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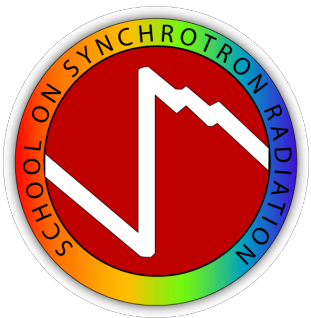


Elettra Sincrotrone Trieste

Introduction to Synchrotron Radiation

Antonella Balerna

DAΦNE-Light Facility
INFN - Frascati National Laboratories



'Gilberto Vlaic' XVIII School

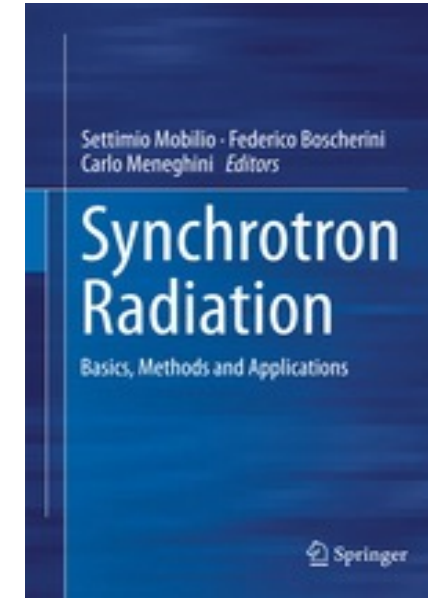
Synchrotron Radiation: Fundamentals, Methods and Applications

<https://indico.elettra.eu/event/62/overview>

Muggia (Trieste), Italy 21 September - 1 October 2026

Introduction to Synchrotron Radiation

This lecture, with some new information, is based on the paper '*Introduction to Synchrotron Radiation*' by **A. Balerna** and **S. Mobilio** published in the proceedings of the School.



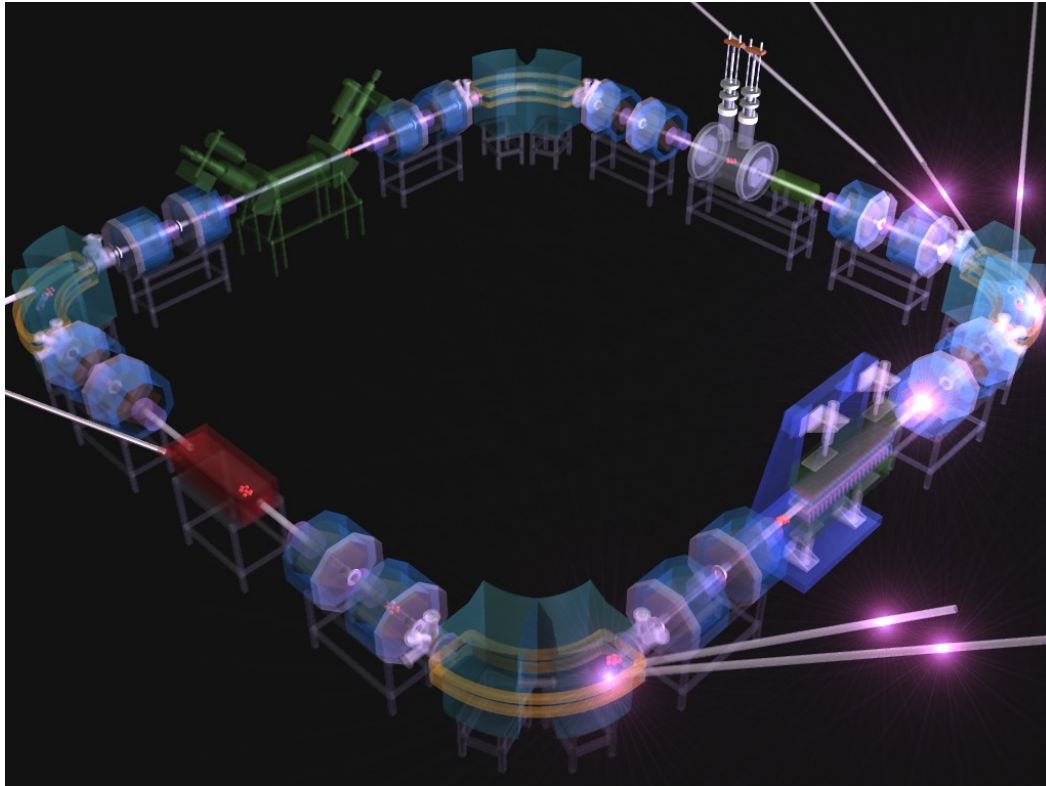
More details on synchrotron radiation properties will be given in the lectures of:

Giorgio Margaritondo

Characteristics and properties of synchrotron radiation

**Progress in science goes in parallel
with technical progress in
developing light sources to explore
the physical world.**

2026 - 79 Years of Science with Synchrotron Radiation



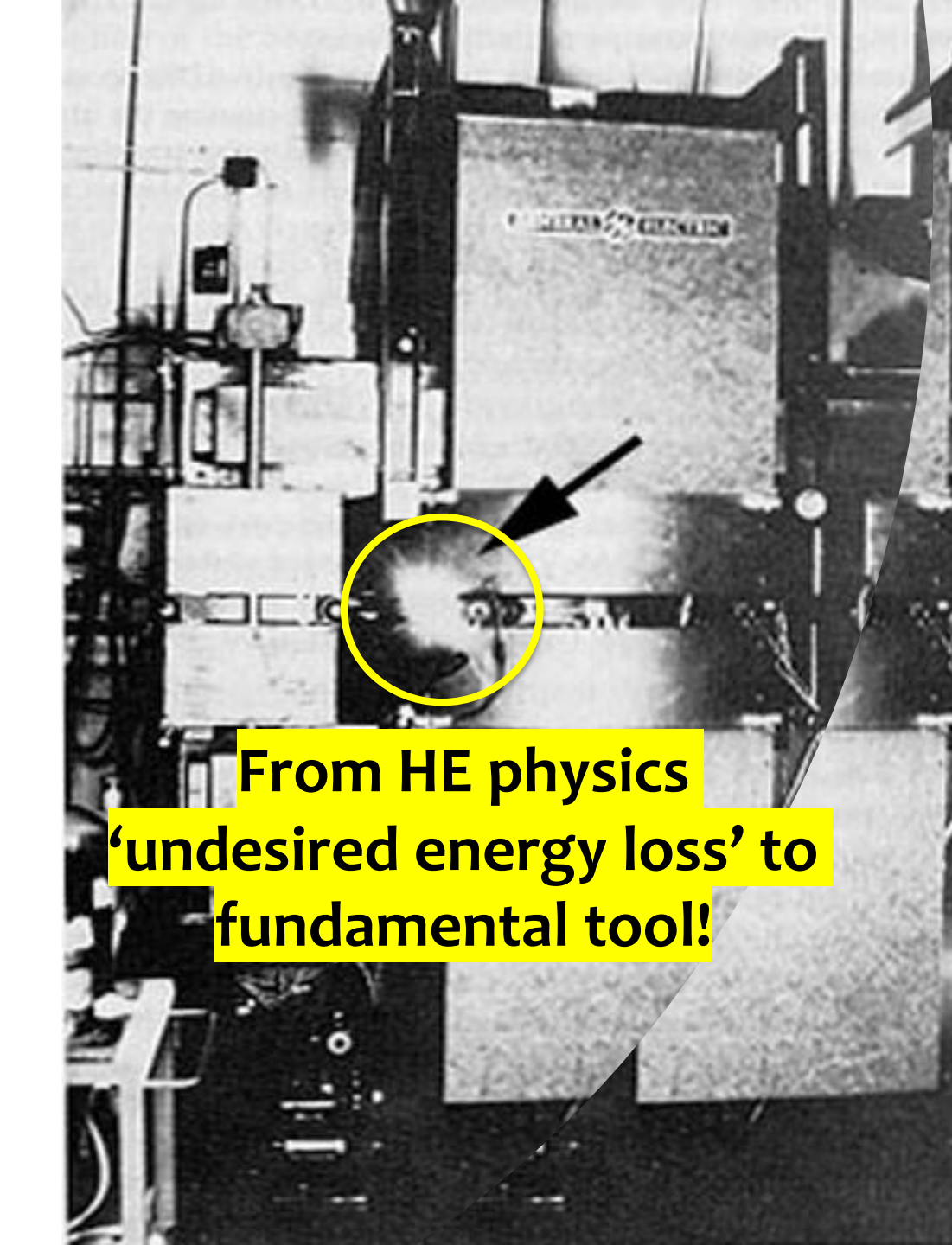
79 years long
adventure started
with its first
observation in 1947!

79 Years of Science with Synchrotron Radiation

1947

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

**Synchrotron radiation opened a new
era of accelerator-based light sources
that have rapidly evolved.**



**From HE physics
'undesired energy loss' to
fundamental tool!**

Historical evolution of Synchrotron Radiation Sources

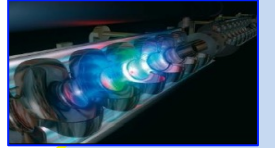
From high energy physics particle accelerators to dedicated synchrotron radiation sources and new technologies

Brightness increase

5th gen. - Advanced accelerator concepts

4th gen. - LINAC based accelerators

FELs and XFELs



3^{rd*} gen. Ultimate Storage Rings - USR

like MAX IV (Sweden) 2016

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



Accelerators to optimize SR - ID

First accelerators built for SR - BM



Using accelerators built for HE physics

ADA - B. Touschek - LNF



Storage rings development 1960

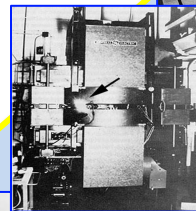
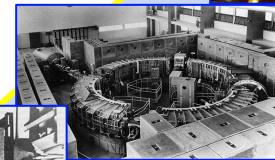
Parasitic use of electro-synchrotrons 1961

First observation of synchrotron radiation 1947

Proof of concepts, tests of theories 1897-1946

Electro- Synchrotrons

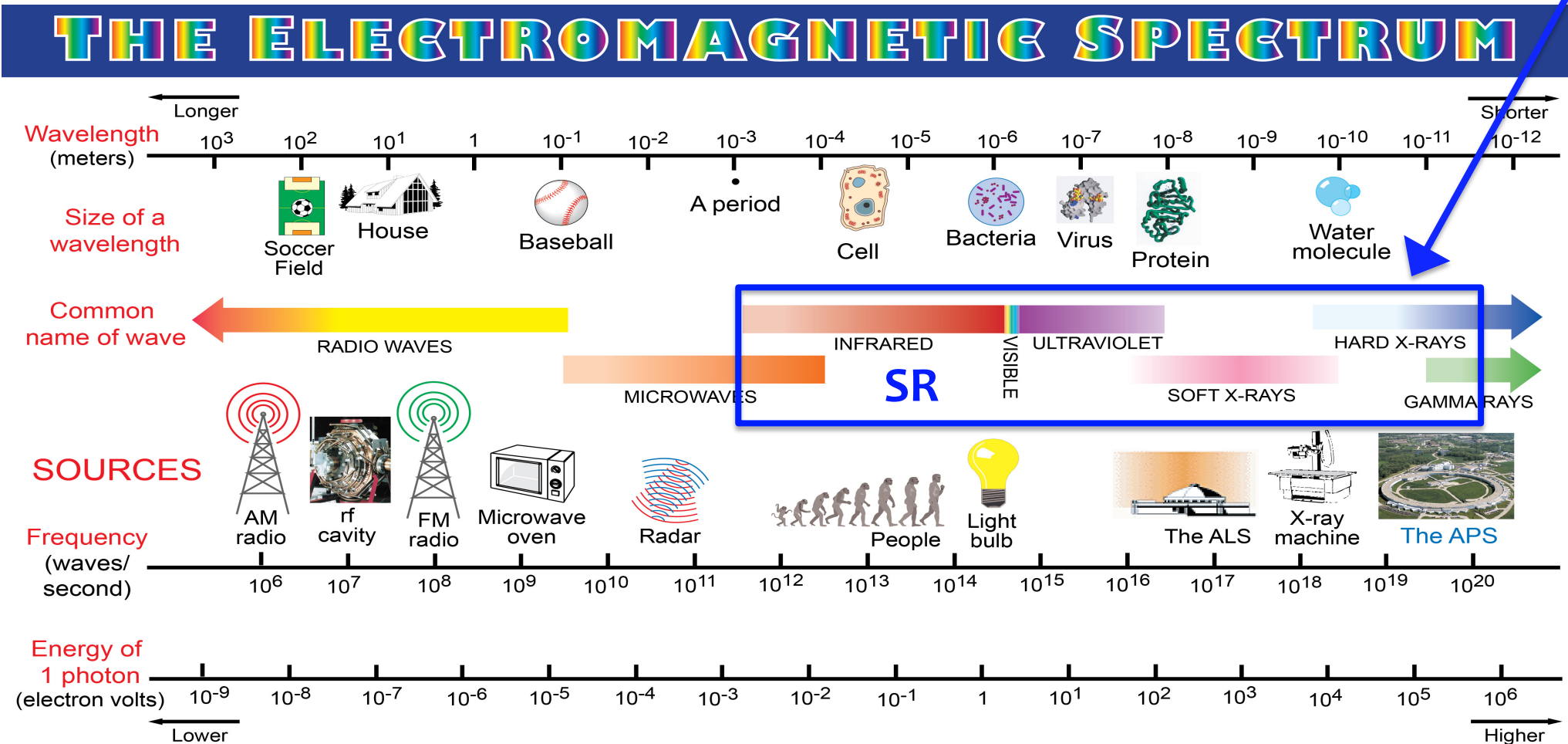
24/04/1947 General Electric Res. Lab. - 70 MeV Electro- Synchrotron (N.Y. USA)



J. Schwinger Nobel Prize 1965 Classical Relativistic quantum field theory

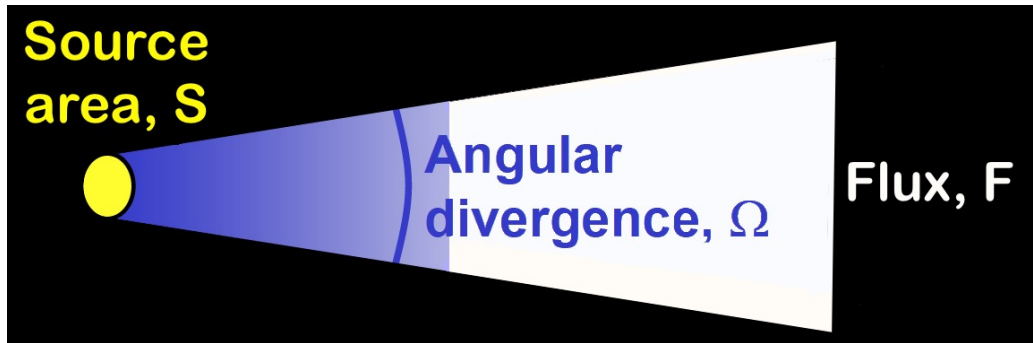


An important characteristic of Synchrotron Radiation: wide photon energy range

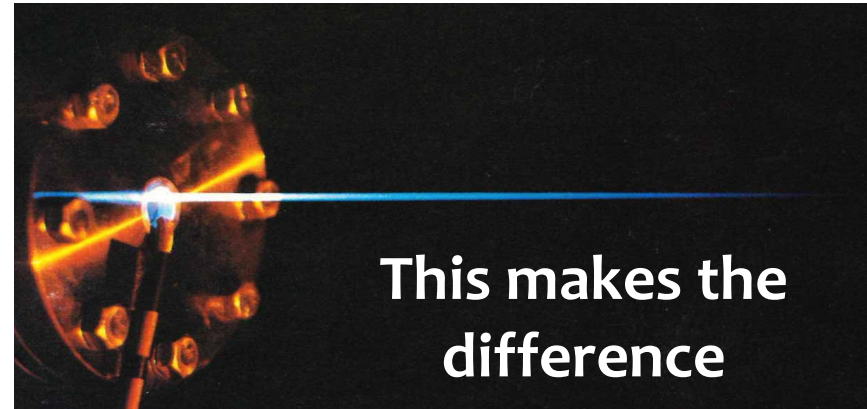


Another important characteristic of synchrotron radiation: brightness

A **bright source** is the one **very effective in illuminating a specific target**. If the specific target is very small a **bright source** must have, **high flux (F)** a **small source area (S)** and **radiation emission concentrated within a very narrow angular divergence (Ω)**.

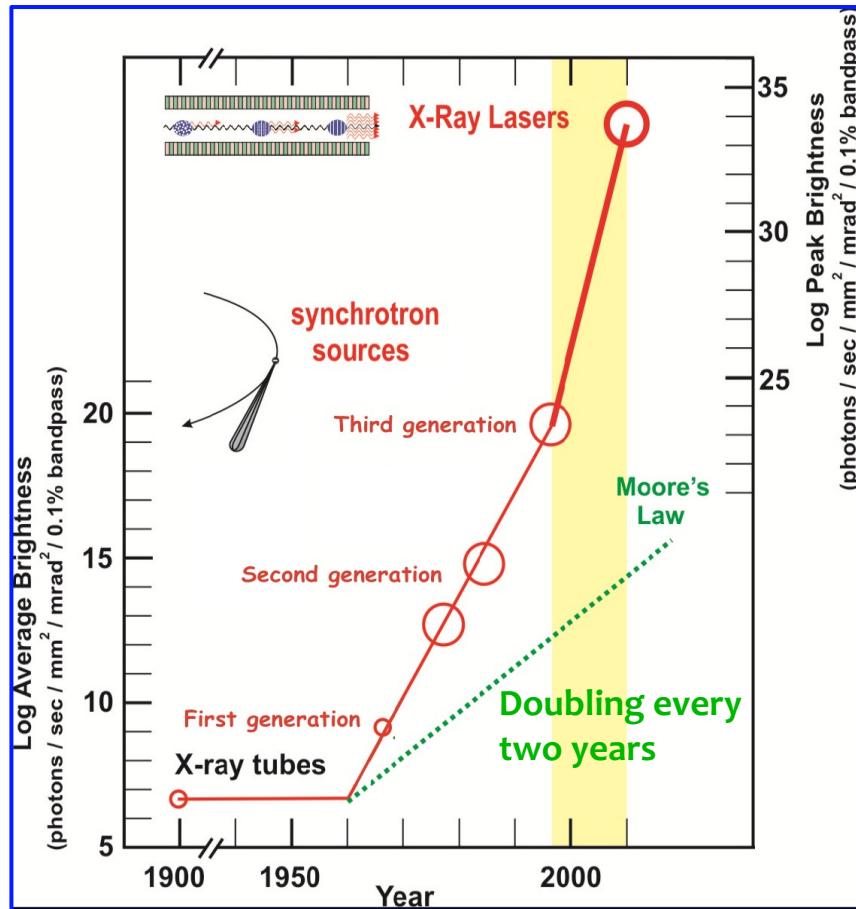


$$\text{Brightness} = \text{constant} \frac{F}{S \times \Omega}$$

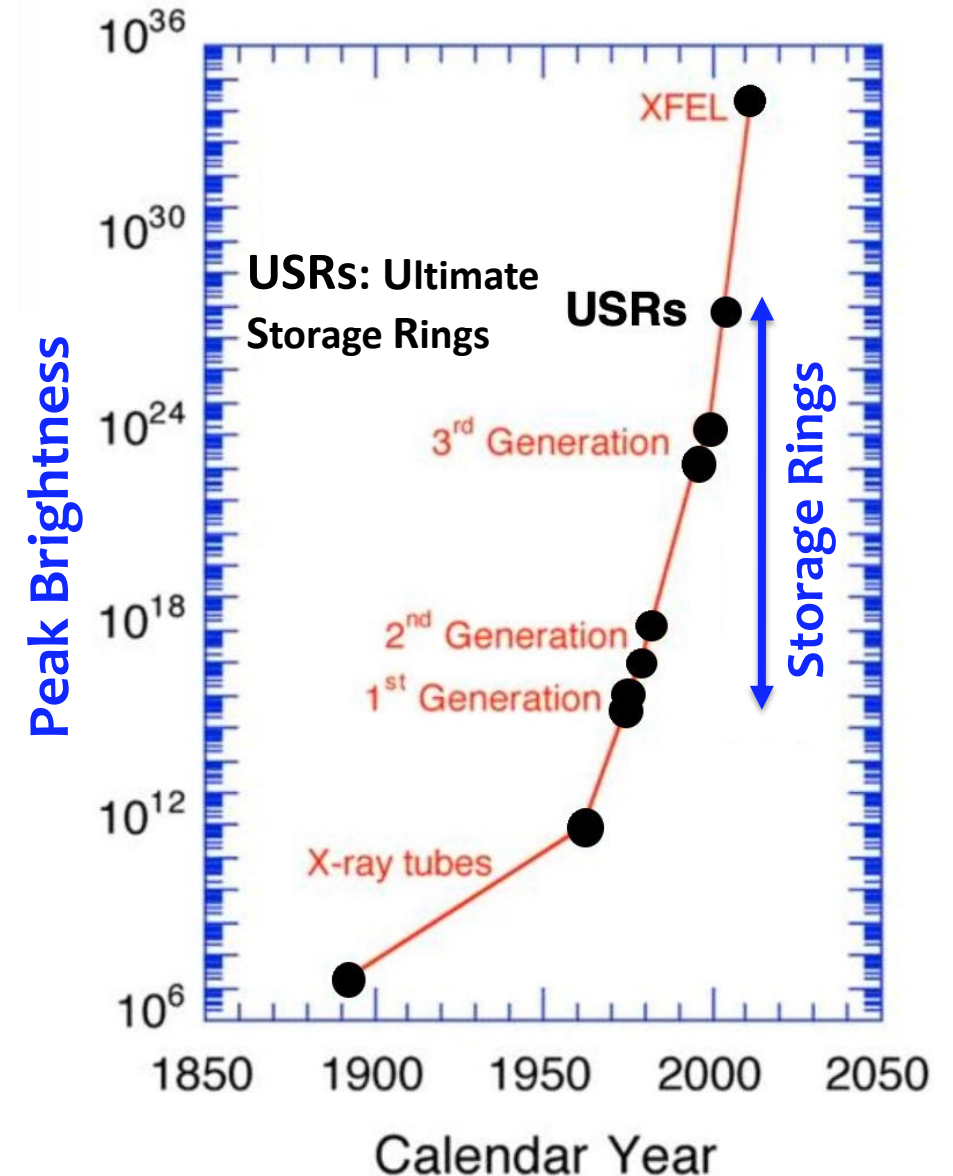


When interested in nm scale details brightness becomes fundamental

Relevant increase of brightness with time



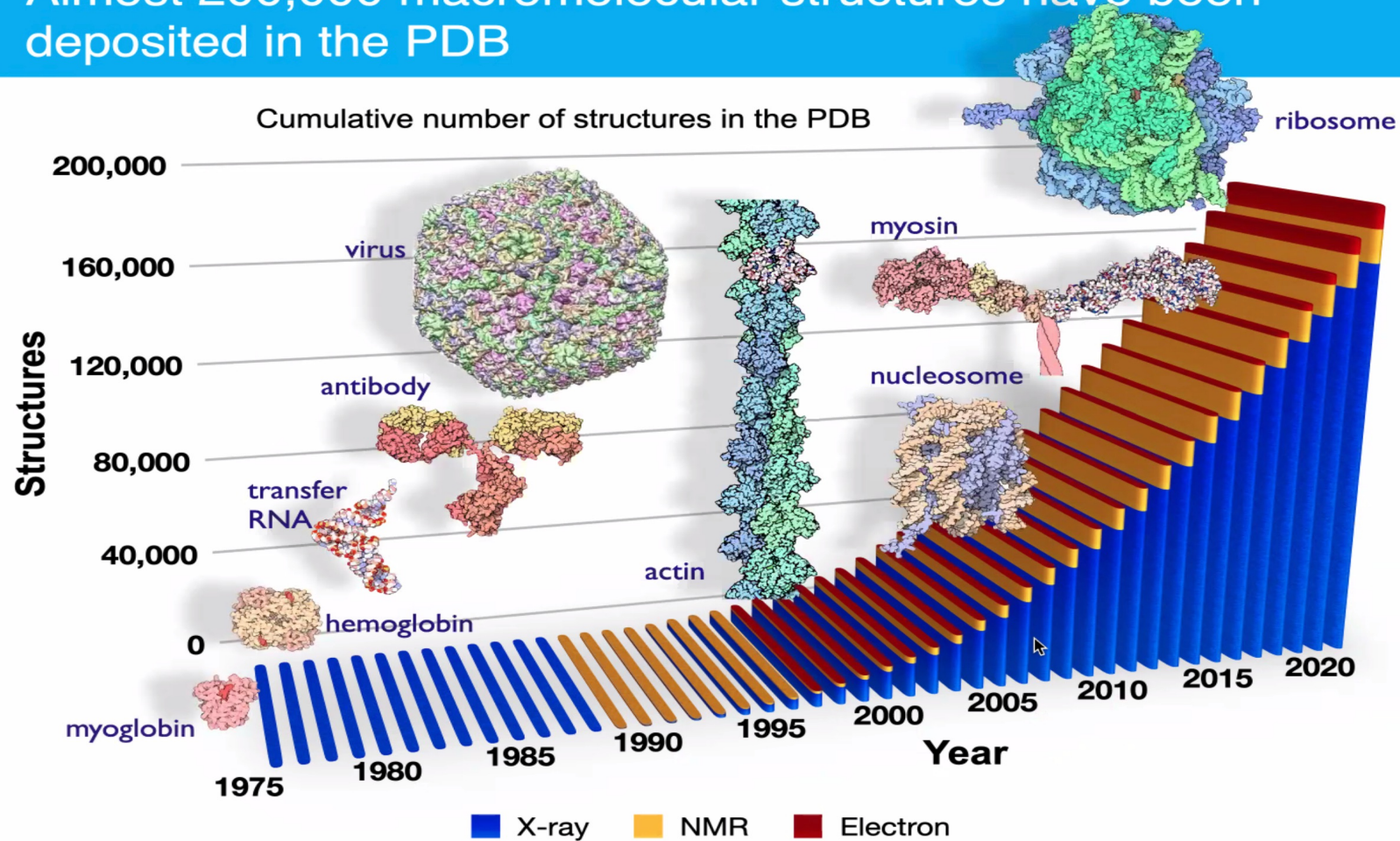
Brightness dramatic improvement over 79 years - outran of Moore's law.



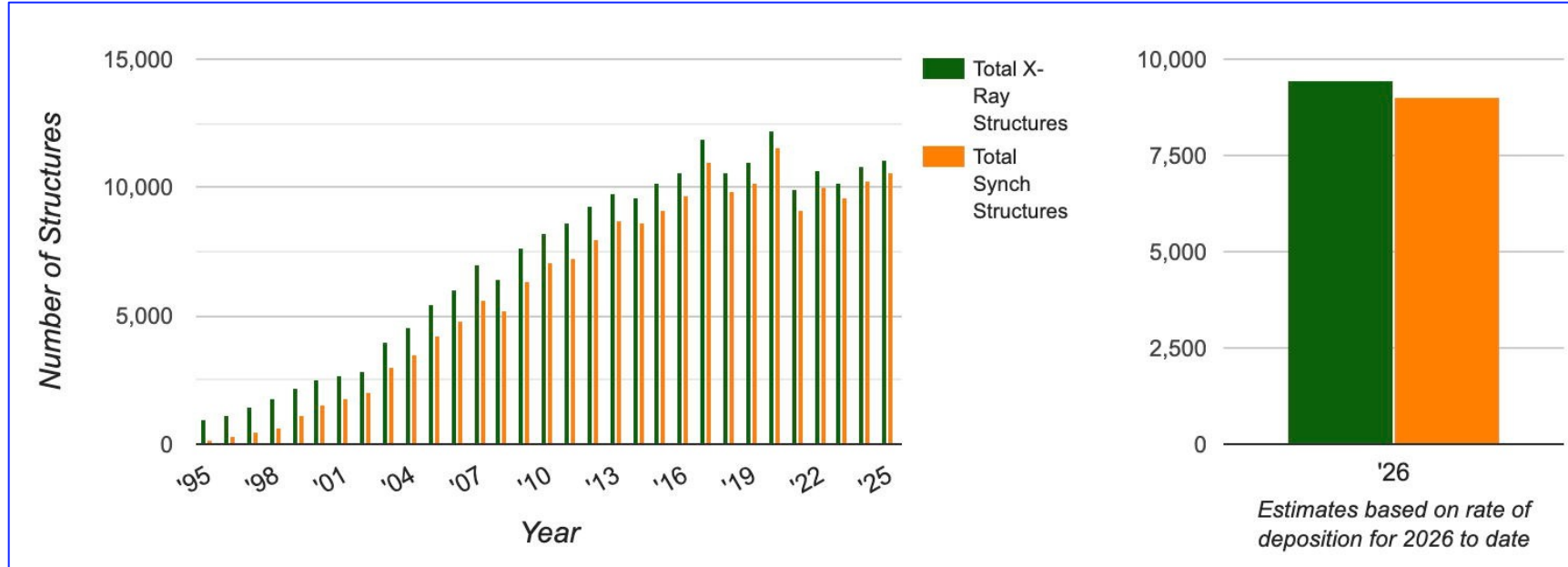
The evolution of synchrotron radiations sources and improvements in science

Biocrystallography and Proteins Data Bank

Almost 200,000 macromolecular structures have been deposited in the PDB

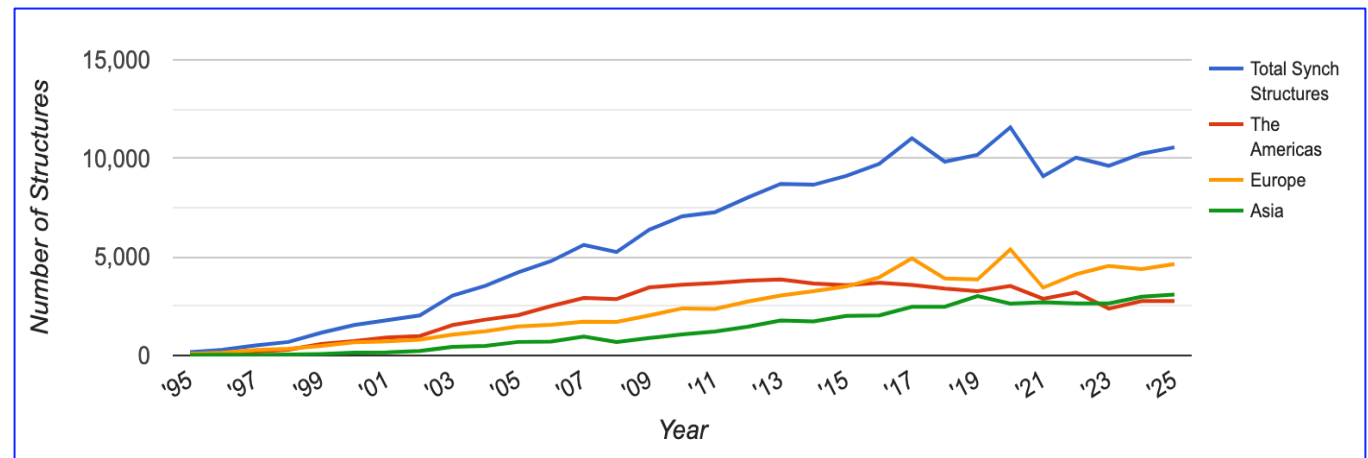


X-ray biocrystallography and synchrotron radiation

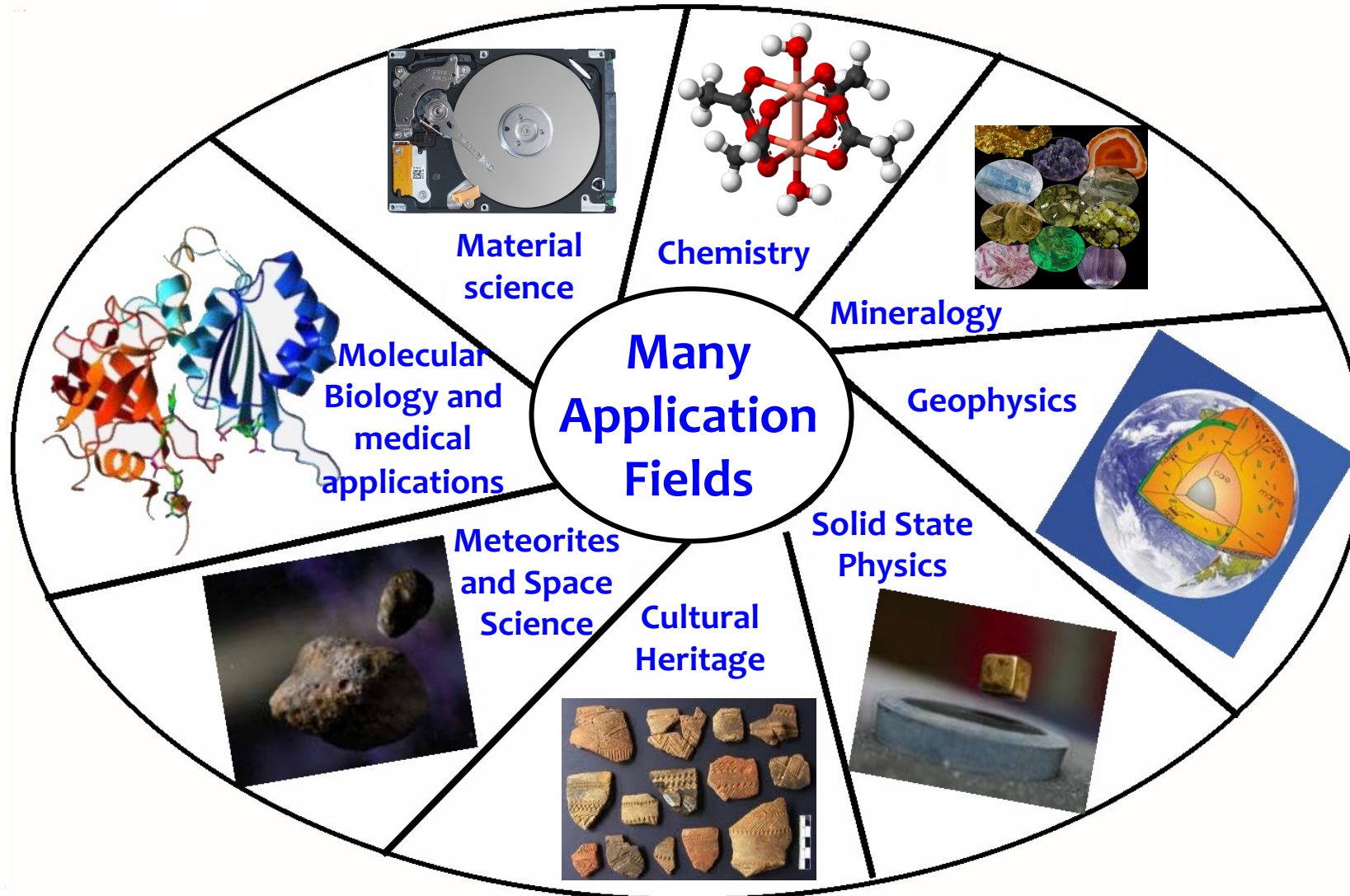


15 July 2026

<http://biosync.sbkb.org/index.jsp>



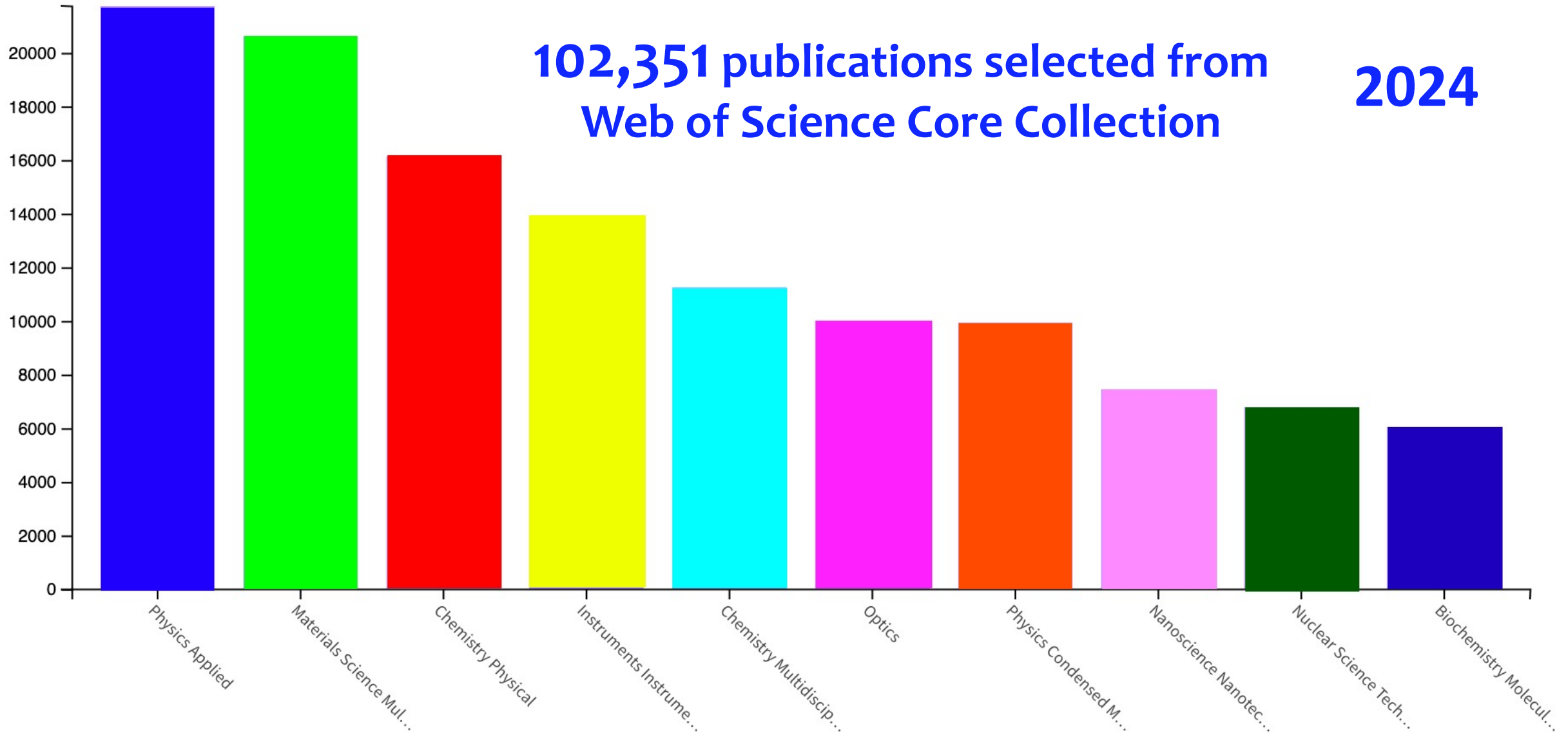
Application Fields of Synchrotron Radiation



Searching 'Synchrotron Radiation'

102,351 publications selected from
Web of Science Core Collection

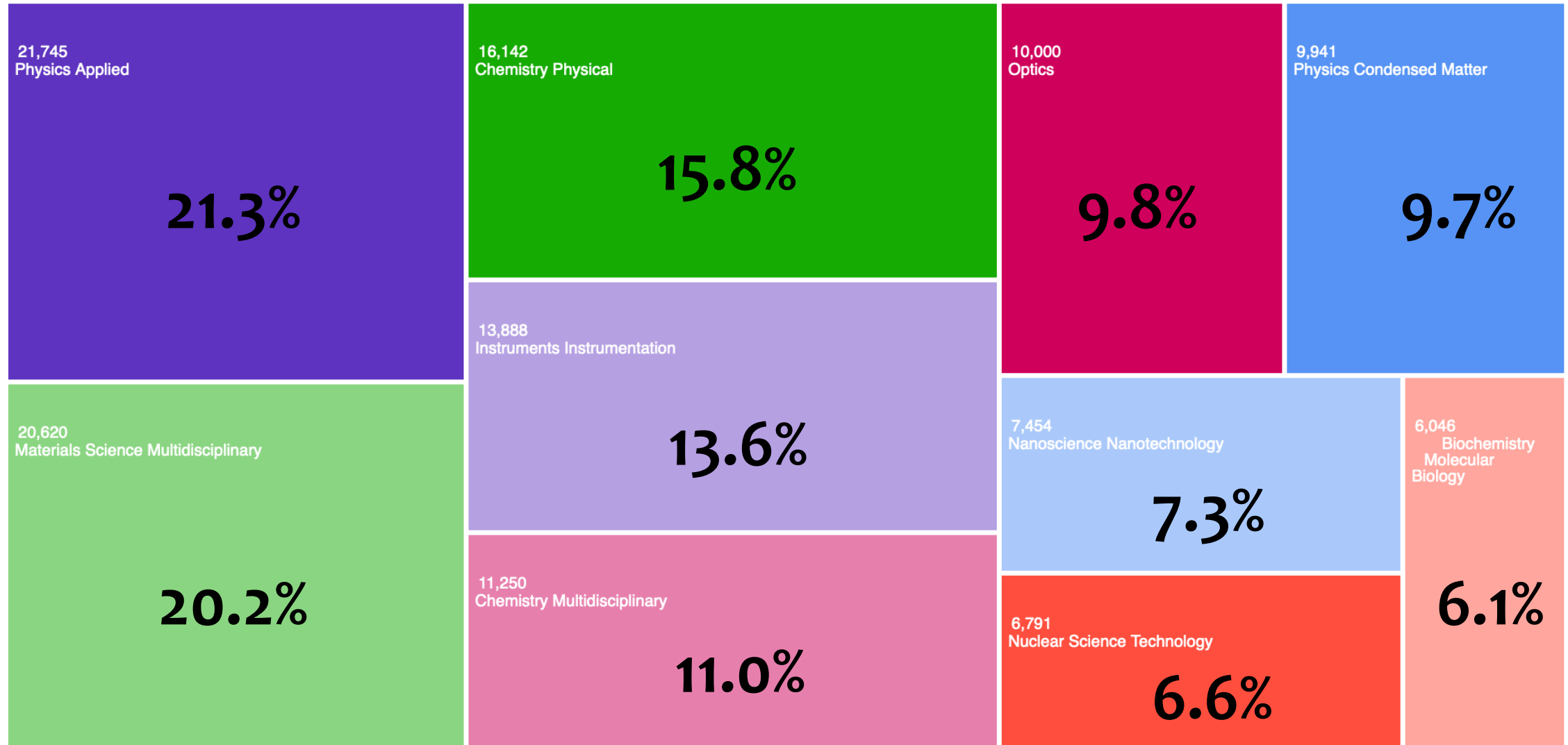
2024



Searching 'Synchrotron Radiation'

102,351 publications selected from Web of Science Core Collection

% of 102,351



Introduction to Synchrotron Radiation

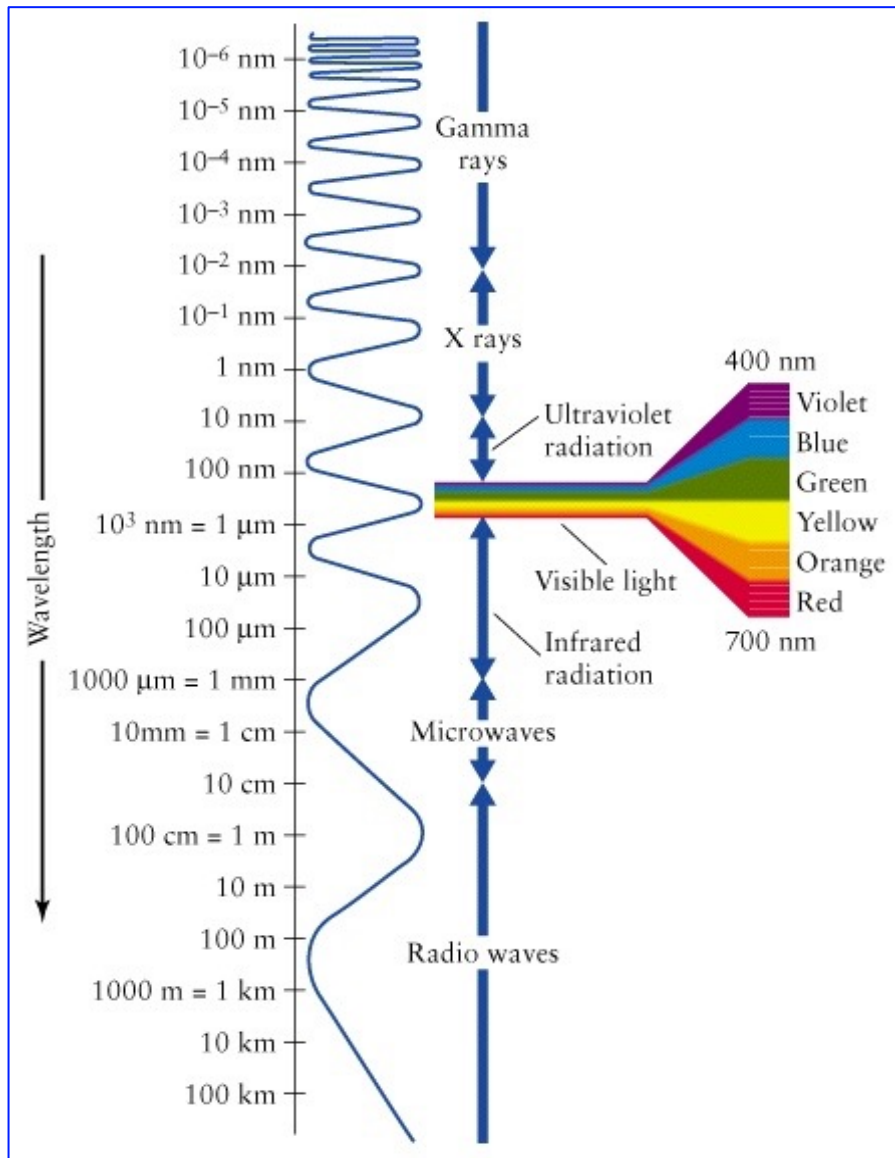
Introduction to Synchrotron Radiation

Outline

- **Electromagnetic Radiation - Remind**
- **Synchrotron radiation**
- **SR main properties**
- **Sources of Synchrotron Radiation**
- **Present and future**

Electromagnetic Radiation - Remind

Electromagnetic radiation/waves – remind



$$\lambda \nu = c \quad E = h \nu$$

λ = photon wavelength

ν = photon frequency

E = photon energy

c = speed of light

h = Planck constant

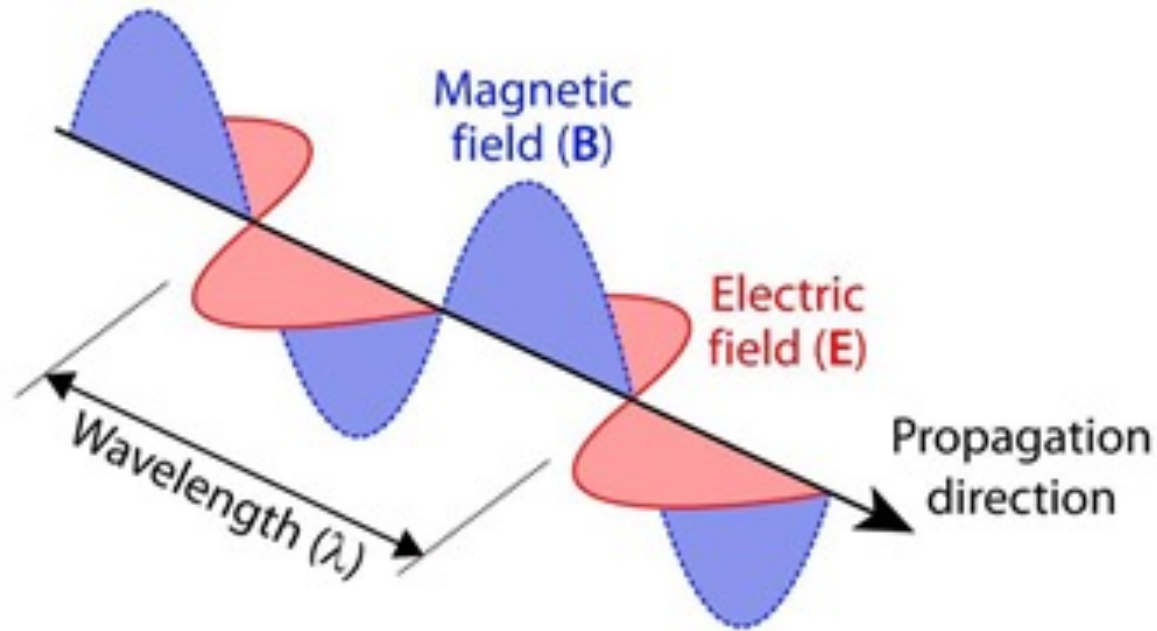
$\hbar = h/2\pi$ reduced Planck constant

$$c = 299792458 \text{ m/s}$$

$$h = 4.135667517 \times 10^{-15} \text{ eV s}$$

$$\hbar = 1.054571817 \times 10^{-34} \text{ J s}$$

Electromagnetic waves - remind



Electromagnetic wave includes both electric field (**E**) and a magnetic field (**B**), in transverse directions with respect to the **wave propagation direction** and perpendicular to each other.

Electromagnetic wave emission requires the **acceleration of electric charges** and the emitted **power** being proportional to the **square of the acceleration**.

Non-relativistic Larmor equation

$$P = \frac{q^2 a^2}{6\pi\epsilon_0 c^3}$$

P is the **radiated power**; **q** is the **electric charge** and **a** is the **acceleration**

Relativity - remind

Electrons $\xrightarrow{v}$

$$\beta = \frac{v}{c}$$

$c = 299792458 \text{ m/s}$ -
speed of light

Lorentz factor

$$\boxed{\gamma} = \frac{1}{\sqrt{1 - \beta^2}}$$

$$E = \gamma m_0 c^2$$

Total energy

$$\gamma = \frac{E}{m_0 c^2} = \frac{E}{510998.9461 \text{ eV}}$$

$$\boxed{\gamma \approx 1957 \text{ E(GeV)}}$$

$E_0 = m_0 c^2 = 0.511 \text{ MeV}$ electron rest energy

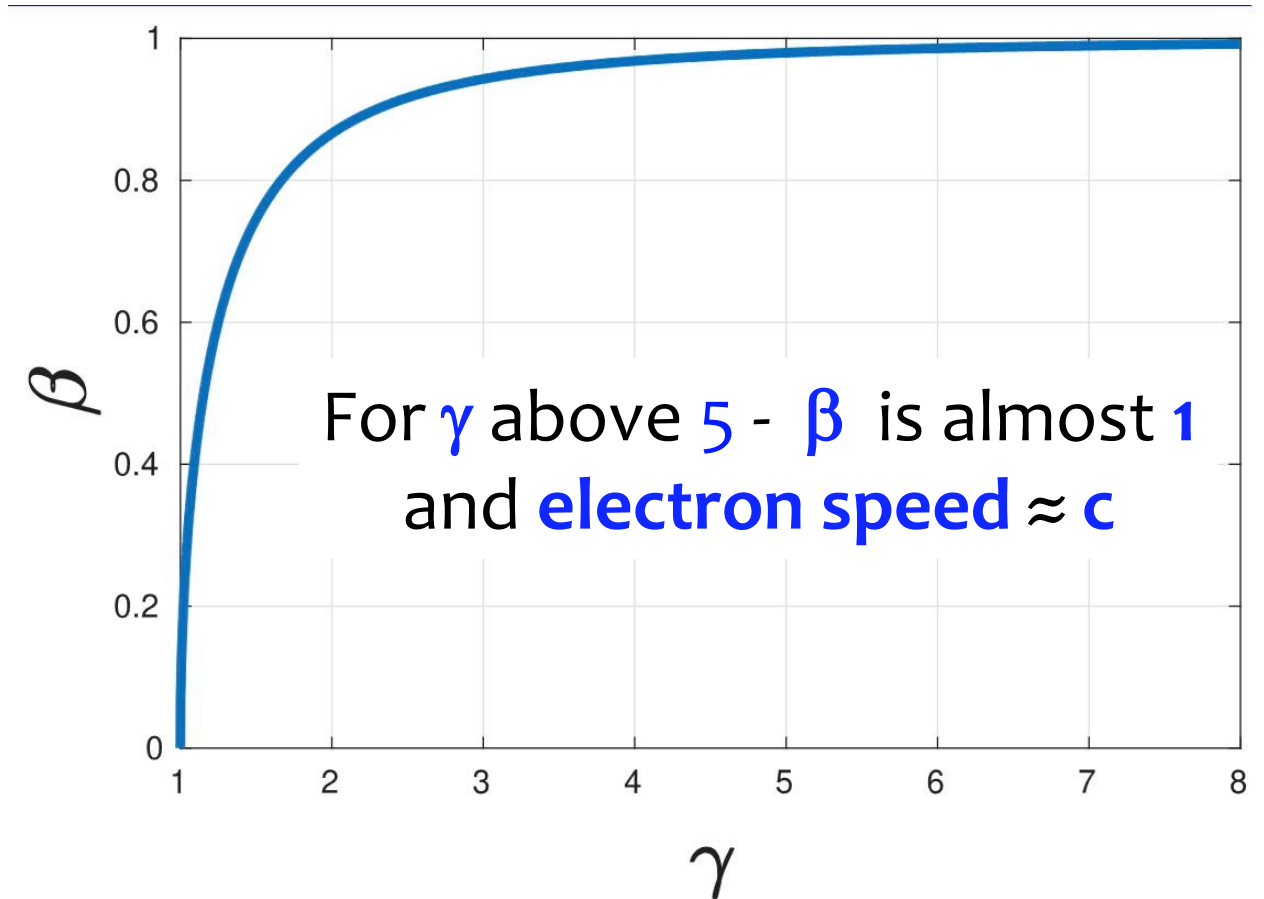
Relativity - remind

$$\beta = \frac{v}{c}$$

v = speed of electrons

c = 299792458 m/s - speed of light

$$\gamma \approx 1957 \text{ E(GeV)}$$



ESRF $E = 6 \text{ GeV}$ $\gamma \approx 11800$

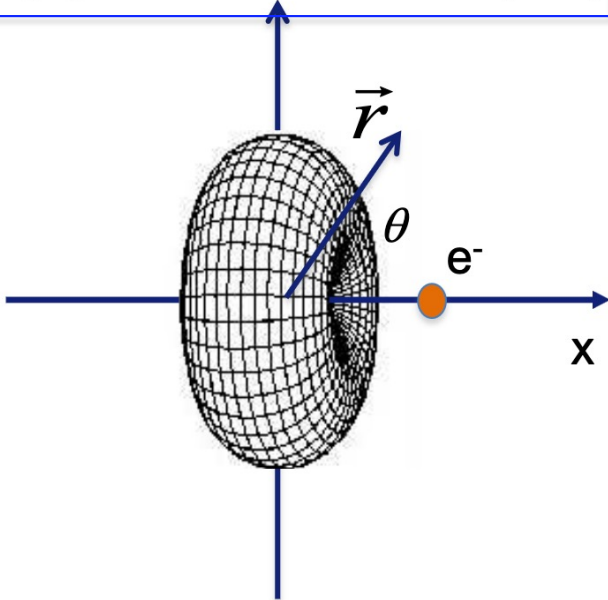
Not-relativistic electromagnetic wave emission

Charge oscillating along x

$$x(t) = A \cos(\omega t)$$

$$v(t) = -A\omega \sin(\omega t)$$

$$a(t) = -A\omega^2 \cos(\omega t)$$



Poynting vector

$$\langle S \rangle \propto \frac{\sin^2 \theta}{r^2} \hat{r}$$

The oscillating charge **emits radiation in all directions** at a frequency **$f = \omega/2\pi$**

S = Poynting vector

Energy per unit of time and surface

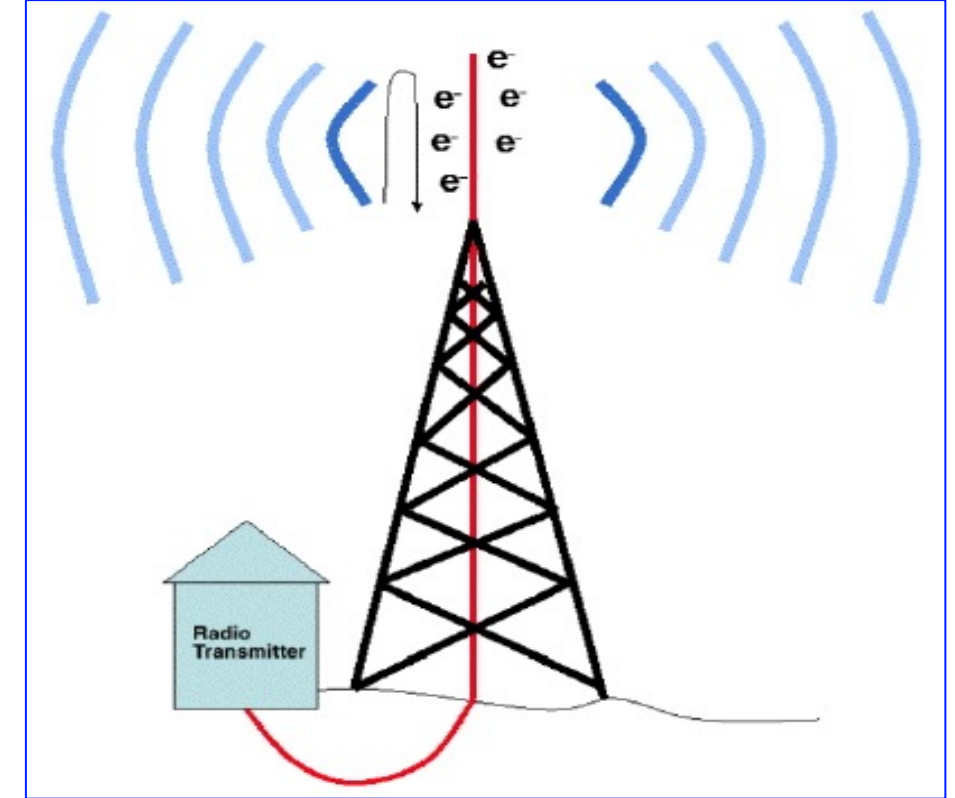
Acceleration, charged particles and radiation emission

Accelerated not-relativistic charged particles like e^- emit electromagnetic radiation when forced to oscillate along an antenna.

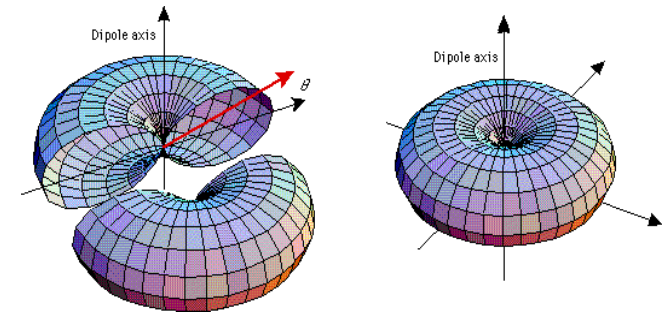
$$v \ll c \quad \text{or} \quad \beta = v/c \ll 1$$

c = speed of light = 2.99782×10^8 m/s

An antenna converts a time-varying electrical current into a propagating electromagnetic wave.



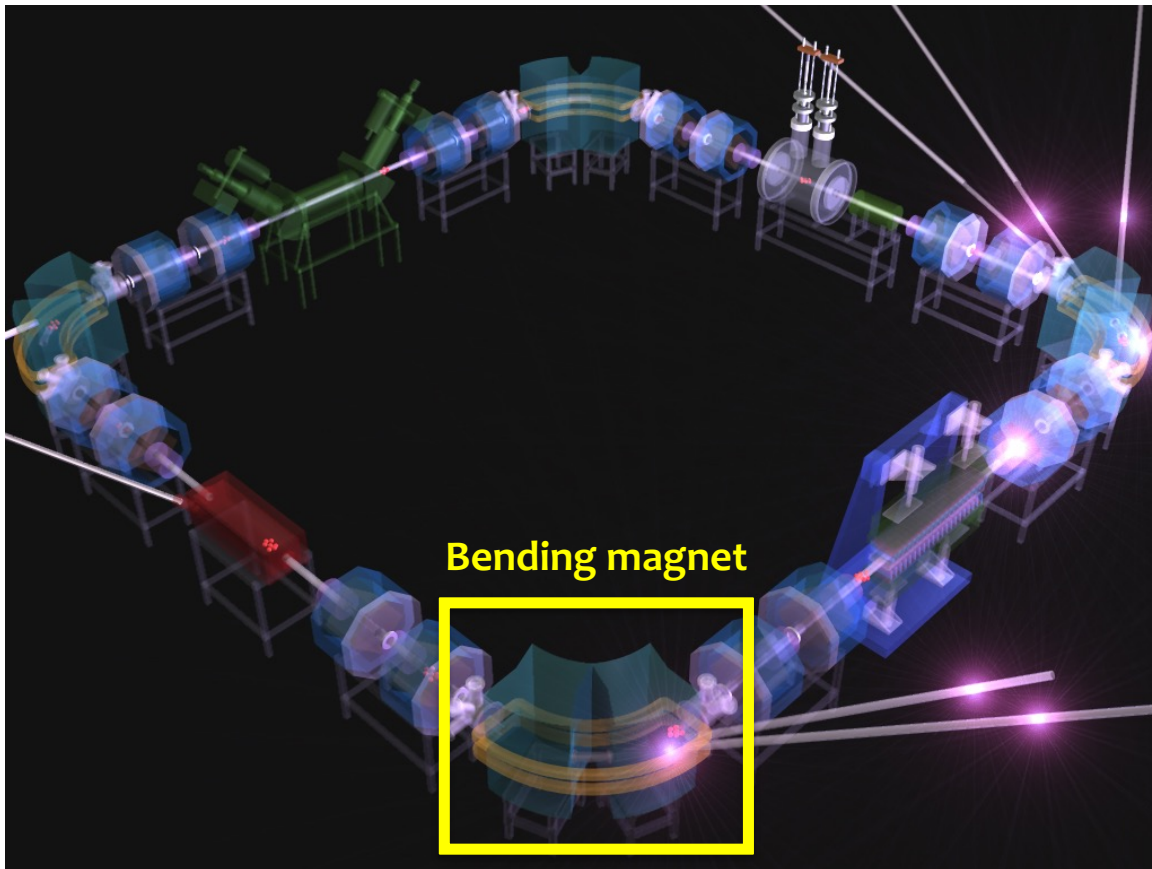
The intensity distribution is rotationally symmetric around the direction of the centripetal acceleration.



Synchrotron radiation

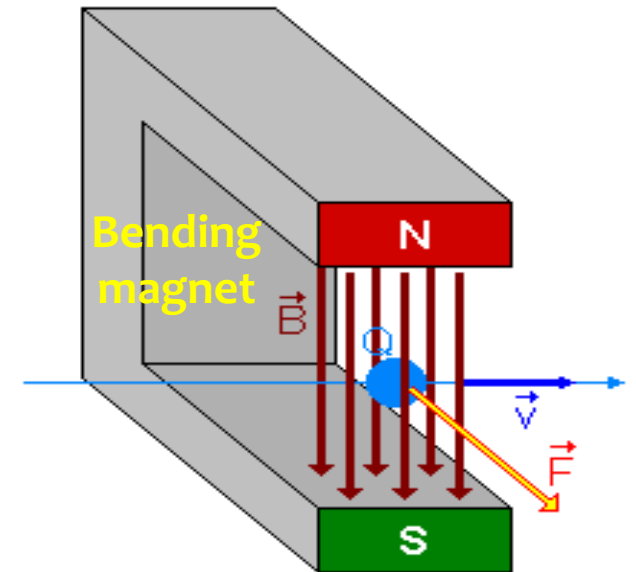
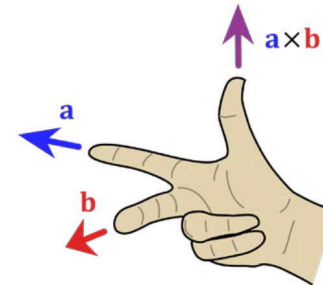
**Relativistic electromagnetic
radiation emission**

Synchrotron Radiation



Charged particles in vacuum forced to move at relativistic speeds on circular paths by the action of bending magnetic field (B) - Lorentz force.

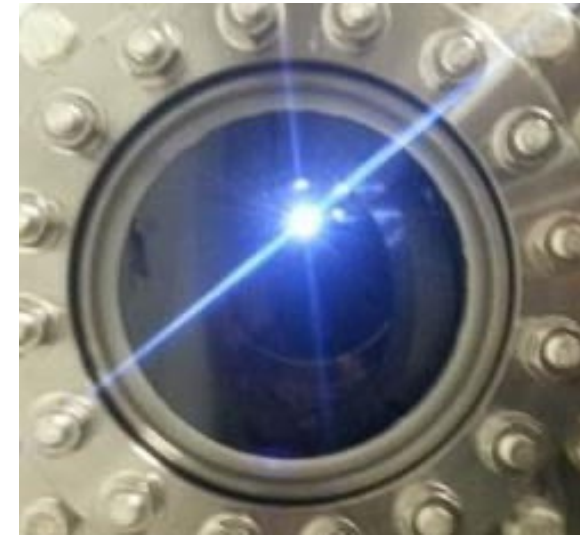
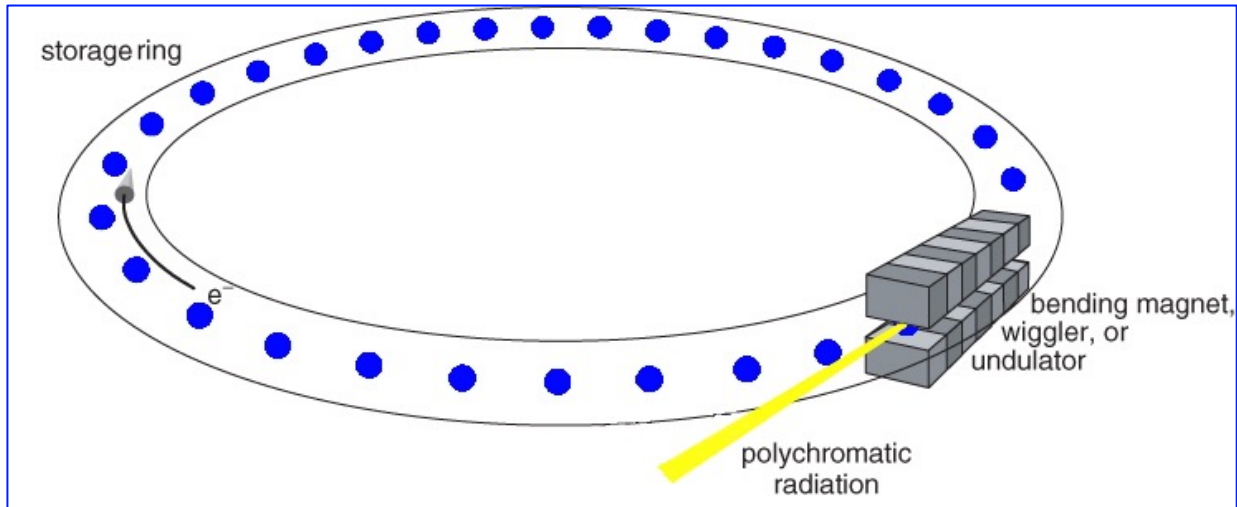
$$\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$



Force and acceleration, are perpendicular to the particle speed. Particles travel on an arc of circumference inside the bending magnets.

Acceleration, charged particles and radiation emission

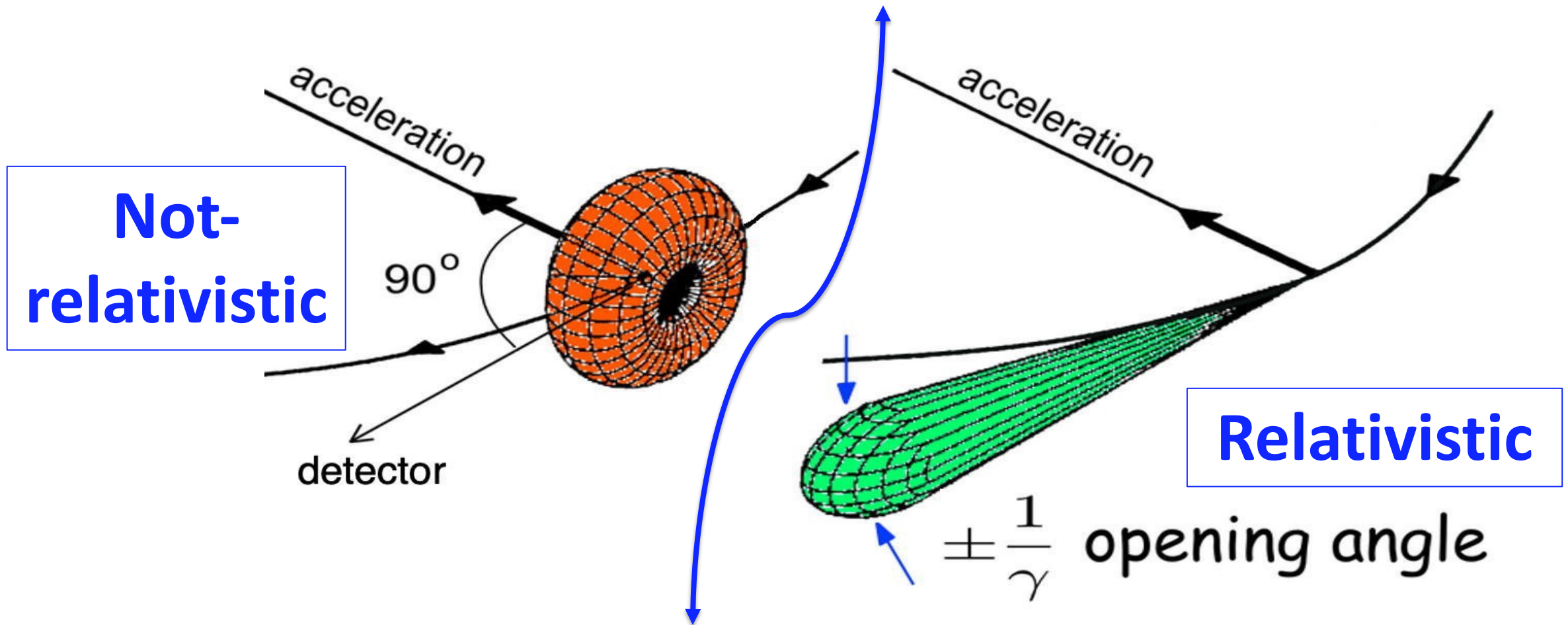
If charged particles, moving at relativistic speeds ($v \approx c$), are forced (Lorentz force) to change the direction of their motion (acceleration), under the effect of magnetic fields, like in circular particle accelerators, there is the emission of synchrotron radiation.



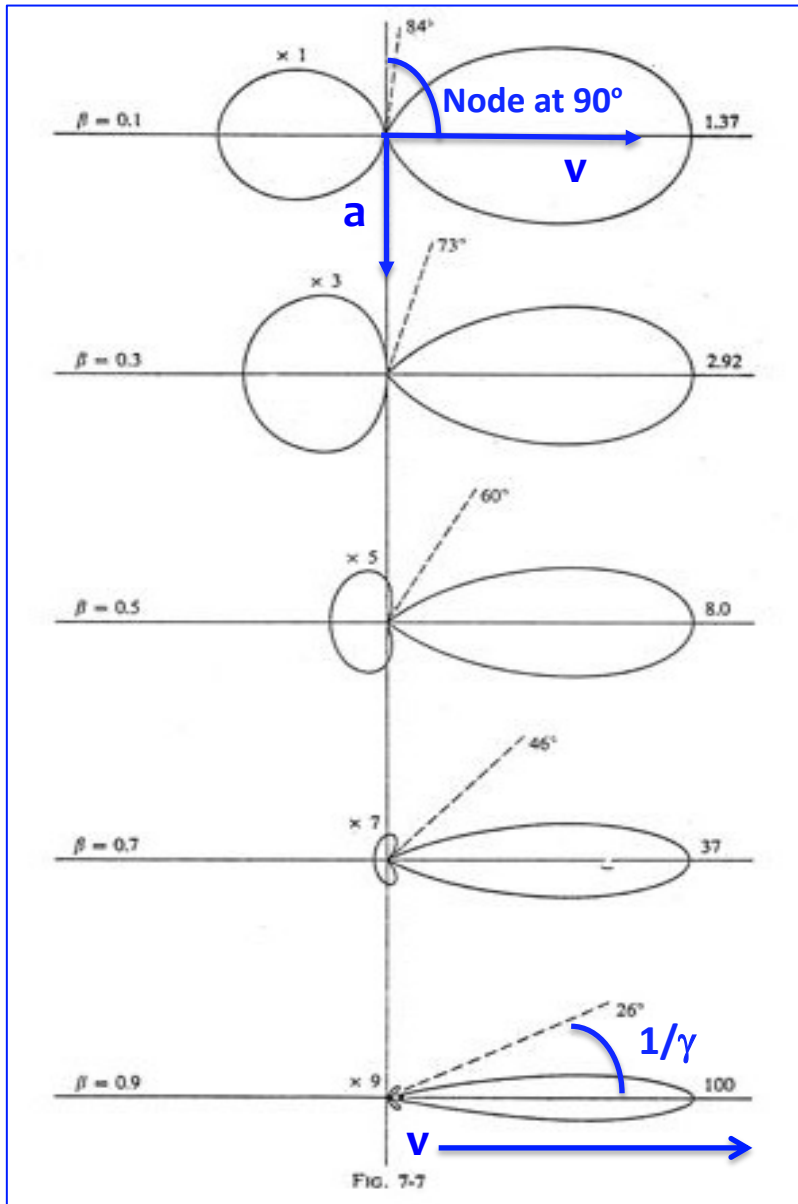
Very intense
SR beam
Max IV Lab

$$v \approx c \quad \text{or} \quad \beta = v/c \approx 1$$

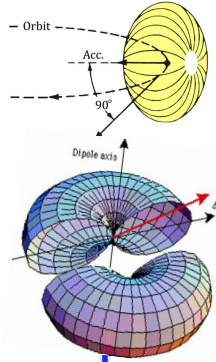
Moving from not-relativistic to relativistic



Synchrotron radiation: physics



$$v \ll c \text{ or } \beta = v/c \ll 1$$



As β approaches 1 :

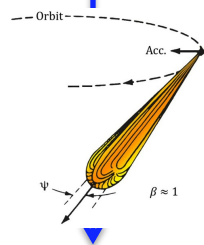
1. the shape of the radiation pattern changes it is more in the forward direction
2. the relativistic Lorentz transformation of angles gives a decrease by a factor of γ (relativistic focusing of the emitted radiation)
3. the node at $\theta' = 90^\circ$ (in the frame of the radiating particle $v \perp a$) transforms to:

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

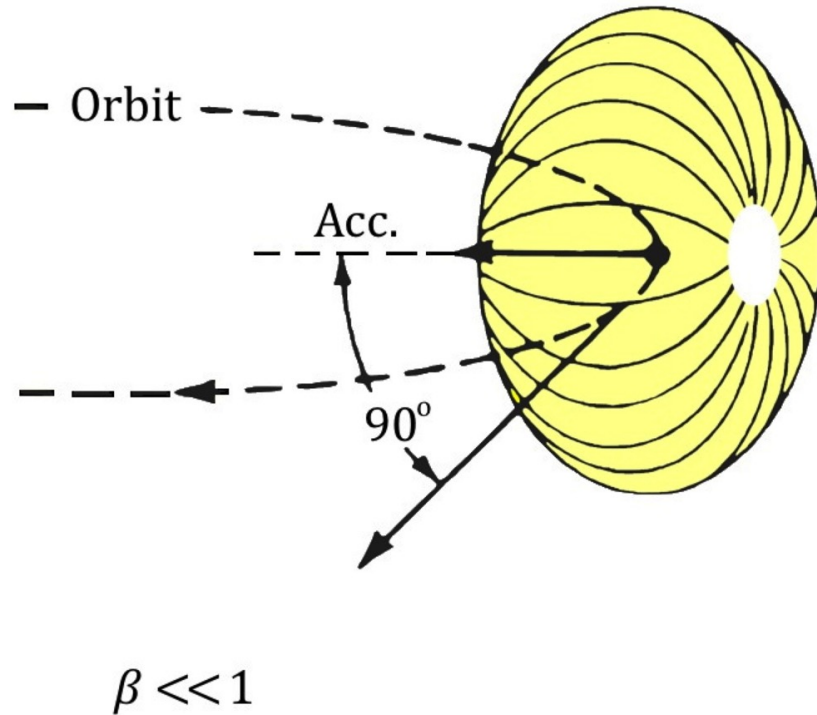
For electron energies in storage rings between 1–5 GeV, γ is between 2000 and 10000. The angle of emission is normally much lower than 1 mrad (0.057°).

$$v \approx c \text{ or } \beta = v/c \approx 1$$

$$\gamma = \frac{E}{mc^2} = \frac{E}{510998.9461 \text{ eV}}$$

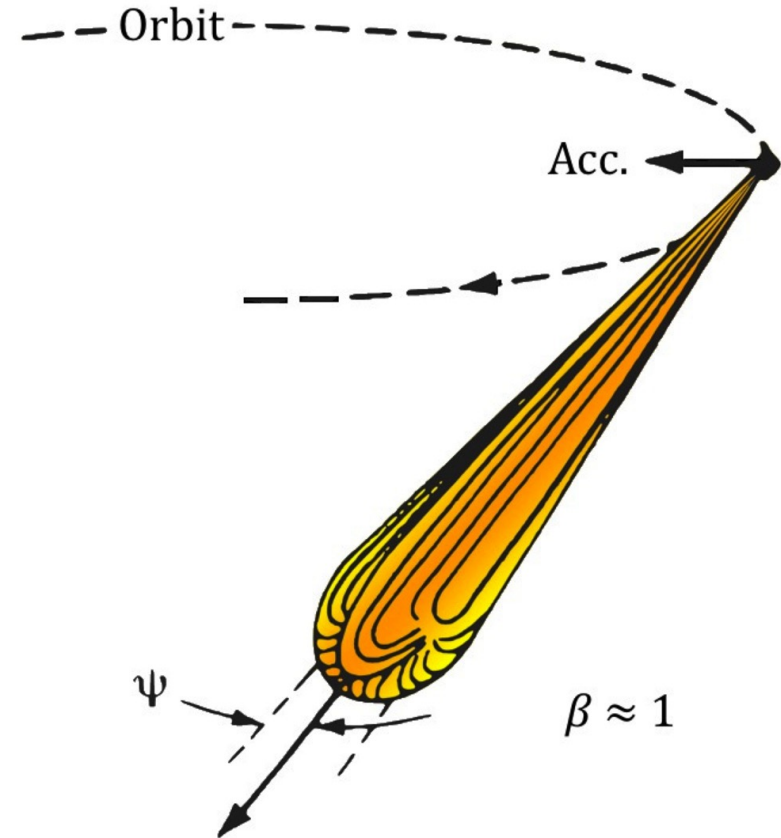


Synchrotron radiation and physics



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

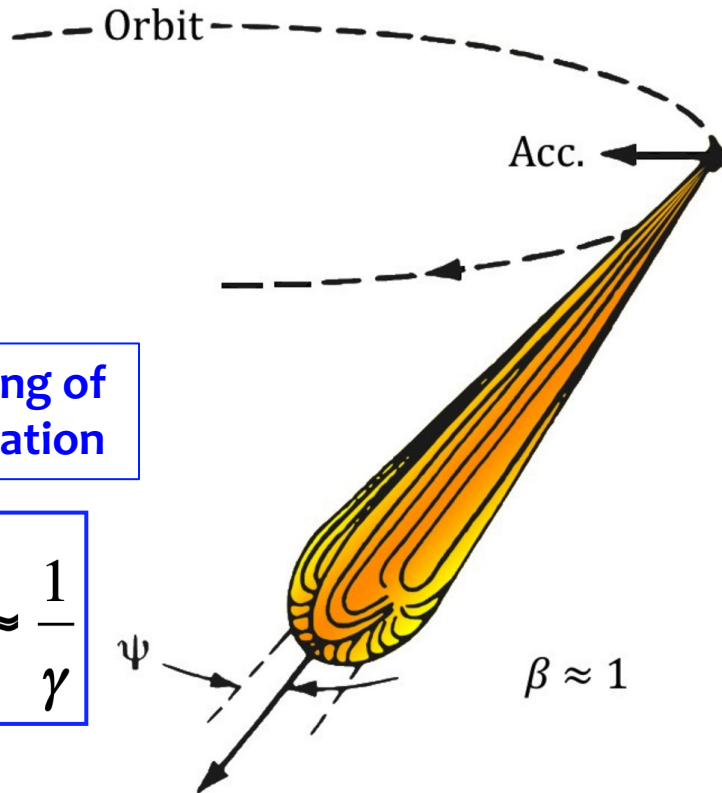
Not-Relativistic



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

Relativistic

Synchrotron radiation: physics



Relativistic focusing of
Synchrotron Radiation

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

$$v \approx c \text{ or } \beta = v/c \approx 1$$

Radiated power

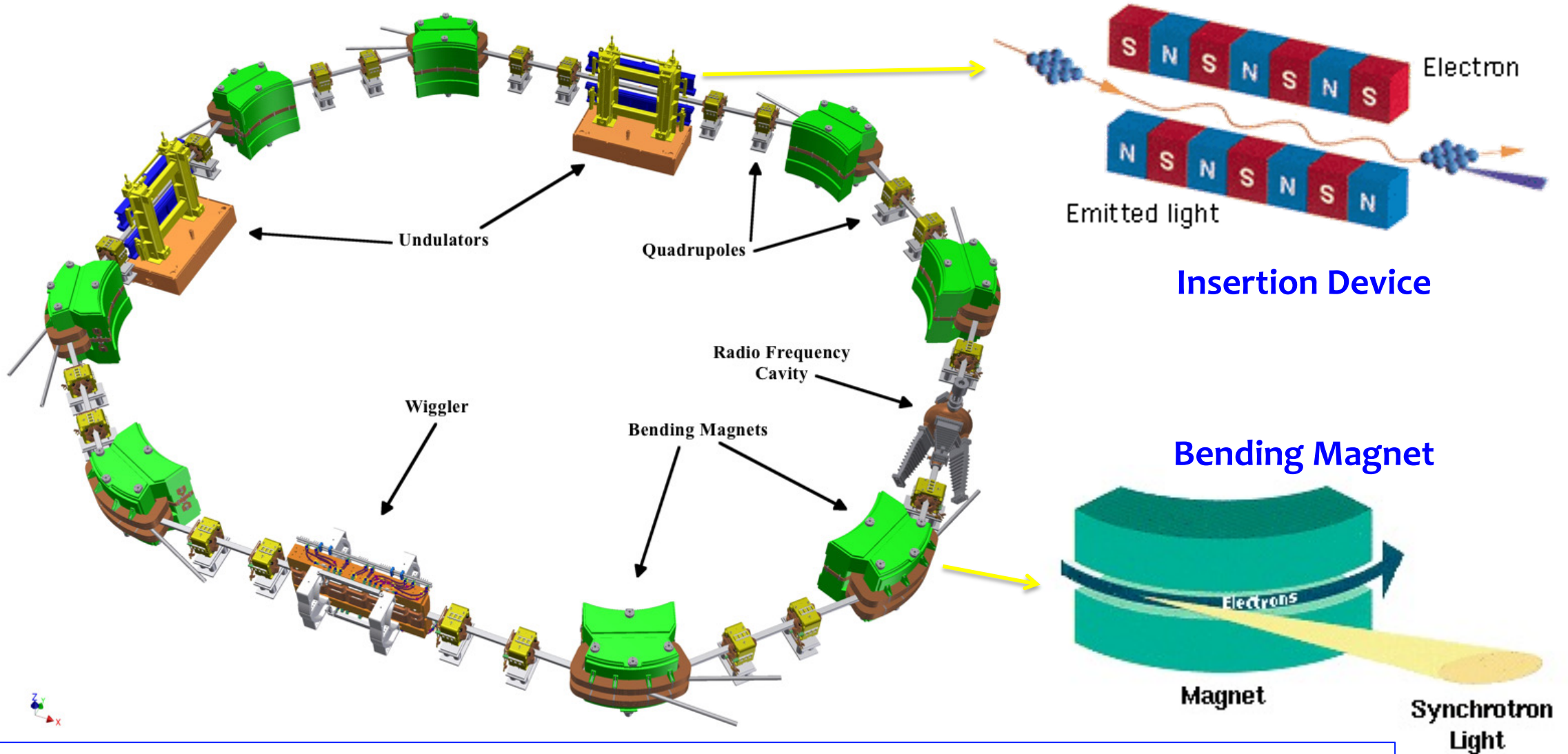
$$P_{rad} = \frac{2}{3} \frac{Q^2 c}{R^2} \left[\frac{E}{m_0 c^2} \right]^4$$

E = particle energy, **m₀** = rest mass, **R** = radius of curvature, **Q** = particle charge

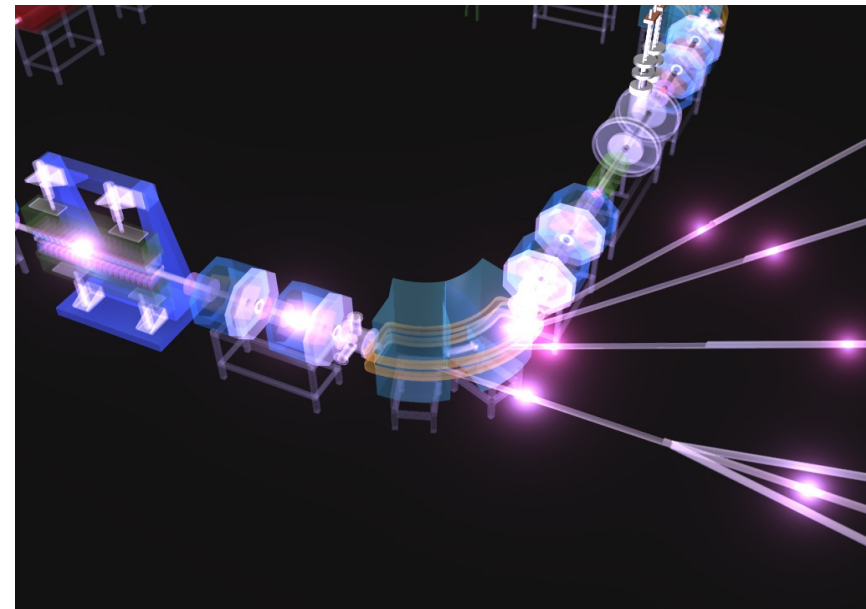
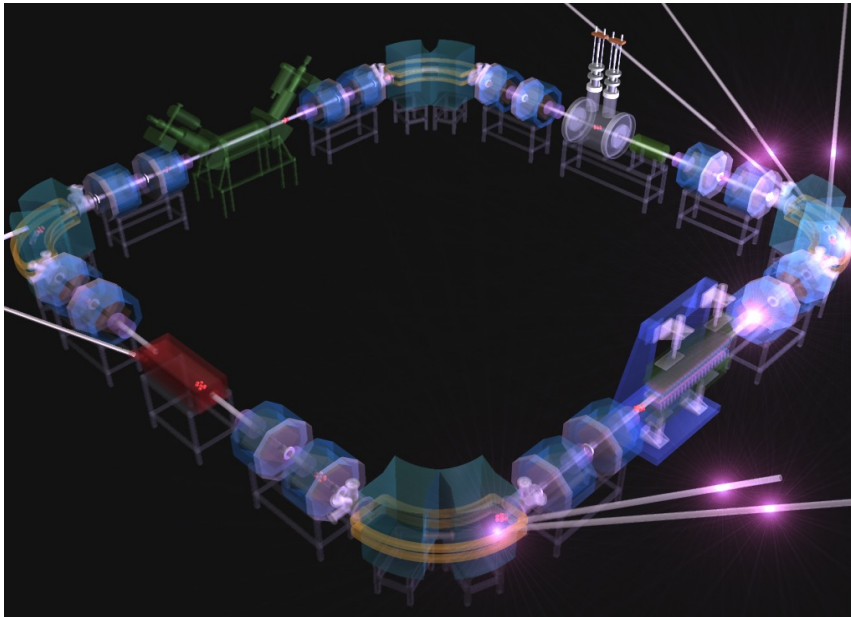
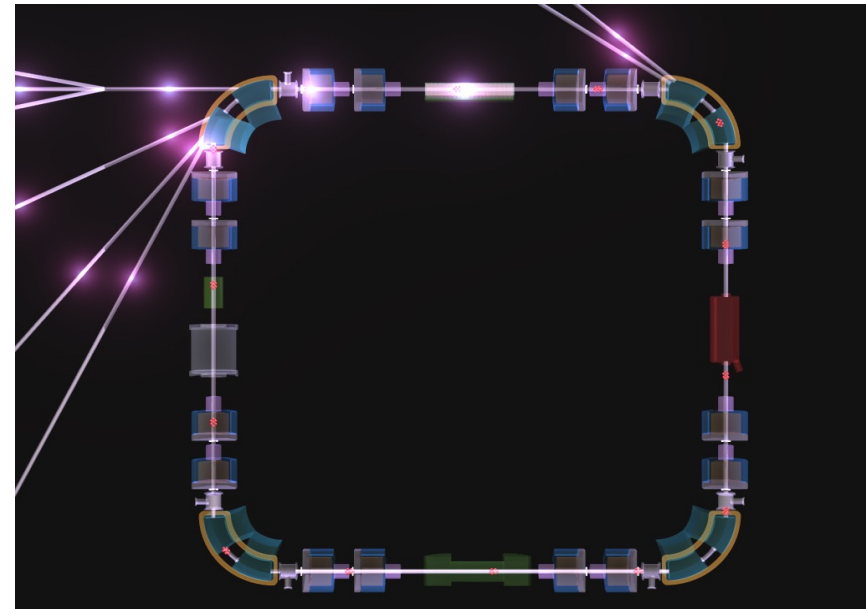
1949 Schwinger: classical theory of radiation from accelerated relativistic electrons (previously orally disseminated)

Tombouliau, 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)

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



... and synchrotron radiation is also the coherent radiation emitted by the undulators of Free Electron Lasers (FELs)

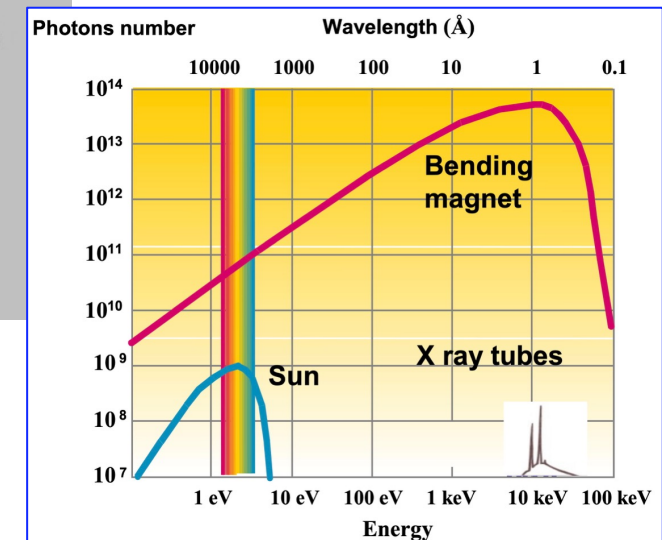
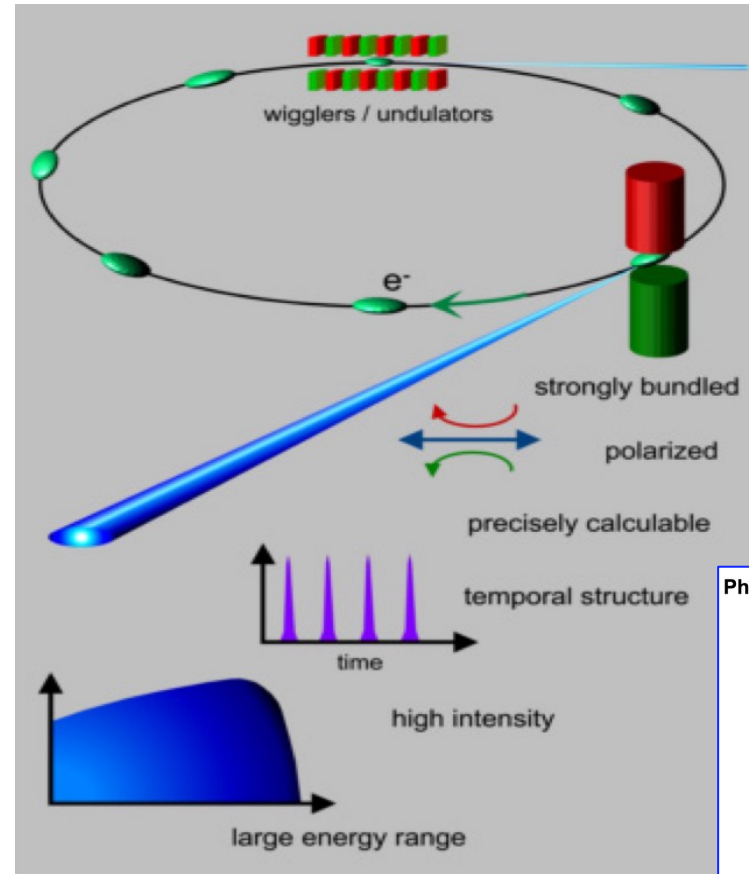


ASTRID (Aarhus - Denmark) <http://www.isa.au.dk/animations/pictures/pic-index.asp>

Synchrotron Radiation Properties

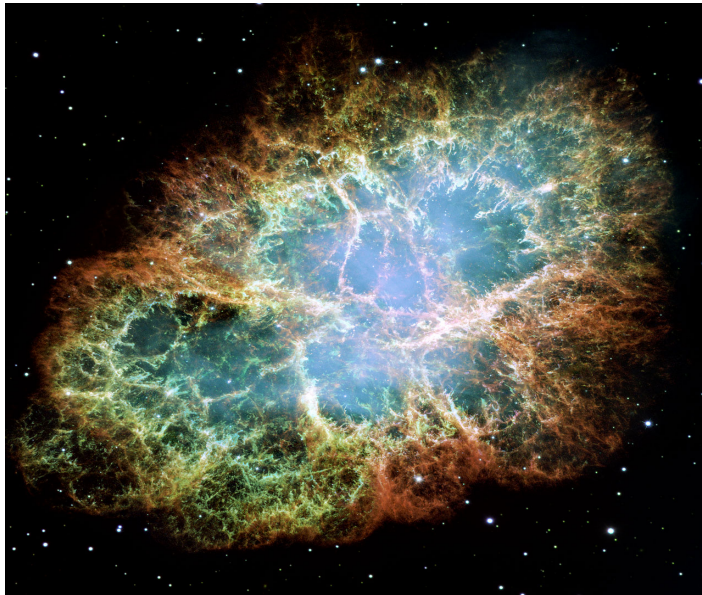
What makes synchrotron radiation interesting, powerful and unique?

1. **Tunability:** large energy range from IR to X-rays; possibility to select the wavelength required for experiments using a **continuous** (Bending Magnets / Wigglers) or **quasi-monochromatic** (Undulators) **emission**
2. Source in a clean UHV environment
3. Very high flux and **brightness** (with undulators) **highly collimated photon beams** with **small divergences** and **small source sizes**.
4. **Highly Polarized**
5. **Pulsed time structure** - pulsed length down to **tens of picoseconds** allows the **resolution of processes on the same time scale**
6. **High stability** (submicron source stability)



Synchrotron radiation is present in nature!

Synchrotron radiation is a very important emission process in astrophysics.

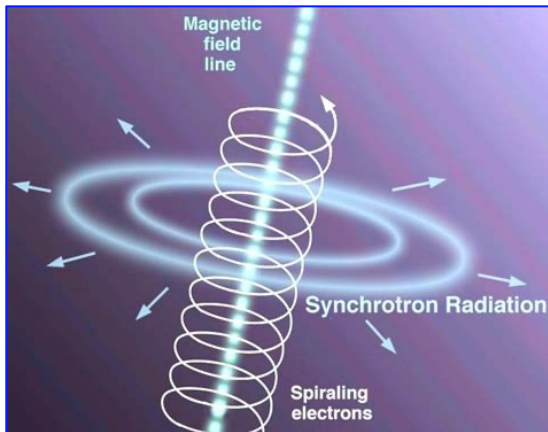


NASA Hubble Space Telescope image of the Crab Nebula (NASA, ESA and Allison Loll/Jeff Hester (Arizona State University)).

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 field 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.

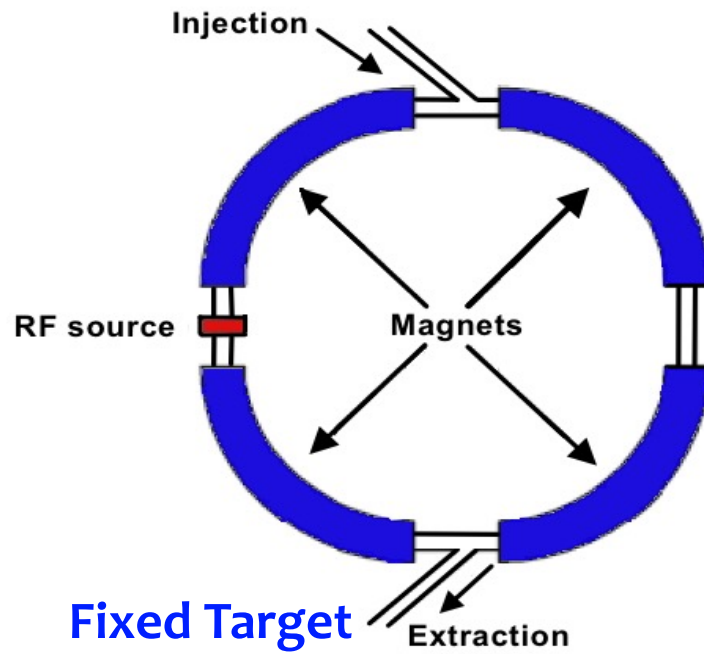


NASA's Great Observatories' View of the Crab Nebula X-Ray-blue: NASA/CXC/J.Hester (ASU); Optical-red and yellow: NASA/ESA/J.Hester & A.Loll (ASU); Infrared-purple: NASA/JPL-Caltech/R.Gehrz (Univ. Minn.)

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
and accelerators:
from synchrotrons (past) to
storage rings (present)**

Synchrotrons, storage rings and high energy physics

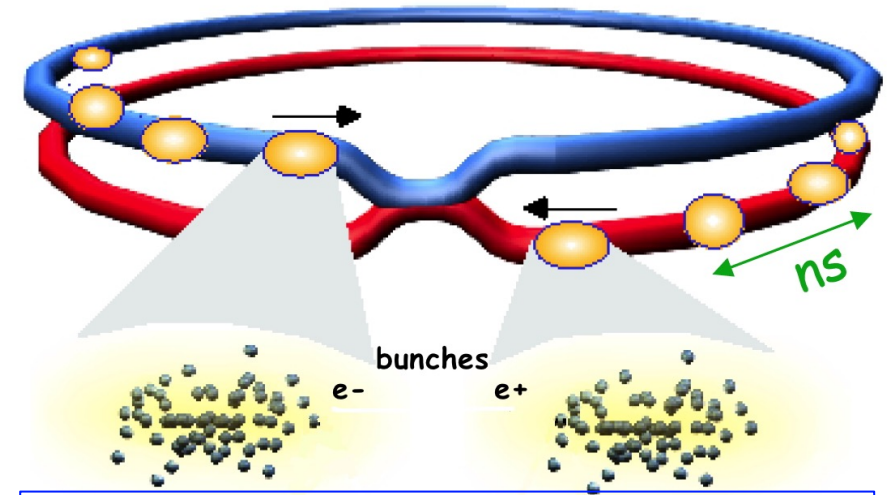


Synchrotrons

Particle beam on fixed target

$$E_{CM} \approx (E_{beam})^{1/2}$$

Energy is lost in the target and only part is used for particle production



INFN-LNF ADA (Anello Di Accumulazione) - first electron-positron storage ring - 0.25 GeV, C= 5 m (1961-1964)

Storage rings and colliders

Colliding particle beams

$$E_{CM} = E_{beam1} + E_{beam2}$$

All the energy used for particle production

Colliders are more efficient

E = particle energy $\gg m_0 c^2$ E_{CM} = total center of mass energy

Comparing synchrotrons and storage rings

storage rings best choice also as synchrotron radiation sources

Synchrotrons

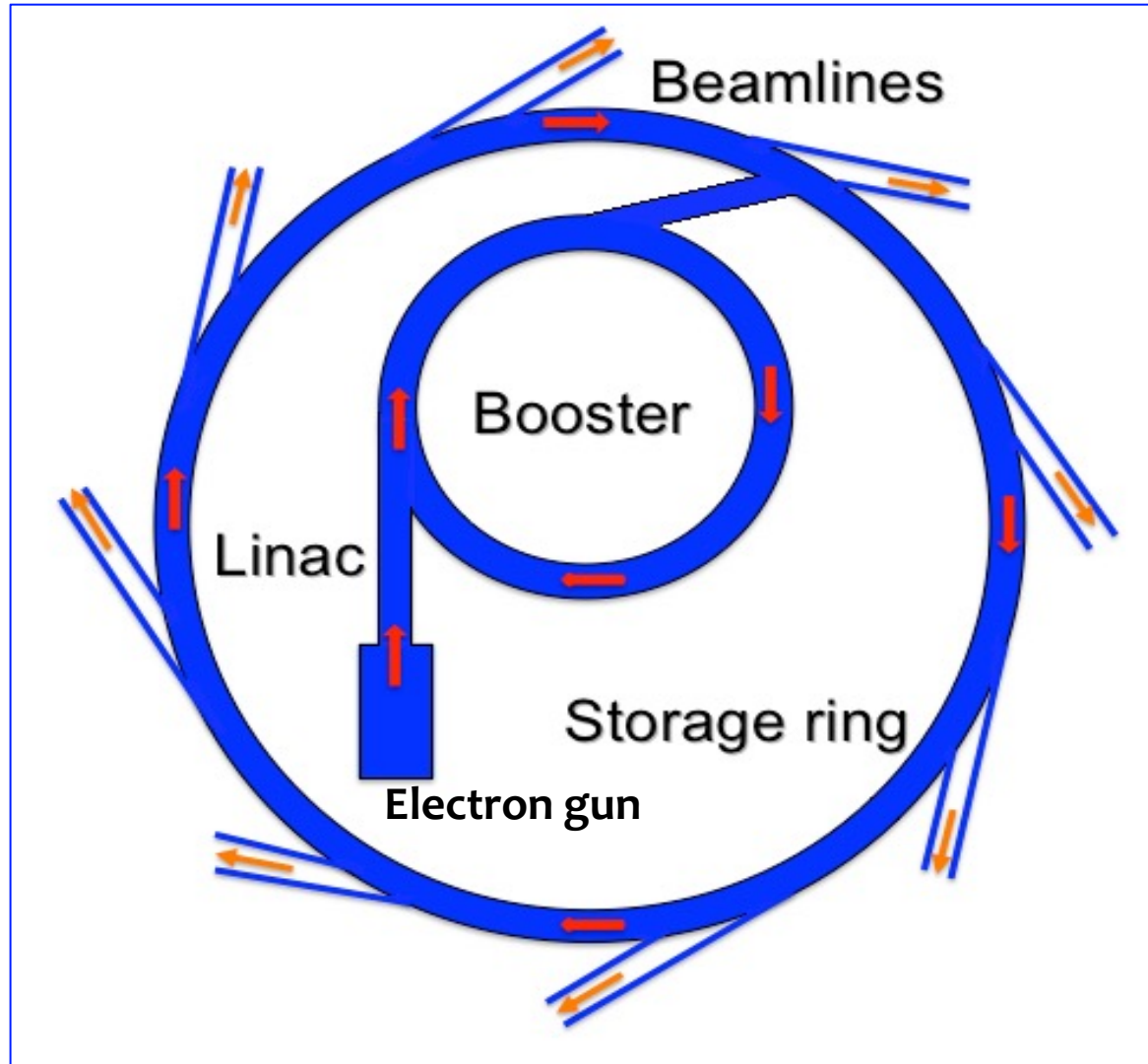
- **Cyclic** - the guiding **magnetic field** used to bend the particles into a closed path, is **time-dependent**, being **synchronized to a particle beam of increasing kinetic energy**.
- **Emitted photon spectrum** **varies** as e^- energy changes during each cycle.
- **Photon intensity** **varies**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

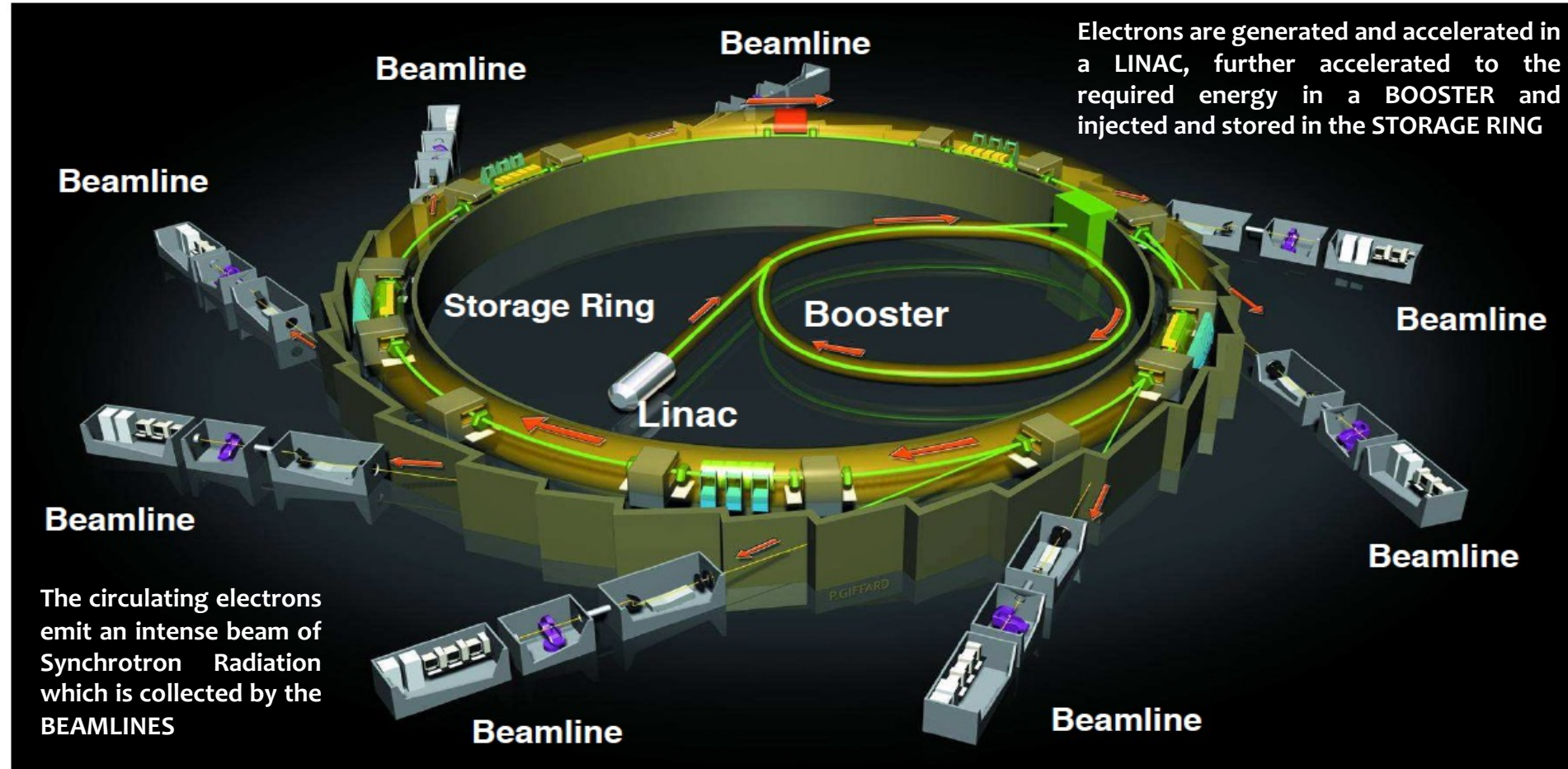
Synchrotron radiation and storage rings

Principal components of a synchrotron radiation source



- **Electron gun:** e^- source (thermionic emission)
- **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.

Some important elements of storage rings

In **storage rings** high energy electrons are kept on **closed paths** using **arrays of magnets** or '**magnet lattice**'.

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

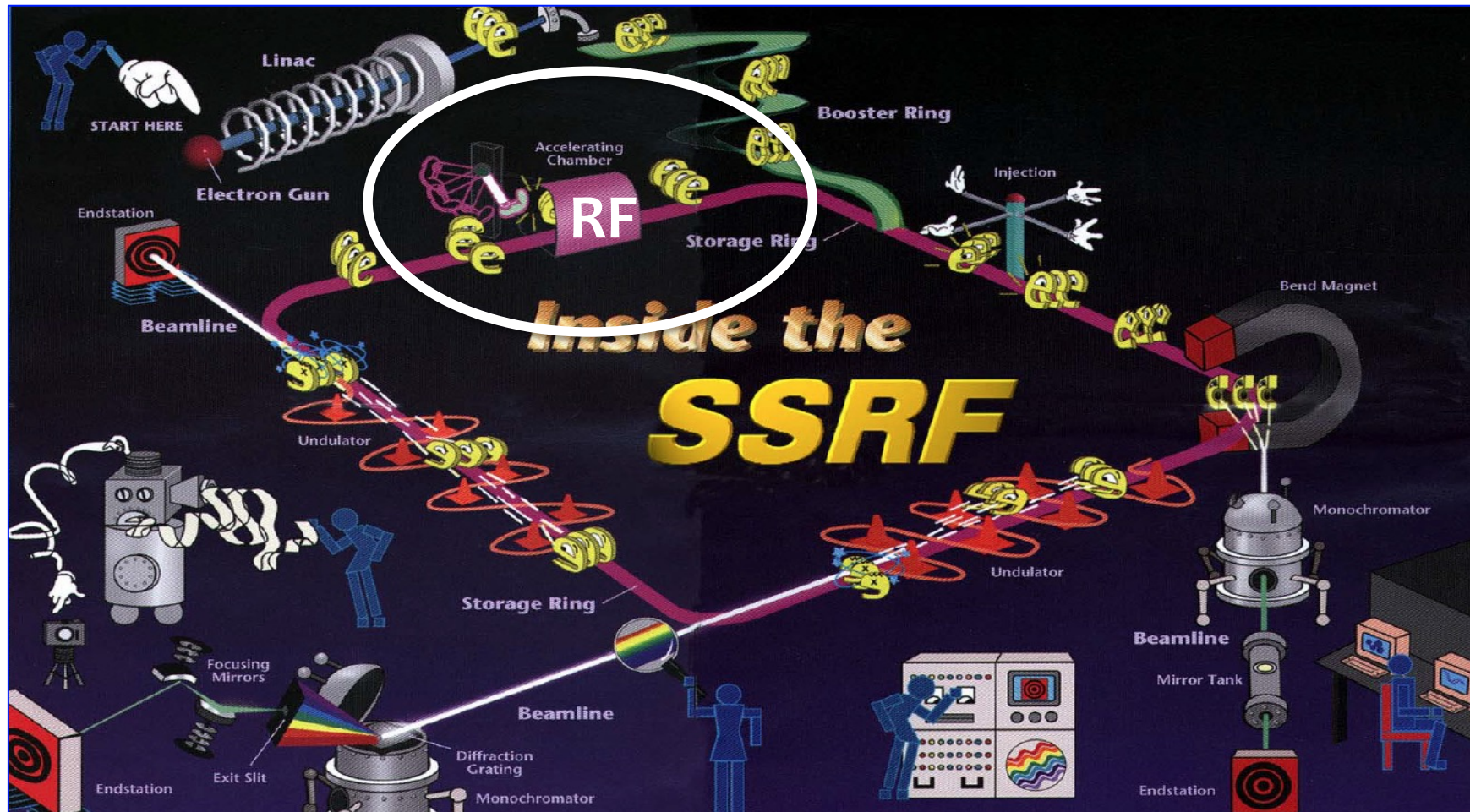
Radiation sources:

- **Dipoles** or **Bending Magnets (BMs)** make electrons 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.
- **Insertion devices (ID)** while the arced sections contain bending magnets, **the straight sections are used for insertion devices (wigglers and undulators)**, that generate synchrotron radiation having different properties if compared to the BM emission .

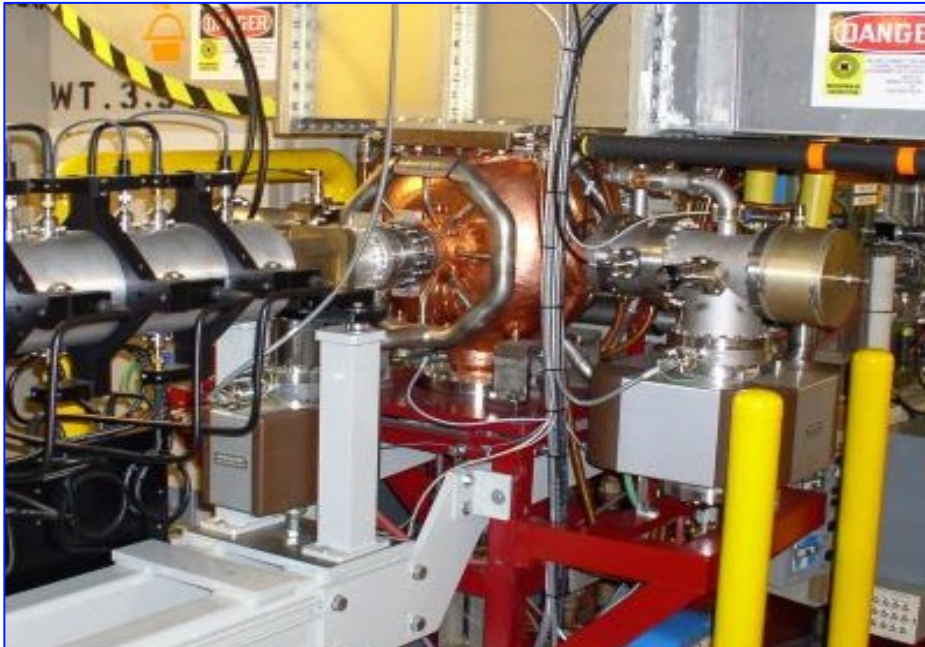
Storage rings: RF cavities and radiation sources

Radio Frequency cavities

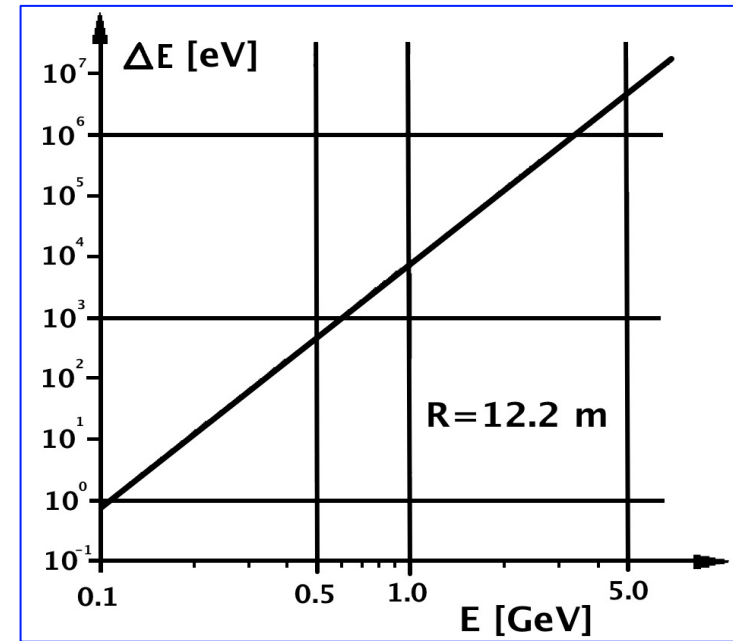
needed to supply the energy lost by electrons emitting synchrotron radiation



RF cavities and time structure



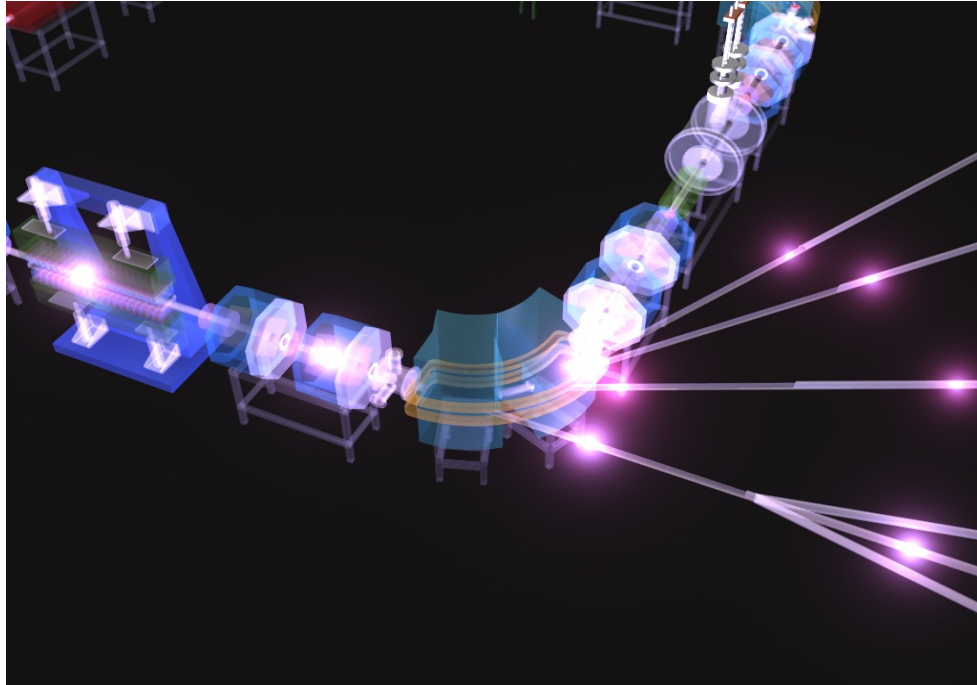
ALS 1.9 GeV storage ring (2015): the electrons lose up to 300 keV per revolution from radiative losses. In the storage ring a pair of RF cavities, with a peak voltage of 1.5 Megavolts, operating at 500 MHz are used.



K. Wille – Energy loss by an electron beam per revolution - **Synchrotron radiations sources** – Rep. Prog. Phys. 1991

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



Average radiated power by electrons

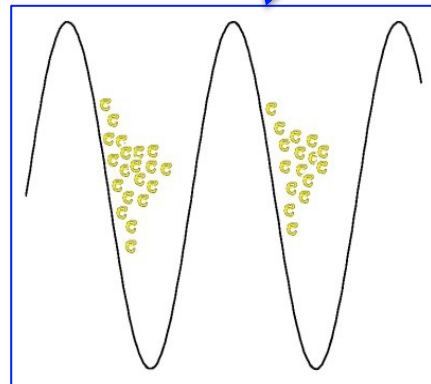
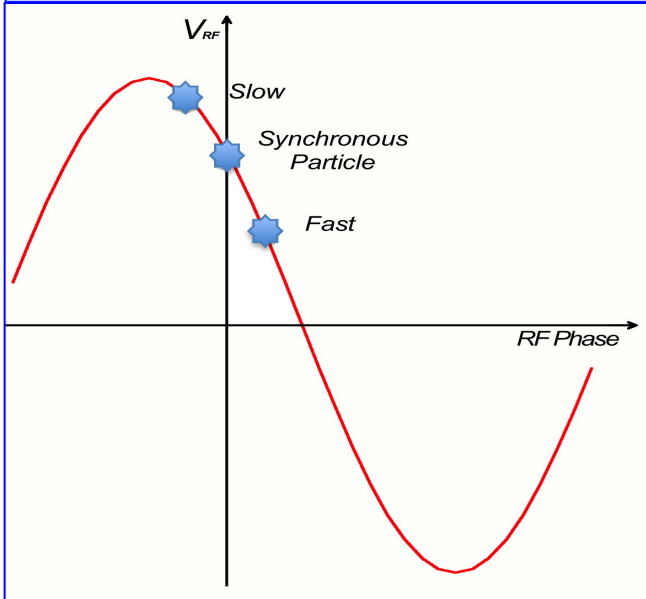
$$P_{ave} = \frac{U_0}{T_0} = \frac{4\pi c r_e}{3(m_0 c^2)^3} \frac{E^4}{RL}$$

U_0 = energy lost per turn, T_0 = revolution period, L = ring circumference, R = dipole bending radius.

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.

Radio Frequency (RF) cavities and time structure

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.



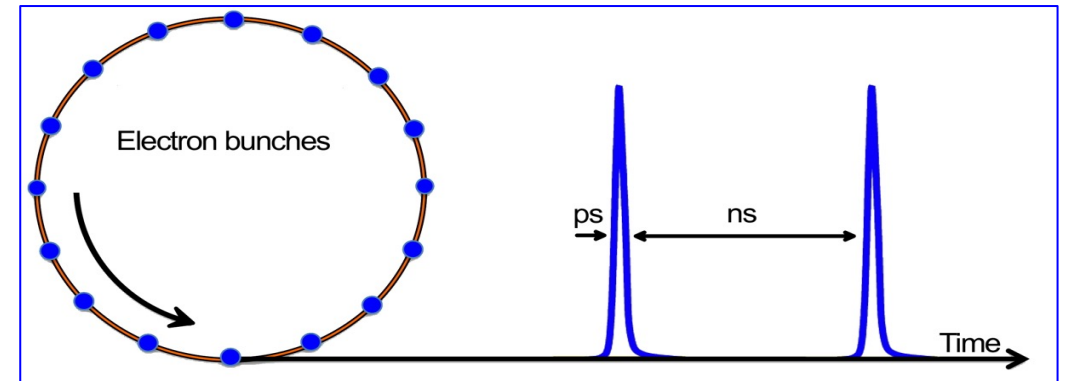
Consequently, the RF acceleration induces a distribution of the electrons in bunches with time lengths that are typically 5% - 10% of the RF period.

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.



EXAMPLE

ESRF: $E = 6$ GeV, $C = 844$ m, $\nu_{RF} = 352$ MHz, $V = 8$ MV and $I_{max} = 200$ mA.

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

$$T_0 = C/c = 2.81 \mu s \quad \nu_0 = (1/T_0) = 355 \text{ kHz (revolution frequency)}$$

T_0 (**period of revolution**) 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: $I_{max} = 200$ mA**

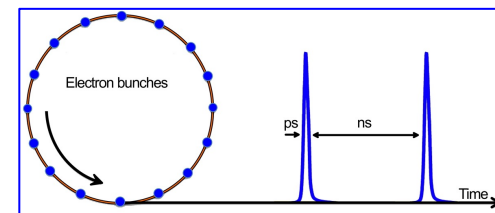
$$T_{RF} = 1/\nu_{RF} = 2.82 \text{ ns}$$

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

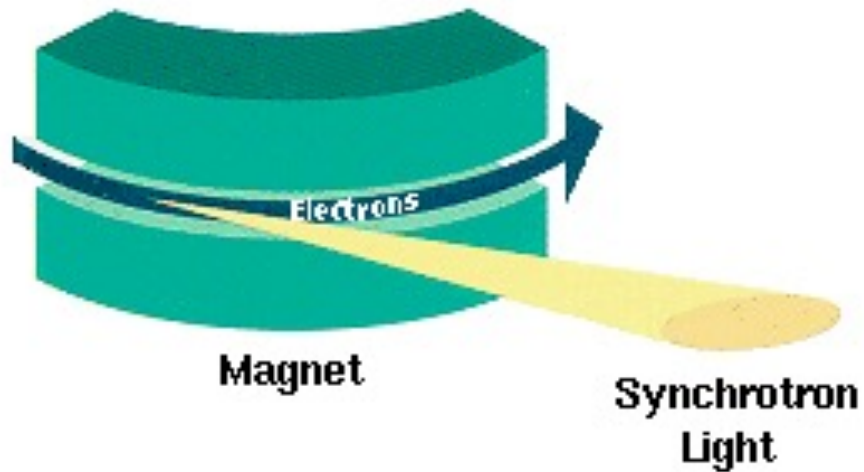
The **maximum number of bunches** that can be stored depends on ν_{RF} and on $\nu_0 = (1/T_0)$:

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

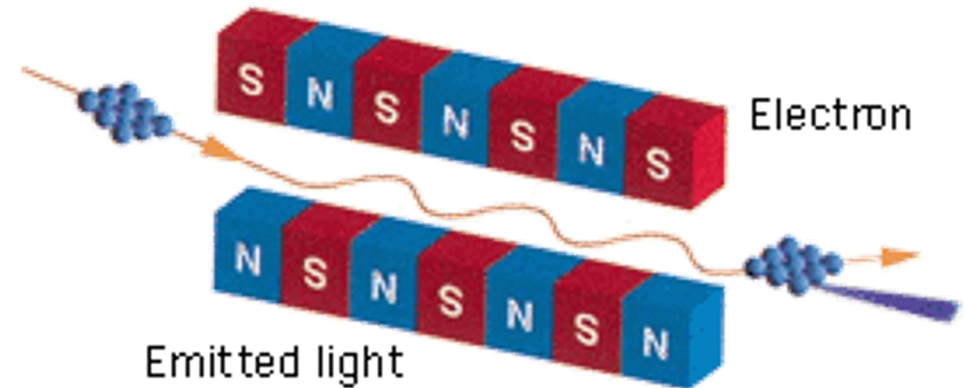
In **uniform bunch mode** the **bunch length** is of the order of **20 ps**.



Radiation sources



**Bending
Magnets - BM**

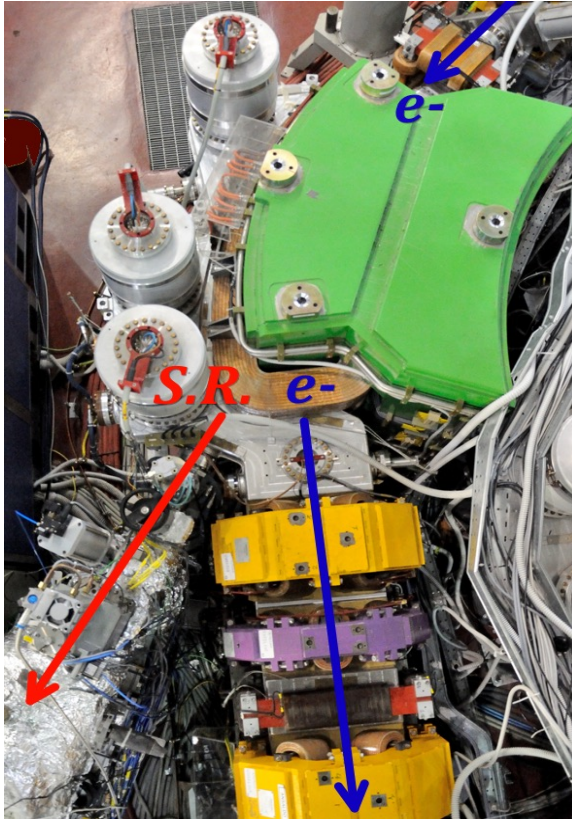


**Insertion
Devices - ID**

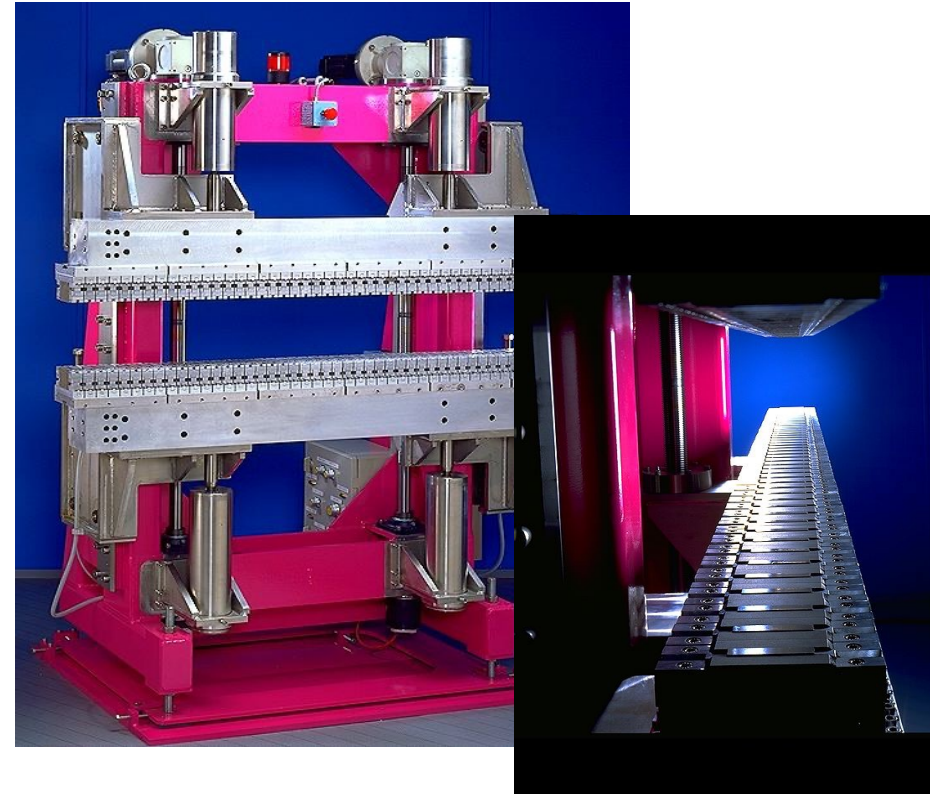
Radiation Sources

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

- bending magnets (BMs)
- insertion devices (IDs) or periodic arrays of magnets inserted in the straight sections (wigglers and undulators)



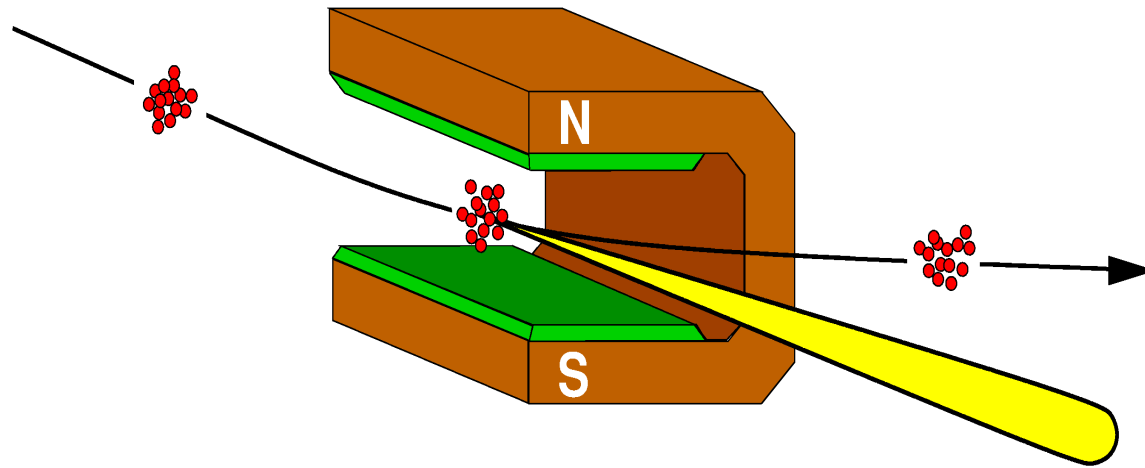
DAΦNE bending magnet (BM)



Insertion Device (ID) - Undulator

BM and ID have different characteristics in terms of spectral distribution, flux, brightness and polarization.

Bending magnets

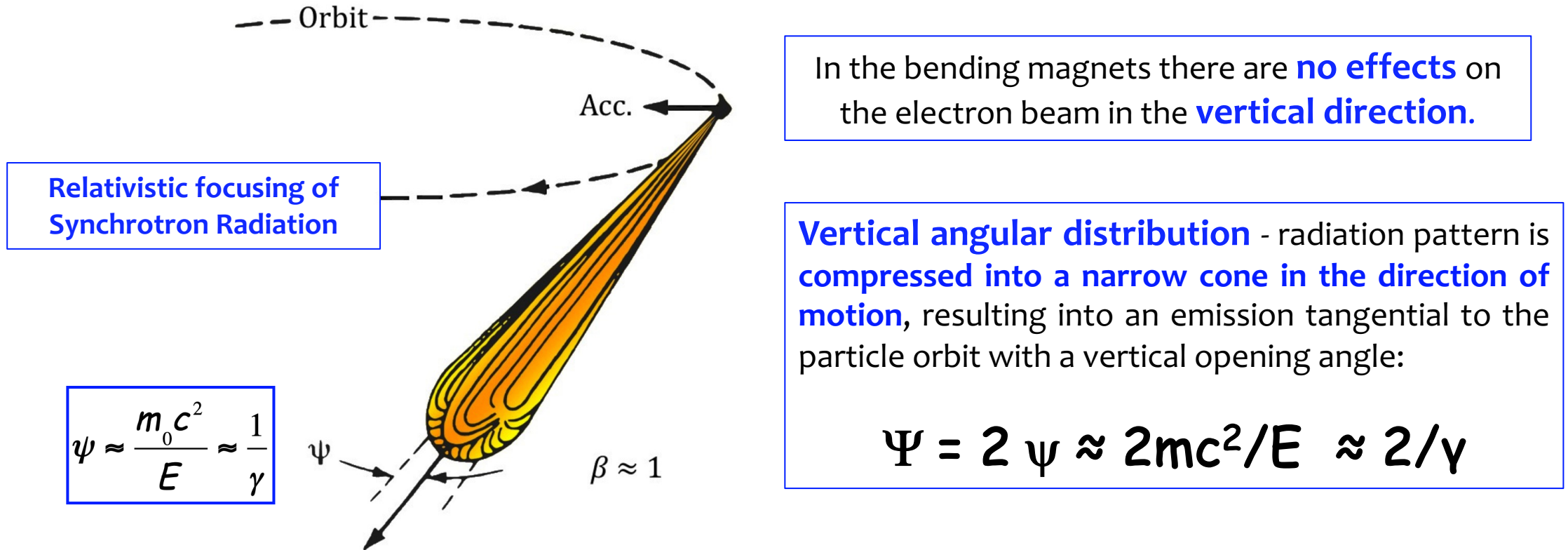


- Bending magnets and angular distribution
- Bending magnets and spectral distribution
- Bending magnets and polarization

Bending magnets and angular distribution

Bending magnets and angular distribution

Vertical angular distribution



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

In the bending magnets there are **no effects** on the electron beam in the **vertical direction**.

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:

$$\Psi = 2 \psi \approx 2mc^2/E \approx 2/\gamma$$

$$E = 1 \text{ GeV} \quad 1/\gamma \approx 0.511 \text{ mrad} \approx (29 \times 10^{-3})^\circ$$

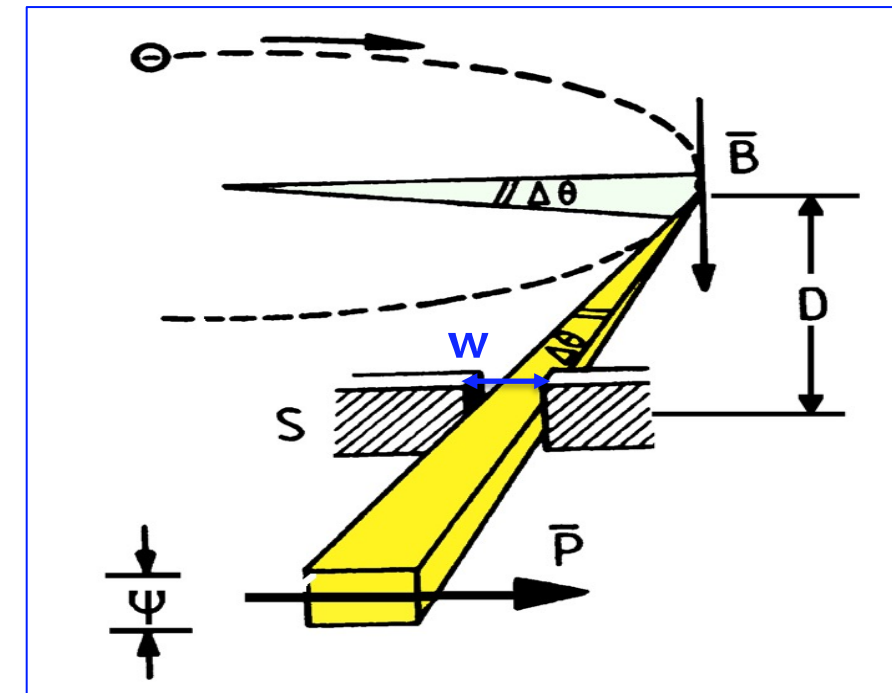
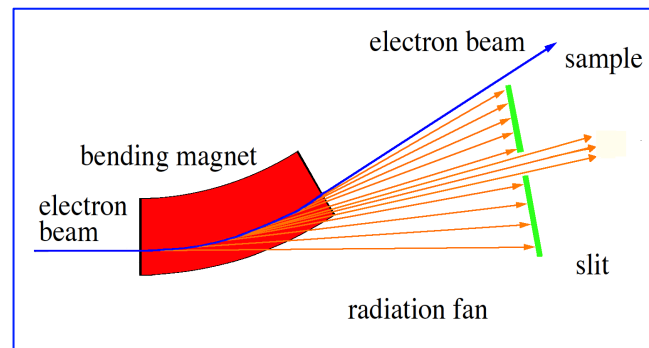
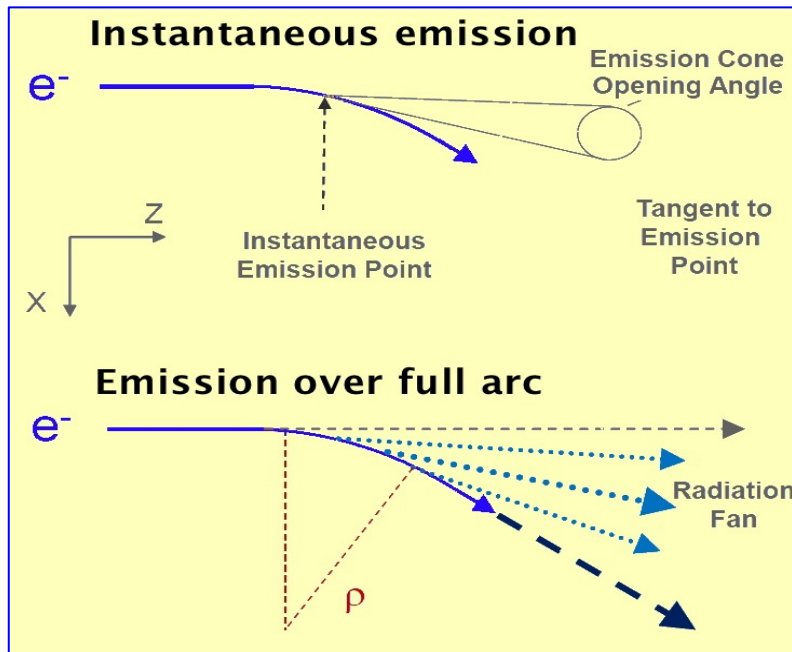
$$1 \text{ deg} = 17.45 \text{ mrad}; 1 \text{ mrad} = (57 \times 10^{-3})^\circ$$

Bending magnets and angular distribution

Horizontal angular distribution

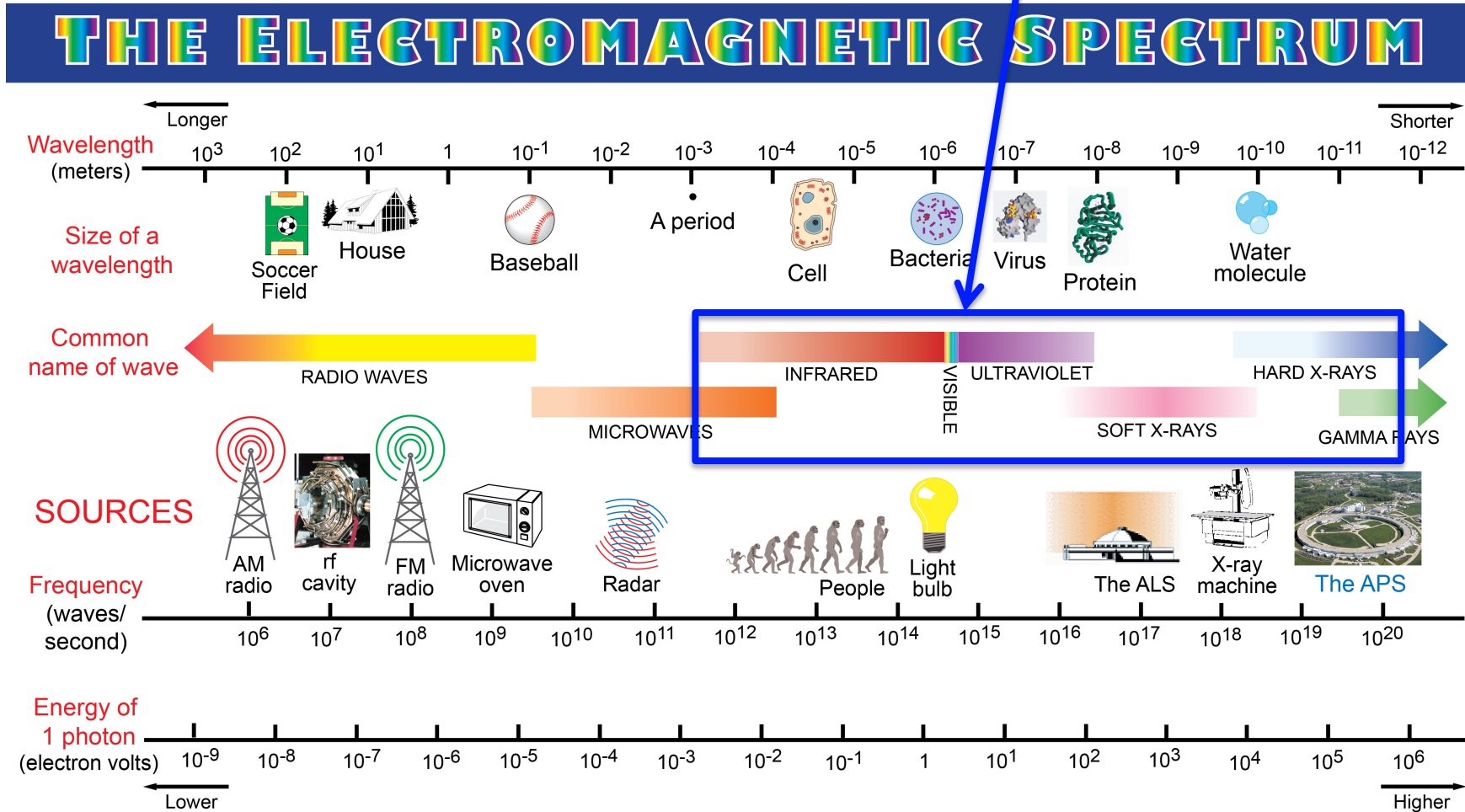
Horizontal angular distribution: in a bending magnet the **horizontal collimation is lost** because the **electrons move along a circular orbit emitting the radiation along the tangent**. The radiation is collected, for experiments, through a **horizontal slit (S)** of width, w , at a distance, D , from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

$$\Delta\theta = w/D \gg \Psi$$

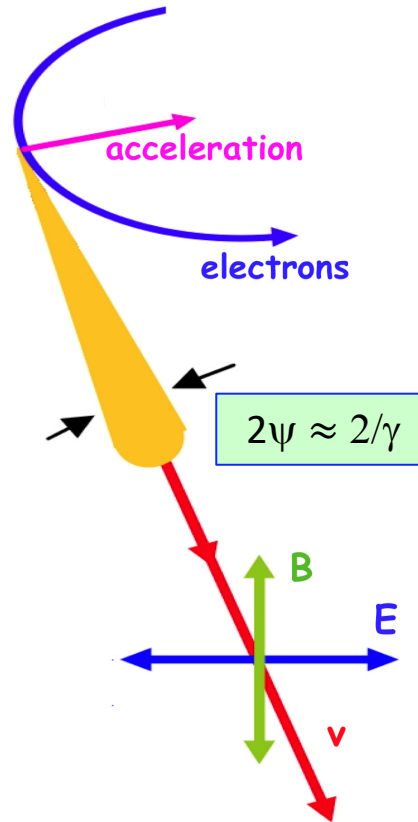
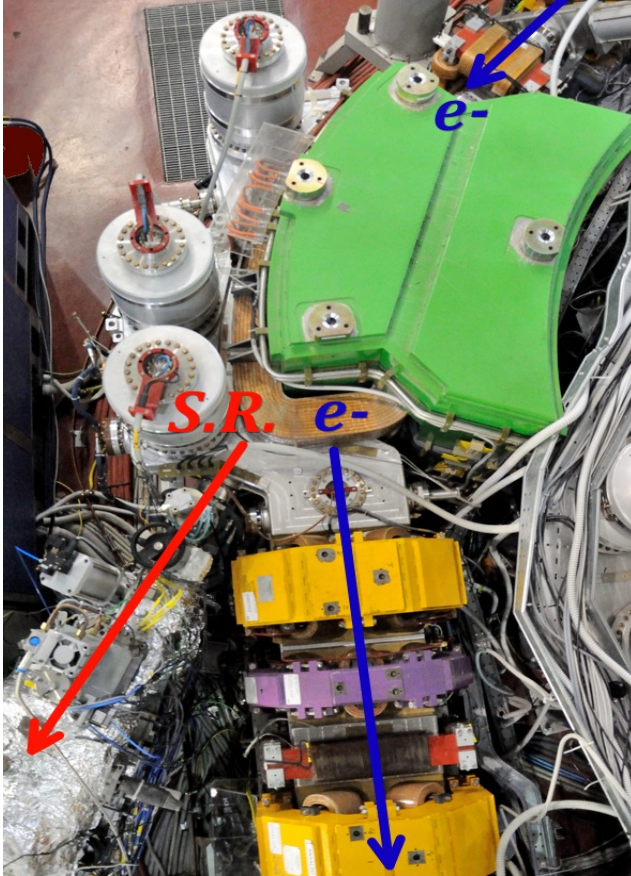


Bending magnets and spectral distribution

An important characteristic of Synchrotron Radiation is the wide spectral range covered!



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** :

$$\mathbf{F} = m\mathbf{a} = d\mathbf{p}/dt$$

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

Bending magnets and spectral distribution

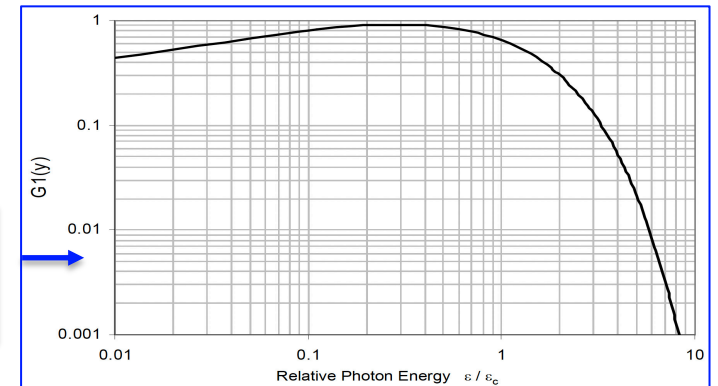
Schwinger in **1949** found that the **spectral distribution of the radiation emitted from accelerated relativistic charged particles**, under the effect of a **constant magnetic field** is a **smoothly varying function of photon energy**.

$$\frac{d^2 F_{bm}(\omega)}{d\theta d\psi} = \frac{3\alpha}{4\pi^2} \gamma^2 \frac{\Delta\omega}{\omega} \frac{I}{e} \left(\frac{\omega}{\omega_c} \right)^2 (1 + \gamma^2 \psi^2)^2 \left[K_{2/3}^2(\xi) + \frac{\gamma^2 \psi^2}{1 + \gamma^2 \psi^2} K_{1/3}^2(\xi) \right]$$

Angular distribution of synchrotron radiation flux emitted by electrons moving through a bending magnet with a circular trajectory in the horizontal plane.

θ observation angle horizontal plane - ψ observation angle vertical plane - α fine structure constant (1/137) - ω light frequency - I beam current - $\xi = (\omega/2\omega_c)(1 + \gamma^2 \psi^2)^{3/2}$. $K_{2/3}$ and $K_{1/3}$ are **modified Bessel functions of the second kind**: $K_{2/3}$ **light linearly polarized parallel to the electron orbit plane**; $K_{1/3}$ **light linearly polarized perpendicular to the orbit plane**.

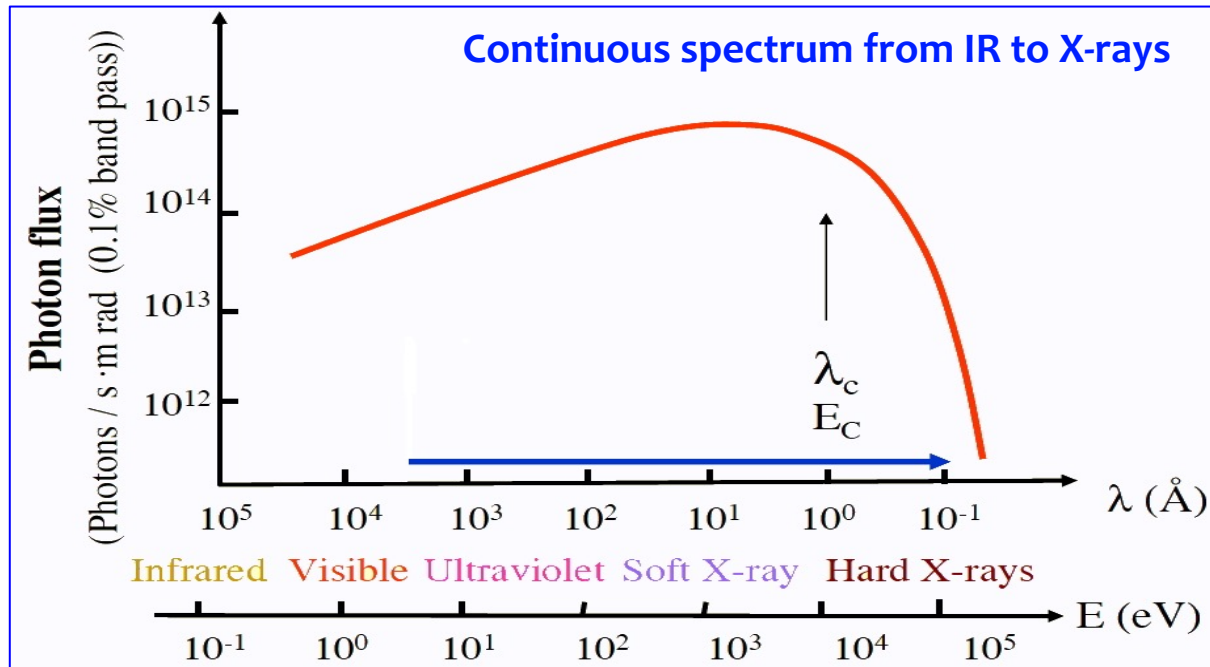
$$\begin{aligned} \frac{dF_{bm}(\omega)}{d\theta} &= \frac{\sqrt{3}}{2\pi} \alpha \gamma \frac{\Delta\omega}{\omega} \frac{I}{e} \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(y) dy \\ &= 2.457 \times 10^{13} \text{ photons / sec / mrad / 0.1\% bandwidth} \times E[\text{GeV}] I[\text{A}] \left[\frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(y) dy \right] \end{aligned}$$



Integrating over all vertical angles the total intensity can be easily evaluated using specific algorithms for the modified Bessel functions of second kind.

Bending magnets and spectral distribution

The continuous spectrum of the smoothly varying function of photon energy is characterized by a critical energy, ε_c , that scales as γ^3 .



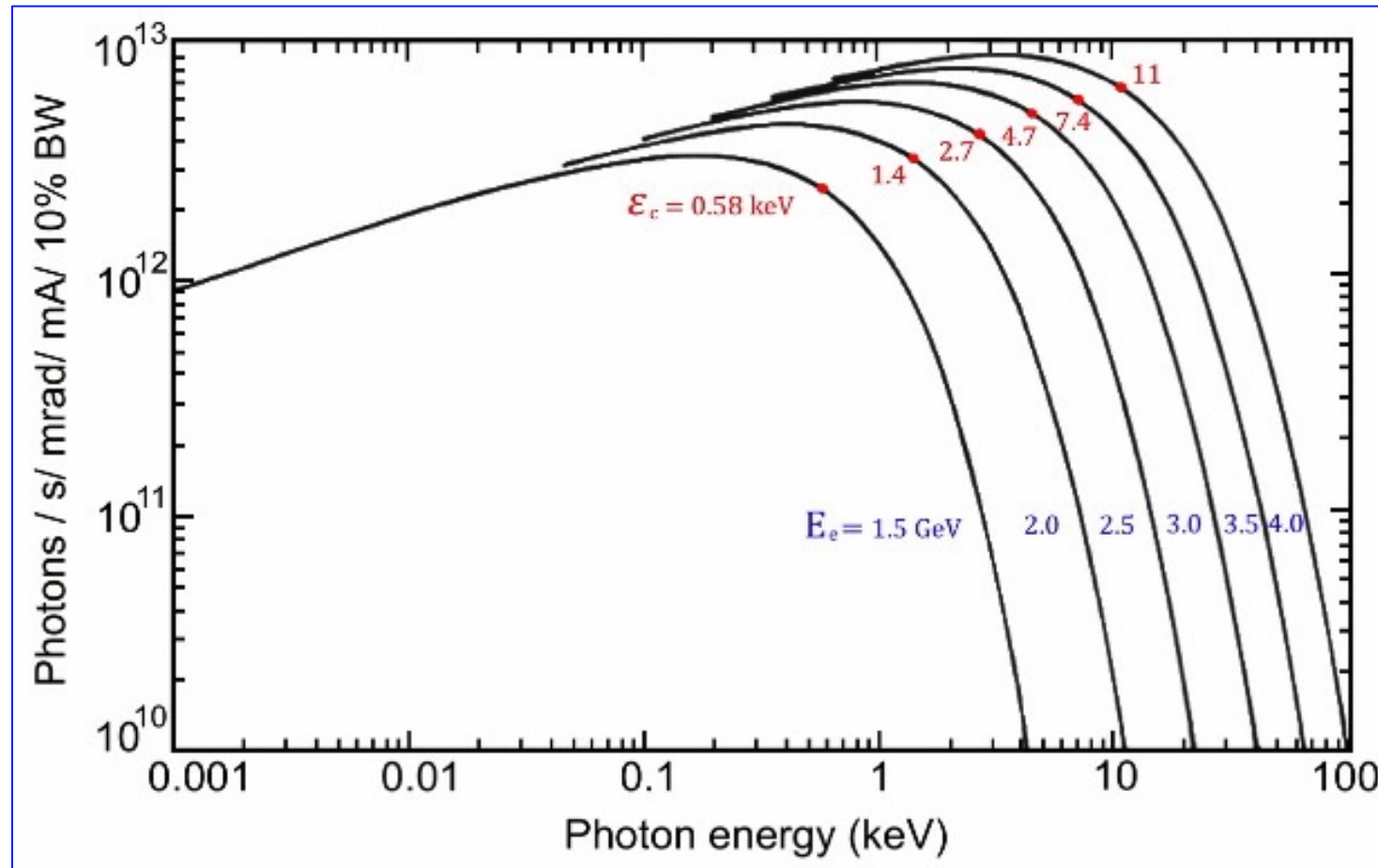
$$\varepsilon_c = \hbar \omega_c = \frac{3}{2} \frac{\hbar c}{R} \gamma^3$$

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

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

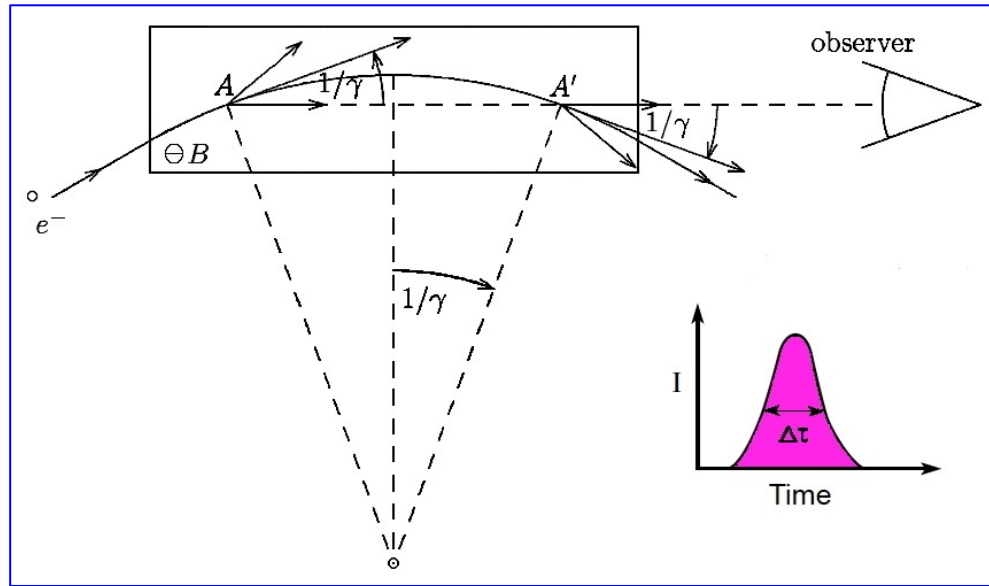
The critical energy, ε_c , divides the spectrum into two parts of equal radiated power: 50% of the total power is radiated at energies lower than ε_c and 50% at energies higher than ε_c .

Bending magnets and spectral distribution



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

Origin of the broad spectral distribution



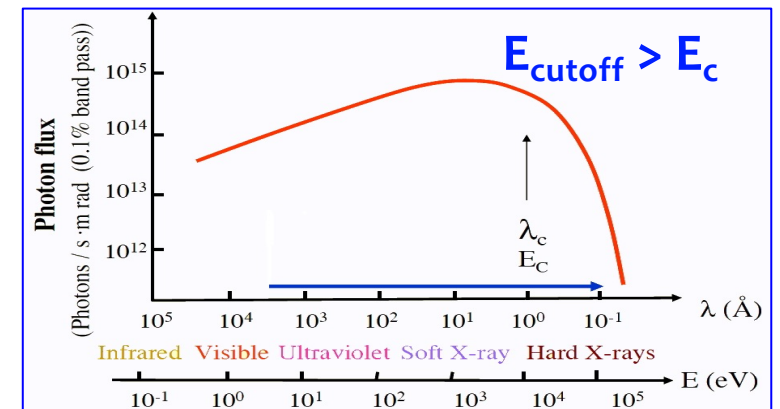
The **time duration of the radiation pulse seen by the observer** is the **difference** between the **time for the ELECTRON to travel along the arc ($2/\gamma$)** and the **time for LIGHT to travel along the chord subtended by this arc**.

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

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 $E > \epsilon_c$ (Schwinger 1949)**.



Bending magnets and polarization

Bending magnets and polarization

$$P = \int \int I(\lambda, \psi) d\lambda d\psi = \frac{2}{3} \frac{e^2 c}{R^2} \left(\frac{E}{mc^2} \right)^4$$

Schwinger - Radiated power

Contribution parallel
to the orbital plane

$$I(\lambda, \psi) = \frac{27}{32\pi^3} \frac{e^2 c}{R^3} \left(\frac{\lambda_c}{\lambda} \right)^4 \gamma^8 [1 + (\gamma\psi)^2]^2 \left[K_{2/3}^2(\xi) + \frac{(\gamma\psi)^2}{1 + (\gamma\psi)^2} K_{1/3}^2(\xi) \right]$$

$$\xi = (\lambda_c/2\lambda)(1 + \gamma^2\psi^2)^{3/2}$$

ψ observation angle -
vertical plane

Contribution perpendicular
to the orbital plane

Angular and wavelength distribution of synchrotron radiation

Bending magnets and polarization

The radiation emitted by an electron, moving in a bending magnet, **in the plane of its orbit (horizontal) is 100% linearly polarized** with the **electric field parallel to the orbital plane**.

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.

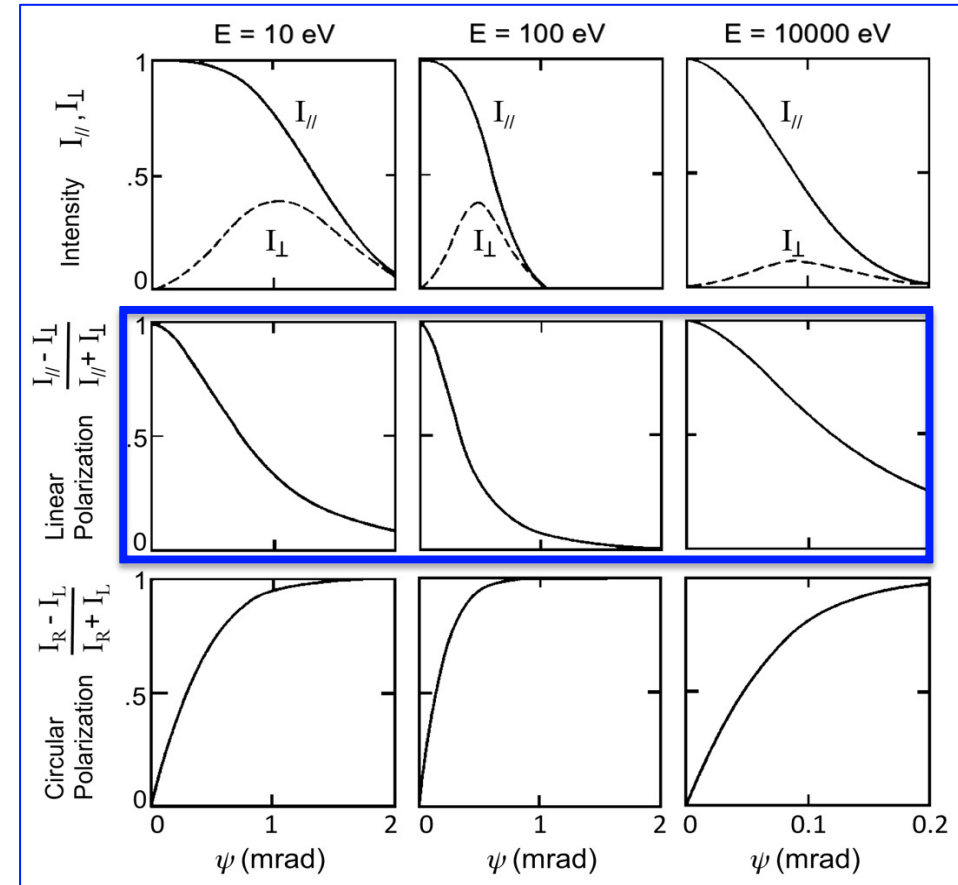
Degree of linear polarization:

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

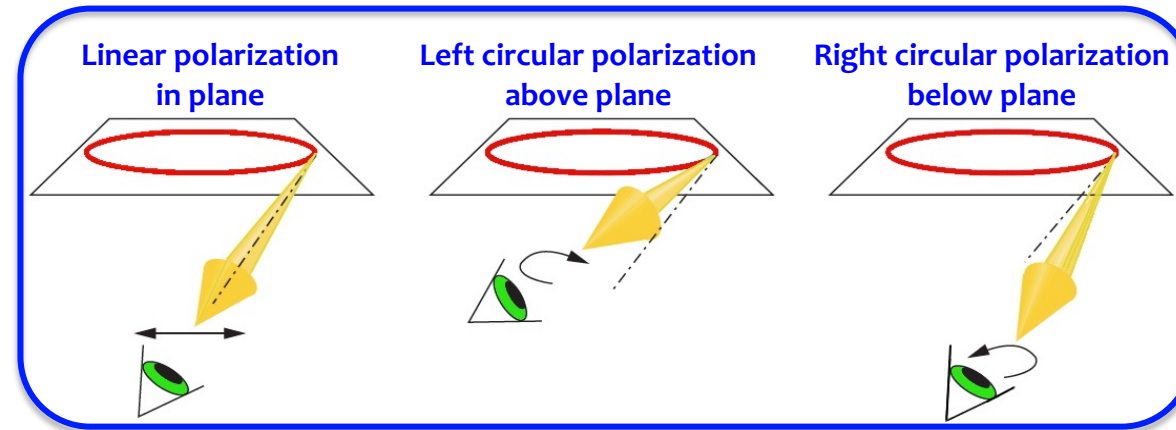
Integrating over all energies:

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

meaning that the degree of linear polarization is about 75%.



Bending magnets and polarization

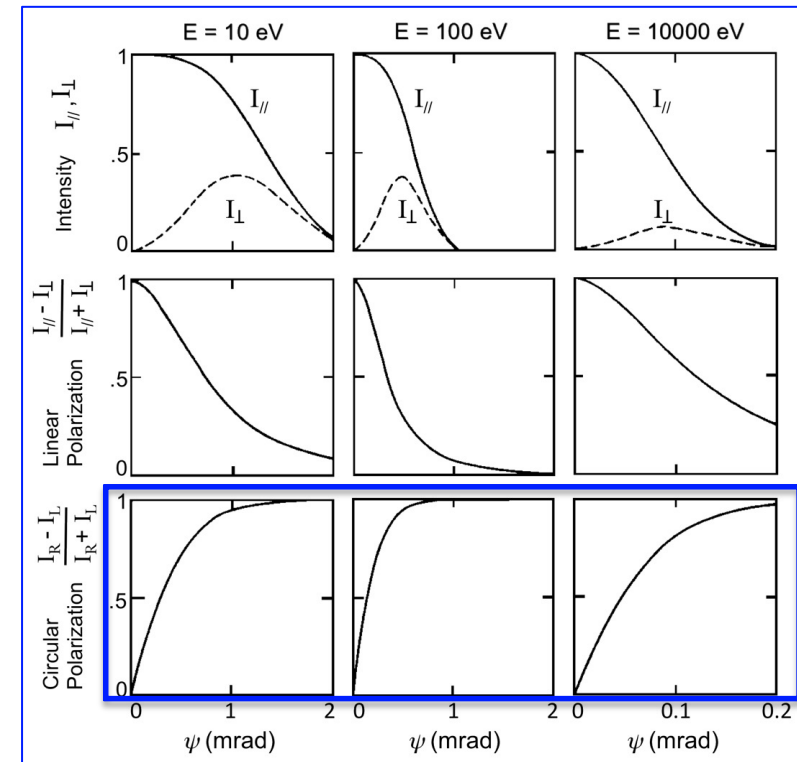


The **horizontal and vertical components** have a **phase difference of $\pi/2$** .

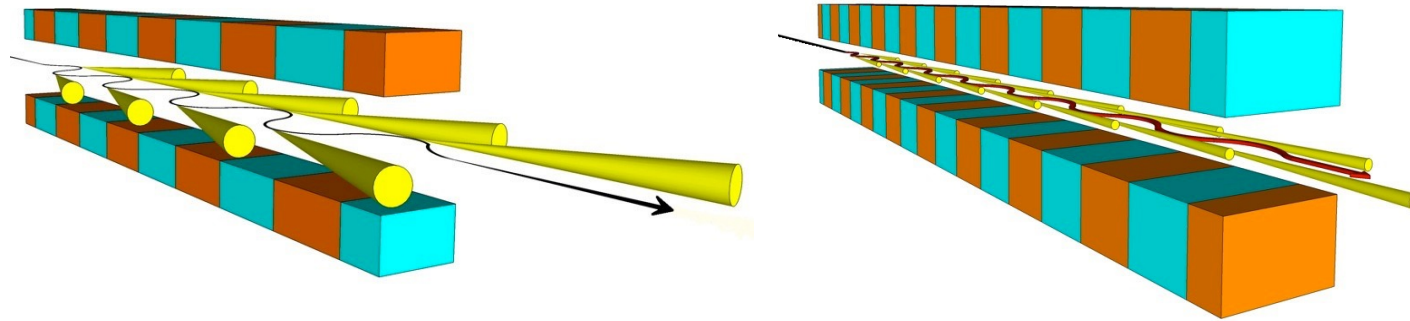
Above and below the plane the constant phase difference is of $+\pi/2$ and $-\pi/2$.

Degree of circular polarization:

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

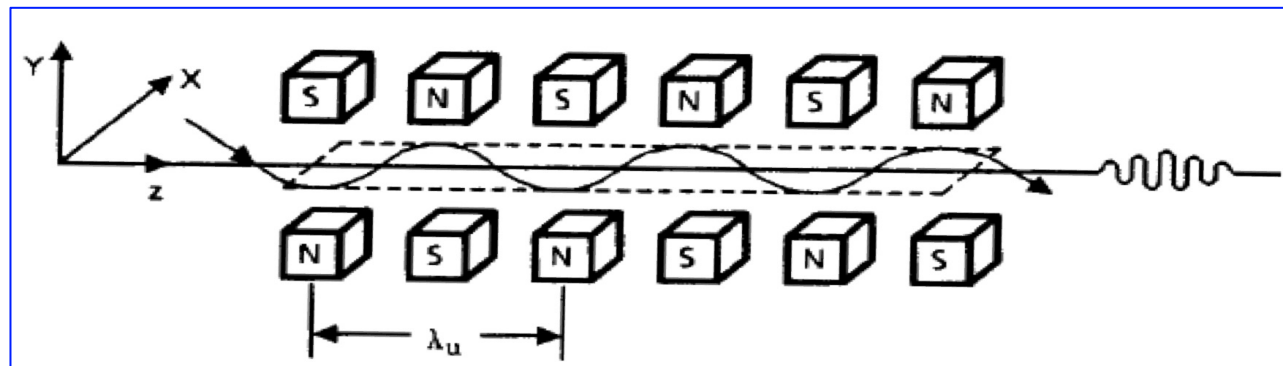
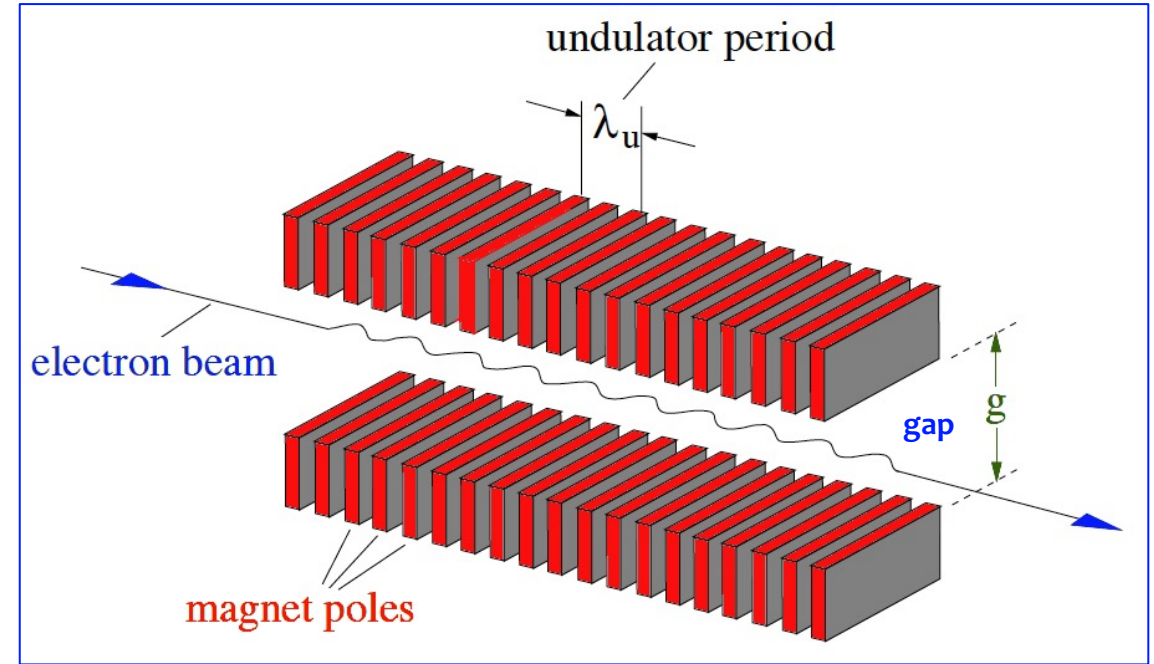


Insertion devices (ID): wigglers and undulators



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: $L = N \lambda_u$

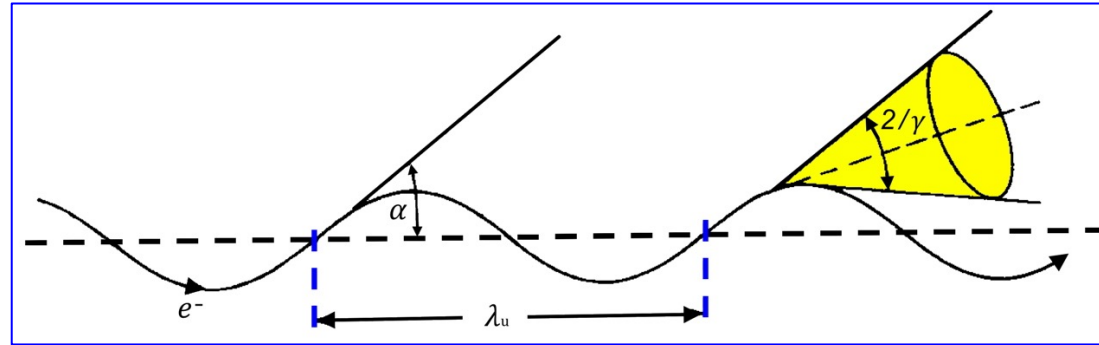
N = number of periods - λ_u = undulator period

Insertion Devices

IDs are **characterized** by the so called ‘deflection parameter’- K .

$$K = \alpha \gamma$$

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



α = wiggling angle

$2/\gamma$ = SR natural angular aperture

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 regime.**
- If $K \gg 1$, α is bigger than $1/\gamma$, so **the radiation spectrum looks like dealing with $2N$ dipole sources - Wiggler regime.**

Calculation of K

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

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

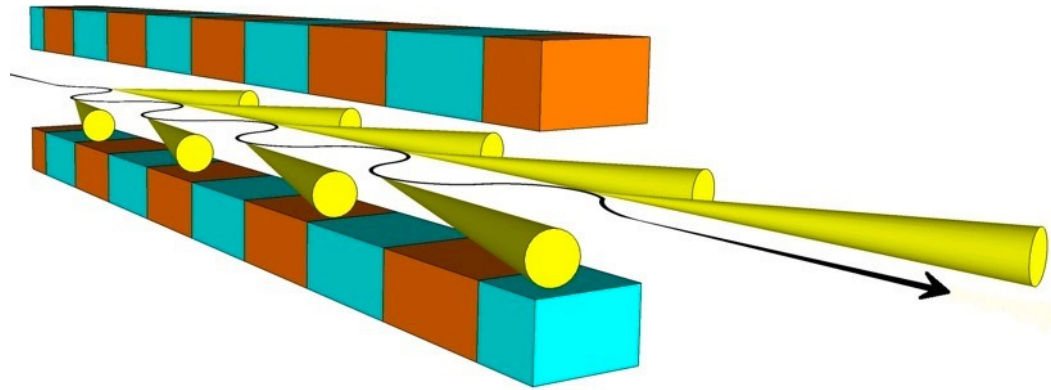
$$\dot{v}_x = \frac{ecB_0}{\gamma m_0} \sin\left(\frac{2\pi z}{\lambda_{TD}}\right) \quad z = ct$$

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

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

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

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**.

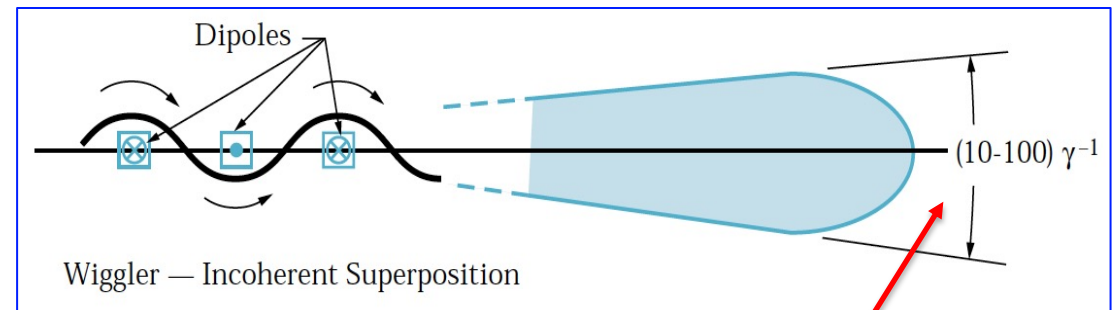
$$\varepsilon_c[keV] = 2.218 \frac{E[GeV]^3}{\rho[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T]$$

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

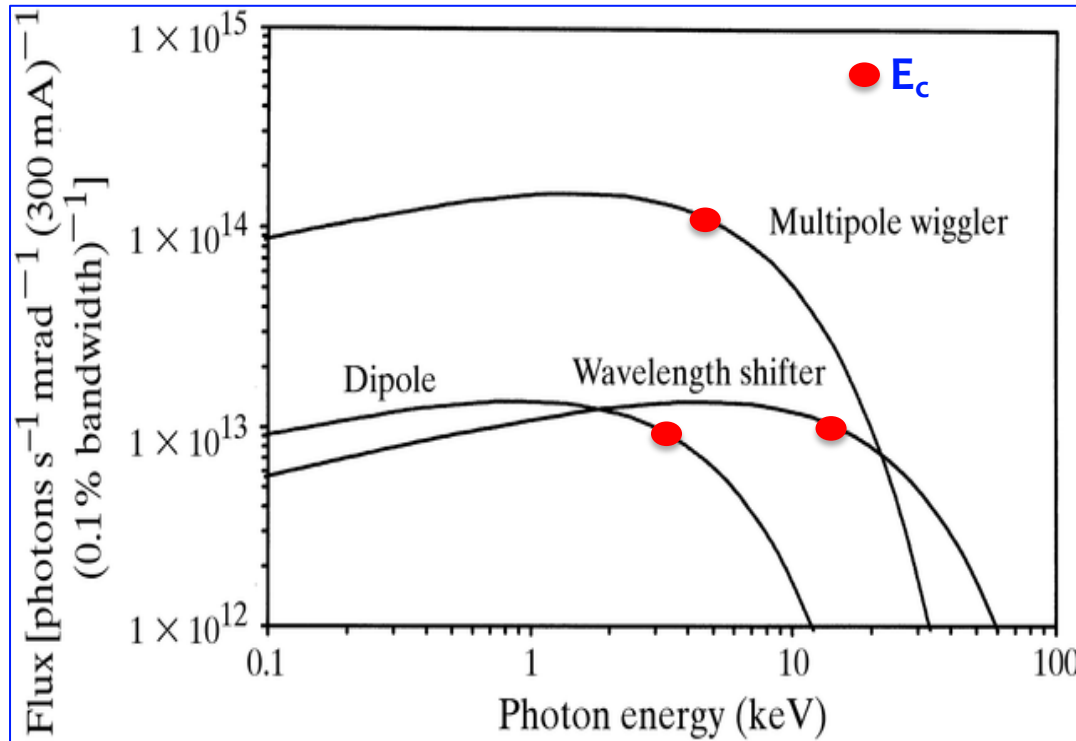
- A **MPW** can be considered a **series of dipoles**, one after the other.
- There are **two source points per period**
- The flux is simply the **product of the number of source points and the dipole flux** for that **critical energy**

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** compared to a bending magnet.



Wigglers



Comparison of the flux **changing magnetic field** values:

1.2 T Bending Magnet - Dipole

6.0T Wavelength Shifter

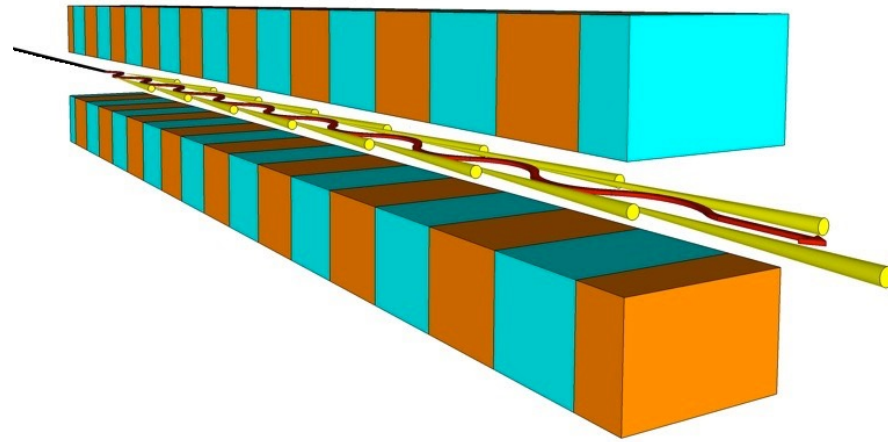
2.0T Multipole wiggler

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

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

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

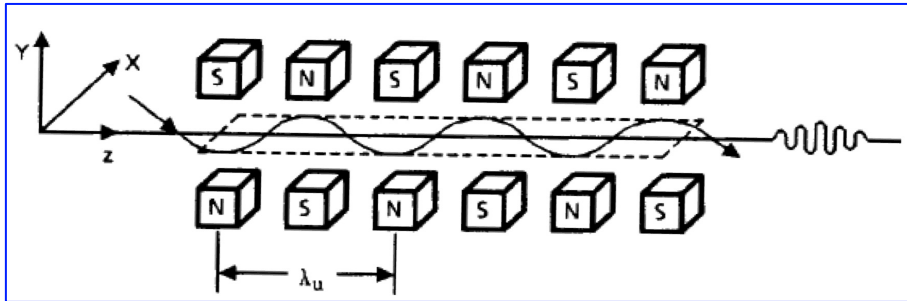
Undulators: very bright radiation sources



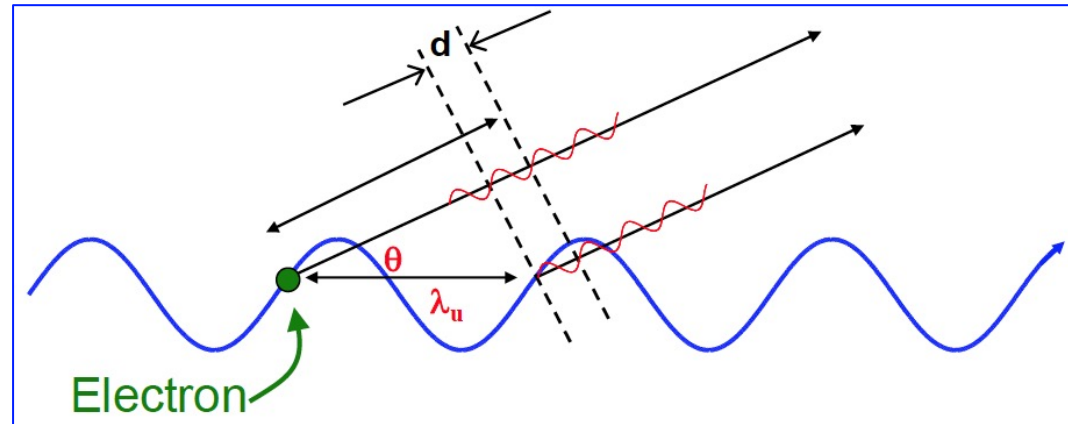
Undulators

In an **undulator** $K \approx 1$, so the **wiggling angle** θ is smaller than, or **close to**, the **photon natural emission angle** $1/\gamma$.

In this case **constructive interference**, at **specific wavelengths** occurs between **the radiation emitted by electrons at different poles along the trajectory**.



Overall undulator length: $L = N\lambda_u$



d = separation between the wavefronts, must **equal a whole number of wavelengths** for constructive interference

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

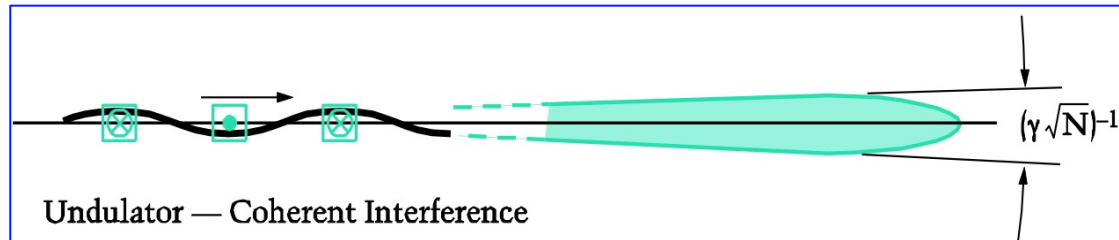
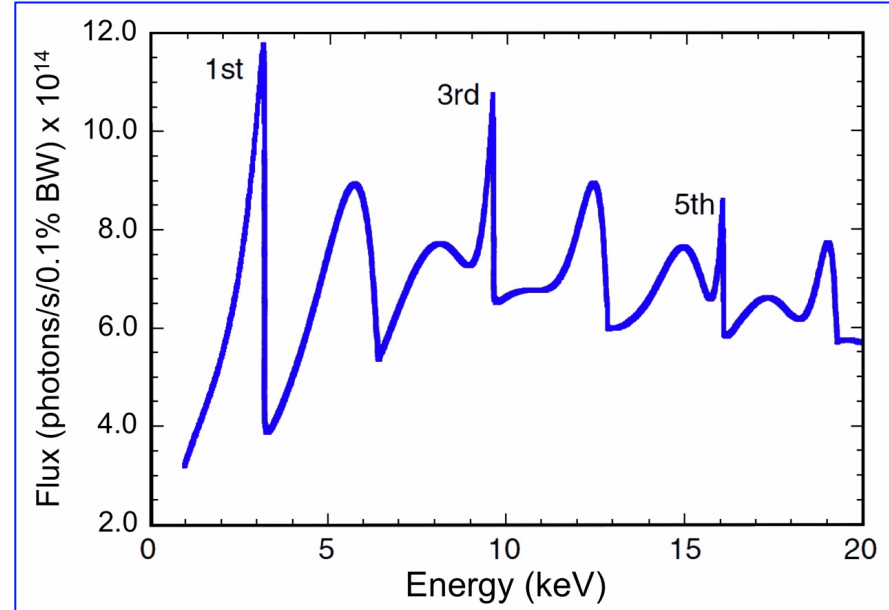
$$\lambda_u = L/N$$

n = the harmonic number

Undulators

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

Undulators produce **quasi-monochromatic spectra** with peaks at energies lower than a wiggler the produced **flux** in the '**undulator**' regime is **proportional to N^2** .



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

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**.

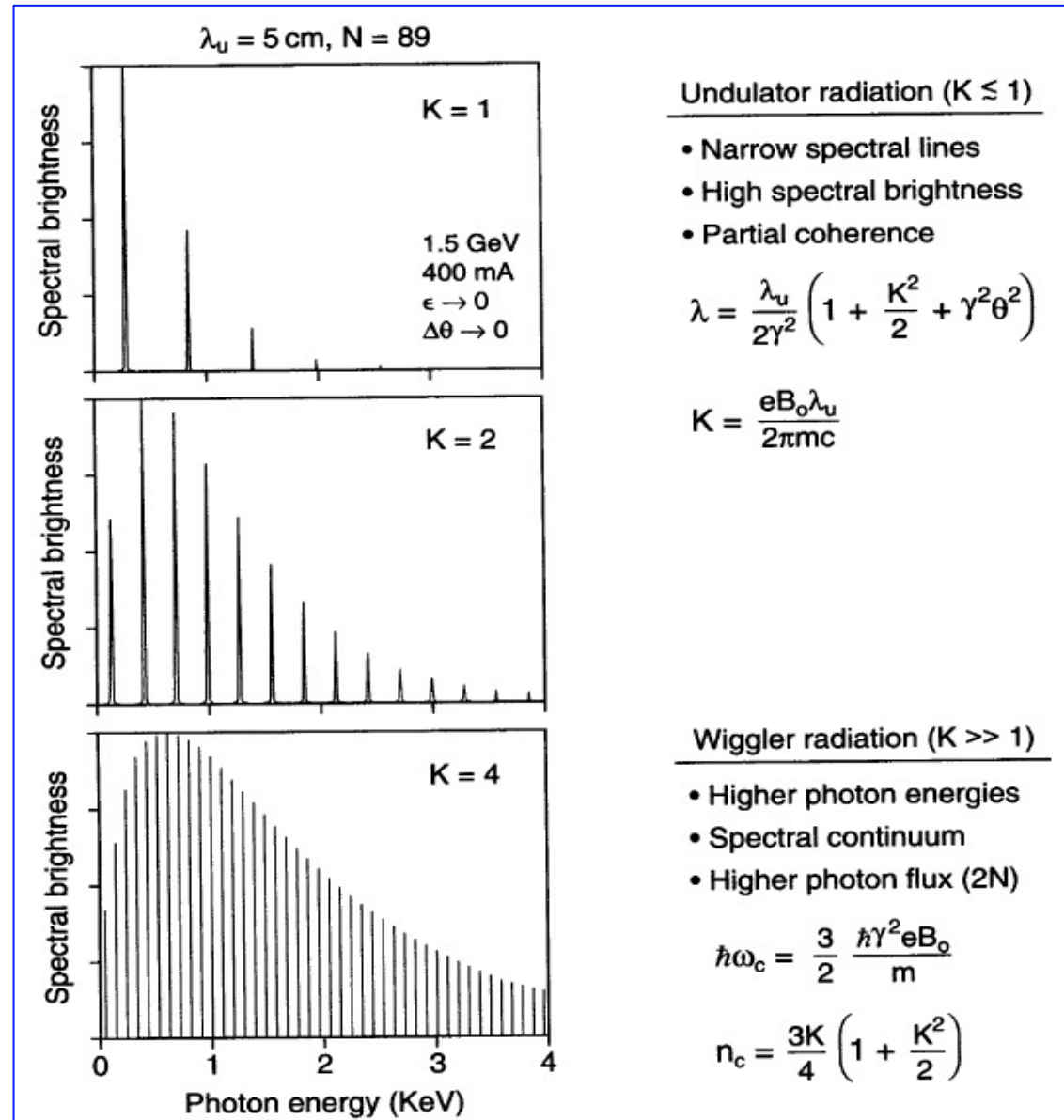
For on-axis radiation θ_{cen} or **central radiation cone** is defined as containing radiation of relative spectral bandwidth, $\Delta\lambda/\lambda = 1/N$.

Undulator equation and wiggler limit

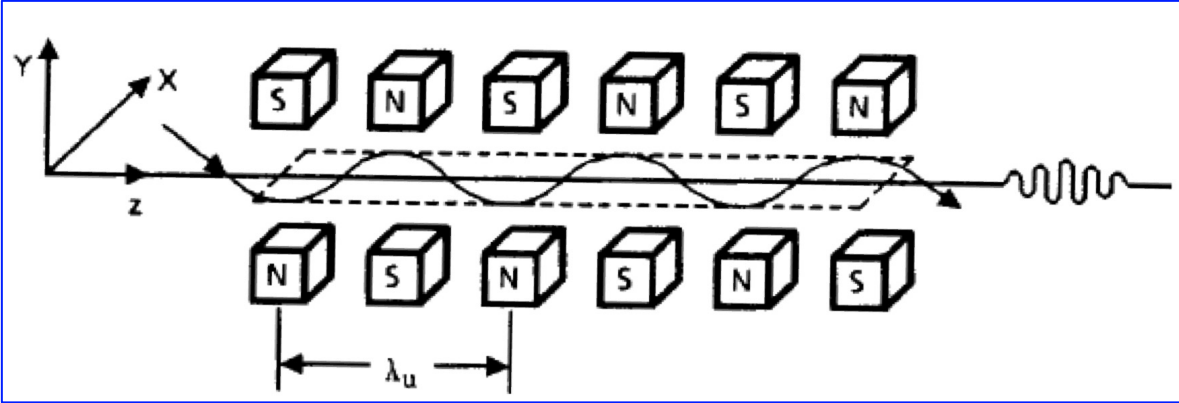
$$E_n(eV) = 9.496 \frac{nE[GeV]^2}{\lambda_u[m] \left(1 + \frac{K^2}{2}\right)}$$

$$K = 93.36 B_0 \lambda_u$$

As B_0 increases (and so K), the photon wavelength, λ_n increases (photon energy decreases).



Undulators



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

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

$\lambda_u = L/N$ in the cm scale

λ_n in the nm scale



How and why, we move from cm to nm scale ?

Undulators

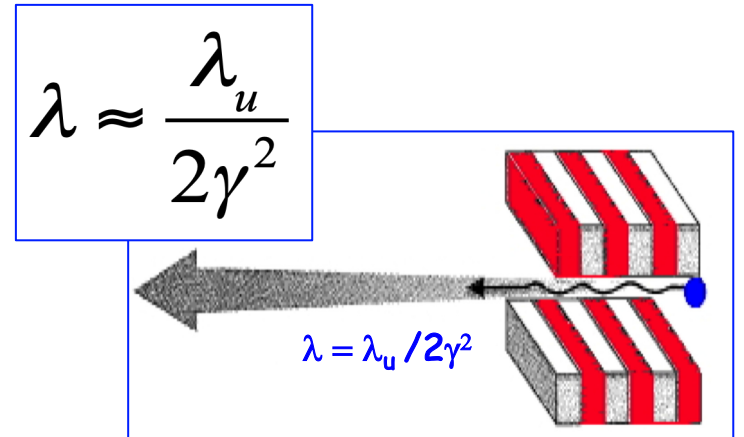
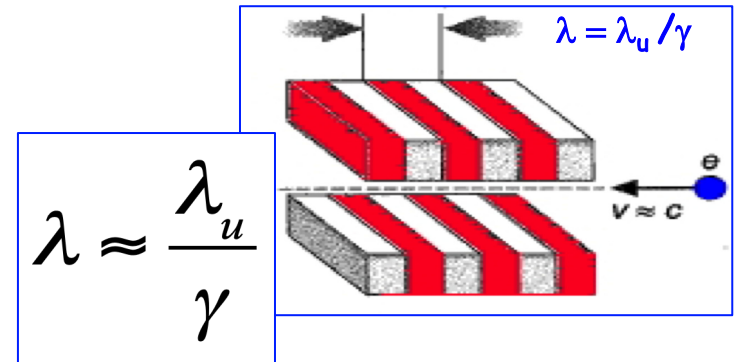
$\lambda_u = L/N$ in the cm scale
 λ_n in the nm scale

How and why, we move from cm to nm ?

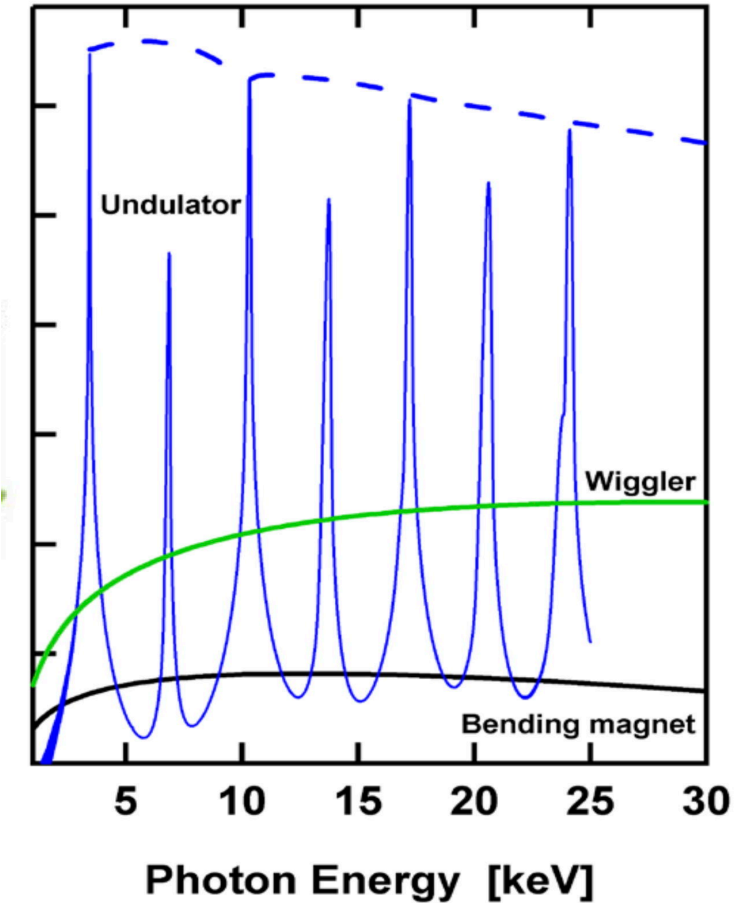
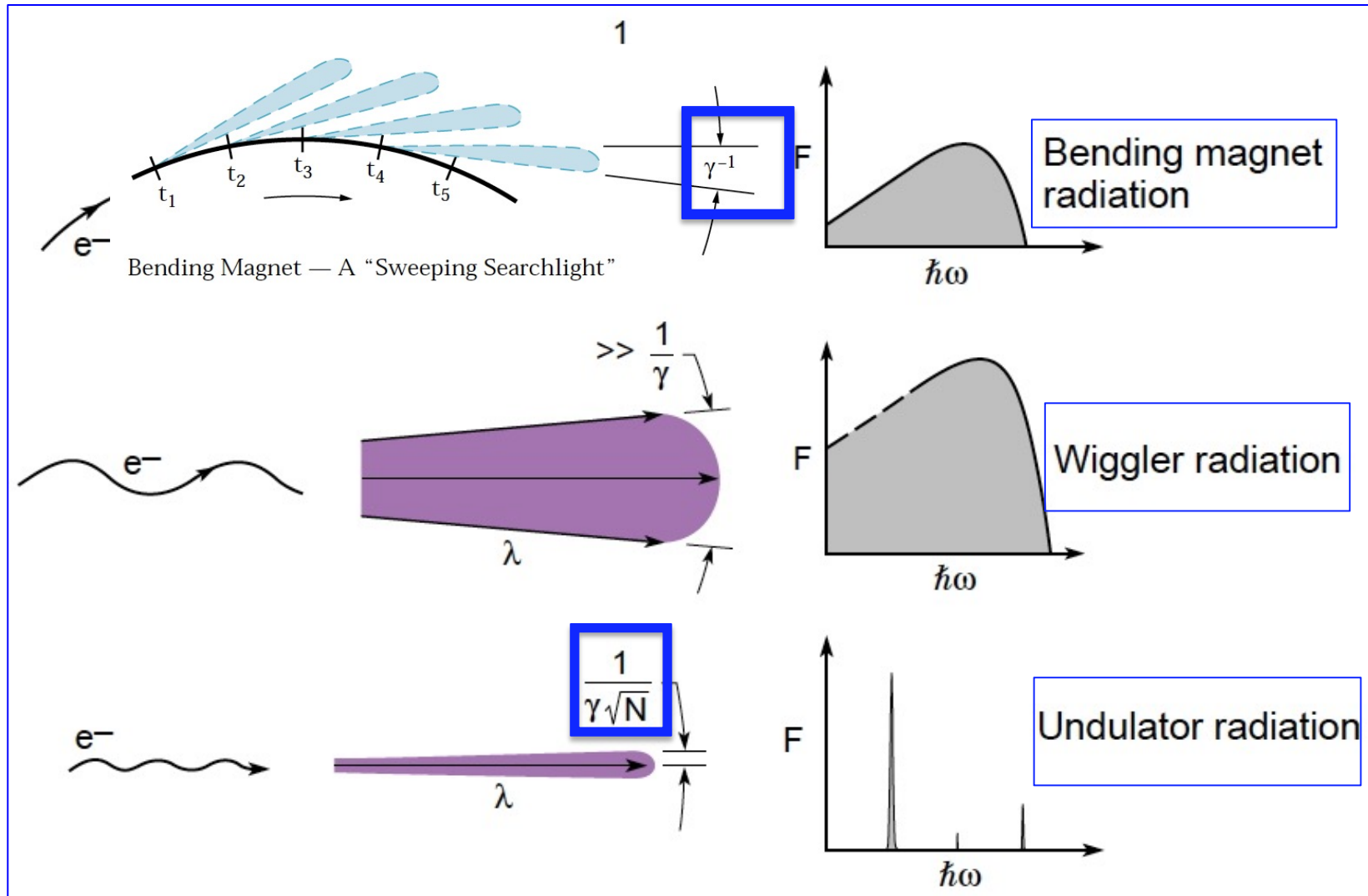
Two relativistic effects :

- **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: $\lambda = \lambda_u / \gamma$
- **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** : $\lambda = \lambda_u / 2\gamma^2$

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

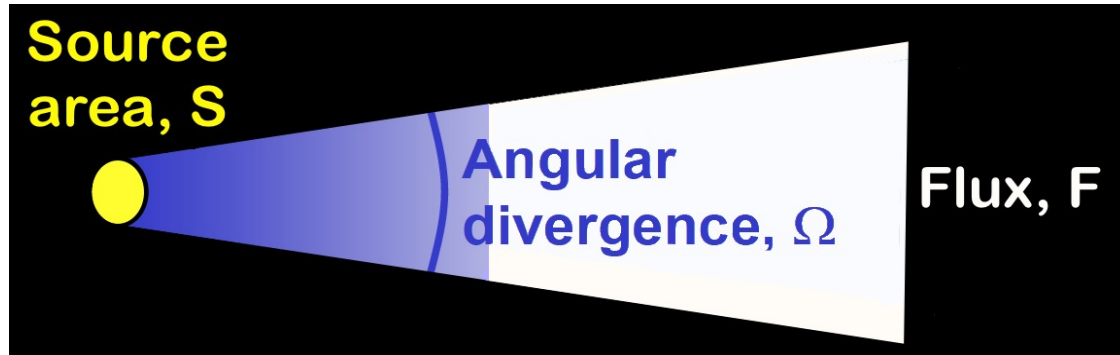


Just to summarize!



Brightness

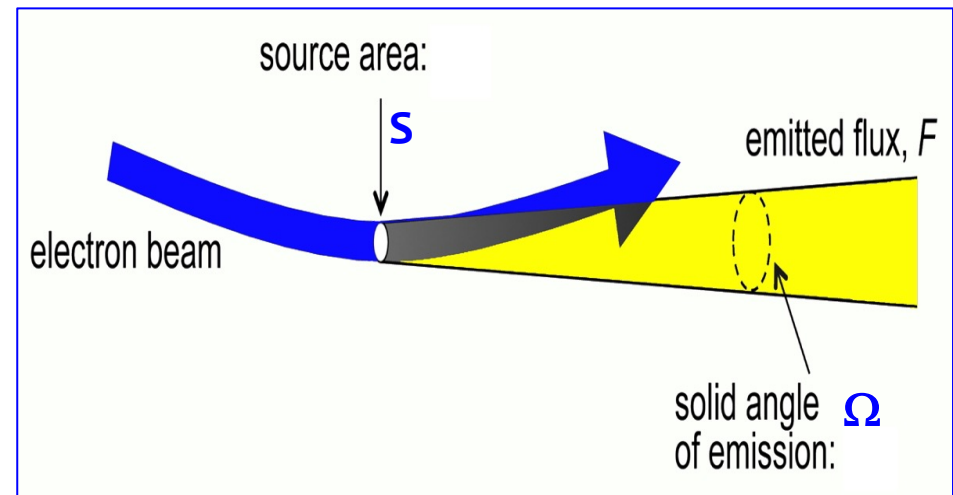
Synchrotron Radiation and Brightness



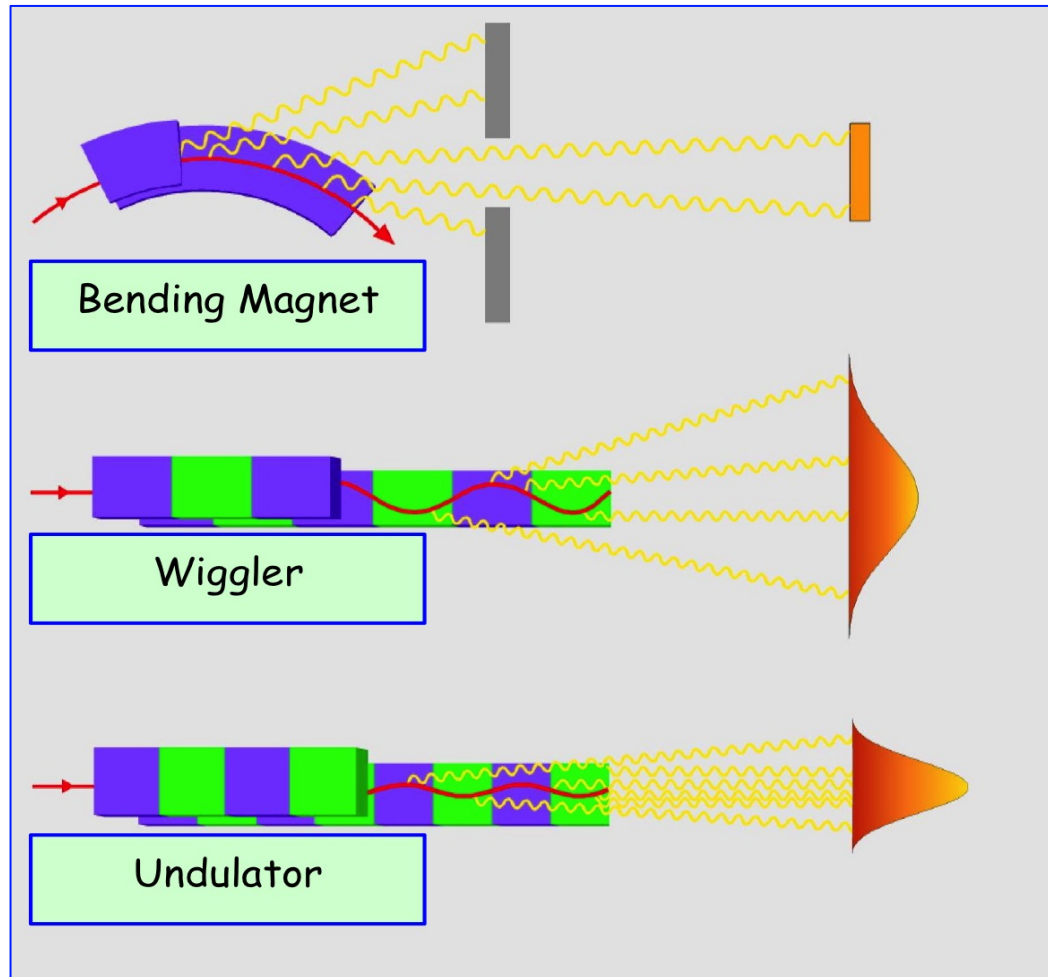
$$\text{Brightness} = \text{constant} \frac{F}{S \times \Omega}$$

Although the **flux** can be determined **without knowledge of the source size and divergence**, **brightness** requires a **more detailed knowledge of the particle beam's size and divergence**.

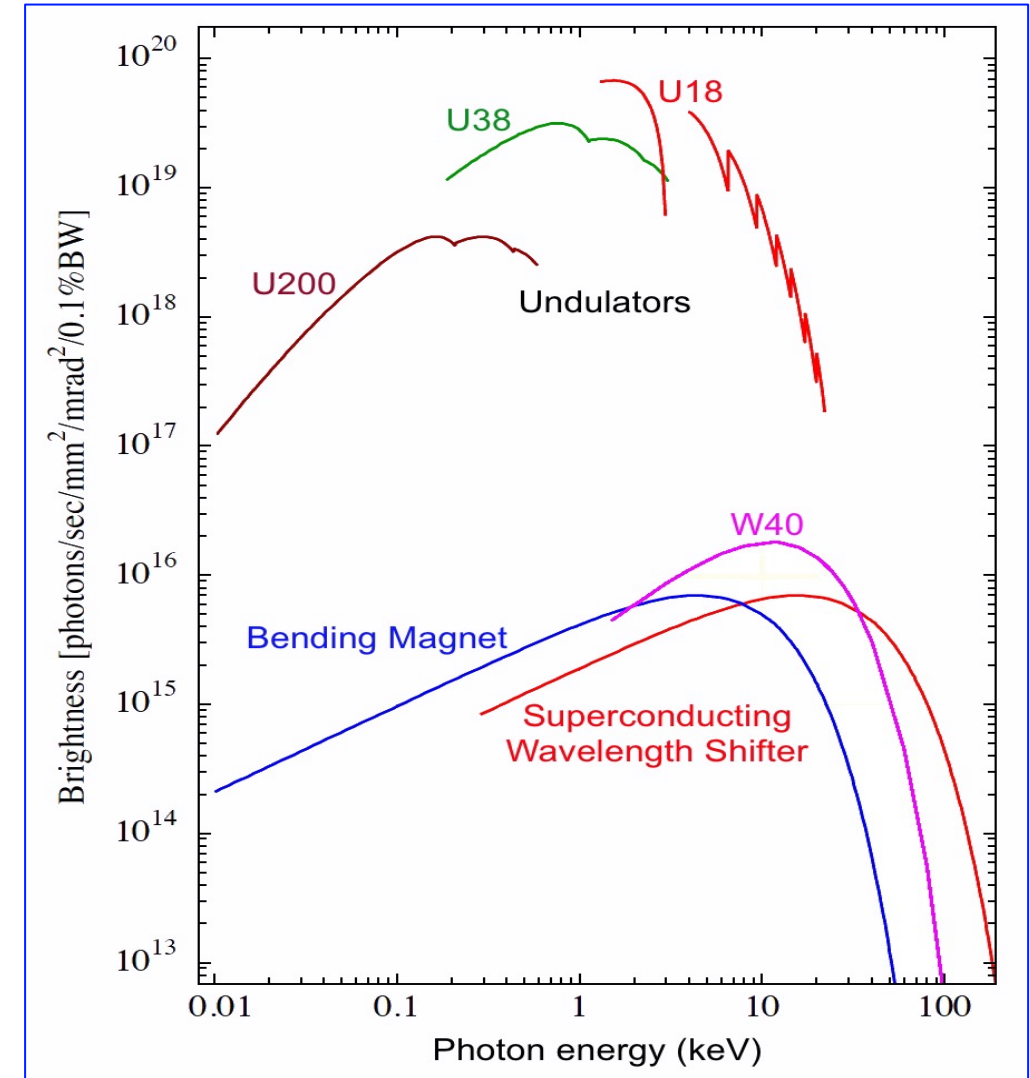
Brightness (flux density in phase space) depends on the **size of the source (S)** (electron beam) and on the **angular divergence of the radiation (Ω)**, given by the **convolution of the angular distribution of synchrotron radiation with the angular divergence of the electron beam**.



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>)

Synchrotron Radiation and Brightness

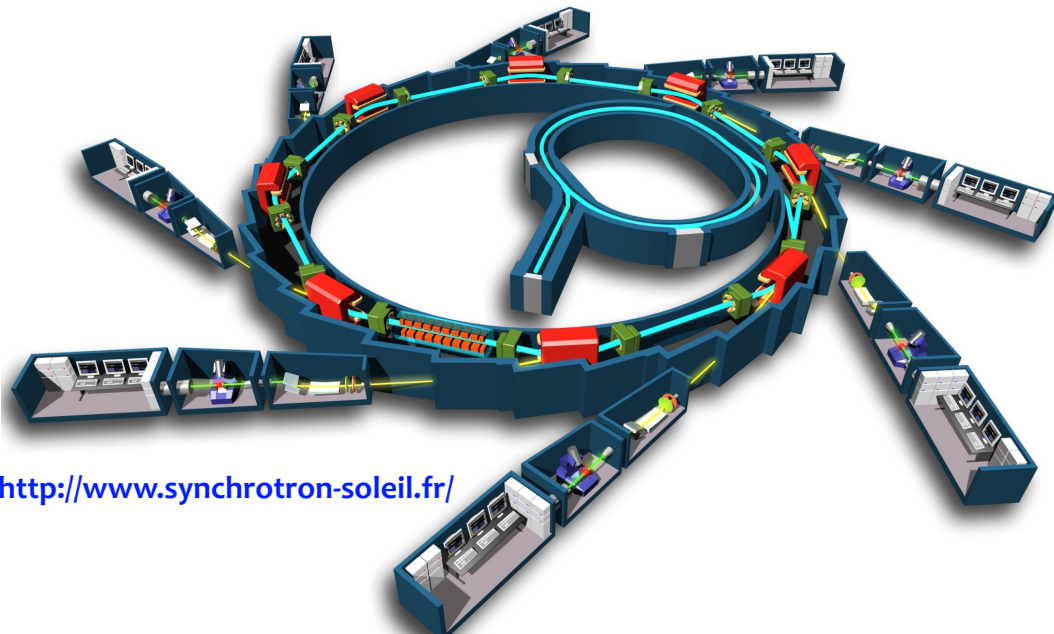
The **primary figure of merit used to compare different sources of synchrotron radiation** has been referred to as the "**brightness**", the "**brilliance**", and the "**spectral brightness**," with the latter **term being recommended** as the best choice by the Working Group on Synchrotron Nomenclature - *Journal of Synchrotron Radiation*. **12 (2005) 385.**

While **brightness** maintains the generally accepted concept of **flux per unit source size and divergence**, the **spectral brightness** conveys the scientific importance of the **number of photons in a given bandwidth** (related to the monochromaticity of the beam $\Delta\omega/\omega$).

Spectral Brightness : (photons/s)/0.1% BW/source area / source divergence.

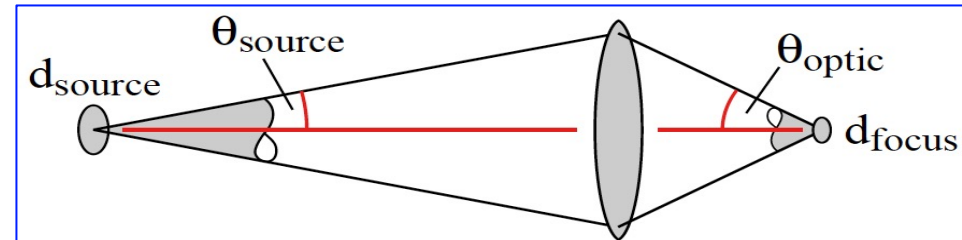
Spectral Brightness in units = photons/s/mm²/mrad²/0.1%BW

Brightness and beamlines



<http://www.synchrotron-soleil.fr/>

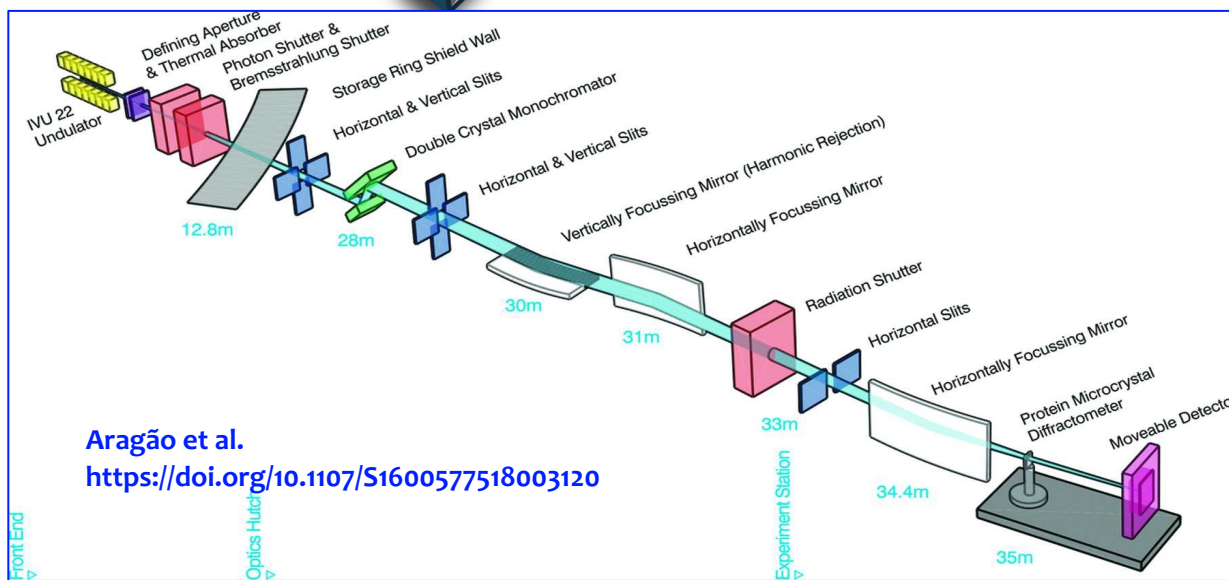
As well known due to **Liouville's theorem**, **focusing preserves brightness**, the brightness of the source is equal to the brightness of the beam when focused on the sample.



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

Smaller after focus

Larger in a focusing optic



Aragão et al.
<https://doi.org/10.1107/S1600577518003120>

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.

**Evolution of synchrotron
radiation accelerators
and brightness increase**

Accelerator x-ray light sources of the world.



https://www.aps.anl.gov/files/APS-Uploads/APS-Science/APS_Science_2014.pdf

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

Evolution and brightness increase

Proof of concepts, tests of theories
1897-1946

First observation of
synchrotron radiation 1947

Parasitic use of electro-
synchrotrons 1961

Storage rings development 1960

1st gen. Tantalus I first dedicated ring to SR but
not designed for its use (USA) 1968

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

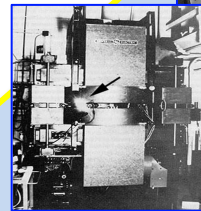
Brightness increase

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

3rd* gen. Ultimate Storage Rings like
MAX IV (Sweden) 2016

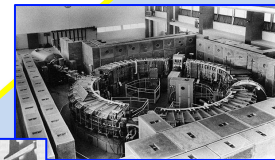
4th gen. - LINAC based accelerators
FELs and XFELs

5th gen. - Advanced accelerator concepts



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

J. Schwinger Nobel Prize 1965 Classical Relativistic
quantum field theory



ADA - B. Touschek - LNF

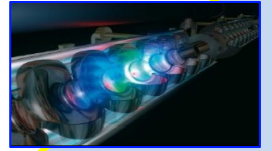
Using accelerators built for HE physics



First accelerators
built for SR - BM



Accelerators built to
optimize SR - ID



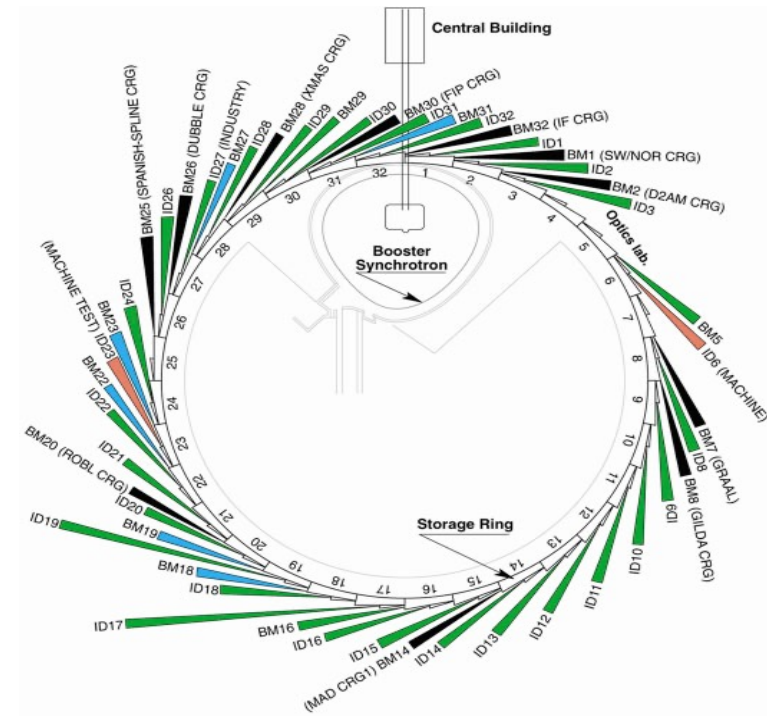
Third generation: optimized sources

Synchrotron light becomes a unique tool for science!



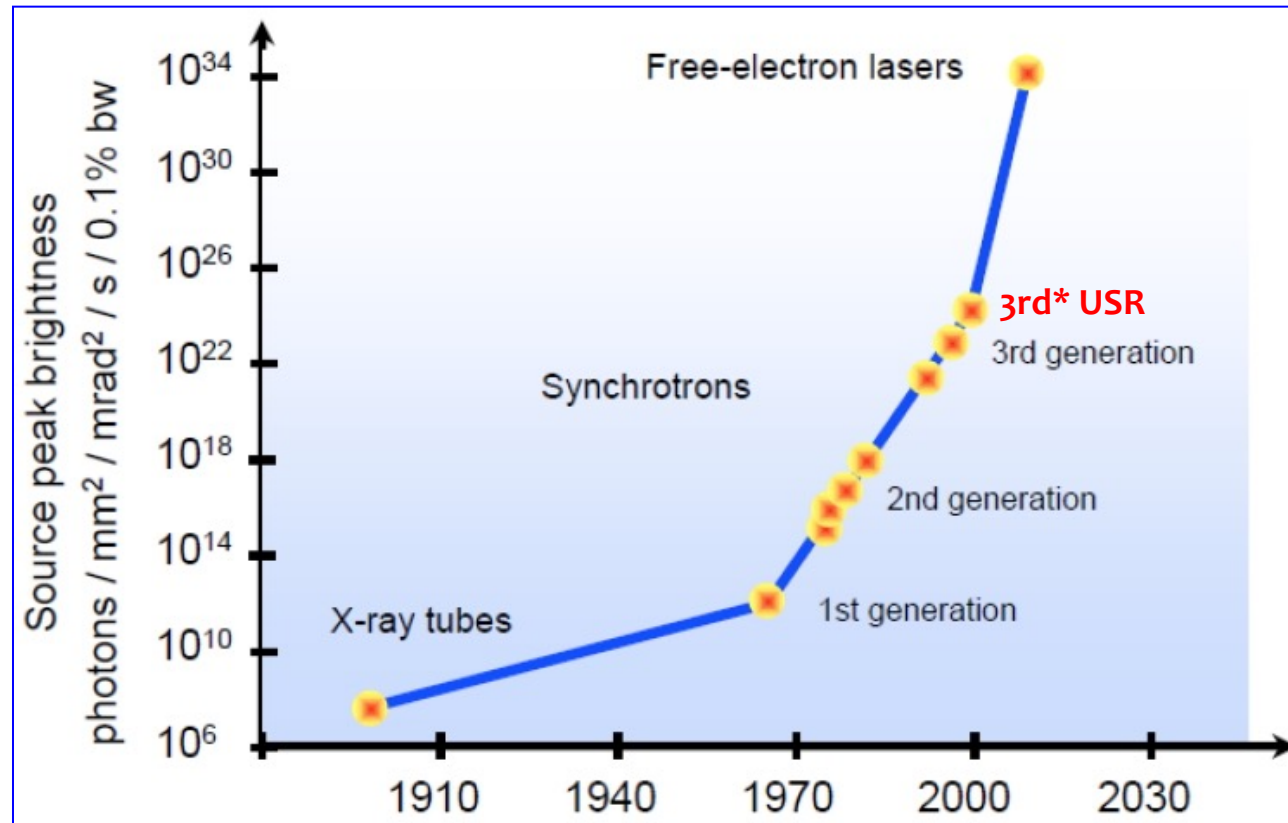
ESRF, Grenoble - France 6 GeV, $C = 844$ m
opened to users from 1994 to 2018

- 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.



Increasing brightness

A further brightness increase, was obtained designing **very low emittance machines**, minimizing the source size and the beam divergence.



Increase of a factor 1000 every 10 years!!!

Ultimate Storage Rings USR

... toward Diffraction Limited Light Sources

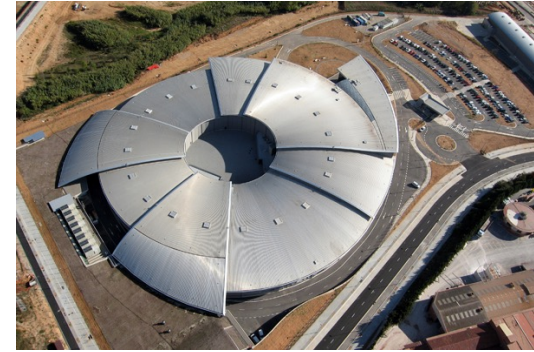
3rd Generation Light Sources



Elettra (2 and 2.4 GeV) - Italy



DIAMOND (3 GeV) - UK



ALBA (3 GeV) - Spagna

All these 3rd generation light sources are moving in the direction of an upgrade.

3rd* Ultimate Storage Rings (USR)



Lund (3 GeV) - Sweden



ESRF - EBS (6 GeV) - France



SSRF (3.5 GeV) Shanghai -China

Brightness and emittance

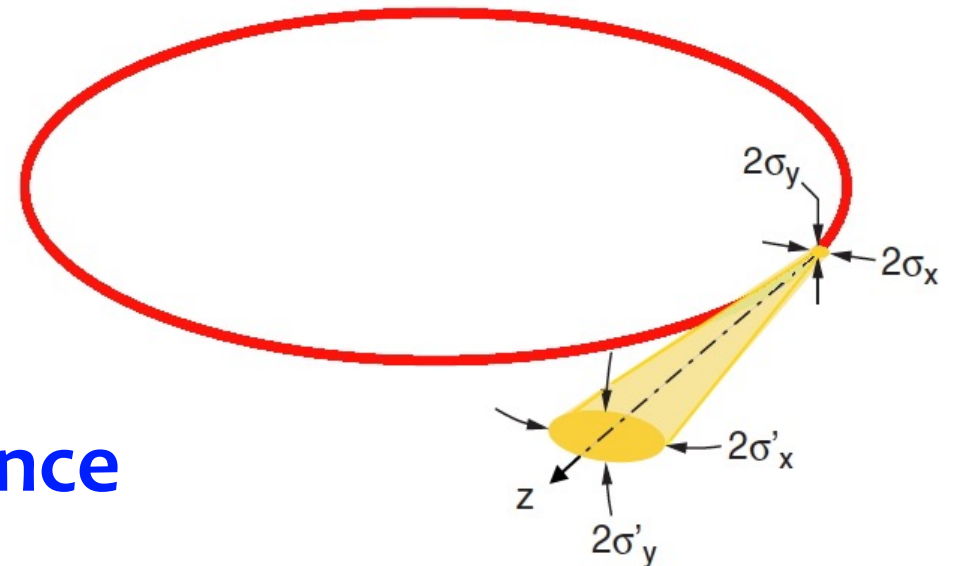
Brightness is the main figure of merit of synchrotron radiation sources and its huge **increase**, was obtained designing low emittance machines, minimizing the source size **and** the beam divergence.

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**.

$$\epsilon_x = \sigma_x \sigma'_x$$
$$\epsilon_y = \sigma_y \sigma'_y$$

$$\epsilon_y \ll \epsilon_x$$

**High brightness and low emittance
are strictly related.**



Emittance and Diffraction Limit

To increase brightness, low emittance machines with minimized source size and the beam divergence are needed.

Diffraction limit gives the limit to emittance minimization.

Electron beam provides “**diffraction-limited**” beam when:

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

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

ϵ_r is the **emittance** given by the **angular divergence** and the effective **radiation source size**.

Emittance and Diffraction Limit

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

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

Typically, 3rd-generation rings the emittance values are:
vertical **horizontal**

$\epsilon_y = 1 - 40$ pmrad and $\epsilon_x = 1 - 5$ nmrad

ESRF Grenoble (2018)

$\epsilon_y = 4$ pmrad

$\epsilon_x = 4$ nmrad

ALS Berkeley

$\epsilon_y = 30$ pmrad

$\epsilon_x = 2$ nmrad

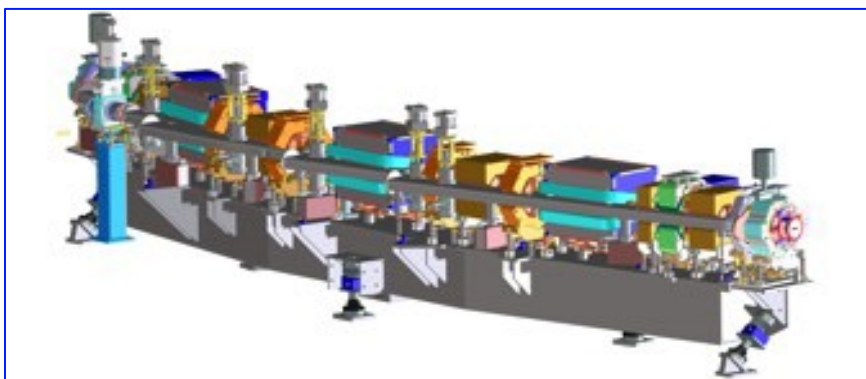
Several orders of magnitude away from diffraction-limited performance in horizontal plane.

Emittance and Multi-bend Achromat Lattice

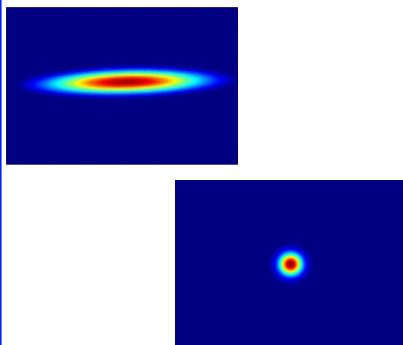
$$\epsilon_{x_0, min} \propto \frac{E^2}{N_B^3}$$

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

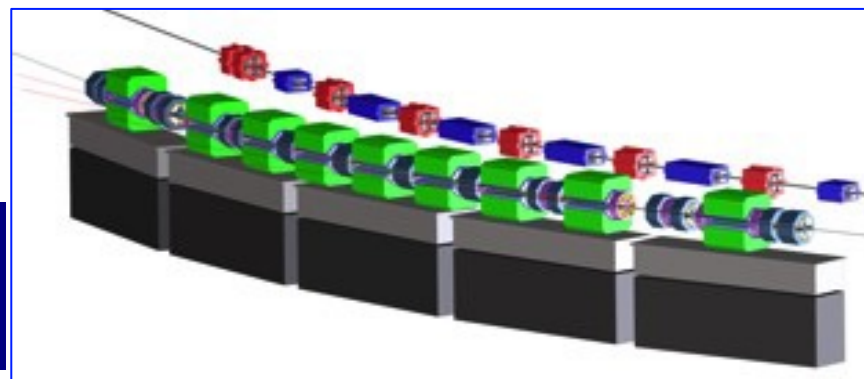
- Emittance is driven by randomness of photon emission in presence of dispersive (energy-dependent) orbits;
- **Breaking up dipoles and putting focusing (quadrupoles) between the parts** allows tightly controlling the magnitude of dispersive orbits



ALS today triple-bend achromat (TBA)
 $\epsilon_x = 2000$ pmrad



C. Steier, ALS SAC



ALS-U multi-bend achromat (9BA) (approved
in 2021 (2025-2027))
 $\epsilon_x = 52$ pmrad

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

Emittance and Multi-bend Achromat Lattice

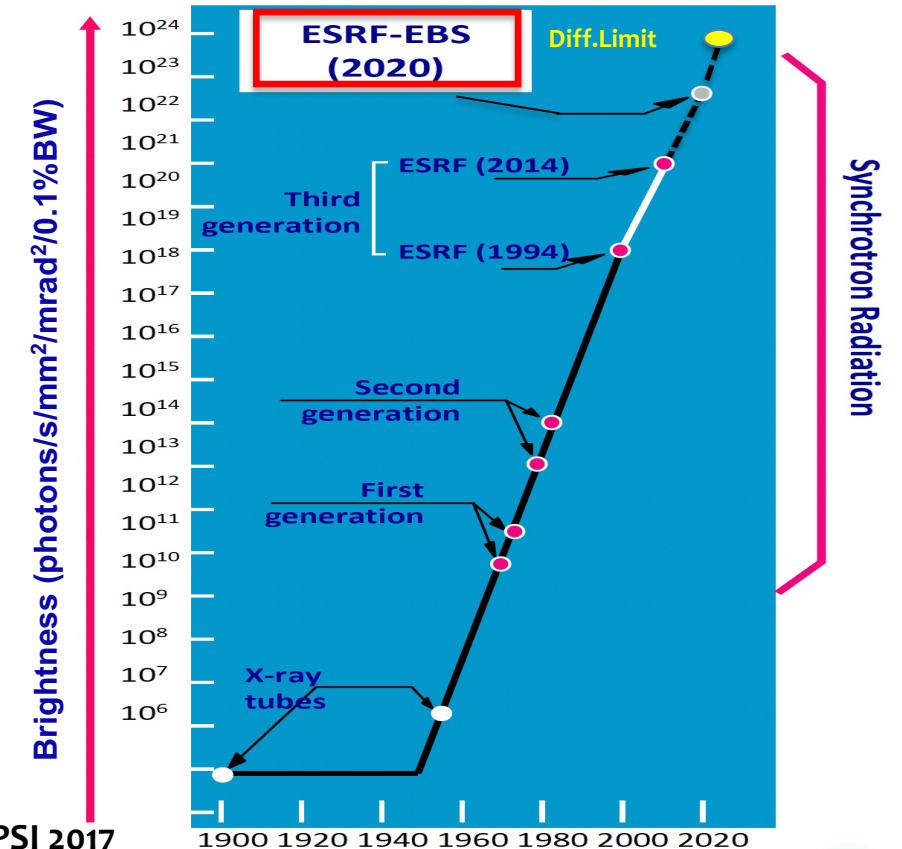
J.Jacob, Status of the
ESRF operation &
upgrade, 2013



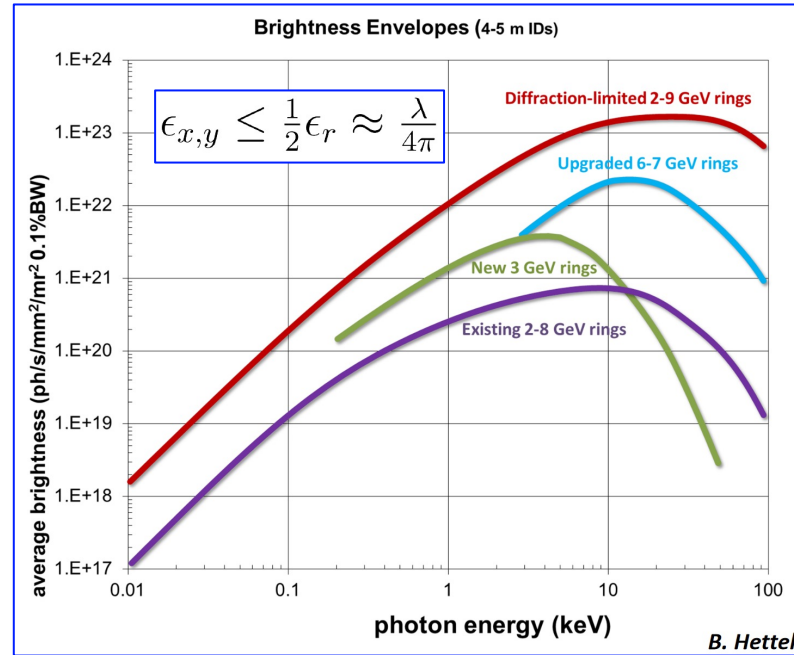
	ESRF	ESRF-EBS
Energy (GeV)	6.03	6
Circumference (m)	844.391	843.977
Beam current (mA)	200	200
Bunch length (mm)	4.28	2.91
Energy spread	$1.06 \cdot 10^{-3}$	$0.93 \cdot 10^{-3}$
Synchrotron frequency (kHz)	2.10	1.30
Oper. Emittance (H/v) (pm)	4000/5	110/5

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

<https://www.esrf.fr/home/UsersAndScience/Accelerators/parameters.html>



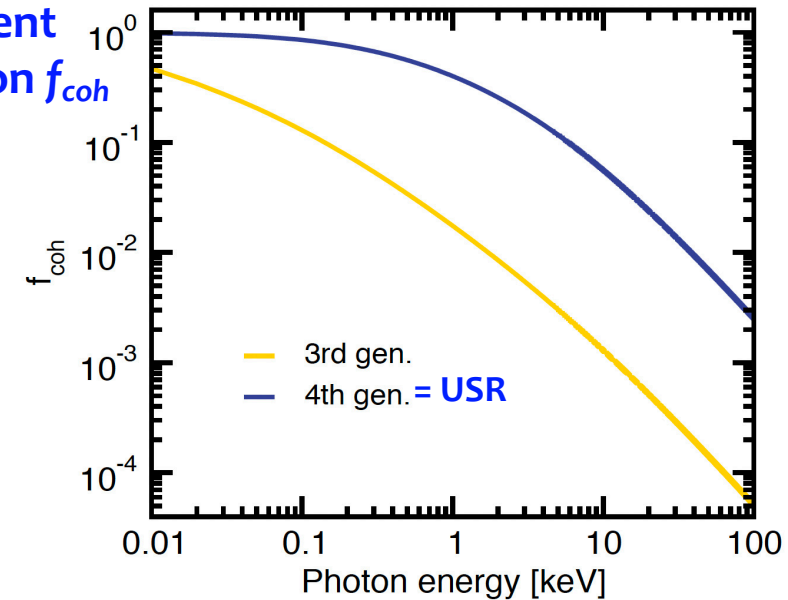
Storage rings generational change



Approaching the diffraction limit there is an increase of the coherent fraction of the beam.

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

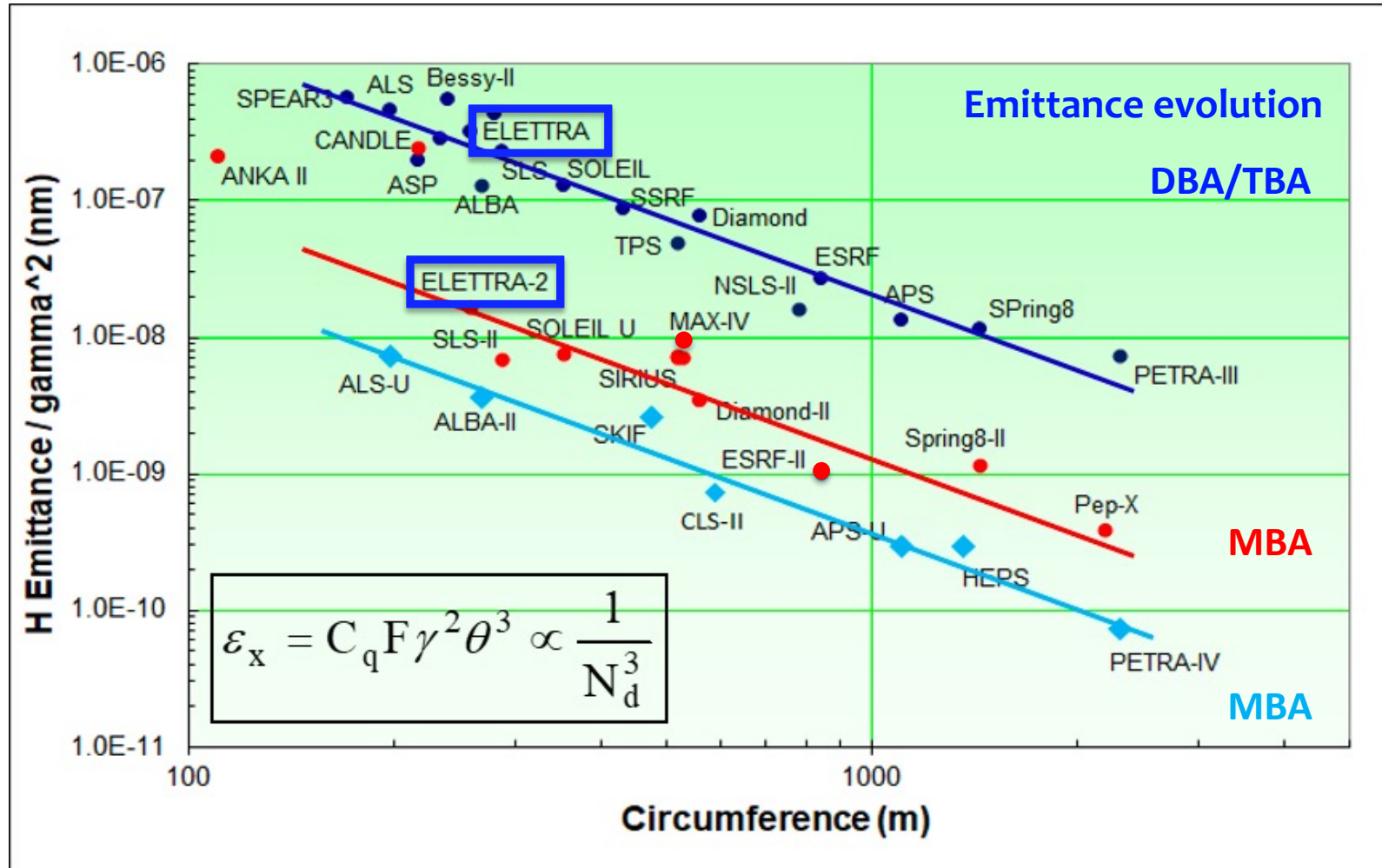
Coherent
Fraction f_{coh}



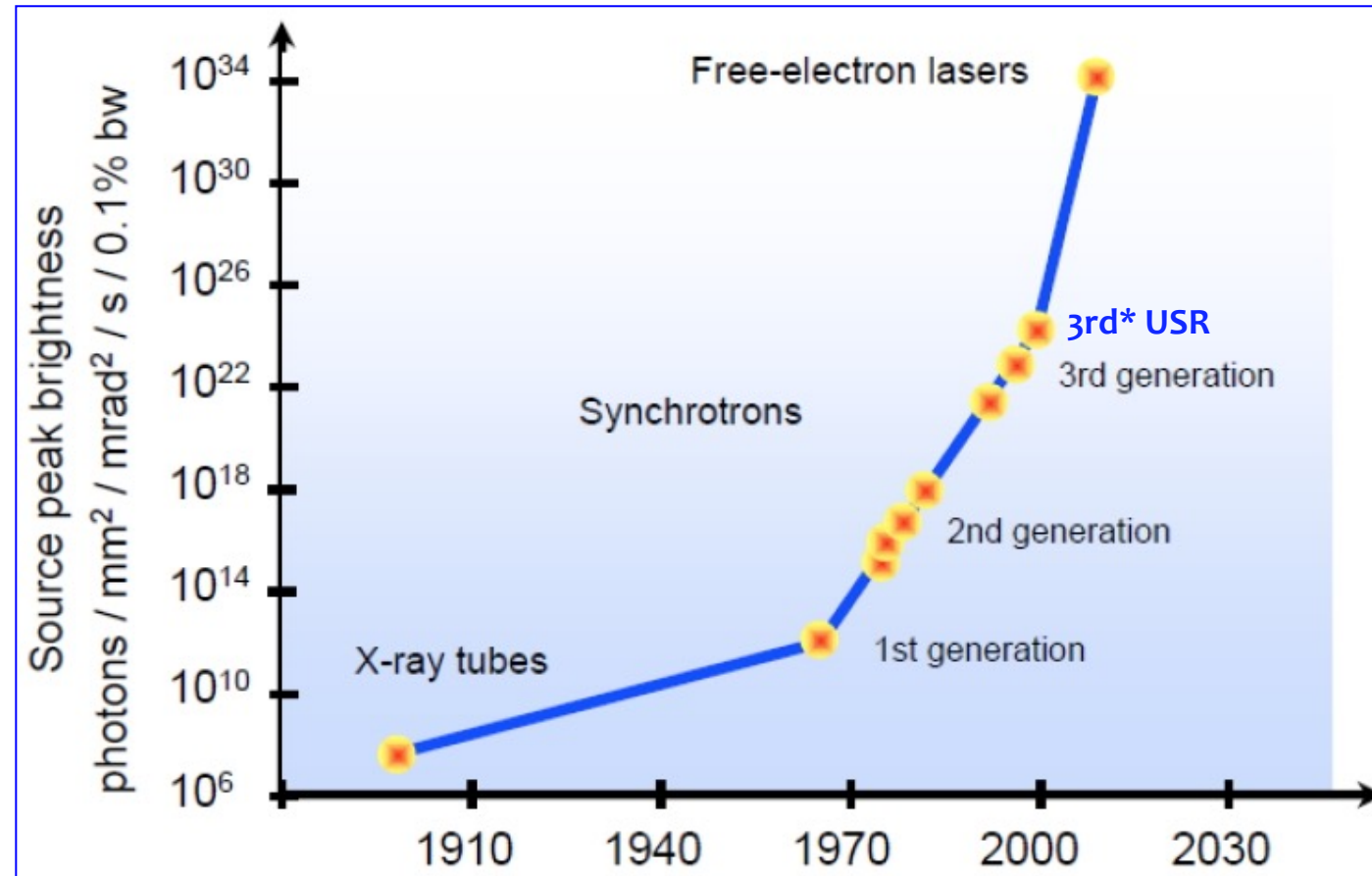
USR - Ultimate
Storage Rings

	3 rd generation	USR
ϵ_x^e	5 nm rad	100 pm rad
ϵ_y^e	1 pm rad	1 pm rad
σ_x^e	100 μm	10 μm
σ_y^e	2 μm	2 μm

Storage rings generational change



Further increase of brightness: Free Electron Lasers

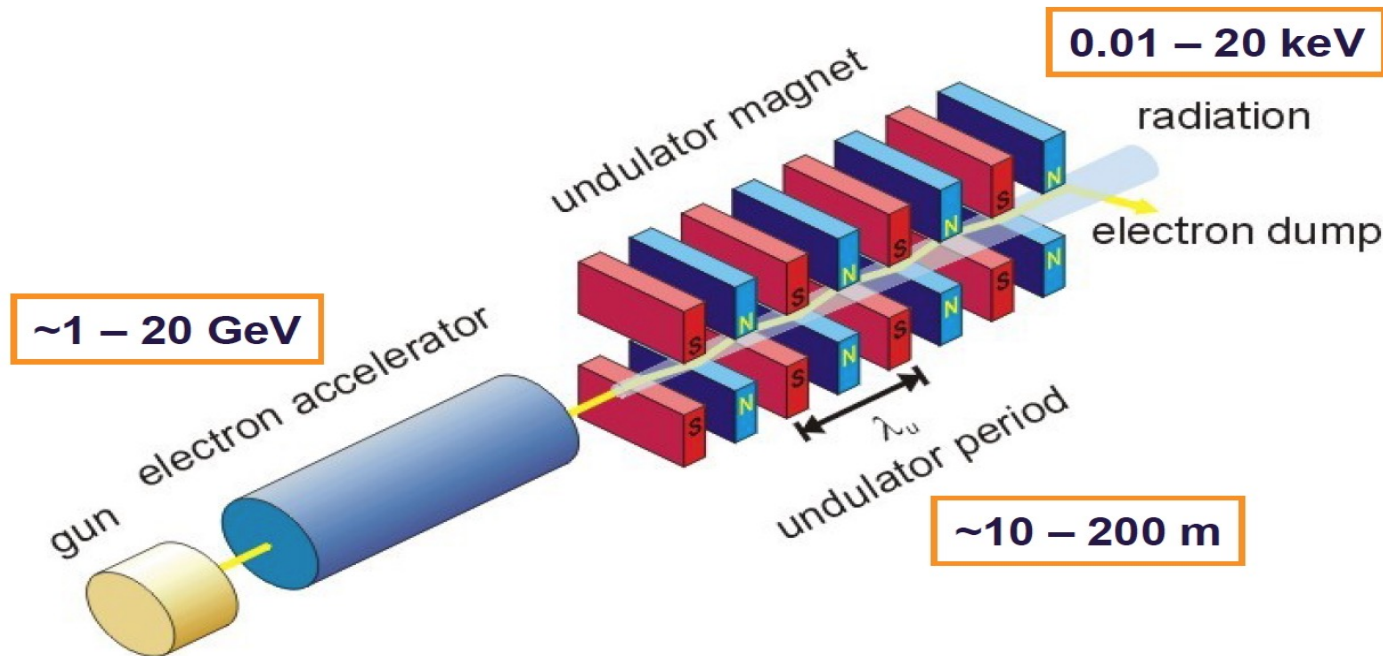


LINAC based sources FELs and XFELs

Fourth generation: LINAC based sources and Free Electron Lasers

Free-electron lasers (FELs) are tunable, coherent, light sources producing extremely bright and short radiations pulses at different energies up to x-rays.

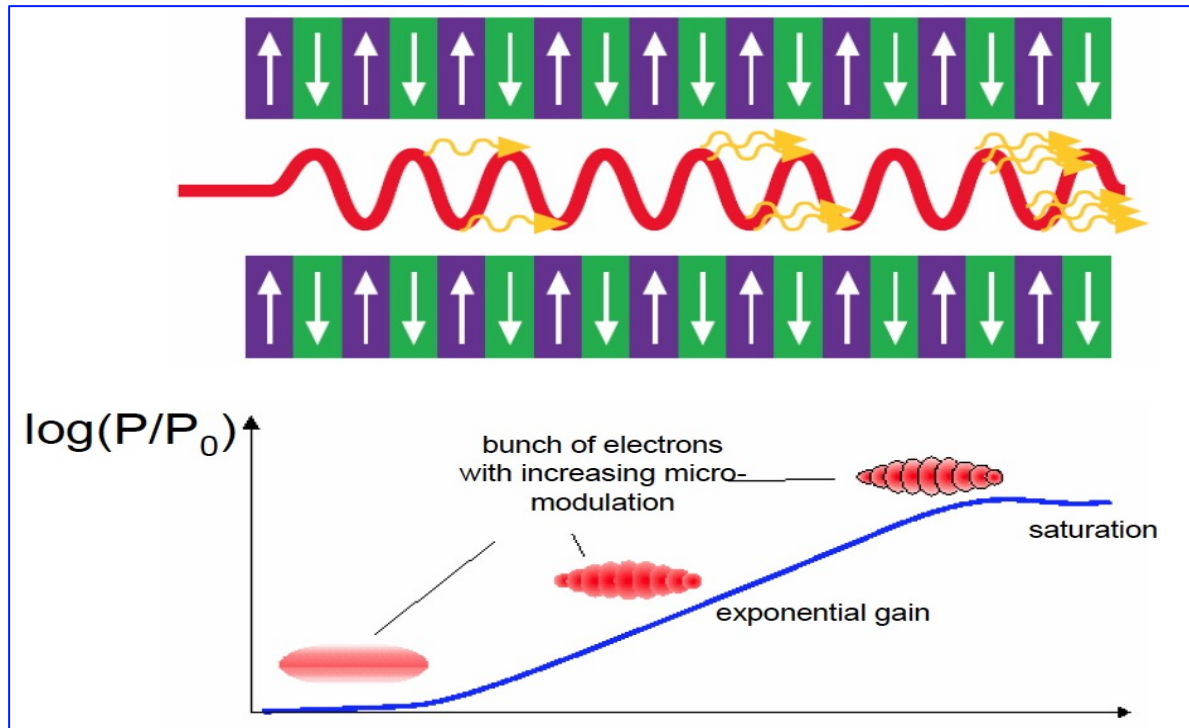
A FEL behaves like a laser but instead of using stimulated emission from atomic or molecular excitations, it uses relativistic electrons. The “free” electrons traverse a series of alternating magnets, called “undulators,” and radiate light at wavelengths depending on electrons energy, undulator period and magnetic field.



John Madey introduced the initial FEL concept in 1971. In 1976 the first coherent infrared radiation at a wavelength of $3 \mu\text{m}$ was observed.

Fourth generation: LINAC based sources and Free Electron Lasers

SASE FEL – Self Amplified Stimulated Emission



Lethargy
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.

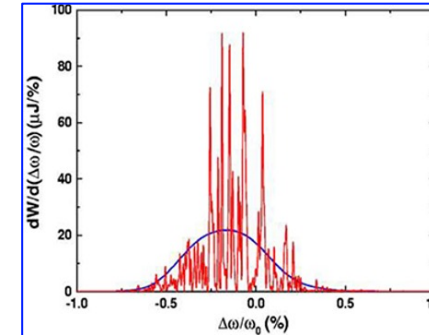
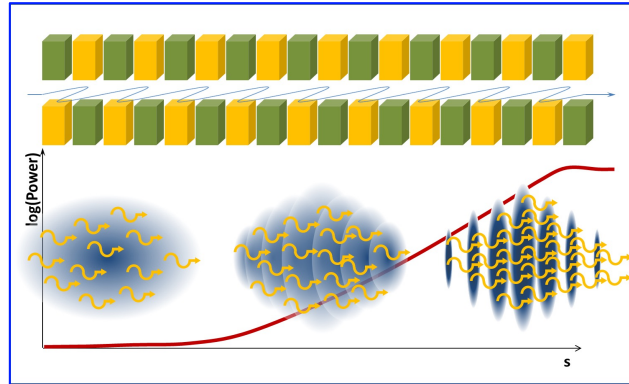
D. Nguyen, S. Russell and N. Moody, Theory and Practice of Free-Electron Lasers, 2009
T. Tschentscher, Free-electron lasers as sources of extremely brilliant x-ray radiation, 2011

Stimulated photon emission: electrons are accelerated by an existing photon field and therefore irradiate additional photons in phase to the existing ones

Fourth generation: LINAC based sources and Free Electron Lasers

SASE FEL

https://www.helmholtz-berlin.de/projects/berlinpro/erl-intro/linac-fel_en.html

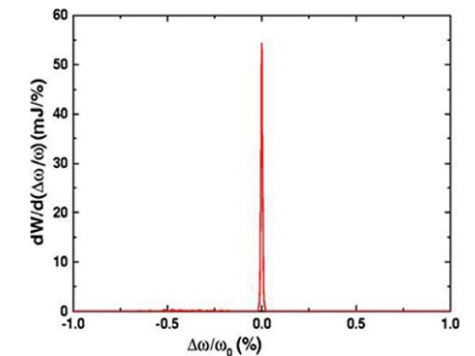
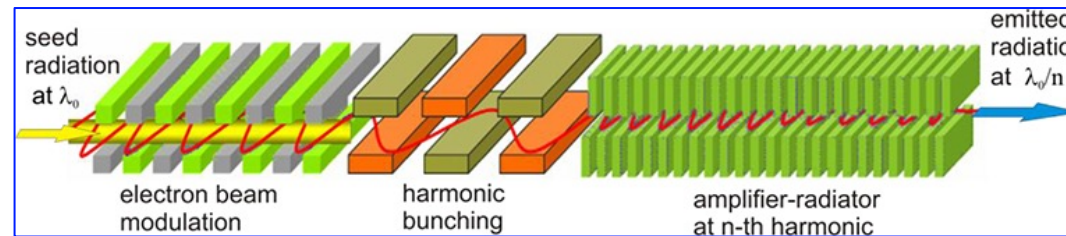


SASE FEL with poor temporal coherence

Starting point: spontaneous emission - random phase

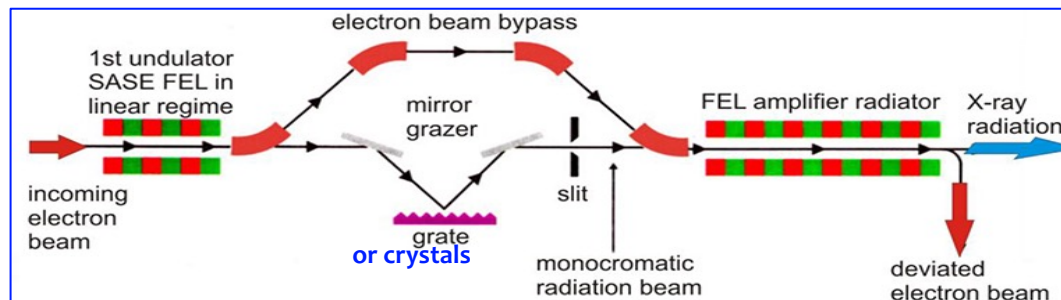
SEEDED FEL

Starting point: external radiation seed laser pulse modulating the energy of the wiggling electron beam.

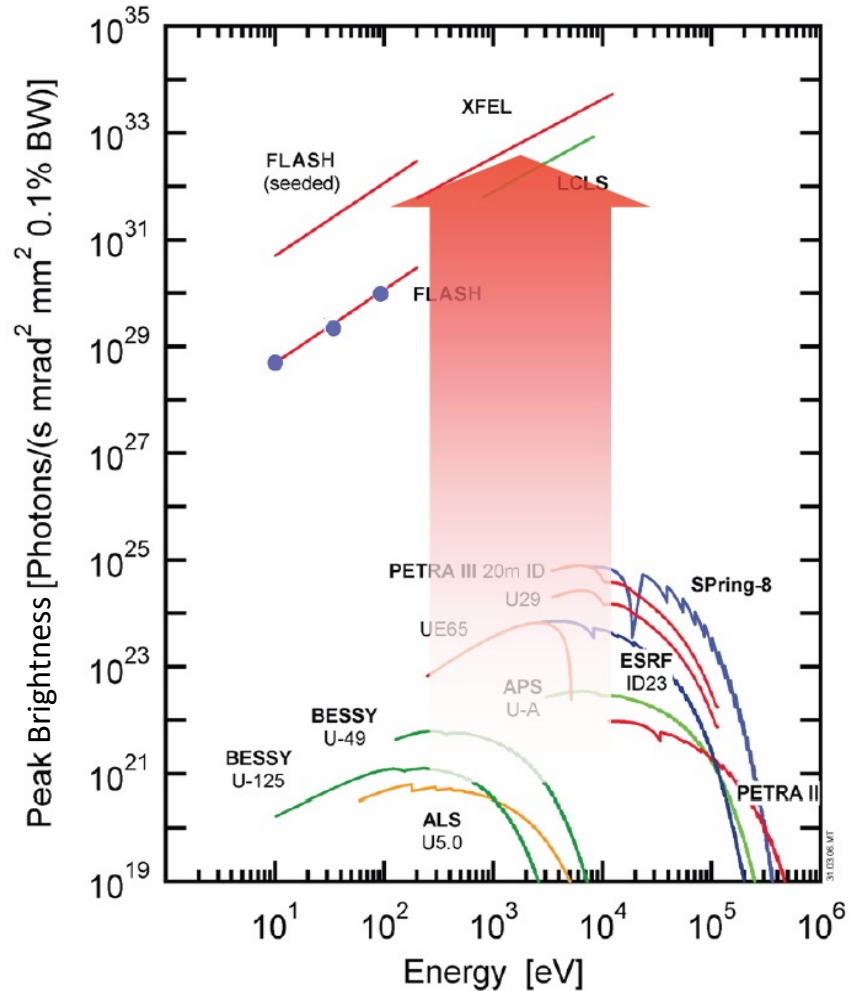


SEEDED FEL also high temporal coherence

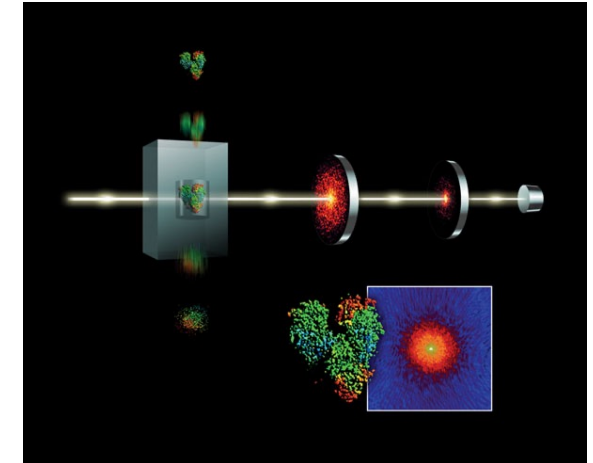
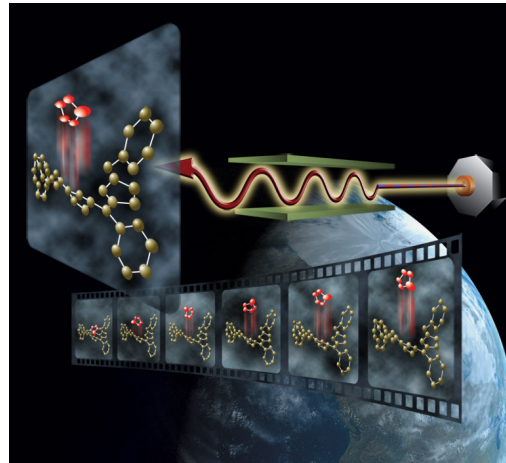
SELF - SEEDED FEL



Fourth generation: LINAC based sources and Free Electron Lasers

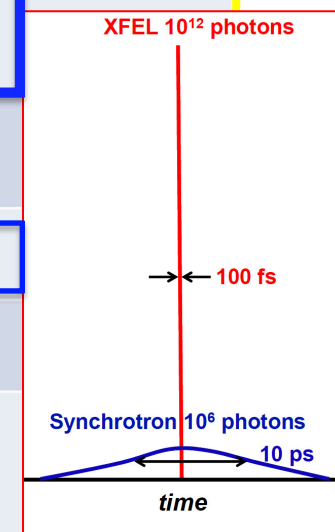


- Extremely bright and coherent sources
- Ultrafast pulses
- Already working in IR to UV and X-ray (first XFEL - LCLS April 2009) ranges
- European XFEL working from 2017
- Filming chemical reactions as they occur
- Protein crystallography no longer needed –image molecules directly



Comparing Ultimate Storage Rings and FELs

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	<.01% (with ~0.1% energy spread)	< 0.1 eV (seeded)
Position	< 0.1 σ (~0.3 μ m H, V)	~0.1 σ
Time	< 0.1 σ (~0.5 ps)	~10 fs
Number of Beamlines	Large (~30-60)	Limited (~3-6 endstations per undulator), multiple undulators per facility



XFELs

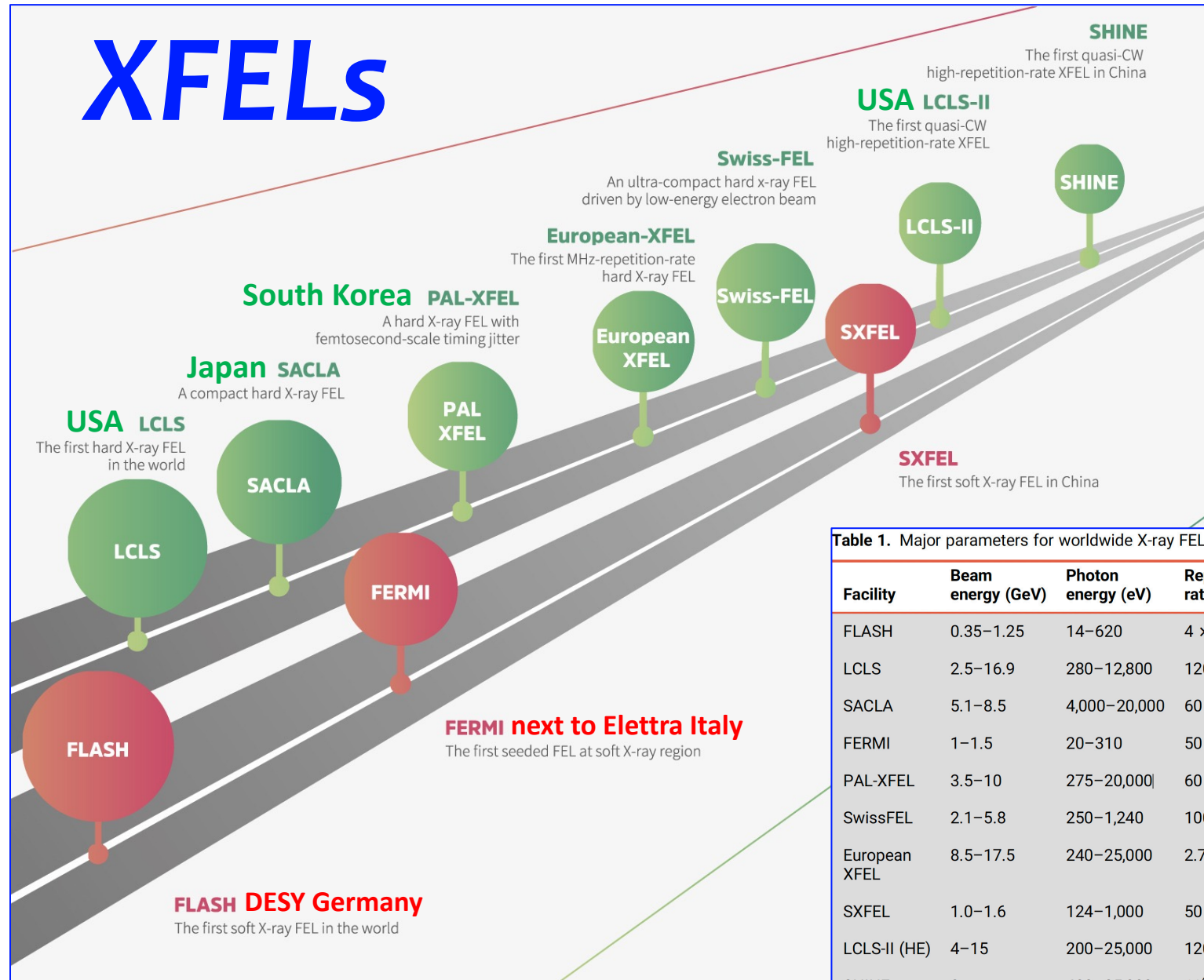
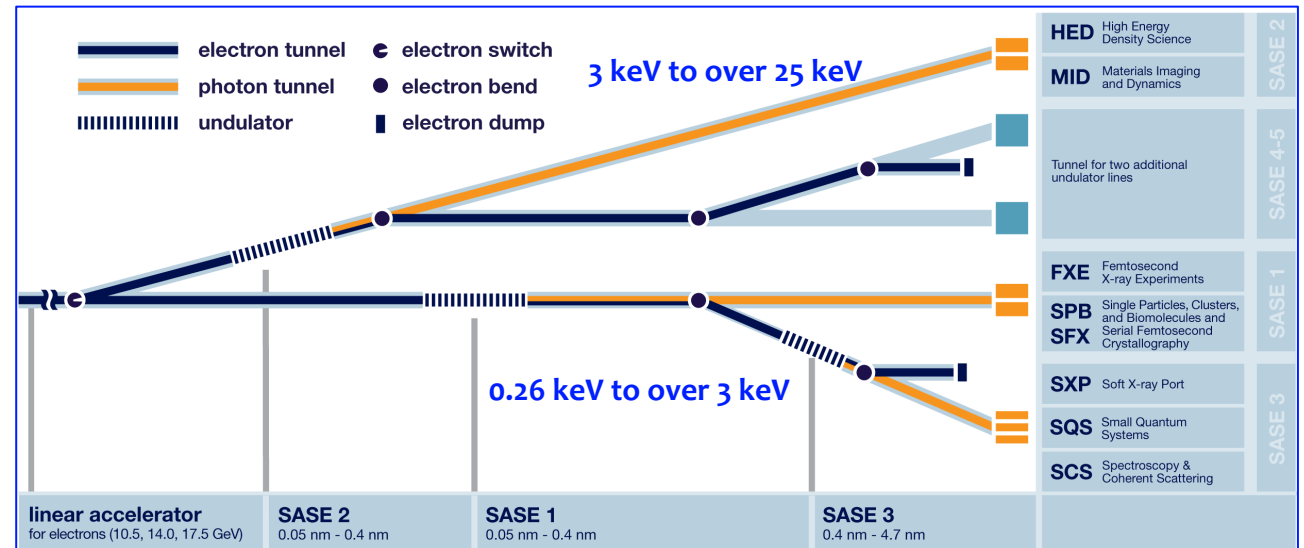


Table 1. Major parameters for worldwide X-ray FEL facilities

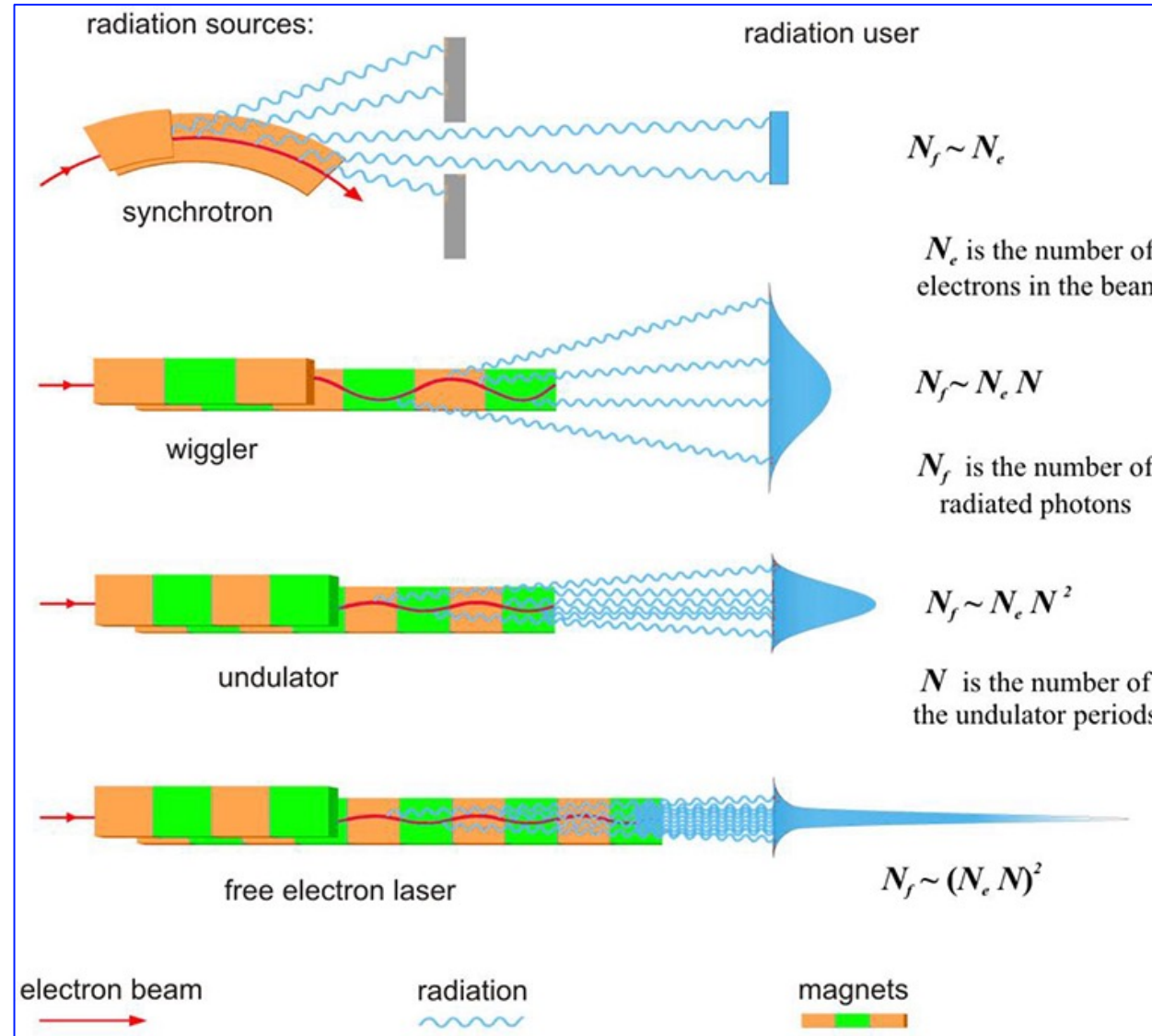
Facility	Beam energy (GeV)	Photon energy (eV)	Repetition rate (Hz)	Pulse duration (FWHM) (fs)
FLASH	0.35–1.25	14–620	4×10^3 to 10^6	10–200
LCLS	2.5–16.9	280–12,800	120	5–400
SACLA	5.1–8.5	4,000–20,000	60	2–10
FERMI	1–1.5	20–310	50	30–100
PAL-XFEL	3.5–10	275–20,000	60	5–100
SwissFEL	2.1–5.8	250–1,240	100	1–20
European XFEL	8.5–17.5	240–25,000	2.7×10^4	3–150
SXFEL	1.0–1.6	124–1,000	50	30–1,000
LCLS-II (HE)	4–15	200–25,000	$120/10^6$	1–500
SHINE	8	400–25,000	10^6	3–600



The **3.4 km-long** superconducting linear accelerator runs from the DESY campus in Hamburg to the town of Schenefeld in Schleswig-Holstein with maximum electron energy of 17.5 GeV and 200 m long undulator section. It generates ultrashort X-ray flashes - **27 000 times per second** and with a brilliance that is a billion times higher than that of the best conventional X-ray radiation sources (operation began in September 2017.)



Just to summarize!



5th Generation Light Sources

... re-invent XFEL to fit in campus laboratory.

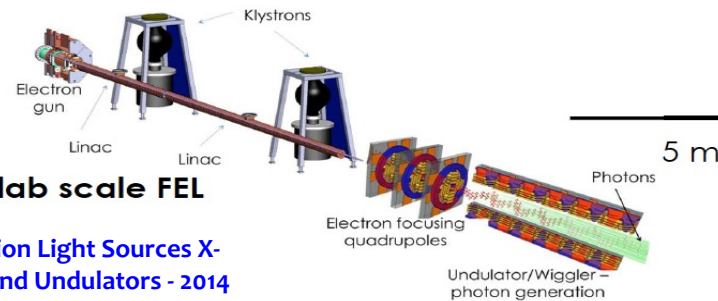
Fifth Generation Light Sources

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



1 km

Into this...



5 m

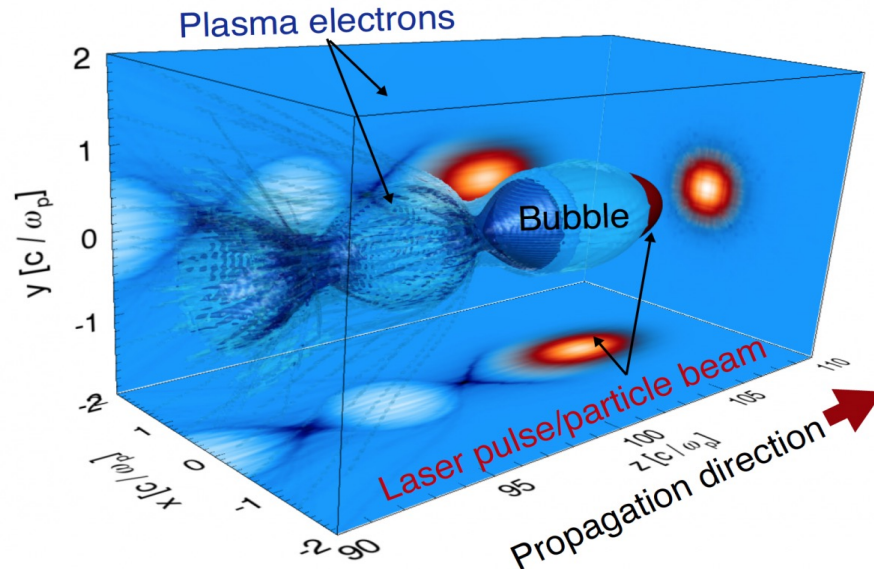
The university lab scale FEL

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**.

The possibility to **accelerate electron beams to ultra-relativistic velocities over short distances by using plasma-based technology** holds the potential for a revolution in the field of particle accelerators.

Wakefield Accelerators



http://case.physics.sunysb.edu/index.php/Wakefield_Accelerators

Wakefield acceleration enables the **miniaturization of accelerating structures** by creating much higher-energy particles in the same footprint as the usual accelerator.

Laser Wakefield Accelerator - LWFA

Drive beam = laser beam

Plasma Wakefield Accelerator - PWFA

Drive beam = high energy electron beam

A plasma is an ionized medium, meaning that the ions and electrons are free to move independently in response to electromagnetic forces. To **generate waves in the plasma**, sources of **intense electromagnetic energy such as lasers or ultra-relativistic electron beams (driver)** are sent **through it**. Because the **electrons are light**, the **forces of the intense driver expel the plasma electrons out of its path, leaving behind the much heavier ions**, which are nearly stationary on the time scale of the interaction. The **ions pull the electrons back towards the axis**, where they induce an **oscillating density wave behind the driver**. The **fields of this wave, which is set up in the wake of the intense driver, are referred to as wakefield**.

Both **laser-driven and particle beam-driven plasma** waves have demonstrated average sustained **accelerating forces** of around **40 GeV/m**, with **laser-driven plasma** waves producing electron beams of **8 GeV from 20 cm plasma channels**, and **electron-beam driven waves** producing **33 GeV of energy from 130 cm plasma**. For comparison, an advanced conventional accelerator such as **LCLS at SLAC produces a beam with similar energy (10 GeV) over 1 km**. Unlike regular accelerating structures **made of copper that are damaged when the fields exceed around 100 MeV/m**, **plasma wakes can support 100 GeV/m (1000x)** in conditions that are relatively easy to achieve.

Free-electron lasing with compact beam-driven plasma wakefield accelerator

EuPRAXIA @ SPARC_Lab (INFN-LNF) EU project

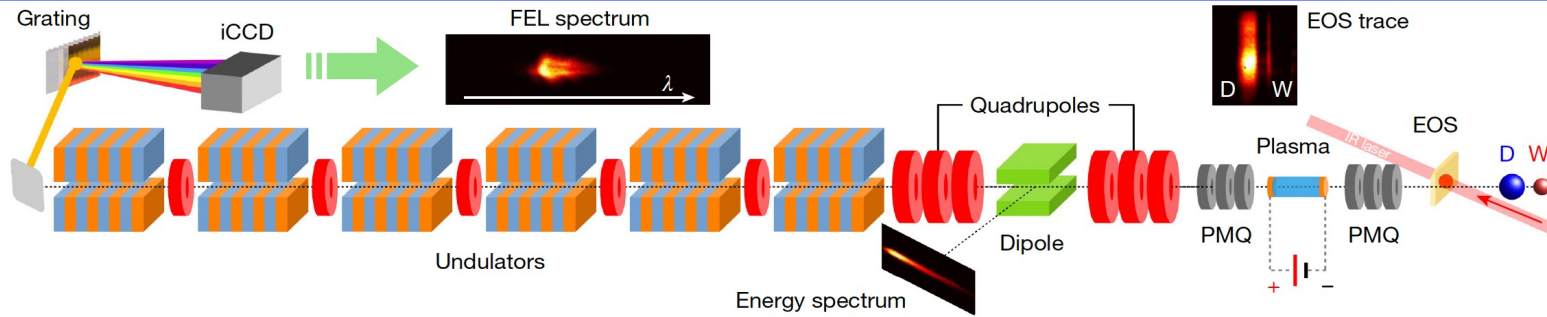


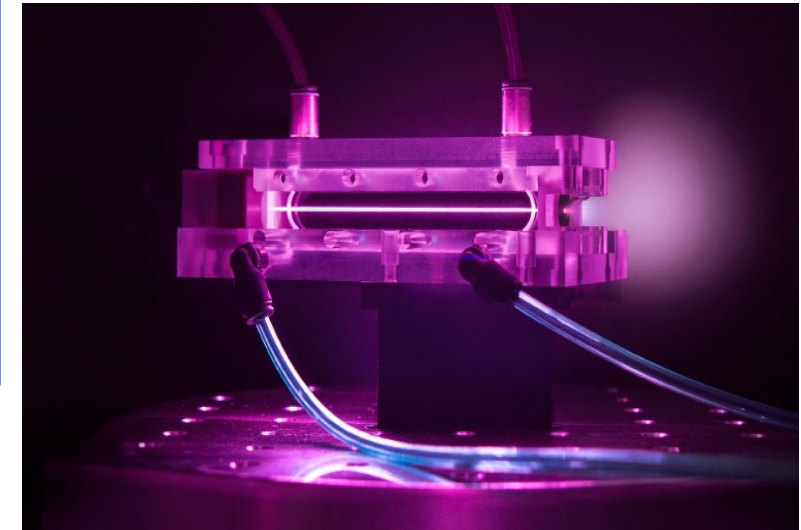
Fig. 1 | Experimental setup. The driver (D) and witness (W) electron bunches are produced by the photo-injector and their temporal separation is continuously monitored with a non-intercepting EOS diagnostics. The bunches are focused by a triplet of PMQs in a 3-cm-long capillary containing the plasma produced by ionizing hydrogen gas with a high-voltage discharge. The accelerated witness is extracted by a second triplet of PMQs and transported using six electromagnetic quadrupoles. A dipole spectrometer is used to

measure its energy with a scintillator screen installed on a 14° beamline. The FEL beamline consists of six planar undulators with tunable gaps and five quadrupoles in between to transport the beam. The emitted FEL radiation is collected by an in-vacuum metallic mirror and measured with an imaging spectrometer equipped with a diffraction grating and a cooled intensified camera (iCCD).

Nature | Vol 605 | 26 May 2022 | 659

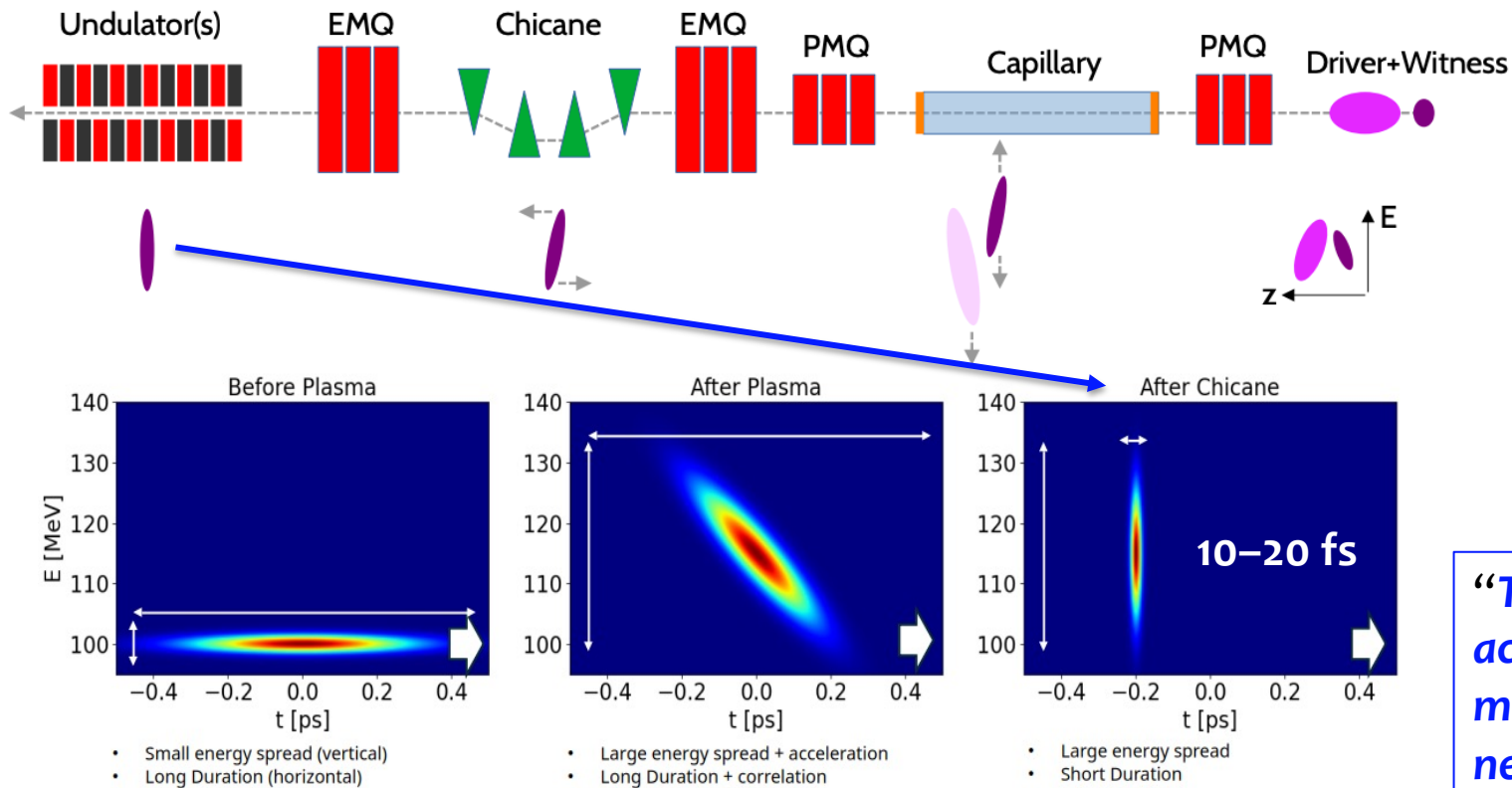
The compact nature of plasma-based accelerators would allow the realization of table-top machines capable of driving a free-electron laser (FEL), a formidable tool to investigate matter at the sub-atomic level by generating coherent light pulses with sub-Å wavelengths and sub-femtosecond durations.

Experimental evidence of FEL lasing by a compact (3 cm) particle-beam-driven plasma accelerator. This allowed the observation of narrow-band amplified radiation in the infrared (IR) range with typical exponential growth of its intensity over six consecutive undulators. This proof-of-principle experiment represents a fundamental milestone in the use of plasma-based accelerators, contributing to the development of next-generation compact facilities.



Milestone towards the realisation of the EuPRAXIA EU project.

INFN-LNF SPARC_LAB ULTRA-SHORT FREE-ELECTRON LASER (FEL) EMISSION FROM A PLASMA-ACCELERATED BEAM



A collaboration between the INFN Frascati National Laboratory, SLAC, and ENEA has demonstrated at SPARC_Lab for the first time the emission of 700 nm FEL radiation generated by an electron beam accelerated in a plasma and then compressed to a few femtoseconds.

LNF News 26 August 2026

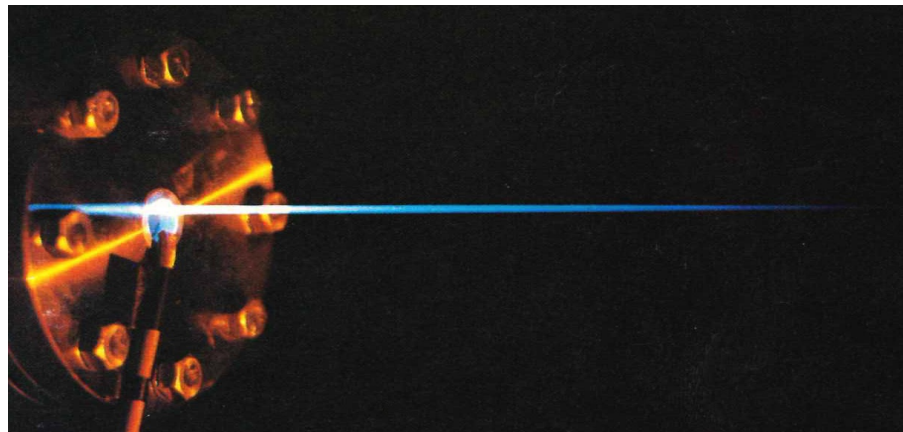
“This result demonstrates that a plasma-accelerated beam, despite its complexity, can be manipulated and compressed with the precision necessary to trigger FEL emission,” commented Riccardo Pompili, scientific coordinator of the SPARC_LAB activities, adding *“that the next step will be to optimize the beam quality to increase the energy and stability of the emission.”*

The experiment conducted at SPARC_LAB represents a proof of principle of the technique: the next step will be to transfer it to FACET-II (SLAC), where the electron beam can reach energies on the order of 10 GeV. At these energies could make it possible to generate FEL radiation not in the visible range, but in the X-ray frequencies.

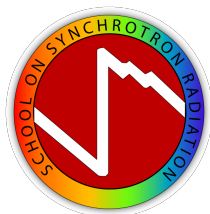
Conclusions

- **Synchrotron radiation has surely revolutionized many research fields.**
- **There are many SR facilities in the world and new ones are being built or upgraded.**
- **Synchrotron radiation sources and techniques still have a very bright future.**

Thank you for your attention



Società
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Sincrotrone



**'Gilberto Vlaic' XVIII School on Synchrotron Radiation:
Fundamentals, Methods and Applications**

Muggia (Trieste), Italy 21 September - 1 October 2026



Elettra Sincrotrone Trieste

Some 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. **Tomboulion, 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 Stuhmann 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** $c = 2.99792458 \times 10^8 \text{ m/s}$
- **Electron charge** $e = 1.6021 \times 10^{-19} \text{ Coulombs}$
- **Electron volts** $1 \text{ eV} = 1.6021 \times 10^{-19} \text{ Joule}$
- **Energy and rest mass** $1\text{eV}/c^2 = 1.78 \times 10^{-36} \text{ kg}$
 - Electron** $m_0 = 511.0 \text{ keV}/c^2 = 9.109 \times 10^{-31} \text{ kg}$
 - Proton** $m_0 = 938.3 \text{ MeV}/c^2 = 1.673 \times 10^{-27} \text{ kg}$
- **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** $E^2/c^2 = p^2 + m_0^2 c^2$
for ultra-relativistic particles $\beta \approx 1, E = pc$
- **Kinetic energy** $T = E - m_0 c^2 = m_0 c^2 (\gamma - 1)$

Radiation emission

Charge oscillating in sinusoidal motion in x direction

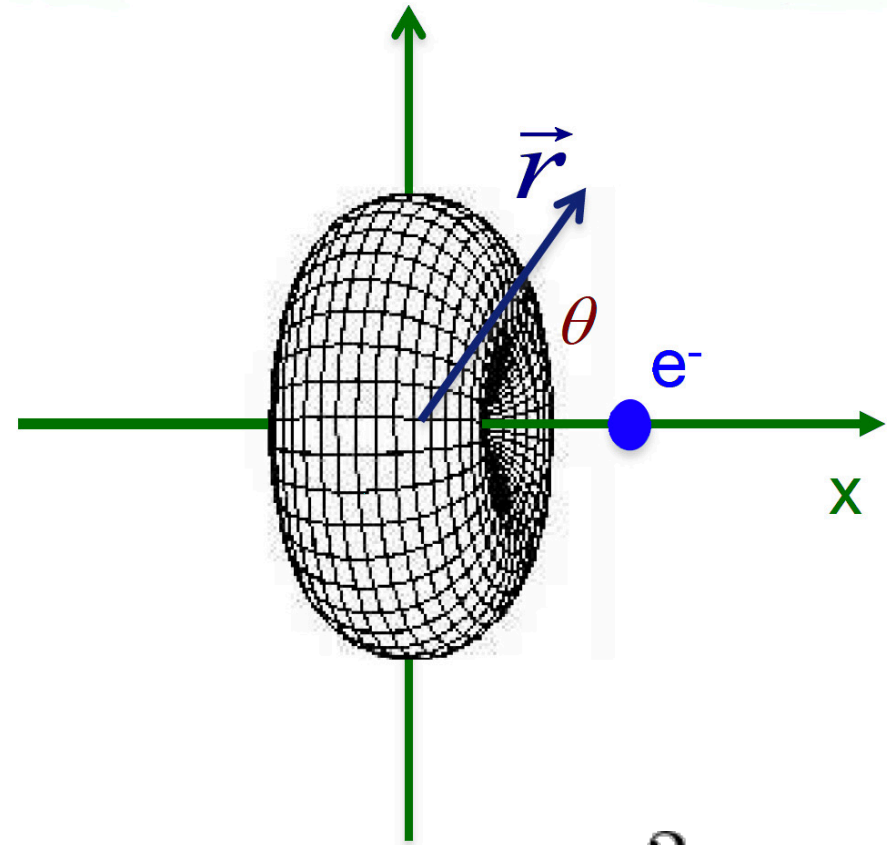
$$x(t) = A \cos(\omega t)$$

$$v(t) = -A\omega \sin(\omega t)$$

$$a(t) = -A\omega^2 \cos(\omega t)$$

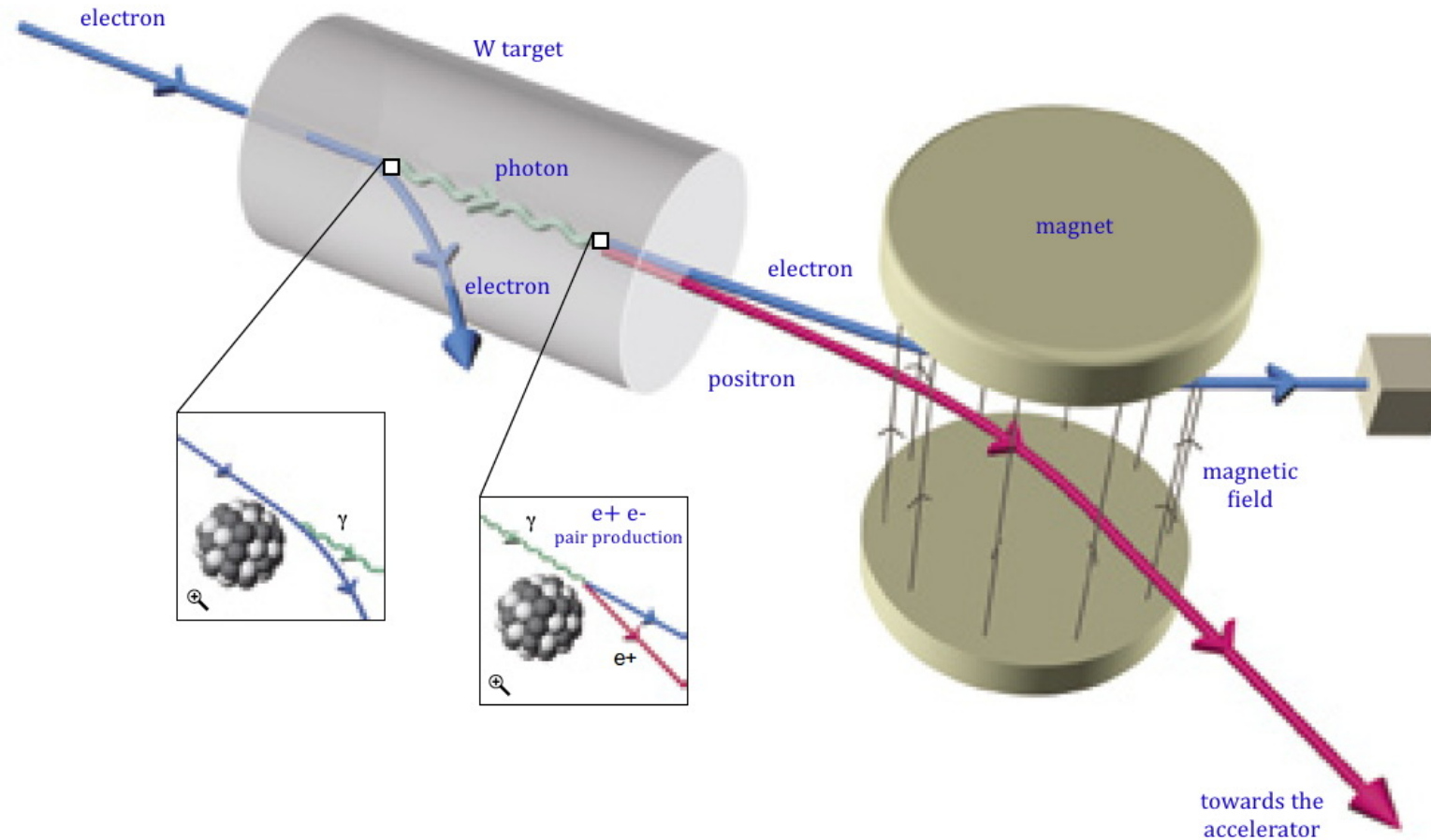
Frequency of the oscillation $f = \omega/2\pi$

Production of a **radiation pattern** given by the **Poynting vector $\mathbf{S}$** (energy per unit of time and surface)



$$\langle S \rangle \propto \frac{\sin^2 \theta}{r^2} \hat{r}$$

Anti-matter positron production



Undulators

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

λ_n = photons wavelength

λ_u = undulator wavelength

$$K = 93.36 B_0 \lambda_u$$

The wavelength changes with θ^2 .

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_0 increases (and so K), the photon wavelength, λ_n increases (photon energy decreases).

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

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

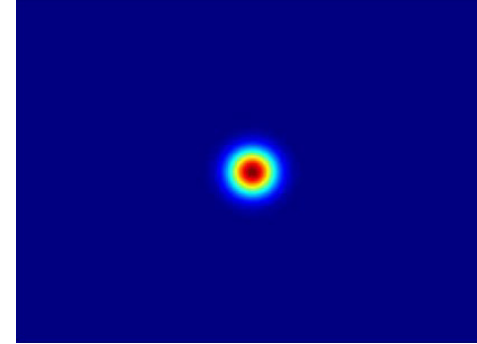
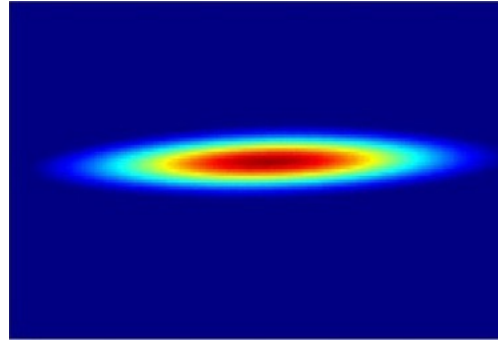
Source horizontal divergence

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

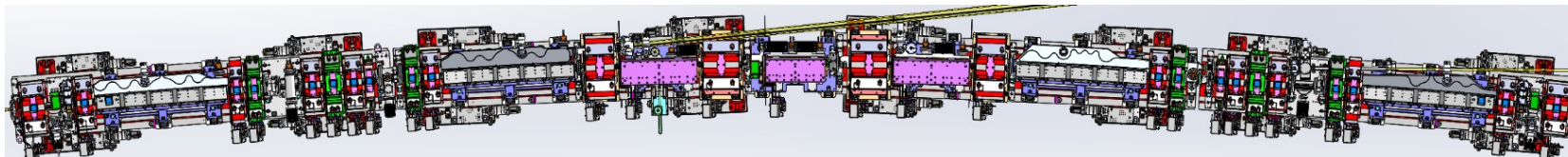
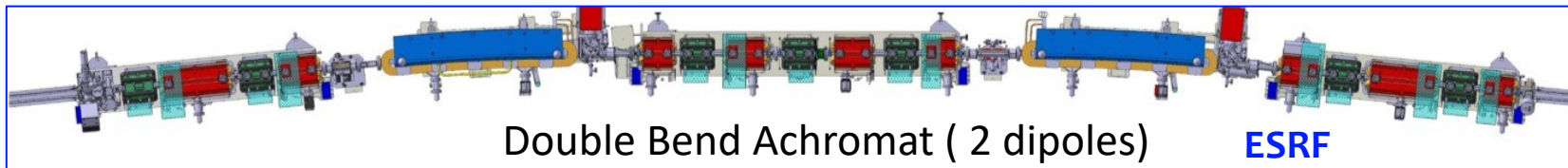
The brightness of an undulator is approximated by dividing the central cone flux by the effective angular divergence and by the effective source size in the horizontal (vertical) directions. These are given by convolution of the Gaussian distributions of the electron beam and the diffraction limited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



ESRF-EBS

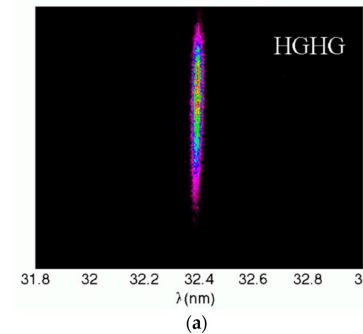
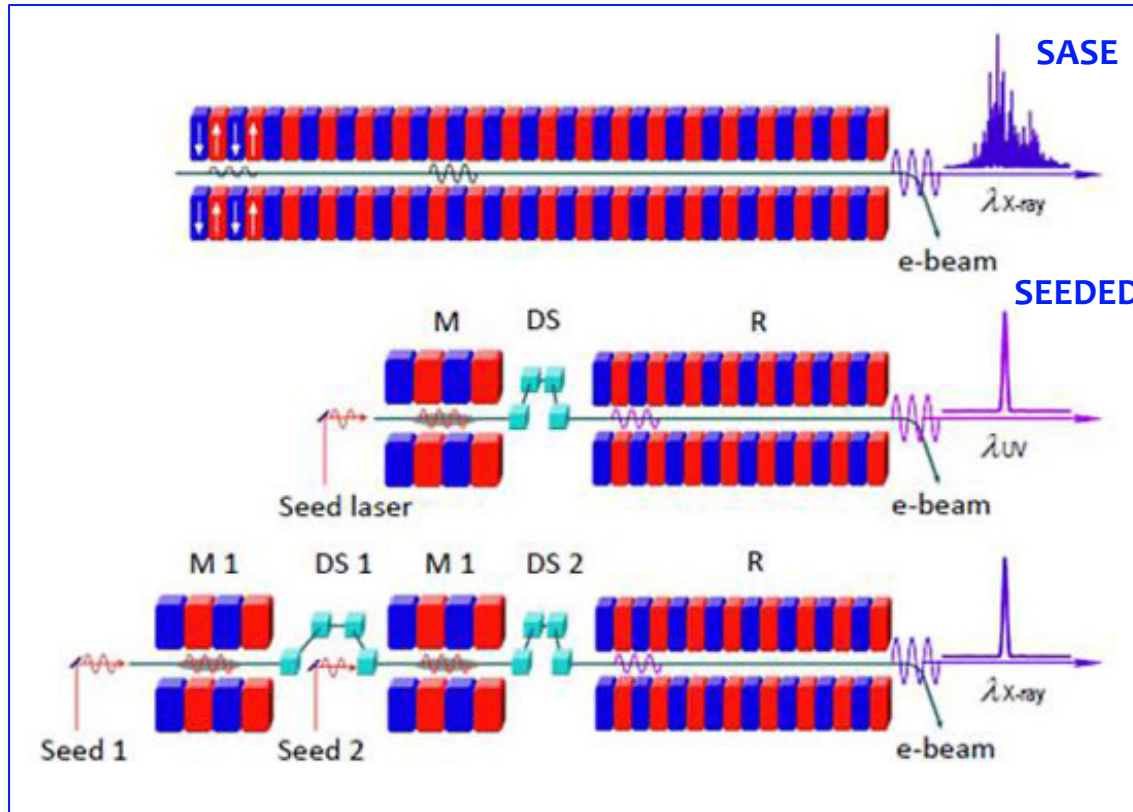


Reduction of the the **horizontal** emittance from **4nm** to **0.14nm**.

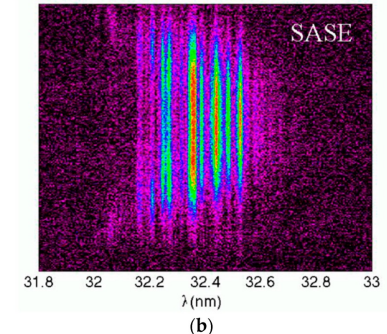


Hybrid 7 Bend Achromat (4 dipoles + 3 dipoles-quad) **ESRF - EBS**

Fourth generation: LINAC based sources and Free Electron Lasers



SEED

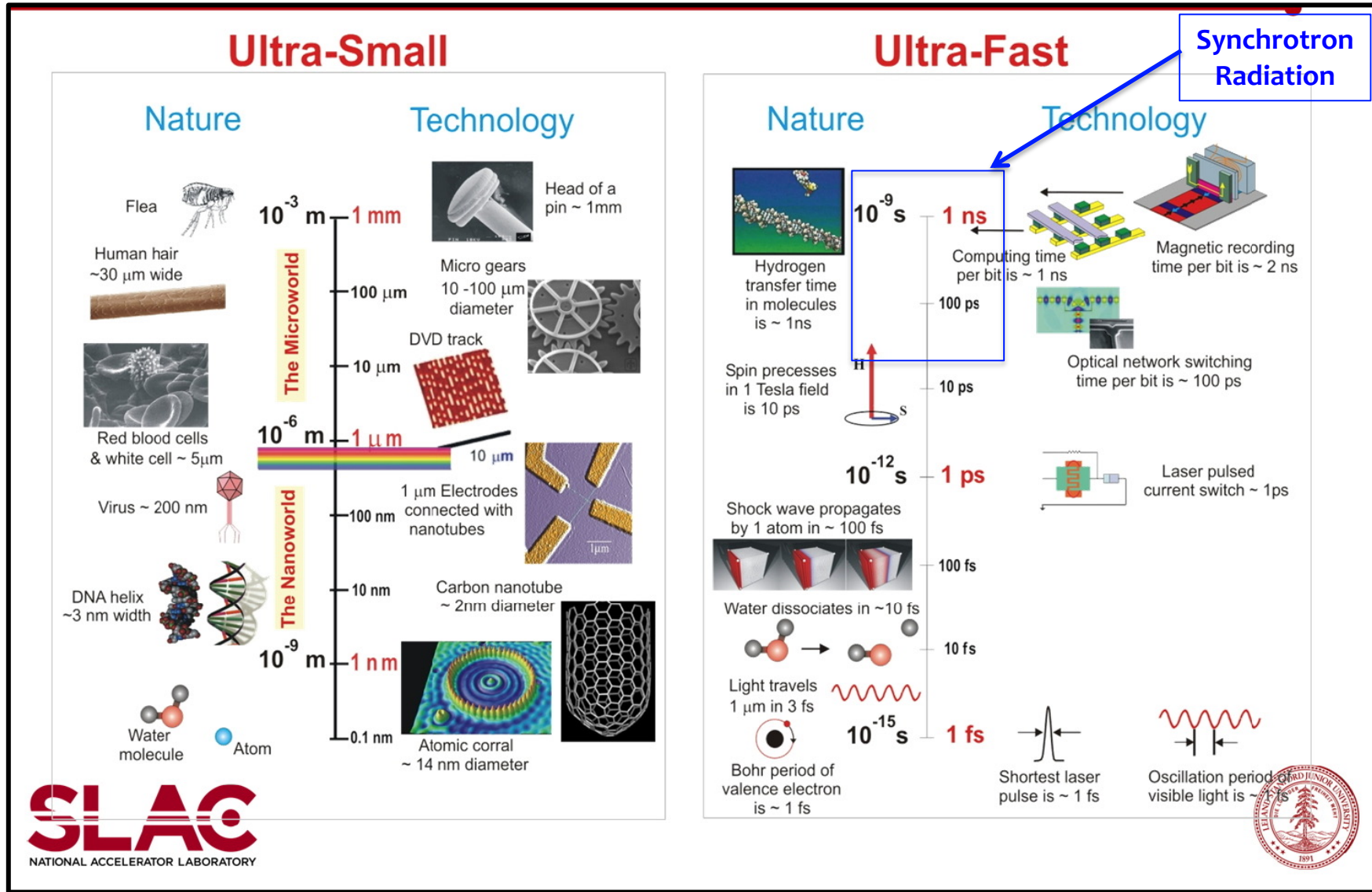


SASE

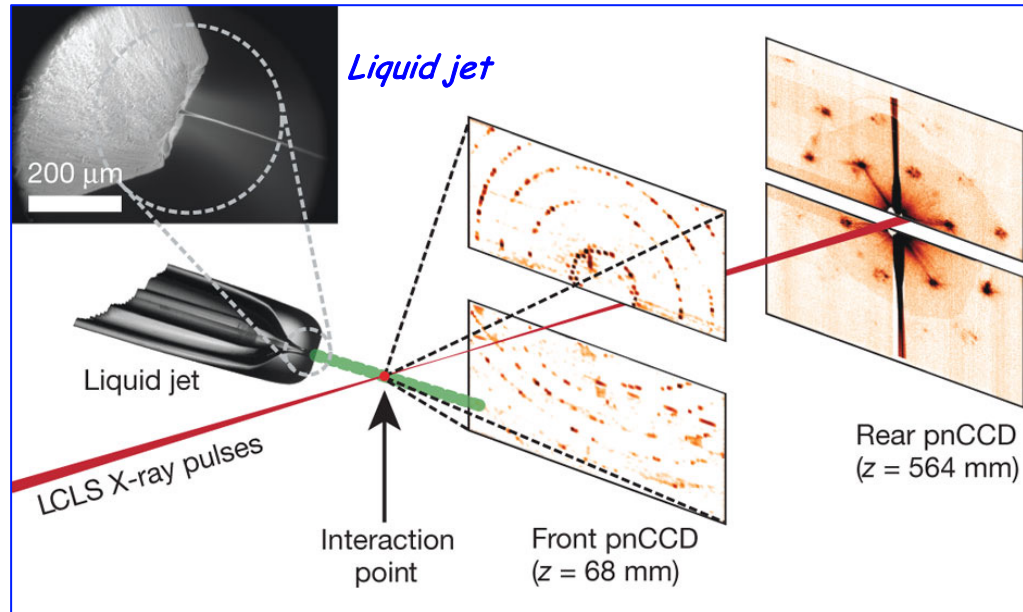
Seeded FEL vs. SASE FEL. Upper, **SASE FEL with poor temporal coherence**; Middle, **HGHG** (High-Gain Harmonic Generation) **FEL**, full temporal coherence with limited harmonic number ($N \sim 10$) for a single stage; Bottom, **EEHG** (Echo-Enabled Harmonic Generation) **FEL**, full temporal coherence with the potentially very high harmonic number in a single stage. (M: modulator, DS: dispersive section, R: radiator)

http://english.sinap.cas.cn/research_progress/top_news/202107/t20210702_273386.html

Fourth generation: LINAC based sources and Free Electron Lasers



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)

