Introduction to Synchrotron Radiation

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INFN – Frascati National Laboratory – LTL 2014

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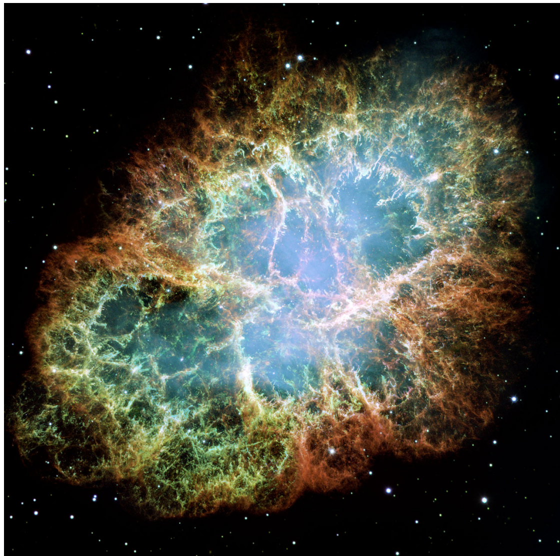
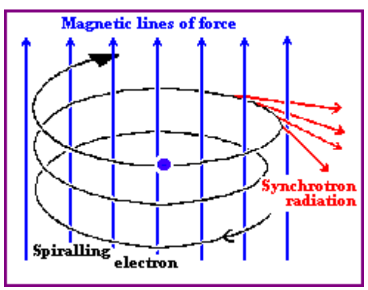
Answers to be given!

- What is synchrotron radiation?
- How is it produced?
- History?
- Present? Future?
- Properties?
- Sources?
- How and why is it used?

Synchrotron radiation 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 !

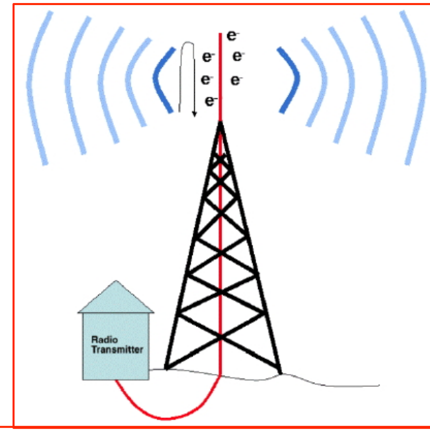
NASA's Great Observatories' View of the Crab Nebula X-Ray-blue: NASA/CXC/J.Hester (ASU); Optical-red and yelllow: NASA/ESA/J.Hester & A.Loll (ASU); Infrared-perple: NASA/JPL-Caltech/R.Gehrz (Univ. Minn.)

In 1953 Iosif Shklovsky proposed that the diffuse blue region is predominantly produced by synchrotron radiation, **which is the radiation emitted by the curving motion of high speed electrons in a magnetic field. In the 1960s it was found that the source of the curved paths of the electrons was the strong magnetic field produced by a spinning neutron star (pulsar) at the center of the nebula.**

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 radiation

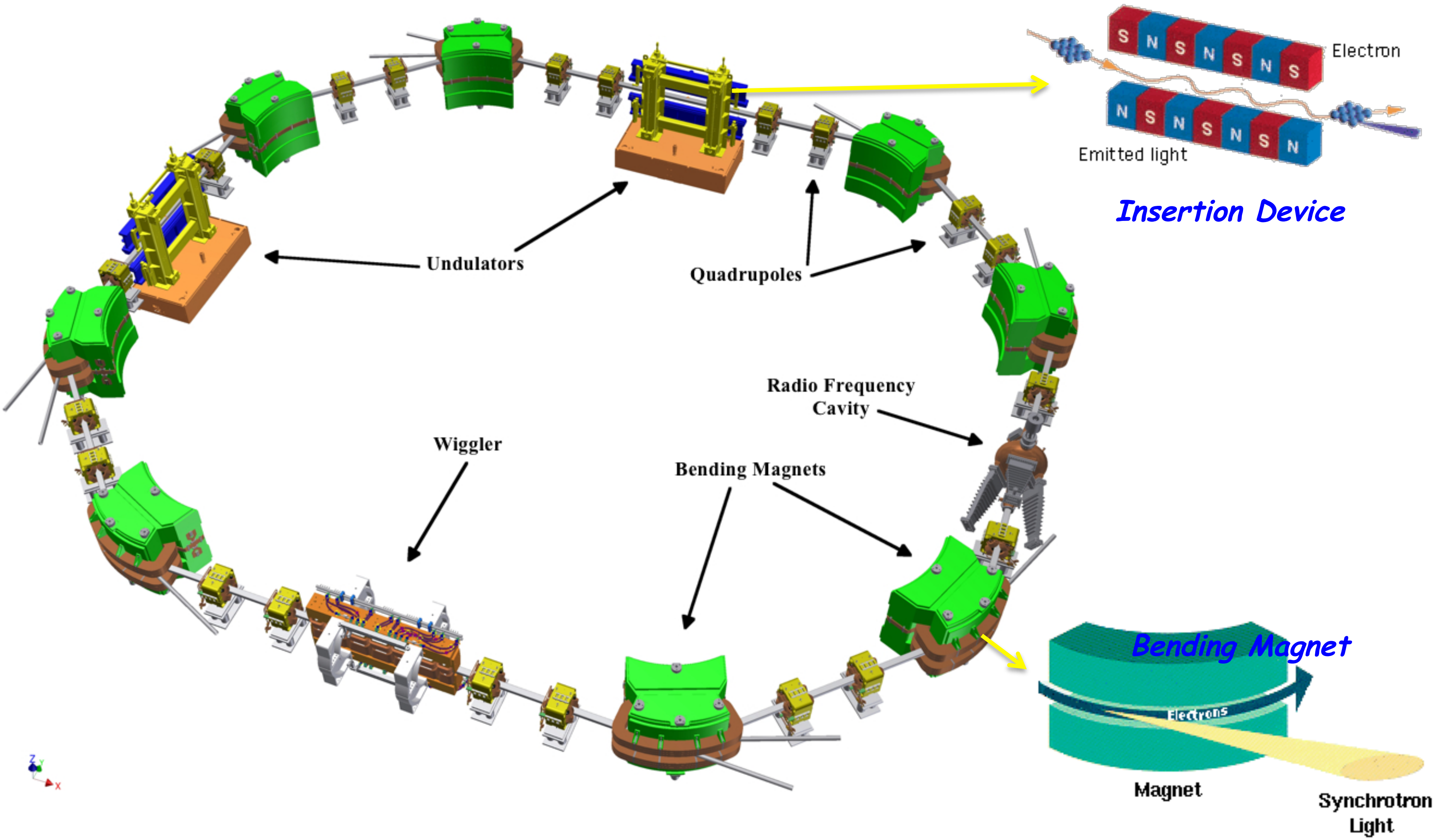
Accelerated charged particle, like e^+, e^- and ions, emit electromagnetic radiation.



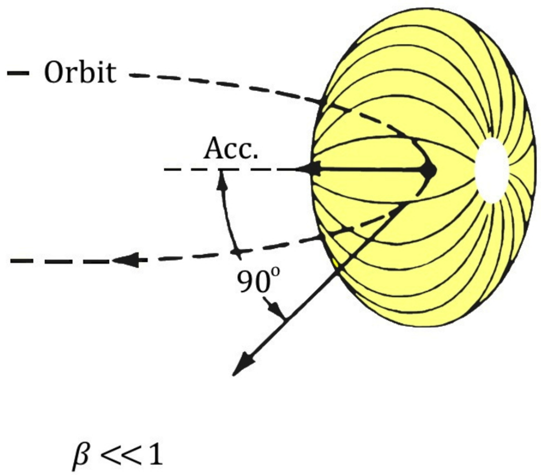
v << c or β = v/c << 1

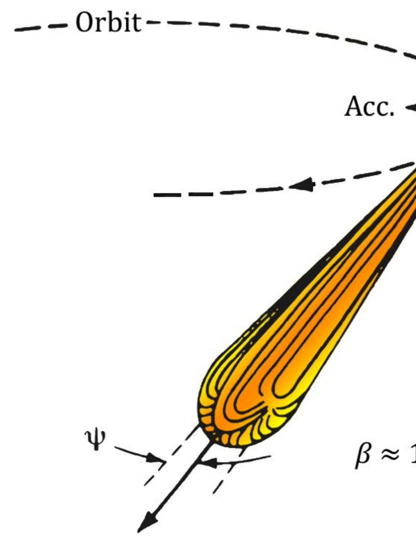
When charged particles, ***moving at relativistic speeds****, are forced to* ***change the direction of their motion (acceleration)****, under the effect of magnetic fields,* ***in circular particle accelerators, like synchrotrons****, the radiation produced is called* ***synchrotron radiation.***

Schematic view of a storage ring



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 *typical dipole pattern*.

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

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:

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

DAΦNE E = 0.511 GeV, ***mc²= 511KeV***

ψ = 1 **mrad** ≈ 0.057° $\gamma = E/mc^2 = 1957\, E\,(GeV)$

Synchrotron radiation: physics

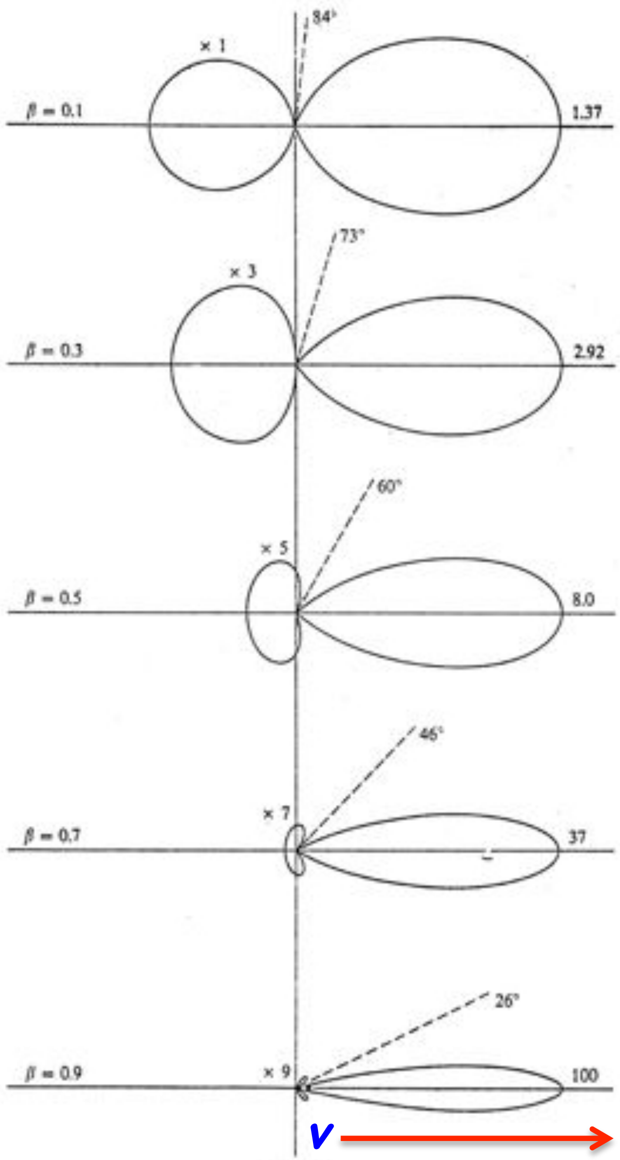


FIG. 7-7

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

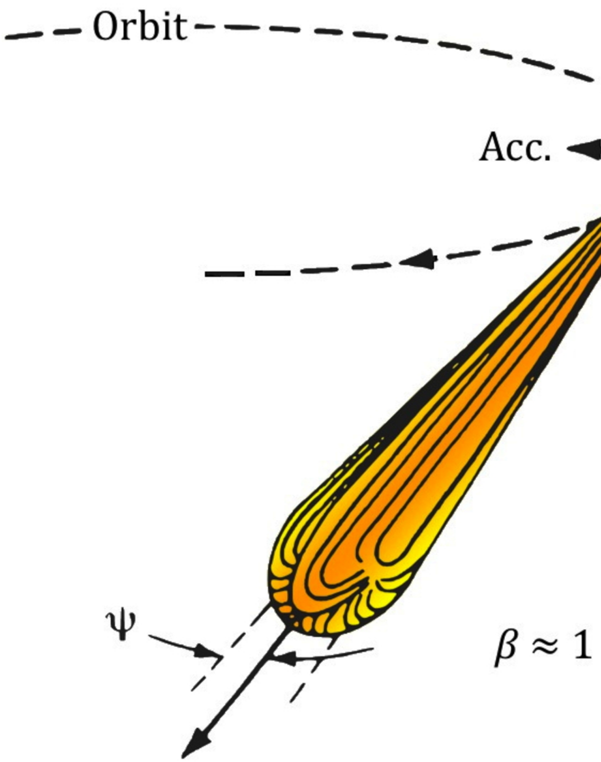
As β approaches 1:

1) The shape of the radiation pattern changes: it is more in the forward direction!
2) the node at θ′ = 90° in the frame of the radiating particle transforms to:

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

v ≈ c or $\beta = v/c \approx 1$

Synchrotron radiation: physics



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

E = particle energy, ***m*** = mass, ***R*** = radius of curvature

1945 Schwinger: classical theory of radiation from accelerated relativistic electrons

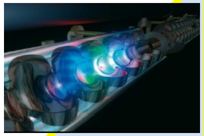
v ≈ c or β = v/c ≈ 1

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]*

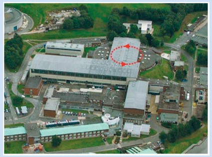
Timeline



4^{th} gen. - LINAC based accelerators
FELs

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

Brightness increase



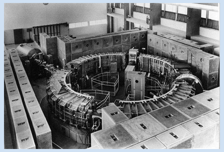
2^{nd} gen. dedicated storage ring SRS (UK)
1981

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

Storage rings development
1960s

ADA - B. Touschek - LNF

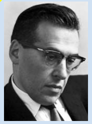
Parasitic use of electro-synchrotrons
1961



First observation of synchrotron radiation
1947

Langmuir, Elder, Gurewitsch, Charlton and Pollock

Proof of concepts, tests of theories
1897-1946

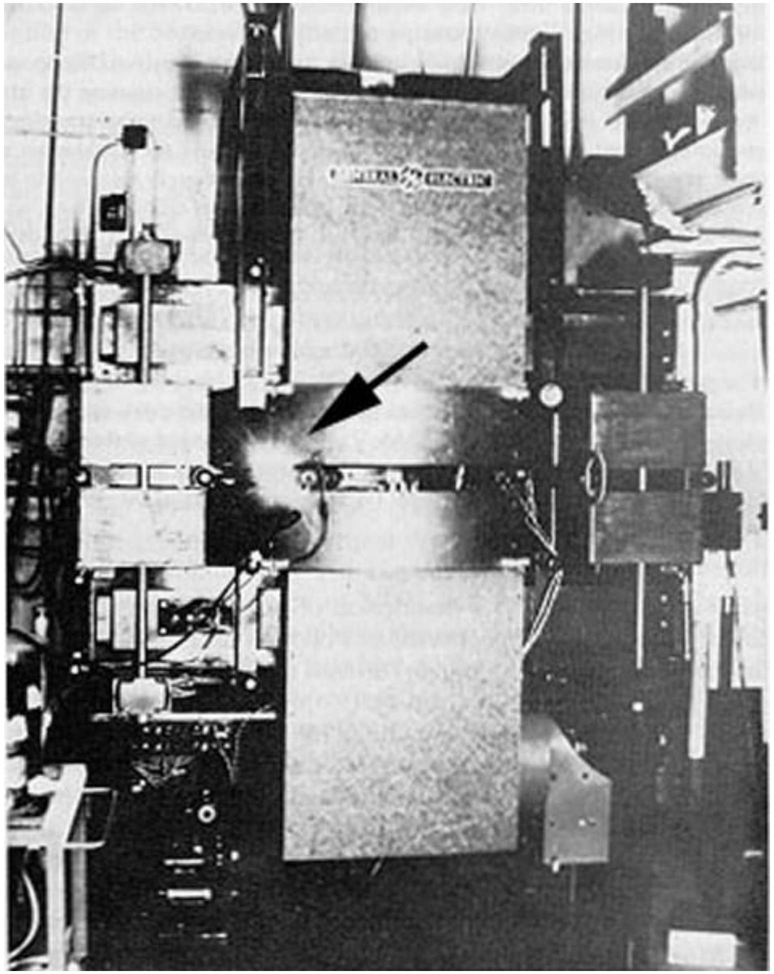


J. Schwinger Nobel Prize 1965 Classical Relativistic quantum field theory

Idea from: **M. Ruffoni**, Let there be light: the History and Evolution of Synchrotron Radiation Sources (1947-2007), **2007**

Synchrotron radiation: history

First generation: parasitic operation and storage rings



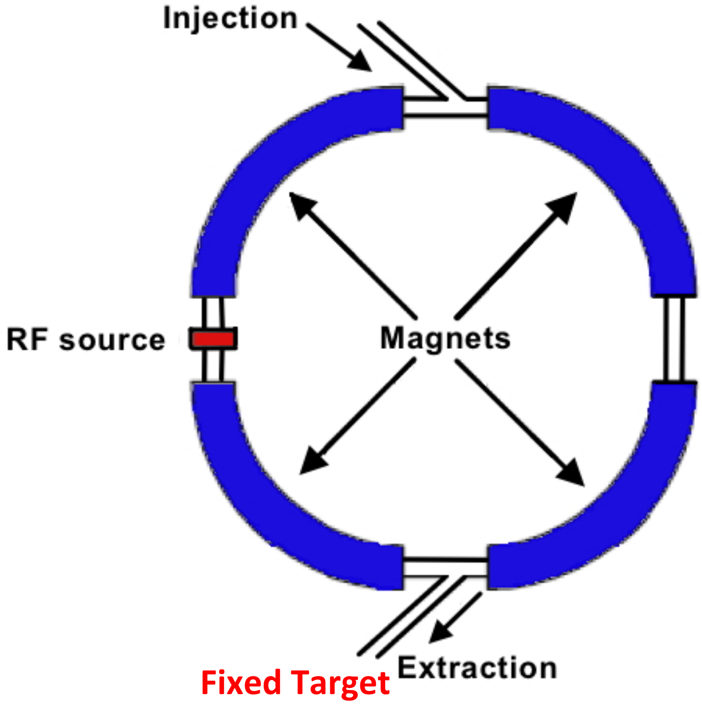
1947 *General Electric Res. Lab.* - 70 MeV Electron Synchrotron – N.Y. USA

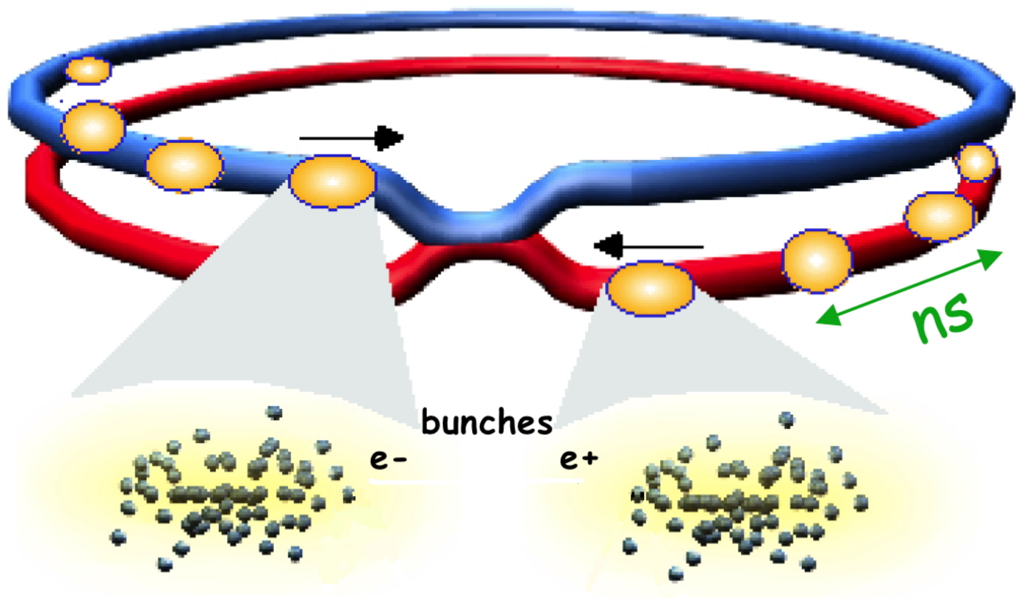
Starting point: Proof of concepts, tests of theories!

- 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. (1976-1993 LNF ADONE 1.5 GeV parasitic/dedicated use for SR experiments PULS/PWA after its use for HE experiments).***

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

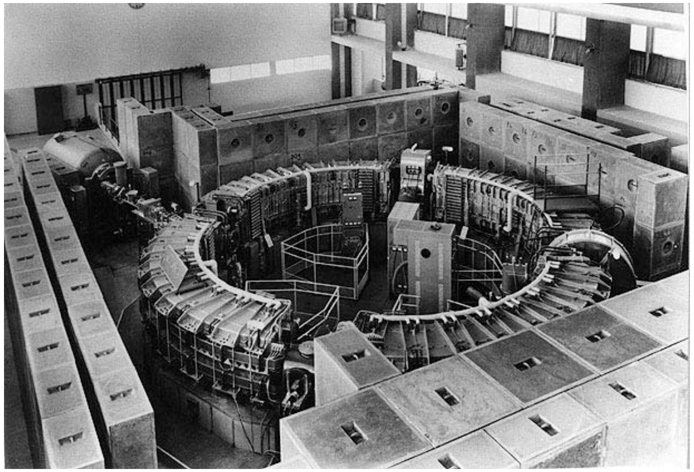
- *Cyclic* - the guiding magnetic field used to bend the particles into a closed path, is time-dependent, being *synchronized* to a particle beam of increasing kinetic energy.
- ***Emitted photon spectrum varies*** as e^- energy changes during each cycle.
- ***Photon intensity varies*** as e^- energy 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

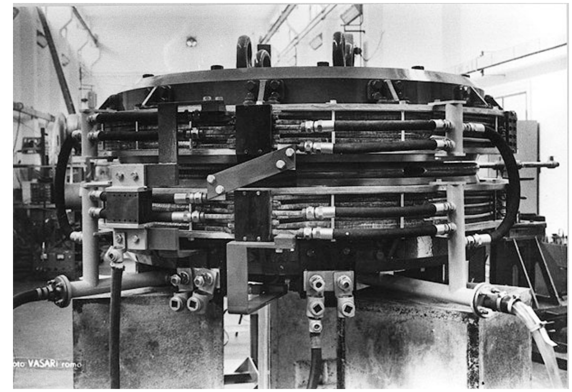
- ***Constant***: as special type of synchrotron in which the kinetic energy of the particles is kept constant.
- ***Emitted photon spectrum constant.***
- ***Photon intensity decays slowly*** over many hours.
- ***Source position constant***- submicron source stability.
- ***High Energy Radiation Background:***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

Frascati: ElettroSincrotrone, 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)

Synchrotron radiation: history
Second generation: dedicated sources

Development of new techniques, and better sources!

SRS storage ring at Daresbury (UK)

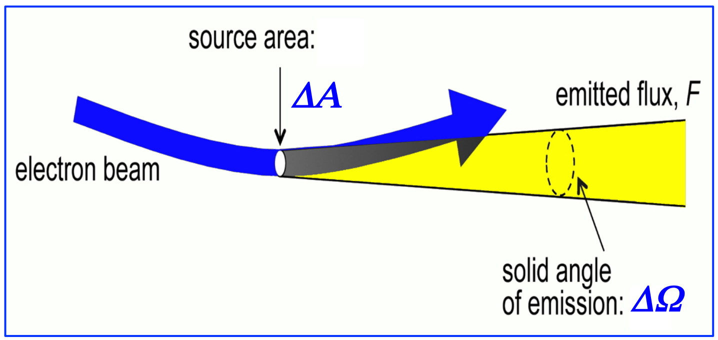
- *First purpose built synchrotron light sources!*
- *SRS (2 GeV) at Daresbury (UK) was the first dedicated machine (1981 – 2008)*
- *First insertion devices (wigglers, undulators) although many were added later*
- *1981 2.5 GeV NSLS, Brookhaven, USA*
- *1982 2.5 GeV 'Photon Factory' KEK, Tsukuba, Japan*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

Increasing brightness

Brightness (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.

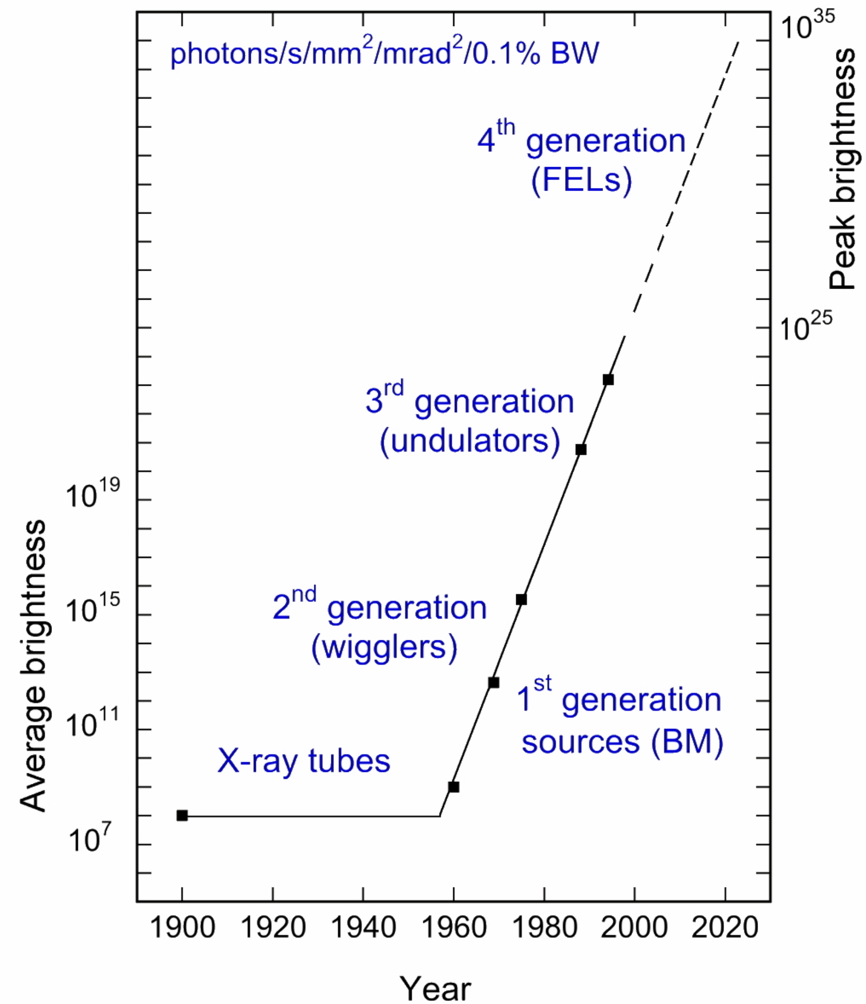
Brightness more important than flux (photons/s).

Brightness = photon flux/ [(ΔA) ($\Delta\Omega$)]



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*** (***vertical*** and ***horizontal emittance).***

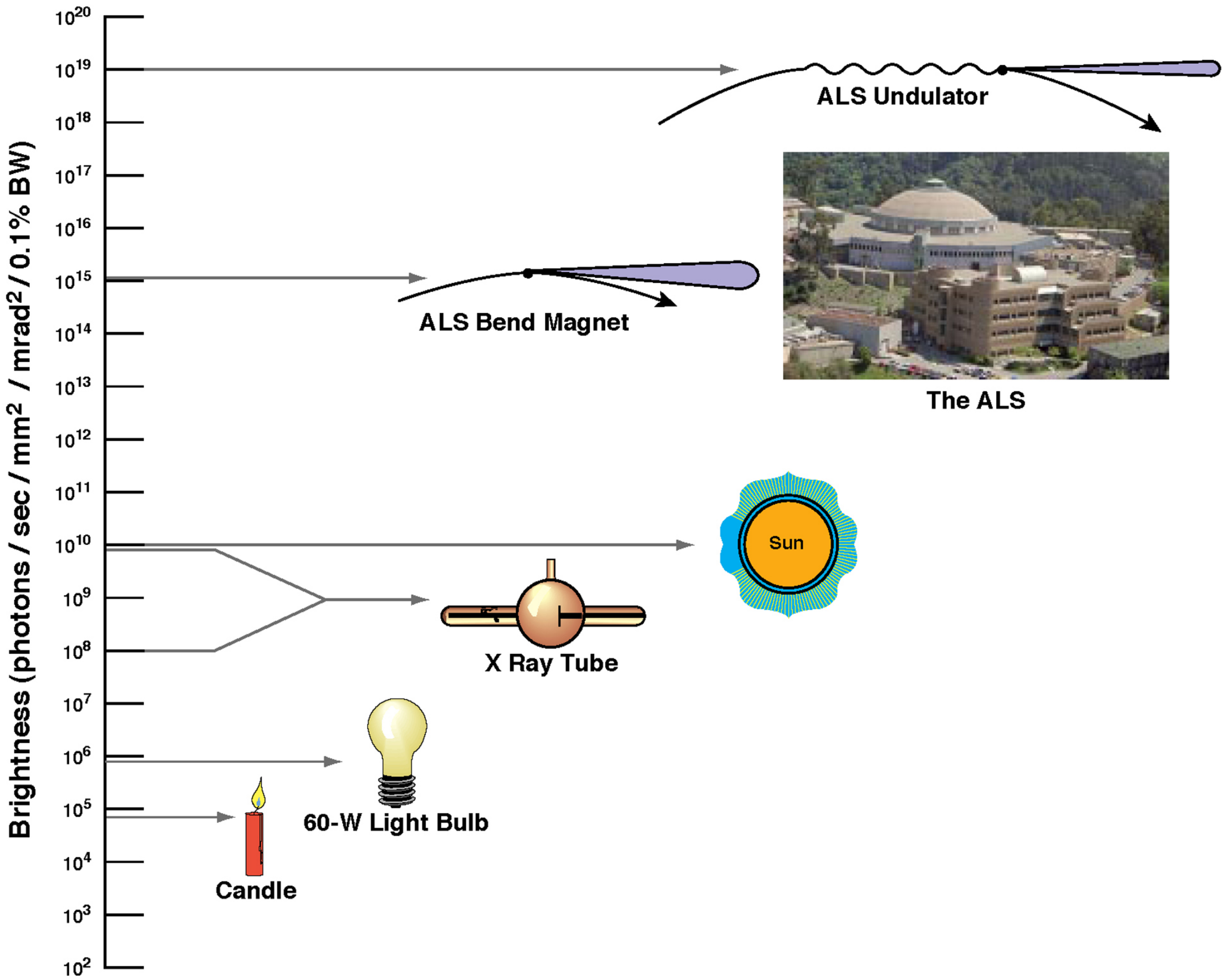
Brightness is the main figure of merit of synchrotron radiation sources and its huge increase, was obtained designing low emittance machines, minimizing the source size and the beam divergence.



Spectral Brightness = photon flux/ [(ΔA) ($\Delta\Omega$) (0.1% BW)]

How Bright Is the Advanced Light Source?

ALS



Synchrotron radiation: history
Third generation: optimized sources

Synchrotron light is now a unique tool for science!

ESRF, Grenoble - France 6 GeV, C = 844m 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.*

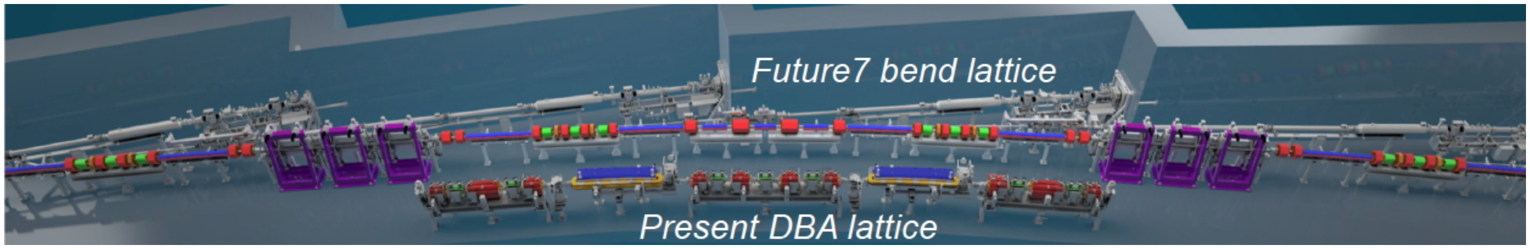
European Synchrotron Radiation Facilities

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

Synchrotron radiation: history

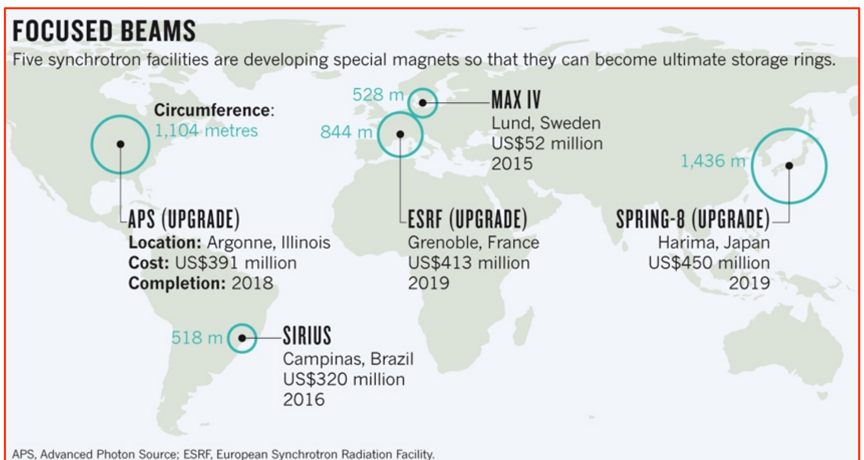
Future : Ultimate Storage Rings

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

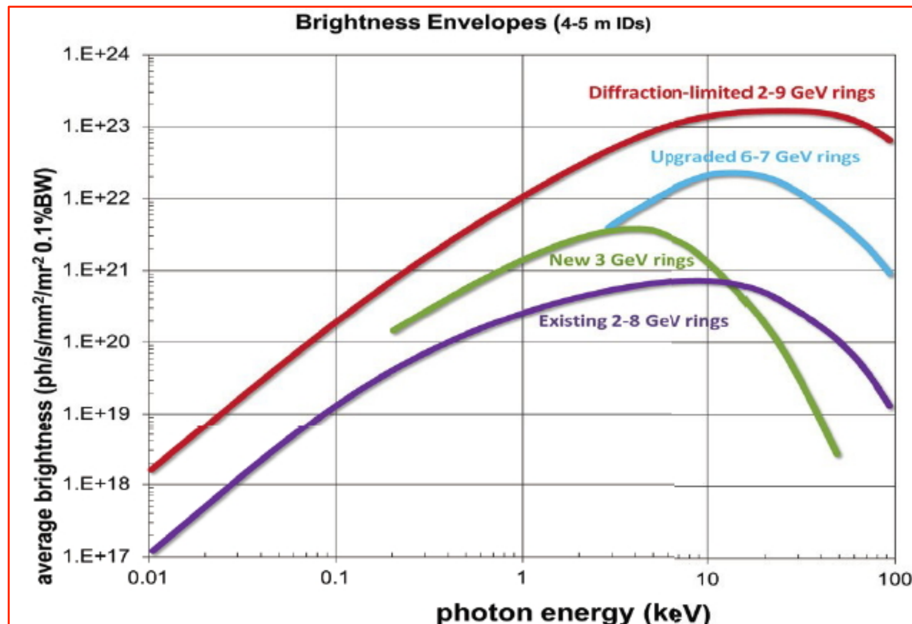


J.Jacob, Status of the ESRF operation & upgrade, 2013

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

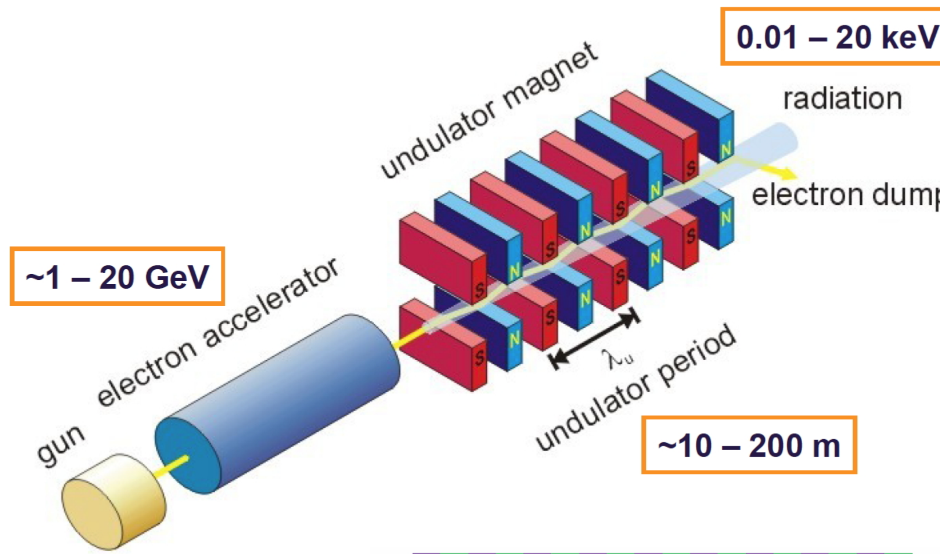


H. Owen – Univ. of Manchester (UK)

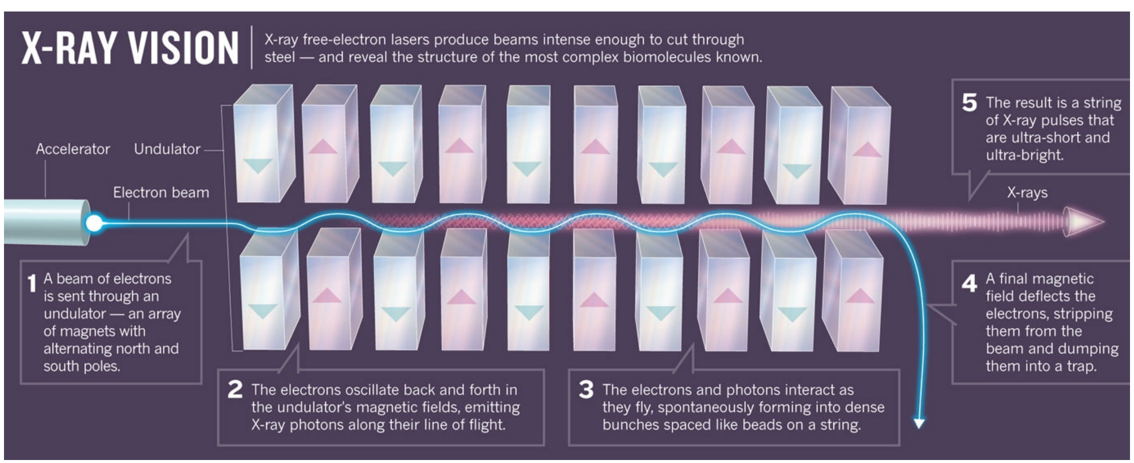
Synchrotron radiation: history

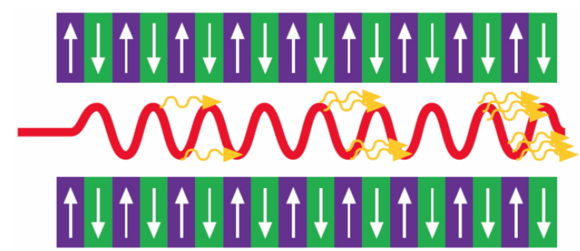
Fourth generation: LINAC based sources and free electron lasers

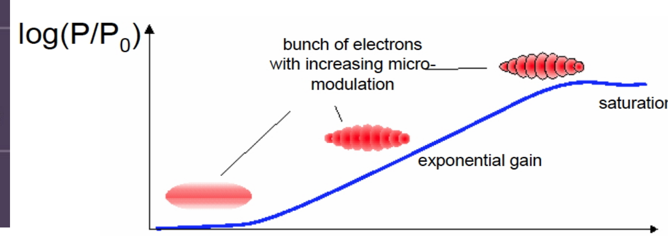
Electrons in an FEL are not bound to atoms or molecules. The "free" electrons traverse a series of alternating magnets, called "undulators," and radiate light at wavelengths depending on electrons energy, undulator period and magnetic field.



SASE FEL – Self Amplified Stimulated Emission



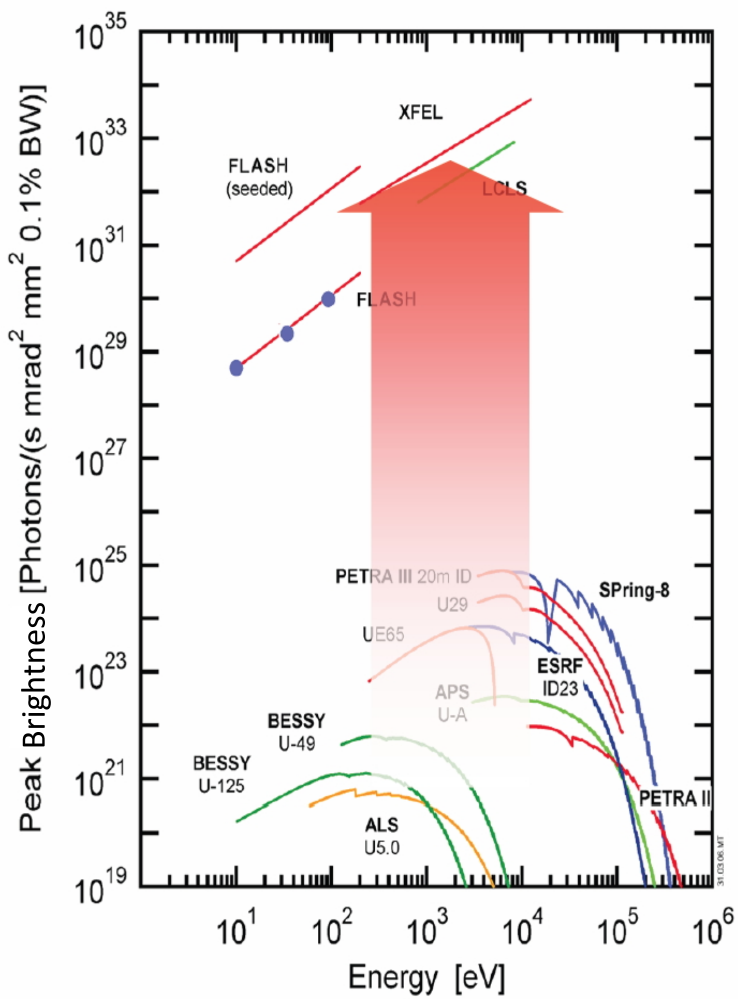




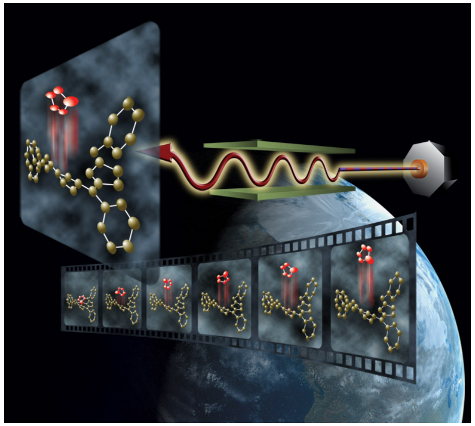
T. Tschentscher, Free-electron lasers as sources of extremely brilliant x-ray radiation, 2011
D. Nguyen et al. Theory and Practice of Free-Electron Lasers, 2009
M. Waldrop, The Big Guns: Powerful X-ray lasers are getting to the heart of matter- Nature 505, 604 (2014)

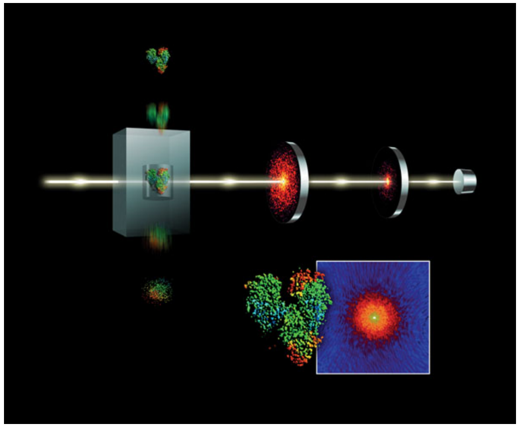
Synchrotron radiation: history

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 (LCLS April 2009) ranges*
- *European XFEL being built*
- *Filming chemical reactions as they occur*
- *Protein crystallography no longer needed – image molecules directly*

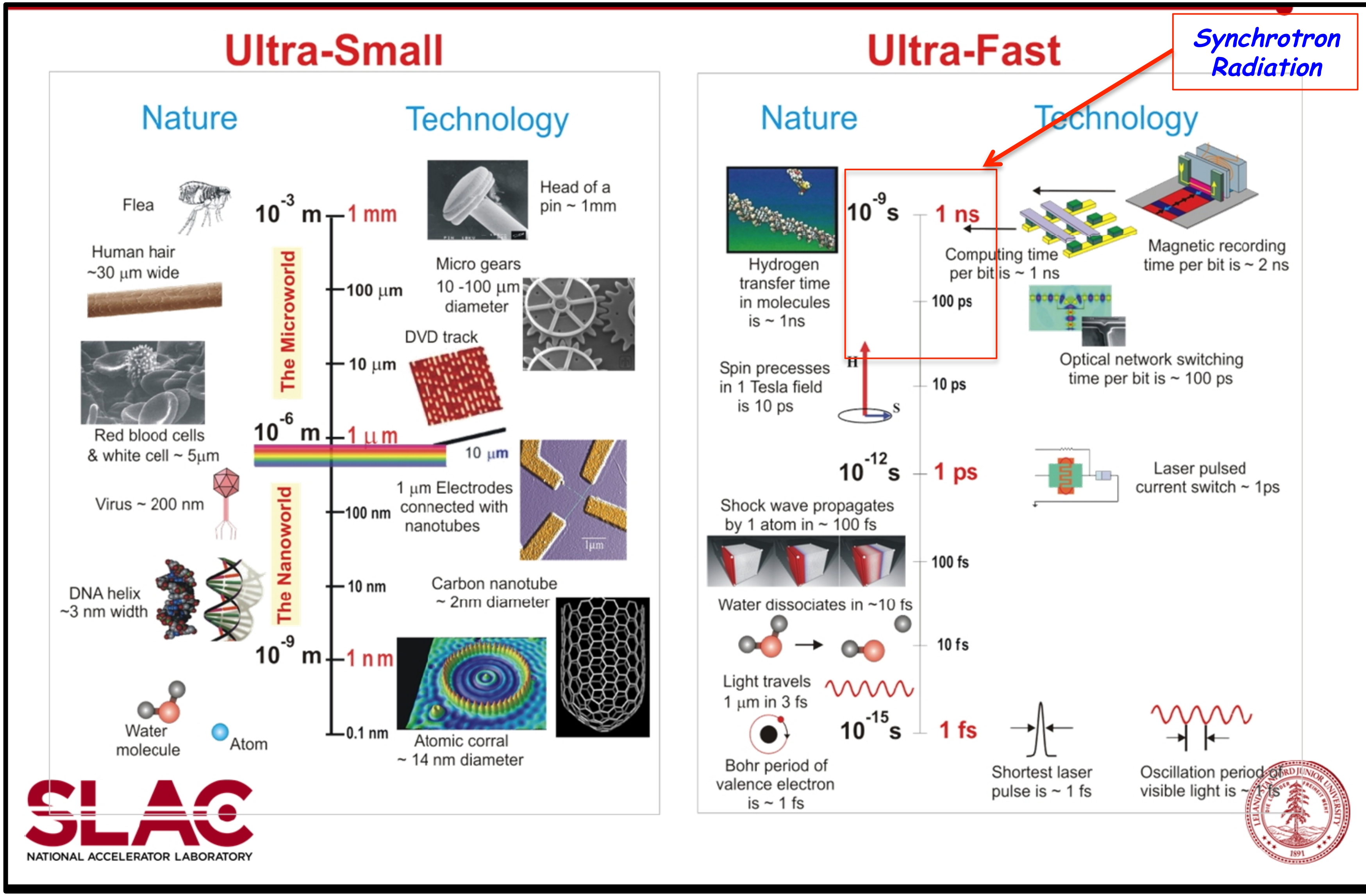




LCLS http://www-public.slac.stanford.edu/lcls/aboutlcls.aspx

Synchrotron radiation: history

Fourth generation: free electron lasers



Comparing storage rings and FELs in the future

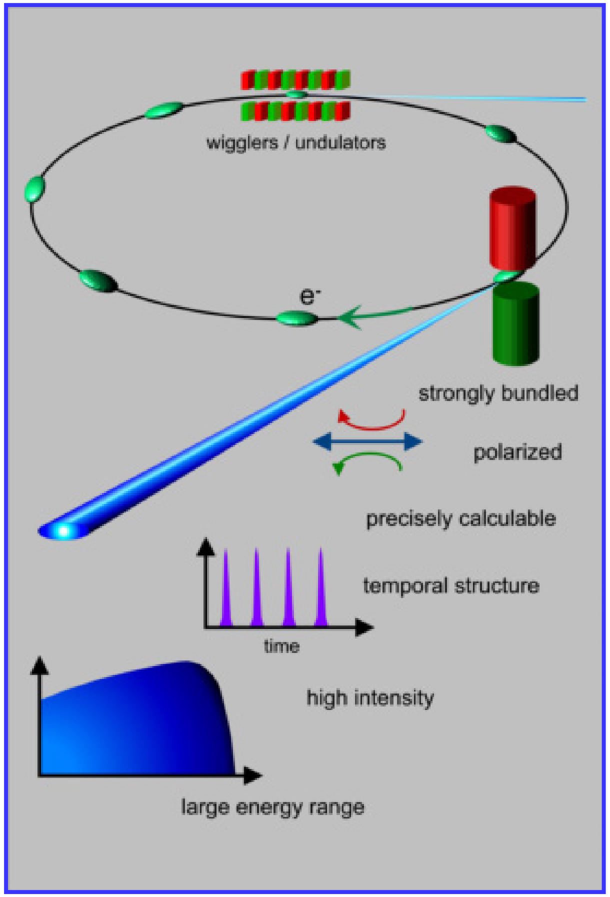
Parameter	Storage Rings	FEL
Wavelength Range	2-3 decades typically	1-2 decades (multiple undulators)
Peak Brightness (ph/s/mr^2/ mm^2/0.1%BW)	$10^{24} – 10^{26}$ (x 100 increase but still modest compared to FEL)	$10^{31} – 10^{33}$
Average Brightness (ph/s/mr^2/ mm^2/0.1%BW)	$10^{21}– 10^{23}$ (x 100 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

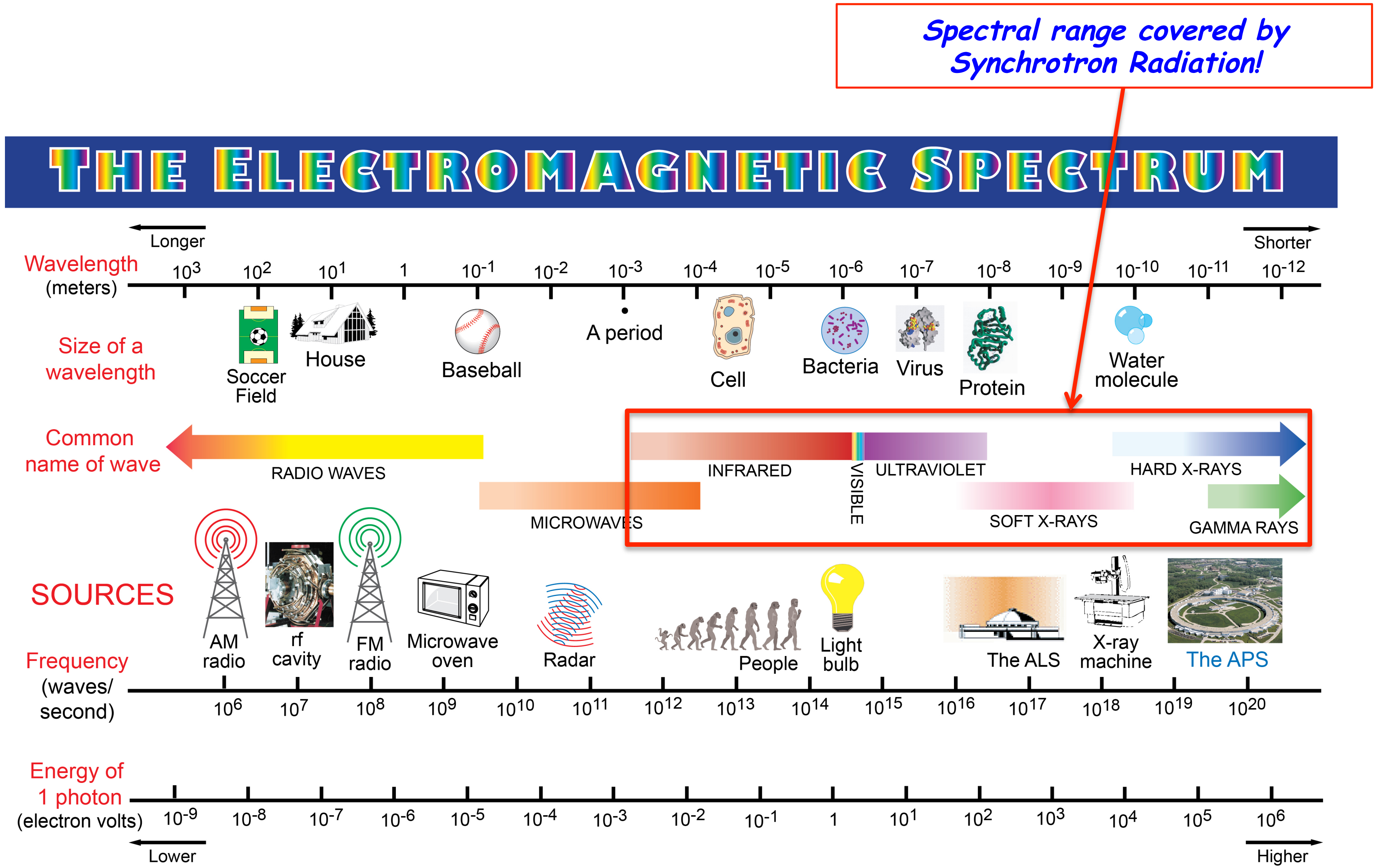
P. S. Drell, Status of International Light Sources: Today and in the Near Future, BESAC 2013
http://science.energy.gov/bes/besac/meetings/meeting-presentations/)

Synchrotron Radiation Properties

What makes synchrotron radiation interesting, powerful and unique?

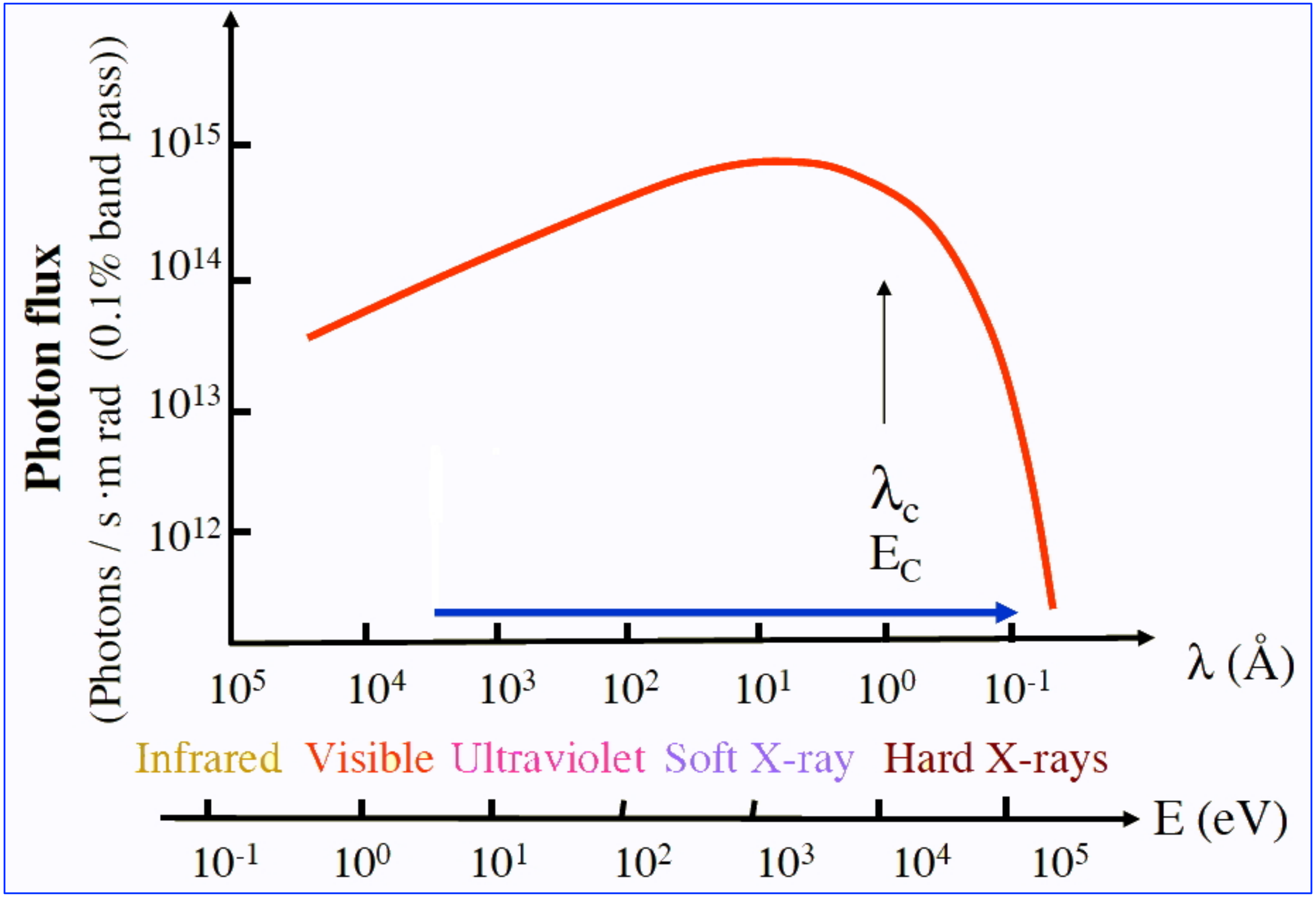
- ***Very high flux and brightness (with undulators)*** highly collimated photon beam generated by a small divergence and small size source (partial coherence)
- ***Broad spectral range (tunability)*** which covers from microwaves to hard X-rays: the user can select the wavelength required for experiment- *continuous (Bending Magnet/Wiggler) - quasi-monochromatic (Undulator)*
- ***High stability (submicron source stability)***
- ***Pulsed time structure*** **-** pulsed length down to tens of picoseconds allows the resolution of processes on the same time scale
- ***Polarization*** *(linear, circular, elliptical with Insertion Devices)*
- ***High vacuum environment***





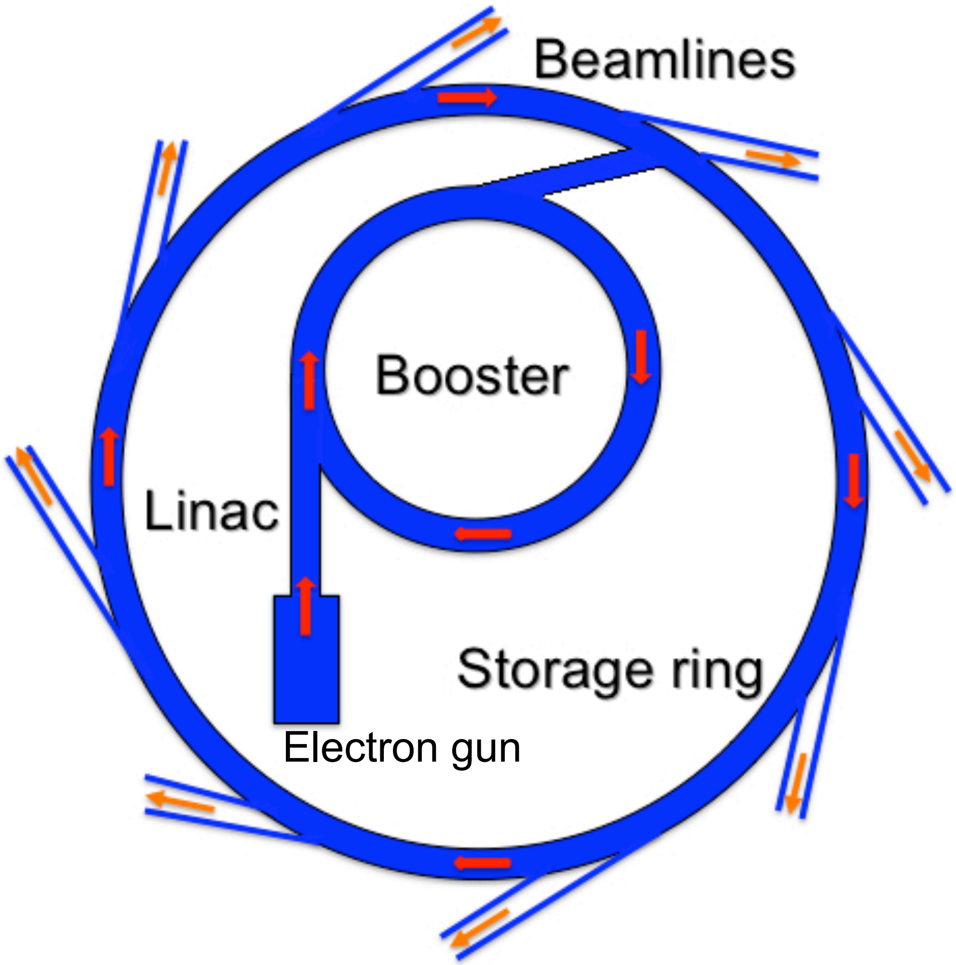
Spectral range covered by Synchrotron Radiation!
THE ELECTROMAGNETIC SPECTRUM
Longer
Shorter
Wavelength (meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
Size of a wavelength
Soccer Field
House
Baseball
A period
Cell
Bacteria
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

Spectral distribution: universal synchrotron radiation function



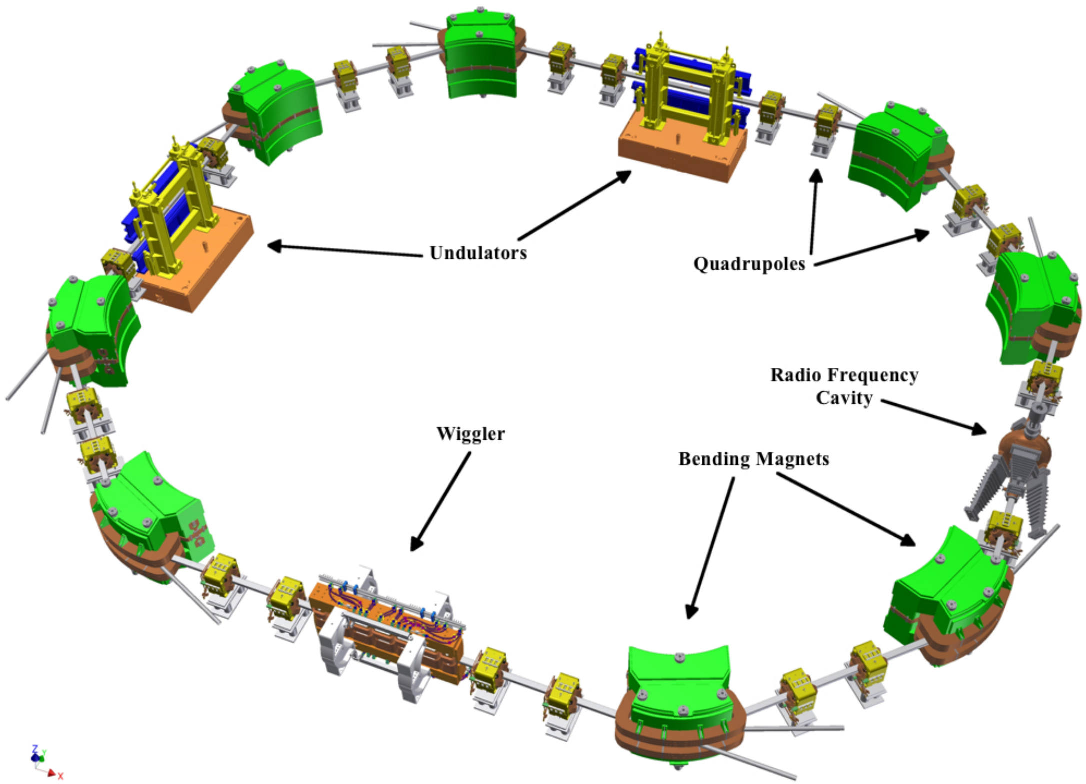
E_c and λ_c respectively critical energy and critical wavelength

Modern synchrotron radiation source



- ***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 runnig off tangentially to the storage ring, along the axes of the insertion devices and tangentially at bending magnets

Schematic view of the 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: ***dipole- 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.

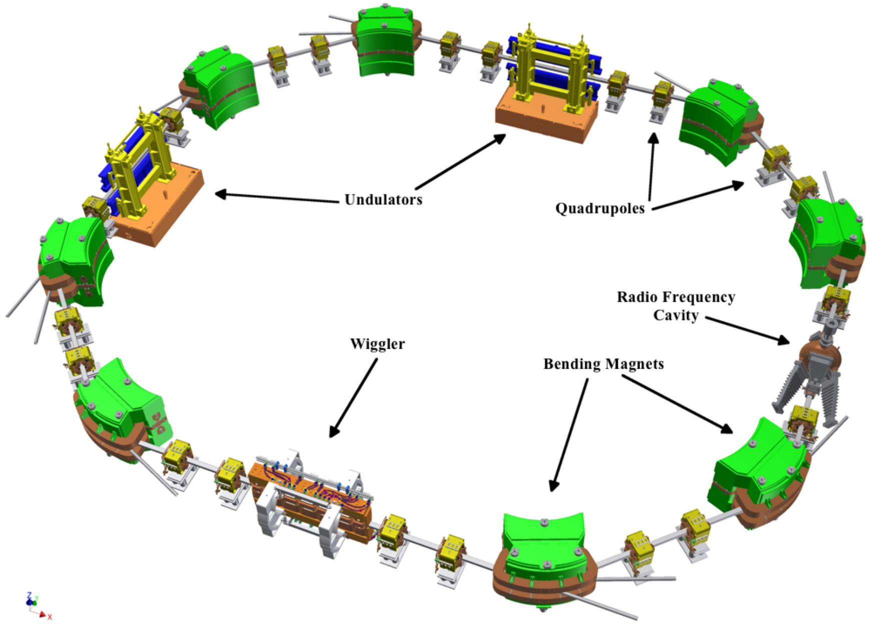
- ***RF cavities*** supply the energy lost by electrons emitting synchrotron radiation.

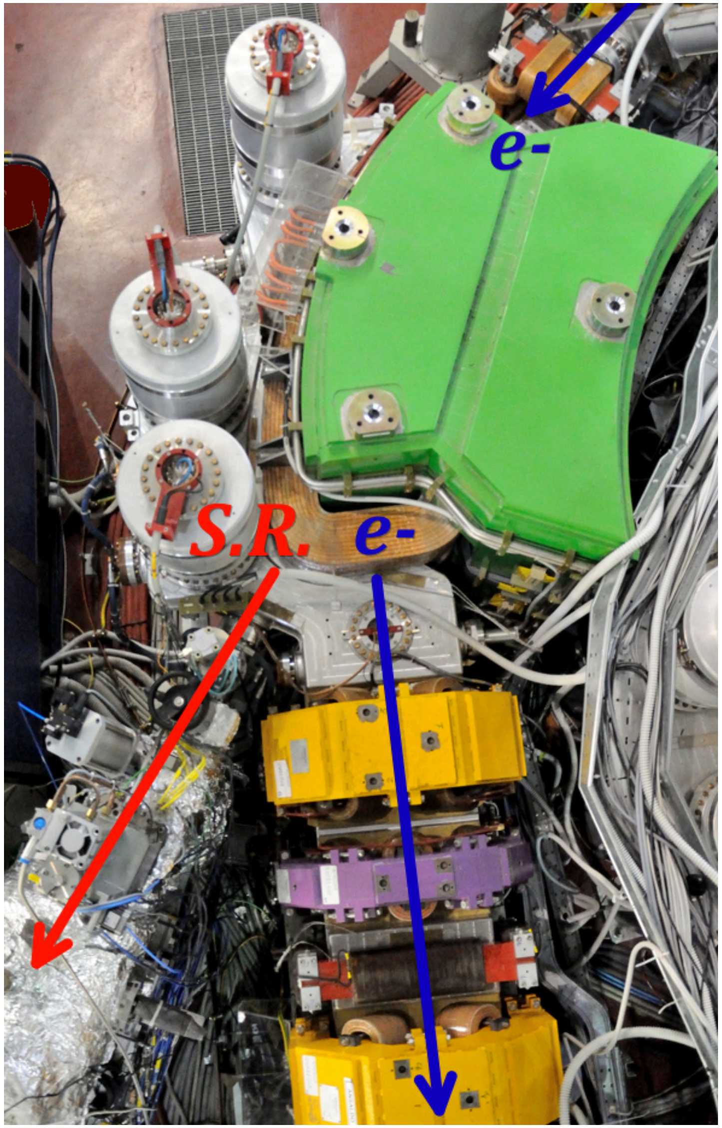
- ***Insertion devices (ID)*** while the arced sections contain bending magnets, the straight sections are used for insertion devices (***wigglers*** and ***undulators***), that generate the most intense synchrotron radiation

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 = 1.6021×10^{-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	$T = E - m_0 c^2 = m_0 c^2 (\gamma - 1)$

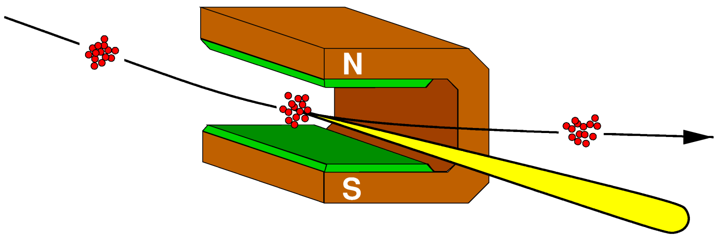
Bending magnets

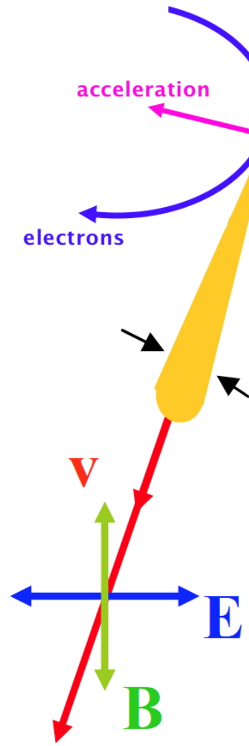




DAΦNE bending magnet

Bending magnets: radiated power





$2\theta \sim 2/\gamma$

For E= 1 GeV, 1/γ ≈ 511 mrad or 29 mdeg: tangent to orbit

1 deg = 17.45 mrad; 1 mrad = 57 mdeg

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*

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

The power radiated by a relativistic electron forced to move along a circular orbit, with a radius of curvature, ρ, is given by the ***Schwinger***'s formula:

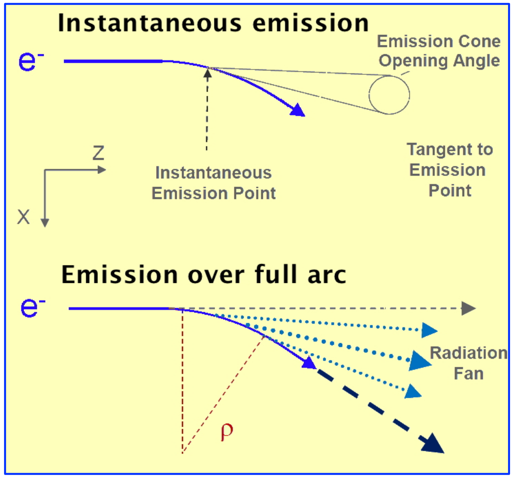
$$P = \frac{e^2}{6\pi\varepsilon_0 c}\left|\dot{\vec{\beta}}\right|^2 \gamma^4 = \frac{e^2}{6\pi\varepsilon_0 c}\left|\dot{\vec{\beta}}\right|^2 \frac{E}{E_o^4}^4 = \frac{e^2}{6\pi\varepsilon_0 m^2 c^3}\left|\frac{d\vec{p}}{dt}\right|^2 \gamma^2 = \frac{e^2 c}{6\pi\varepsilon_0}\frac{\gamma^4}{R^2} = \frac{e^4}{6\pi\varepsilon_0 m^4 c^5} E^2 B^2$$

strong dependence on the rest mass 1/m^4

proportional to 1/R^2 (R is the bending radius)

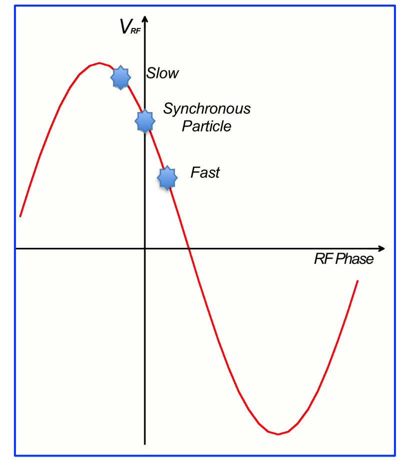
proportional to E^2 and B^2 (B is the magnetic field of the bending magnet) ***[B(T) R(m)=3.336 E(GeV)]; [γ= 1957 E (GeV)]***

Bending magnets: time structure

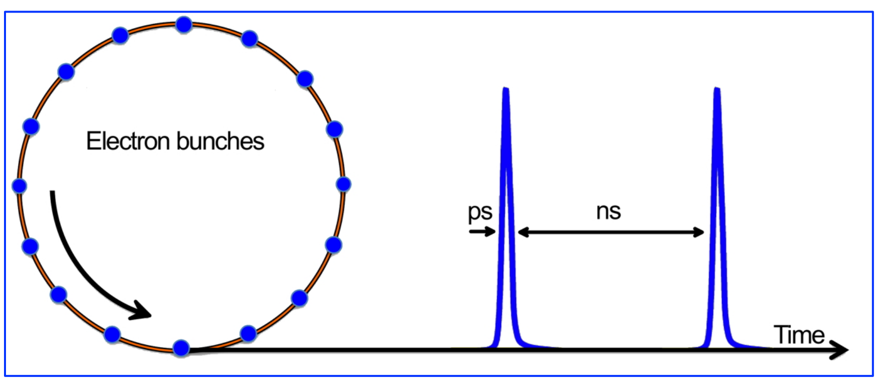


$$P(kW) = \frac{e\gamma^4}{6\pi\varepsilon_0 R^2} LI = 14.08 \frac{L(m)I(A)E(GeV)^4}{R(m)^2}$$

Power radiated by a beam of average current I in a dipole of length L (energy loss per second).

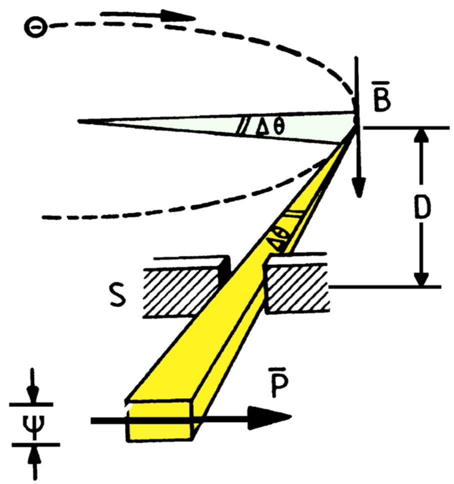


In order to replenish the energy lost with the emission of radiation and keep the electrons at a constant energy, radio frequency ***(RF) cavities*** are used. In a RF cavity a ***longitudinal electric field accelerates the electrons.*** The RF fields have an accelerating effect only during one half of their period and a decelerating action during the other half; ***so the RF is effective in restoring the electron energy only for one half of the time.***



Stability condition are very more strict and ***only 5% - 10% of the RF period is effective in restoring the electron energy***. All the electrons, passing through the RF, not in phase with this 5% - 10% effective time, do not follow the ideal circular orbit of the ring and therefore are lost. ***As a consequence the electrons in the storage ring are grouped in bunches with time lengths that are typically 5% - 10% of the RF period***. Also the ***radiation appears in pulses with the same time duration and separation***. Along the storage ring ***many bunches can be distributed***. 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***.

Angular, spectral and intensity distribution

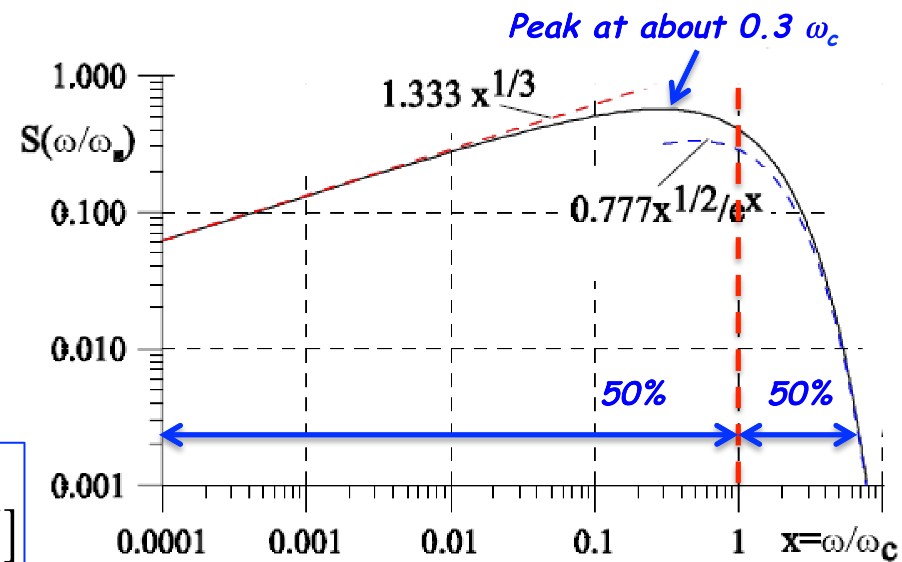


Vertical direction: radiation pattern is compressed into a narrow cone in the direction of motion, resulting into an emission tangential to the particle orbit with a vertical opening angle, $\Psi \approx 2mc^2/E \approx 2\gamma^{-1}$. ***Horizontal direction***: in a bending magnet the horizontal collimation 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, $\Delta\theta = w/D >> \Psi$.

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

Critical energy

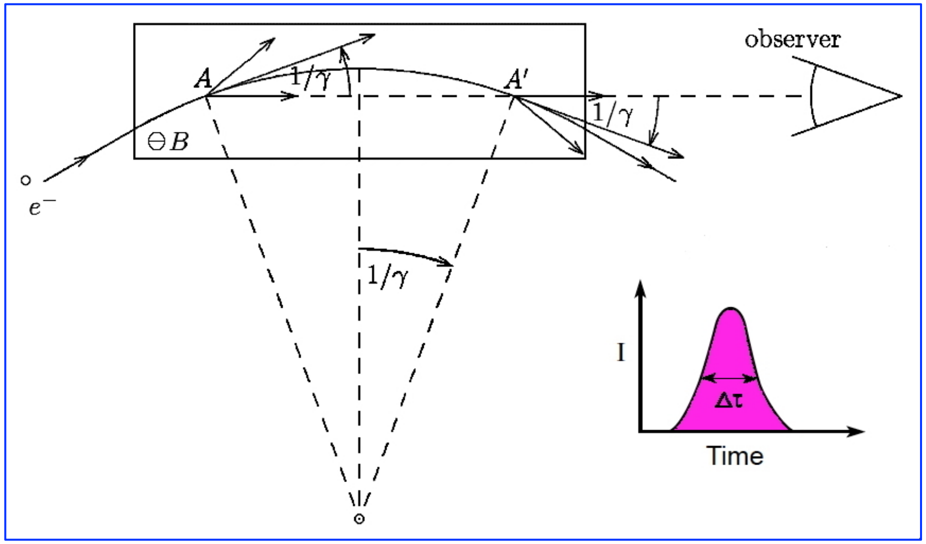
$$\varepsilon_c[keV] = 2.218\frac{E[GeV]^3}{R[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T]$$



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

The ***spectral distribution of the BM synchrotron radiation flux, is a continuous function***, that extends from infrared to the x-ray region. The ***critical energy***, ε_c , represented by the discontinuous red line ***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 .

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/γ) and the time for **light to travel along the chord subtended by this arc.**

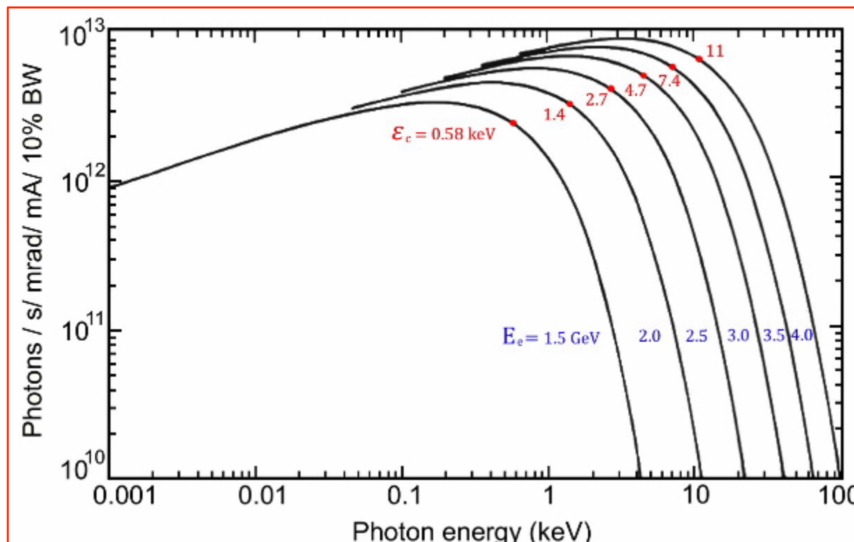
$$\Delta\tau = \frac{R}{c}\left[\frac{1}{\gamma\beta} - 2\sin\left(\frac{1}{2\gamma}\right)\right] \simeq \frac{R}{c\gamma^3}$$

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.



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.

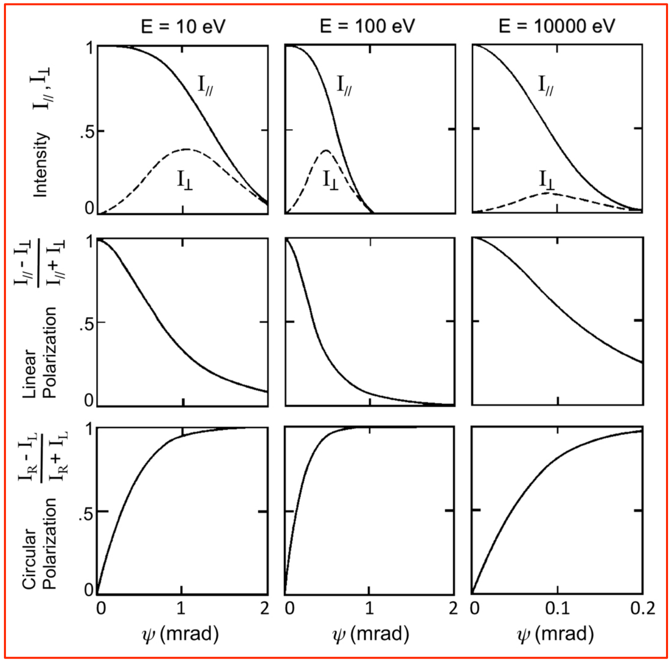
$$P_{Linear} = \frac{I_{//} - I_{\perp}}{I_{//} + I_{\perp}}$$

Degree of linear polarization

Integrating over all energies:

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

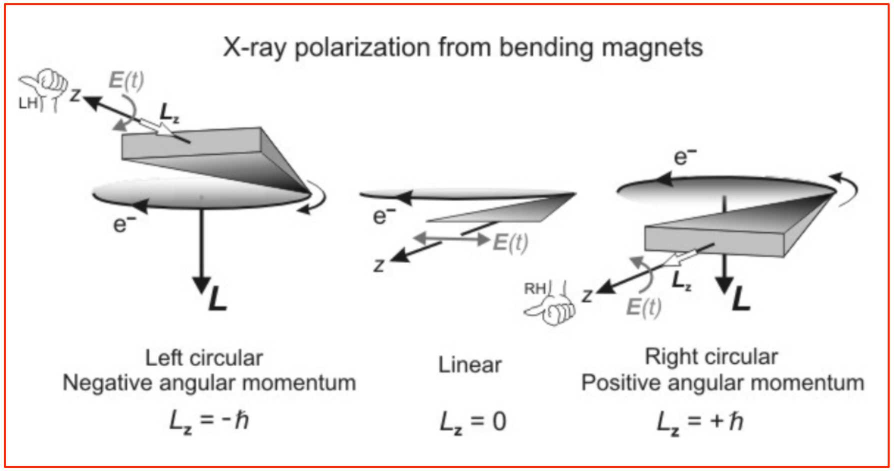
that means a linear polarization degree of about 75%.



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.

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

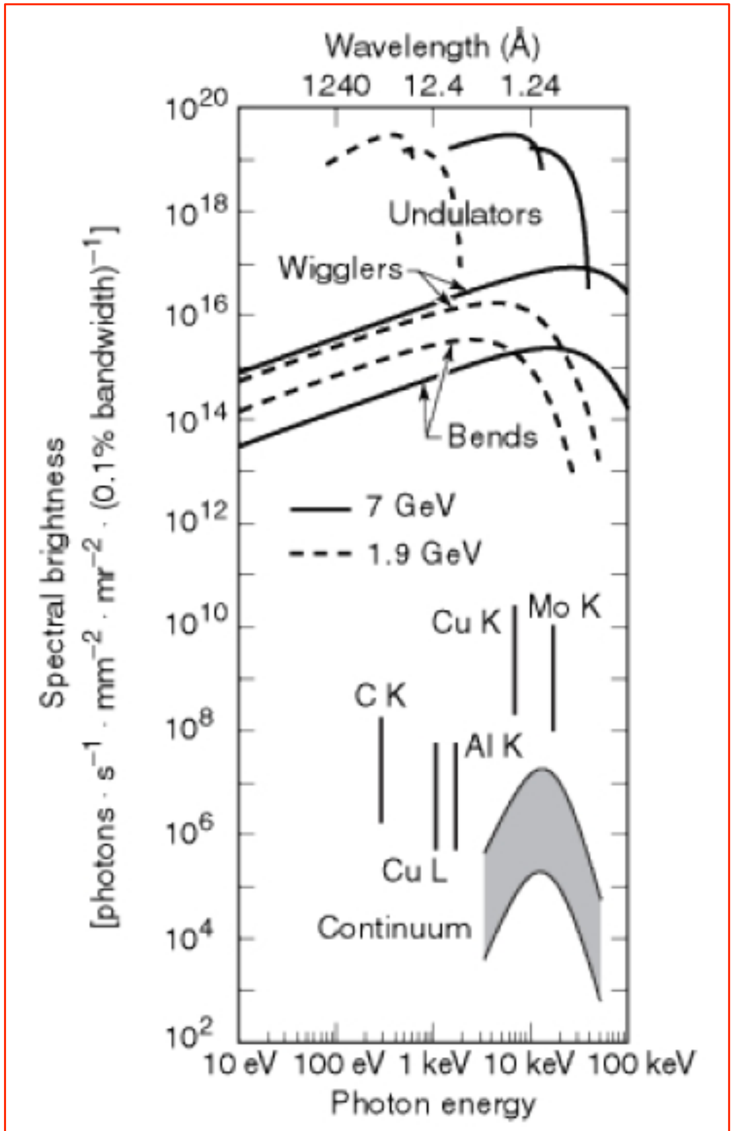
Degree of circular polarization



Circularly polarized light is fundamental in techniques like ***spin-resolved x-ray photoelectron spectroscopy.***

__J. Stöhr, H. C.Siegmann,__ Magnetism – from fundamentals to nanoscale dynamics, Springer, __2006__

Spectral brightness and emittance

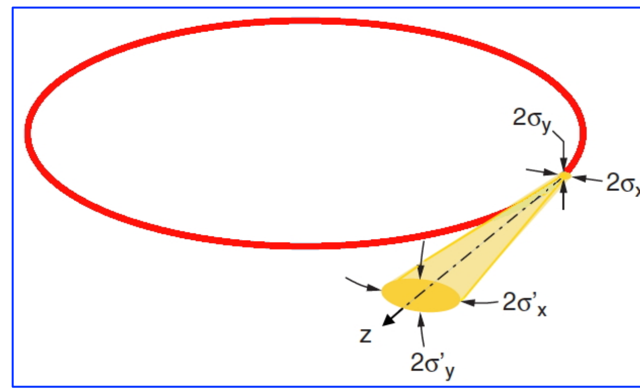


X-ray data booklet, http://xdb.lbl.gov/

The spectral brightness of the source must be calculated. It is defined as ***the number of photons emitted per second, in a spectral bandwidth ΔE /E = 0.1% in an unit source area and per unit of solid angle.***
As well known due to the Liouville's theorem, focusing preserves the brightness, i.e. the brightness of the source is equal to the brightness of the beam when focused on the sample. The ***brightness is determined by the size of the source, that is given by the size of the electron beam*** and ***by the angular spread of the radiation, given by the convolution of the angular distribution of synchrotron radiation, with the angular divergence of the electron beam.*** 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 is measured in nanometer-radians*** (nm-rad). The vertical emittance is normally a few percent of the horizontal one.

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

ESRF Grenoble
ε_y = ***4 pmrad***
ε_x = ***4 nmrad***



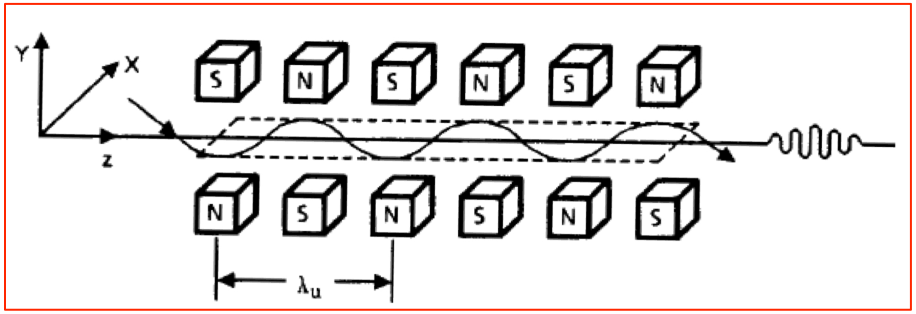
Lower limit to the emittance called '***diffraction limited emittance***':

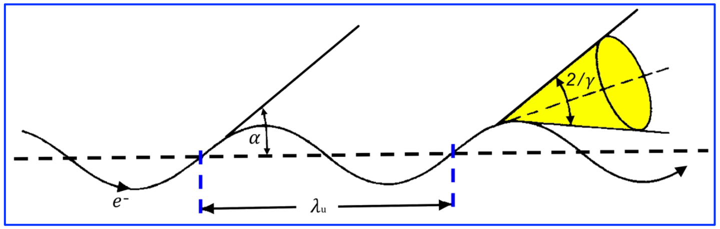
$$\varepsilon_{min} = \lambda / 4\pi$$

for 1 Å radiation, the diffraction-limited photon-beam emittance is some 8 pmrad.

Insertion devices: wigglers

Insertion devices (ID) are ***periodic arrays of magnetic poles*** installed in the straight sections of storage rings providing **a sinusoidal magnetic field on axis.**



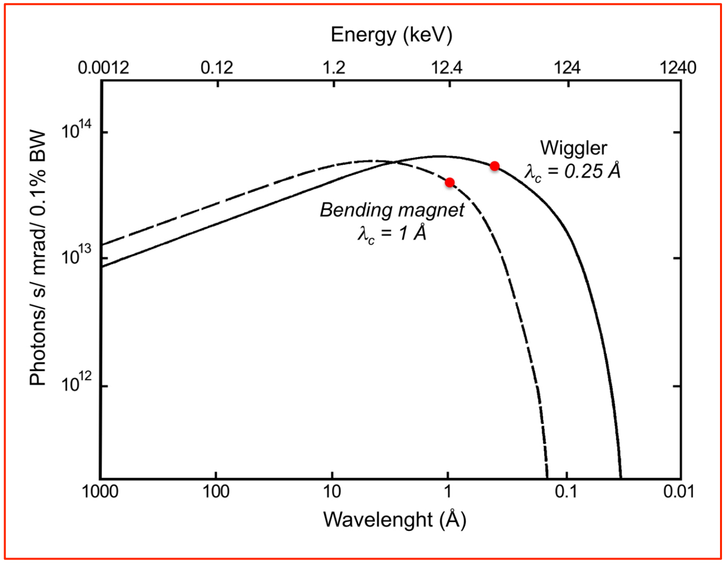


A ***wiggler*** is a ***multipole magnet*** made up of a periodic series of magnets (***N periods of length λ_u***, the ***overall length being L=Nλ_u***). ***Electrons are forced to follow a sinusoidal trajectory*** with a ***smaller local radius of curvature*** with respect to the one of the dipole-bending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

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

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

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

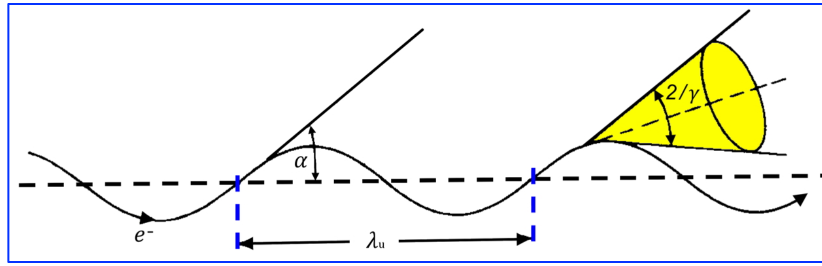


Comparison between the spectral flux from ***a bending magnet*** (--) (B = 0.74 T) and from a ***wiggler*** (wavelength shifter: N=1, B = 3.0 T)).

Undulators

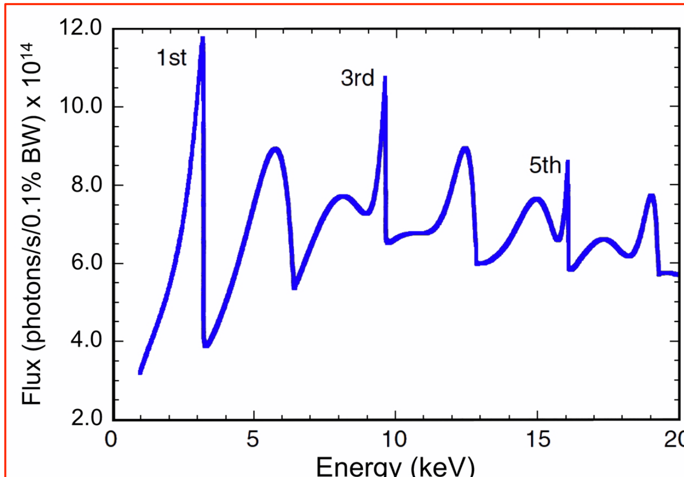
K is a ***dimensionless parameter*** given by the ***ratio between*** the ***wiggling angle of the trajectory***, α , and the ***natural angular aperture of synchrotron radiation, 1/γ, given also by:***

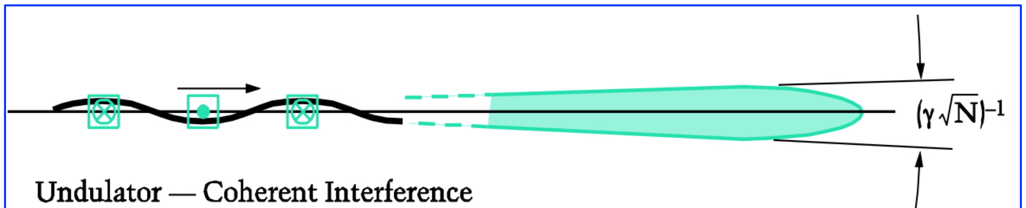
$$K = \frac{e}{2\pi mc}\lambda_u B = 0.934\lambda_u[cm]B[T]$$



While in *a* ***wiggler*** the transverse oscillations of the electrons are very large, the angular deviations, α , much wider than the natural opening angle γ^{-1} , and therefore ***K>>1***, in this case the interference effects between the emission from the different poles can be neglected and the overall intensity is obtained by summing the contribution of the individual poles.

An ***undulator*** is very similar to a wiggler, but its ***K < 1*** so the ***wiggling angle*** α ***is smaller than, or close to, the photon natural emission angle*** γ^{-1} and in this case ***constructive interference occurs between the radiation emitted by electrons at different poles along the trajectory***.





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

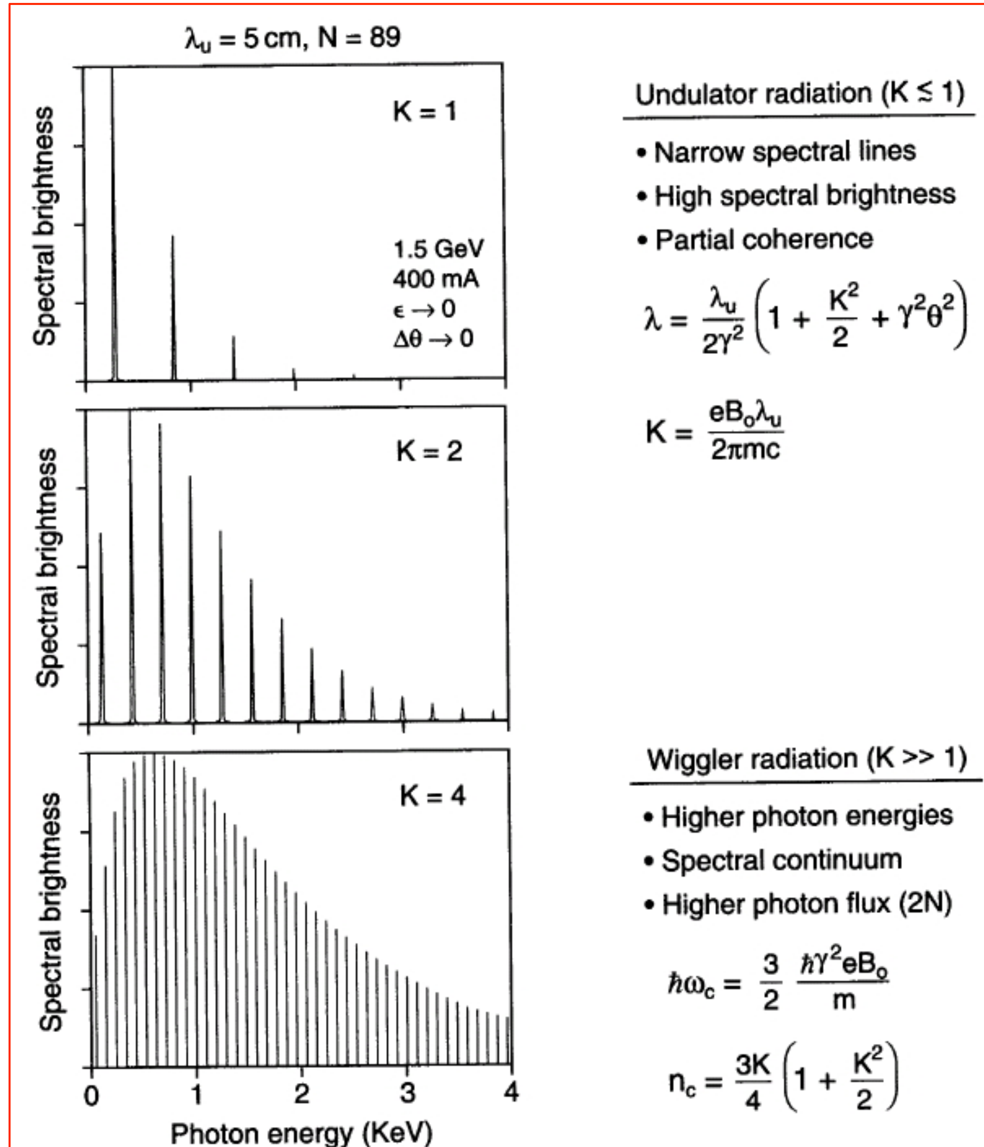
Undulators produce ***quasi-monochromatic spectra*** with peaks at lower energy than a wiggler.

The ***very narrow angular distribution*** together with the N^2 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.***

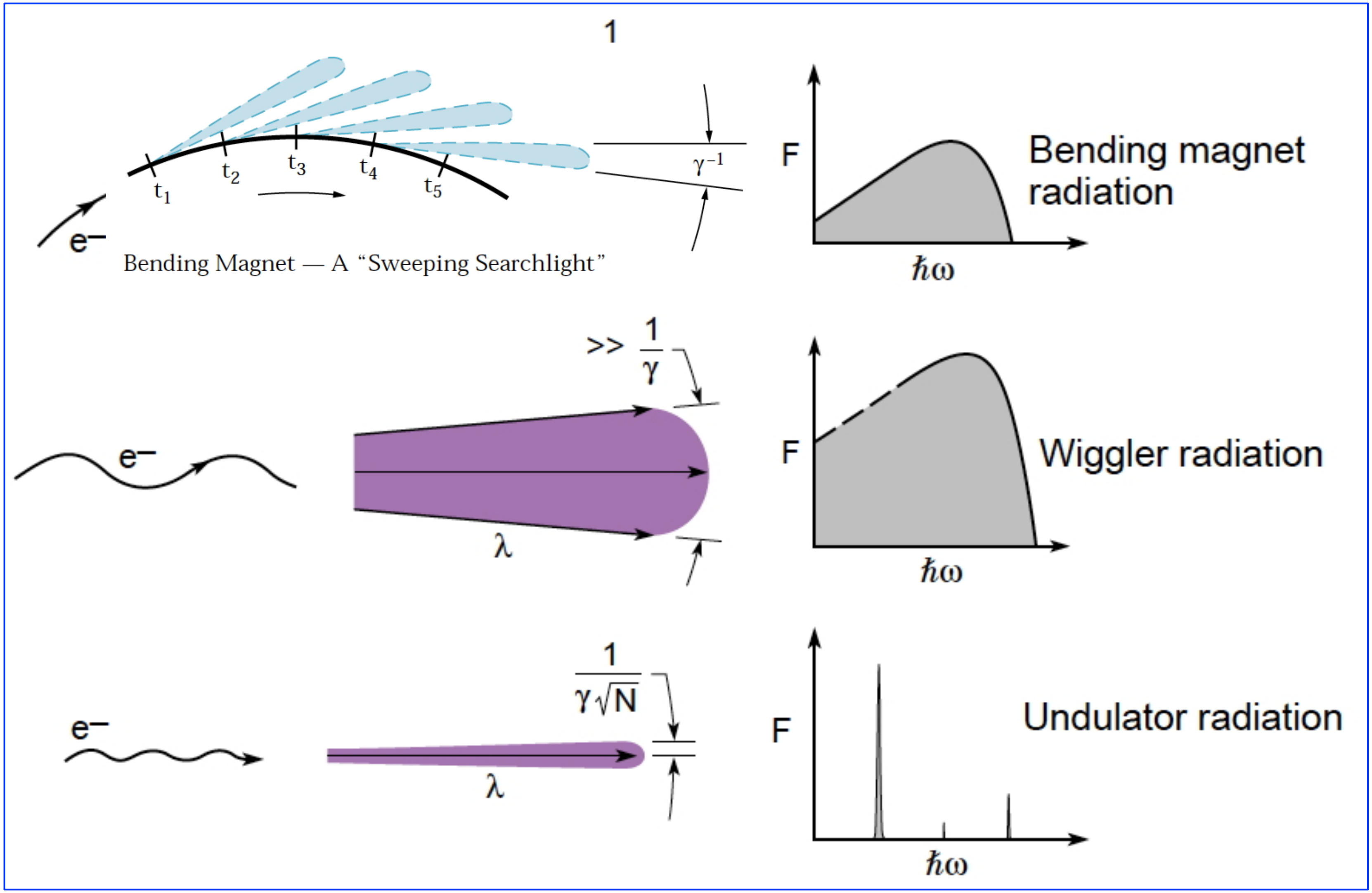
$$E_n(eV) = 9.496\frac{nE[GeV]^2}{\lambda_u[m]\left(1+\frac{K^2}{2}\right)}$$

Undulator equation and wiggler limit

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

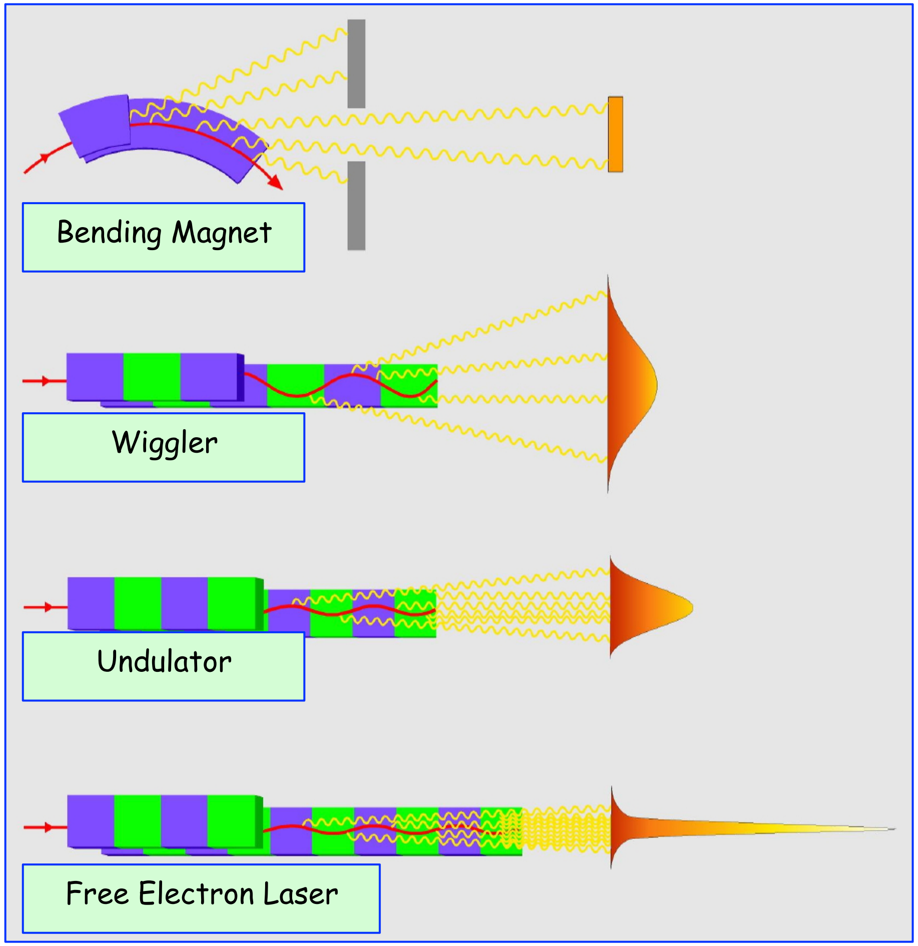


Just to summarize!

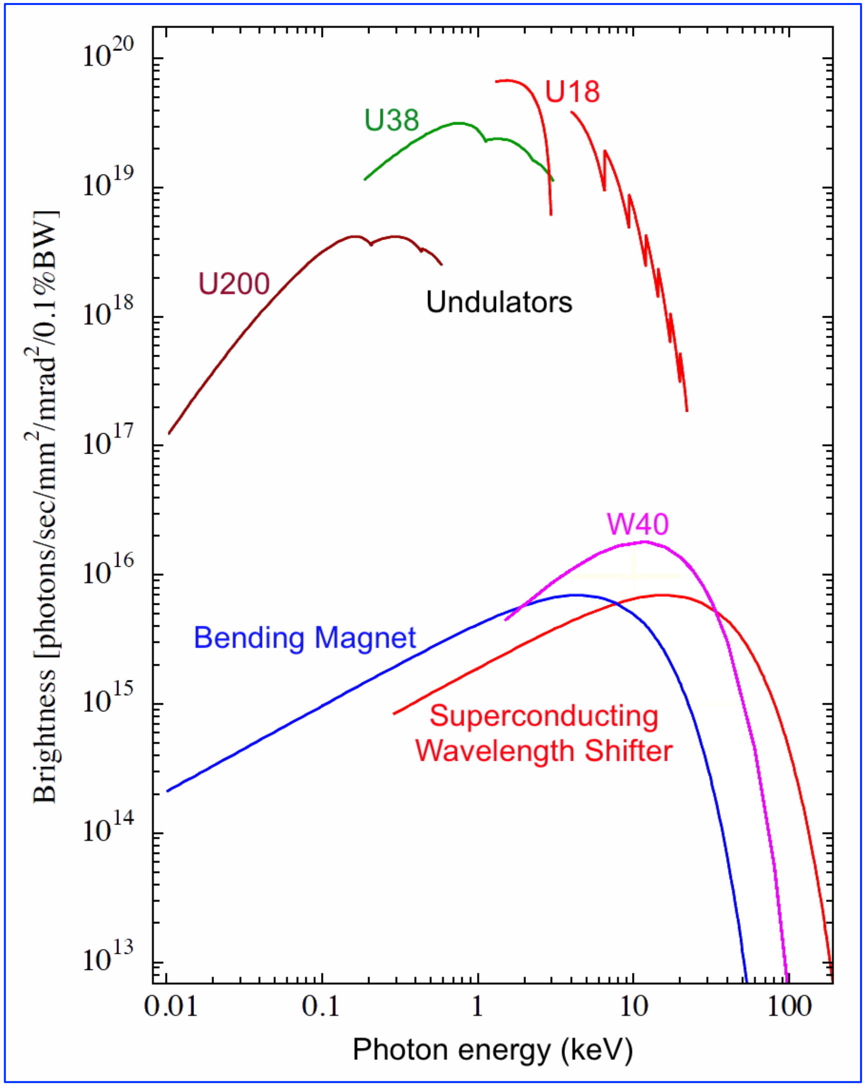


D. Attwood, Intro Synchrotron Radiation, Bending Magnet Radiation - http://ast.coe.berkeley.edu/srms/2007/Lec08.pdf

Comparing the achievable brightness

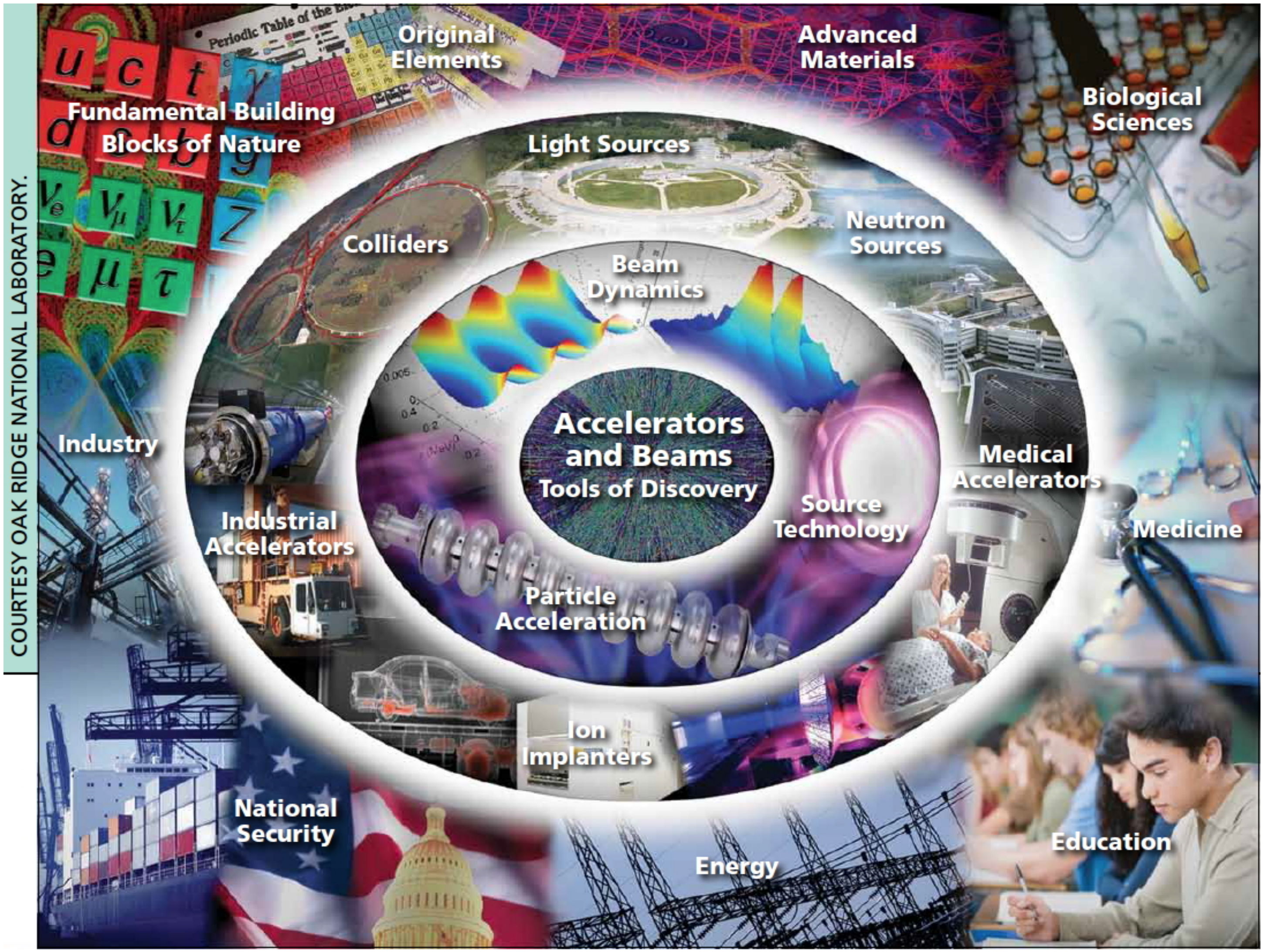


Courtesy DESY



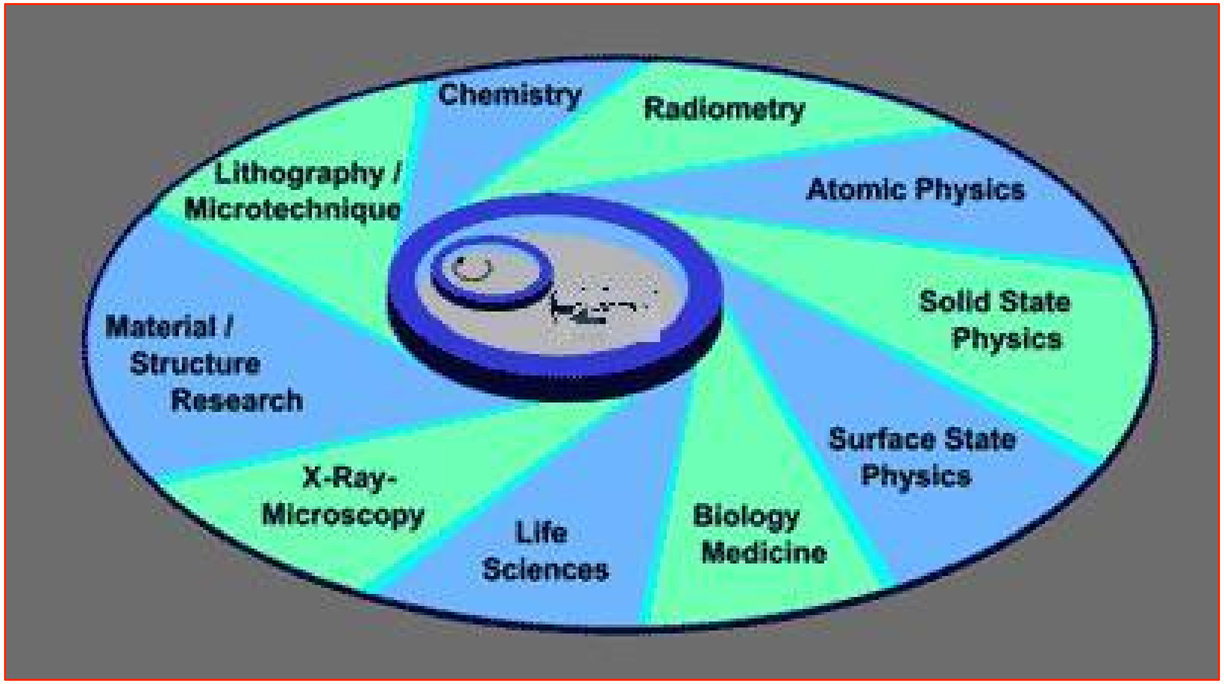
Calculated brightness of beams emitted by undulators (200 mm (L= 10 m), 38 mm (L= 4 m) and 18 mm (L= 2 m) periods), wigglers (wavelength shifter and 40 mm (L= 2 m) period) and bending magnets for a 2.4 GeV storage ring with 400 mA circulating current (**M. Boge** http://accelconf.web.cern.ch/Accelconf/e98/PAPERS/MOP28G.PDF)

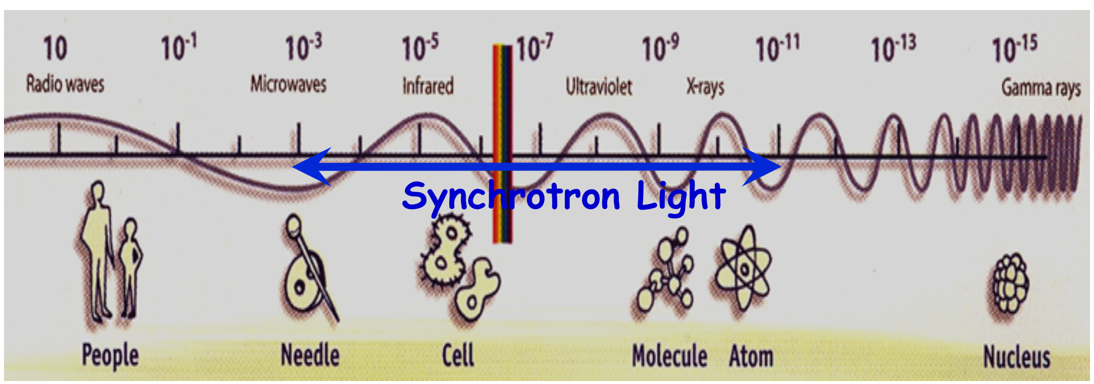
From accelerators to applications



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

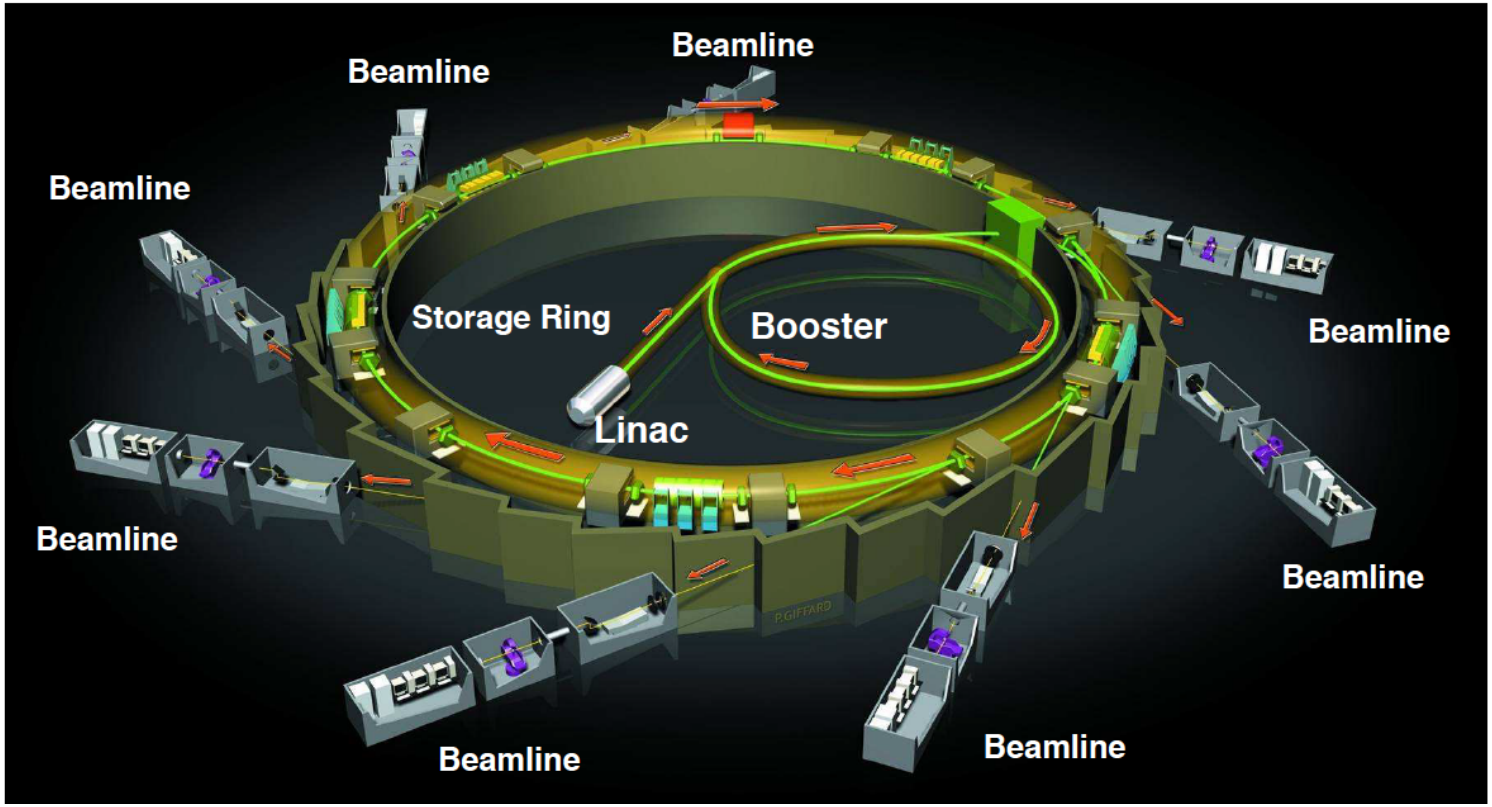
Synchrotron radiation applications





Beamlines

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



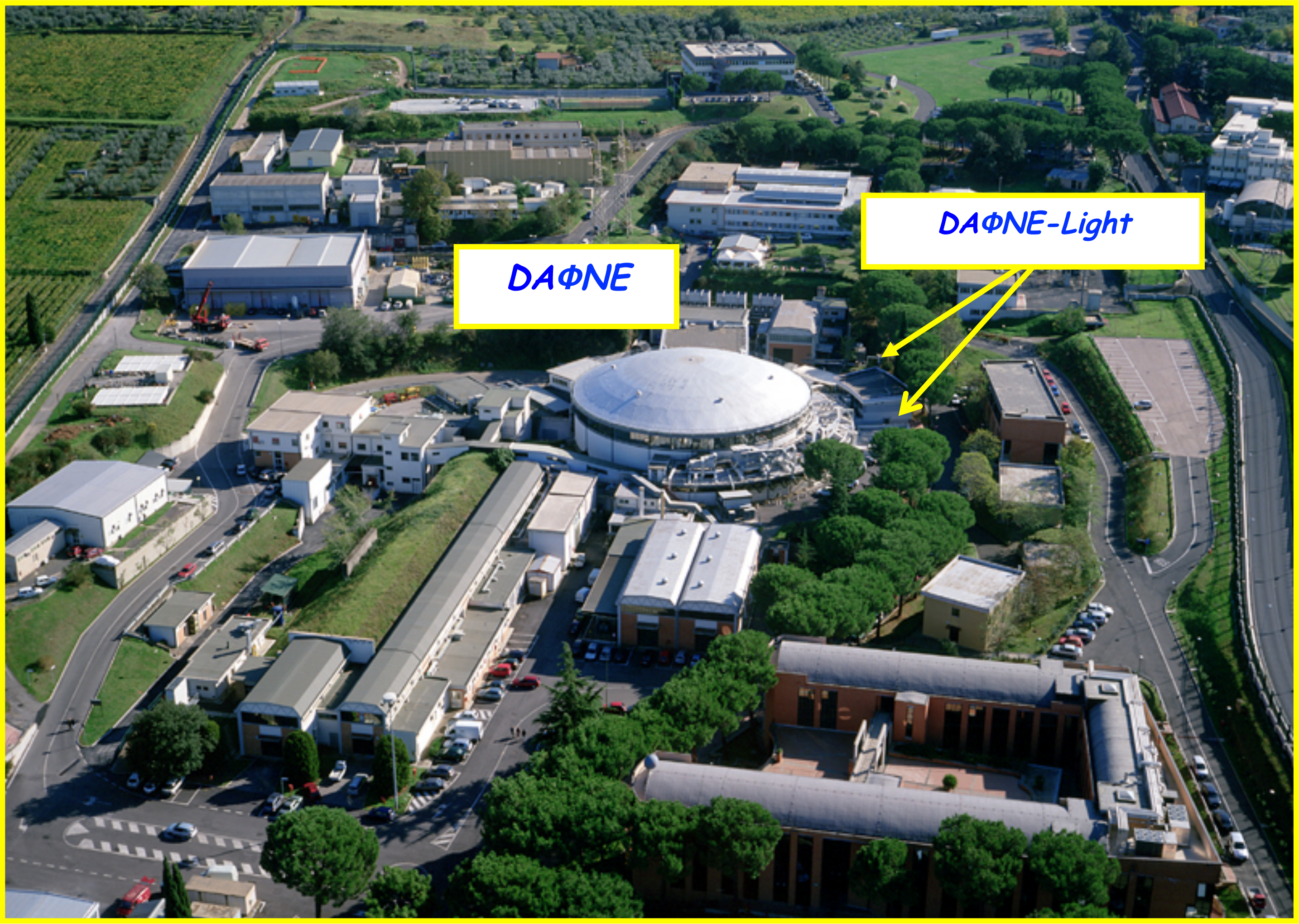
Beamline schematic composition:

- *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.

DAΦNE-Light 

INFN-LNF Synchrotron Radiation Facility



Beamlines @ DAΦNE

SINBAD - IR beamline (1.24 meV-1.24 eV)

DXR1- Soft x-ray beamline(900-3000 eV)

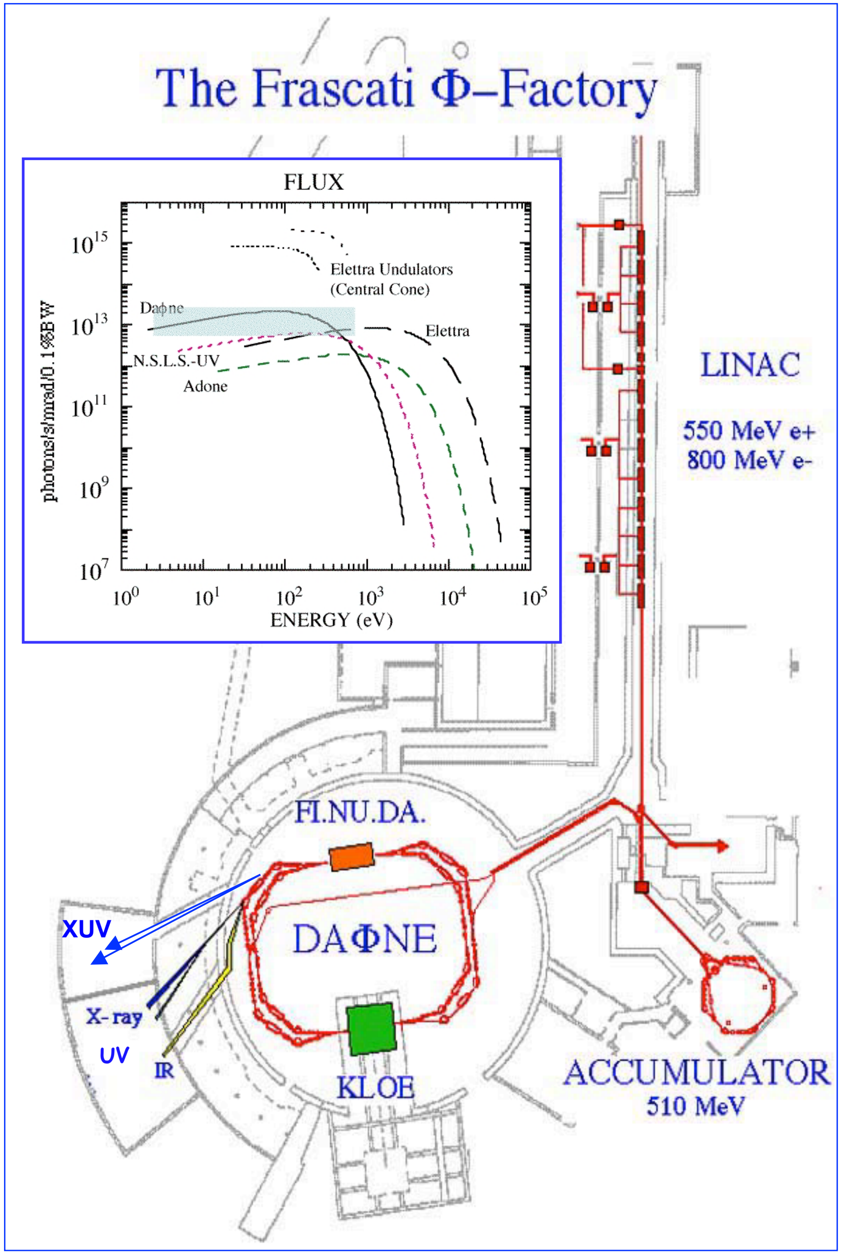
Open to Italian and EU users

DXR2 - UV-VIS beamline (2-10 eV).

2 new XUV beamlines

Low Energy Beamline (35-200 eV) ready for commissioning;

High Energy Beamline (60-1000 eV) ready for commissioning.



Available techniques

- FTIR spectroscopy, IR microscopy and IR imaging

- UV-Vis absorption spectroscopy

- Photochemistry: UV irradiation and FTIR micro-spectroscopy and imaging.

- Soft x-ray spectroscopy: XANES (X-ray Absorption Near Edge Structure) light elements from Na to S

- SEY (secondary electron yield) and XPS (X-ray photoelectron spectroscopy) – by electron and photon bombardment

http://web2.infn.it/DAFNE_Light

DAFNE-LIGHT

INFN-LNF Synchrotron Radiation Facility

INFN | LNF | DAFNE Storage Ring | DAFNE-Light

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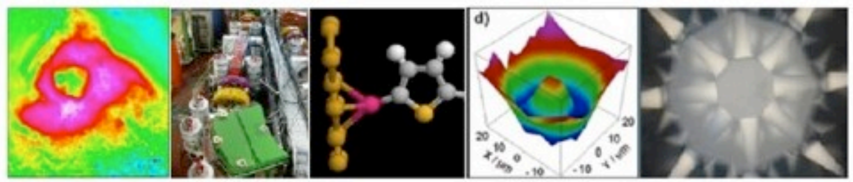

DAFNE-Light

DAFNE-Light is the Synchrotron Radiation Facility at the Laboratori Nazionali di Frascati (LNF).

Three beamlines are operational using, in parasitic and dedicated mode, the intense photon emission of DAFNE, a 0.51 GeV storage ring with a routinely circulating electron current higher than 1 Ampere. Two of these beamlines (DXR1 and DXR2) have one of the DAFNE wiggler magnets as synchrotron radiation source, while the third beamline (SINBAD-IR) collects the radiation from a bending magnet. New XUV bending magnet beamlines are nowadays under construction.

The beamlines DXR1 and SINBAD-IR are open to external users.

Login

Username

Password

Remember Me

Login

- Forgot your password?
- Forgot your username?
- Create an account

Who is online

We have 1 guest online

More details in the next lectures!

Thank you for your attention!!!

References

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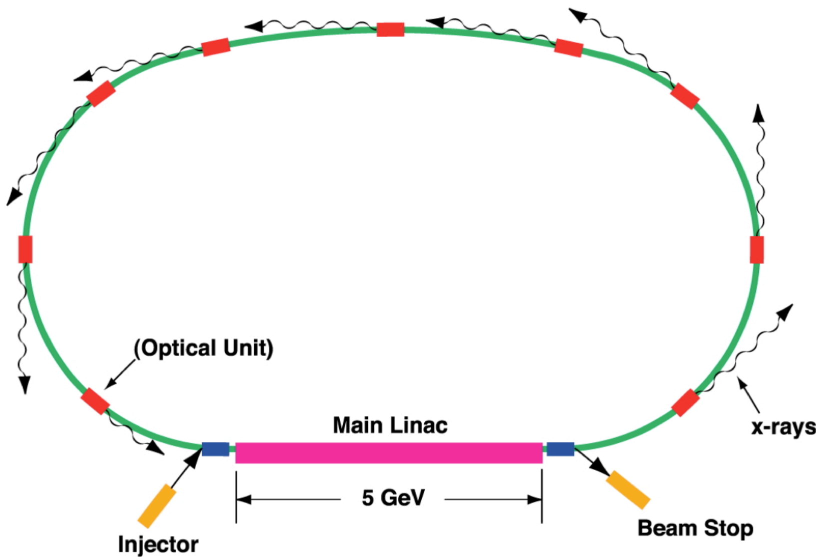
Appendices

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/)