Elettra Sincrotrone Trieste

1993 – 2023 | 30 years of light

# Synchrotron radiation: basic concepts

Giuliana Aquilanti
giuliana.aquilanti@elettra.eu

Elettra Sincrotrone Trieste

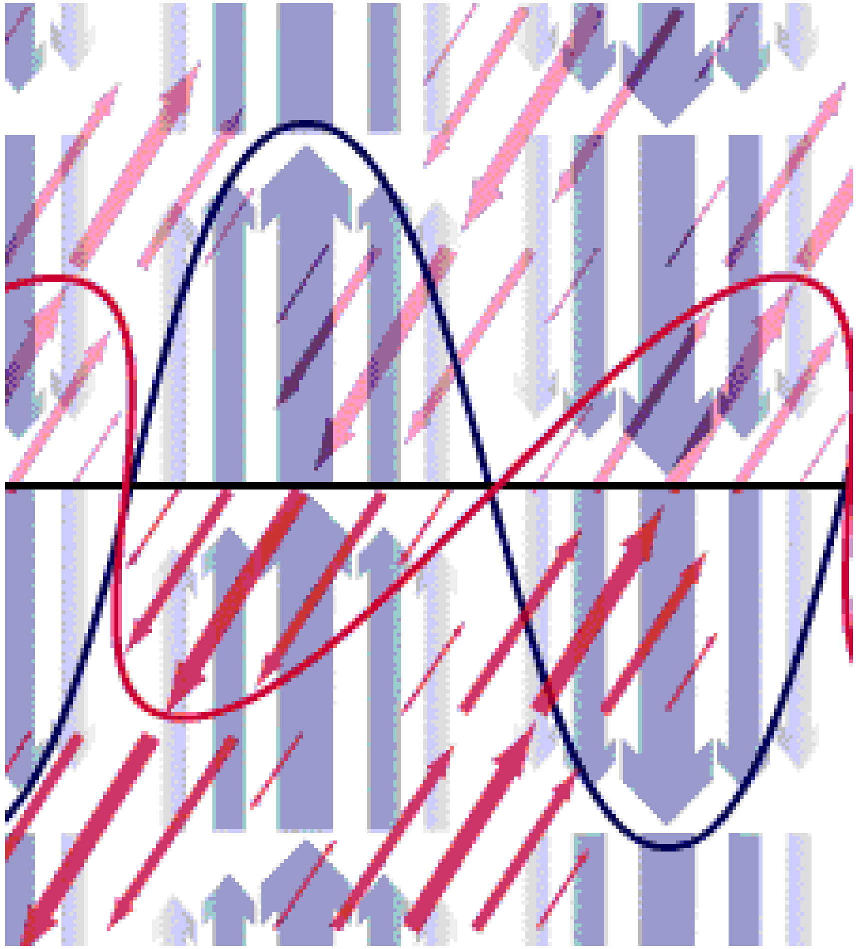
Synchrotron radiation

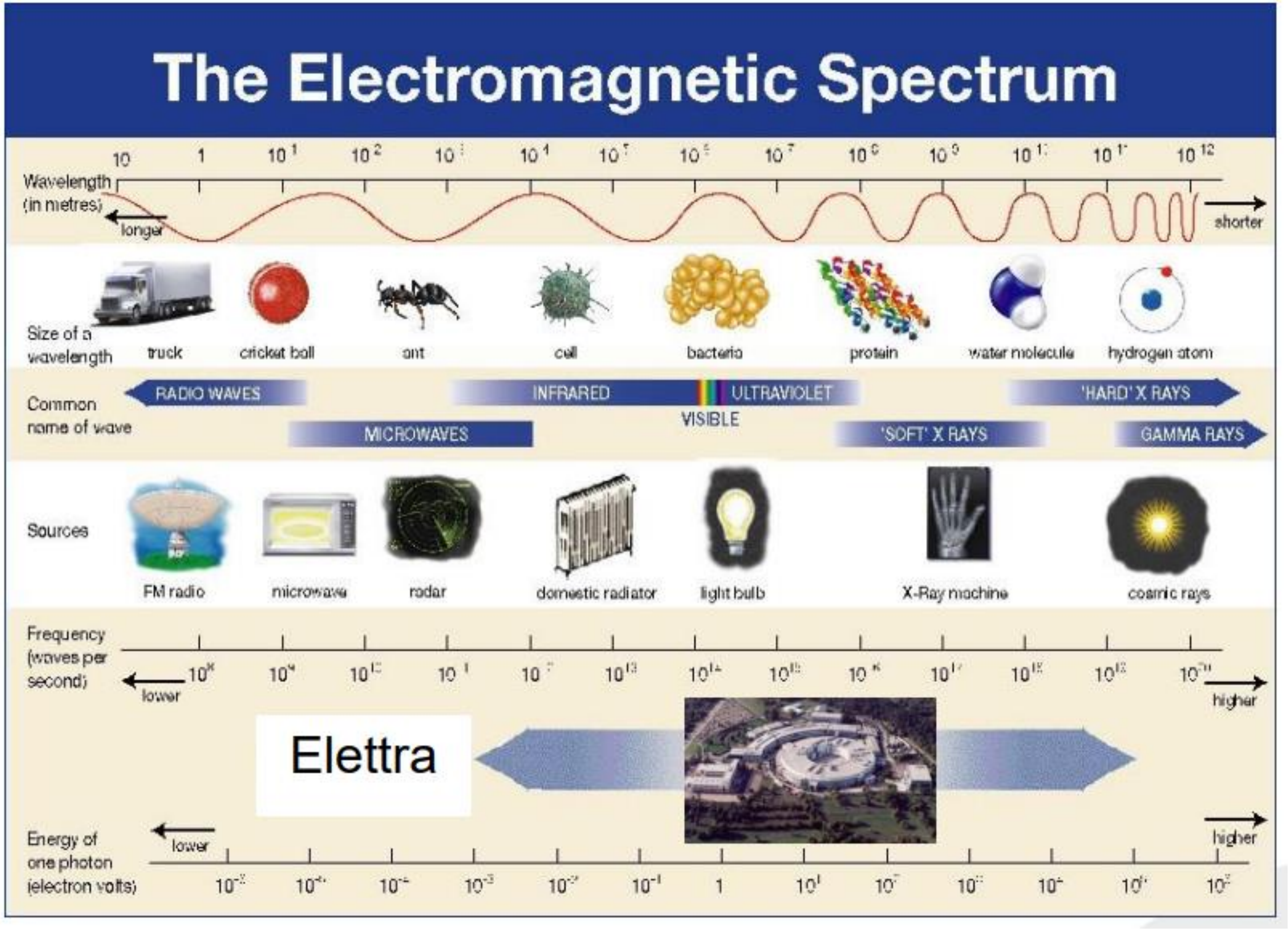
or

synchrotron **light**

is

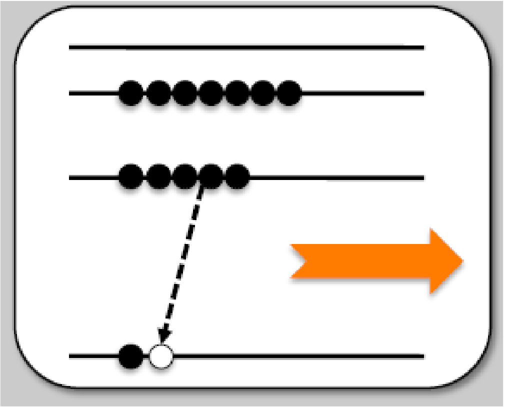
**electromagnetic radiation**



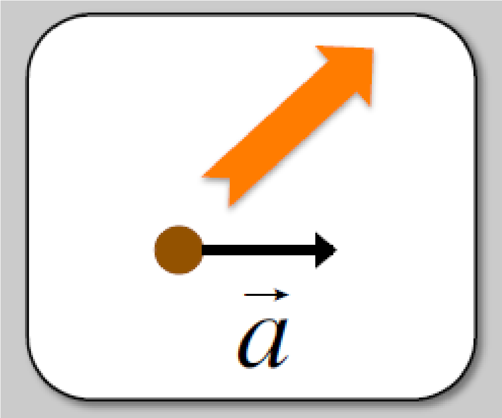

The Electromagnetic Spectrum
Wavelength (in metres)
longer
shorter
Size of a wavelength
truck
cricket ball
ant
cell
bacteria
protein
water molecule
hydrogen atom
Common name of wave
RADIO WAVES
MICROWAVES
INFRARED
VISIBLE
ULTRAVIOLET
'SOFT' X RAYS
'HARD' X RAYS
GAMMA RAYS
Sources
FM radio
microwave
radar
domestic radiator
light bulb
X-Ray machine
cosmic rays
Frequency (waves per second)
lower
higher
Elettra
Energy of one photon (electron volts)
lower
higher

# Mechanisms of production of electromagnetic radiation

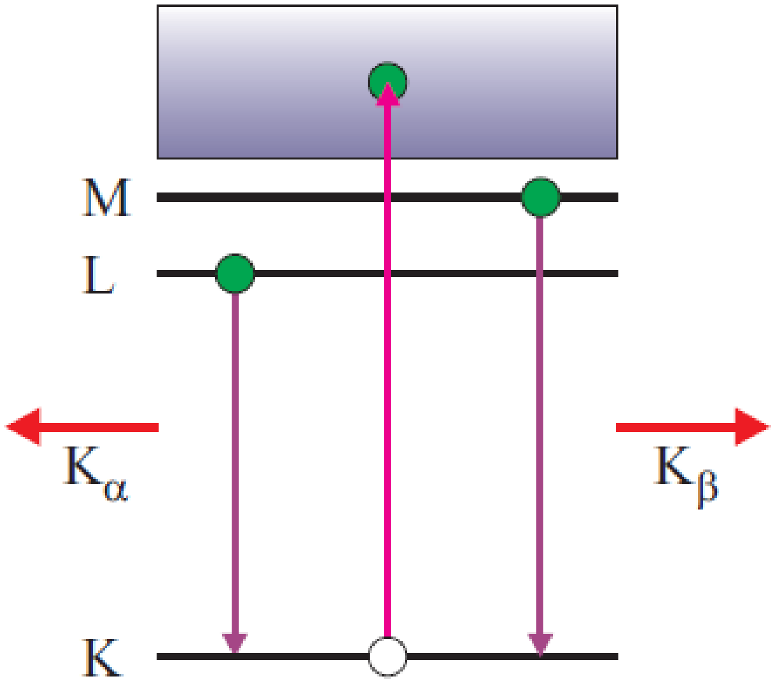
1) Emission as effect of quantum transitions

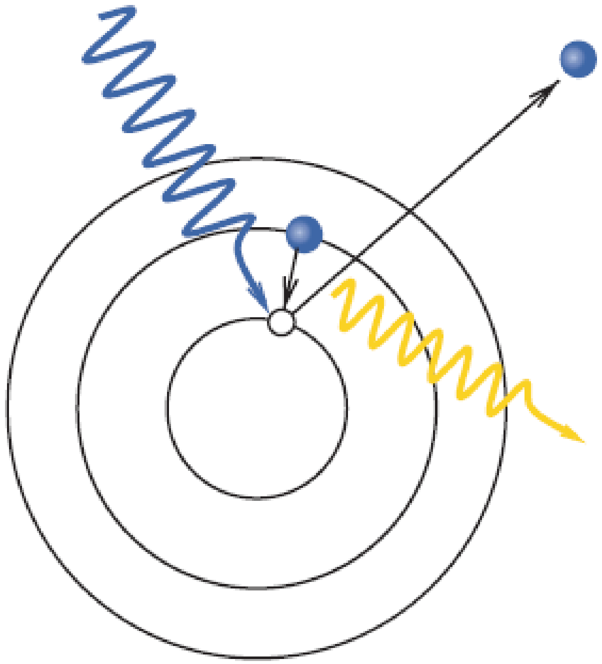


2) Emission from accelerated electric charges



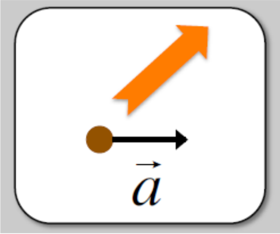
# 1) Emission as effect of quantum transitions



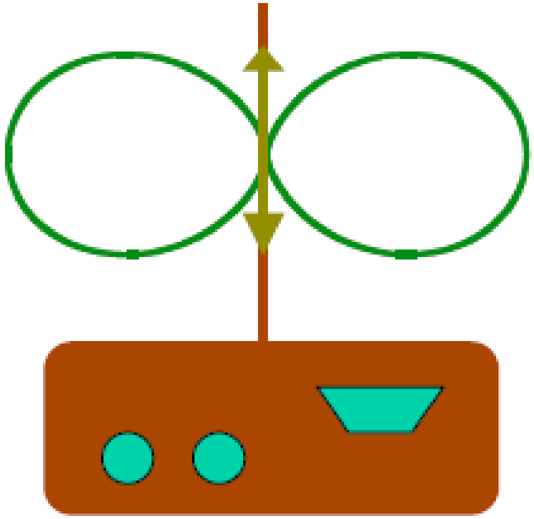



$$h\nu = E_{high} - E_{low}$$

# 2) Emission from accelerated charges

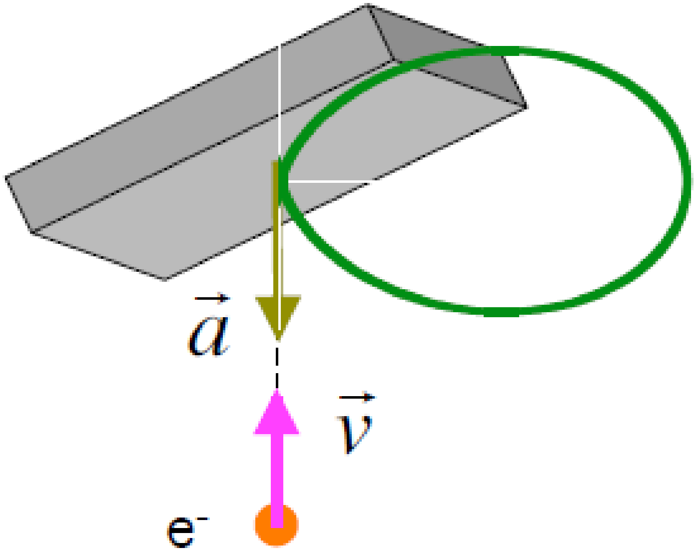



Oscillating motion



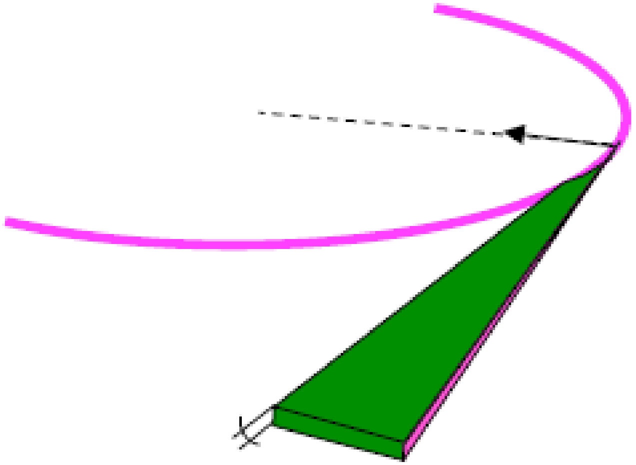
Broadcasting antenna

Average linear deceleration




Bremsstrahlung in x-ray tubes

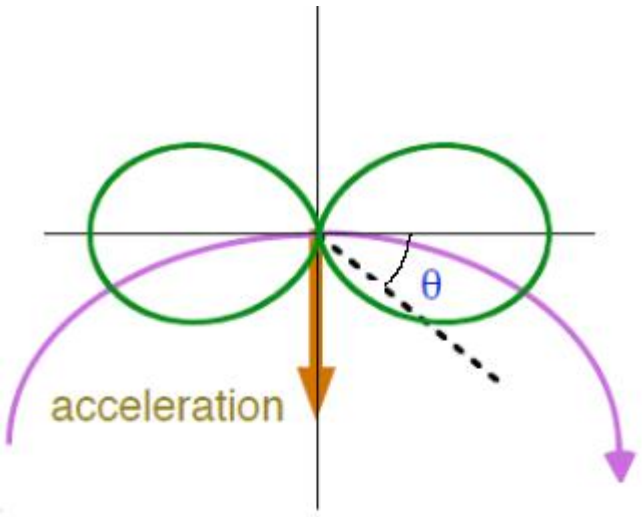
Relativistic circular motion

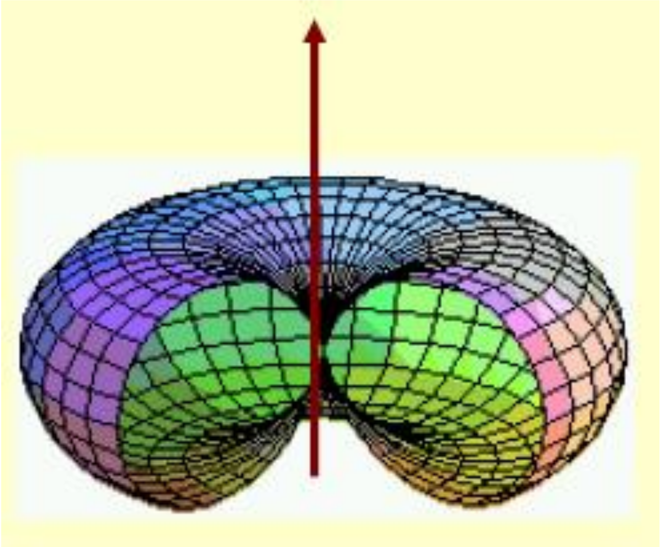


Synchrotron radiation

# Emission from accelerated charges: dipole radiation

An accelerated charged particle emits e.m. radiation
The emission of the radiation is symmetric with respect to the acceleration
The emission is zero in the direction of the acceleration
The emission is maximum in the perpendicular plane

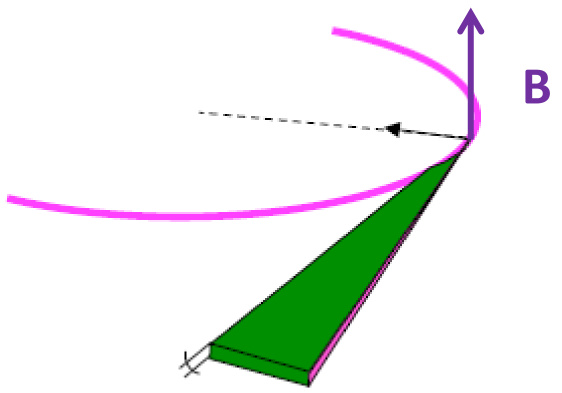


Radiated power

$$P \propto cos^2\,\theta$$

# Synchrotron Radiation




Definition:

Radiation emitted by charged particles moving at **relativistic speed** forced by magnetic fields to follow curved trajectories

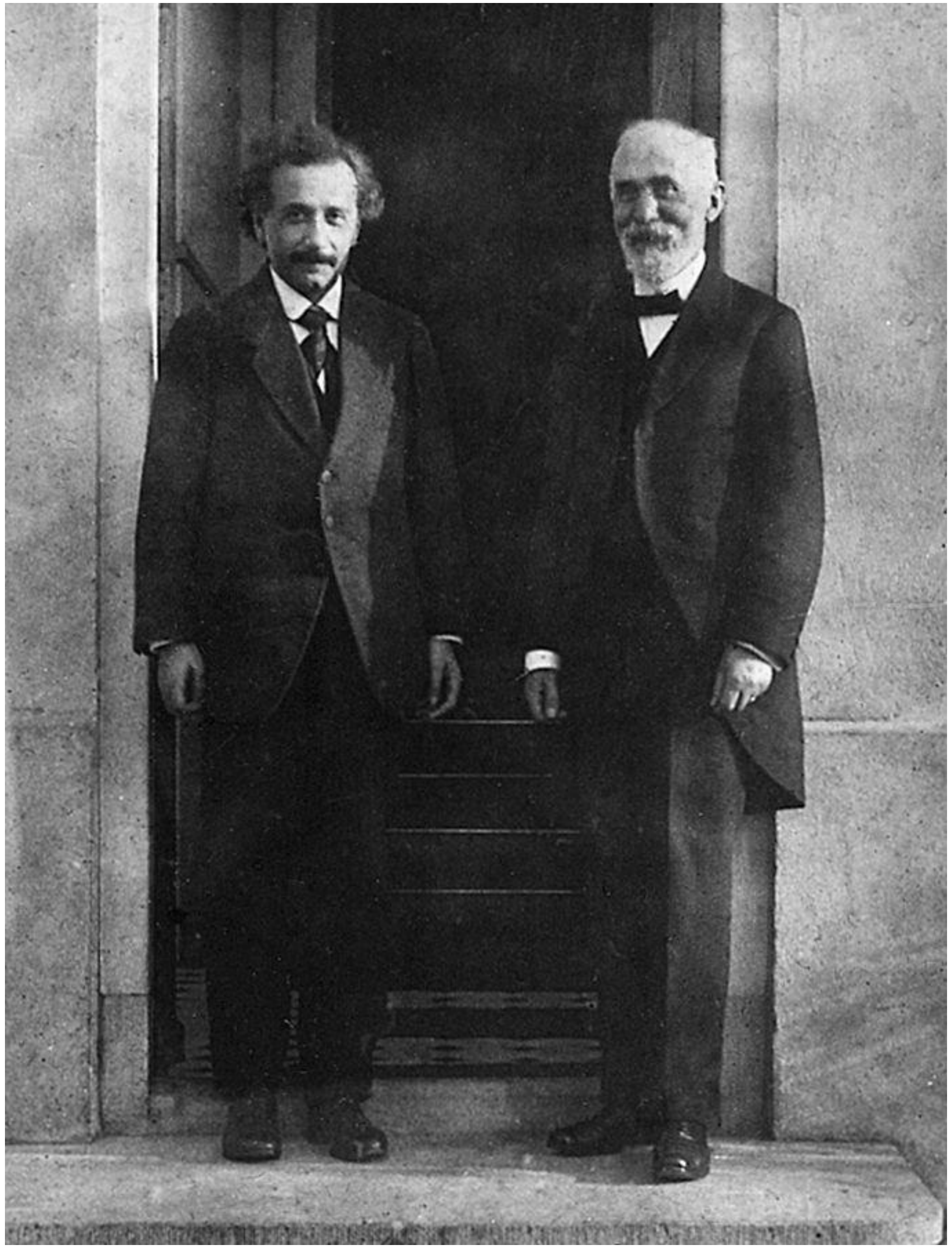
The magnetic field, perpendicular to the direction of the electron motion centripetally accelerate the electrons.

$$\mathcal{E}_e = \gamma m_0 c^2$$

$$\mathcal{E}_e = \frac{m_0 c^2}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

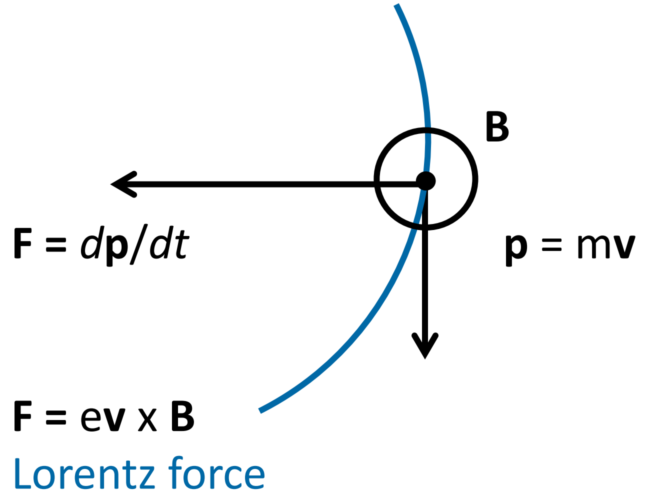
$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

Lorentz factor



# Equation of motion - 1

## An electron moving in a magnetic field radiates energy




An electron of momentum **p** = m**v** moving in a constant magnetic field **B** experiences the Lorentz force F= d**p**/dt = e**v** x **B**. In response to this force the electron accelerates and moves in a circular orbit in a plane perpendicular to **B**.

The Lorentz force, being perpendicular to the motion, does no work and *cannot change the energy of the electrons,* but is does cause a centripetal acceleration that changes the direction of the velocity

# Equation of motion - 2

Considering the relativistic formulae:

$$\mathbf{p} = \gamma m_0 \mathbf{v}$$

$$\mathbf{F} = \frac{d}{dt}(\gamma m_0 \mathbf{v}) = e\mathbf{v} \times \mathbf{B}$$

They are perpendicular

$$\gamma m_0 \frac{d}{dt}\mathbf{v} = evB$$

Centripetal acceleration

$$\gamma m_0 \frac{v^2}{\rho} = evB$$

Orbital radius

Since $v \approx c$,

$$\gamma m_0 \frac{c^2}{\rho} = ecB$$

# Equation of motion - 3

$$\rho = \frac{\gamma m_0 c}{eB}$$

Since $\gamma = \frac{\mathcal{E}}{m_0 c^2}$

$$\rho = \frac{\mathcal{E}}{ceB}$$

In practical units:

$$\rho[\mathrm{m}] = 3.3\frac{\mathcal{E}[\mathrm{GeV}]}{B[\mathrm{T}]}$$

As typical magnetic field strengths of bending magnets are 1 Tesla and storage rings electron energies are normally of the order of few GeV, the bending radius is typically a few meters

High energy synchrotron are places in big storage rings

# Characteristics of the SR

1) Collimation

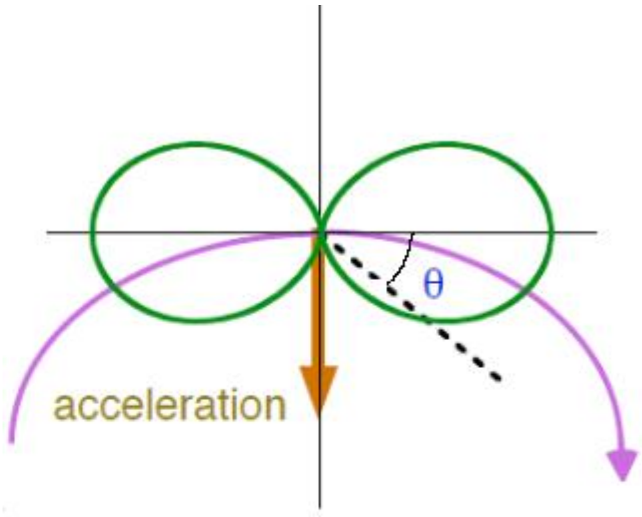
2) Broad band

3) Polarization

4) Time structure

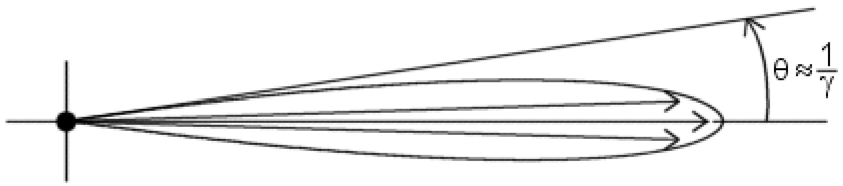
5) Coherence

# 1) Collimation




In the moving frame of the electron (v <<c) the power emitted by an accelerated particle has a characteristic two-lobe distribution around the direction of the acceleration.

In the laboratory frame of reference (v ~c) all the emitted power is beamed into a narrow cone in the direction of motion.

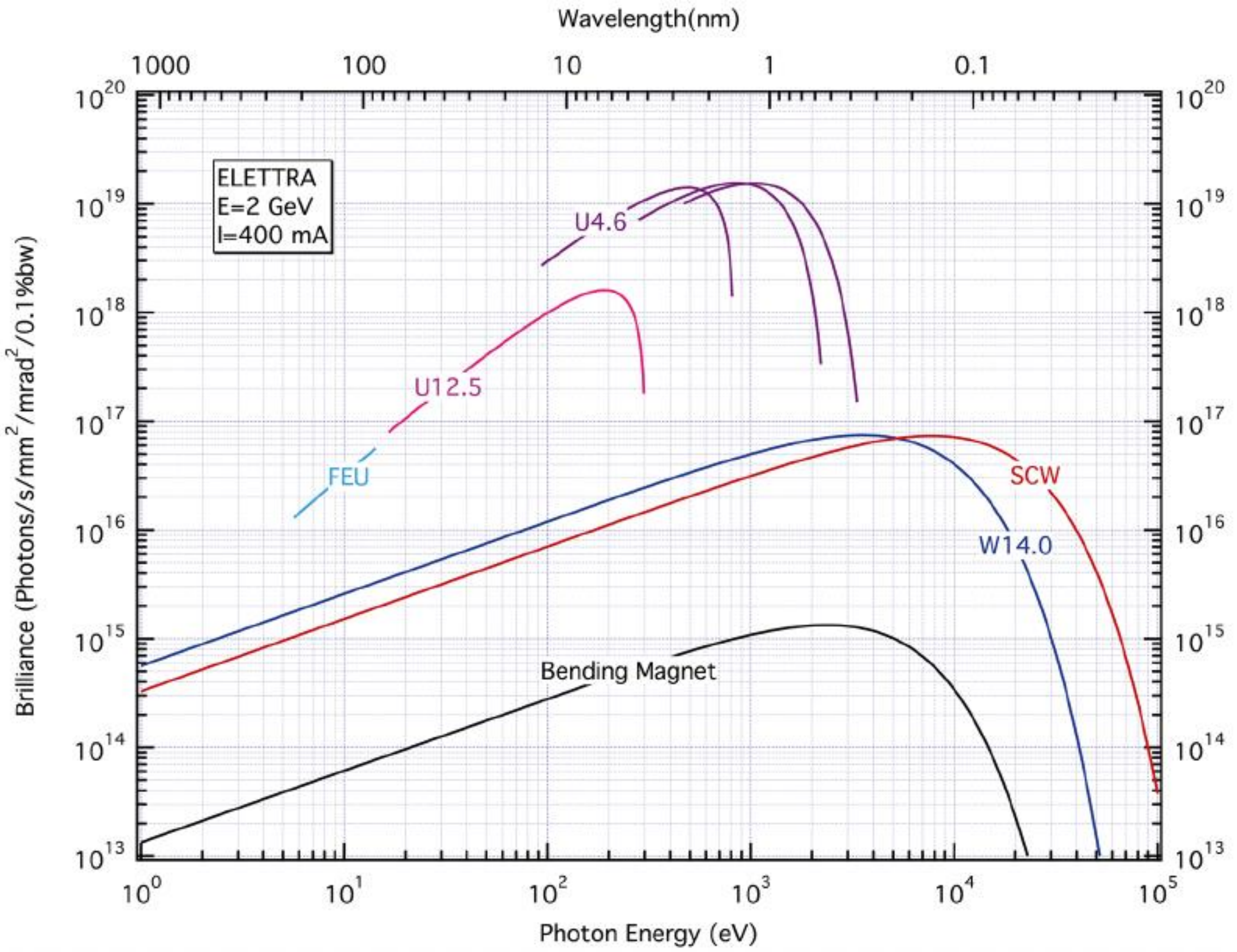



All the forward power is radiated in a beam of angle $\frac{2}{\gamma}$

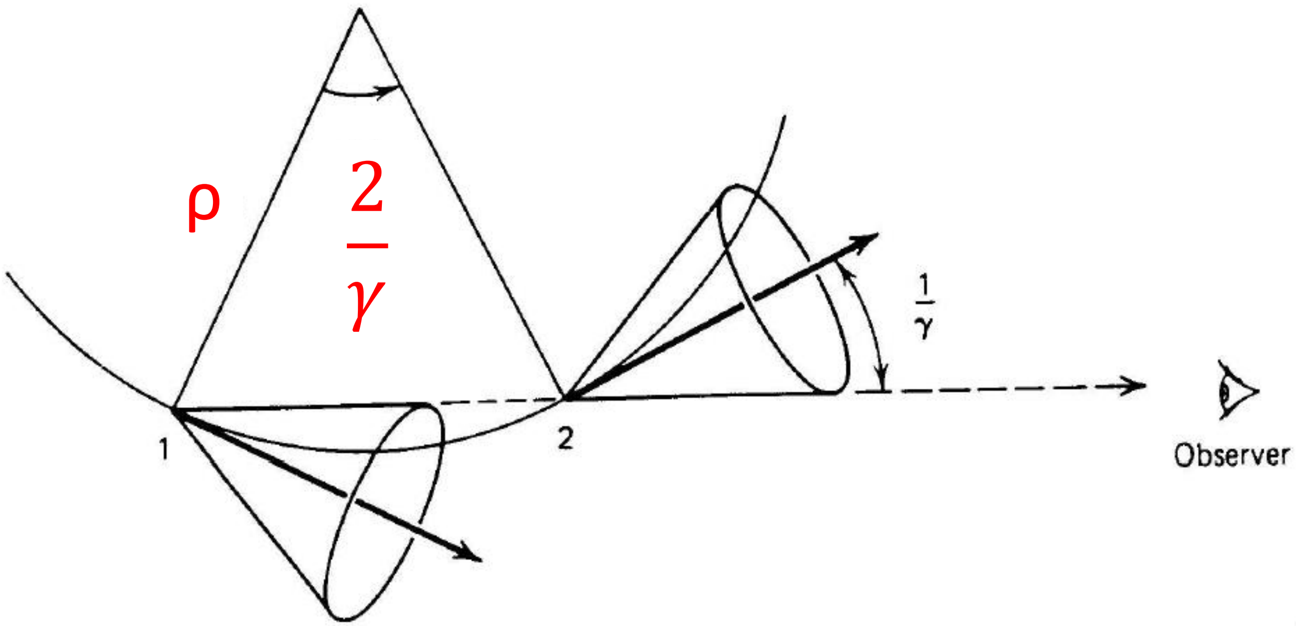
# More on collimation of SR

- The collimation of synchrotron radiation is a direct consequence of the relativistic speed of the electrons
- The collimation conserves energy: the emission found in the electron frame is now concentrated in a small cone.
- This affects a fundamental figure of merit for light sources: the “brightness”. (The brightness is proportional to the emitted flux divided by the angular spread and by the source size.)
- Very high fluxes on very small area also at distances of tens of meters from the storage rings.

# 2) Broadband emission



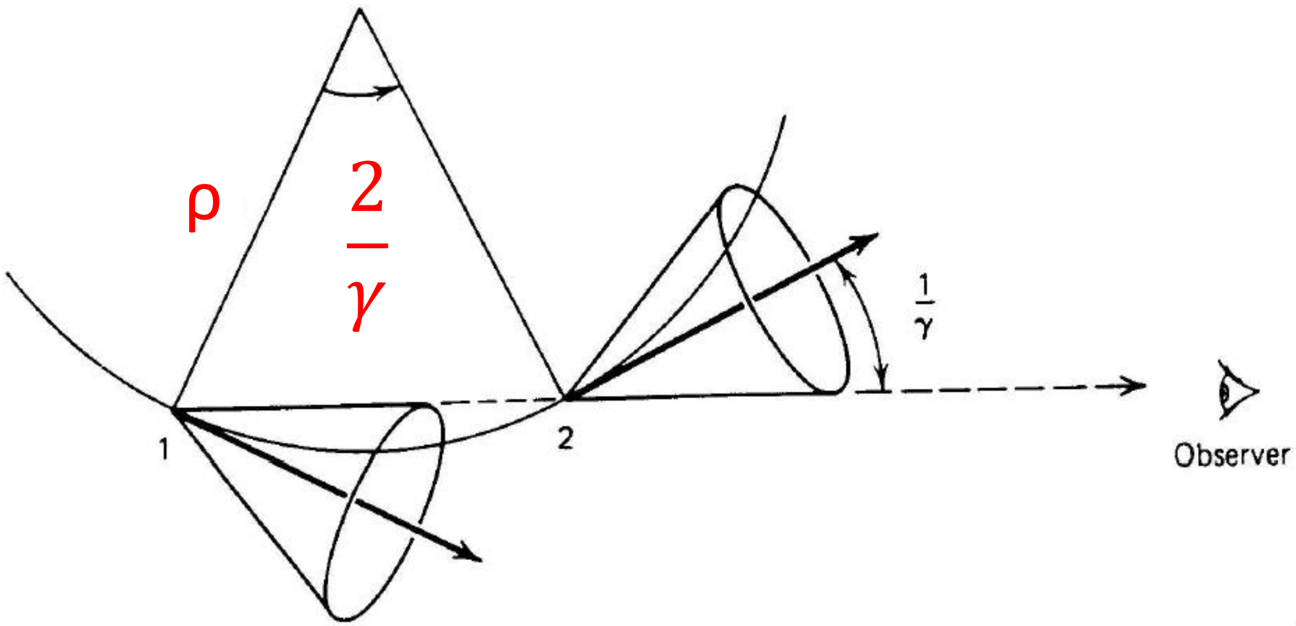
# Broadband emission: pulse duration




The time of emission of radiation is given by the time the electron runs at speed v along the arc from 1 to 2

However the radiation emitted at 1 will reach the observer with a delay given by the fact that the radiation must travel (at speed c) to the observer

# Broadband emission: pulse duration



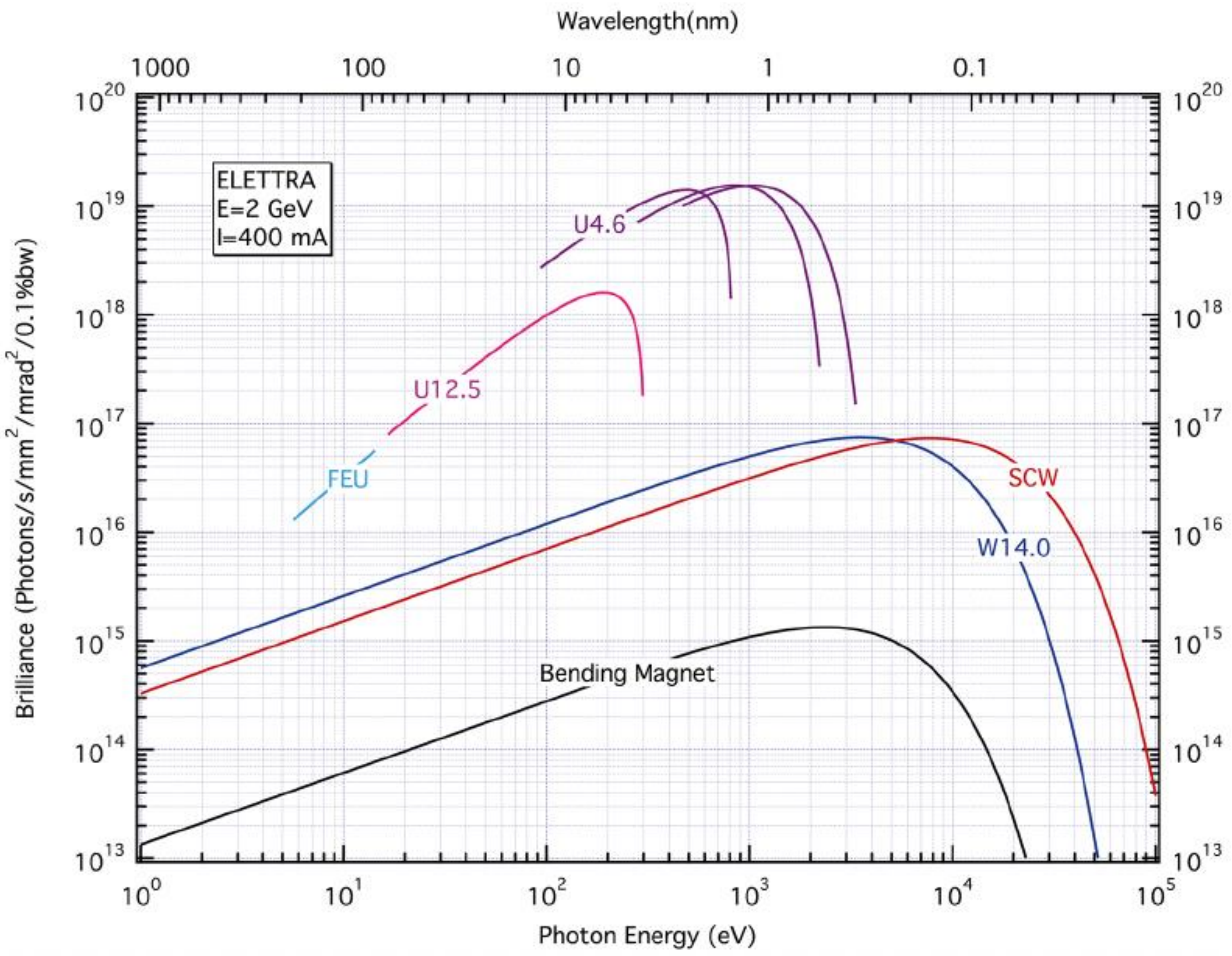

The pulse duration Δτ:

$$\Delta\tau = \frac{\text{arc length}}{v} - \frac{\text{radiation path}}{c}$$

$$\Delta\tau = \frac{\varrho 2/\gamma}{v} - \frac{2\varrho \sin(1/\gamma)}{c}$$

$$\Delta\tau \approx \frac{\rho}{c\gamma^3}$$

# 2) Broadband emission



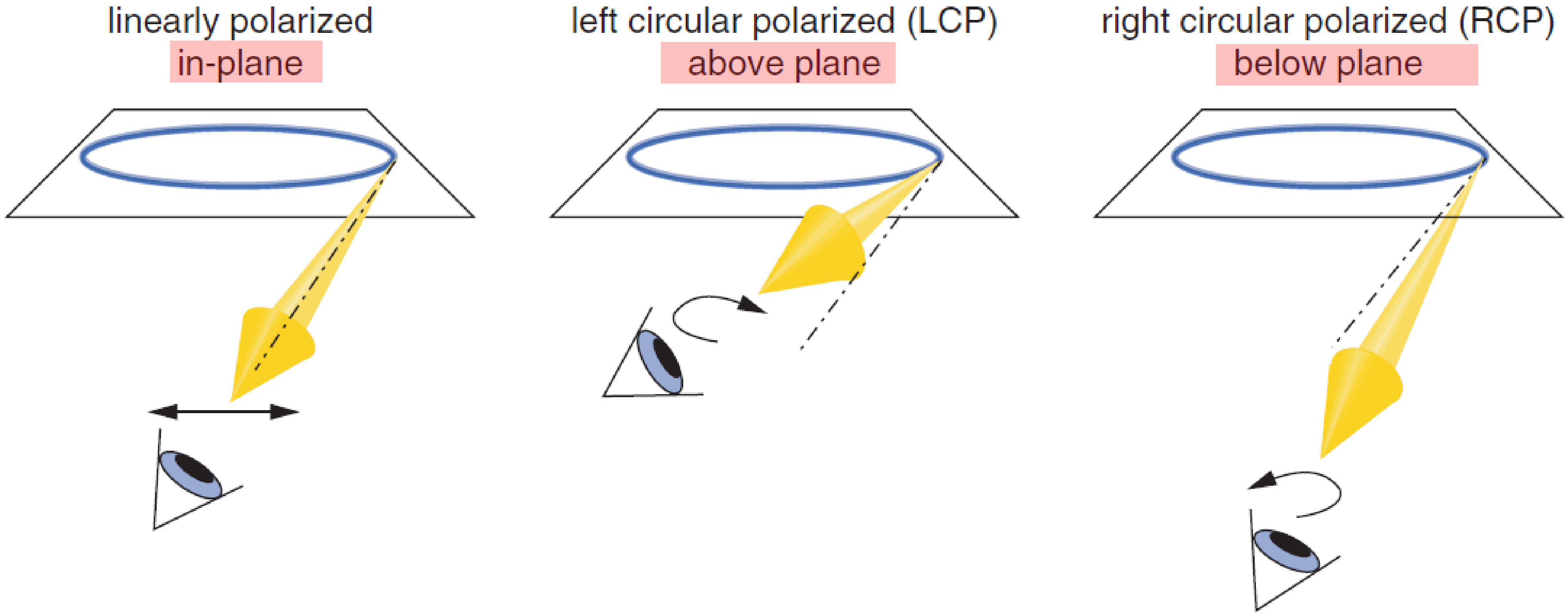

The Fourier theorem relates this pulse duration Δτ toΔ$\nu$

$$\Delta\nu \approx \frac{1}{2\pi\Delta\tau}$$

$$\Delta E \approx \frac{hc\gamma^3}{2\pi\rho}$$

# 3) Polarization

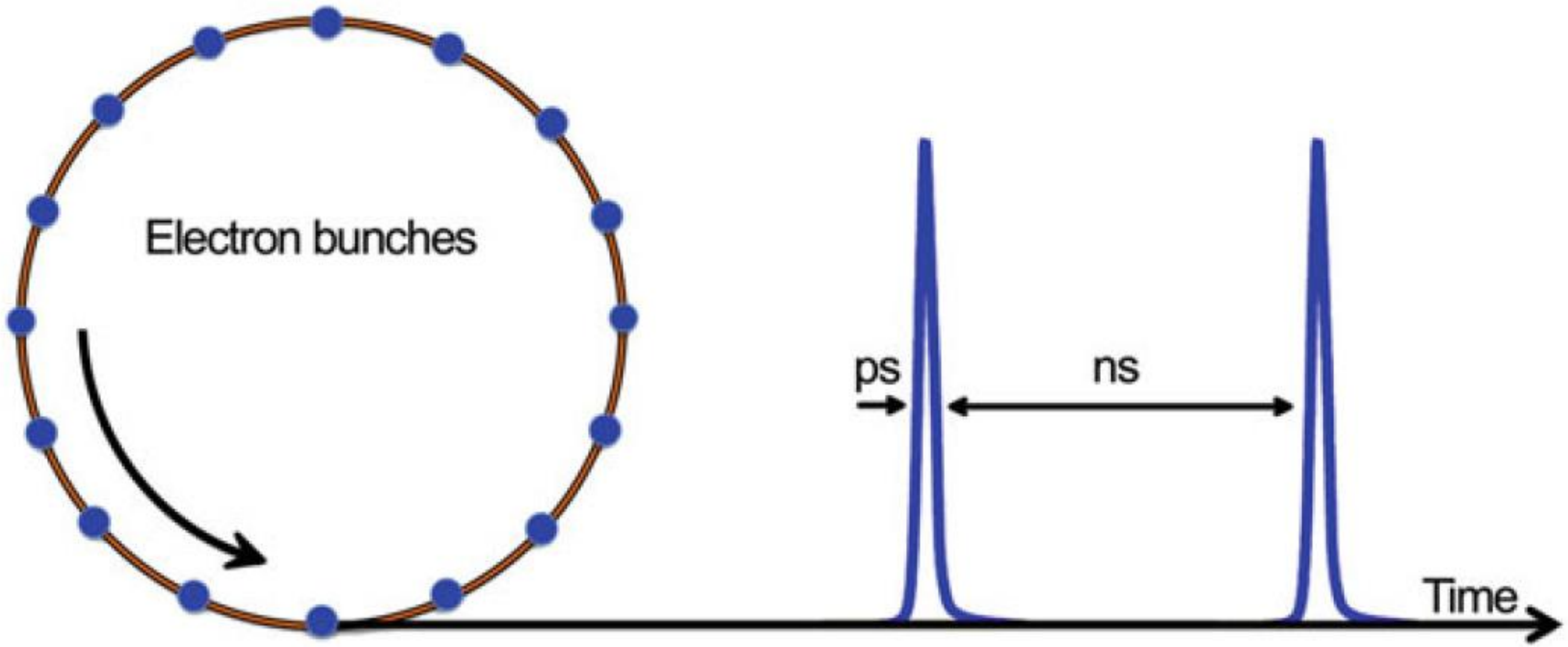
The polarization of the x-rays emerging from a storage ring depends on the line of sight



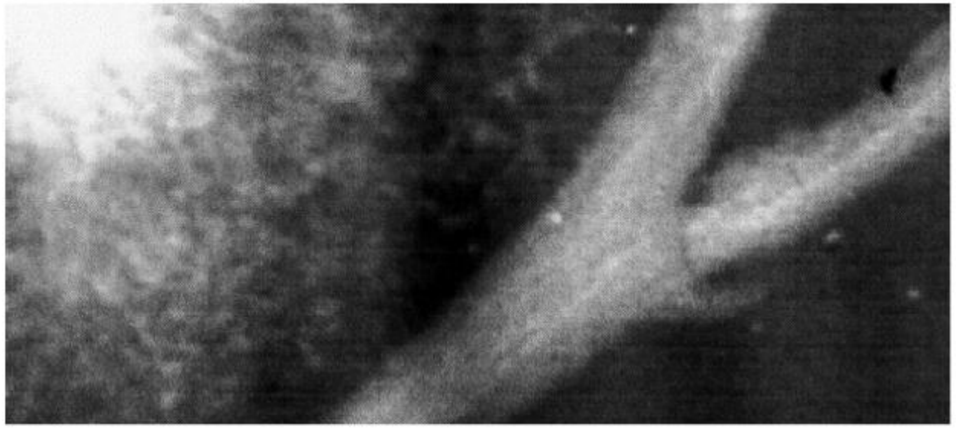

The electrons appear to oscillate in the horizontal plane

The electrons appear to execute an elliptical orbit in clockwise/anticlockwise direction.

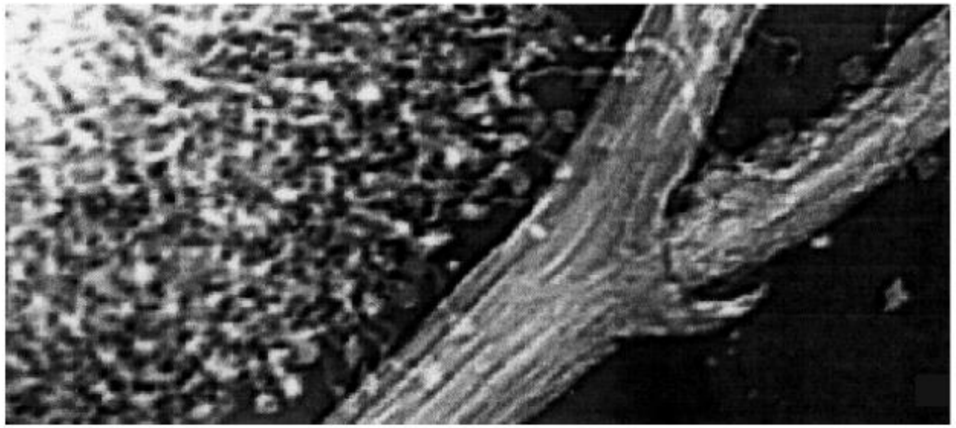
# 4) Time structure



# 5) Coherence



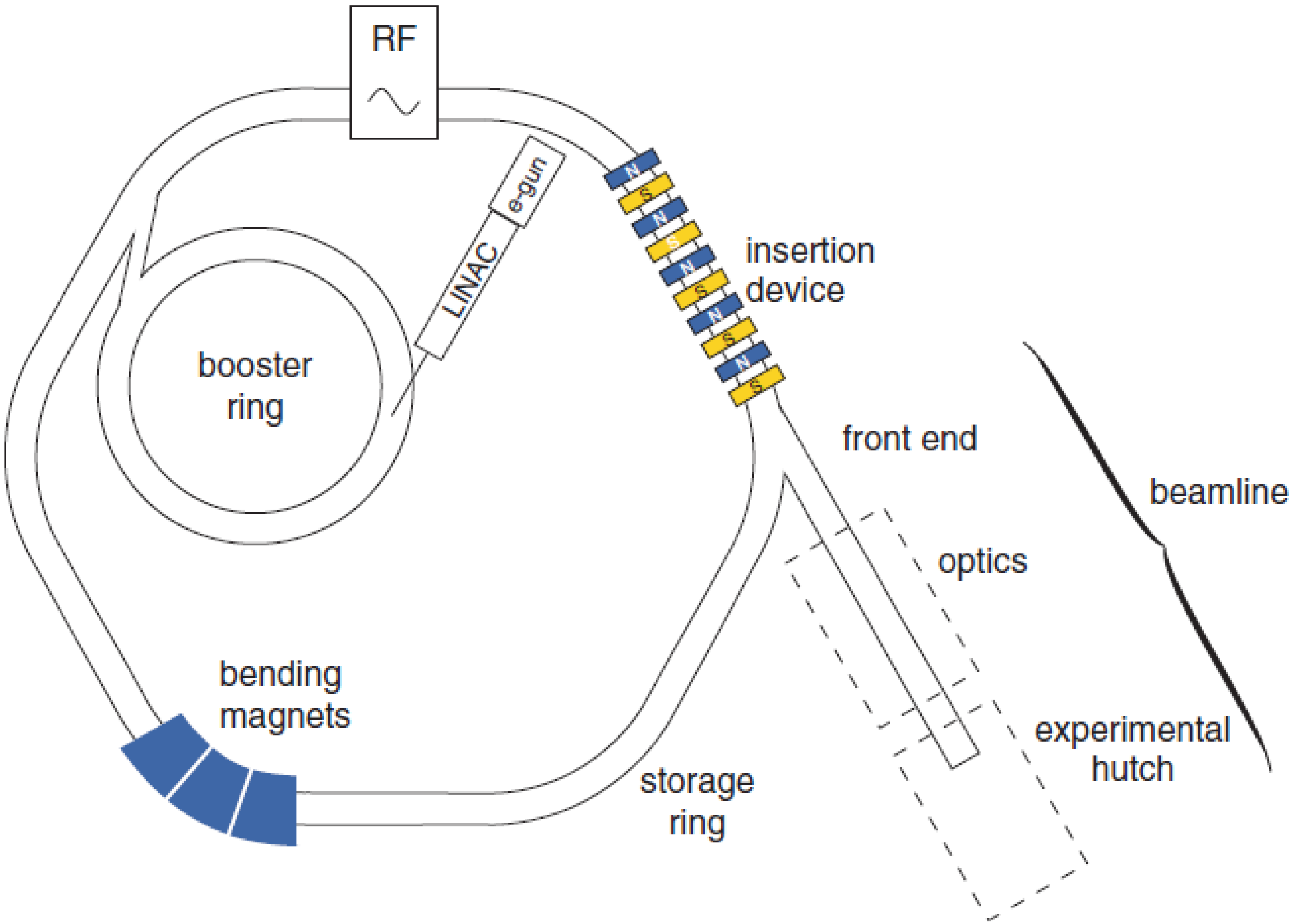
Conventional absorption image

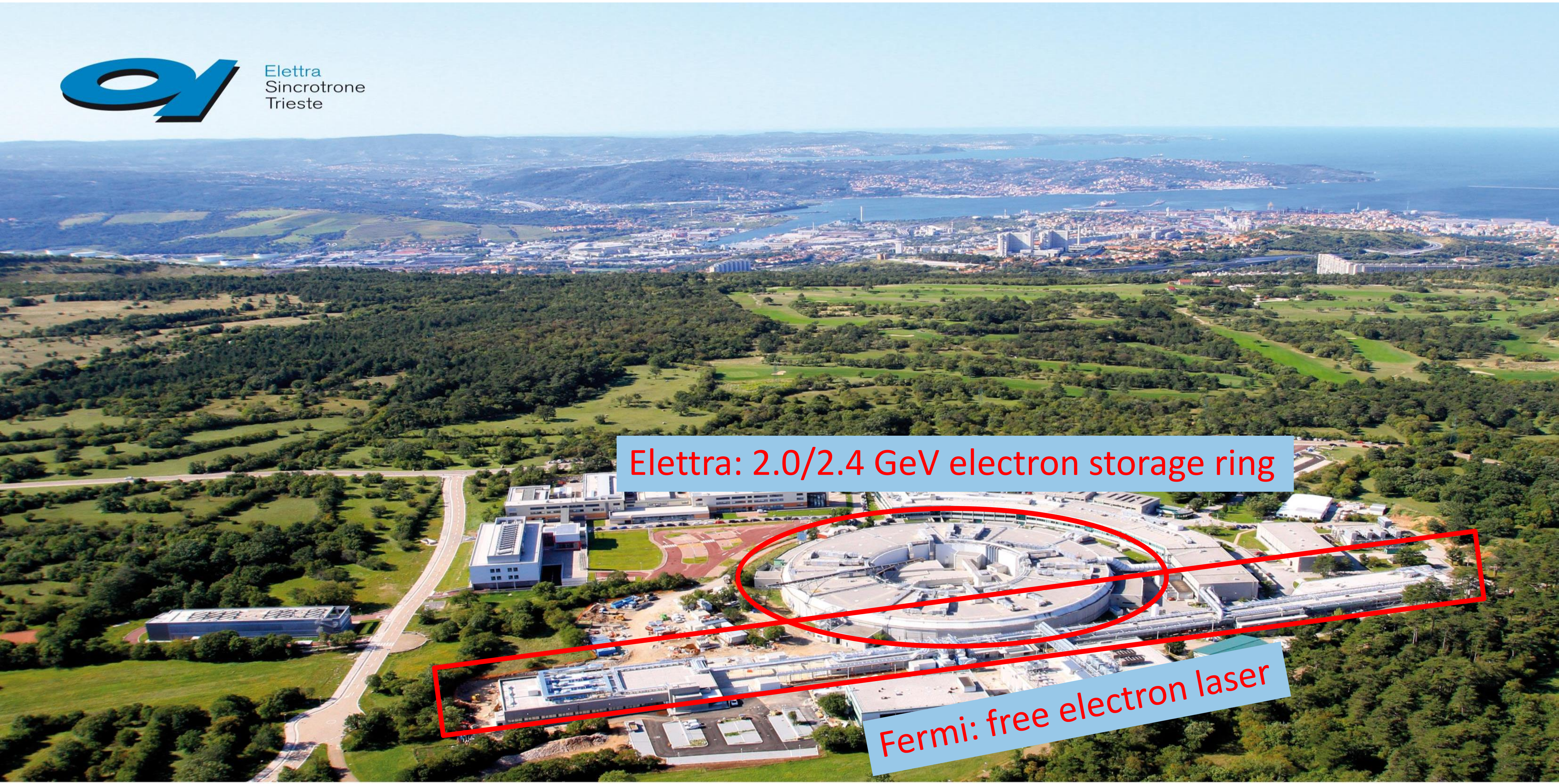


Coherence- enhanced image

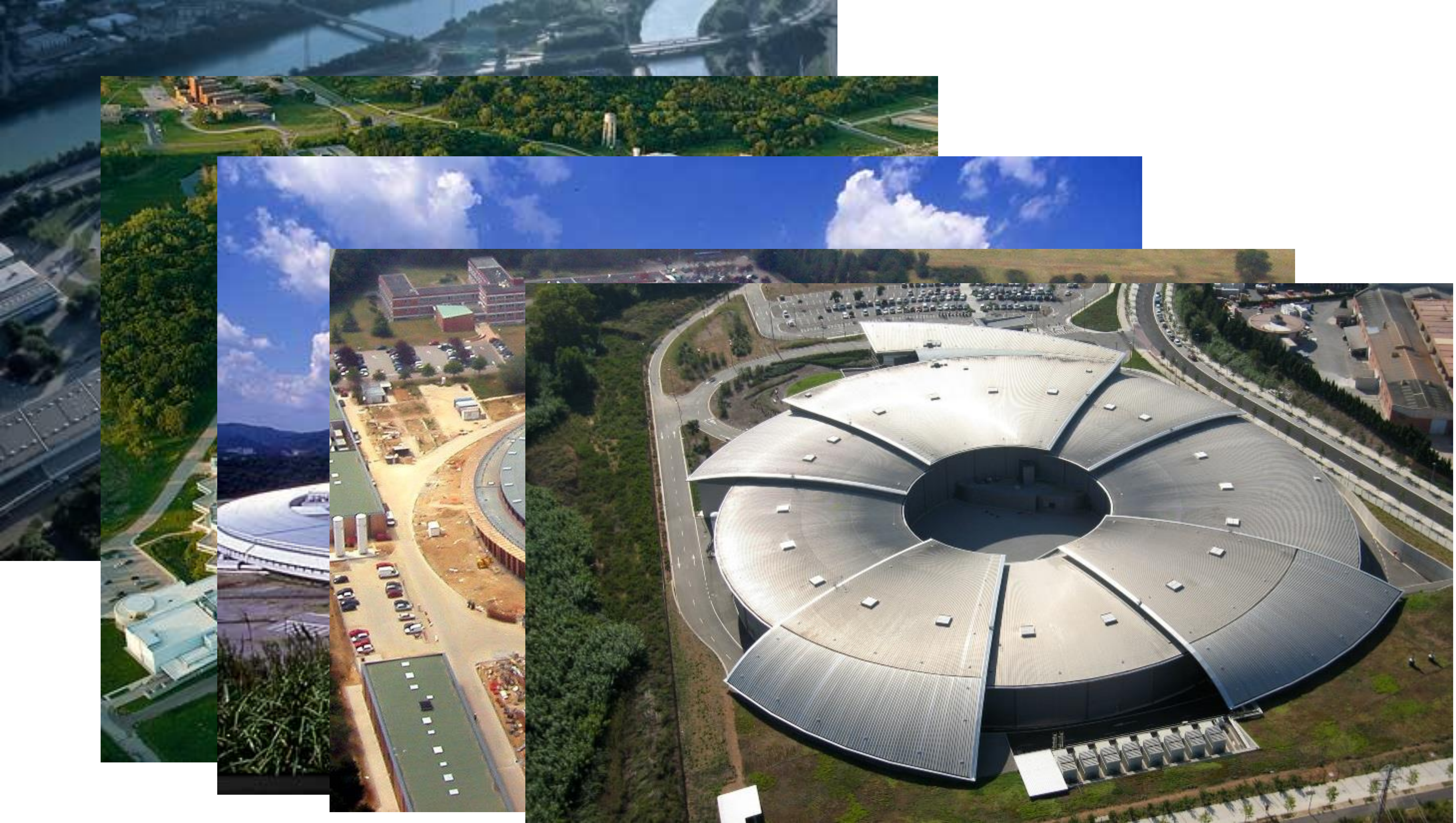
# How do we make Synchrotron Radiation?

Man-made SR is produced using **storage rings**






www.elettra.eu

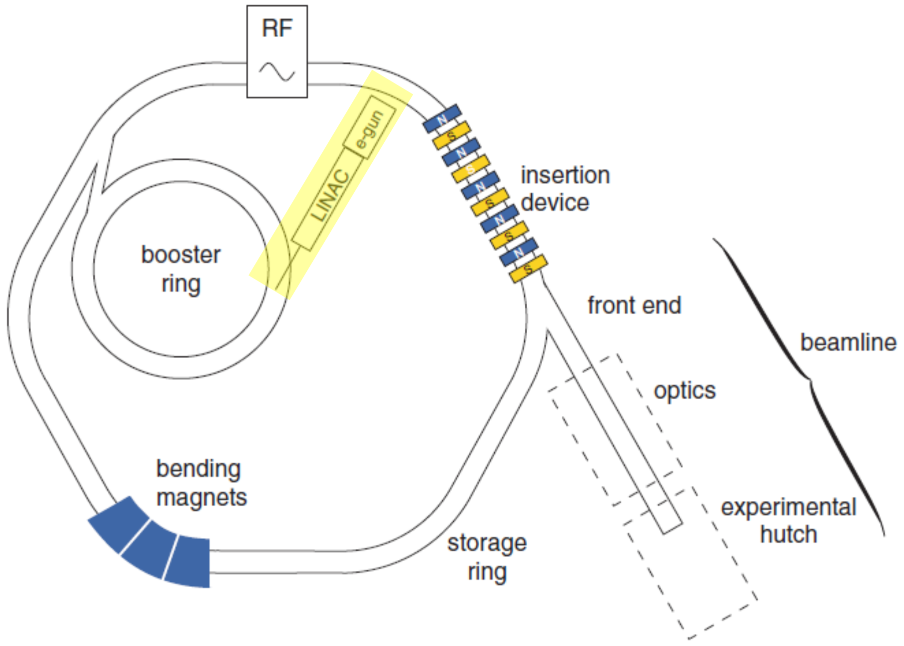


# Electron gun and linac

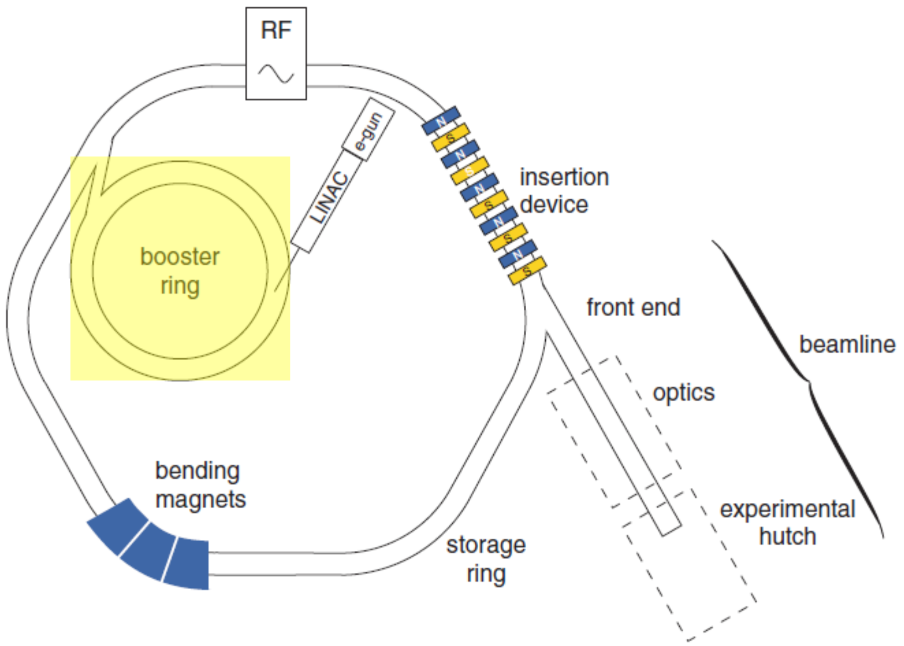
Electrons are generated by thermoionic emission from a hot filament in an electron gun

The electrons are accelerated using a Linac to about 100 MeV

A regular supply of electrons is required, as they are always being lost in the machine, due to collisions with residual gas particles in the storage ring



# Booster ring




Electrons are injected from the linac and further accelerated.

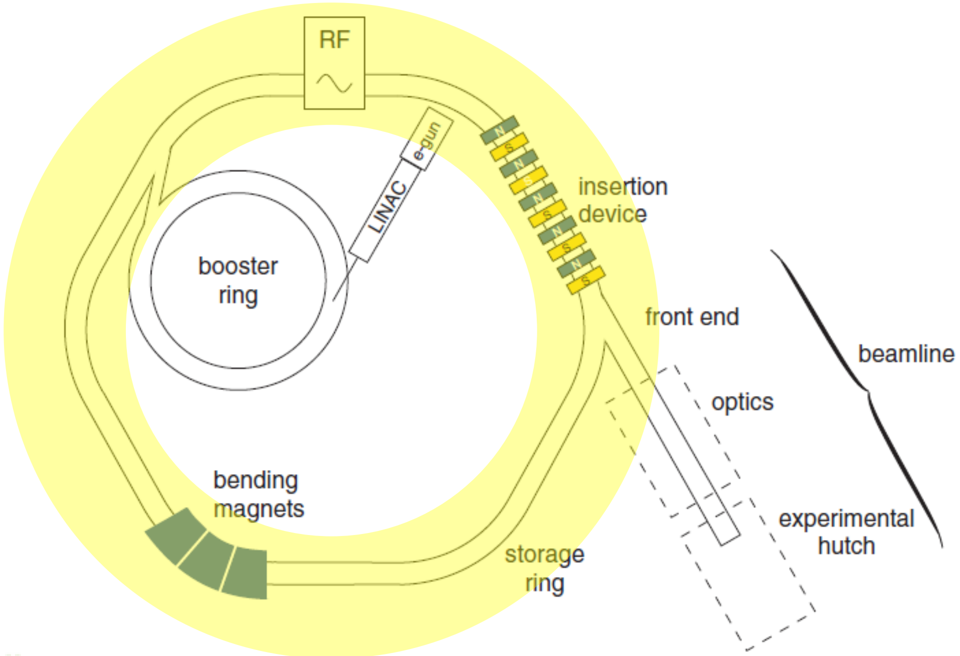
They may either be accelerated to the energy of the electrons in the main storage
ring, or (less commonly, especially for modern facilities) to a somewhat lower energy.

# Storage ring

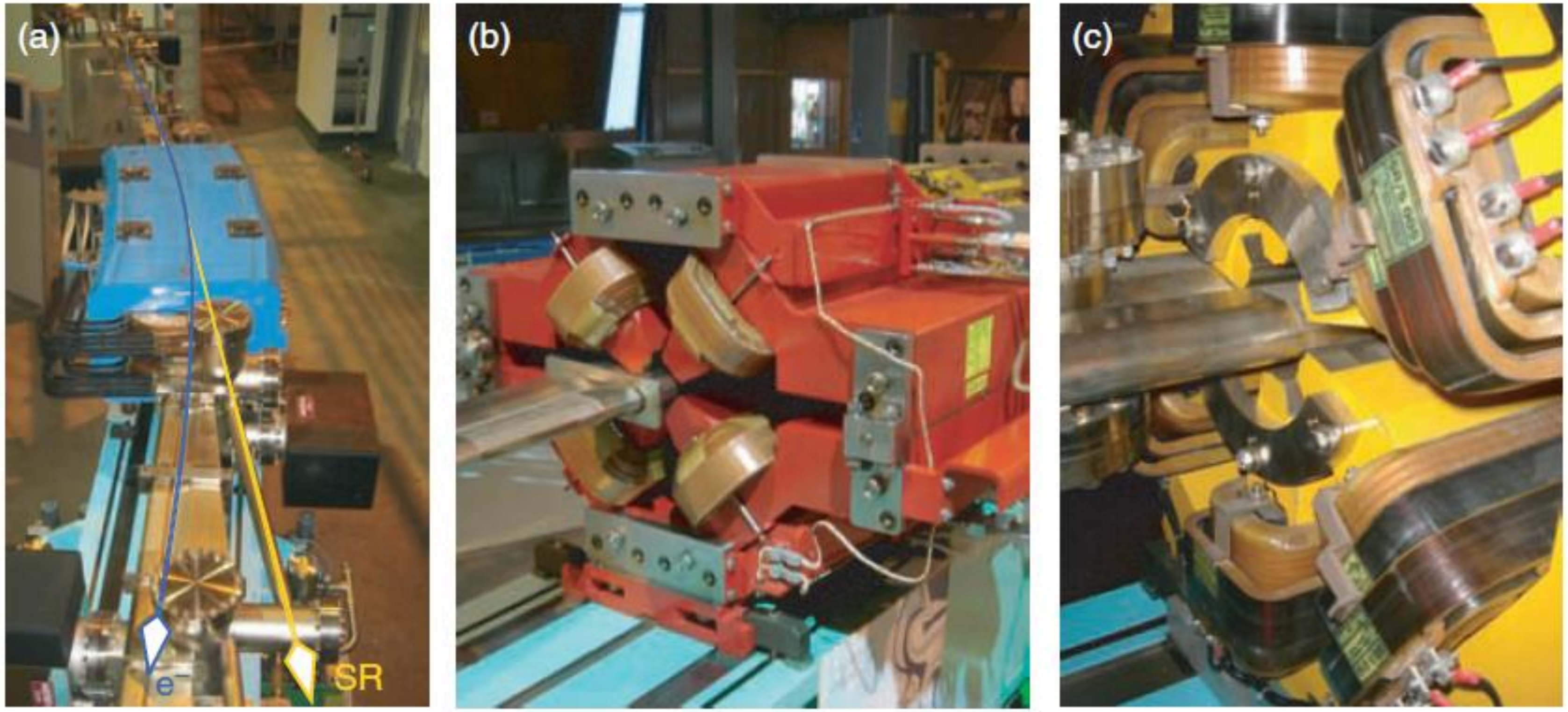
Electrons are injected from the booster periodically so that the specified current is maintained. This is done when the current drops to about 1 - 1/e ≈ 70 % or more often in case of top up mode

The storage ring contains the electrons and maintains them on a closed path by the use of an array of magnets, commonly referred to as the 'magnet lattice' of the ring.

The electrons have kinetic energies measured in GeV, and their velocities are highly relativistic, that is, only very marginally less than the velocity of light.



# Storage ring: magnet lattice

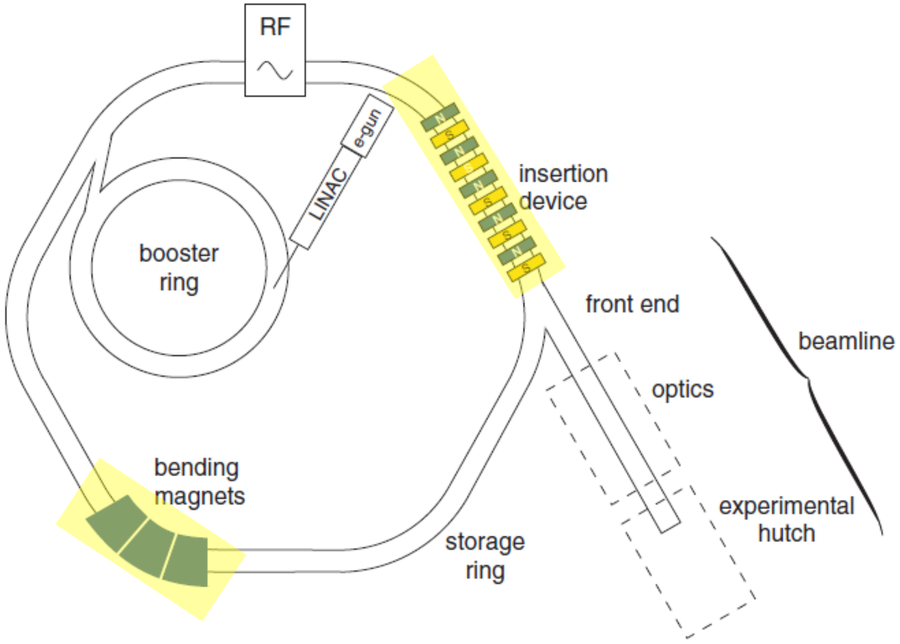


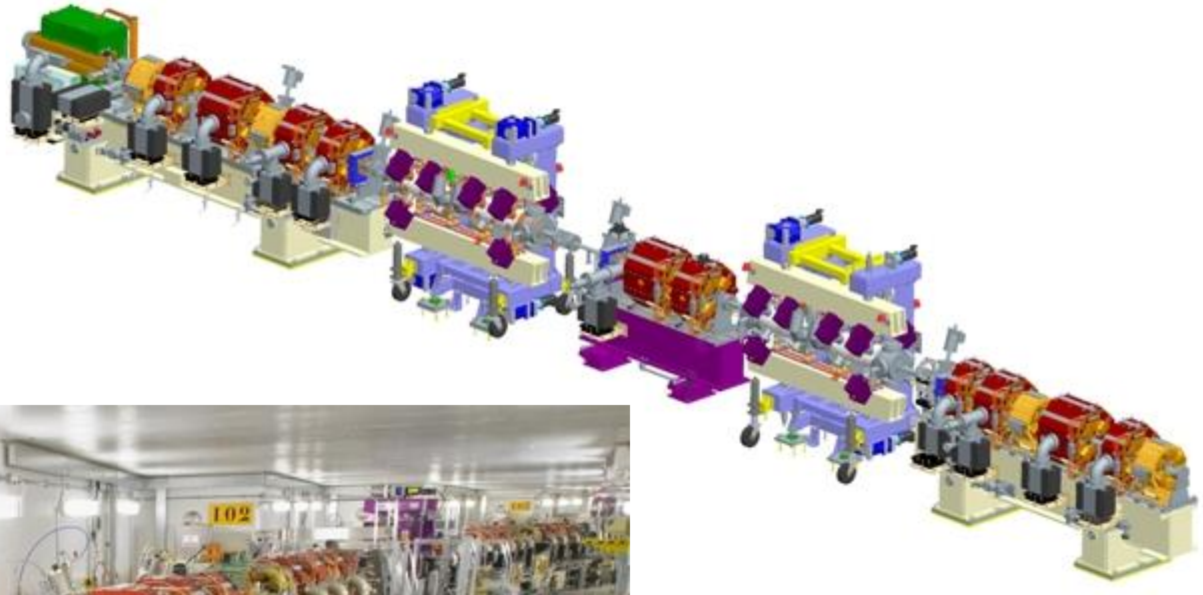

| Bending, dipole-magnets | Quadrupole-magnets | Sextupole-magnets |
|---|---|---|
| They cause the electrons to change their path and thereby follow a close path | They are used to focus the electron beam and for Coulomb repulsion between electrons | They correct the chromatic aberration that arise from focusing by the quadrupoles |

# Storage ring: BMs and IDs

The ring has a structure consisting of arced sections containing bending magnets (BMs) and straight sections used for insertions devices (IDs), which generates the most intense SR.

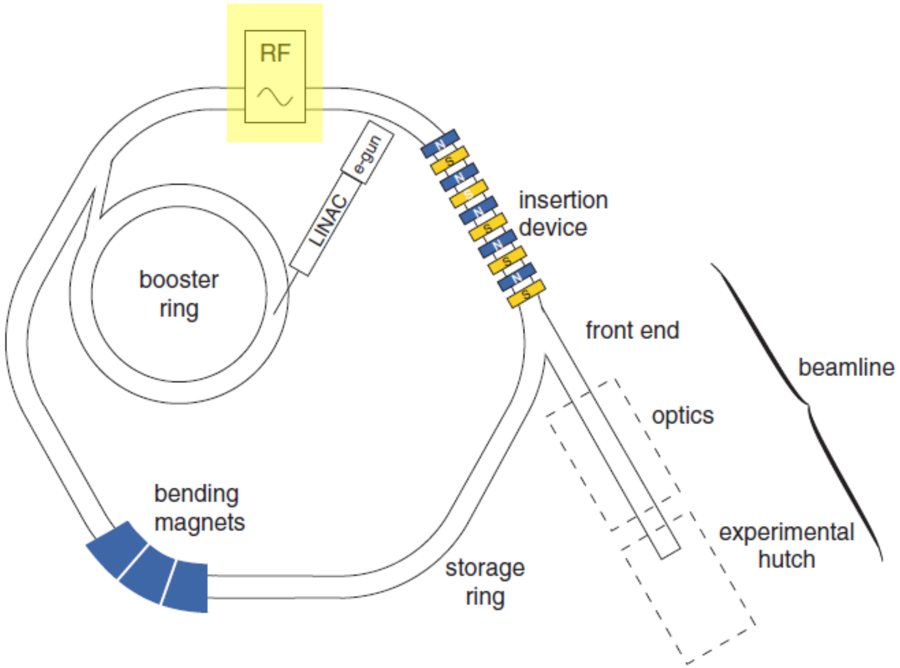
The BMs, used to deflect the electrons round the arced sections that connect the straight sections are also often used to provide BM radiation – although their brilliance is significantly lower than that produced by IDs, even monochromated BM-radiation is still orders of magnitude more intense than that can be provided by laboratory-based sources.






B01
I02

# Radio frequency supply



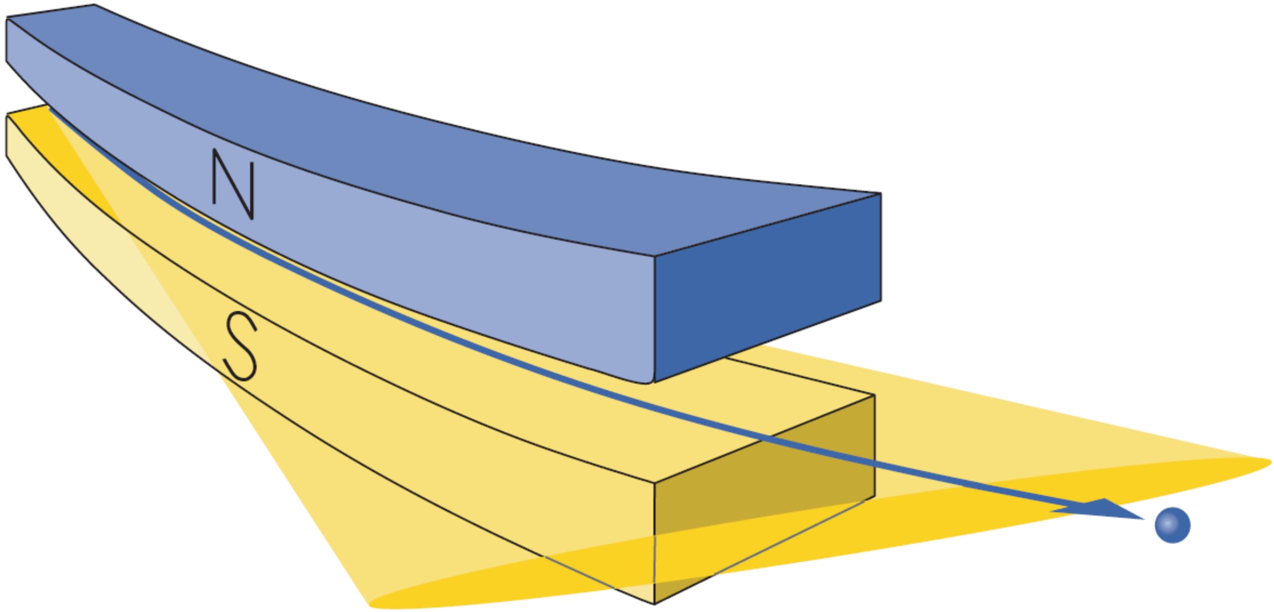

The kinetic energy of the electrons dissipated due to emission of radiation at BMs and IDs must be replenished before they spiral into the inner wall of the storage ring.

This is achieved by giving them a small boost at every turn as they pass through a radio-frequency cavity (klystron).

# Synchrotron Radiation sources

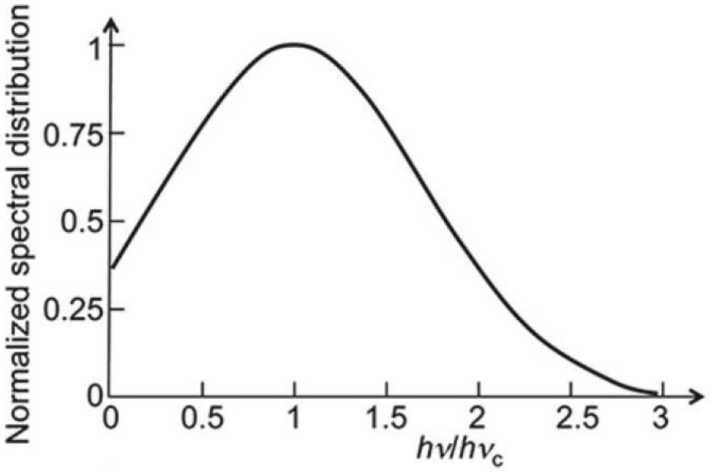
# Bending magnet: angular distribution

- The primary purpose of the bending magnet is to circulate the electron beam in the storage ring in a close path
- The bending magnet is also used as source for synchrotron radiation

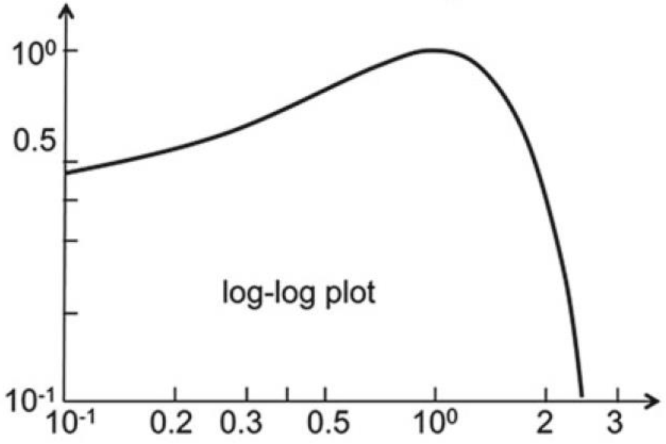



The angular spread of the BM radiation is a flattened cone ($2/\gamma$ vertically) with an horizontal angle equal to the angular change of the path of the electrons

# Bending magnet: spectral distribution




Linear-linear plot of the approximate lineshape for broadband bending magnet emission




Log-log plot of the approximate lineshape for broadband bending magnet emission

# Bending magnet: critical energy

$h\nu_{CR}$

The critical energy is defined by saying that equal amounts of synchrotron radiation energy are emitted at photon energies lower and higher than $h\nu_{CR}$

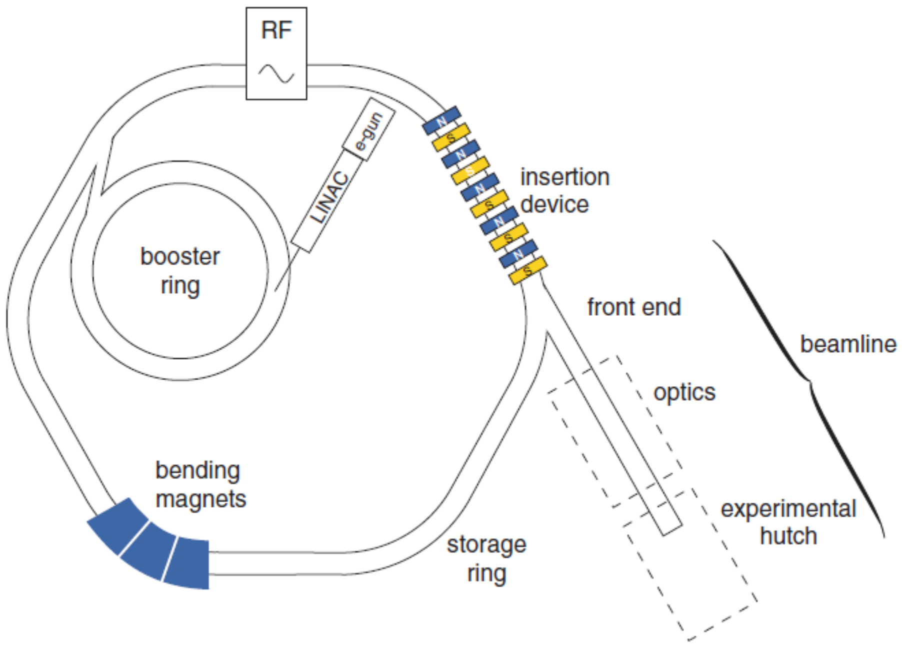
In practical units:

$$h\nu_{CR}[\text{keV}] = 0.665\mathcal{E}^2[\text{GeV}]B[\text{T}]$$
$$h\nu_{CR}[\text{keV}] = 2.21\mathcal{E}^3[\text{GeV}]/\rho[\text{m}]$$

# Insertion devices - 1

Third generation synchrotrons are characterized by the use of insertiondevices (IDs).

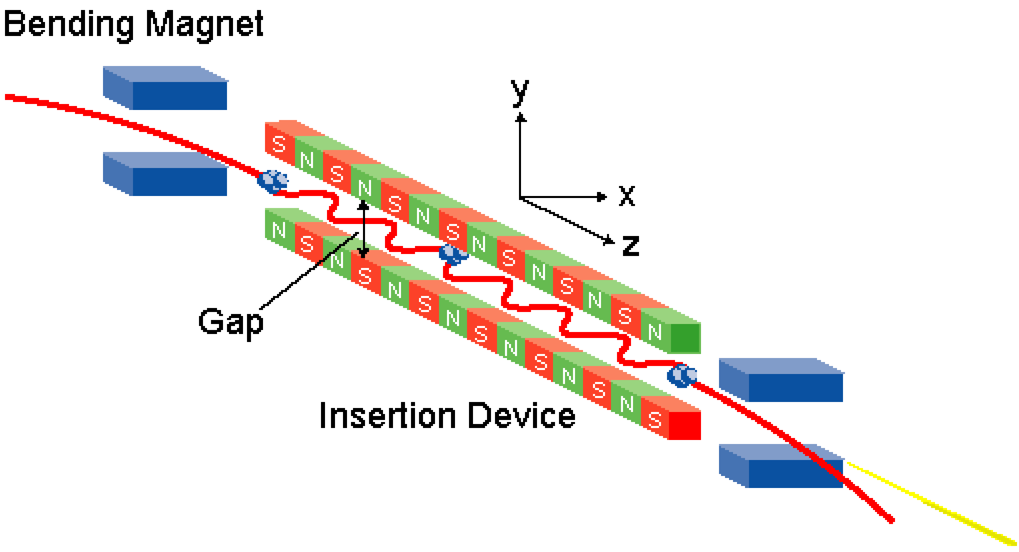
These are placed in the straight sections between the bending magnet arc segments



# Insertion devices - 2

Insertion devices are periodic magnetic structures
(e.g. permanent magnets: NdFeB).

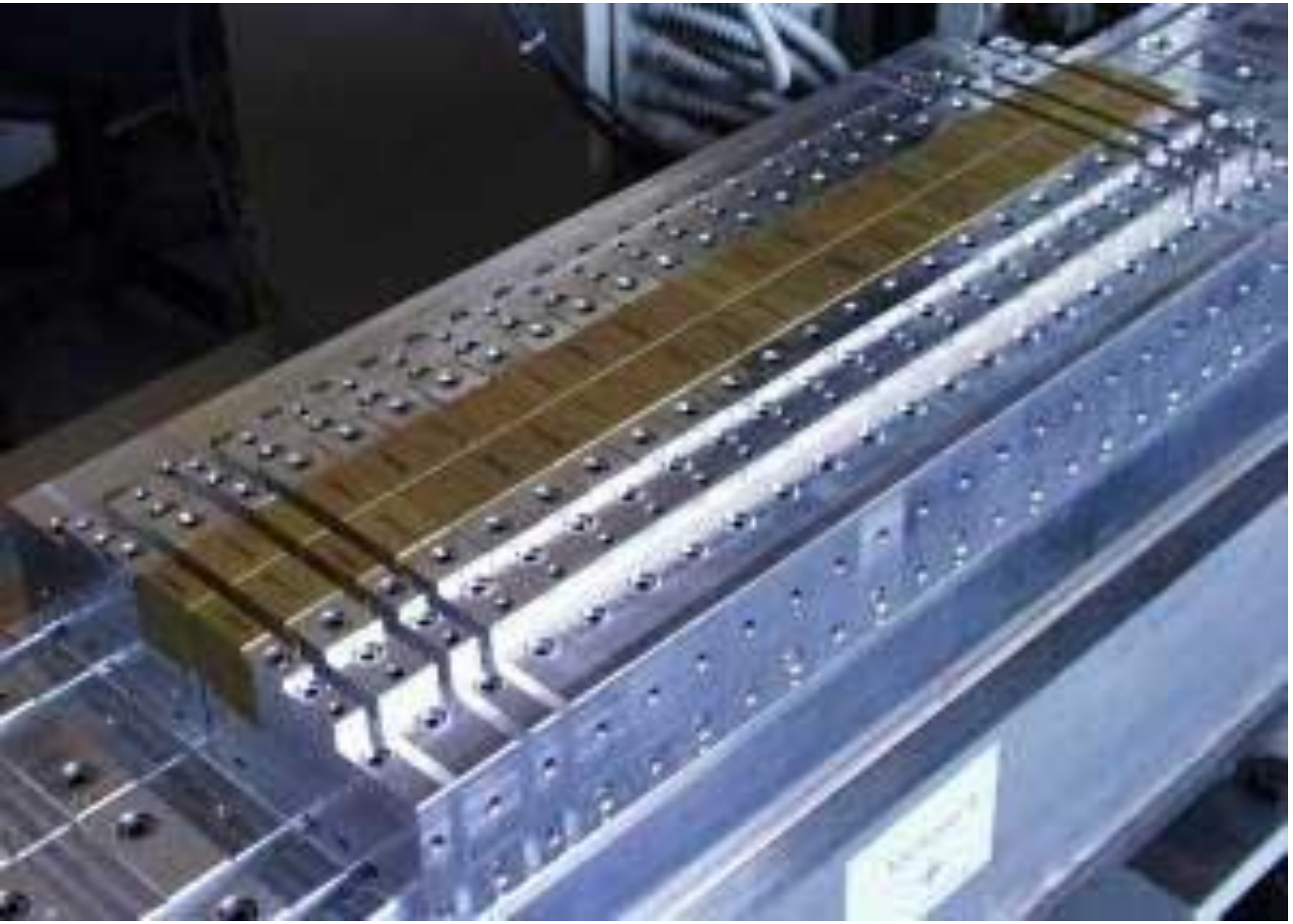
Passing through such alternating magnetic field structures, electrons oscillate perpendicularly to the direction of their motion and therefore emit SR during each individual wiggle

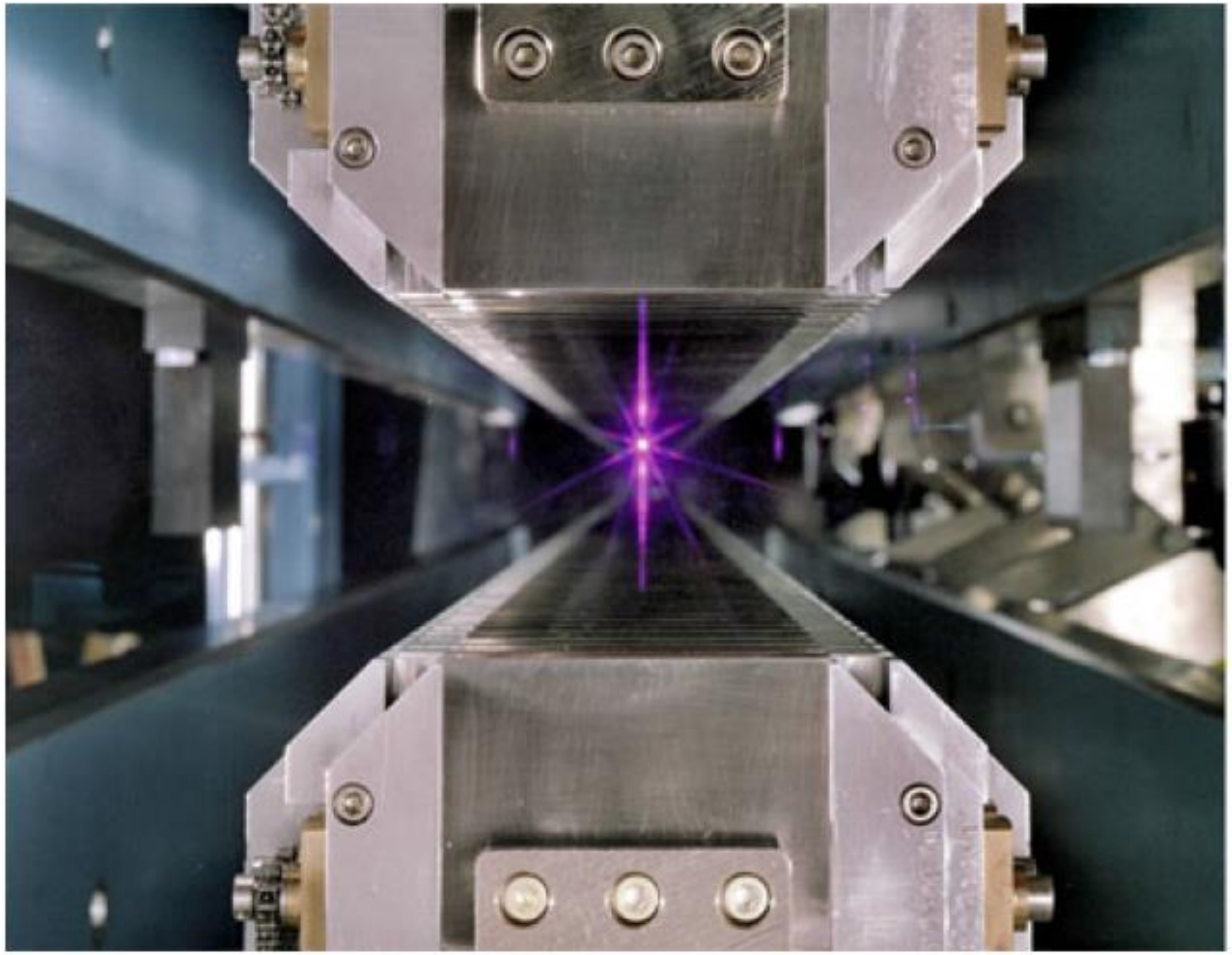


# Insertion devices - 3

Effect of insertion devices:

- To shift the critical energy $h\nu_{CR}$ to higher values due to the smaller bending radius ρ with respect to the bending magnets
- To increase the intensity of the radiation by a factor related to the number of wiggles induced by many poles of the magnetic structure
- To increase the spectral brightness

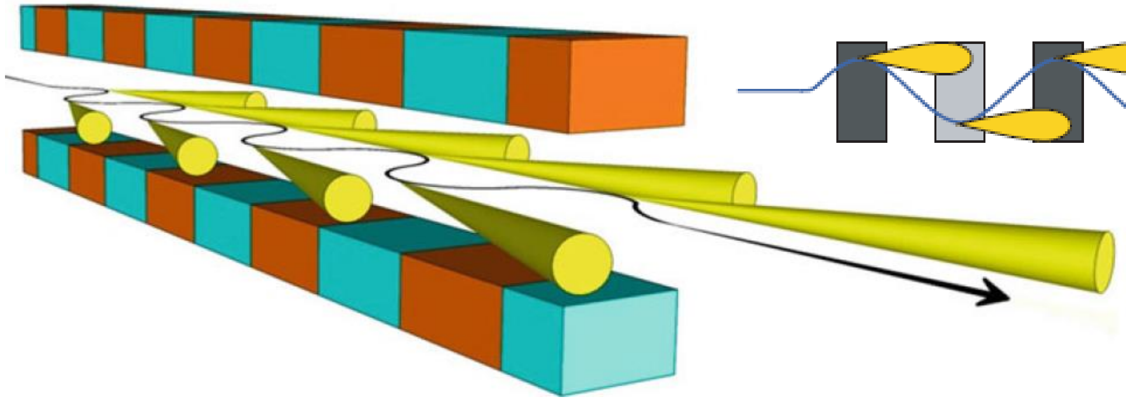


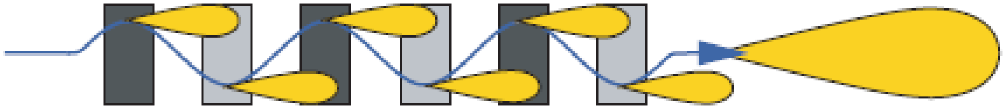


# Wigglers and undulators - 1

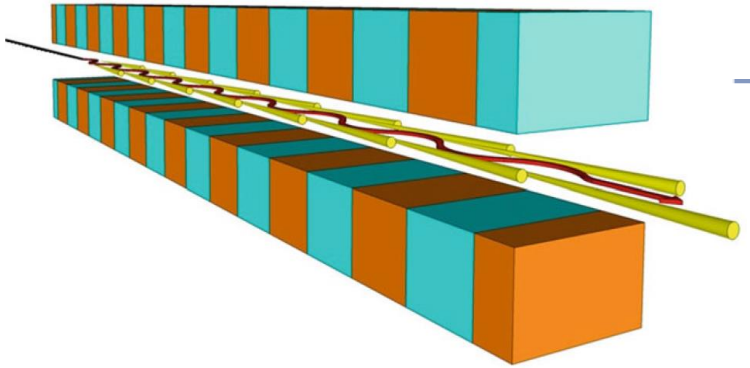
Wigglers and undulators are different from one another by the degree to which the electrons are forced to deviate from a straight path

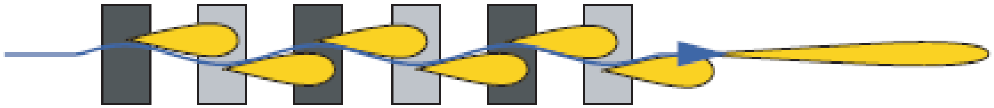
## Wigglers





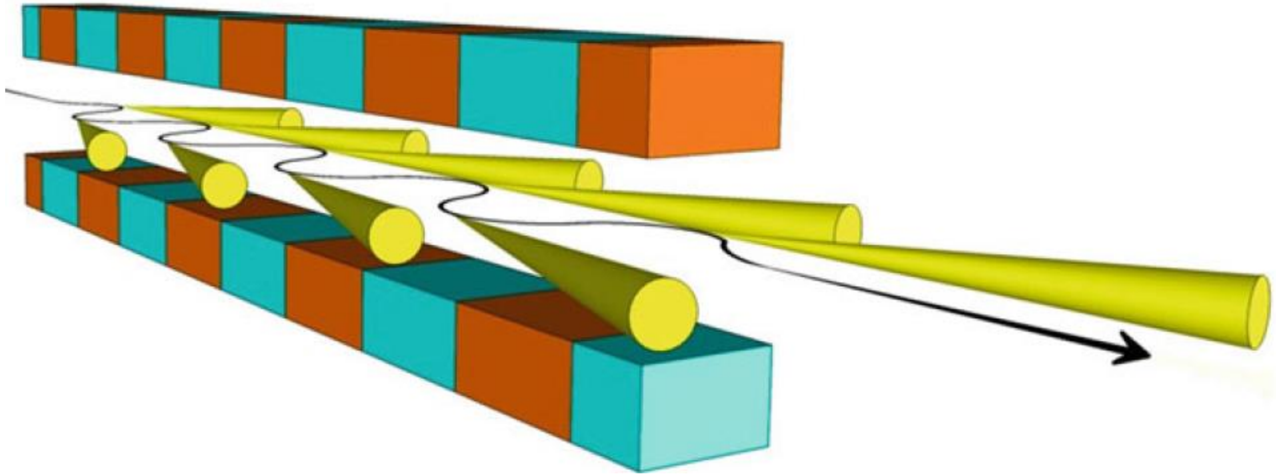
## Undulators





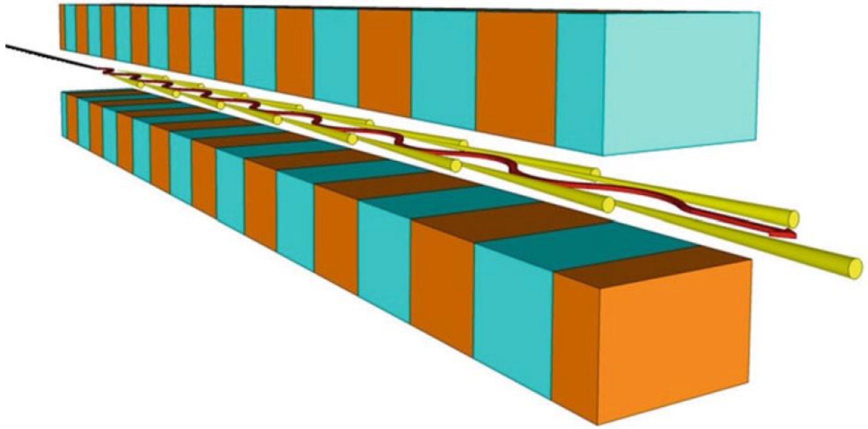
# Wigglers and undulators - 2

Wigglers



- Just like a BM except:
- Larger $B$ →higher $h\nu_{CR}$
- More bends → more power

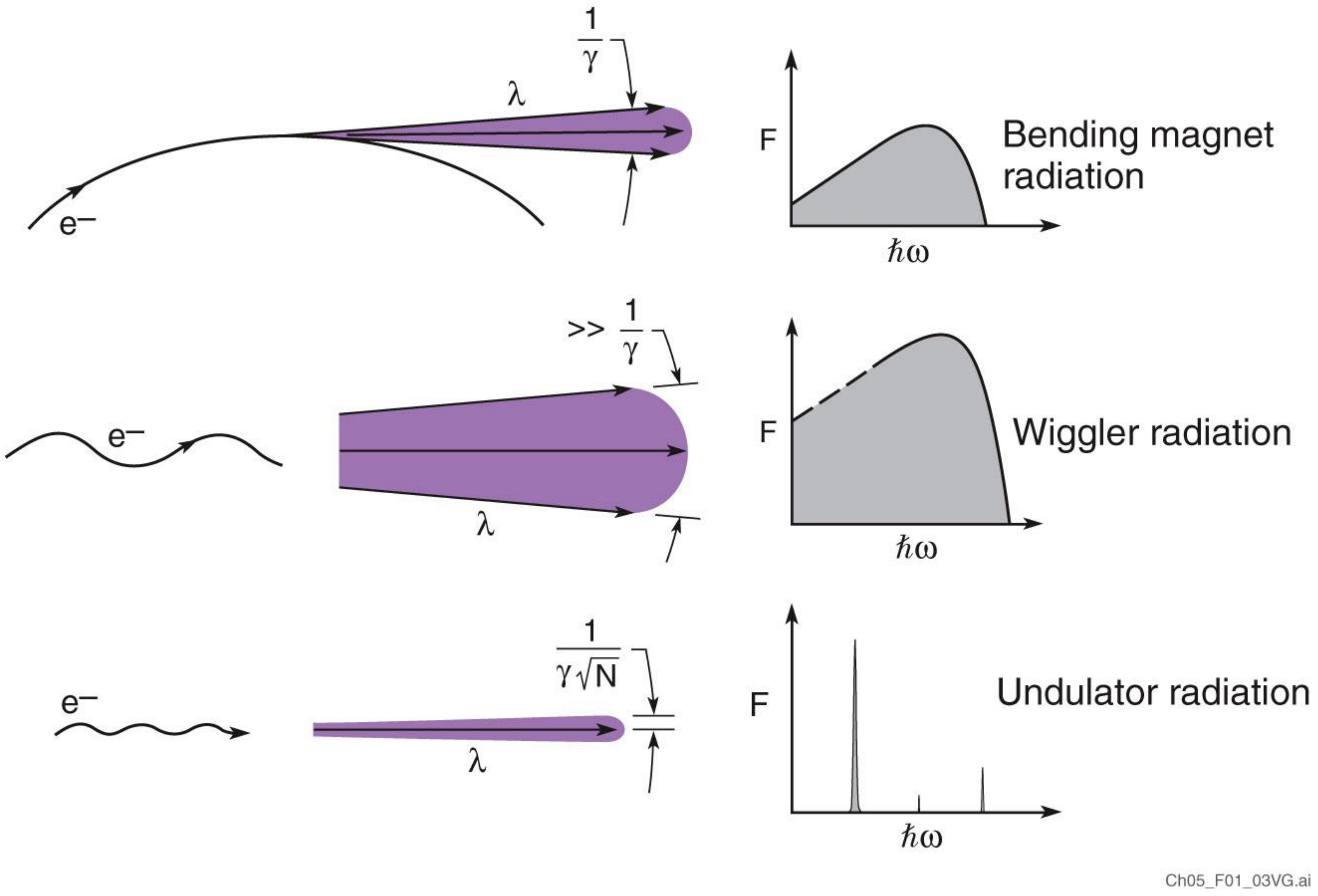
Undulators



Different from BM:

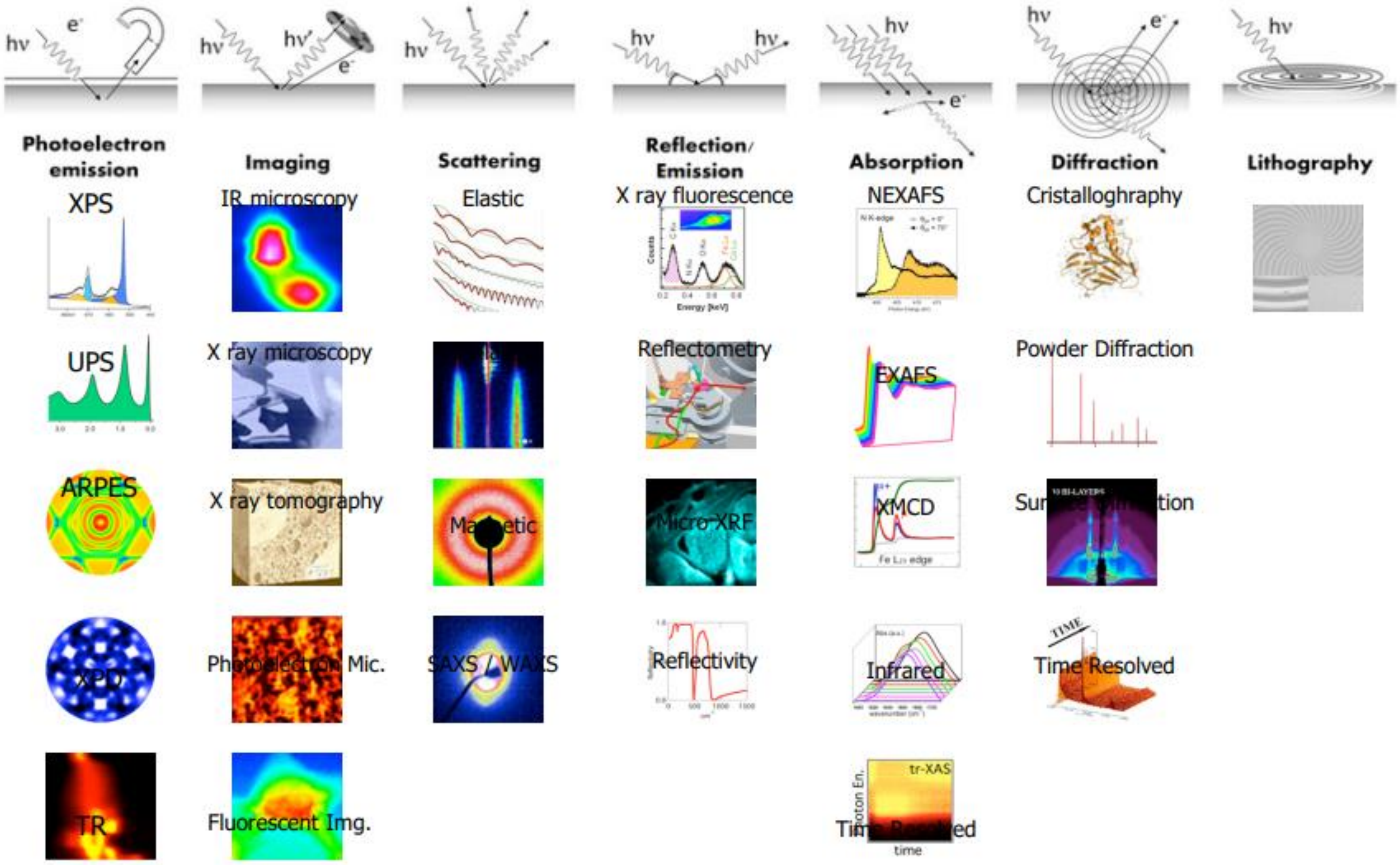
- Shallow bends → small source
- Interference effect → highly peaked spectrum

# Summary of the 3 SR sources



# What is Synchrotron radiation for

# Many different experimental techniques



# Many applications

What synchrotron radiation is

Properties of synchrotron radiation

How synchrotron radiation is produced

- different elements of a storage ring
- Synchrotron radiation sources

Introduction of techniques and applications