CONTENT

Lecture 1 : 3rd generation light sources

- Objectives
- Principle of synchrotron radiation emission
- Main characteristics and features
- What is a beamline ?
- Examples of application
- Main facilities existing or in project

OBJECTIVES

Synchrotron radiation facilities are designed to provide light simultaneously to many beamlines

The light ranges from Infra-Red up to hard X-Ray (~50 keV)

The characteristics of these beams make them very attractive to investigate matter be it solid, liquid or gazes.

A 3rd generation light source is a photon factory which enables scientists of many different fields to perform thousands of experiments per year.

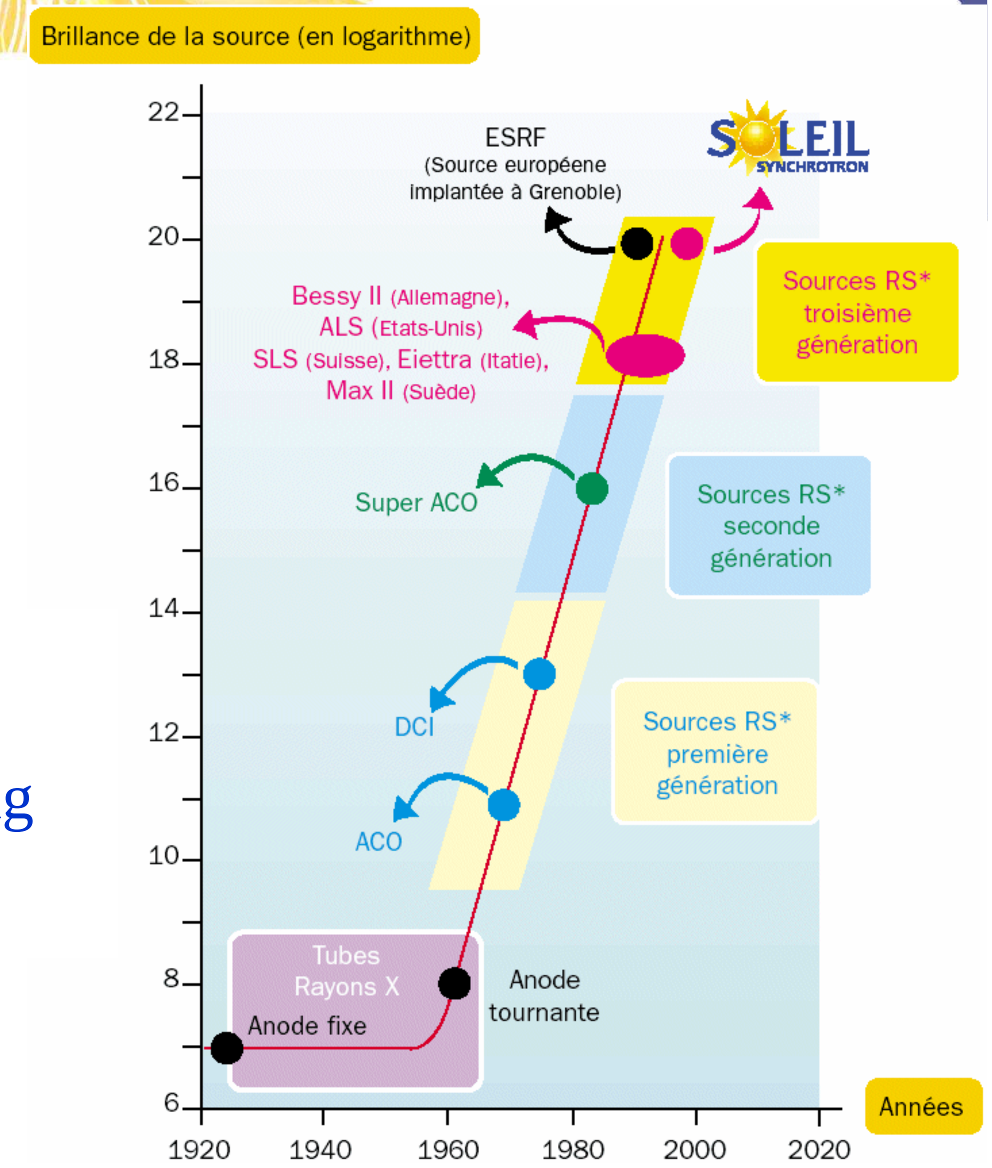
Synchrotron generations

Enhancement of radiation sources last century

1st generation : Parasitic use on Nuclear physics machines

2nd generation : Dedicated machines. Radiation from Bending Magnets and Wigglers (Flux).

Multipurpose beamlines



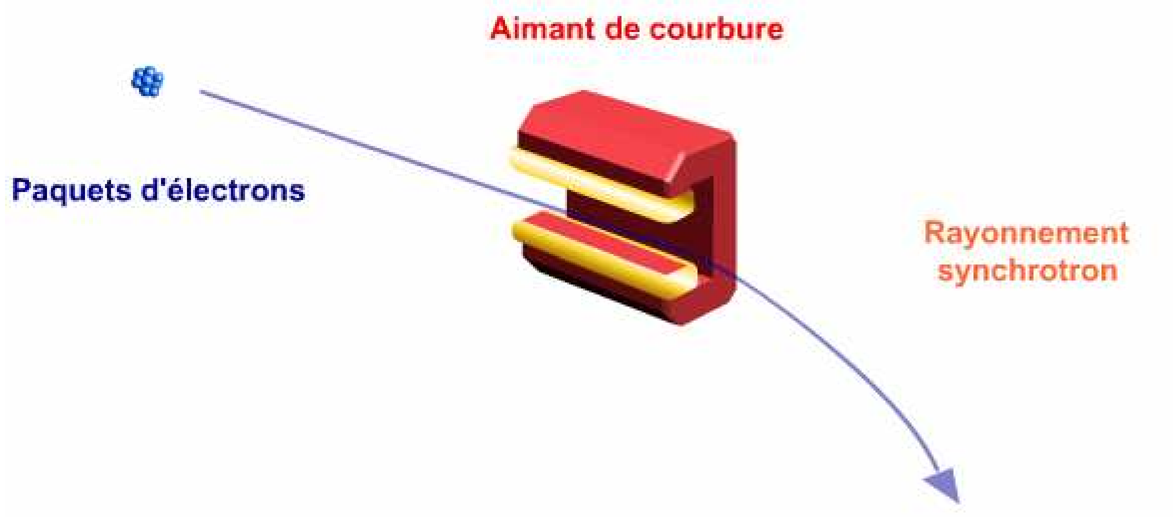
3rd generation Synchrotron light sources

- **Machines optimised for High Brilliance**
- Smaller source sizes, higher current
- Highly performing **insertion devices** matched to the beamline needs
- Beamlines much more accurate (specific scientific use).

Synchrotron radiation

Synchrotron radiation is generated when a charged particle travelling at the speed of light is submitted to the action of a magnetic field.

Its trajectory is bent (Lorentz Force) and the particle suffers a deceleration : It radiates some light and loses a small fraction of its energy.



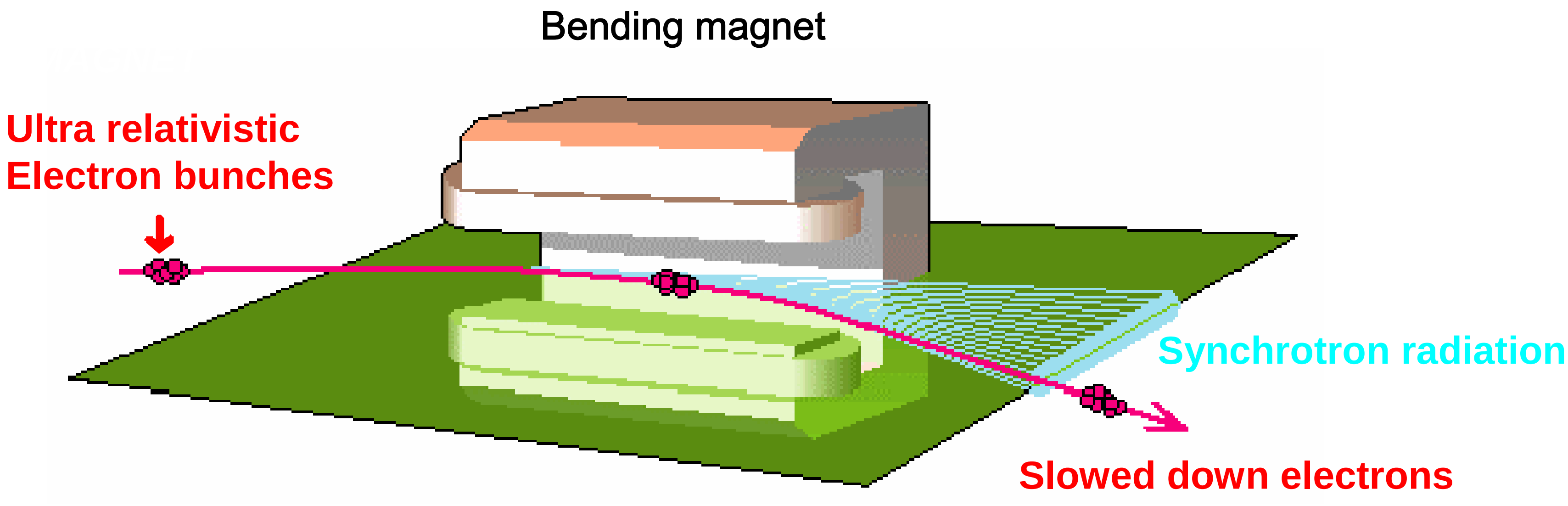
The light is emitted in a fan tangent to the trajectory of the particle

Synchrotron radiation

Due to the bending of their trajectory, the electrons are slowed down by their self field and lose energy.

They emit photons in a direction tangent to their trajectory

=>This is synchrotron radiation



Synchrotron radiation

The Radiated Power with transverse acceleration in case of relativistic particle (v~c) :

$$P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0 \left(m_0 c^2\right)^4} \frac{E^4}{\rho^2}$$

c = light velocity ; ρ = radius of curvature ; E = particle energy ; $m_o c^2$ = particle rest mass ;

Introducing γ, with $E=\gamma\, m_o c^2$ =>

$$P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0} \frac{\gamma^4}{\rho^2}$$

=> The power radiated is much easier to produce with electrons than with protons.

SOLEIL SYNCHROTRON

Synchrotron radiation

The energy loss per turn in a circular accelerator is :

$$U_0 = \oint P_{rad} dt = P_{rad} t_{BM} = P_{rad} \frac{2\pi\rho}{c} = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho}$$

c = light velocity ; ρ = radius of curvature ; E = particle energy ; $m_o c^2$ = particle rest mass ; t_{BM} = traveling time in the bending magnets

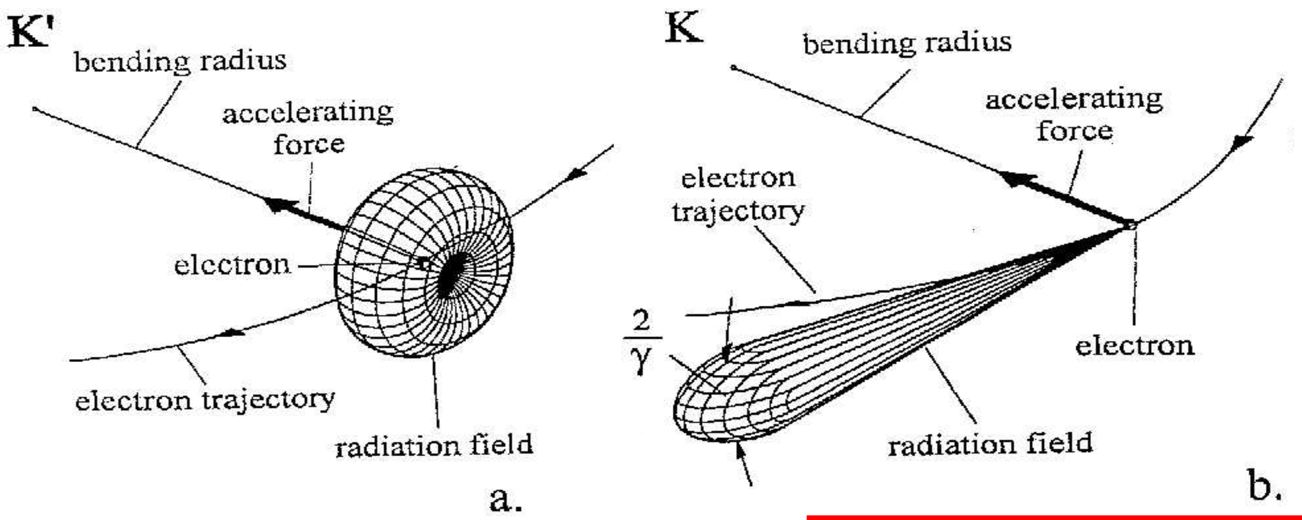
or in practical units (for electrons)

$$U_0[keV] = 88.5 \frac{E^4[GeV^4]}{\rho[m]} = 26.6 E^3[GeV^3].B[T]$$

	L(m)	(GeV)	ρ(m)	B(T)	U_0(MeV)
SOLEIL	354.1	2.75	5.36	1.71	0.944
ESRF	844	6.	23.40	0.855	4.9
LEP	27×10^3	70.	3000	0.078	708

Synchrotron radiation

The axially-symmetric radiation distribution in the moving frame K' (a.) transforms into a sharply forward peaked distribution in the laboratory frame (b.), with a half opening-angle $\theta = 1/\gamma$.



Emission angle
(in the laboratory frame)

$$\tan\theta = \frac{p_y}{p_z} = \frac{p_0'}{\gamma\beta p_0'} \approx \frac{1}{\gamma}$$

This is one of the most useful features of synchrotron radiation.

For E = 2.75 GeV: $\gamma = 5382$ then $\tan\theta \sim \theta = 0.186$ mrad = 0.01°

Synchrotron radiation

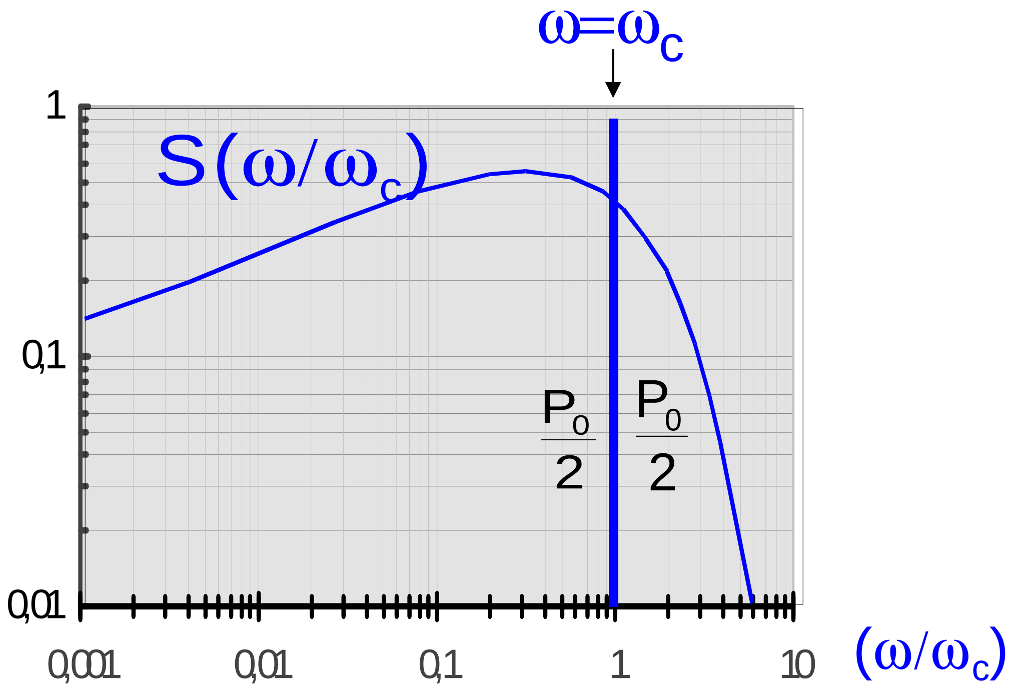
Radiation from a bending magnet (magnetic field B):

Broad spectrum, with critical energy :

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

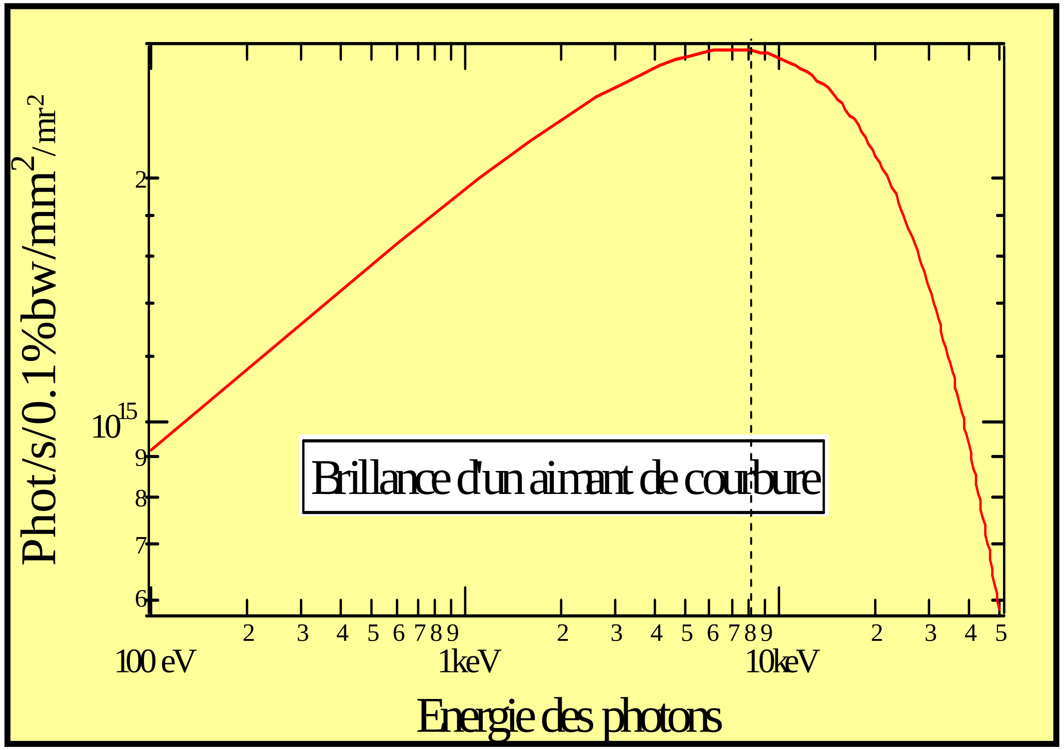
Power radiated

$$P_{rad} \; \alpha \; E^2 B^2$$



SOLEIL Bending Magnet

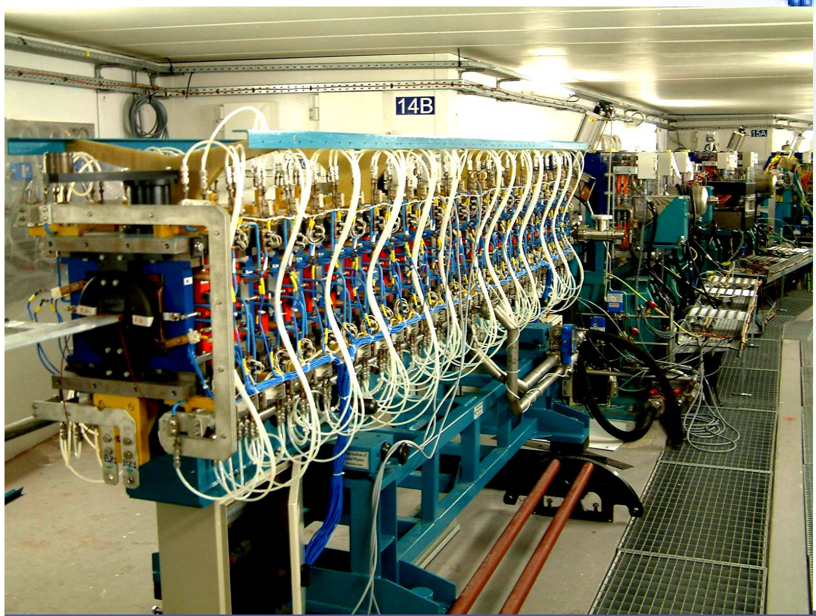
B (T)	1.71
ρ (m)	5.36
ε_c (keV)	8.6
λ_c (Å)	1.44
P (kW)	472
dP/dθ (W/mrad)	75

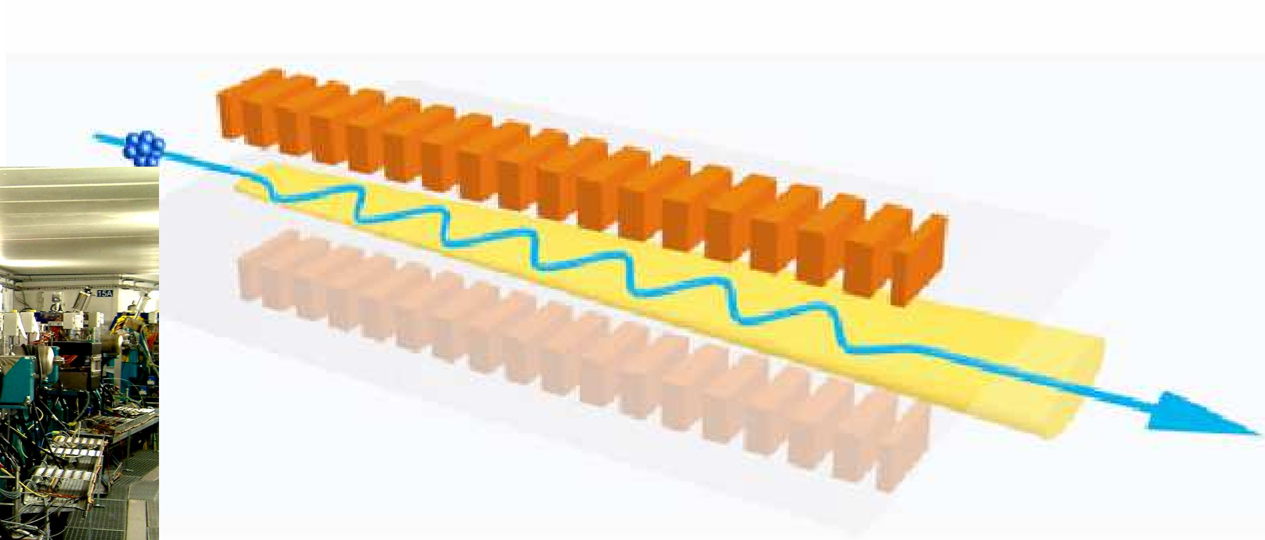


Insertion device Synchrotron radiation

The Undulator technology: Periodic magnetic field +B/-B

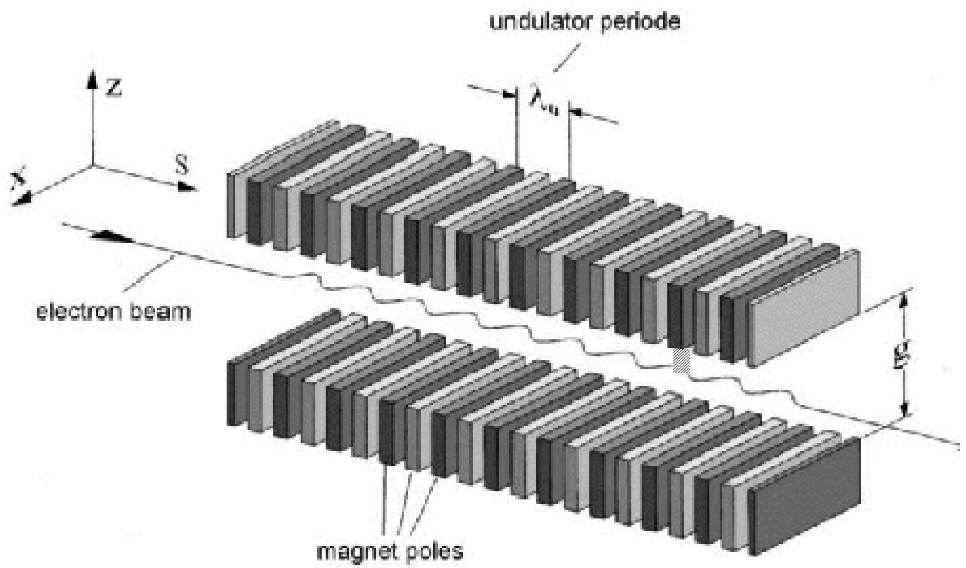
summing up many oscillations enables to enhance the radiation brightness by several orders of magnitude





Insertion device Synchrotron radiation

Insertion Device : **sinusoidal field** $$B_Z = B_0 \cos\left(\frac{2\pi s}{\lambda_0}\right)$$



Electron trajectory

$$X = -\frac{K\lambda_0}{2\pi\gamma}\cos\left(\frac{2\pi s}{\lambda_0}\right) \qquad X_{max} = \frac{K\lambda_0}{2\pi\gamma}$$

$$X' = \frac{K}{\gamma} sin\left(\frac{2\pi s}{\lambda_0}\right) \qquad X'_{max} = \frac{K}{\gamma} = \alpha$$

Insertion strength

$$K = 0.0934\, B_{0[T]}\lambda_{0[mm]}$$

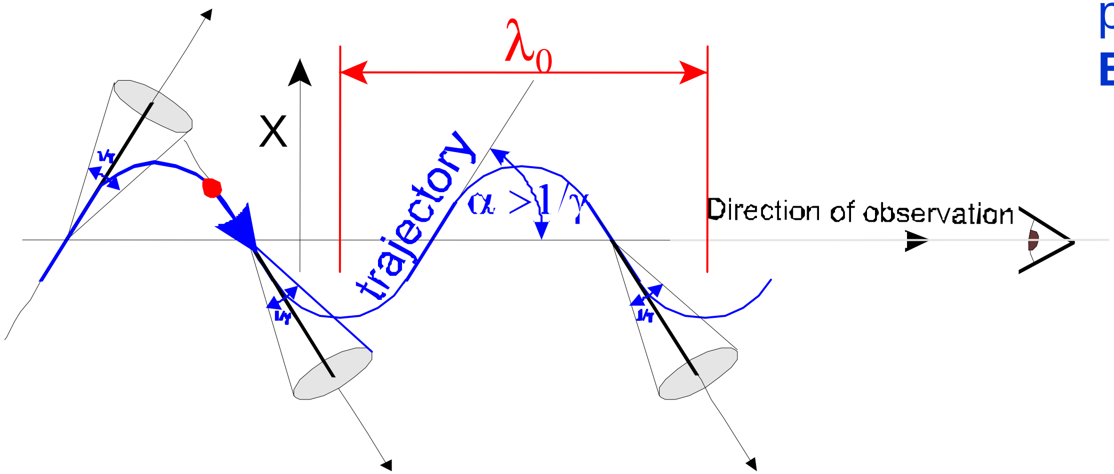
It consists of a periodic arrangement of short bending magnets of alternating polarity.

$K = \alpha\ \gamma$

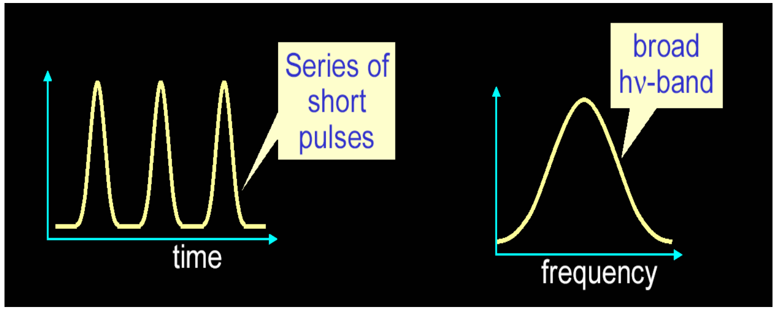
with α = max deflection angle

Wiggler Synchrotron radiation

Wiggler Regime $\alpha > 1/\gamma$



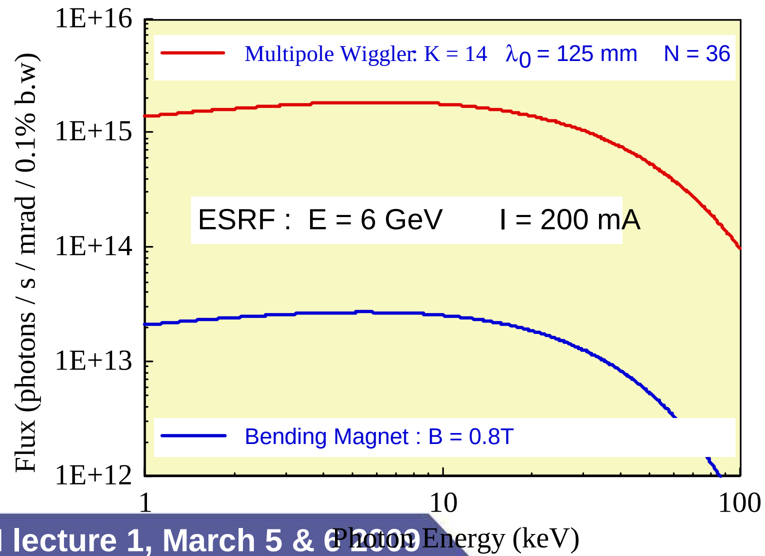
In the wiggler regime K >>1 the observer sees a train of distinct light pulses, which adds incoherently => **Broad spectrum**



Bending Magnet: **Flux ~ Ne$^-$**

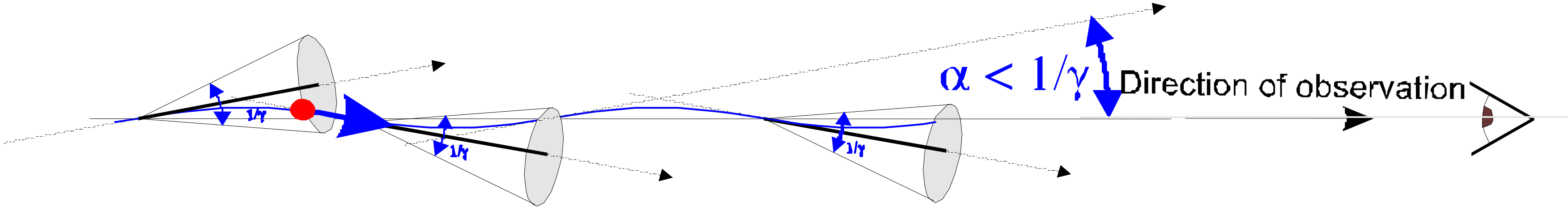
Wiggler: **Flux ~ Ne$^-$ x N$_{period}$**

gain (10 – 100)



Undulator Synchrotron radiation

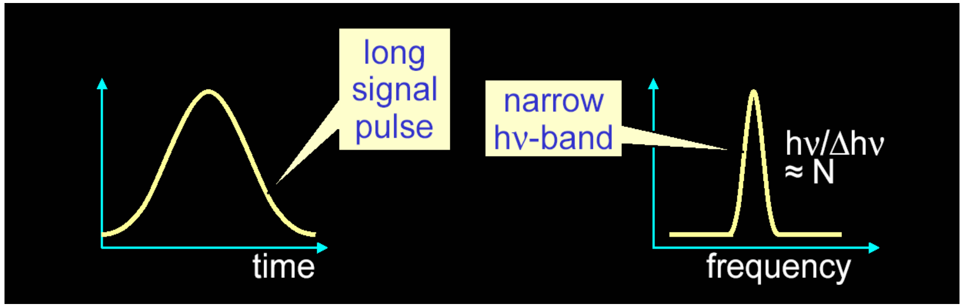
Undulator Regime $\alpha \sim 1/\gamma$



In the undulator regime K ~2 the angle and the transverse displacement of the electron is so small that the observer can see the electron during the full length of the ID therefore during a much longer time interval. This results in a much thinner spectrum around privileged photon energies called **undulator harmonics**.

Undulator: **Flux ~ Ne$^-$ x [N$_{period}$]^2**

gain (10^4 – 10^5)

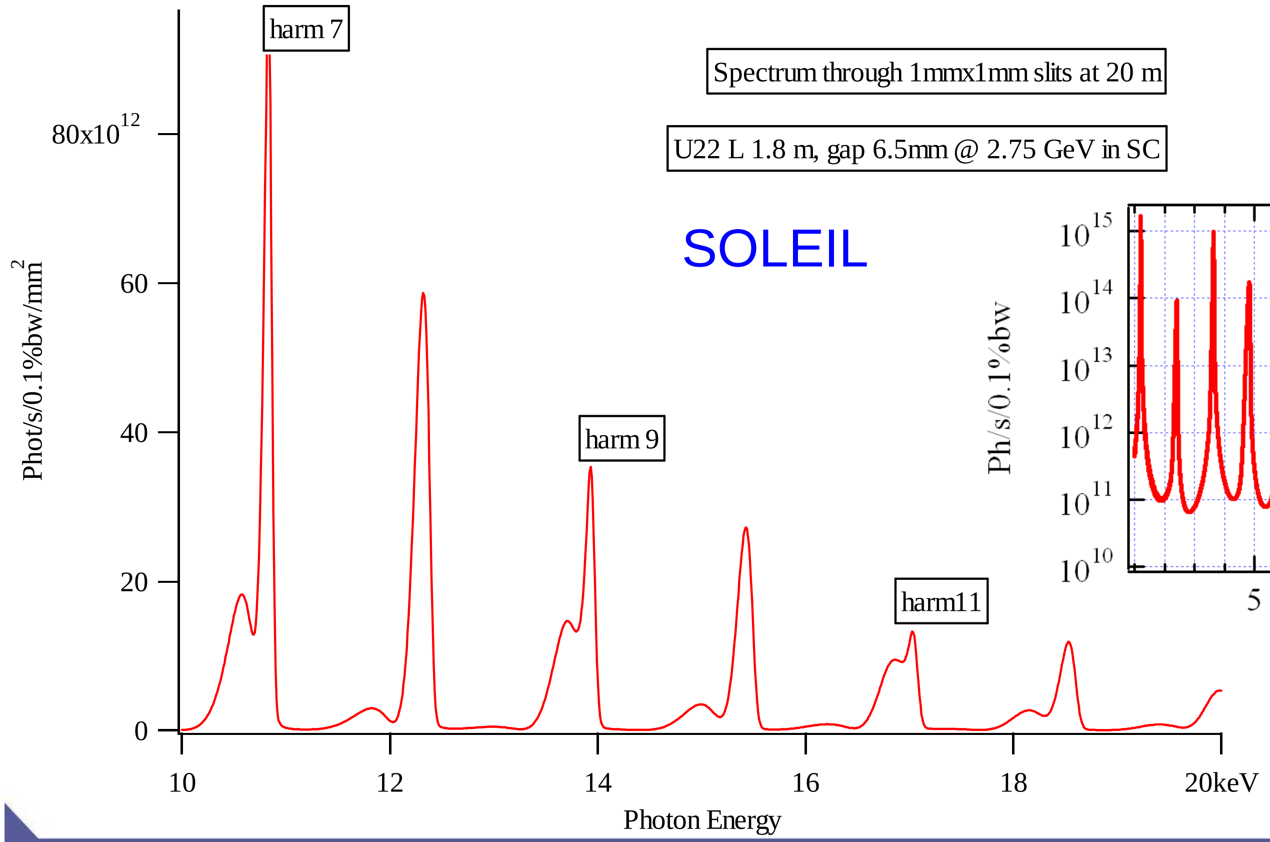


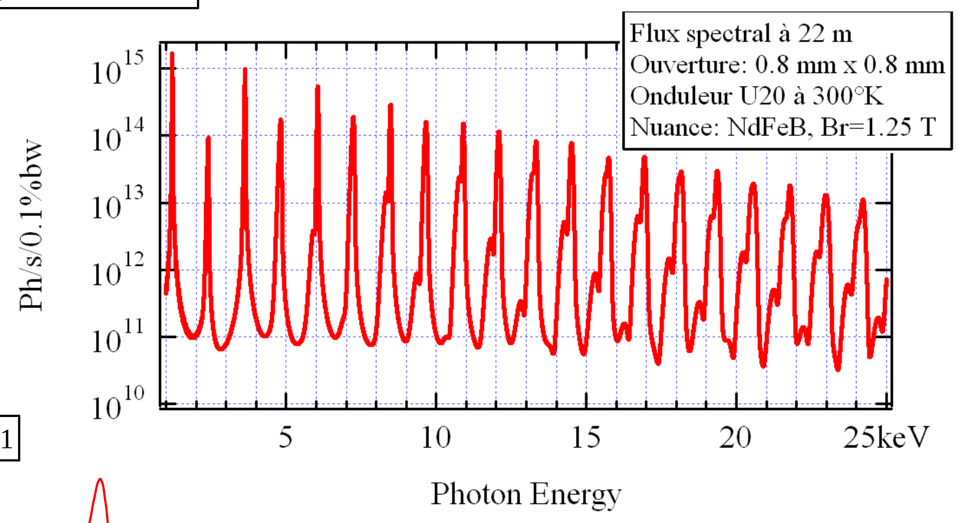
Undulator Synchrotron radiation

Interferences along the N periods =>

Discrete lines spectrum with :

- Line width scaling as $(\Delta\lambda/\lambda)_{harm\ n}$ ~1/nN
- Peak value scaling as N^2



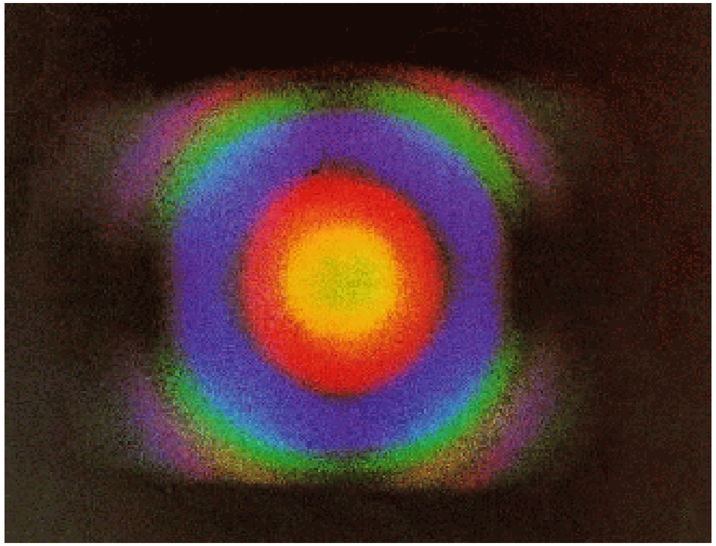


Undulator Synchrotron radiation

Wave length emitted on harmonic n

$$\lambda_n = \lambda_u (1 + K^2/2 + \gamma^2\theta^2) / (2n\,\gamma^2)$$

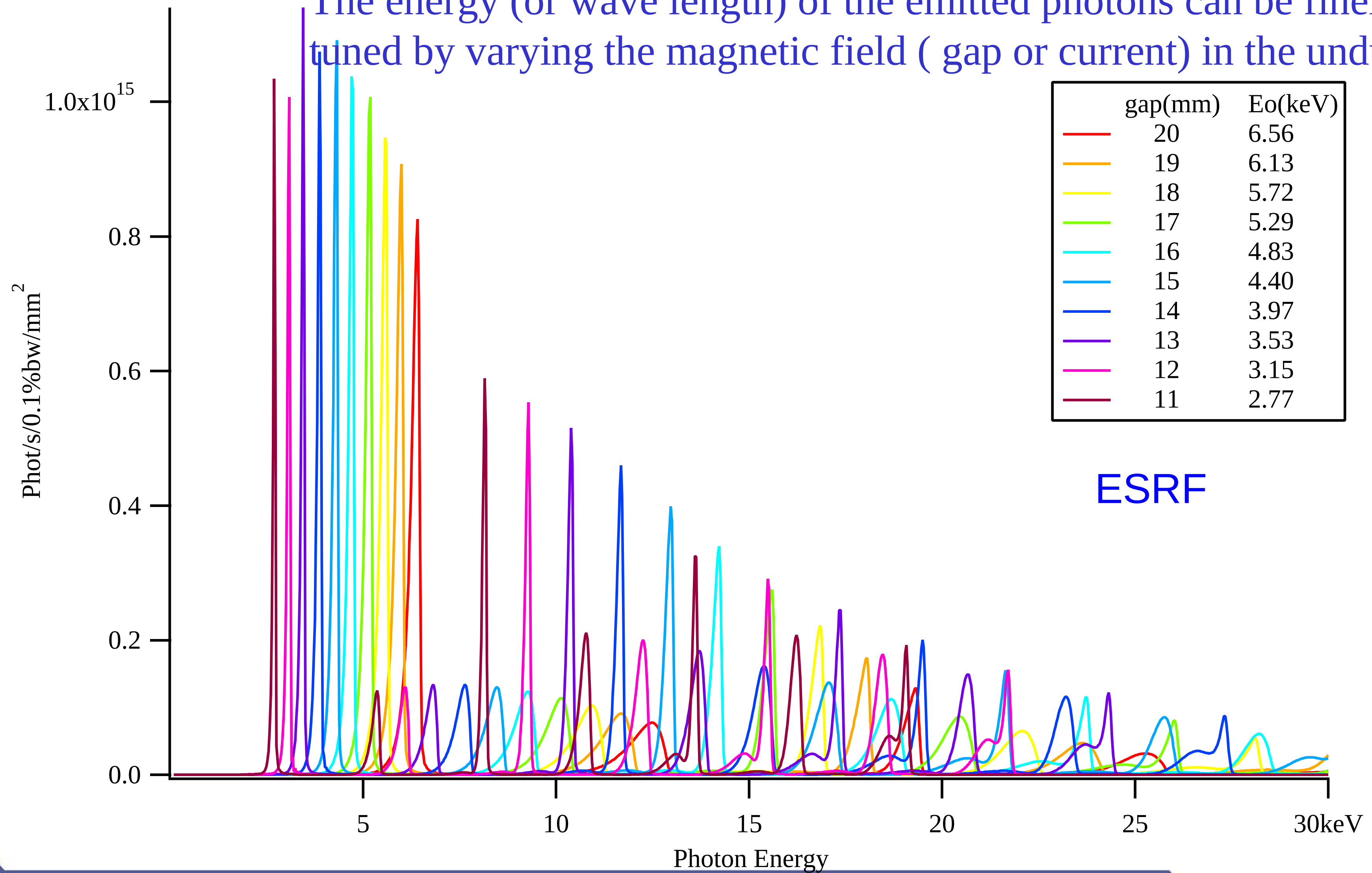
λ_u is the undulator magnetic period
θ is the angle of observation



⇒**Photon energy depends on the observation angle**
⇒**Great sensitivity to spread in θ or γ**

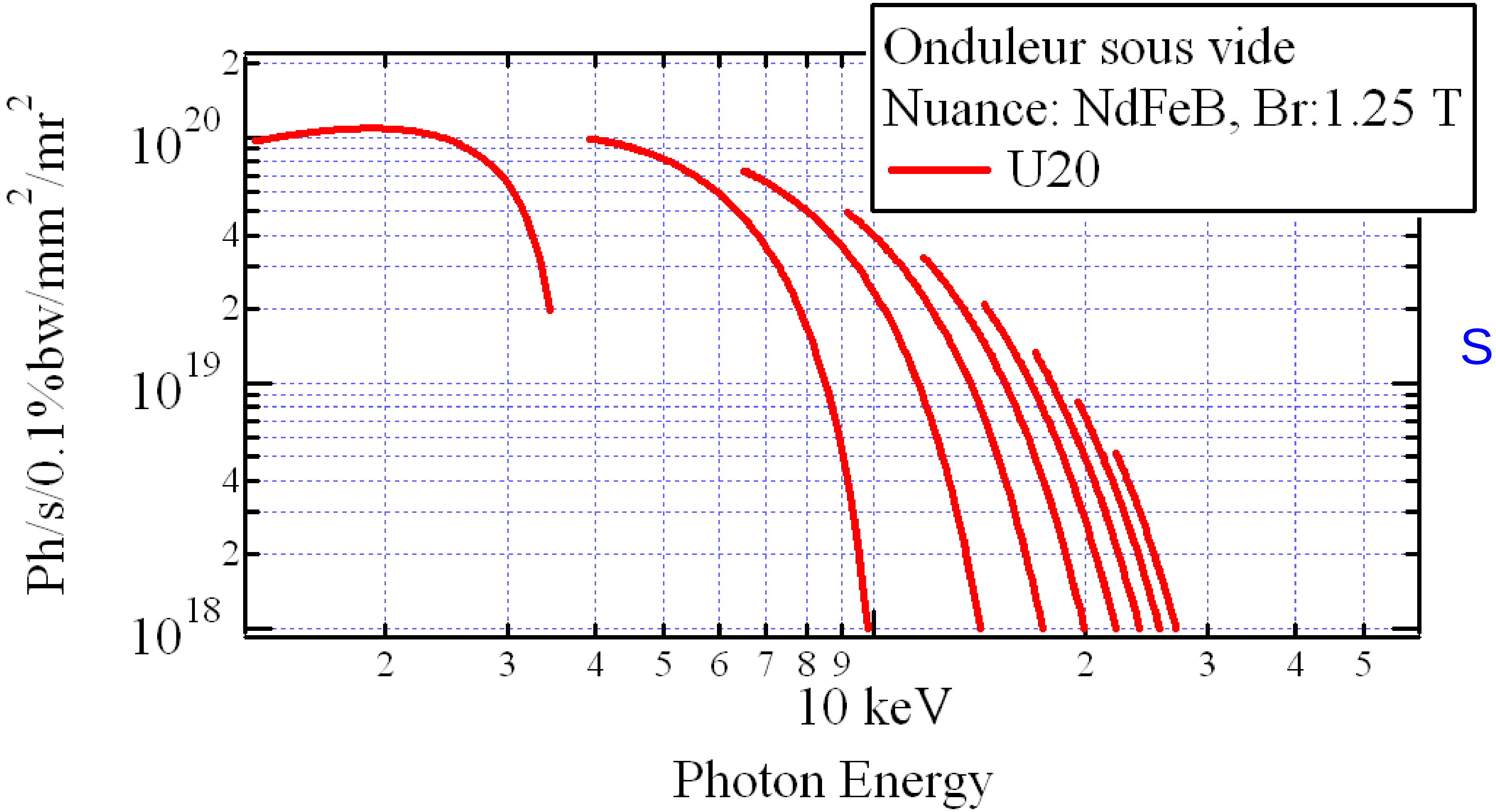
Undulator Synchrotron radiation

The energy (or wave length) of the emitted photons can be finely tuned by varying the magnetic field (gap or current) in the undulator



Undulator Synchrotron radiation

The energy (or wave length) of the emitted photons can be finely tuned by varying the magnetic field (gap or current) in the undulator



SOLEIL

SOLEIL SYNCHROTRON

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- ❑ What is a beamline ?
- ❑ Examples of application
- ❑ Main facilities existing and in project : ESRF, SOLEIL, DIAMOND, SLS, ELETTRA, BESSSY II, ALBA, PETRA3, NSLSII, MAXIV

Synchrotron radiation

Synchrotron radiation properties :

Broad Spectrum which covers from IR to hard X-rays.

White source (Bending magnets) or Narrow spectrum **tunable** (Undulators)

High Flux: high intensity photon beam

Flux = Photons / (s x 0.1% BW)

High Brilliance (Spectral Brightness): highly collimated photon beam generated by a small divergence and small size source (partial coherence)

Brilliance = Photons / (s x mm^2 x mrad^2 x 0.1% BW)

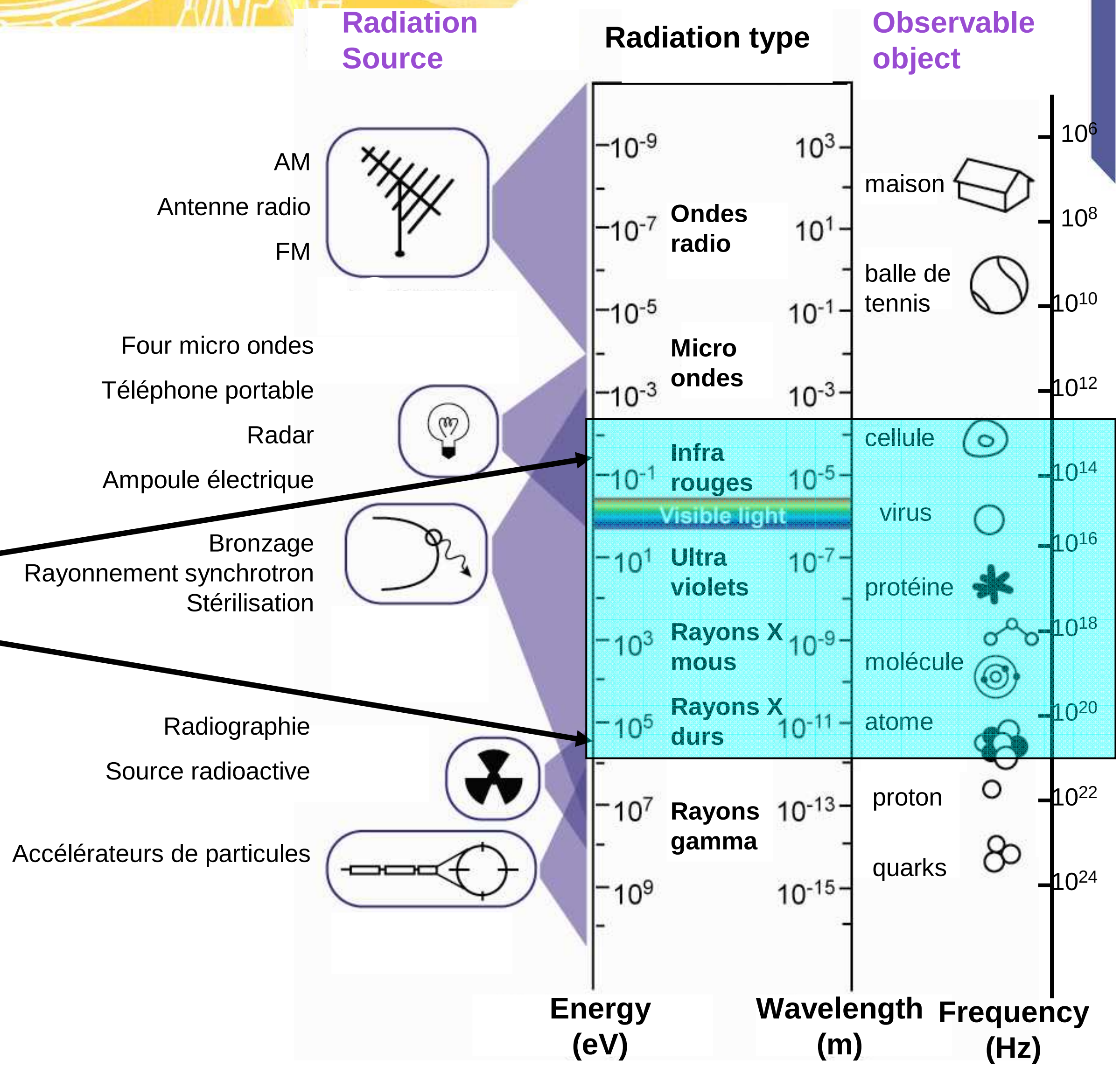
Polarisation: both linear and circular (tunable with IDs)

Pulsed Time Structure: pulsed durations down to tens of picoseconds

Synchrotron radiation

From **FAR INFRA RED**

Up to **HARD X RAYS**



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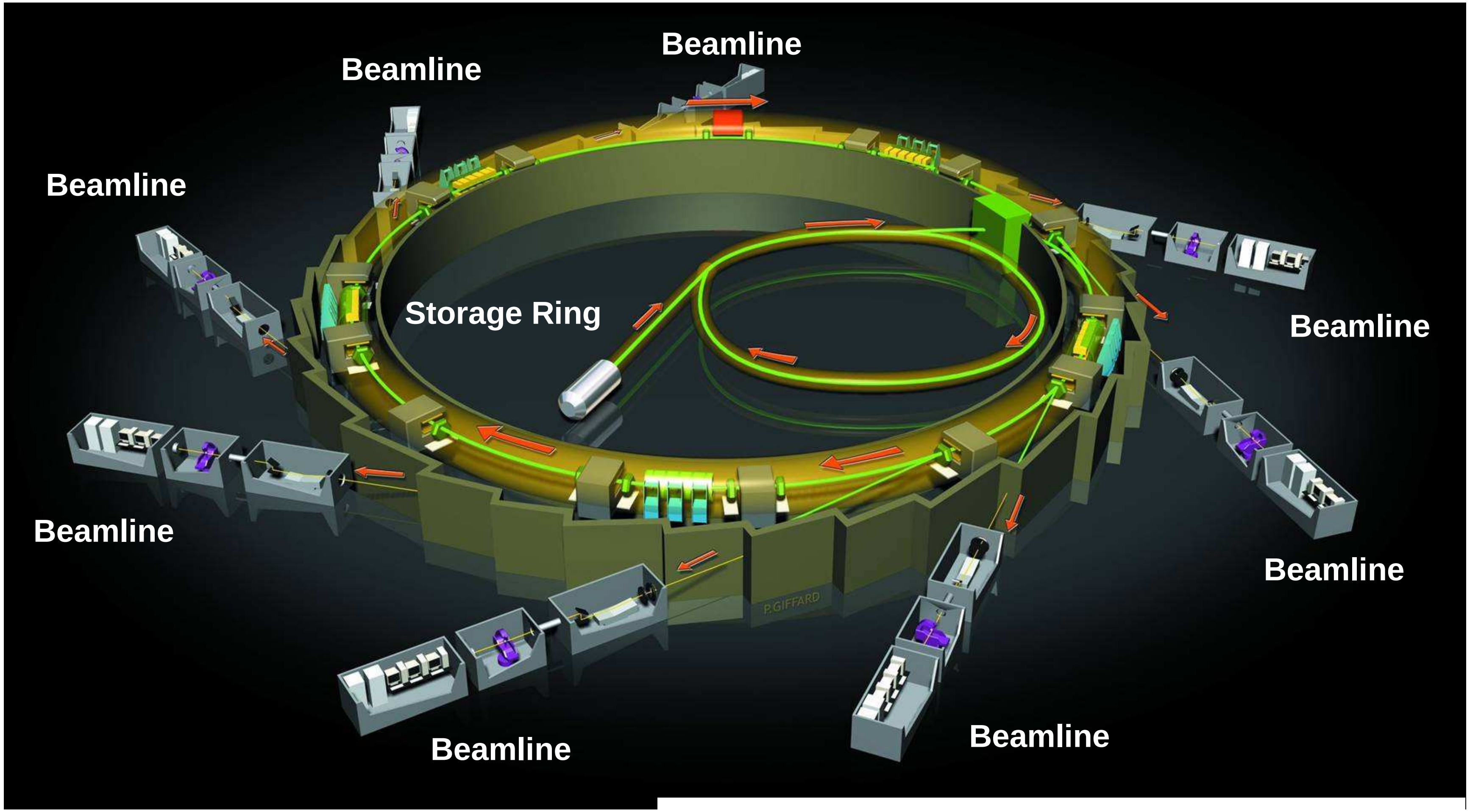
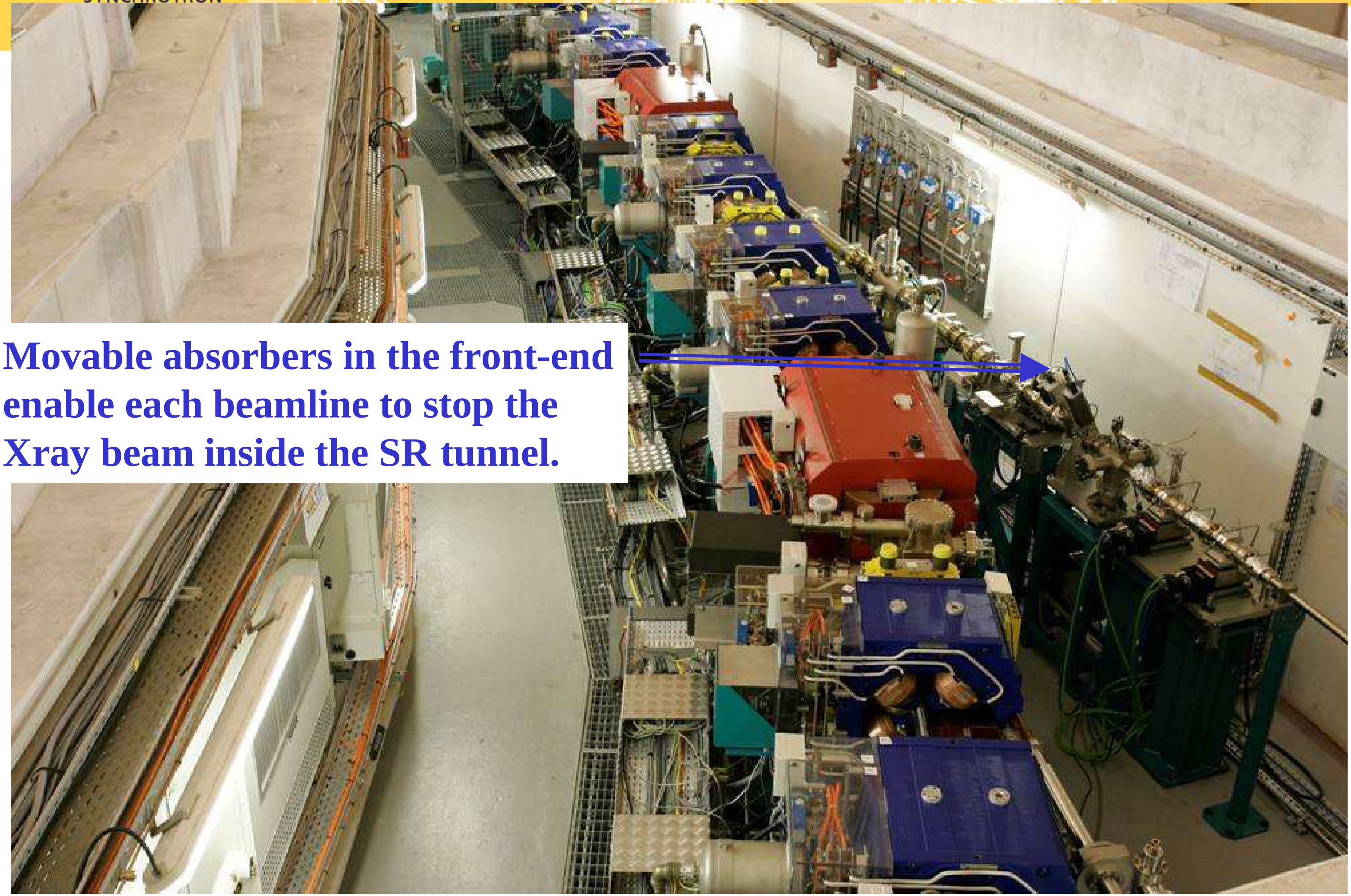
Synchrotron radiation facility



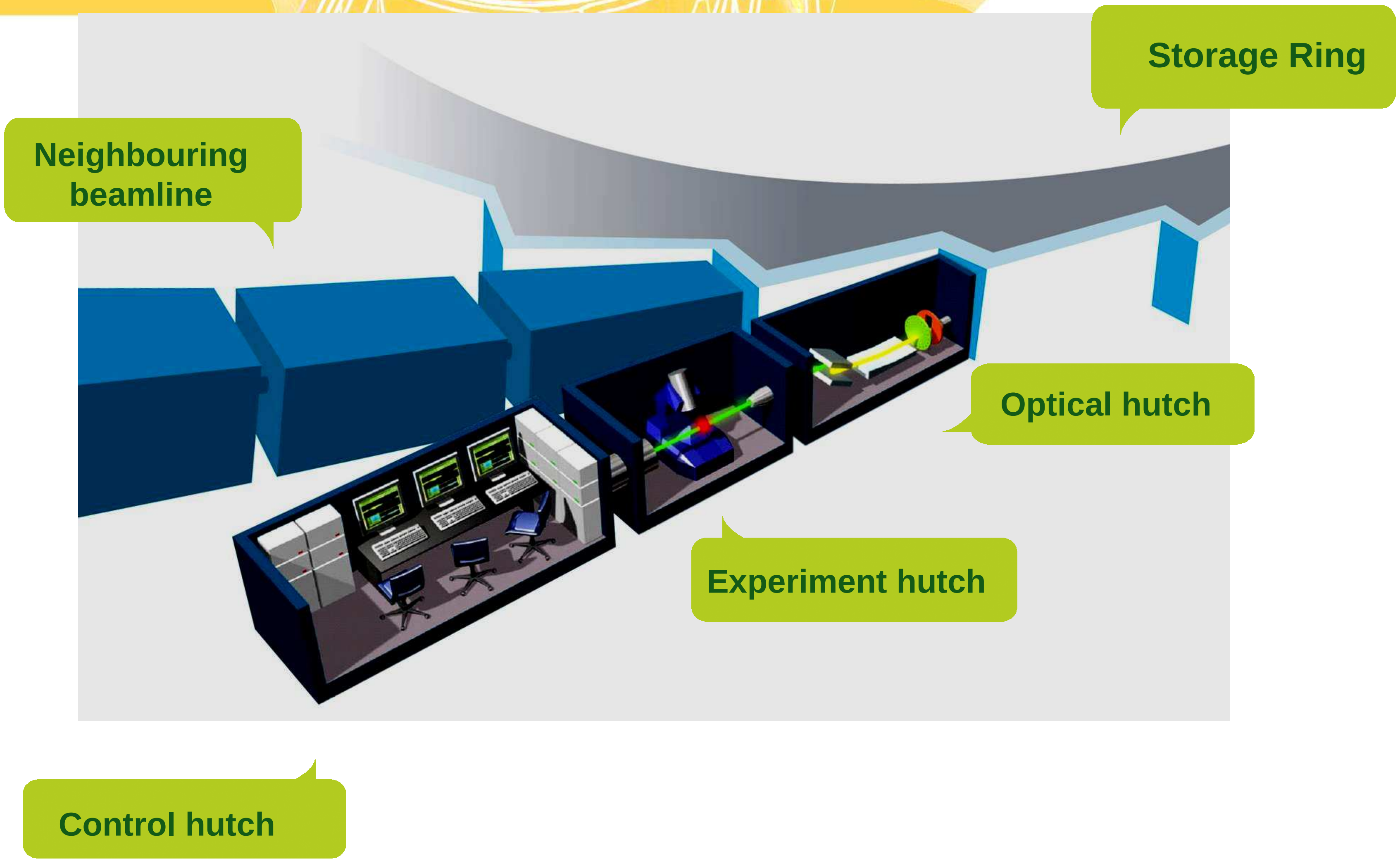
All beamlines get beam simultaneously

Synchrotron radiation facility

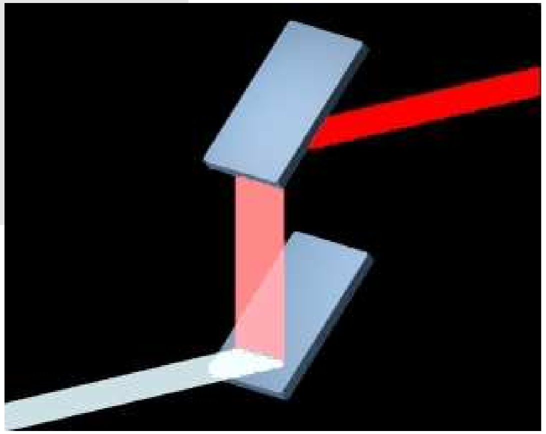


Movable absorbers in the front-end enable each beamline to stop the Xray beam inside the SR tunnel.

A Beamline = several hutches

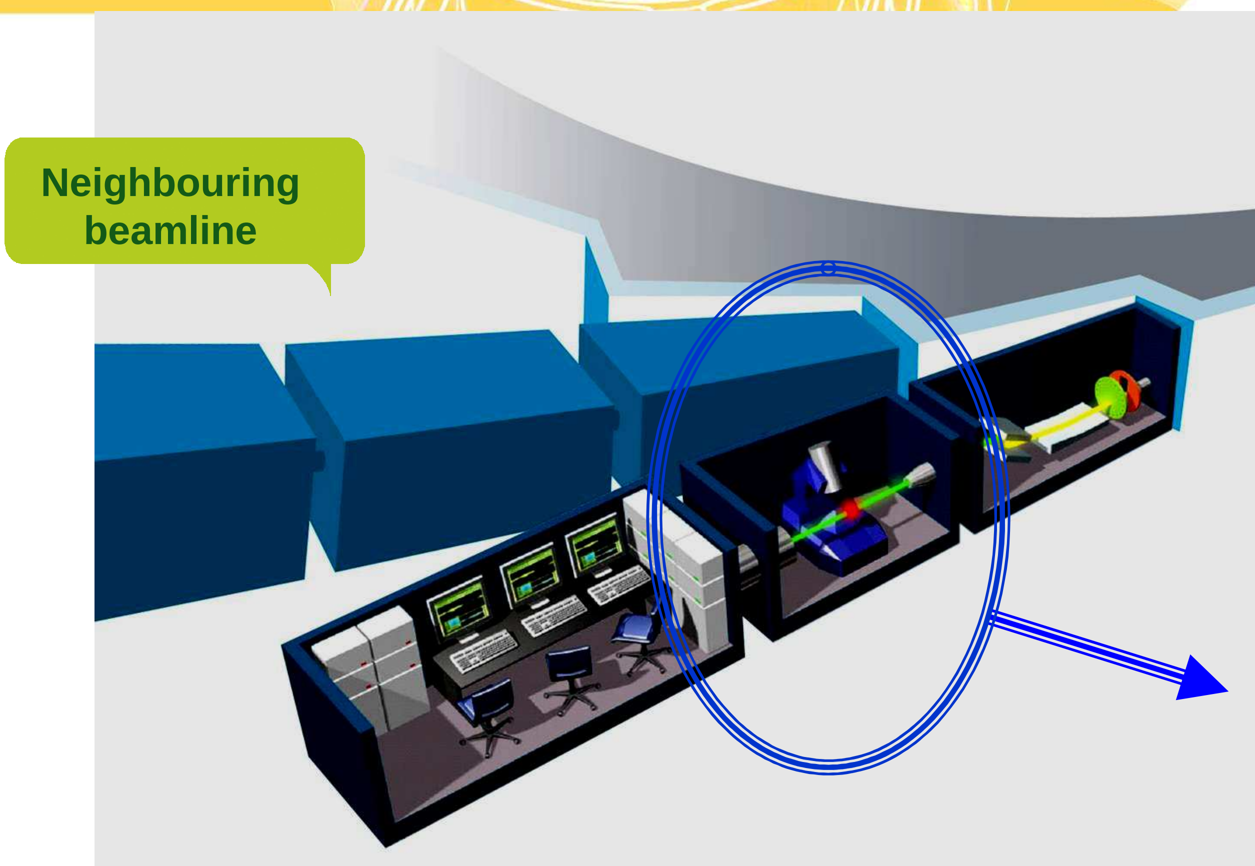


A Beamline = several hutches



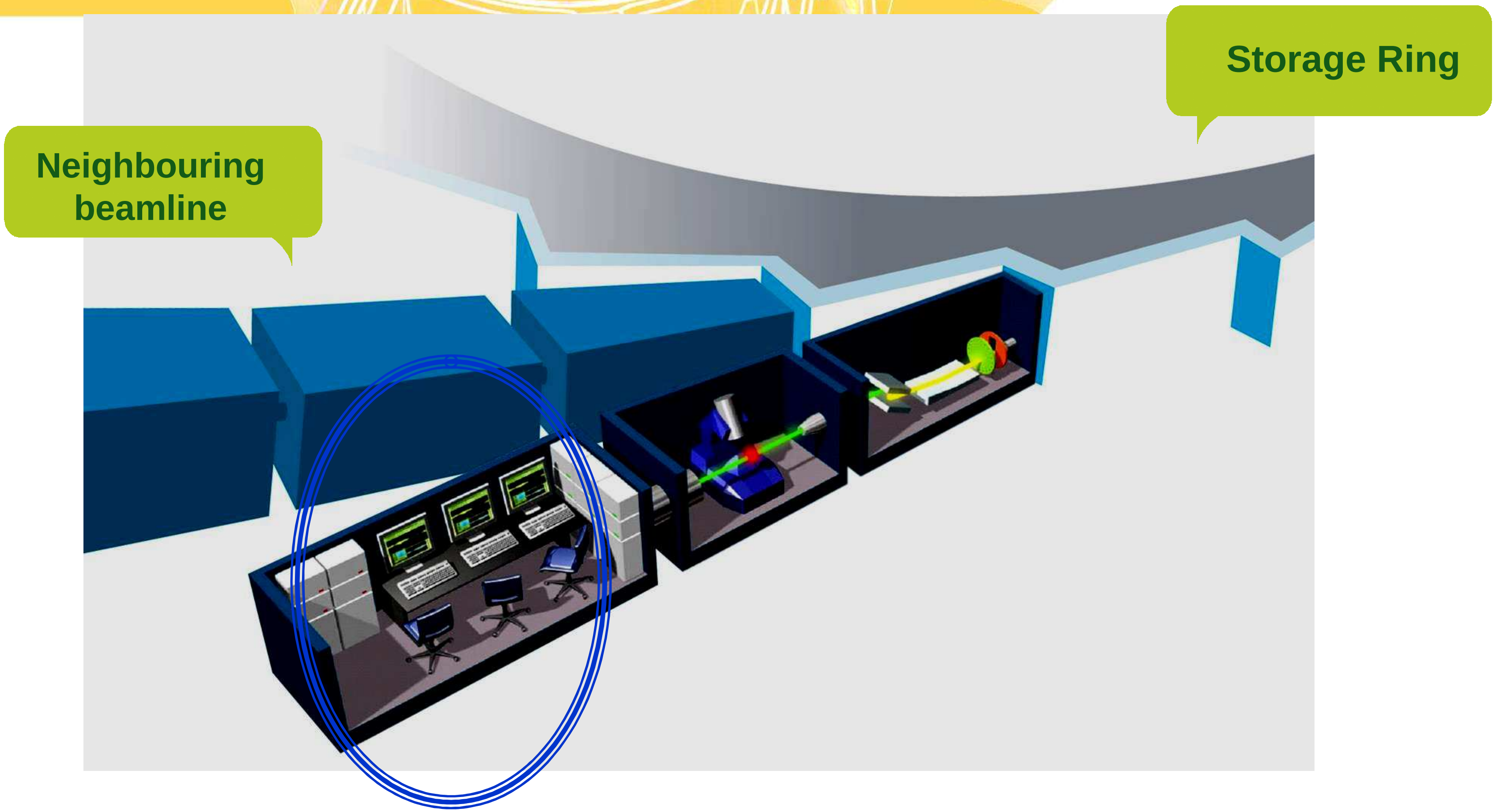
Optical hutch : where the photon energy is selected, the Xray beam focused =>Monochromator, mirrors, slits
Lead shielding required to stop bremsstrahlung from SR tunnel

A Beamline = several hutches



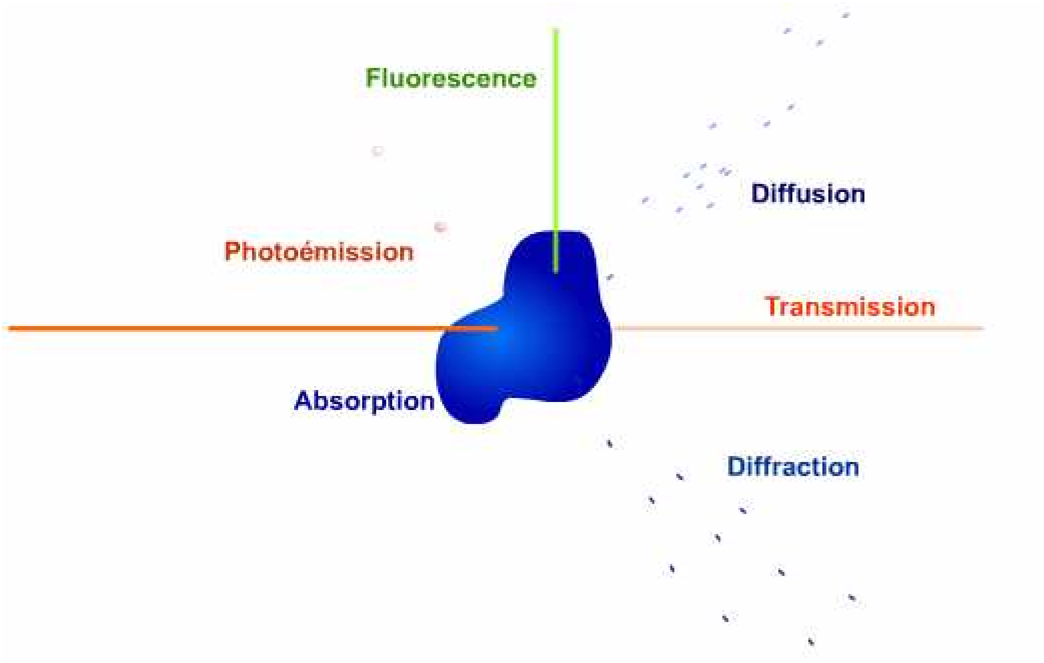
Experimental hutch : where the sample is exposed to SR
=> Goniometer, diffractometer, detectors,..
Lead shielding required if E_{xray} > ~5 keV

A Beamline = several hutches



Control hutch : where the scientists control the experiment
Computers, storage disks (up to Gbit/sec !),.. Coffee machine

Interaction of light in matter

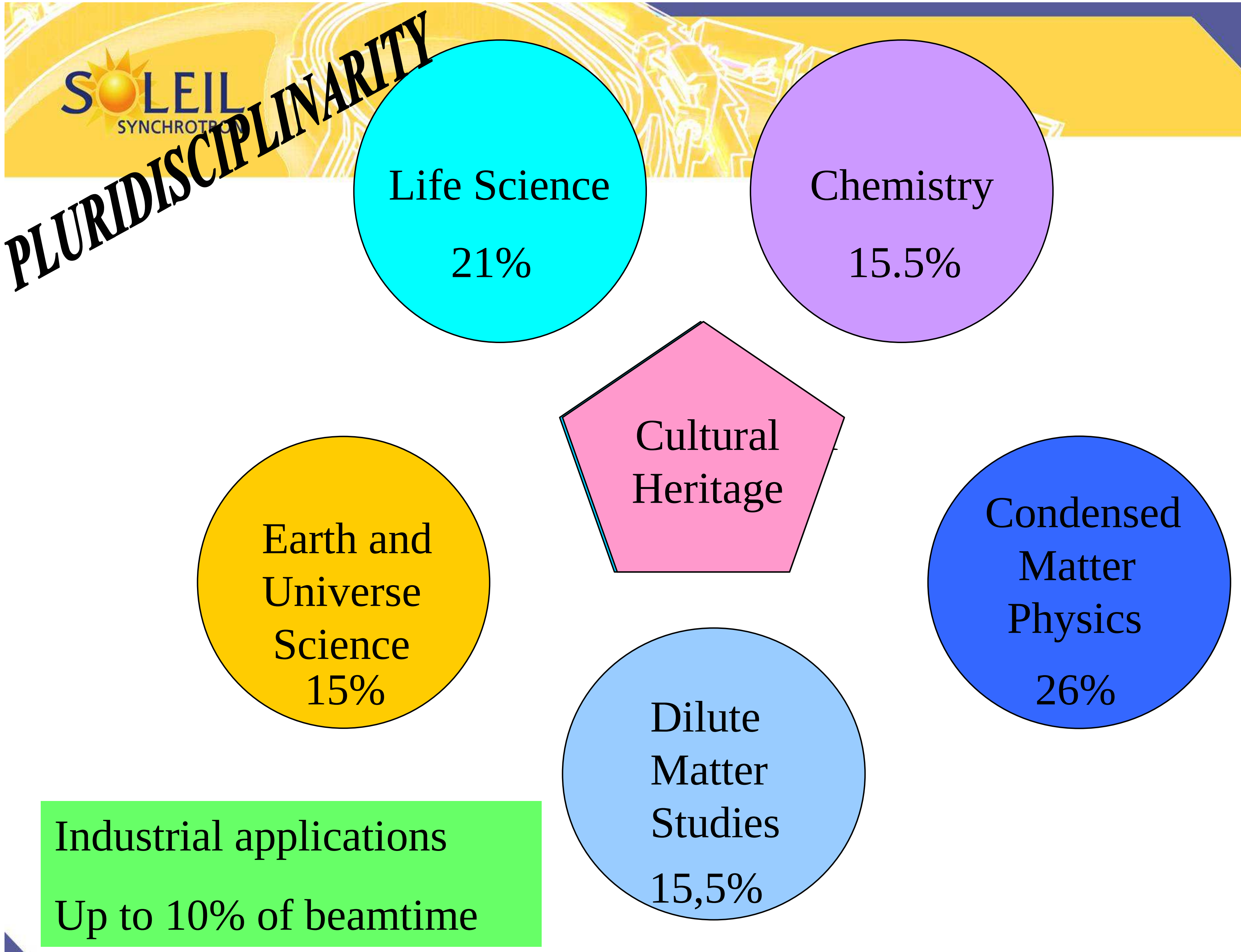


SYNCHROTRON SPECIFICITIES:
- Enhanced performances in fluorescence, in diffraction and in Xray micro-tomography

- specific techniques in Xray absorption and Xray microscopy (energy scanning, phase contrast)

These techniques enable to analyse

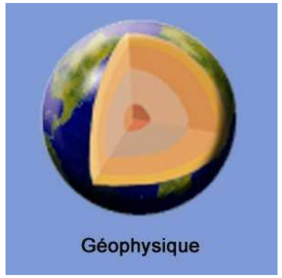
- **the chemical composition (with ultra high sensitivity)**
- **the atomic order, or the type of chemical bonding,**
- **…**

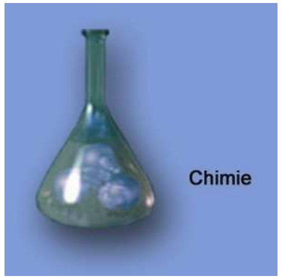

PLURIDISCIPLINARITY
Life Science
21%
Chemistry
15.5%
Cultural
Heritage
Earth and
Universe
Science
15%
Condensed
Matter
Physics
26%
Dilute
Matter
Studies
15,5%
Industrial applications
Up to 10% of beamtime

Fields of application

Détection de substances polluantes, optimisation de pôts catalytiques, nouveaux matériaux…

Connaissance de la structure des matériaux du manteau terrestre…

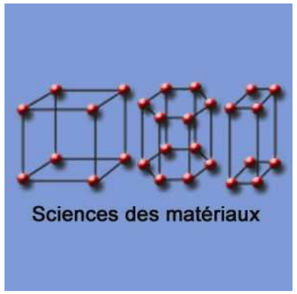


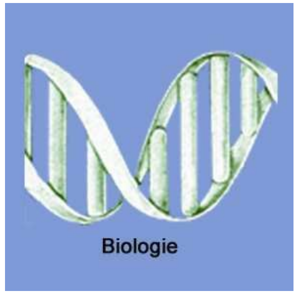


Procédés catalytiques, exploration de la matière et connaissance de ses propriétés électroniques, magnétiques (ex: stockage magnétique haute densité)

Recherche de nouveaux médicaments, imagerie des tissus osseux, vaisseaux sanguins, étude de l'ADN...

Élaboration de nouveaux matériaux, (ex : semi et supra conducteurs, disque durs et mémoire magnétique,batteries, étude de la prise rapide de ciment)



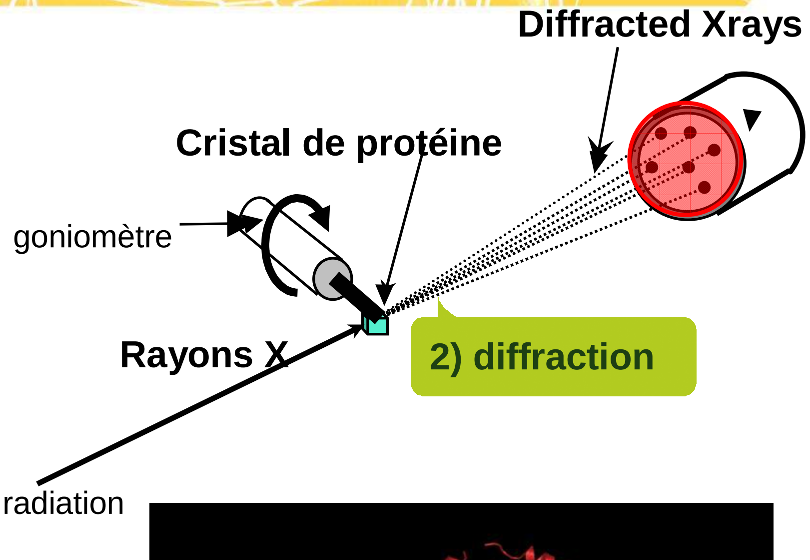


Dans tous les domaines, un large accueil est prévu pour les industriels

Archéologie, patrimoine, aéronautique, pharmacologie, microélectronique…

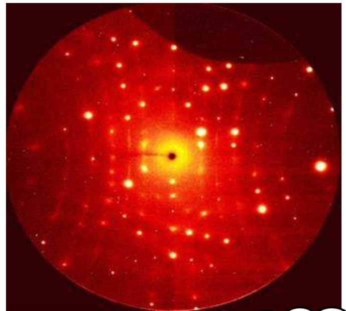
Protein crystallography

1) Frozen cristal

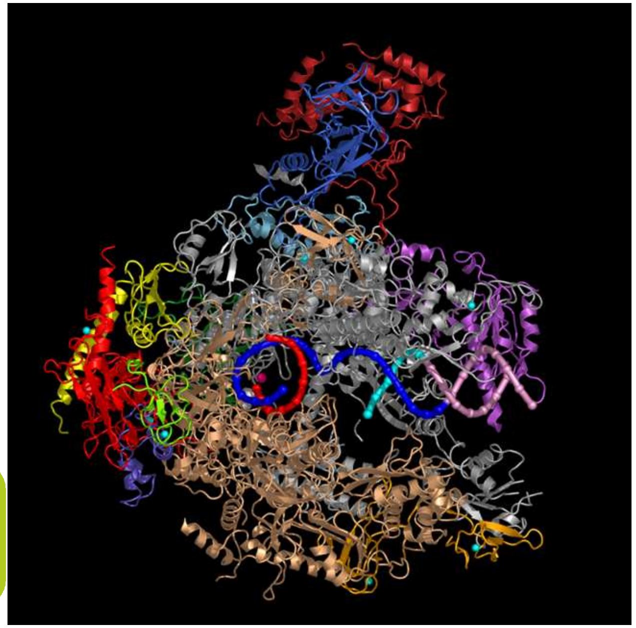


2) diffraction

3) Laue patterns recording



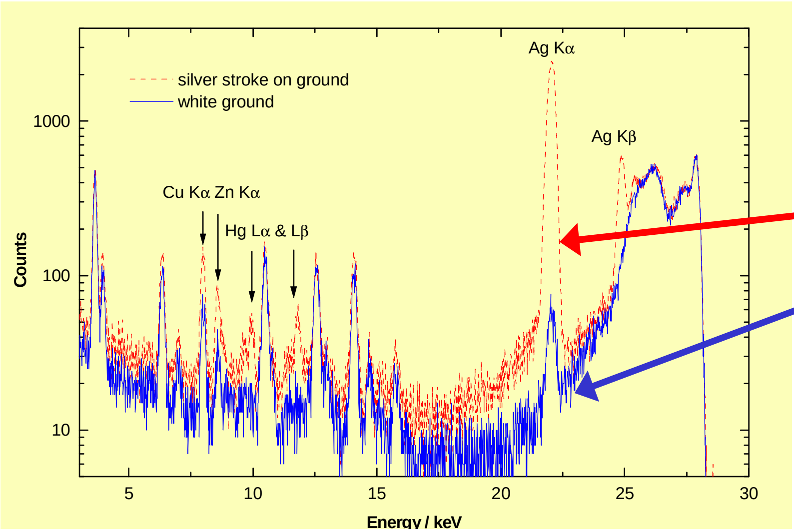
4) Data processing



5) Protein Structure

Millions of atoms !

Painter authentification : Durer

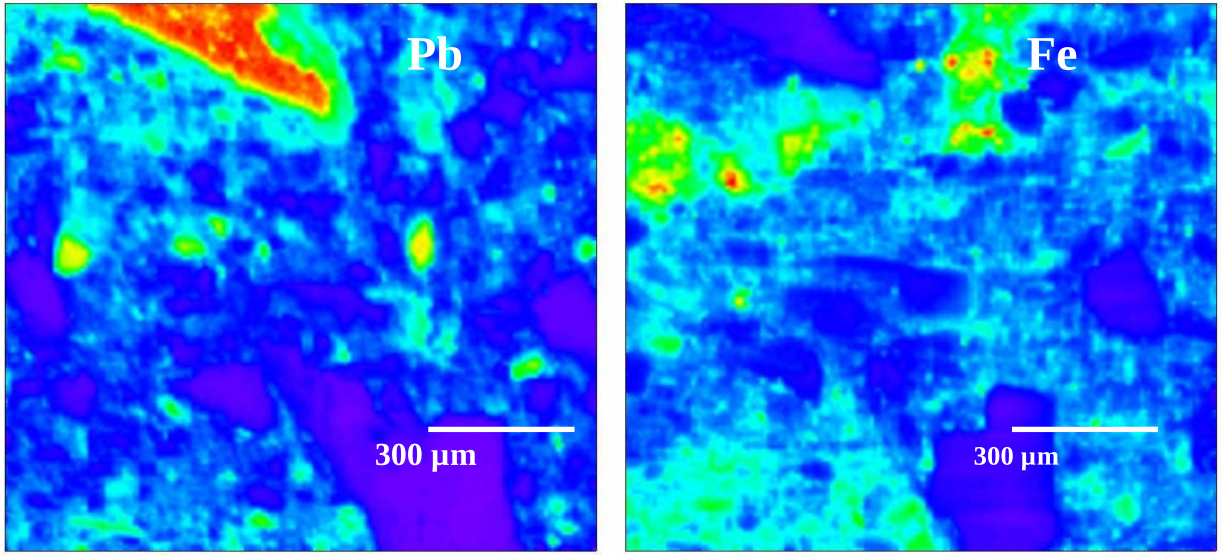


I. Reiche et al. CRRMF

From the analysis of micro samples =>

Composition of the pen : silver + copper , Traces of mercury : impairing phenomenon

Environmental science



Microfluorescence mapping of polluted soil:
spatial correlation between concentrations of lead and iron in the soil of a shooting stand
(D. Vantelon et R. Kretzschmar)

High sensitivity to identify week traces of material

Complex multi-layered varnishes on historical musical instruments

- Varnishes often present a complex structure of layers often thinner than 10-20 µm (mixture of organic (oils, natural resins,…) and inorganic (pigments, siccatives,…) materials.

- re-create an ideal ancient varnish, typically the one of Antonio Stradivari

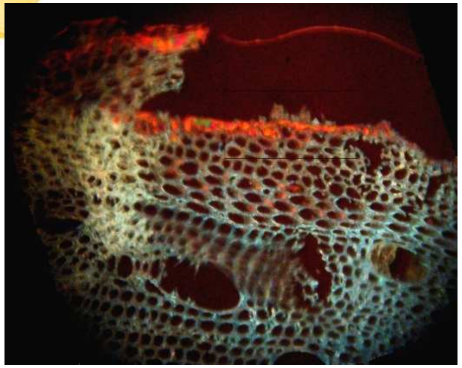
- **The IR microscope at SMIS** has a complementary fluorescence accessory, which helps identifying the region of interest (a)

- Presence of protein has been identified through its characteristic **IR spectrum** (b)
- One of layer is made of protein (c)

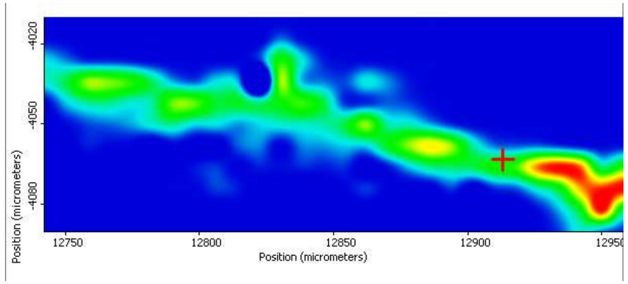
- **This is the first time a protein layer has been identified in a ancient violin multilayers**

Dr J.P. Echard** (Cité Musique Paris)* ***Dr.Loïc Bertrand** (SOLEIL)* , ***Dr.A.S Le Hô (SOLEIL), ***Dr.S. Vaiedelich*** (Cité Musique) ***Dr. S. Le Conte*** (Cité Musique). ***Alex VON BOHLEN*** (Germany)

(a)



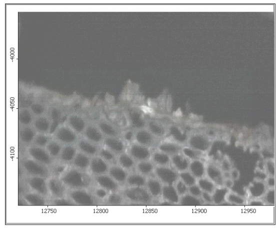
(b)



3500 3000 2500 2000 1500 1000

Wavenumbers (cm-1)

(c)

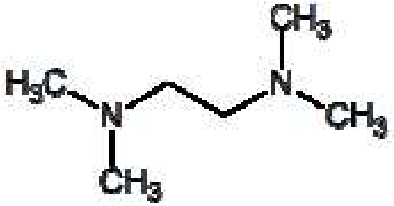


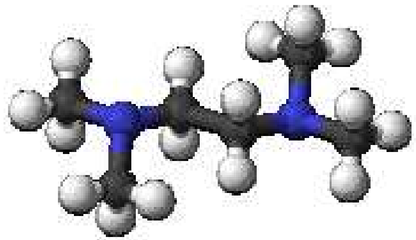
50 µm

Surface reaction kinetics

Time dependent study of the adsorption modes for the

N,N,N',N' Tetra methyl ethylenediamine on Si(001)-2×1



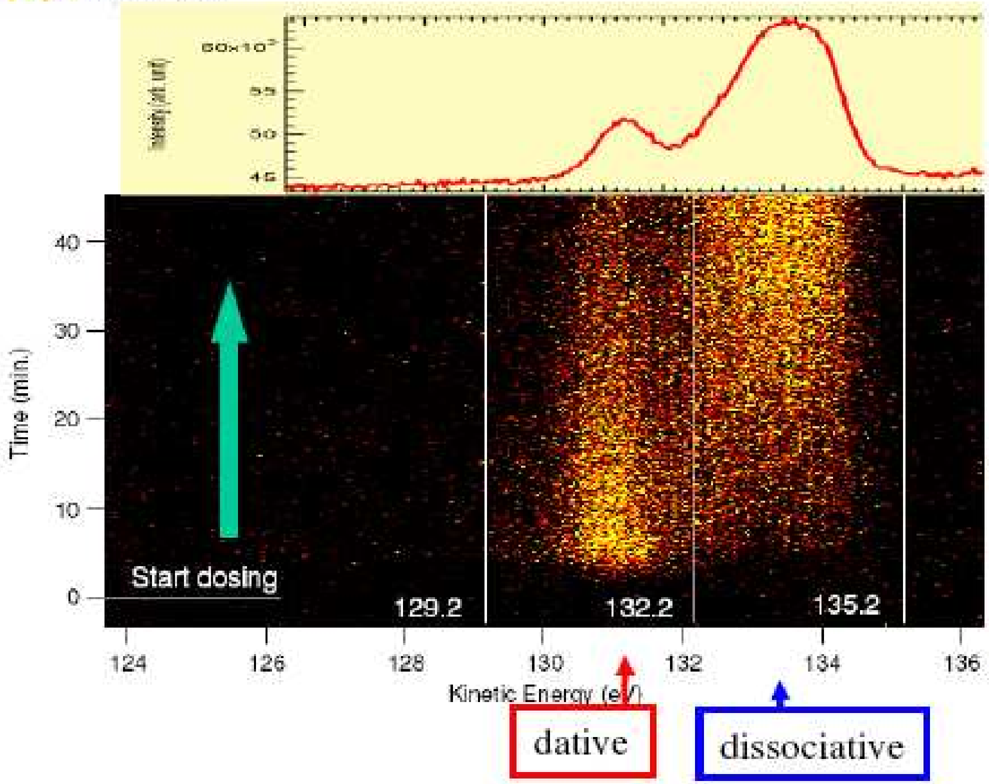


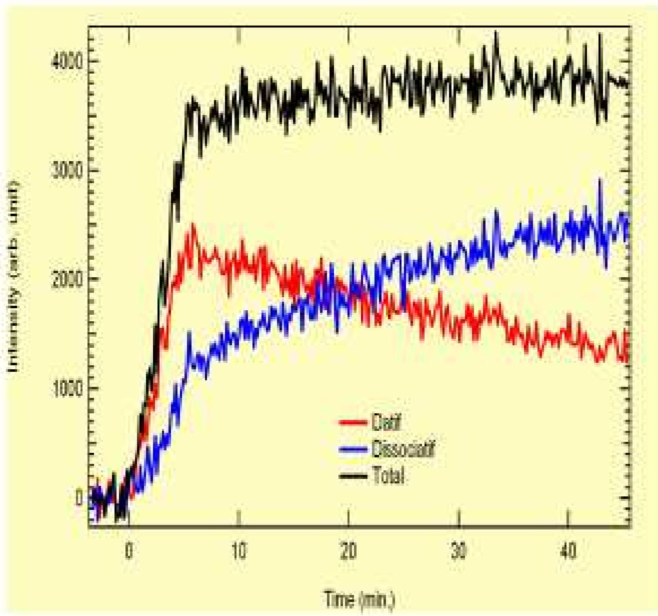
2 possible adsorption configurations on Si

C.Mathieu, J.-J. Gallet,
F. Bournel, G. Dufour, F. Rochet

LCPMR

Surface reaction kinetics





N - 1s Photoemission spectra
Integration time 0.5 s
Binding energy variation: 2 eV

Time Evolution:
Constant Nitrogen amount
Transformation :
Dative → dissociative
During exposure

TEMPO

LCPMR

Existing 3rd GLS

1992	**ESRF**, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	**TLS,** Taiwan	1.5 GeV
1994	**ELETTRA**, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	**APS**, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	**Spring-8**, Japan	8 GeV
1998	**BESSY II**, Germany	1.9 GeV
2000	**ANKA**, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	**SPEAR3**, US	3 GeV
	CLS, Canada	2.9 GeV
2006:	**SOLEIL**, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV

3rd GLS under construction

under construction or planned

2009	**ALBA**, Spain	3 GeV
	Petra-III, Germany	6 GeV
> 2009	**NSLS-II**, US	3 GeV
	SESAME, Jordan	2.5 GeV
	MAX-IV, Sweden	3 GeV
	TPS, Taiwan	3 GeV
	CANDLE, Armenia	3 GeV

3rd GLS under construction

The 3rd Generation Light Sources can be sorted in 2 categories :

The medium size / low energy Storage Rings

⇒ Circumference = 100 to 300 m,

⇒ Energy = 1 to 3 GeV

⇒ X-Ray energy = 10 eV to 30 keV

The large size / high energy Storage Rings

⇒Circumference = 800 to 1300 m,

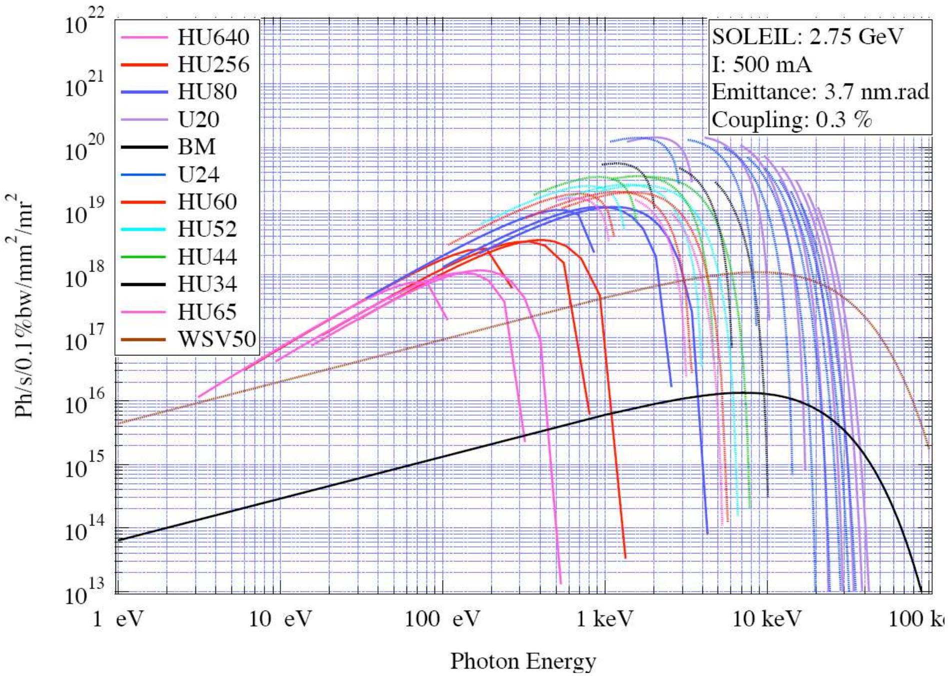
⇒ Energy = 6 to 8 GeV

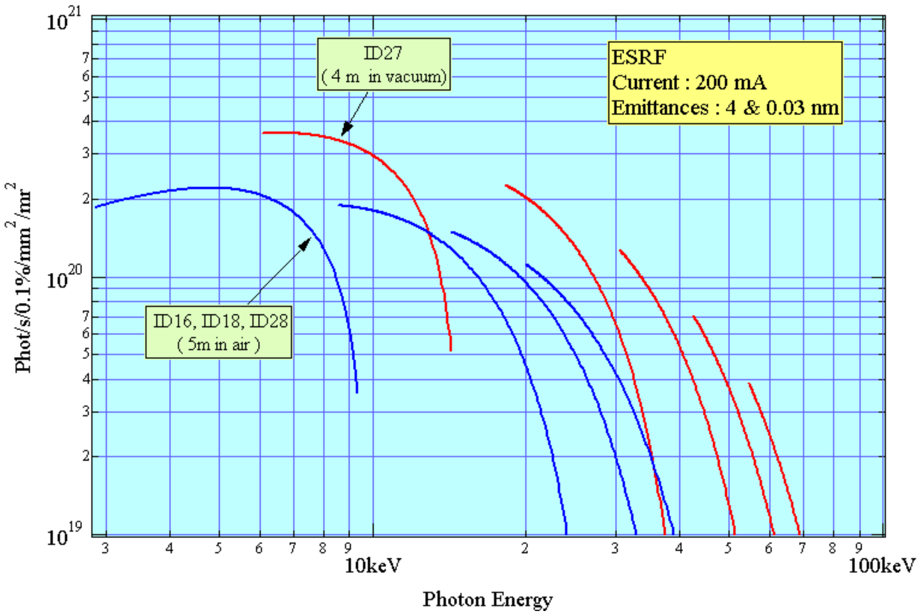
⇒ X-Ray energy = 0.1 to 300 keV

ESRF (Grenoble, France), APS (Chicago, USA), SPRING8 (Hyogo,Japan) **,**

Brilliance

Thanks to the progress with IDs technology storage ring light sources can cover a photon range from few tens of eV to tens 10 keV or more with high brilliance





Medium energy storage rings with In-vacuum undulators operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of 10^{20} ph/s/0.1%BW/mm²/mrad²