ESI2013: **3rd EIROforum School on Instrumentation**

An Introduction to Synchrotron Radiation

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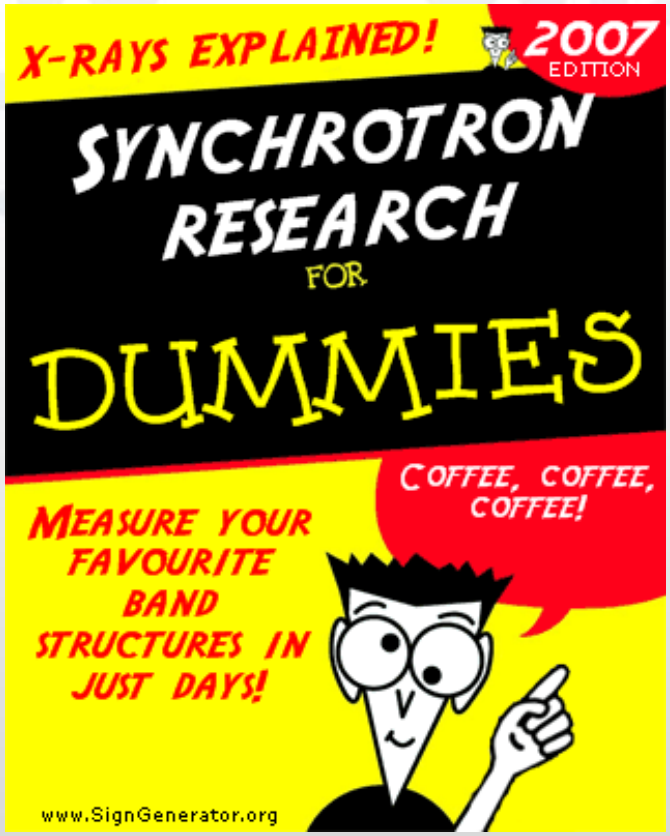
Outline

Part I

Introduction
to
synchrotron radiation
(SR)



Part II

SR Research

Mostly Illustrated by examples from the ESRF

Outline

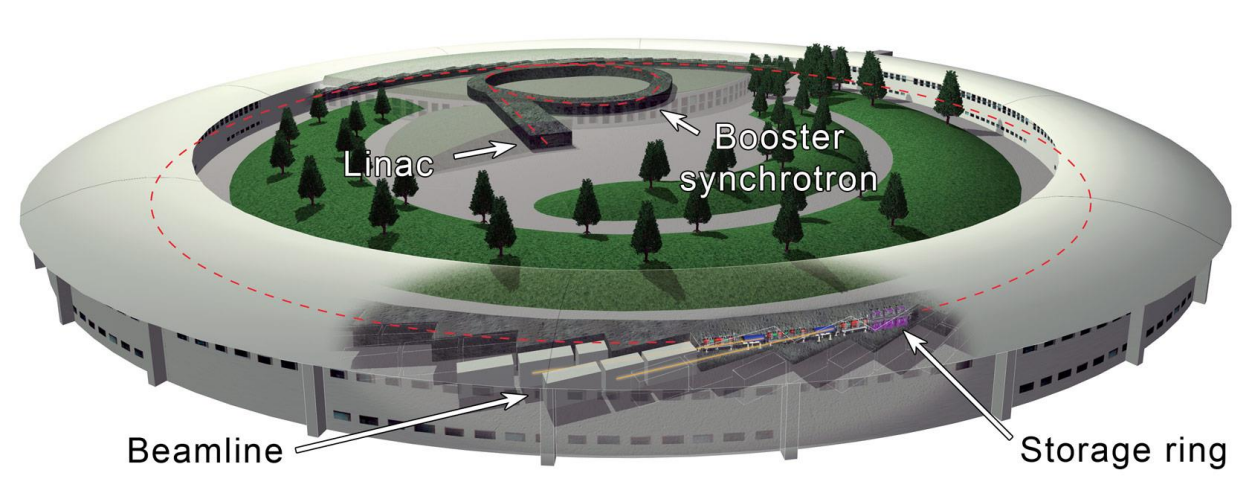
PART I

Introduction to synchrotron radiation

1. Origin and physics
2. Historical evolution
3. Synchrotron radiation facilities
4. Three forms of synchrotron radiation
5. Sources and their operation

What's a synchrotron radiation source?

- An extremely intense source of X-rays (also IR & EUV)
  - Typically produced by highly energetic electrons (or positrons) moving in a large circle in the synchrotron (or more usually Storage Ring).



•Highly collimated X-rays are emitted tangentially to the storage ring and simultaneously serve multiple beamlines for scientific applications spanning physical, chemical and life sciences

Origin of synchrotron radiation

The Crab Nebula – a natural SR source
CHANDRA (2001)

L. Shklovsky (1953)

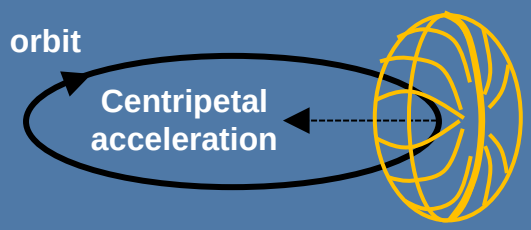
- Synchrotron radiation is electromagnetic energy emitted by charged particles (e.g., electrons and ions) that are moving at speeds close to that of light when their paths are altered, e.g. by a magnetic field.

- It is thus termed because particles moving at such speeds in particle accelerators known as a synchrotrons produce electromagnetic radiation of this type.

Basic Principles

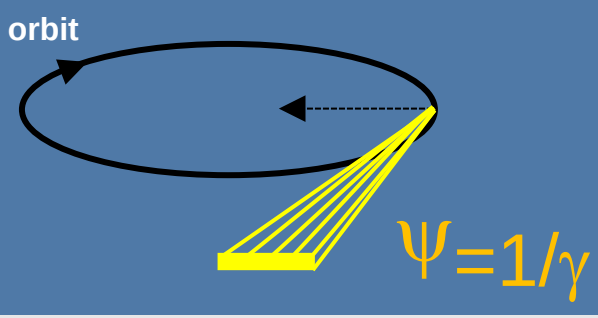
Classical case

v* << *c

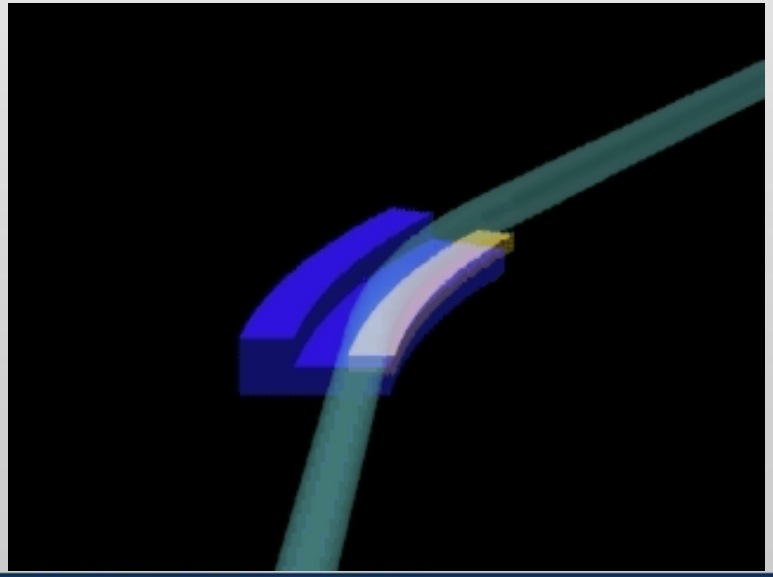


Relativistic case

v* ~ *c



Isotropic emission



Emission concentrated within a narrow forward cone

$$\gamma = \frac{E_e}{mc^2}$$

E_e = 6 GeV (ESRF)

mc^2 = 511keV

Ψ = 10^{-4} rad = a few 10^{-3} deg

Man-made synchrotron radiation

1947

First observation of synchrotron radiation at General Electric (USA).

Considered first as a nuisance by particle physicists, synchrotron radiation was recognised in the 70s as having exceptional properties to explore matter.

EVOLUTION

1930

First particle accelerators

1947

First observation of synchrotron radiation

More and more energetic particles,

Bigger and bigger machines

1980

Construction of the first dedicated machines

Particle physics

Synchrotron radiation

3rd Generation Storage Rings

Timeline

1994
ESRF

1981
SRS

1968
Tantalus

1961
Parasitic use

1950'
Characterization

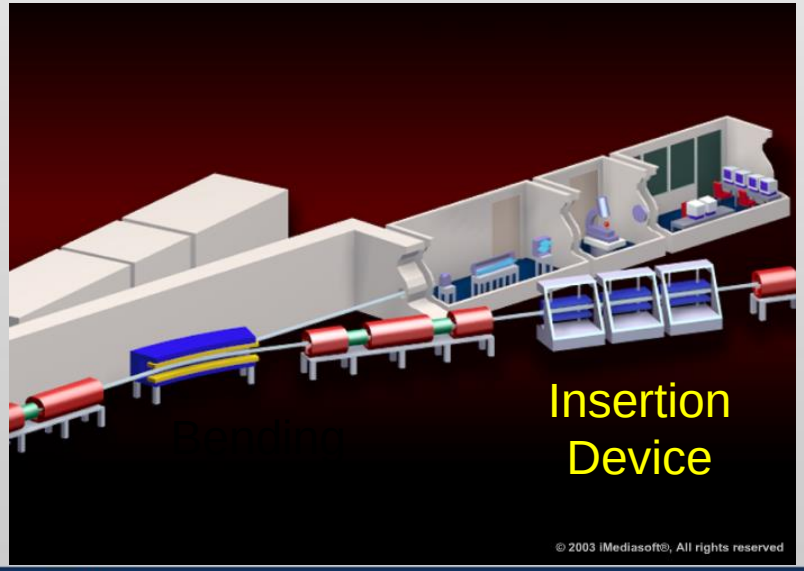
1947
Observation

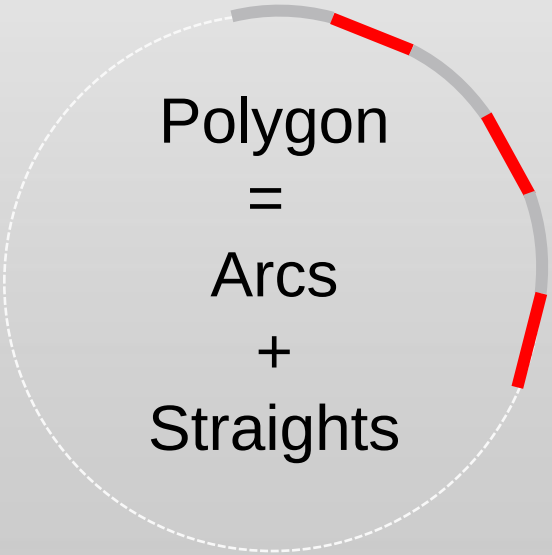
1897-1946
Predictions

ESRF

- Storage ring: 844 m circumf.
- 6 GeV electrons
- ~200 mA fill current
- Typical beam lifetime ~ 50 h
- Reinjection twice/day
- 24 hour operation 6 days/week

Fully optimized to produce bright X-ray beams





Synchrotron Radiation Sources

Major X-Ray sources in the world

ESRF was the world's first 3rd generation hard X-ray source

Other hard X-ray sources: APS (USA) - SPring-8 (Japan) – Petra-III (D)

New national sources in Europe: Swiss Light Source (CH), Soleil (F) in 2006, Diamond (UK) in 2007, Petra-III (D) in 2009, ALBA (E) in 2010, Max IV (Sweden), Poland, Russia.....

New plans also in Brasil, China, India, ...

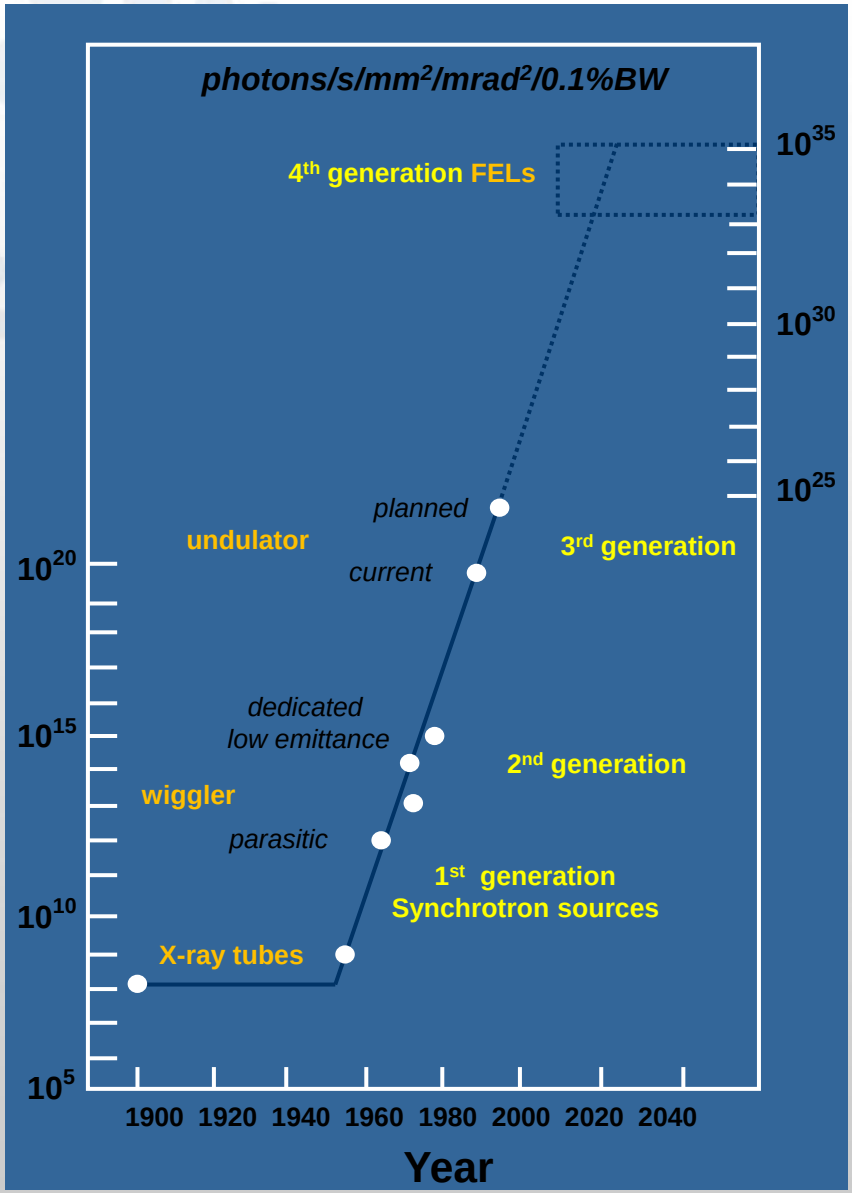
Figure of Merit of the source: brilliance

Brilliance or *Brightness* *(flux density in phase space) is an invariant quantity in statistical mechanics, so that* *<u>no optical technique can improve it</u>*.

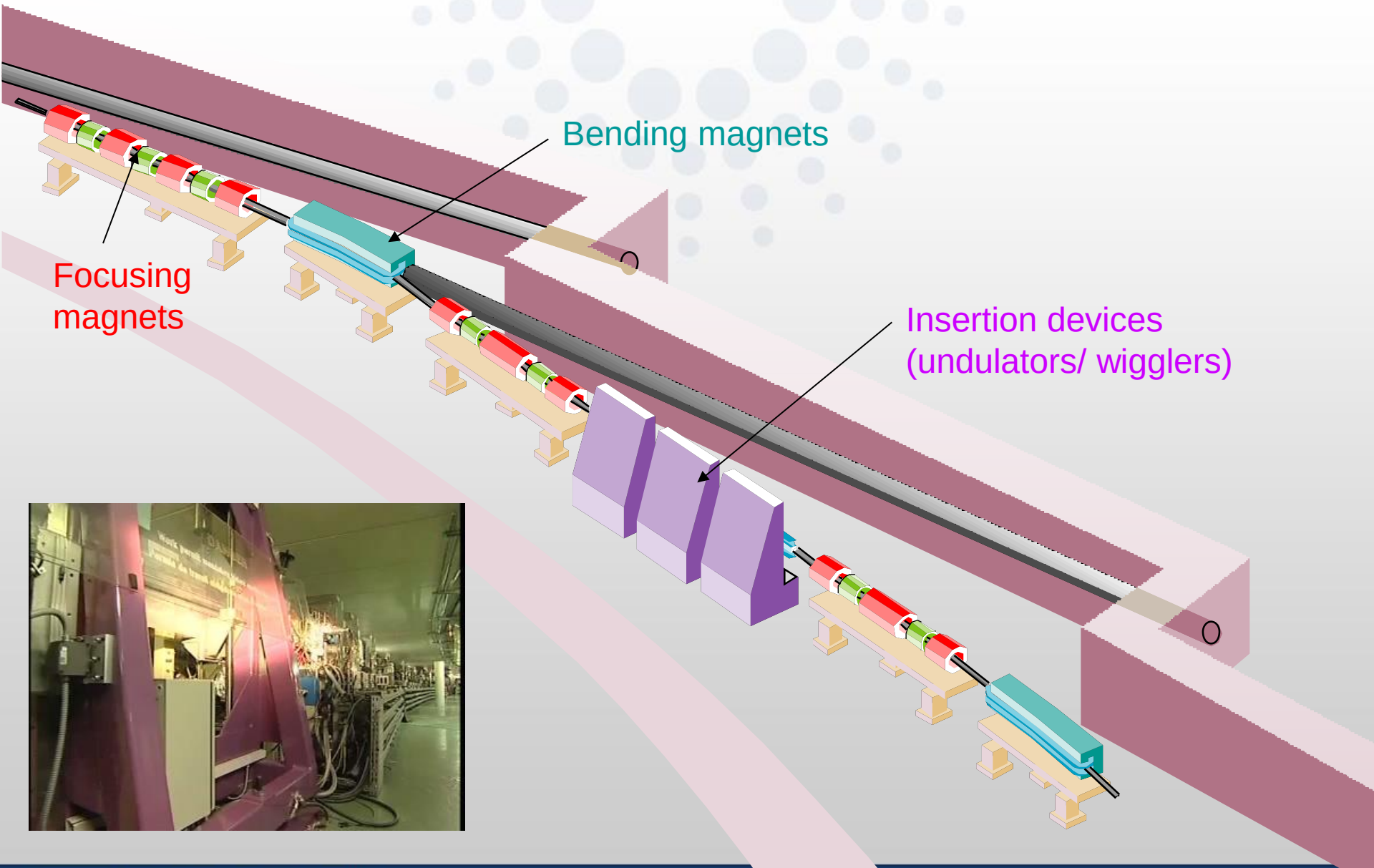
$$\text{Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta\Omega)}$$

$$\text{Spectral Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta\Omega)\,(\Delta\lambda/\lambda)}$$

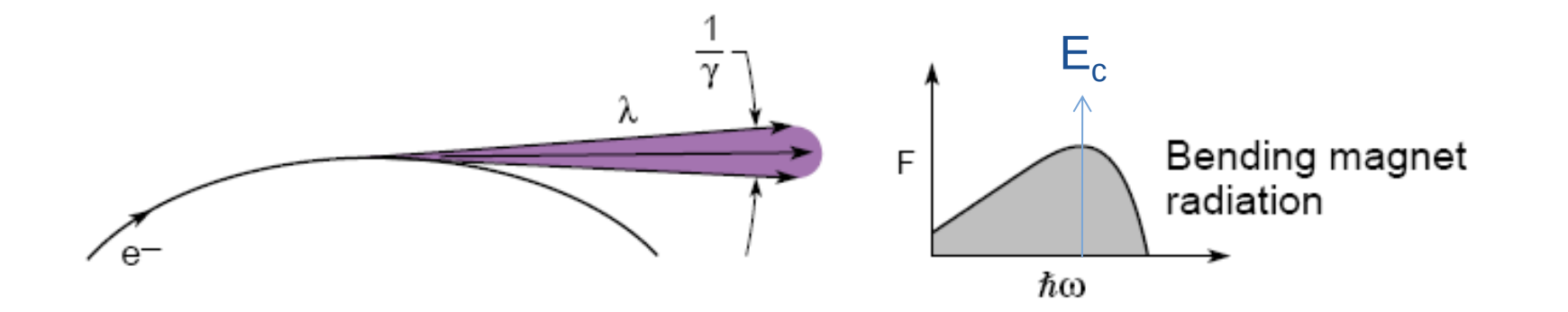
$$\frac{[\text{Photons/sec}]}{[\text{mm}]^2\,[\text{mrad}]^2\,[0.1\%\ \text{bandwidth}]}$$

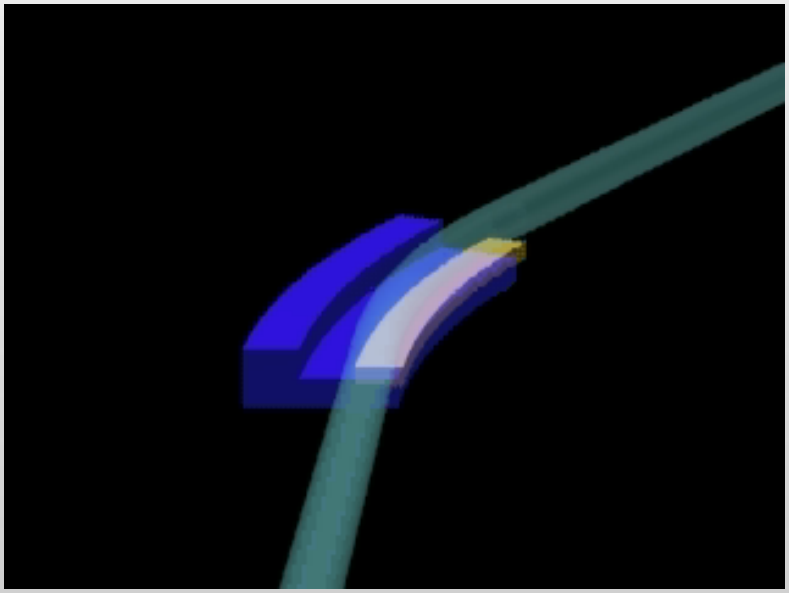


The ESRF storage ring



Bending Magnet Radiation



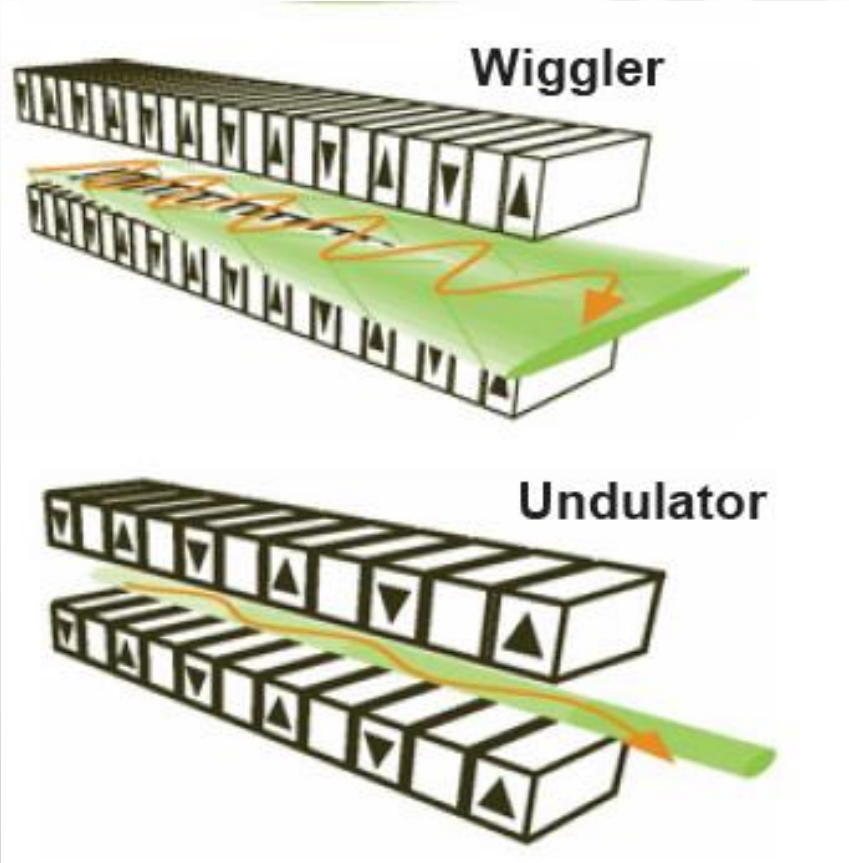


$$\gamma = \frac{E_e}{mc^2} = 1957 E_e(GeV)$$

$$E_c = \frac{3e\hbar B\gamma^2}{2m}$$

$$E_c(keV) = 0.665\, E_e^2(GeV)B(\mathrm{T})$$

Insertion devices



- *A Periodic magnetic field causes local oscillations of electron trajectory. The influence of the field on the electron motion is characterized by the deflection parameter K*

$$K=0.934\ \lambda_u\ [\mathrm{cm}]\ B_0\ [\mathrm{T}]$$

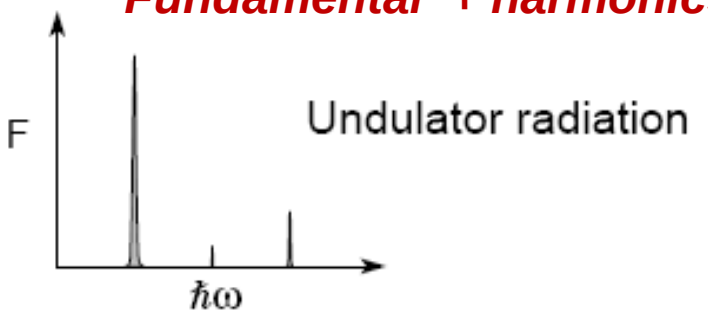
- The maximum angular deflection of the orbit is K/γ

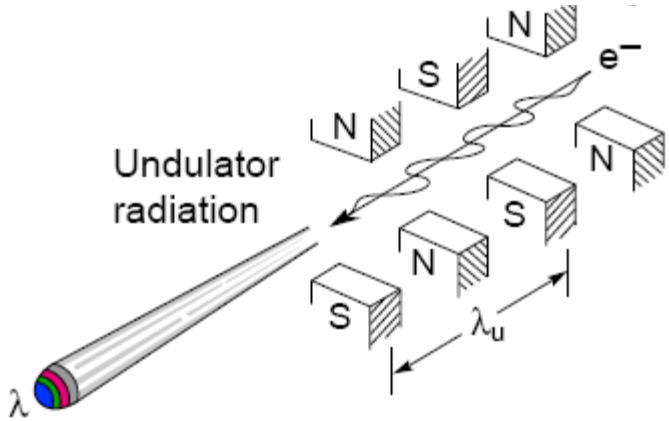
- $K >> 1$ Wiggler regime
  radiation from different parts of the electron trajectory adds <u>incoherently</u>
  → *interference effects are less important*

- $K < 1$ Undulator regime
  radiation from different periods interferes <u>coherently</u>
  → *strong interference phenomena*

Undulator Radiation – K< 1

Fundamental + harmonics



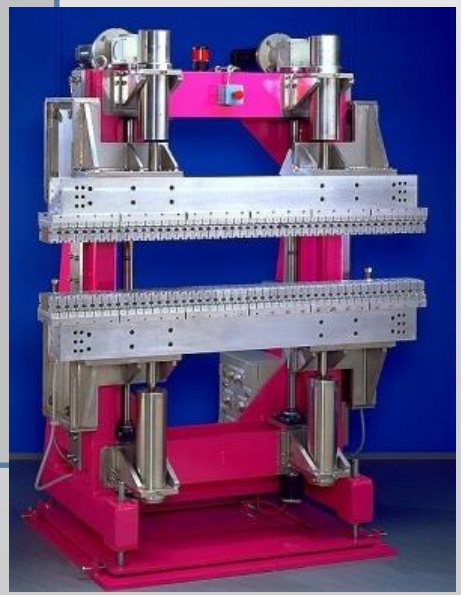


On-axis

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$E(keV) = \frac{0.949\, E_e^2(GeV)}{\lambda_u(cm)\left(1+\frac{K^2}{2}\right)}$$

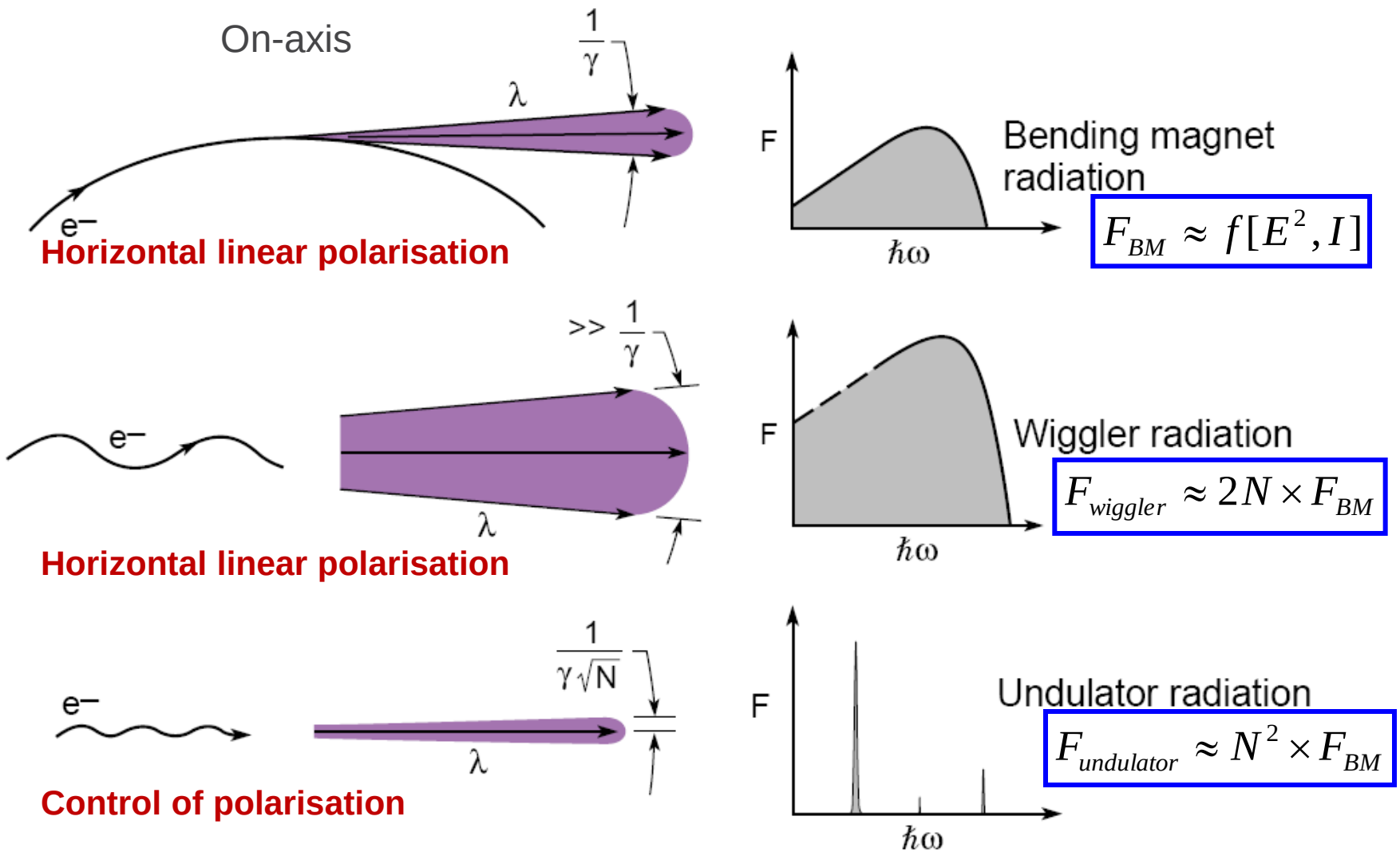
$$\frac{\Delta\lambda}{\lambda} = \frac{1}{N}$$



To tweak (or to scan) energy:

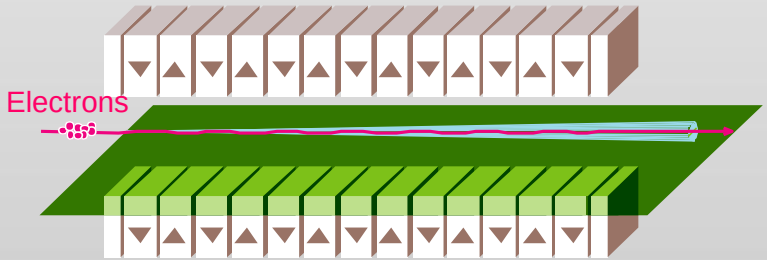
- E = *f* [K]
- K = *f* [B(z)]
- B(z) = *f* [gap]

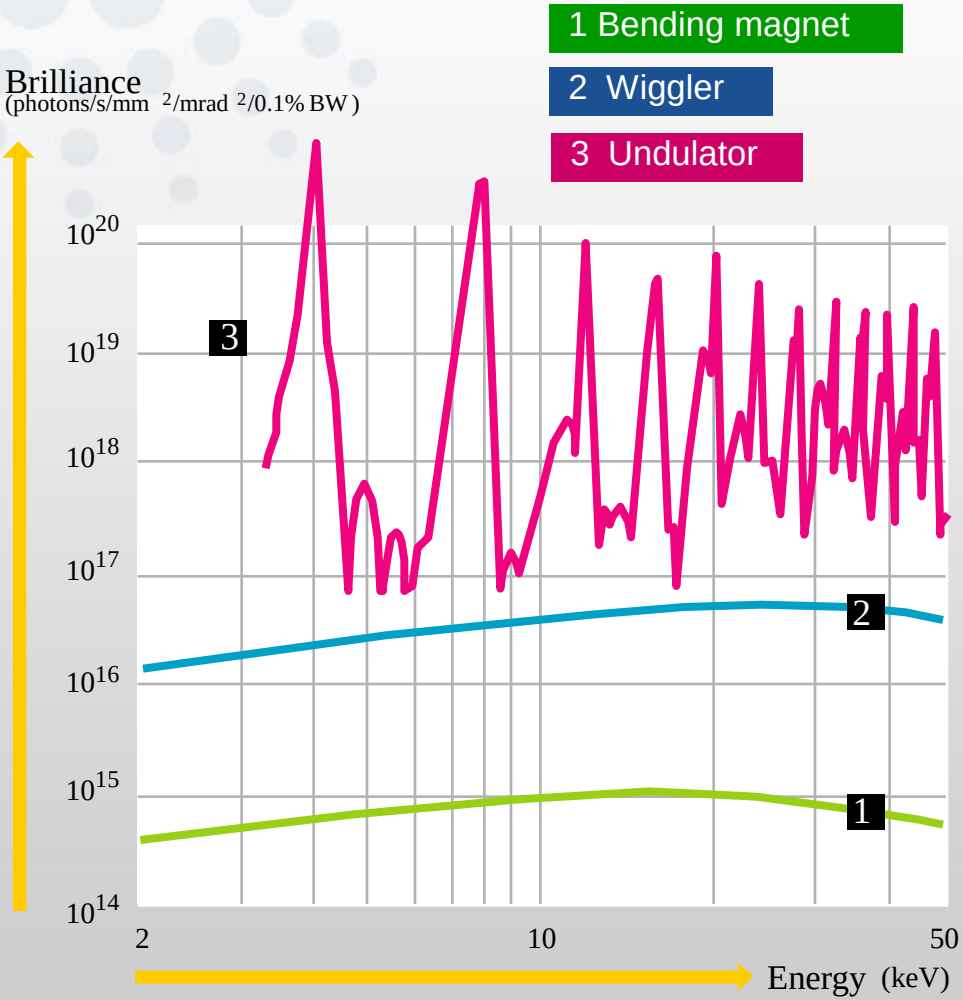
Three forms of Synchrotron Radiation



From "Introduction to Synchrotron Radiation", D. Attwood, Univ. California, Berkeley

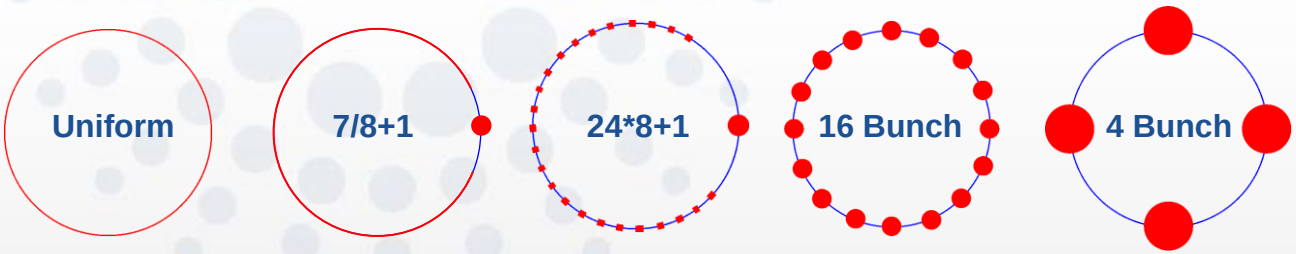
Insertion devices





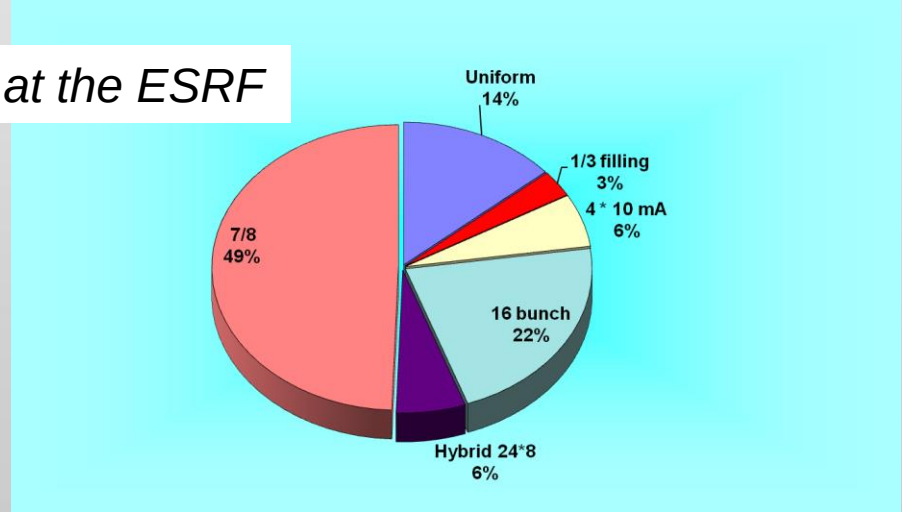
Filling patterns & radiation time structure

Filling patterns



	Uniform	7/8+1	24*8+1	16 Bunch	4 Bunch
Number of bunches	992	870	24x8+1	16	4
Maximum current [mA]	200	200	200	90	40
Rms bunch length [ps]	20	20	25	48	55

Typical filling modes at the ESRF



X-ray beams at 3rd generation SR sources

A Light for Science

- Brightness
  - 10^{+22} ph/sec/mrad^2/mm^2/0.1% b.w. (10^{+11} higher than conventional sources)
- Small source and highly collimated beam
  - ~ 10µm and 10µrad
- Broad emission spectrum: wavelength tunability
  - 0.1eV < E < 100keV or 1.2µm < λ < 0.01Å
- Polarized radiation
  - 100% linear or circular or elliptical
- Pulsed radiation
  - 50 ps pulses every ns
- Power
  - several kW total power, several 100 W/mm^2 power density.
- High degree of coherence

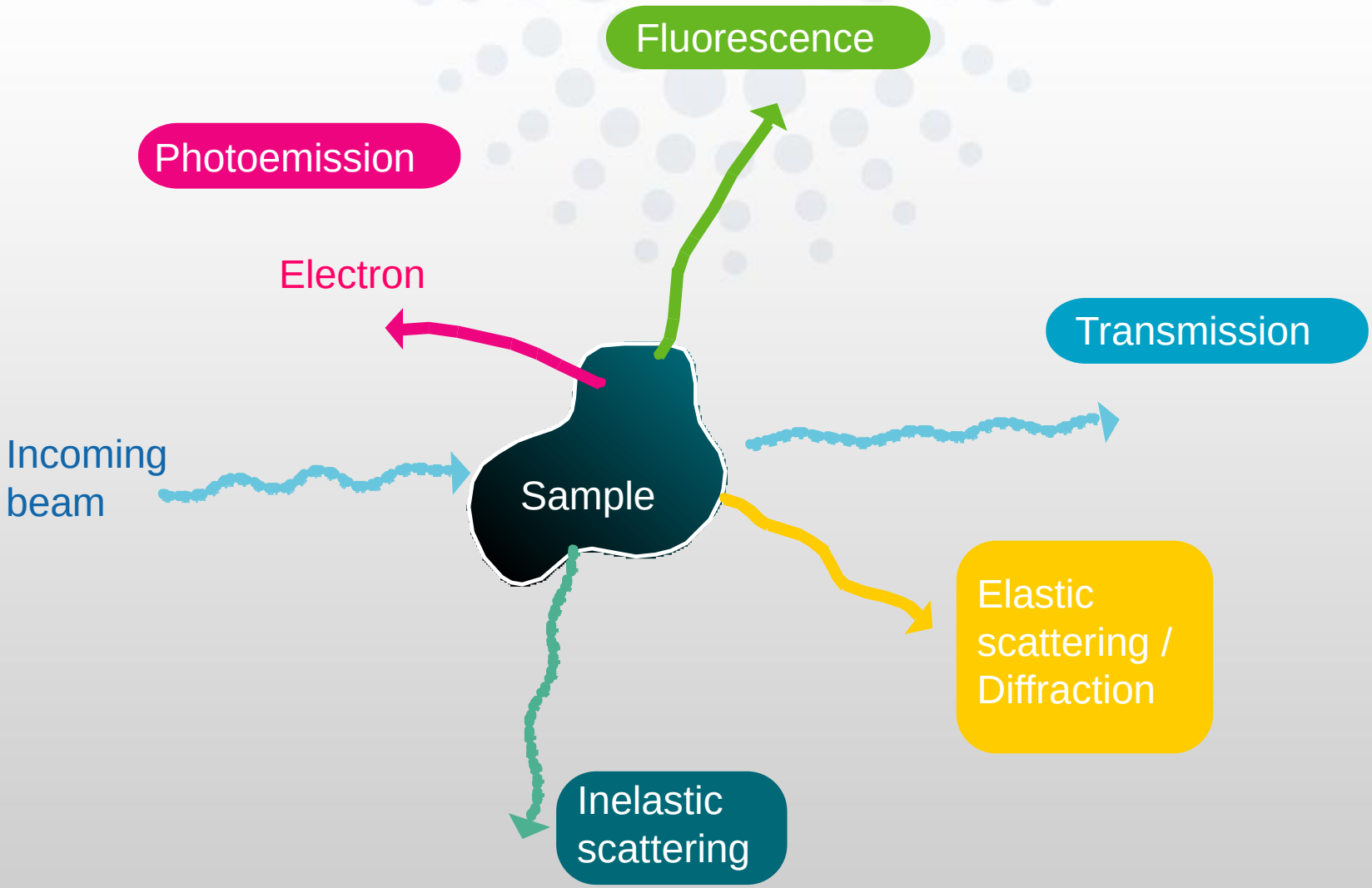
Outline

PART II

SR Research

1. SR techniques
2. Some examples

Interactions between light and matter



A complete suite of techniques

X-Ray Fluorescence

- Composition
- Quantification
- Trace element mapping

X-ray Diffraction & scattering

- Long/short range structure
- Electron density mapping
- Crystal orientation mapping
- Stress/strain/texture mapping

Specific

Sample environments

Absorption & Phase contrast X-ray imaging

- 2D/3D Morphology
- High resolution
- Density mapping

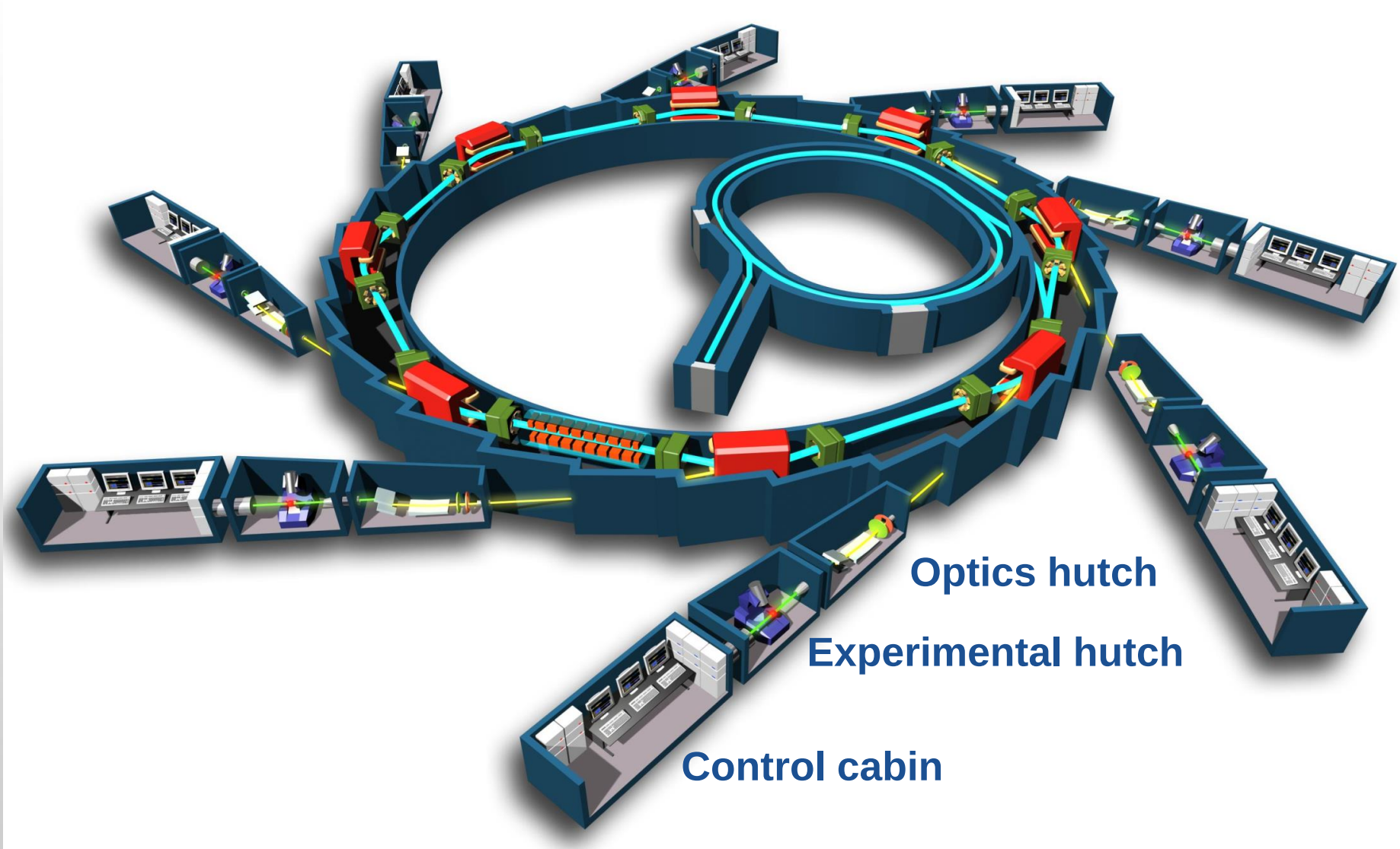
Infrared FTIR-spectroscopy

- Molecular groups & structure
- High S/N for spectroscopy
- Functional group mapping

X-ray spectroscopy

- Short range structure
- Electronic structure
- Oxidation/speciation mapping

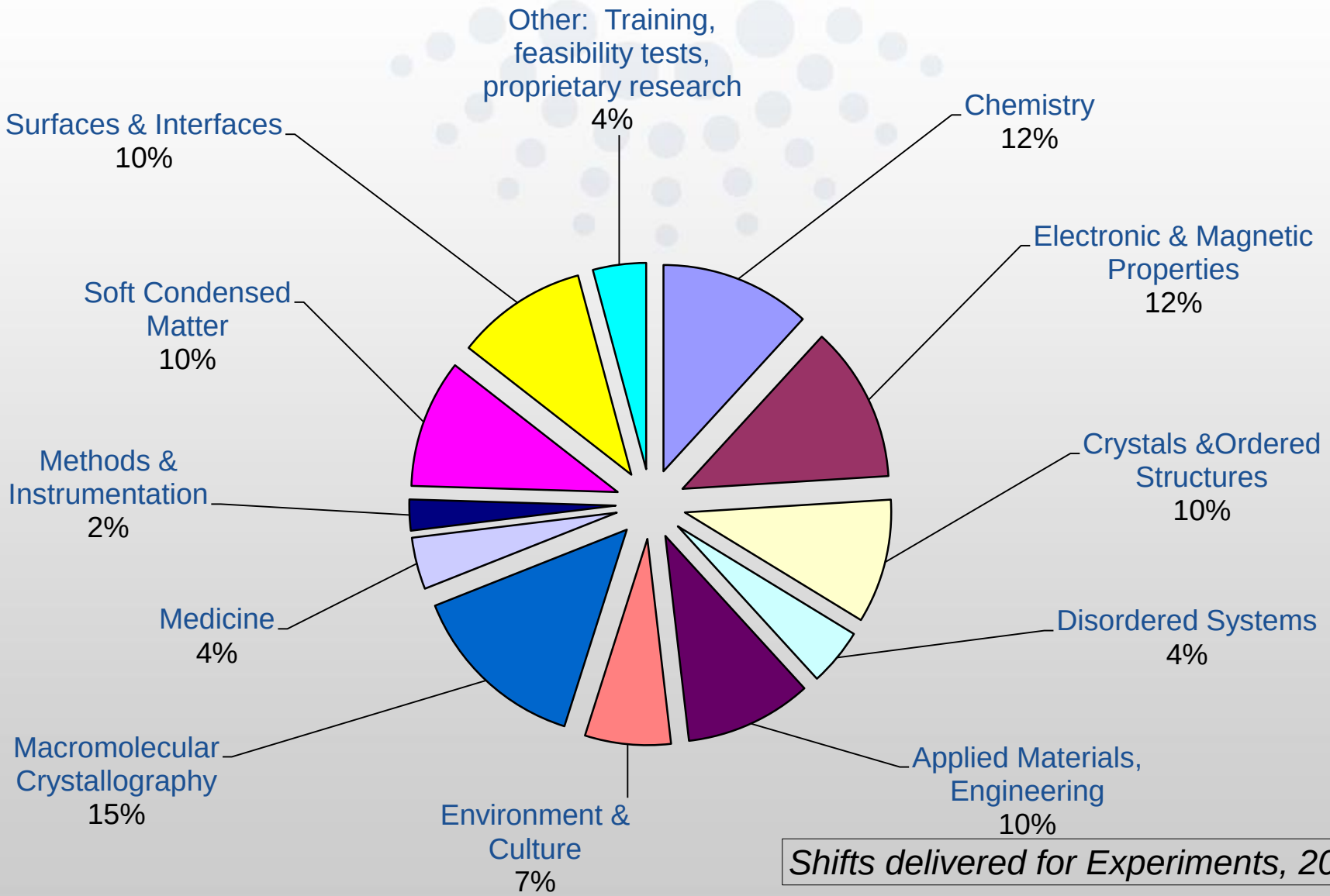
A typical synchrotron source layout



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

A broad range of applications

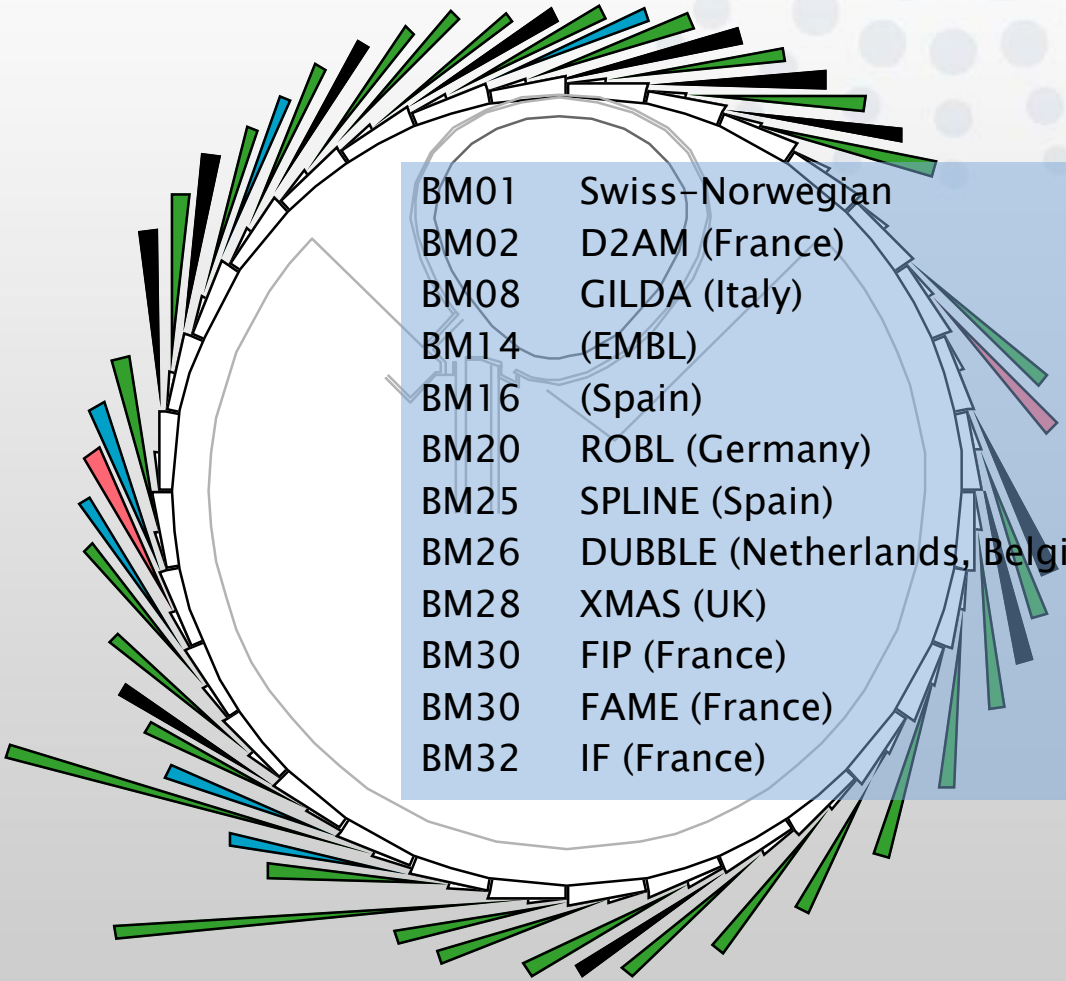
Beamtime use at the ESRF



Shifts delivered for Experiments, 2010

List of ESRF beamlines

Over 40 different experiments can be conducted simultaneously

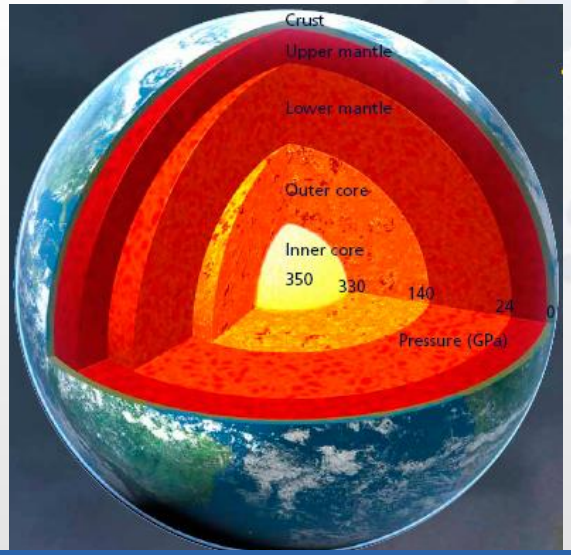


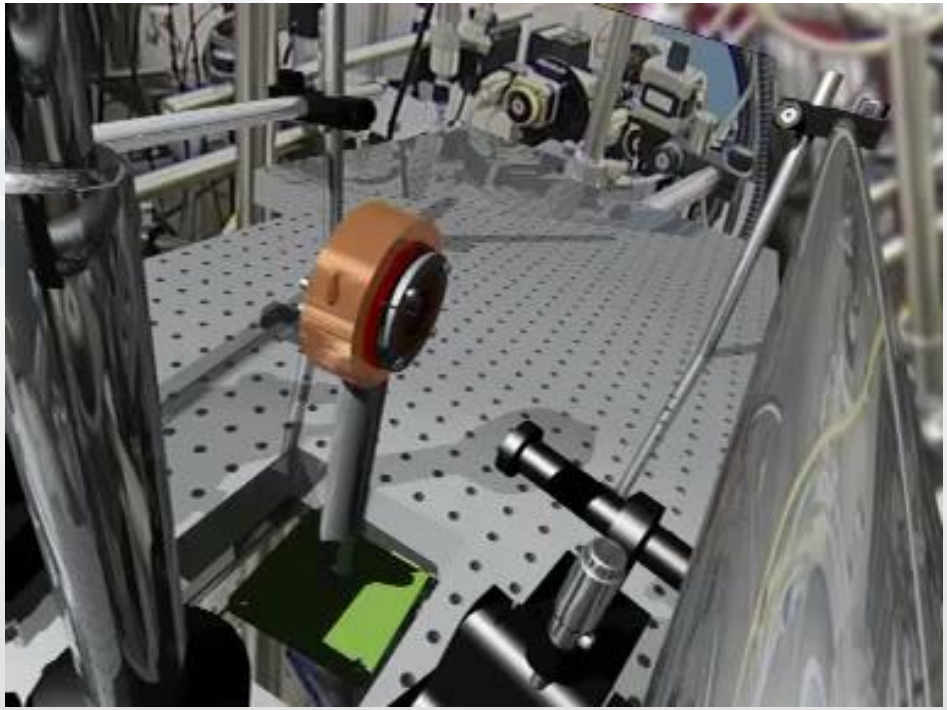
BM01	Swiss-Norwegian
BM02	D2AM (France)
BM08	GILDA (Italy)
BM14	(EMBL)
BM16	(Spain)
BM20	ROBL (Germany)
BM25	SPLINE (Spain)
BM26	DUBBLE (Netherlands, Belgium)
BM28	XMAS (UK)
BM30	FIP (France)
BM30	FAME (France)
BM32	IF (France)

ID01	Anomalous scattering
ID02	High brilliance
ID03	Surface diffraction
ID06	Instrumentation development
ID08	Dragon / Spectroscopy using polarised soft X-rays
ID09	Biology / High pressure
ID10	Troika / Multipurpose
ID11	Materials science
ID12	Circular polarisation
ID13	Microfocus
ID14	Protein crystallography
ID15	High energy diffraction
ID16	Inelastic scattering
ID17	Medical

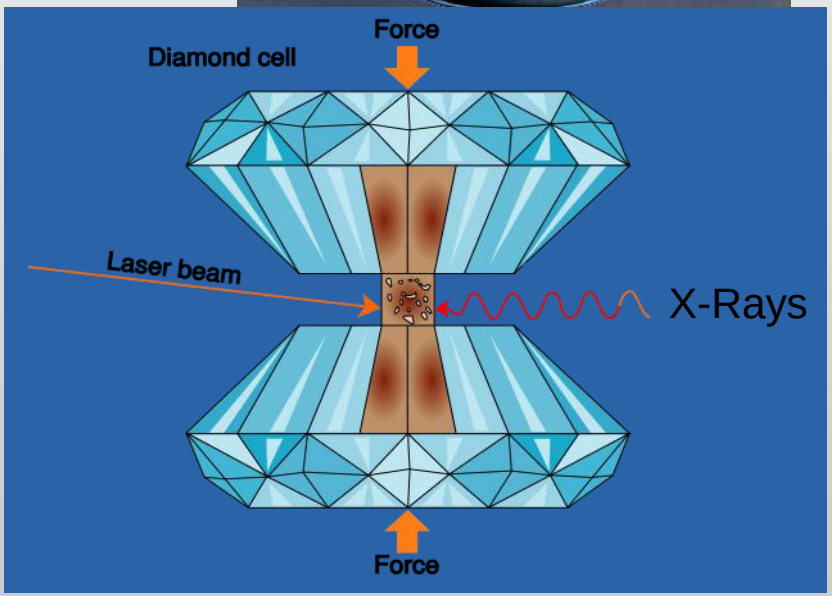
Extreme conditions (T, P, M)

One can better understand the structure of matter at the center of the Earth …





Diamond Anvil Cell (DAC)



… by studying samples put under extreme conditions of pressure and temperature.

- 200GPa (2Mbar)
- T=3600K

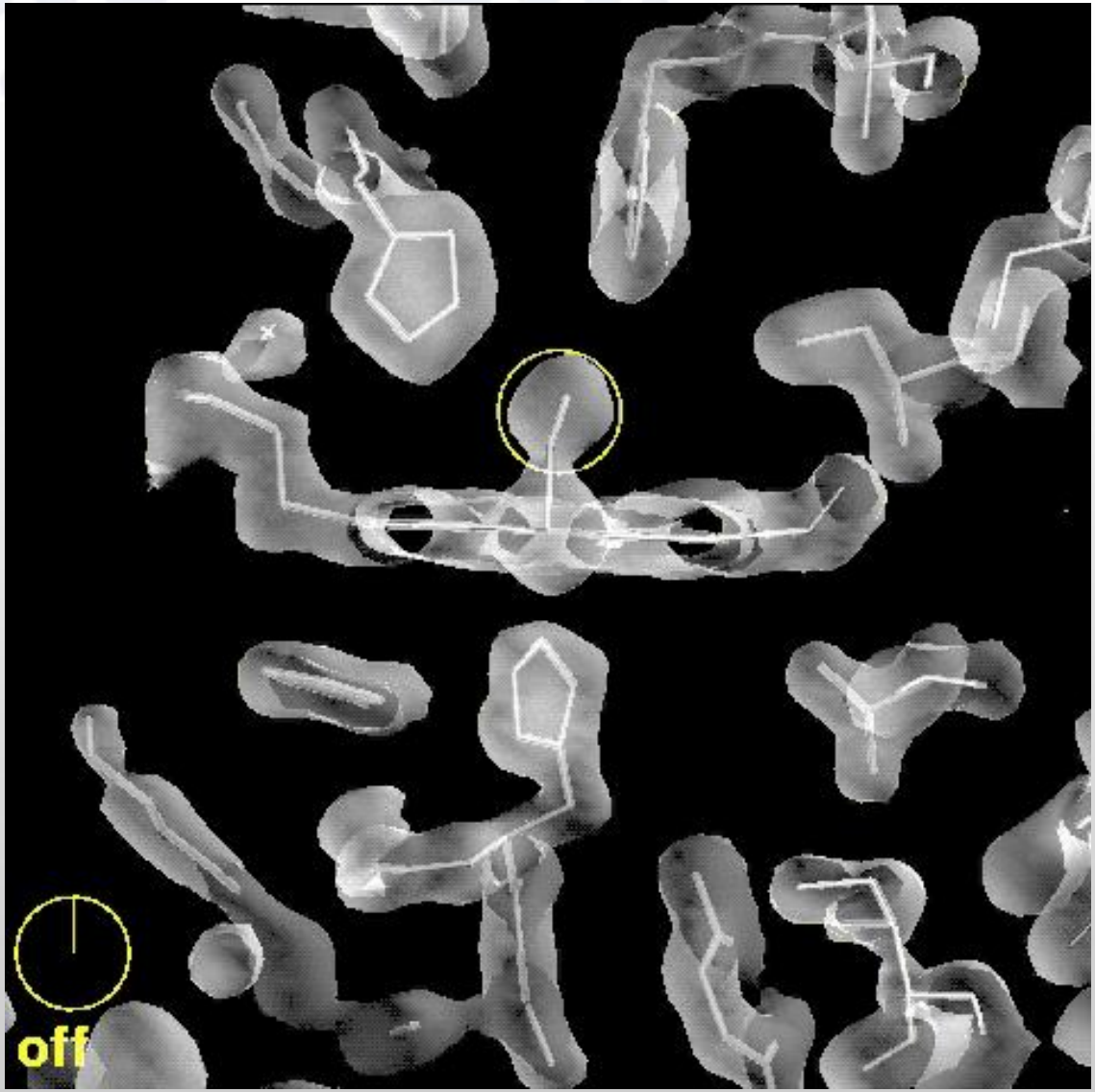
Down to the picosecond

Molecular movies obtained by using the pulsed time structure of the SR

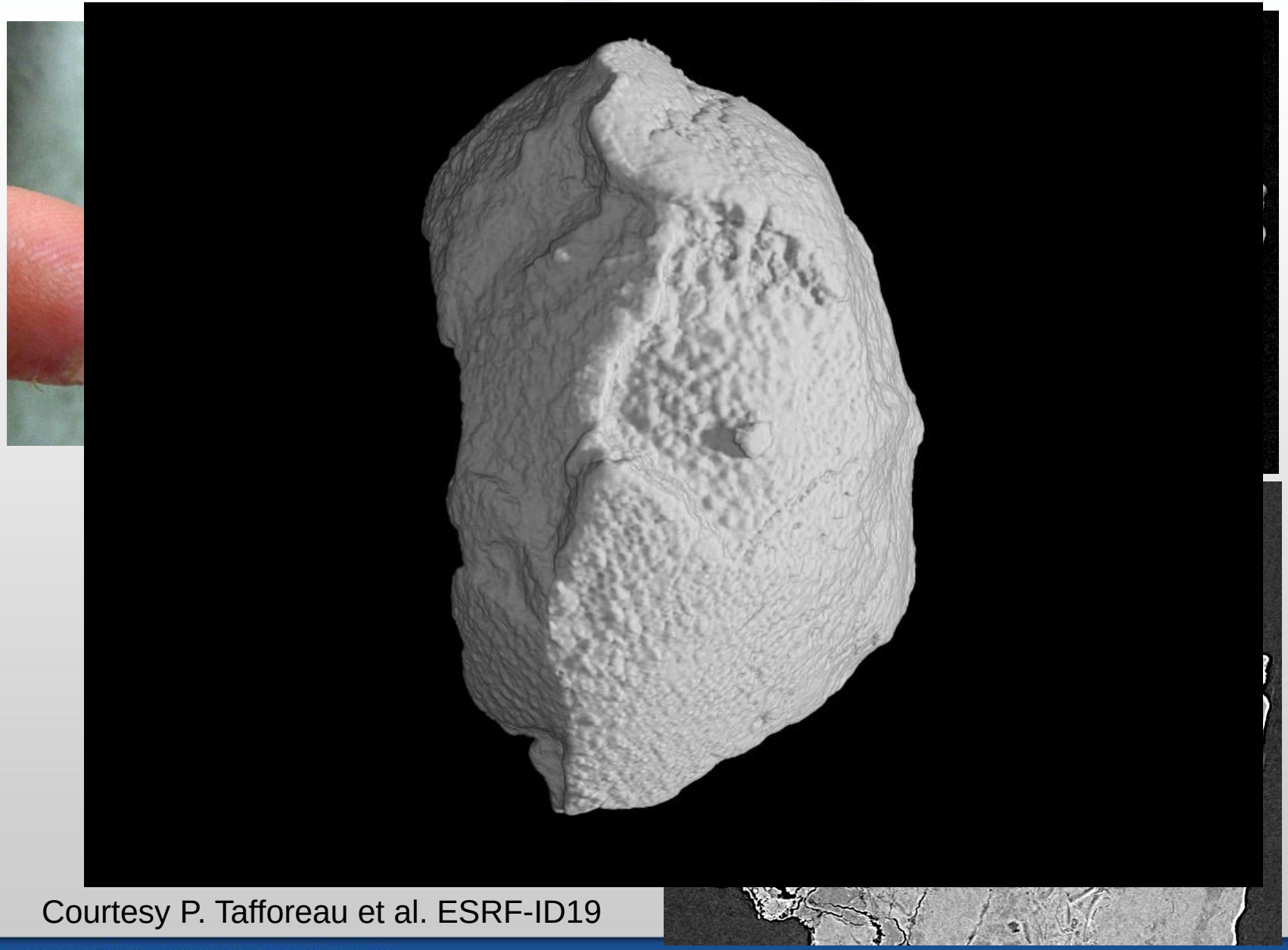
Migration of photodissociated CO in myoglobin (iron- and oxygen-binding protein in muscle tissue) using time-resolved single crystal diffraction in pump-probe experiment

Courtesy: M. Wulff,ESRF ID09

Srajer V, et al., Photolysis of the carbon monoxide complex of myoglobin: nanosecond time-resolved crystallography. Science. 1996;**274**:1726–1729



Jurassic Park I



Courtesy P. Tafforeau et al. ESRF-ID19

To go further…