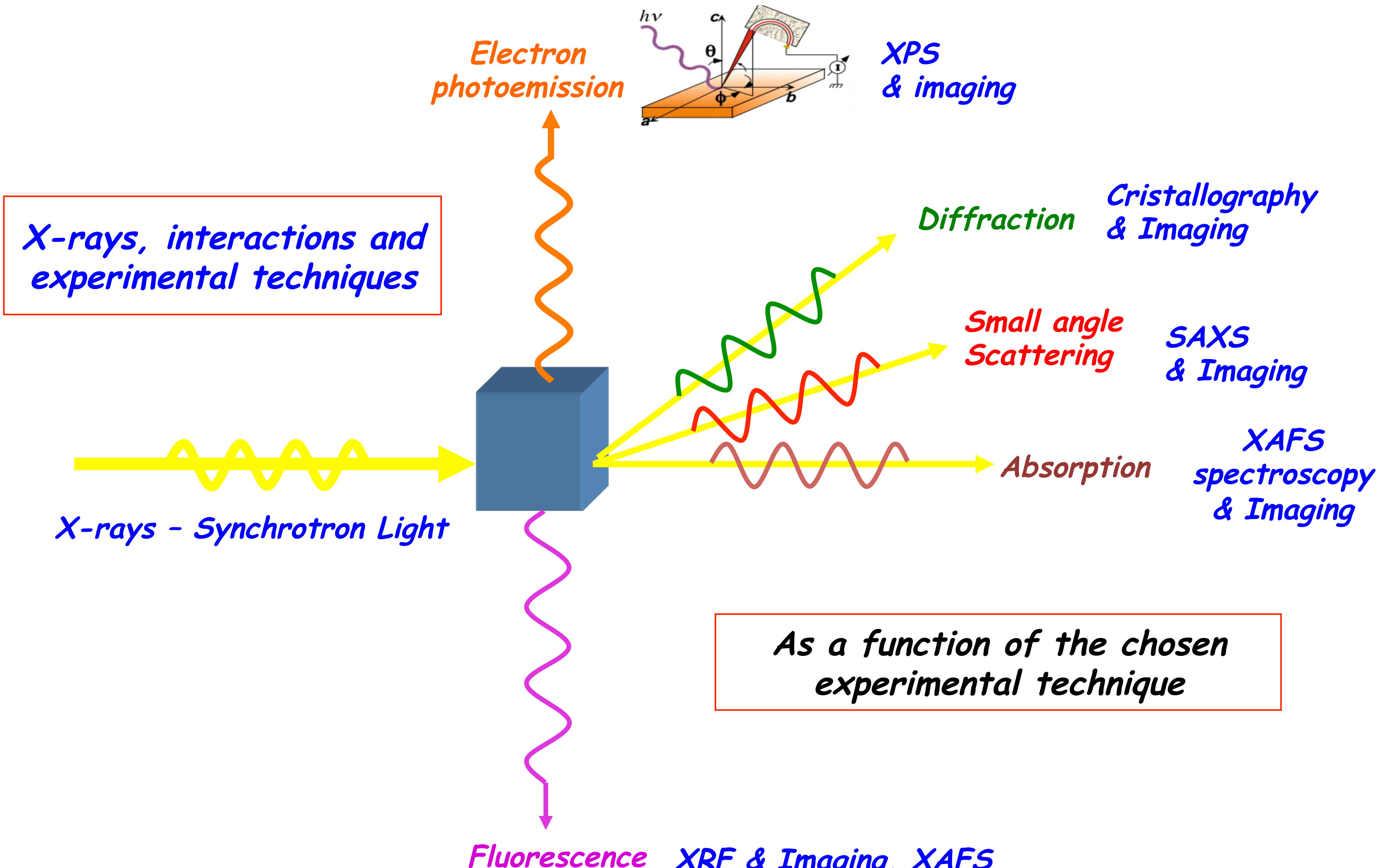
Interaction of X-rays with matter





There are different types of interaction of X-rays with matter but taking into account the energy range of interest the ones that will be taken into account are ***absorption*** and ***elastic*** or ***Thomson scattering***.

X-rays interactions with matter and experimental techniques



Some applications using X-rays (synchrotron light)

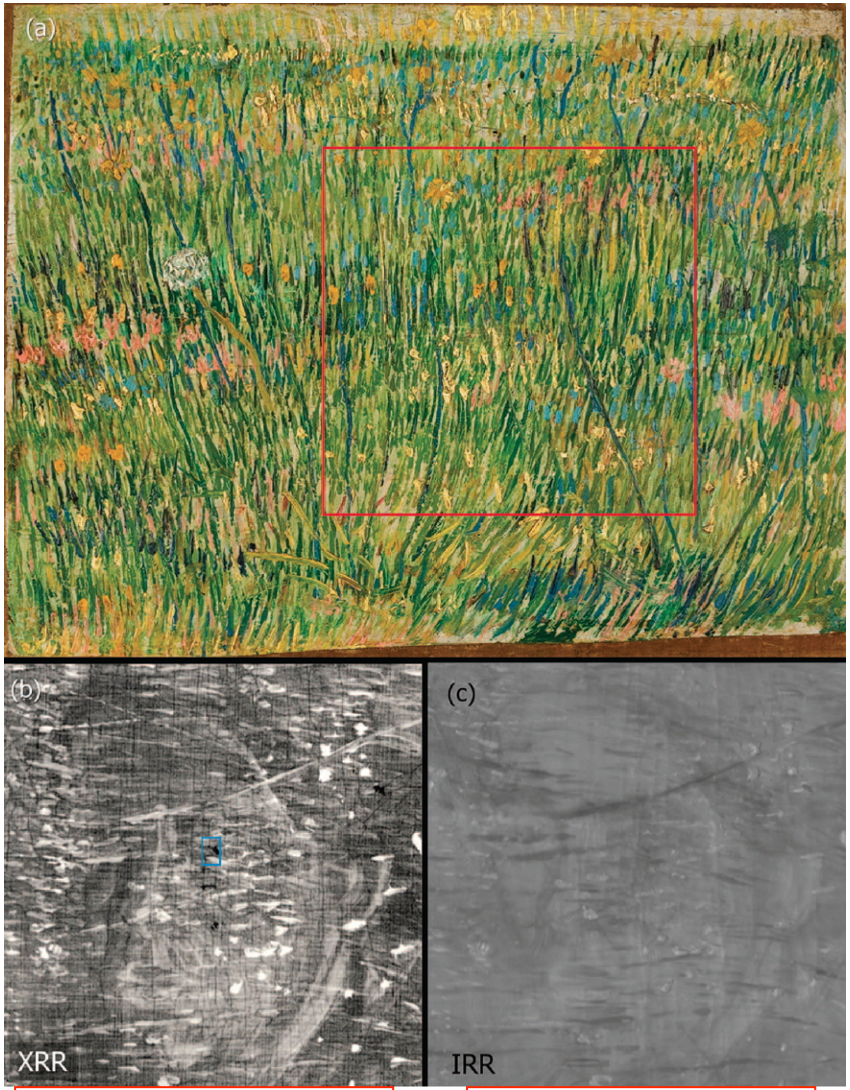
Cultural heritage

Imaging and paleontology

Crystallography

Applications in the field of cultural heritage

Vincent van Gogh



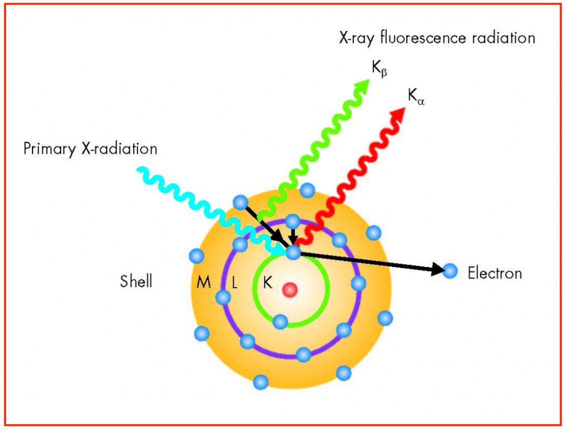
***Vincent van Gogh*, Patch of Grass**, Paris 1887, Kroller-Muller Museum, Otterlo, The Netherlands, (KM 105.264; F583/JH1263).

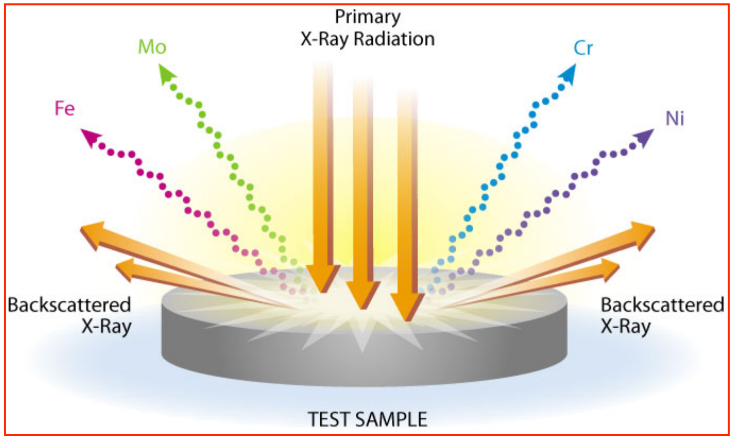
Conventional X-Ray Radiation (XRR) transmission radiography

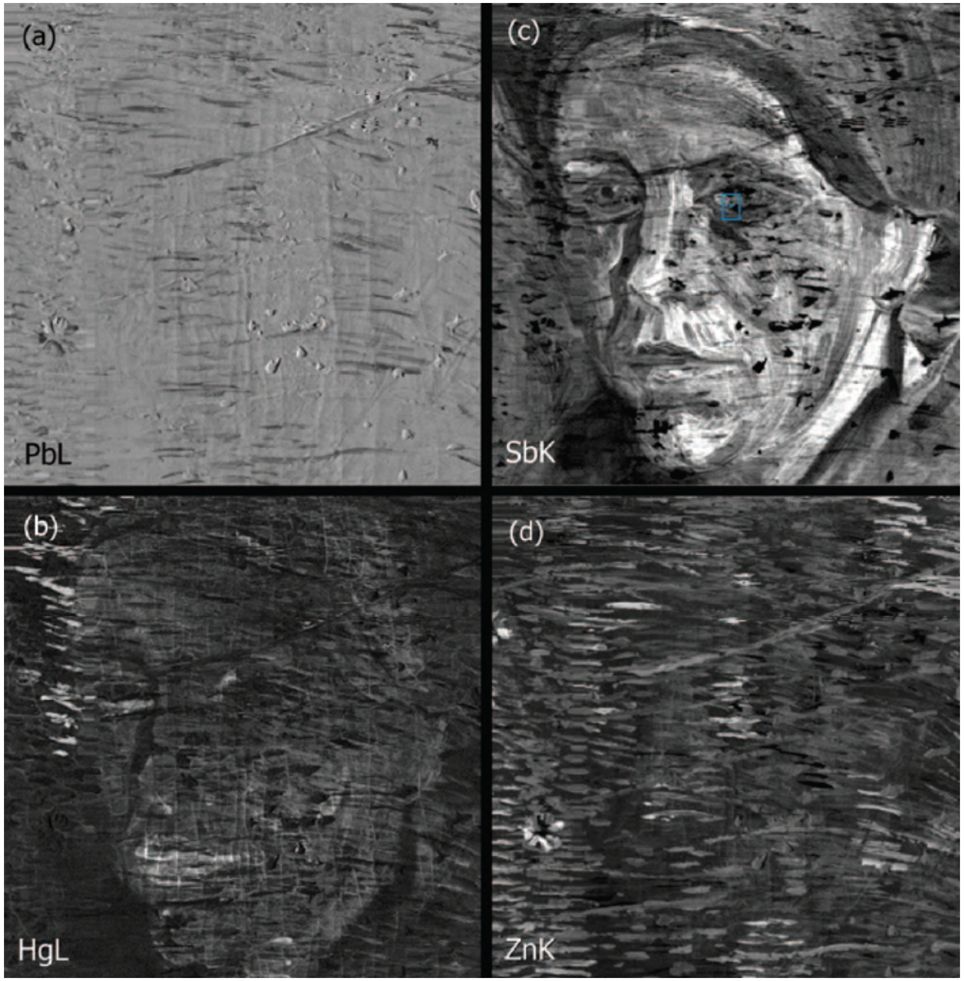
Infrared reflectography (IRR)

J. Dik et al., *Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping*, **Anal. Chem. 2008**, 80, 6436

Visualization of a Lost Painting of van Gogh using XRF







J. Dik et al., *Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping*, **Anal. Chem. 2008**, **80**, 6436

Synchrotron Radiation – XRF (black, low intensity and white, high intensity). Hg L shows the distribution of vermillion, Sb K of Naples yellow and Zn K of zinc white.

Visualization of a Lost Painting of van Gogh

a) ***Tritonal color reconstruction*** of Sb (yellowish white) and Hg (red) (b) **Detail from Vincent van Gogh, Head of a Woman**, Nuenen 1884-85,Kro ller-Muller Museum, Otterlo (KM 105.591;F154/JH608). (c) **Detail from Vincent van Gogh, Head of a Woman**, Nuenen 1884-85, Van Gogh Museum, Amsterdam (F156/ JH569).

Vincent van Gogh (1853-1890), is best known for his vivid colors and his short but highly productive career. His productivity is even higher than generally realized, as many of his known paintings cover a previous composition. Van Gogh would often reuse the canvas of an abandoned painting and paint a new or modified composition on top. These hidden paintings offer a unique and intimate insight into the genesis of his works.

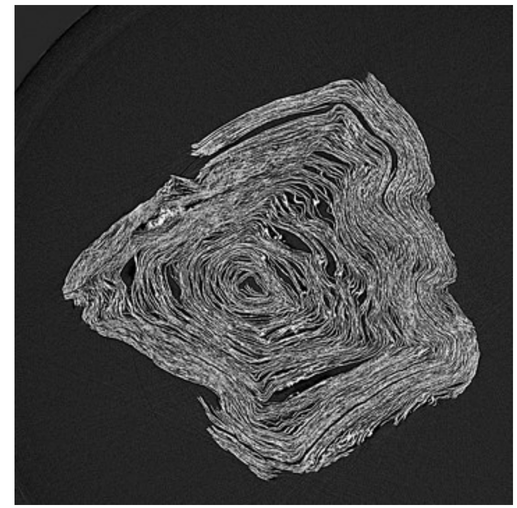
J. Dik et al., *Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping*, **Anal. Chem. 2008**, **80**, 6436

Revealing letters in rolled Herculaneum papyri using X-ray phase-contrast tomography

Close up photography of ***Herculaneum Papyrus*** scroll PHerc.Paris.4. The photographed zone is 5cm. (*Credit: E. Brun*)

Hundreds of papyrus rolls, buried by the eruption of Mount Vesuvius in 79 AD and belonging to the only library passed on from Antiquity, were discovered 260 years ago at Herculaneum.

These carbonized papyri are extremely fragile and are inevitably damaged or destroyed in the process of trying to open them to read their contents.



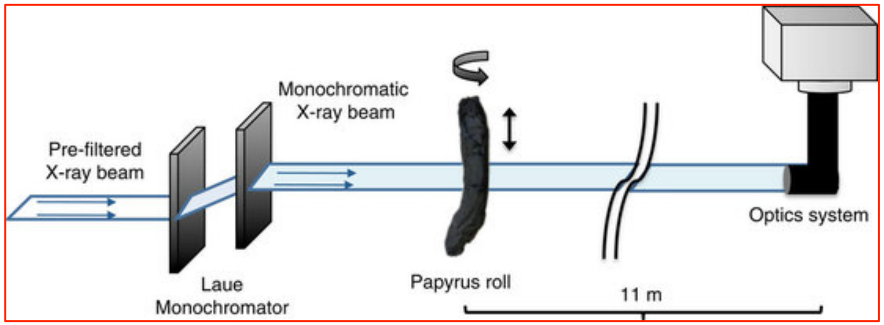
A section of papyrus. Letter sequences are found in a fragment of a hidden layer. (*Credit: CNRS-IRHT UPR 841 /* ***ESRF*** */ CNR-IMM Unité de Naples*)

V. Mocella *et al.*, **Nature Communications** - DOI: 10.1038/ncomms6895- ***January 2015***

https://www.youtube.com/watch?v=d3aWBgNYOCU

Revealing letters in rolled Herculaneum papyri.

In recent years, new imaging techniques have been developed to read the texts without unwrapping the rolls. ***Until now, specialists have been unable to view the carbon-based ink of these papyri***, even when they could penetrate the different layers of their spiral structure.
For the first time ***X-ray phase-contrast tomography*** (*beamline ID17 of the ESRF, Grenoble, France*) can ***reveal various letters hidden inside the precious papyri without unrolling them***.
This attempt opens up new opportunities to read many Herculaneum papyri, which are still rolled up, thus enhancing our knowledge of ancient Greek literature and philosophy.



The ***papyrus alphabet from PHerc.Paris.4. as revealed by the XPCT experiment***, primarily from the ***innermost region of the papyrus***, where the individual coils are more distinguishable, are reported on lines 1 and 2; on ***line 3 the infrared images of the same letters from the unrolled (opened) papyrus PHerc. 1471***, which was used as a reference for the writing style of the scroll PHerc.Paris. 4.

V. Mocella** et al.*, **Nature Communications** - DOI: 10.1038/ncomms6895- ***January 2015

Imaging and paleontology

Imaging and paleontology

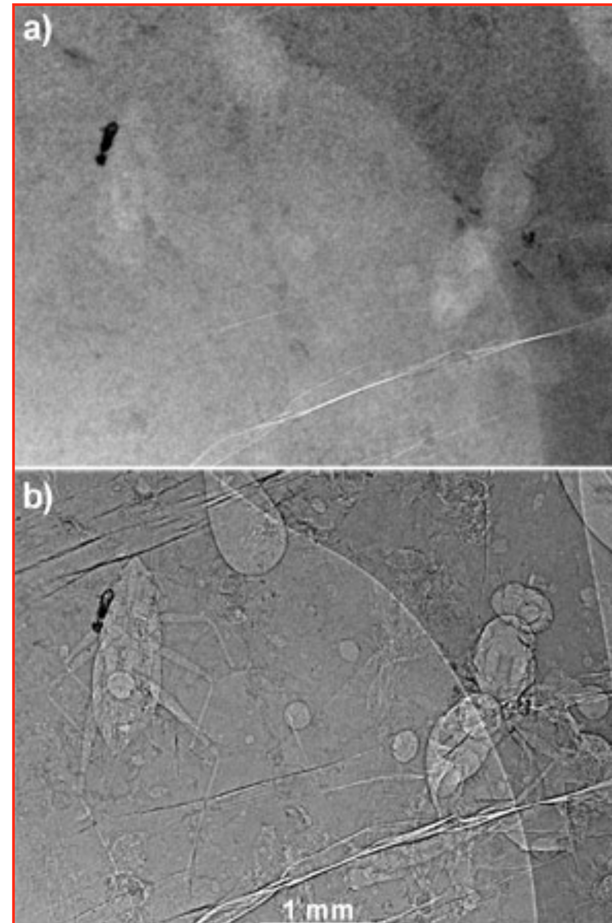
Amber has always been a rich source of fossil evidence. X-rays now make it possible for paleontologists to ***study opaque amber, previously inaccessible using classical microscopy techniques***. Scientists from the University of Rennes (France) and the ESRF found ***356 animal inclusions, dating from 100 million years ago***, in two kilograms of opaque amber from ***mid-Cretaceous*** sites of Charentes (France).

Pieces of opaque amber-
Image credits: V. Girard/D. Néraudeau, UMR CNRS 6118 Rennes

Fossil inclusions in opaque amber

Radiography of an amber block with inclusions viewed in absorption mode.

Propagation phase contrast X-ray synchrotron imaging (990 mm prop. distance)



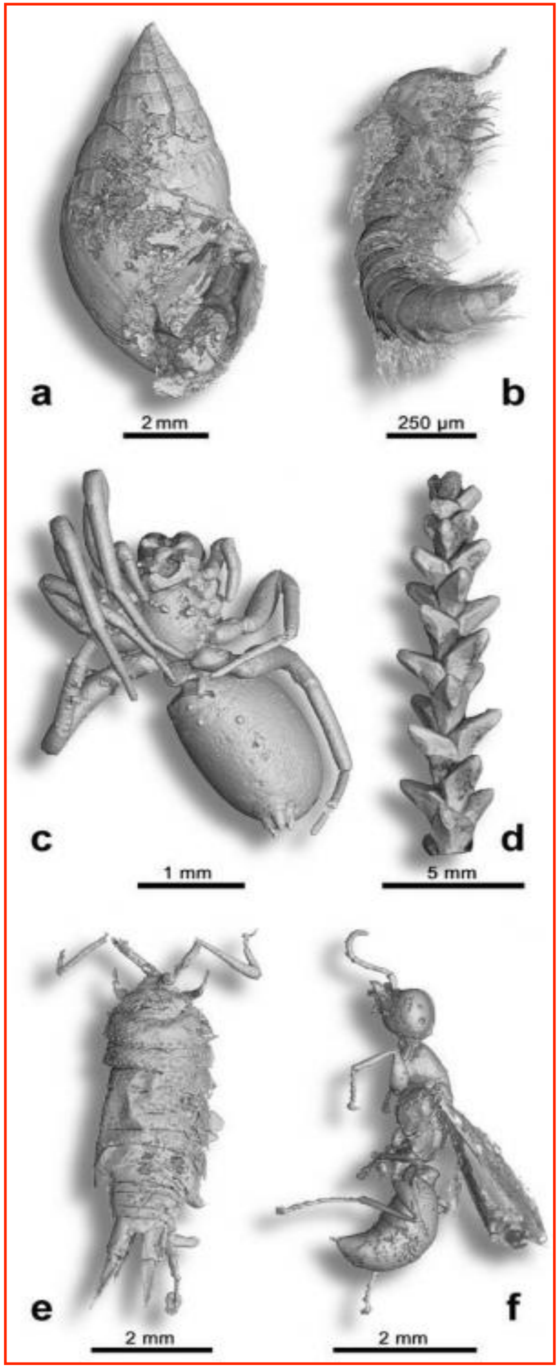
M. Lak, D. Neraudeau, A. Nel, P. Cloetens, V. Perrichot and P. Tafforeau, *Phase Contrast X-ray Synchrotron Imaging: Opening Access to Fossil Inclusions in Opaque Amber*, ***Microscopy and Microanalysis, (2008), 14:251-259***

Imaging and paleontology

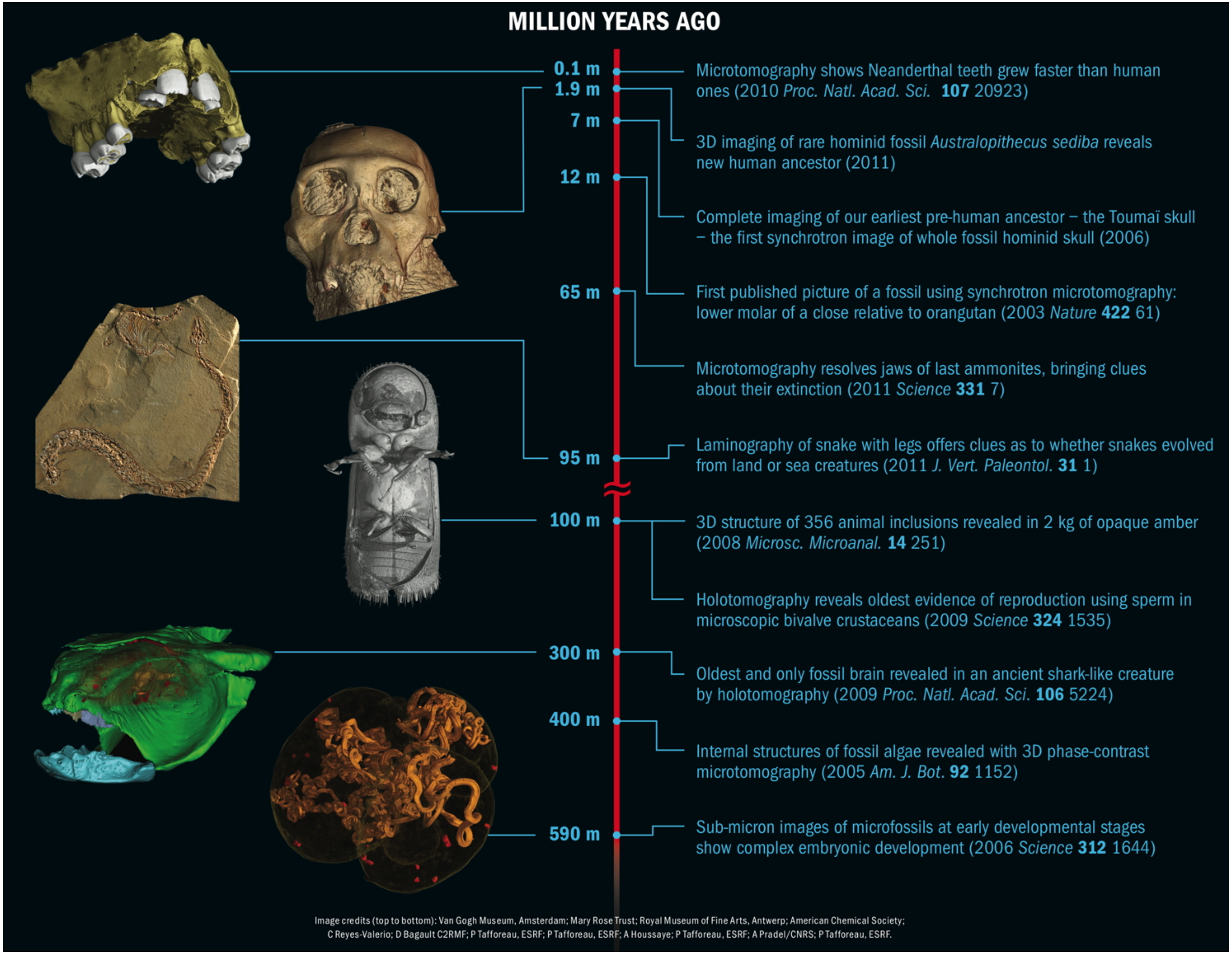
Synchrotron X-ray microtomography was used to determine the 3D reconstruction and allowed the paleontologists to study the organisms in detail and to describe them.

Cretaceous beetle

Examples of virtual 3D extraction of organisms embedded in opaque amber: a) Gastropod Ellobiidae; b) Myriapod Polyxenidae; c) Arachnid; d) Conifer branch (Glenrosa); e) Isopod crustacean Ligia; f) Insect hymenopteran Falciformicidae.



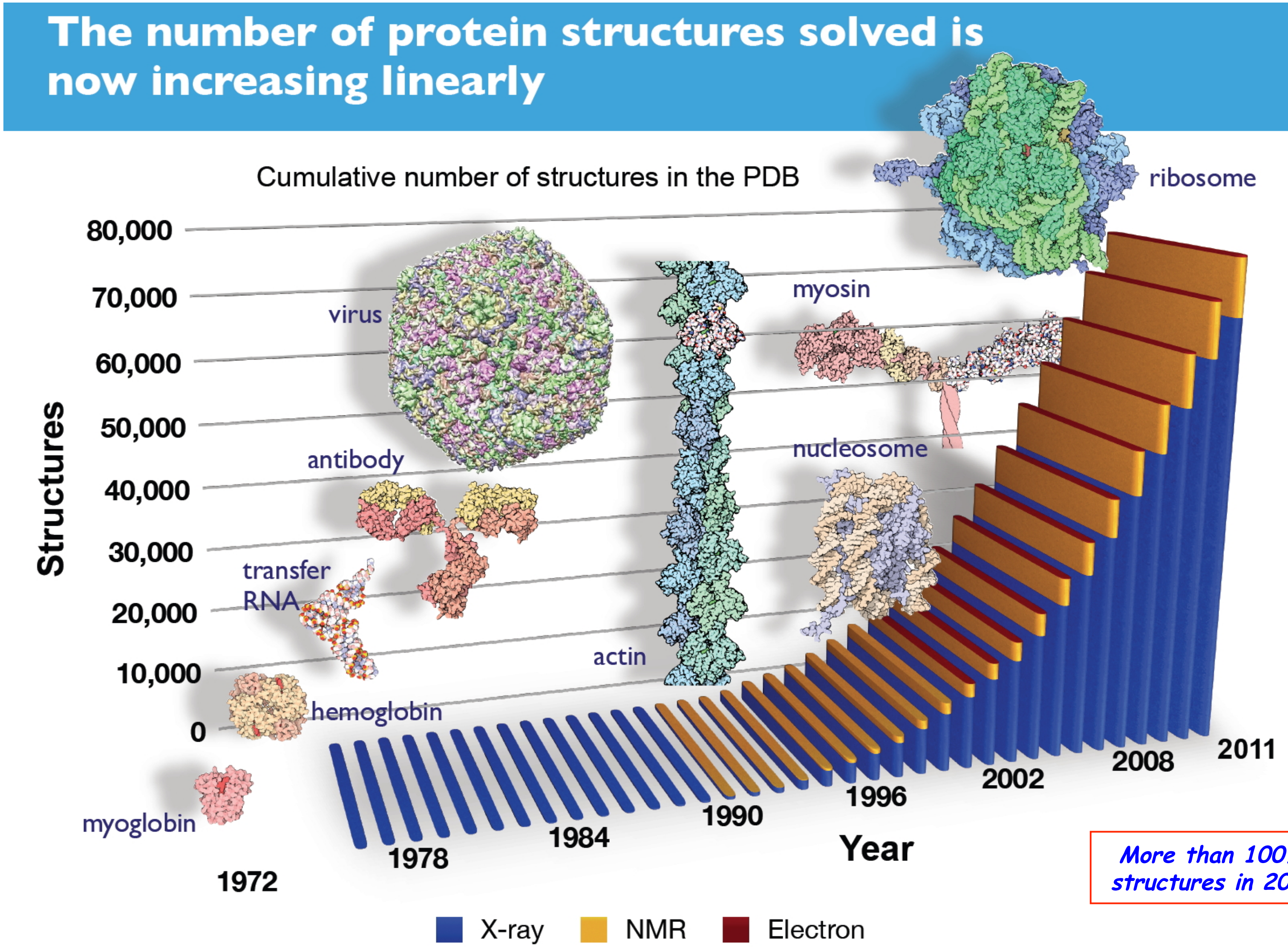
M. Lak, D. Neraudeau, A. Nel, P. Cloetens, V. Perrichot and P. Tafforeau, Phase Contrast X-ray Synchrotron Imaging: Opening Access to Fossil Inclusions in Opaque Amber, Microscopy and Microanalysis, (2008)



Marine Cotte - *Synchrotron culture : Focus on: paleontology and cultural heritage* – ***ESRF News –June 2011***

Biocrystallography

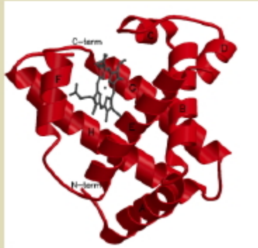
Biocrystallography



More than 100.000 structures in 2014 !!!

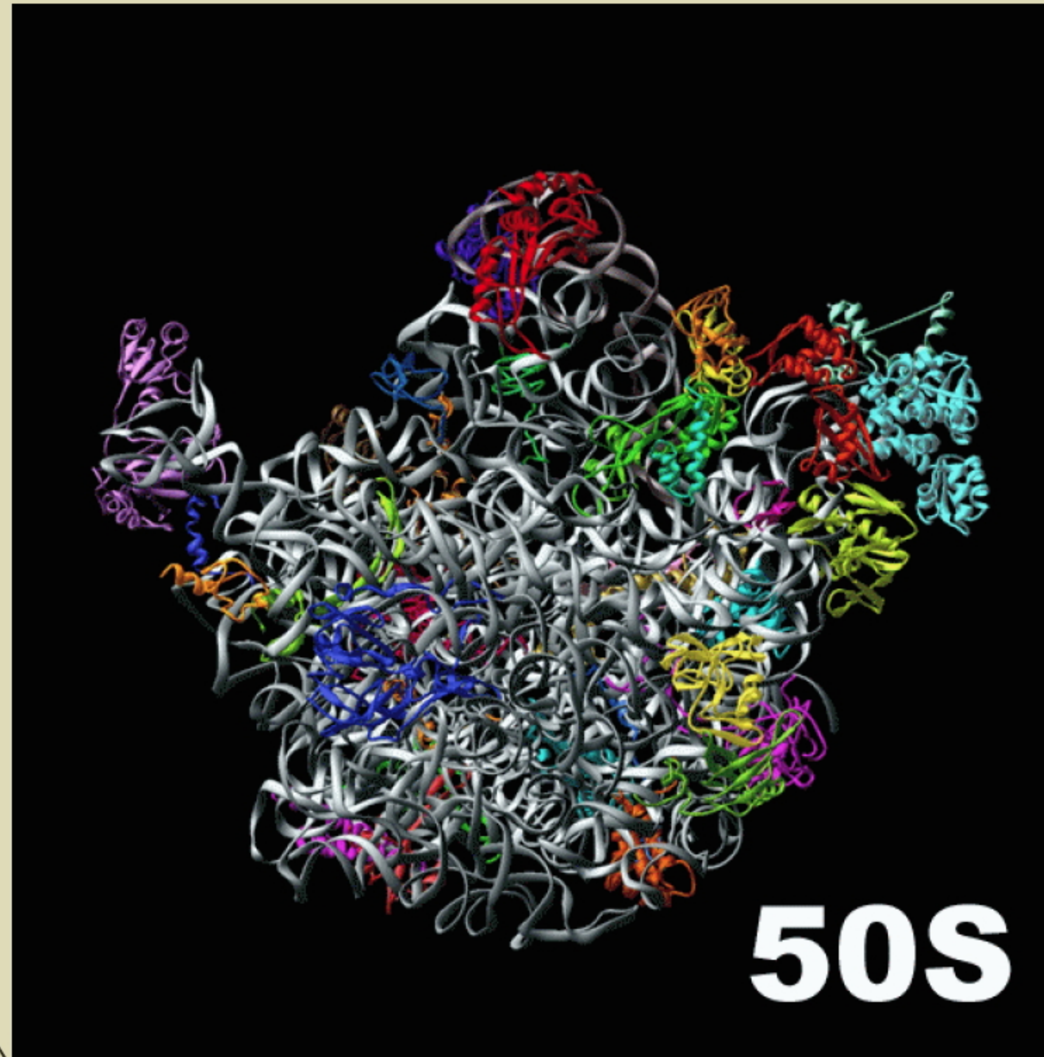
H. Chapman – Lecture on Imaging Molecules with X-ray Free-Electron Lasers - 2012

Peso molecolare:
1kDa = 1000 g mol^{-1}



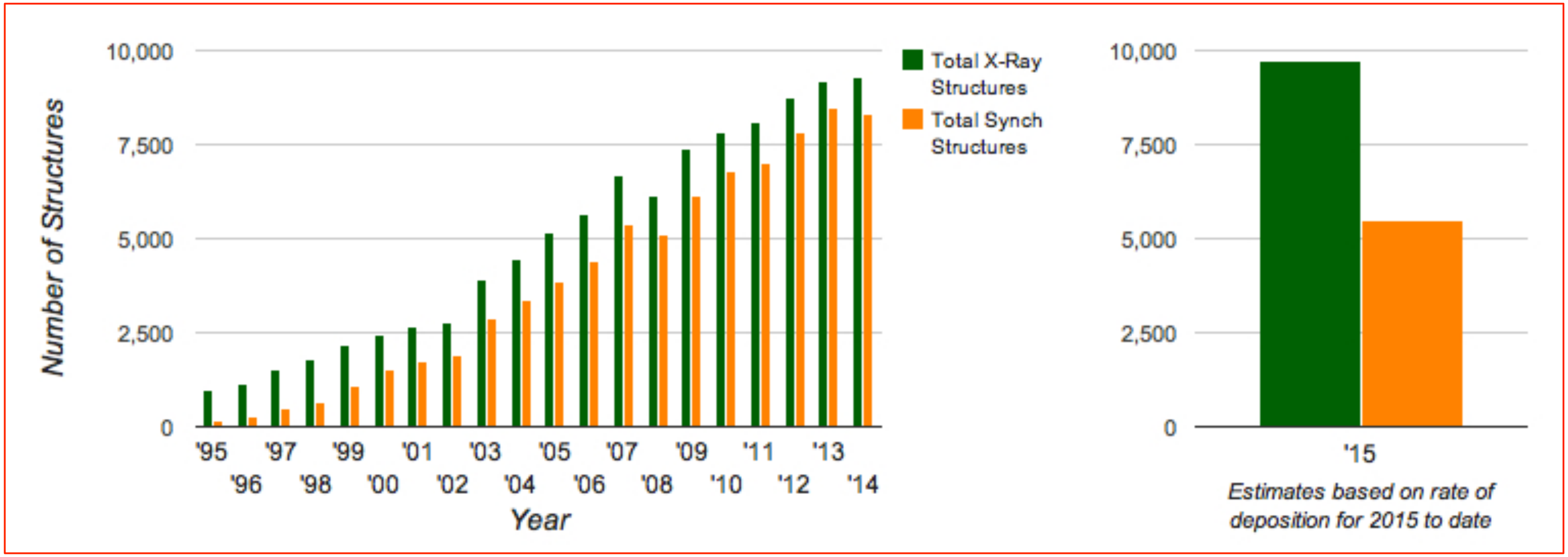
Myoglobin
16 kDa

50 YEARS



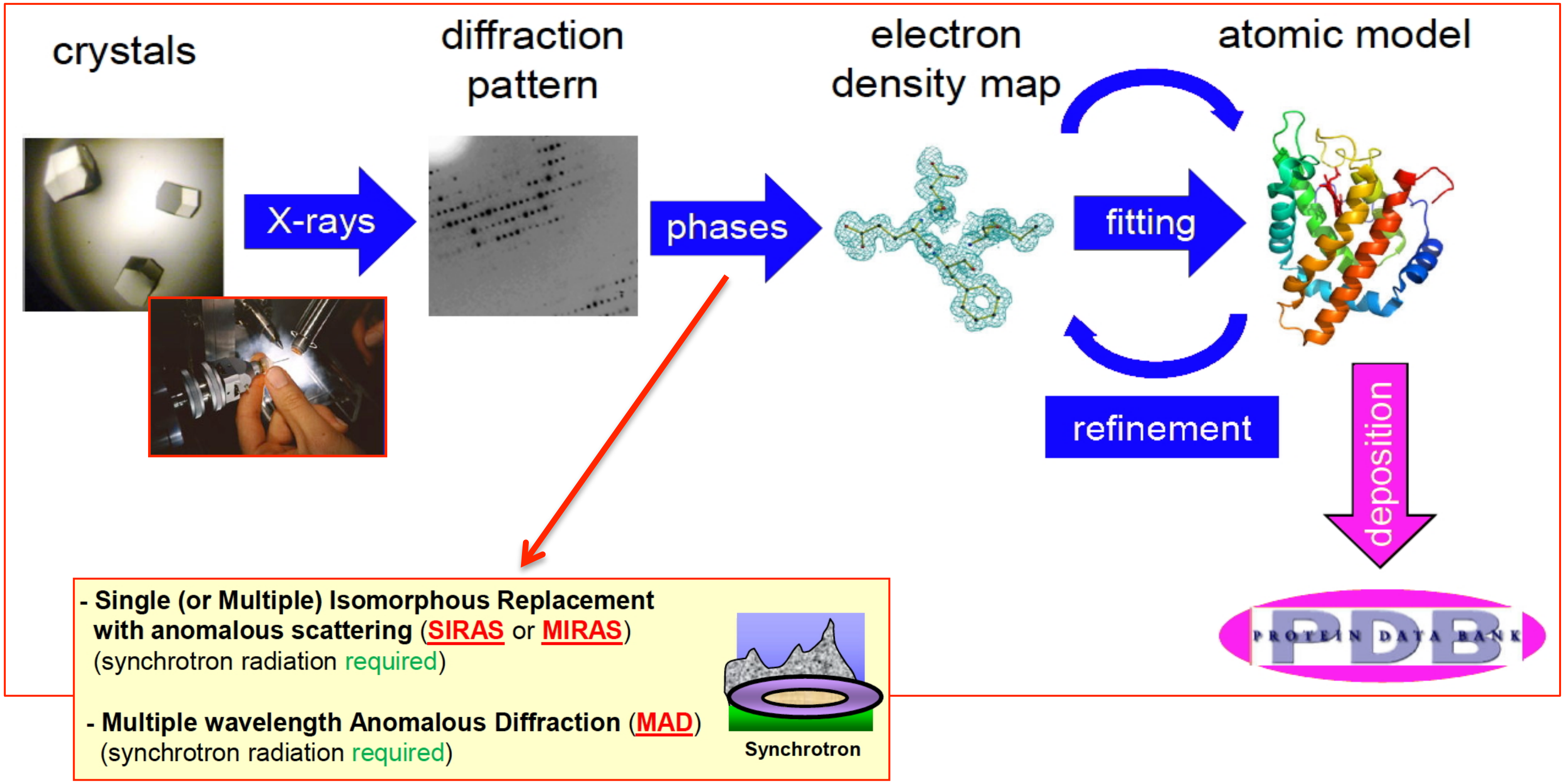
Ribosome 2.5 MDa

X-ray biocrystallography and synchrotron radiation



22 July 2015   http://biosync.sbkb.org/index.jsp

Crystallographic experiment



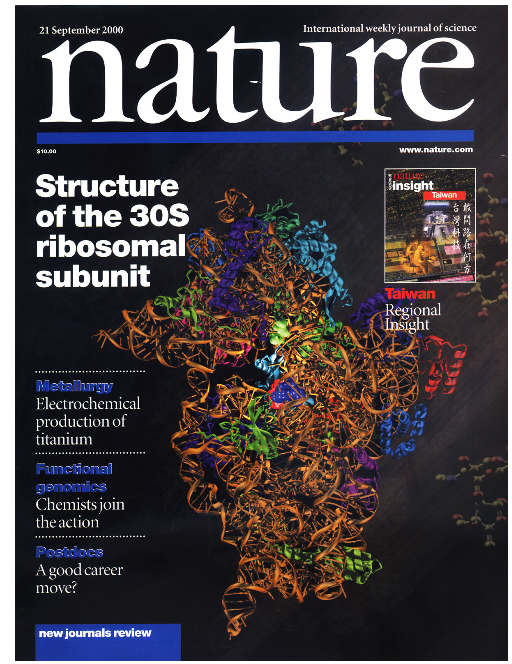
MAD with Se-methionine substituted protein: prerequisites enough Met must be present (one Se-Met can phase about 15 kD of protein)

M. Nardini, Univ. Milano, Lecture on: Synchrotron Radiation and Biocrystallography, 2013

Very recent Noble Prizes in Chemistry

2009 "for studies of the structure and function of the ribosome"

Biocrystallography vs. Structural Biology



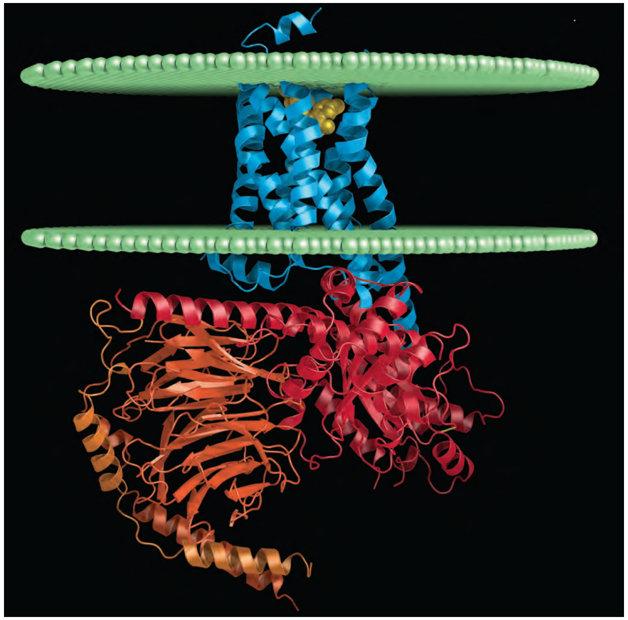
Using Synchrotron radiation Research

An understanding of the ribosome's innermost workings is important for a scientific understanding of life. This knowledge can be put to a practical and immediate use; **many of todays antibiotics cure various diseases by blocking the function of bacterial ribosomes**. Without functional ribosomes, bacteria cannot survive. This is why **ribosomes are such an important target for new and more efficient antibiotics**.

Very recent Noble Prizes in Chemistry

2012 "for studies of G-protein-coupled receptors"

Biocrystallography vs. Structural Biology



G-Protein Coupled Receptor (blue) sits within lipid bilayer (green) to respond to hormone (yellow)- **Image by Wayne Decatur** - http://www.hhmi.org/bulletin/winter2013/features/index.html

Using Synchrotron radiation Research

G protein coupled receptors (GPCRs) represent ***the largest family of membrane proteins*** (about 800 different proteins) ***controlling body functions***, ***drug transit across membranes*** and representing the richest source of targets for the pharmaceutical industry.

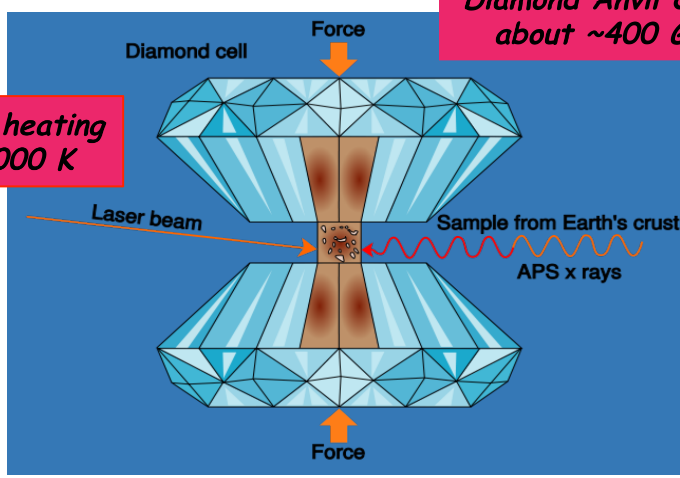
X-ray crystallography and extreme conditions

X-ray crystallography and extreme conditions (P,T) : new opportunities

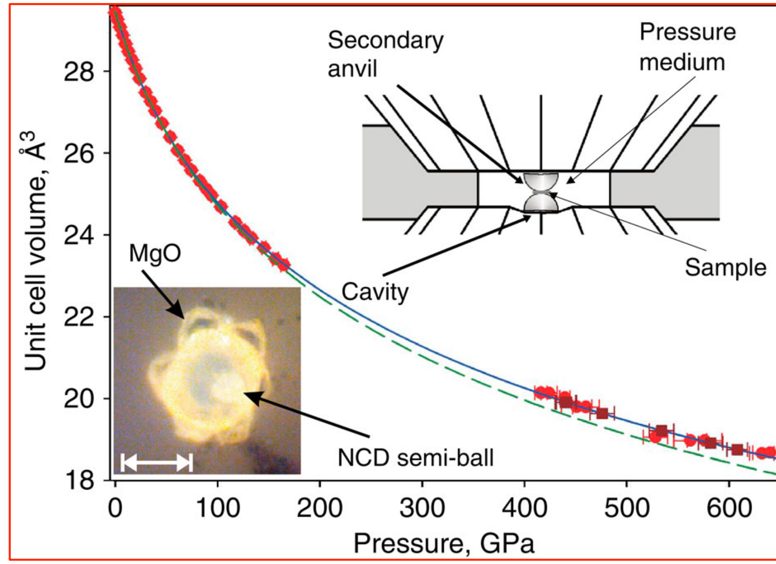
P. W. Bridgman (Nobel Prize in Physics in 1946 – discoveries made in the field of high pressure physics)- ***"Compression offers a route to breaking down the electronic structure of the atoms themselves and to the possibility of creating entirely different bulk properties".***

Diamond Anvil Cell (DAC) about ~400 GPa, RT

Laser heating ~ 7000 K



100GPa=1Mbar



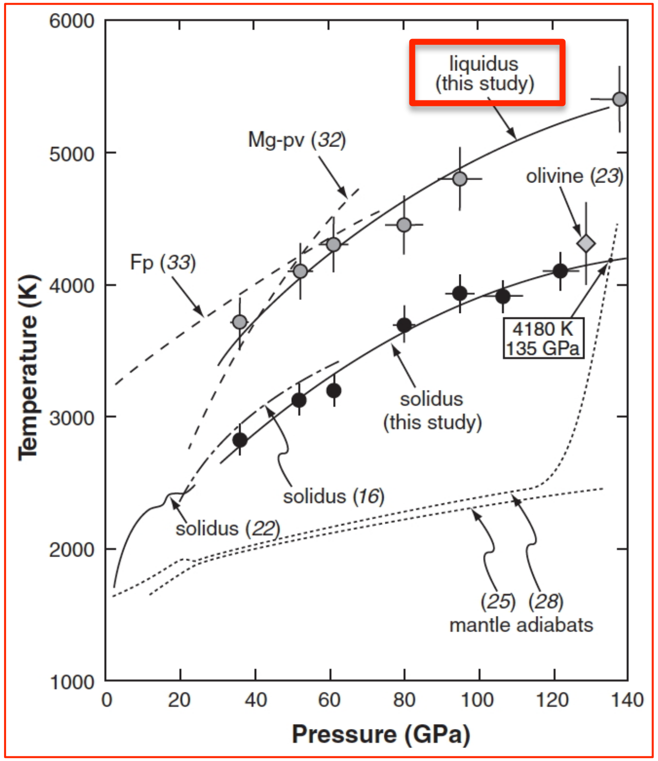
New system to increase Pressure

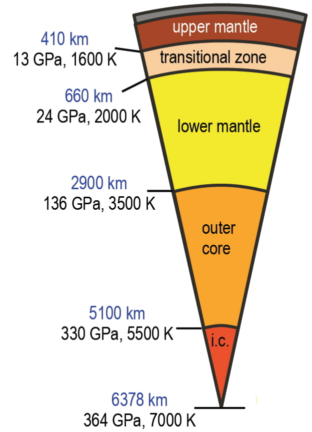
L. Dubrovinsky et al. *Implementation of micro-ball nano-diamond anvils for high-pressure studies above 6 Mbar* - **Nature Comm. (2012)**

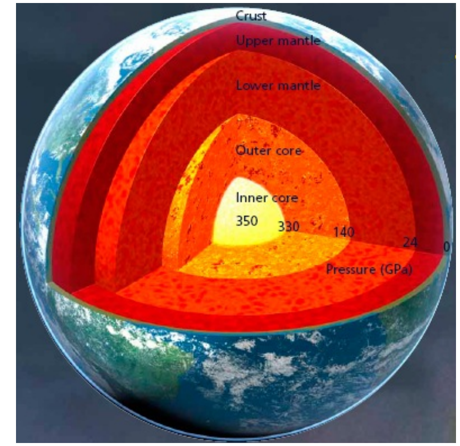
Application fields:
- **Earth and Planetary Science**
- **Condensed Matter Physics**
- **Chemistry and Materials Science**
- **Biology and Soft Matter**

- **Novel transformations: solids, liquids, glasses**
- **Structures: unexpected complexity**
- **Molecules break down, but new ones form**
- **Novel electronic and magnetic phenomena**
- **New chemical reactions: low to high pressure**
- **New recoverable materials**

Extreme conditions (P,T)

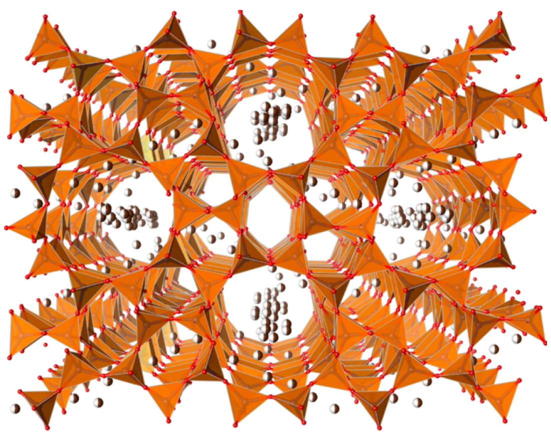






Melting of Peridotite (Olivine and iron-magnesium silicates)
First direct evidence (ESRF ID27) that the ***layer located at the bottom of the Earth's mantle*** (2900 km depth) ***contains partially molten minerals.*** This result supports the existence of a deep magmatic ocean. (**P: 36 –140 GPa T:2500-5000 K**)

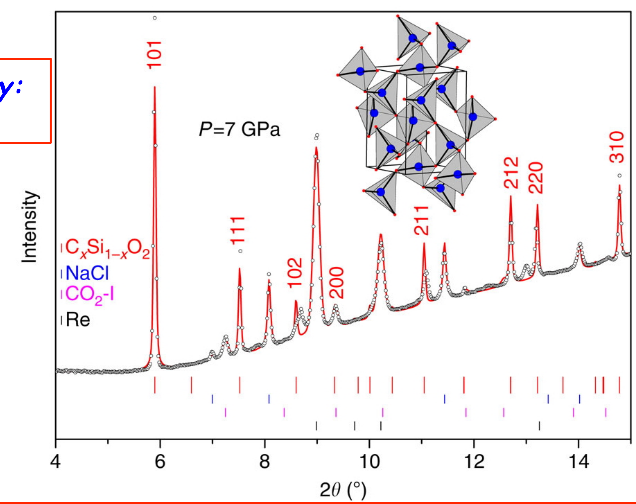
G. Fiquet, et al. *Melting of Peridotite to 140 GPa* **Science (2010)**



New materials: conducting polymers

D. Scelta et al. *High Pressure Polymerization in a Confined Space: Conjugated Chain/Zeolite Nanocomposites.* ***Chem. Mater. (2014)***

New oxide chemisty:
$C_{0.6(1)}Si_{0.4(1)}O_2$



M. Santoro et al. *Carbon enters silica forming a cristobalite-type CO_2–SiO_2 solid solution,* ***Nature Comm. (2014)***

Conclusions

- Synchrotron radiation has surely revolutionized many research fields.
- There are many SR facilities in the world and new ones are being built.
- Synchrotron radiation gives to many applications also a very bright future.

INTERNATIONAL
YEAR OF LIGHT
2015

Thank you for your attention

DAΦNE Light
Synchrotron Radiation Facility

References

1. **Koch, E. E., Eastman, D. E., Farges, Y.**: Synchrotron radiation - a powerful tool in science. In: Koch E.E. (ed.) Handbook of Synchrotron Radiation, pp. 1-63. North-Holland Publishing Company, Amsterdam (1983)
2. **Lightsources of the World**: http://www.lightsources.org/regions
3. **Mills, D.M.** et al.: Report of the Working Group on Synchrotron Radiation Nomenclature Brightness, spectral brightness or brilliance? J. Synchrotron Rad. 12, 385 (2005)
4. **Winick, H.**: Synchrotron Radiation Sources - Present Capabilities and Future Directions. J. Synchrotron Rad. 5, 168–175 (1998)
5. **Schwinger, J.**: On the Classical Radiation of Accelerated Electrons. Phys. Rev. 75, 1912–1925 (1949)
6. **Tomboulian, D. H. and Hartman, P.L.** : Spectral and Angular Distribution of Ultraviolet Radiation from the 300-Mev Cornell Synchrotron. Phys. Rev. 102, 1423–1447 (1956)
7. **Raoux, D.**: Introduction to synchrotron radiation and to the physics of storage rings. In J. Baruchel et al. (eds) Neutron and synchrotron radiation for condensed matter studies, pp. 37-78. Les Editions de Physique - Springer - Verlag (1993)
8. **Duke,P. J.**: Synchrotron Radiation Sources. In Michette, A.G. and Buckley, C.J. (eds.) X- ray Science and Technology, pp. 64-109. Institute of Physics Publishing-London (1993)
9. **Green,G. K.**: Spectra and Optics of Synchrotron Radiation, Report BNL 50522 : Particle Accelerators and High-Voltage Machine-TID 4500 pp. 1-63 Brookhaven National Lab. (1976)
10. **Materlik, G.**: Properties of synchrotron radiation. In Stuhrmann H.B. (ed.) Uses of Synchrotron Radiation in Biology, pp. 1-21. Academic Press Inc. -London (1982)
11. **Krinsky,S., Perlman, M.L., Watson, R.E.**: Characteristics of synchrotron radiation and of its sources. In: Koch E.E. (ed.) Handbook of Synchrotron Radiation, pp. 65-171. North-Holland Publishing Company, Amsterdam (1983)
12. **LeeW-K., Fernandez P., Mills D. M.** : X-ray crystal optics. In Onuki H. and Elleaume P. (eds) Undulators, Wigglers and their Applications, pp. 369-420. Taylor & Francis - London (2003)
13. **Willmott P.**:An Introduction to Synchrotron Radiation- Techniques and Applications, J. Wiley and Sons, 2011
14. **Boge M. et al.**: The Swiss Light Source Accelerator Complex: An Overview. http://accelconf.web.cern.ch/Accelconf/e98/PAPERS/MOP28G.PDF
15. **X-ray data booklet,** Center for X-ray Optics and Advanced Light Source, Lawrence Berkeley National Laboratory , http://xdb.lbl.gov/

Supplementary material- f.y.k.

Reminder

• *Speed of light*	$c = 2.99792458 \times 10^8$ m/s
• *Electron charge*	$e = 1.6021 \times 10^{-19}$ Coulombs
• *Electron volts*	1 eV $= 1.6021 \times 10^{-19}$ Joule
• *Energy and rest mass*	$1 eV/c^2 = 1.78 \times 10^{-36}$ kg
Electron	$m_0 = 511.0$ keV$/c^2 = 9.109 \times 10^{-31}$ kg
Proton	$m_0 = 938.3$ MeV$/c^2 = 1.673 \times 10^{-27}$ kg
• *Relativistic energy, E*	$E = mc^2 = m_0 \gamma c^2$
• *Lorentz factor,* γ	$\gamma = 1/[(1-v^2/c^2)^{1/2}] = 1/[(1-\beta^2)^{1/2}]$ $\beta = v/c$
• *Relativistic momentum, p*	$p = mv = m_0 \gamma \beta c$
• *E-p relationship*	$E^2/c^2 = p^2 + m_0 c^2$
for ultra-relativistic particles	$\beta \approx 1$, $E = pc$
• *Kinetic energy*	$T = E - m_0 c^2 = m_0 c^2 (\gamma - 1)$

X-rays discovery

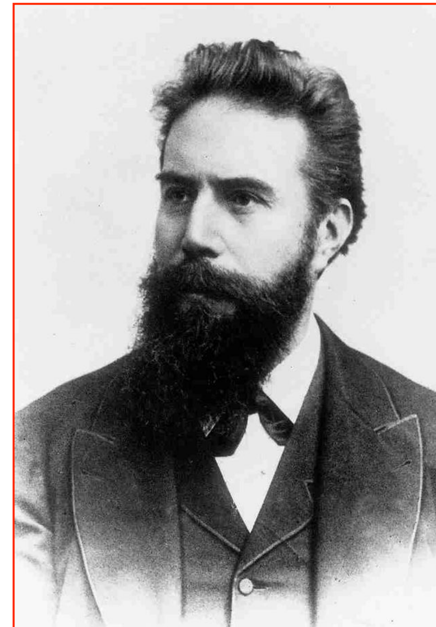

EINE NEUE ART
VON
STRAHLEN.

Von
DR W. RÖNTGEN,
O. O. PROFESSOR AN DER K. UNIVERSITÄT WÜRZBURG.

WÜRZBURG.
VERLAG UND DRUCK DER STAHEL'SCHEN K. HOF- UND UNIVERSITÄTS-
BUCH- UND KUNSTHANDLUNG.
Ende 1895.
60 ₰.

On a New Kind of Rays

While ***Wilhelm Roentgen*** was working on the effects of ***cathode rays*** during ***1895***, he discovered X-rays. His experiments involved the passing of electric current through gases at extremely low pressure. On **November 8, 1895** he observed that certain rays were emitted during the passing of the current through discharge tube. His experiment that involved working in a totally dark room with a well covered discharge tube resulted in the **emission of rays which illuminated a barium platinocyanide screen**. ***The screen became fluorescent even though it was placed two meters away from discharge tube***.



Wilhelm Conrad Roentgen

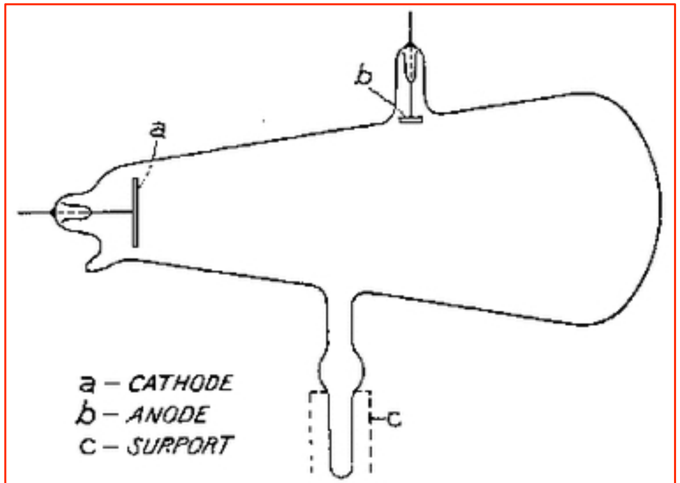
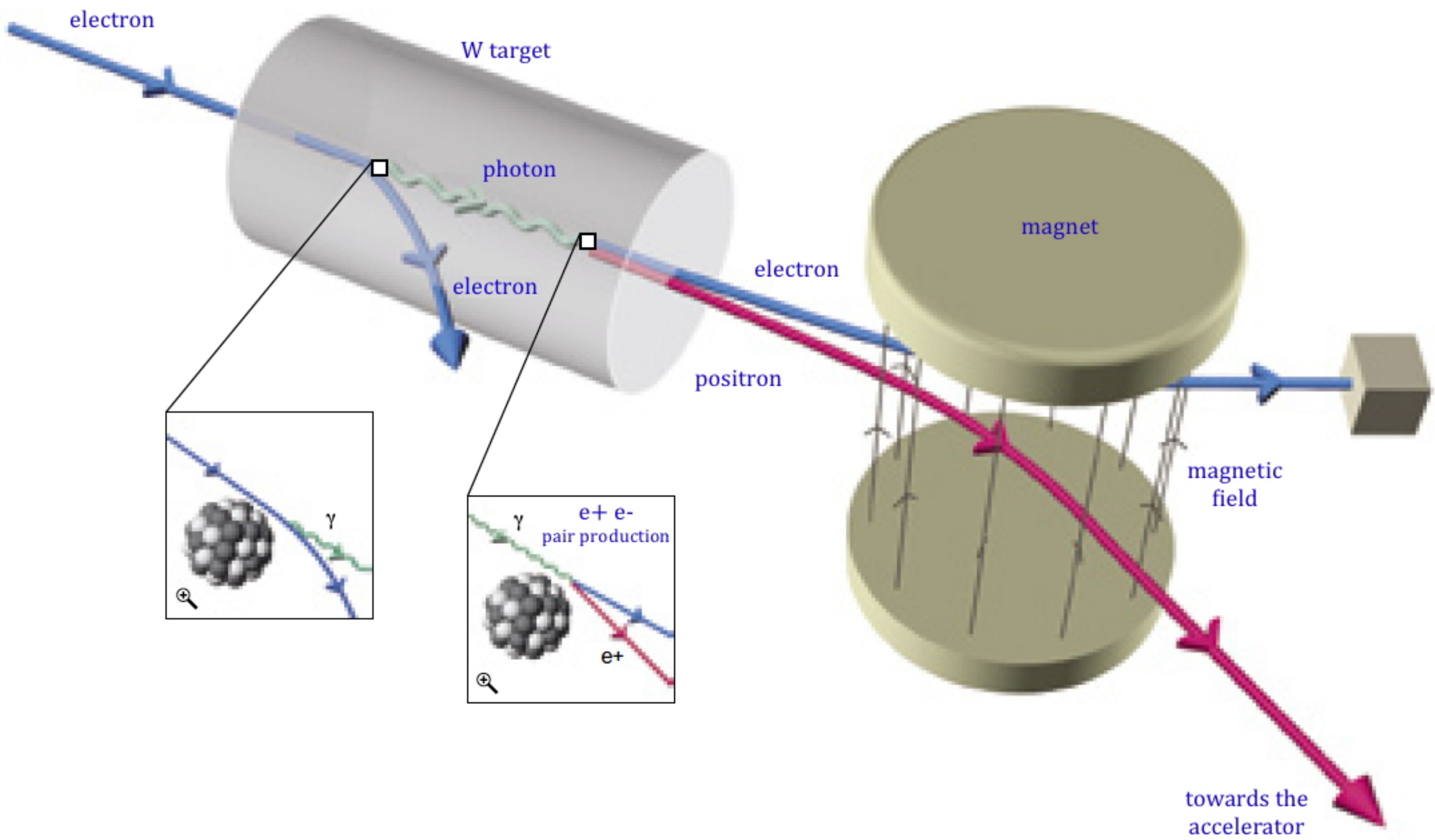


Fig. 1. Earliest type of roentgen tube.

Gas tube: electrons are freed from a **cold cathode by positive ion bombardment, thus necessitating a certain gas pressure.**

He continued his experiments using **photographic plates** and generated the very ***first "roentgenogram"*** by developing the image of ***his wife's hand*** and analyzed the variable transparency as showed by her bones, flesh and her wedding ring.

Anti-matter positron production



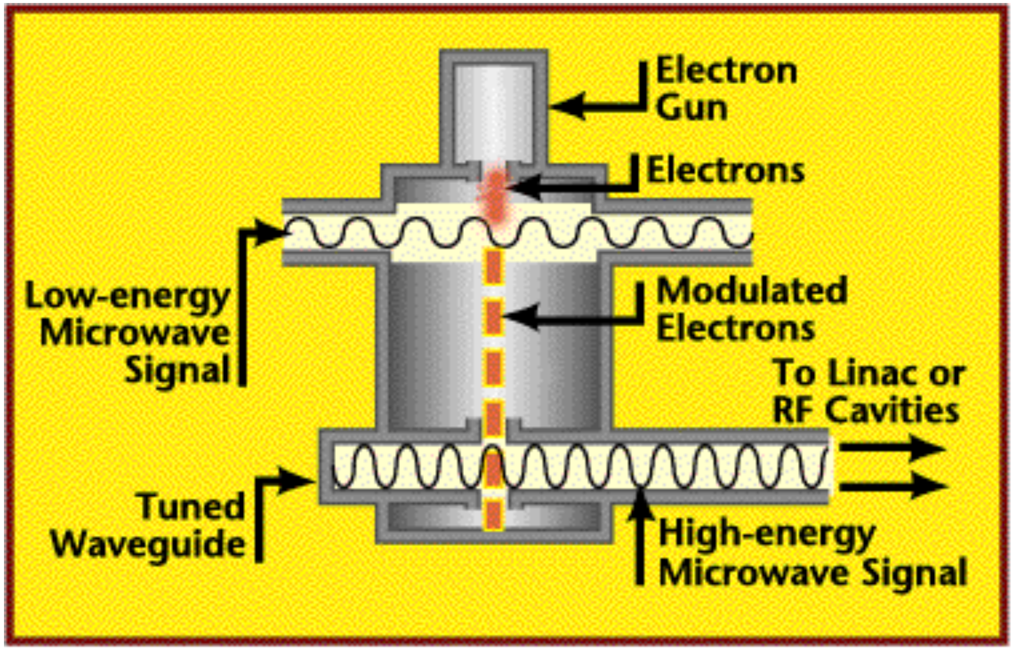
M. Calvetti, *Antiparticelle accelerate*, ***Asimmetrie*** 7, 16-21 (***2008***)

RF system

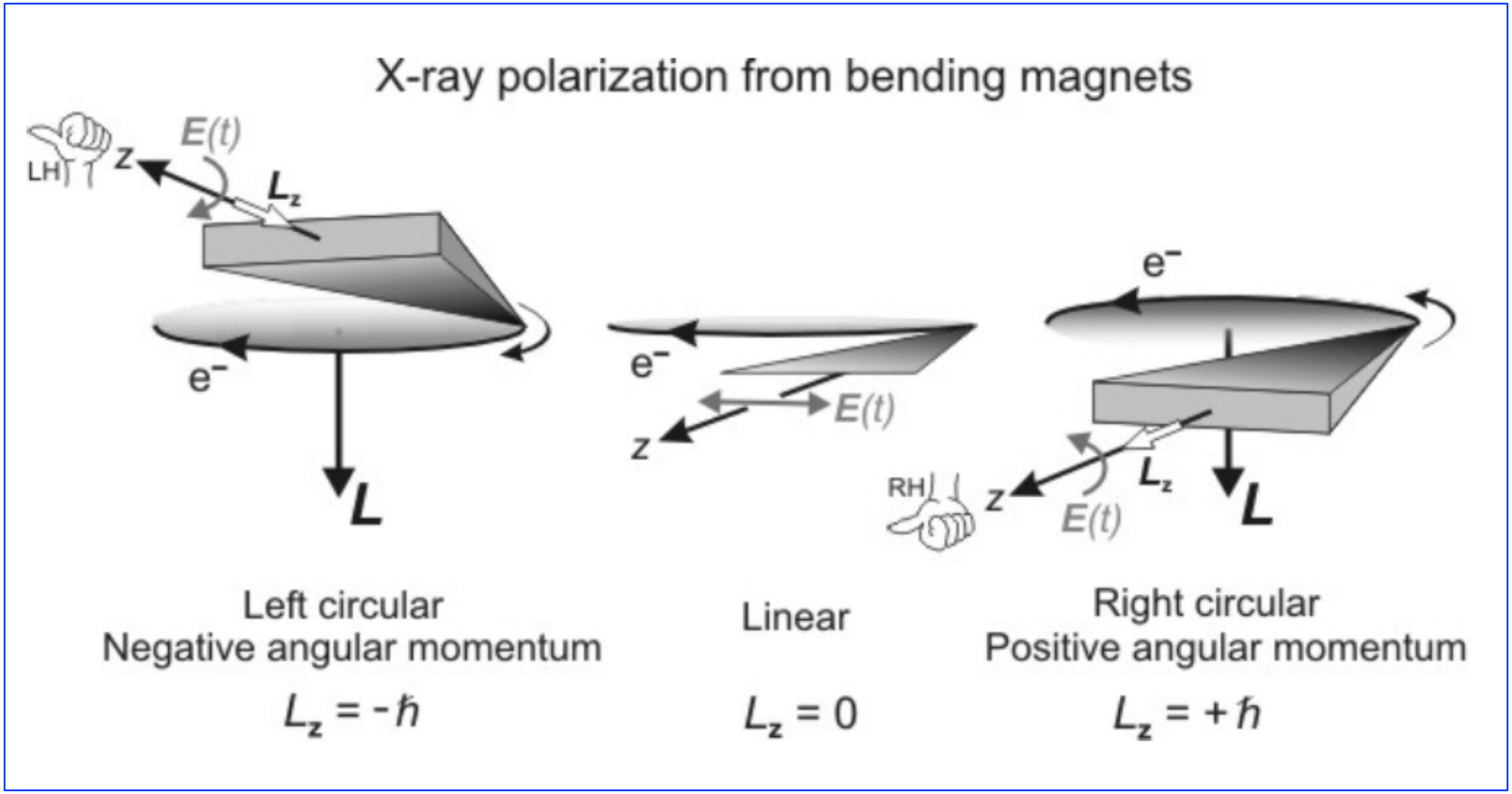
The basic components of the RF system include: **Klystrons, Waveguides and RF Cavities**

A **klystron is a very powerful type of microwave amplifier** that works on the following way:

1. An **electron gun** produces an intense flow of electrons into the klystron.
2. A **low-energy microwave signal** intersects this continuous electron beam, breaking it up into a pulsed beam consisting of separate "bunches" of electrons.
3. The pulsed electron beam passes through a **tuned waveguide**, inducing a **powerful high-energy microwave signal**.
4. High-energy microwave power travels along the waveguide to the linac, booster synchrotron, or storage ring, where it passes its energy to electrons, accelerating them to relativistic velocity.



Polarization and angular momentum L



J. Stöhr, H. C.Siegmann, Magnetism – from fundamentals to nanoscale dynamics, Springer, 2006

Undulator Brightness

Brightness is the main figure of merit of synchrotron radiation sources and its huge increase, was obtained designing low emittance machines, minimizing the source size and the beam divergence.

$$\text{Brightness} = \frac{\text{Flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

Source horizontal size

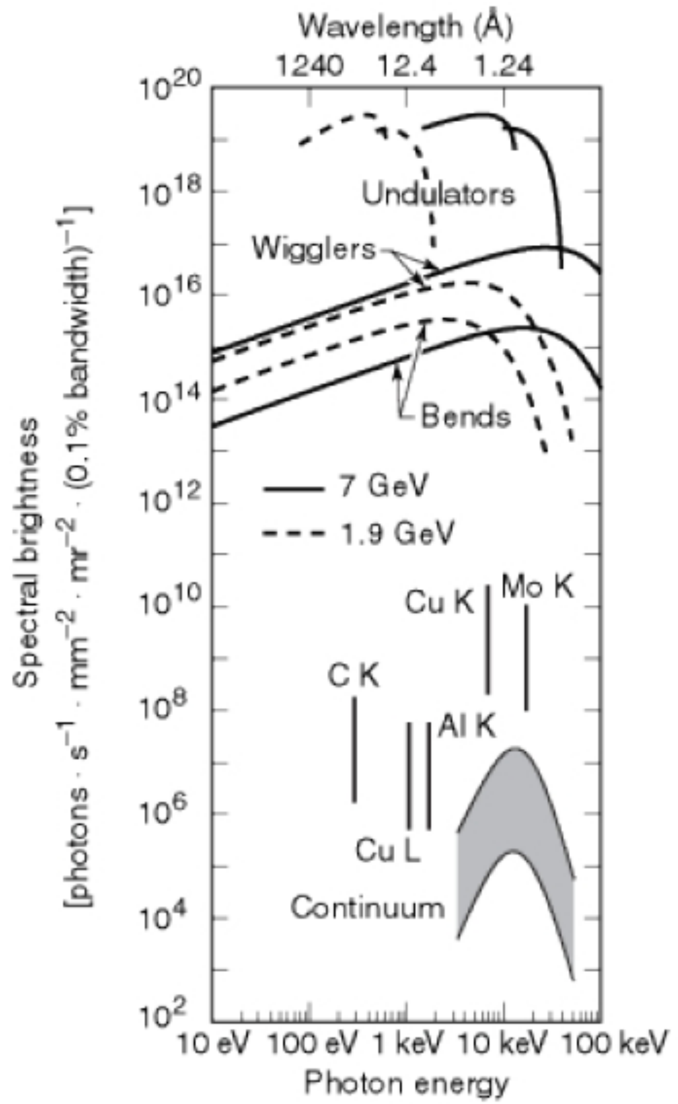
$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2}$$

Source horizontal divergence

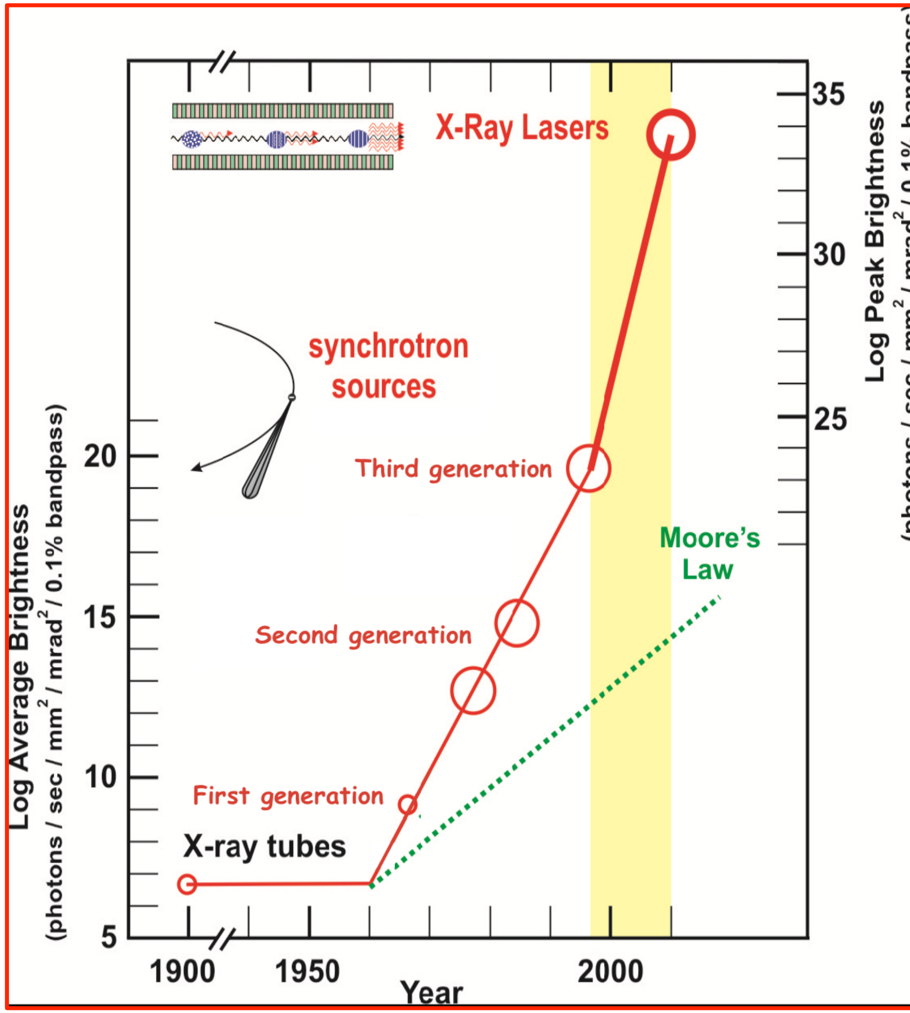
$$\Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma'^2_{ph,e}}$$

The brightness of an undulator is approximated by dividing ***the central cone flux*** by the ***effective angular divergence*** and by the ***effective source size in the horizontal (vertical) directions.*** These are given by ***convolution of the Gaussian distributions*** of the ***electron beam and the diffraction limited photon beam, in both space and angle.***

Brightness



X-ray data booklet, http://xdb.lbl.gov/

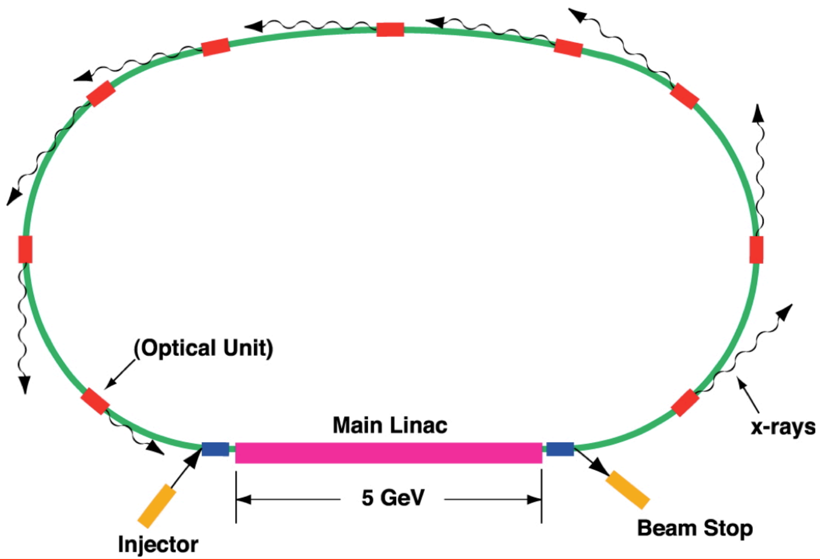


The dramatic improvement of brightness over 60 years easily outran Moore's law.

Z. Huang - Brightness and Coherence of Synchrotron Radiation and Free Electron Lasers – IPAC 2013

ERL or Energy Recovery Linac

Energy Recovery Linac (ERL)



***ERL as synchrotron light source**: 10 MeV electrons are injected into a few hundred meter long superconducting LINAC and brought to full energy. The electrons are then guided around a one-turn arc made, for example, of triple bend achromat (TBA- optical units) magnets with undulators producing the X rays. The electrons have a path length such that they return out of phase with the LINAC and their energy is recovered before being steered to the dump at an energy of about 10 MeV by another weak field magnet.*

ERLS and XFELS are both based on LINAC technology, both will optimally utilize long undulators and both will deliver short bunches. How do these two synchrotron radiation sources differ?

Source Type	*ESRF Storage Ring*	*UHXS Storage Ring*	*Cornell ERL*	*LCLS SASE FEL*	*TESLA SASE FEL*
Electron Energy [GeV]	6	7	5.3	15	25
Average Current [mA]	200	500	100	7.20E-5	0.063
Hor. Emittance [nm]	4	0.2	0.15	0.05	0.02
Vert. Emittance [nm]	0.01	0.005	0.15	0.05	0.02
FWHM Bunch Length [ps]	35	13	0.3	0.23	0.09
Undulator Length [m]	5	7	25	100	200
Fundamental [keV]	8	12	8	10	12.4
Average Flux [Ph/s/.1%]	1.3E+15	2.0E+16	1.5E+16	2.4E+14	4.0E+17
Average Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.1E+20	3.5E+22	1.3E+22	4.2E+22	8.0E+25
Peak Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.3E+22	1.0E+25	3.0E+25	1.2E+33	7.0E+33

The performance of an energy recovery LINAC falls between a storage ring and a FEL.

*P. Elleaume, **The Ultimate Hard X-Ray Storage-Ring-Based Light Source (UHXS)**, 2002*

X-Ray Light Source Comparison

Parameter	Storage Rings	FEL	ERL
Wavelength Range	+	+	+
Peak Brightness		+	~
Pulse Structure	CW	Pulsed/Burst CW in future	CW
fs Pulse Width		+	~
Coherence	~	+	~
Stability	+		+
Number of Beamlines	+		+

P. S. Drell, Status of International Light Sources: Today and in the Near Future, BESAC 2013
http://science.energy.gov/bes/besac/meetings/meeting-presentations/)