Introduction to X-ray production

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Outline

1. Mechanisms for X-ray production

Charge acceleration: bremsstrhalung

Electronic quantum transitions

2. X-ray tubes for X-ray diffraction measurements

3. Principles of synchrotron radiation

Synchrotron Radiation:

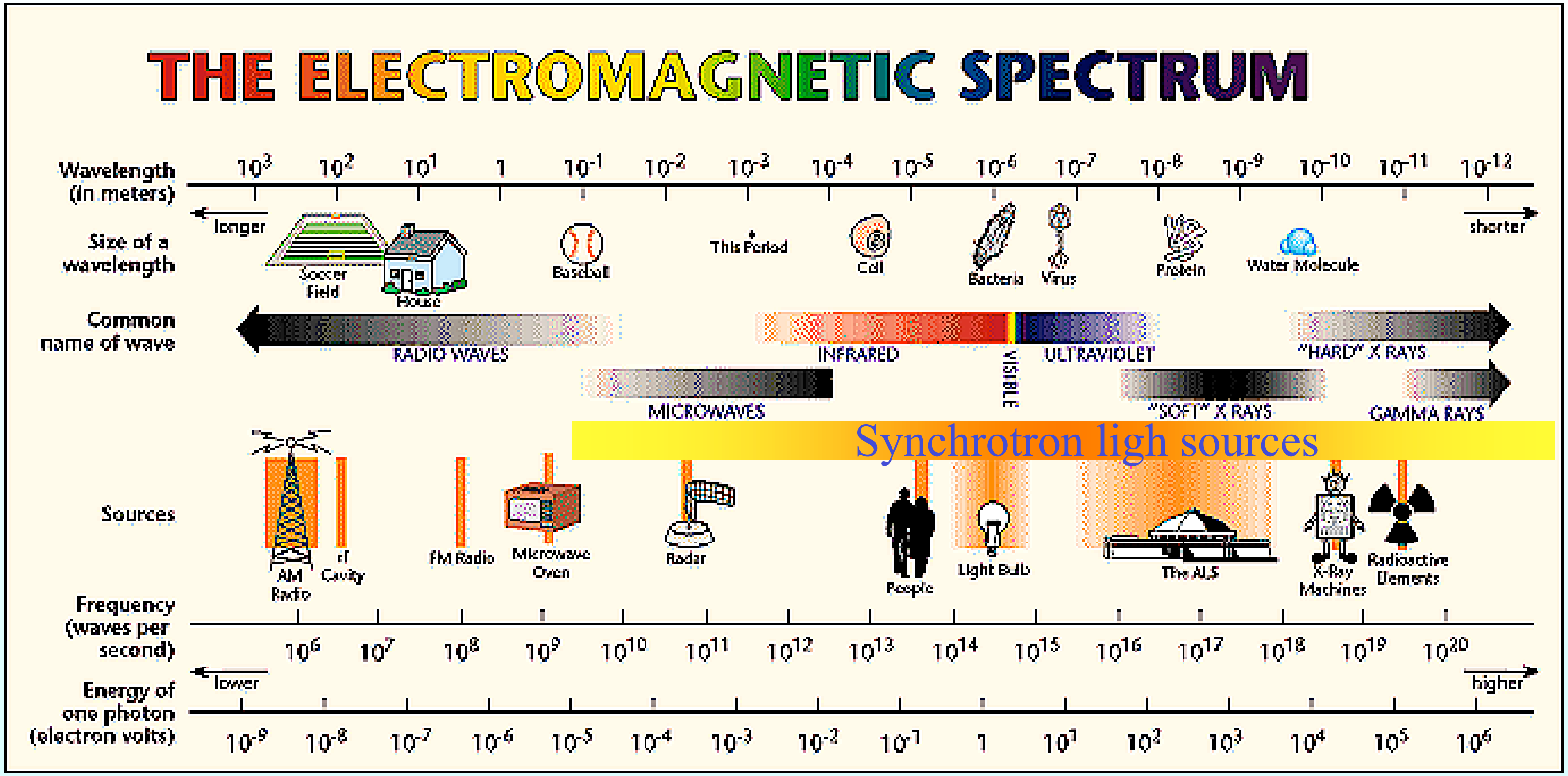
What is it?

How is it produced?

Which are their properties?

... which the main uses?

Electromagnetic Radiation and Structure of matter



The shorter the wavelength, the greater the resolution for observing small object

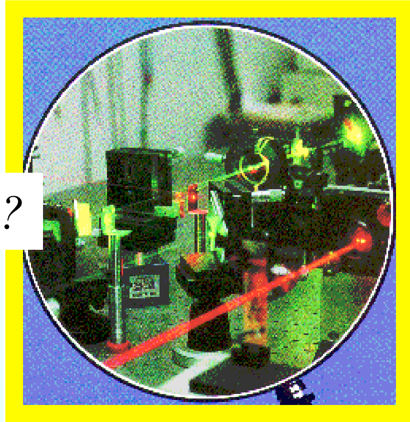
Synchrotron radiation sources span wide regions of the electromagnetic spectrum

Who are the responsibles of light emission?

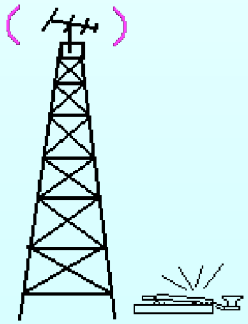
From a candle?

da una lamfrom a lamppada?

From lasers?



By a broadcasting antenna?

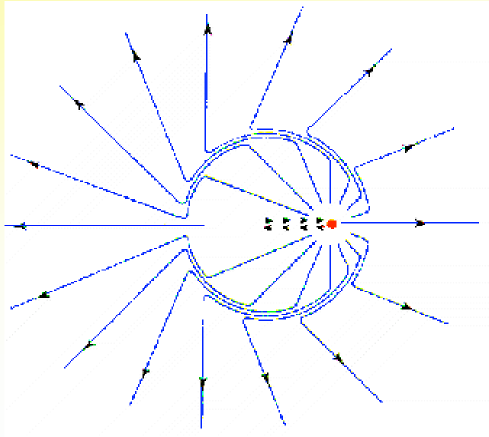


The amin responsible are the electrons

Radiation production mechanisms

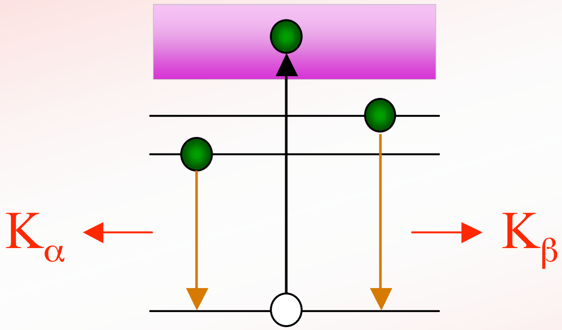
There are two ways to produce synchrotron radiation:

Classical mechanism: acceleration of charged particle (for instance, electrons and positrons)



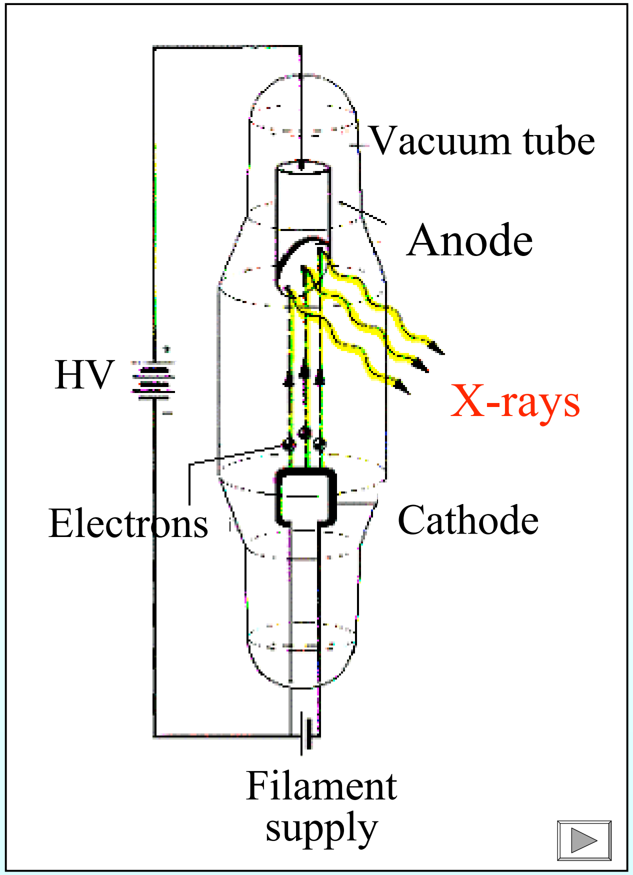
- Bremsstrahlung: deceleration of high energy electrons in a metal
- Synchrotron radiation emitted by relativistic charged particles in particle accelerators
- Cosmic synchrotron radiation

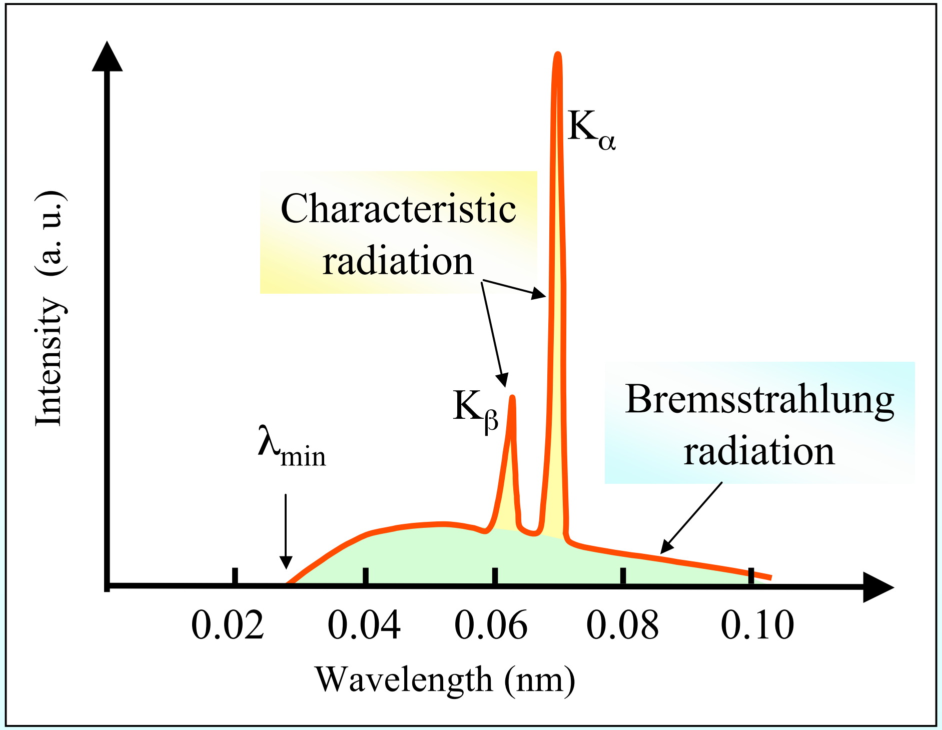
Quantum mechanism: transitions of electrons from outer to inner empty energy levels



- Emission lines
- Characteristic radiation

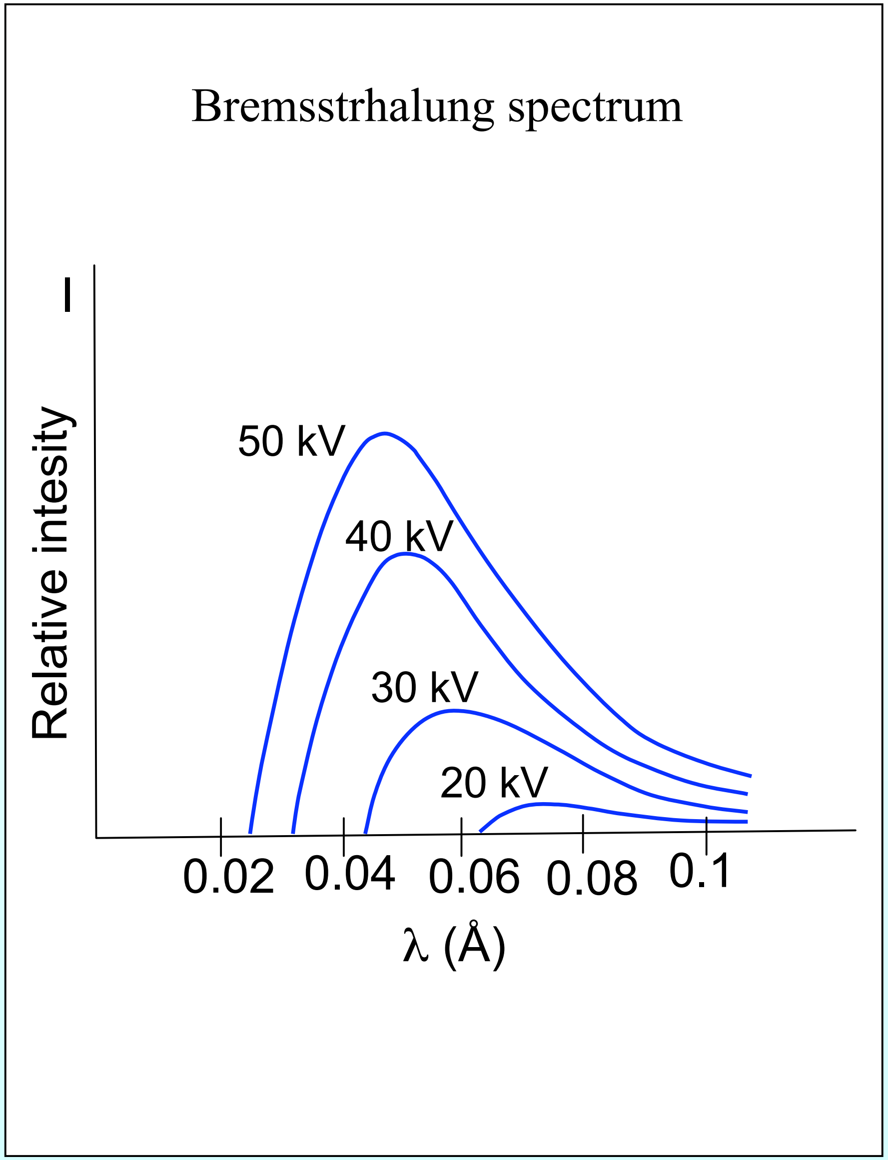
X ray production by tubes

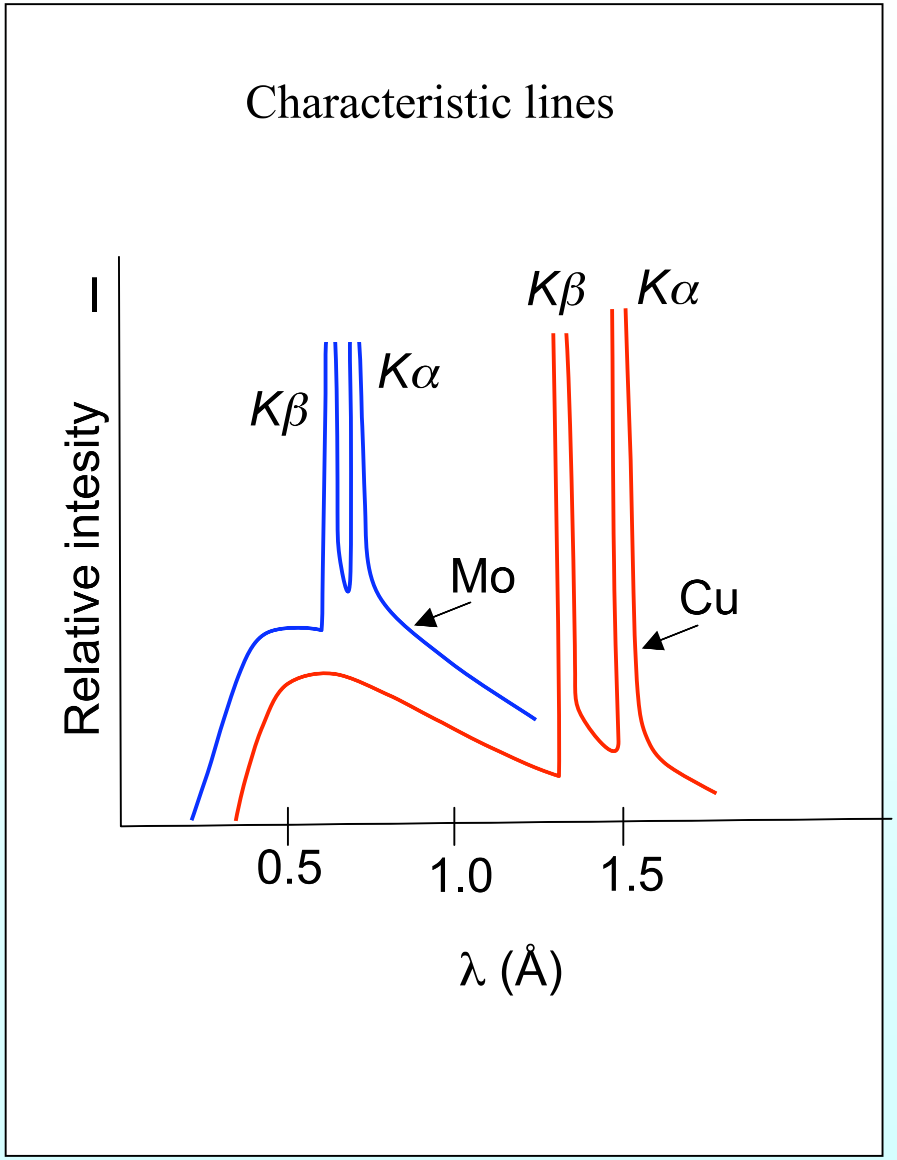




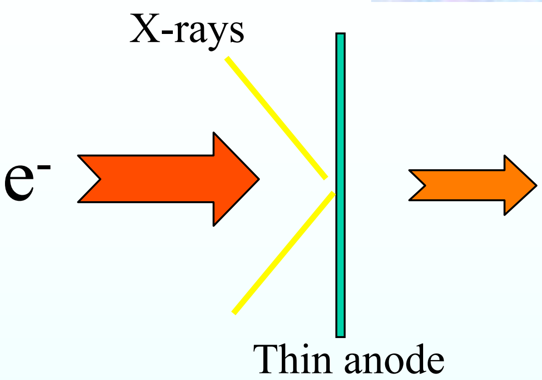
The spectrum from an X ray tube has discrete fluorescent lines superimposed on the continuous bremsstrahlung radiation

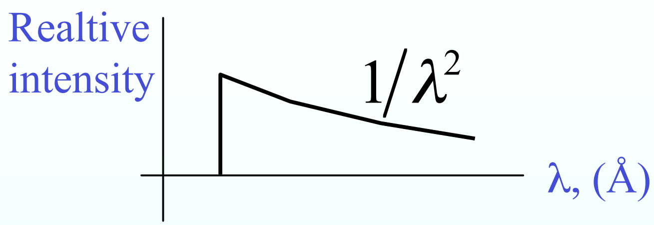
Spectra of different anodes

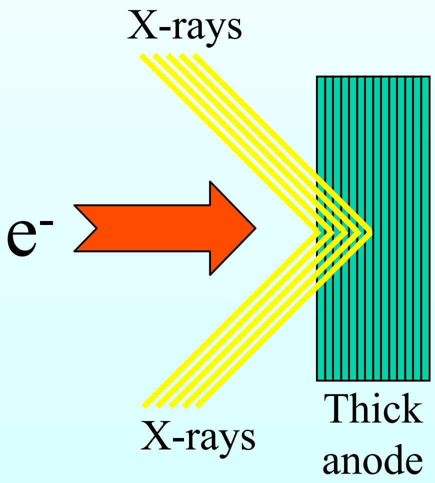


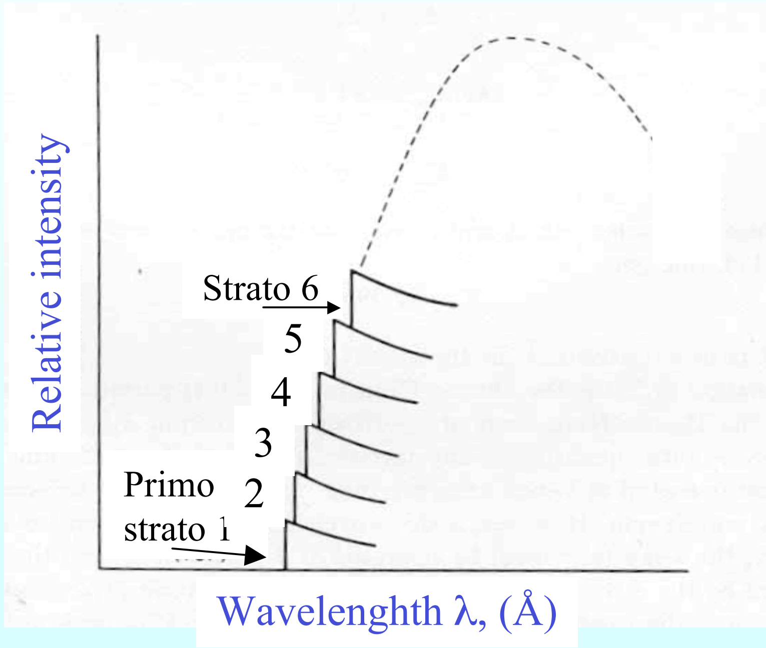


Distribuzione spettrale









The continuous spectrum emitted by a thich anode can be considered as the sommation of spectra emitted by thin layers of the anode

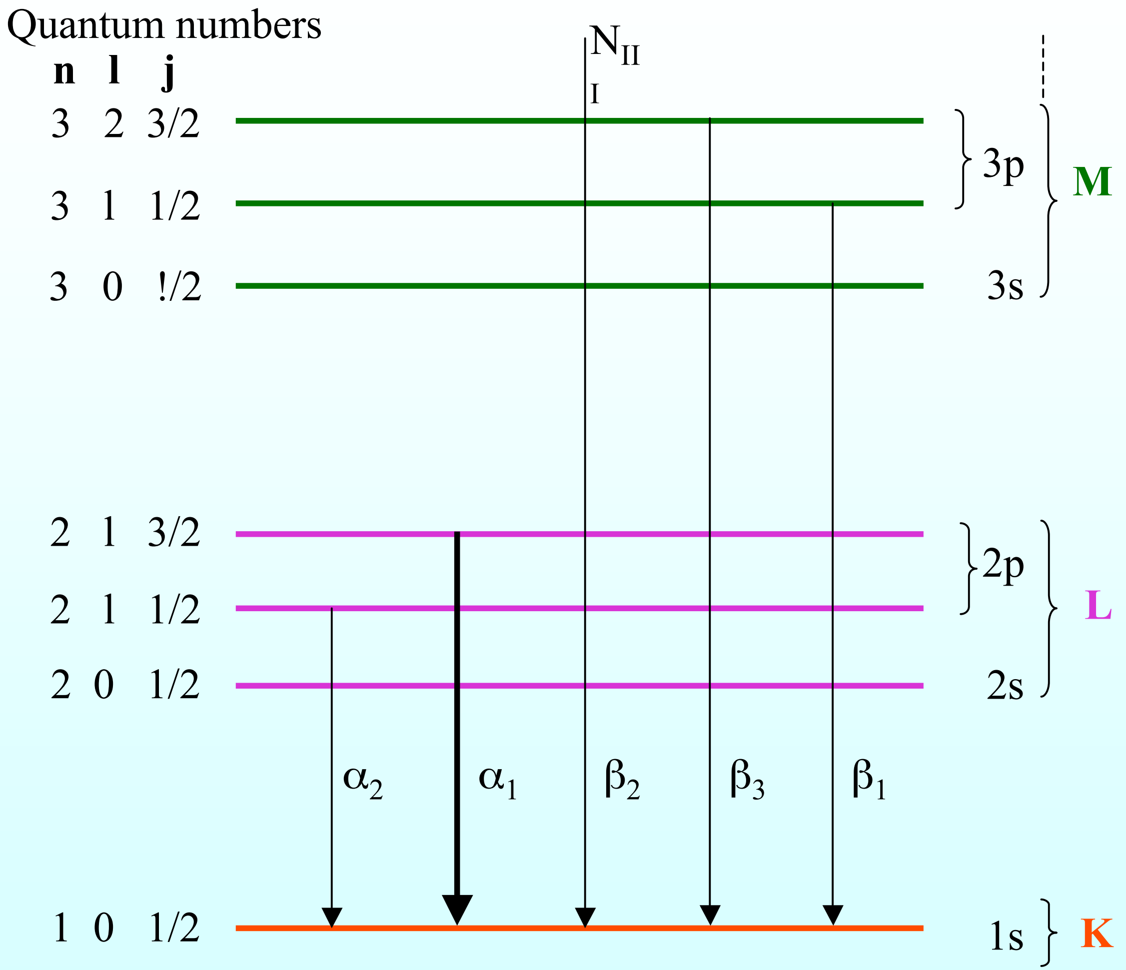
Electronic transitions and K emission lines

Selection rules

$\Delta n \neq 0$

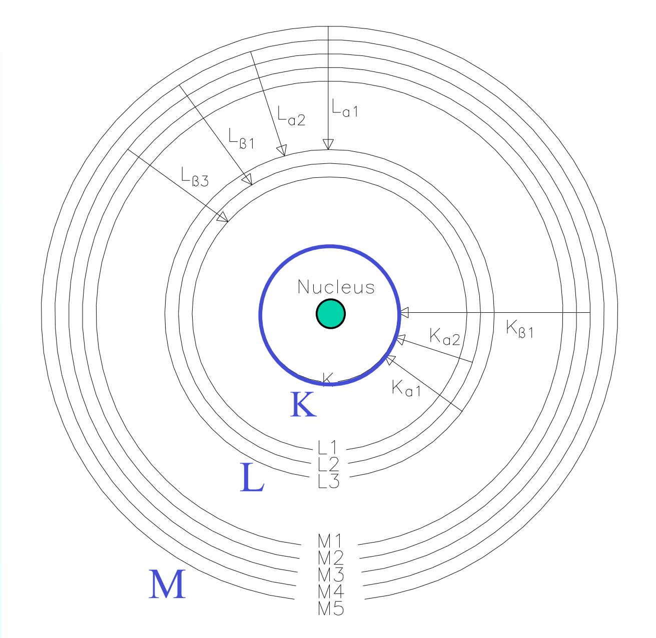
$\Delta l = \pm 1$

$\Delta j = \pm 1$ o 0



Simplified diagram of transitions from energy states characteristic of the K emission line series

Characteristic spectrum



It consists of series of discrete lines whose energy is equal to the energy difference of two atomic levels.

Each element has its own characteristic spectrum

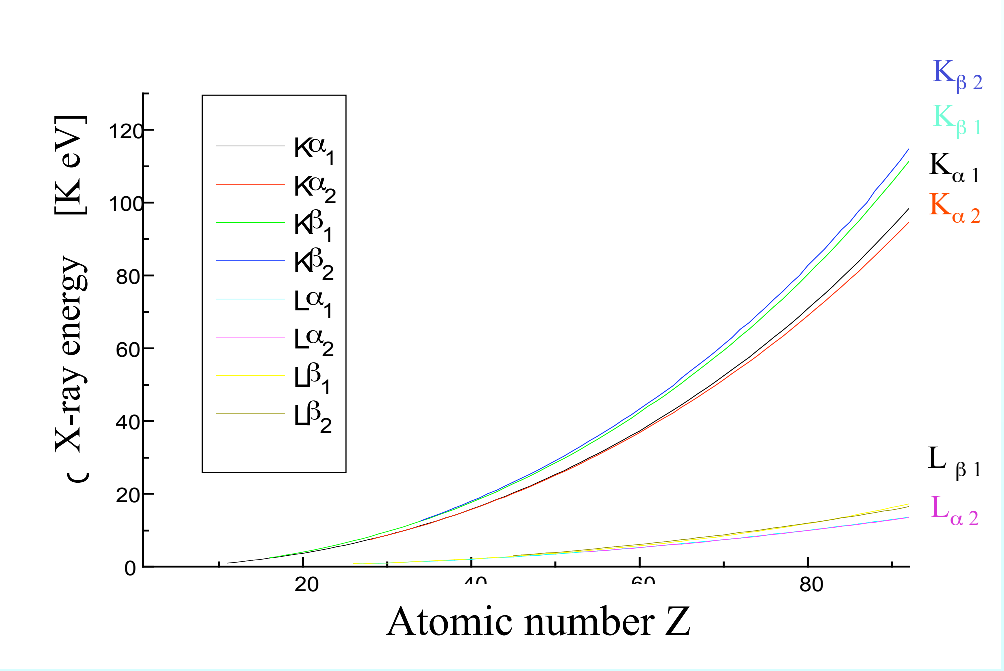
Line emission denomination

Siegbahn	IUPAC	Siegbahn	IUPAC
K?$_1$	K-L3	L?$_1$	L3-M5
K?$_2$	K-L2	L?$_2$	L3-M4
K?$_1$	K-M3	L?$_1$	L2-M4
K?$_2$	K-N2,N3	L?$_2$	L3-N5
K?$_3$	K-M2	L?$_3$	L1-M3
		L?$_4$	L1-M2

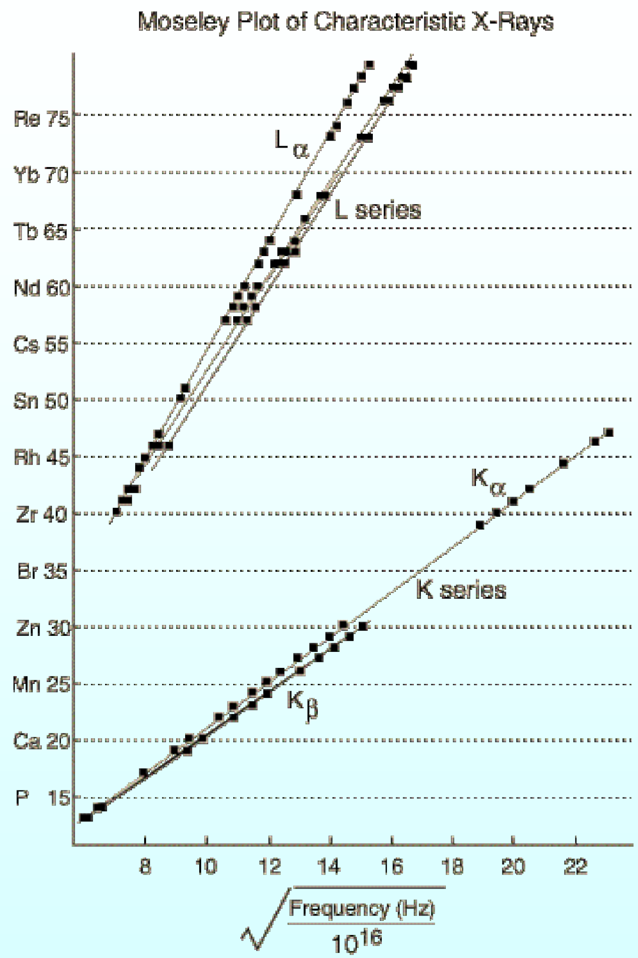
Moseley law

Relationship between the atomic number of an element and the energy of its spectral emission lines

$$E(Z) = k_j (Z - \sigma_j)^2$$



In terms of wavelenghth, the previous equation is: $\lambda \propto \frac{1}{Z^2}$

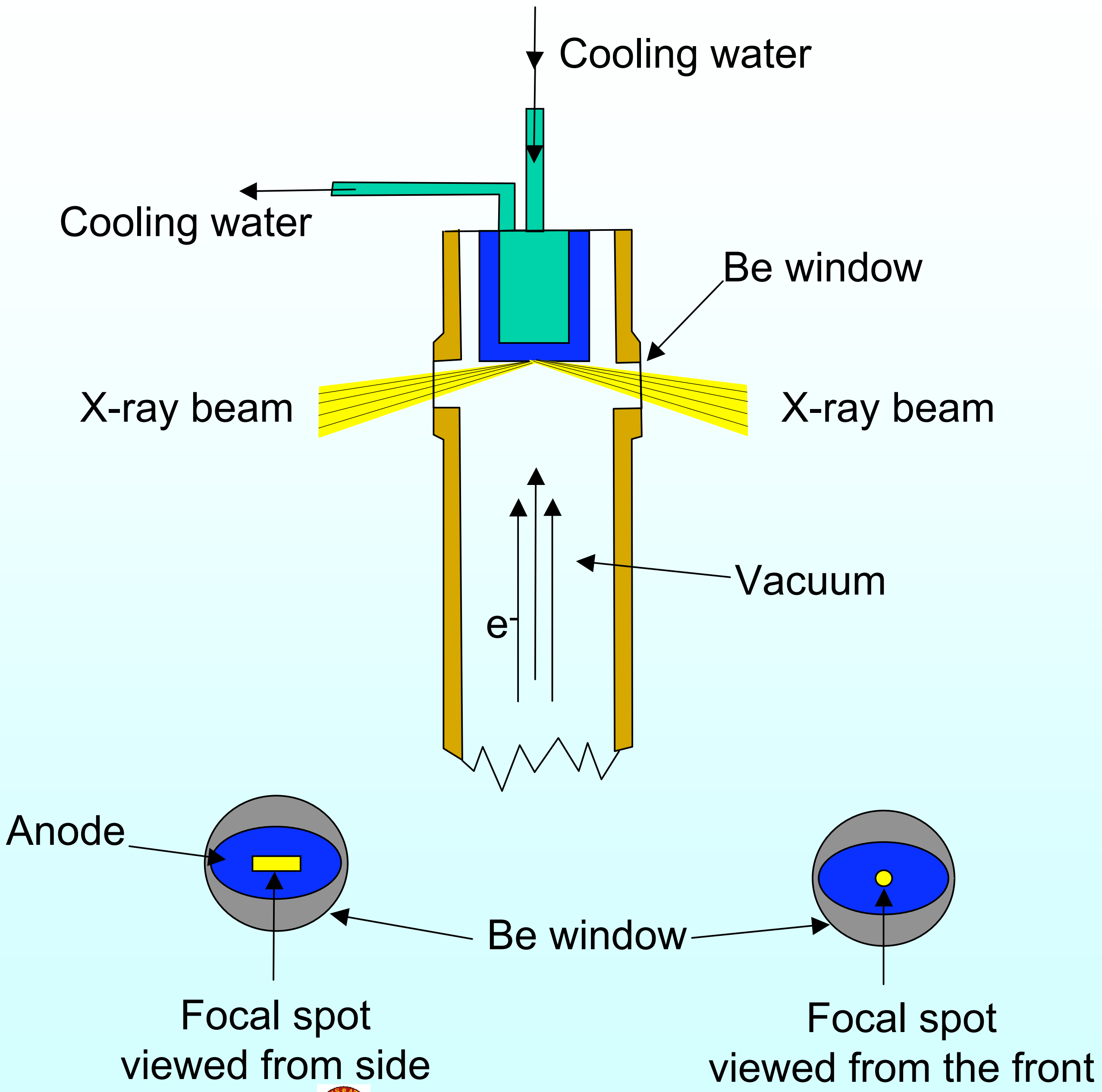


Adapted from Moseley's original data (H. G. J. Moseley, Philos. Mag. (6) 27:703, 1914)

$$h\nu_{K\alpha} = 13.6eV\ (Z-1)^2\left[\frac{1}{1^2}-\frac{1}{2^2}\right] = \frac{3}{4}13.6\,(Z-1)^2\ \ eV$$

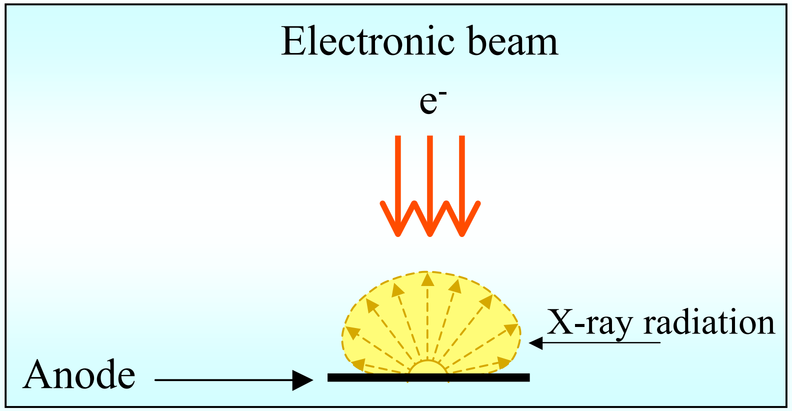
Target materials and associated constants

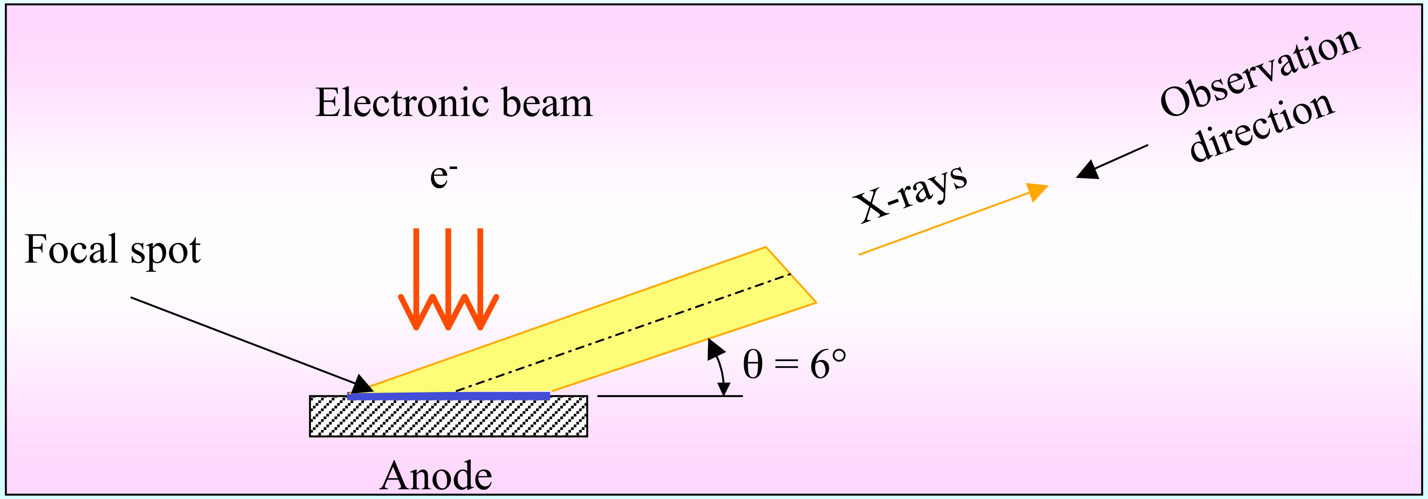
	Cr	Fe	Cu	Mo
Z	24	26	29	42
$k_{\alpha 1}$, (Å)	2.2896	1.9360	1.5405	0.70926
$k_{\alpha 2}$, (Å)	2.2935	1.9399	1.5443	0.71354
$K_{\alpha 1\text{-}2}$, (Å)	2.2909	1.9373	1.5418	0.71069
$k_{\beta 1}$, (Å)	2.0848	1.7565	1.3922	0.63225
β filter	V	Mn	Ni	Nb
α filter	Ti	Cr	Co	Y

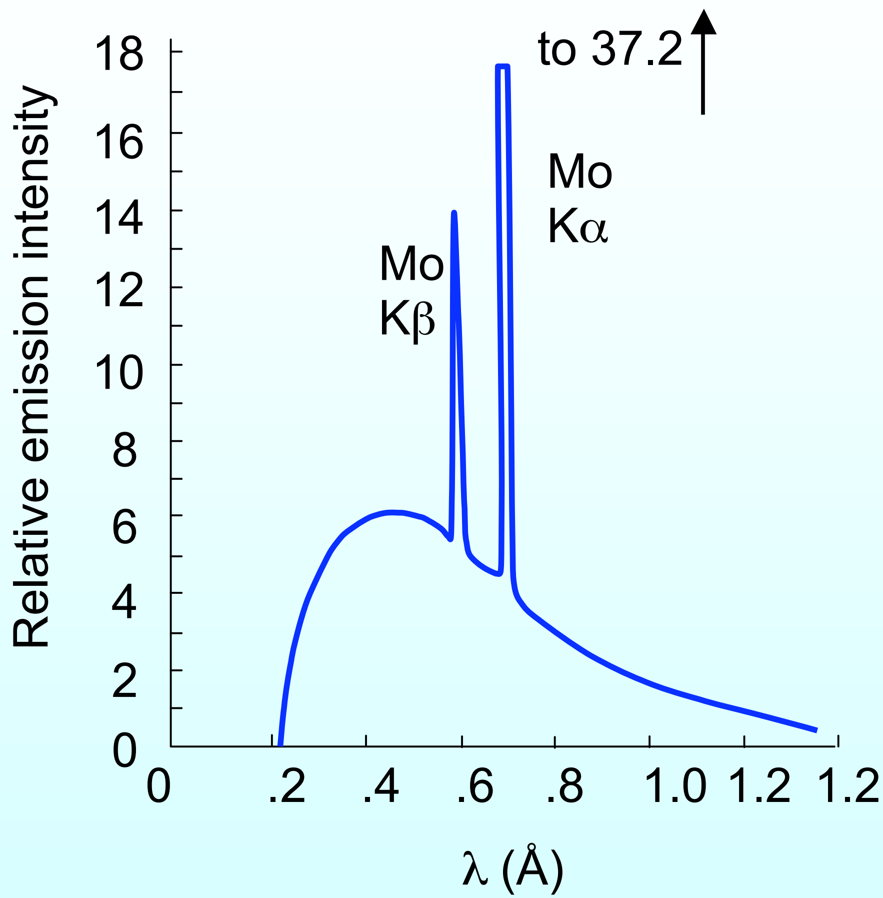


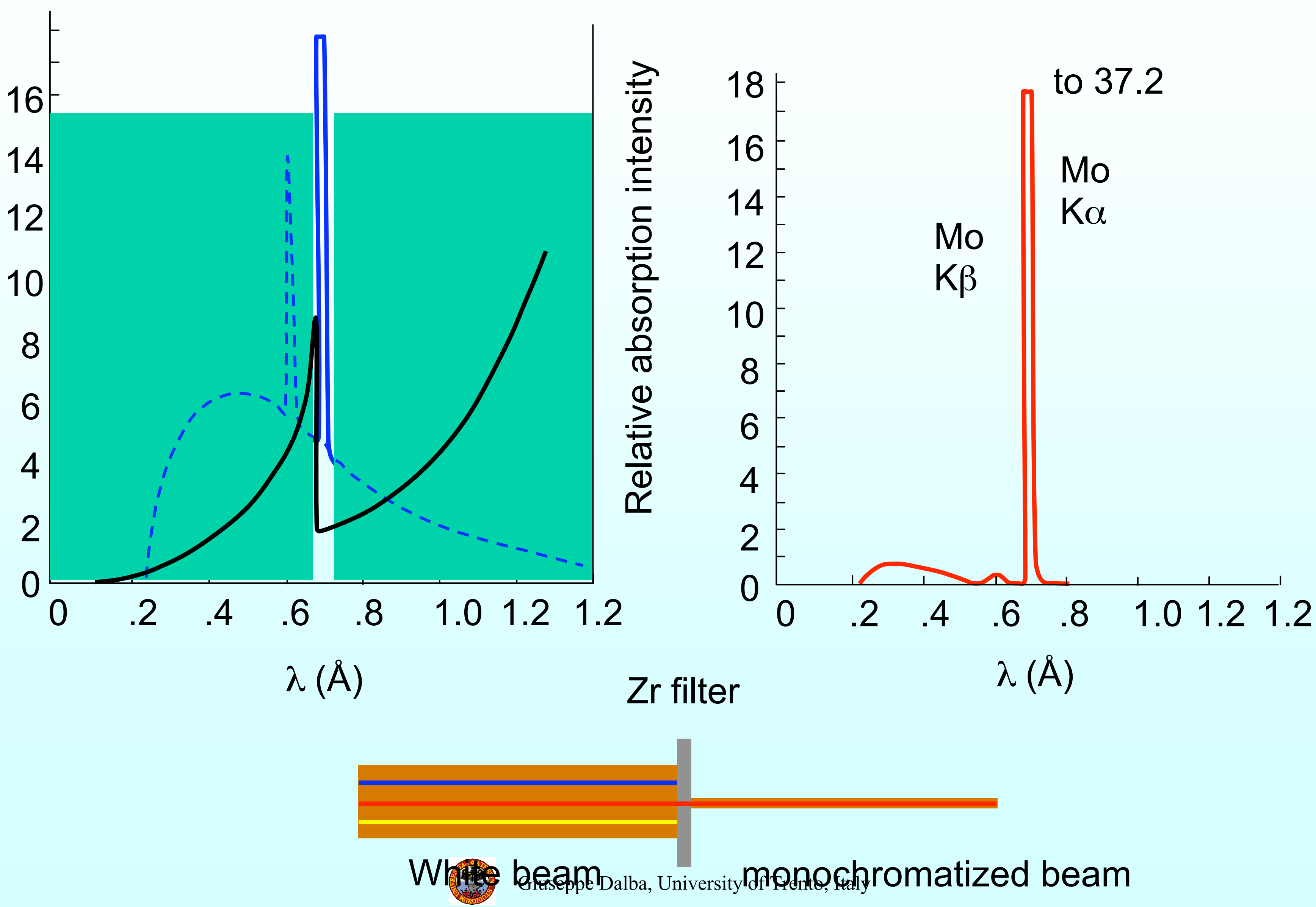
Cooling water
Cooling water
Be window
X-ray beam
X-ray beam
Vacuum
e⁻
Anode
Be window
Focal spot
viewed from side
Focal spot
viewed from the front

Angular distribution of the radiation emitted by an X-ray tube






to 37.2
Mo
Kα
Mo
Kβ
Relative emission intensity
18
16
14
12
10
8
6
4
2
0
0
.2
.4
.6
.8
1.0
1.2
1.2
λ (Å)

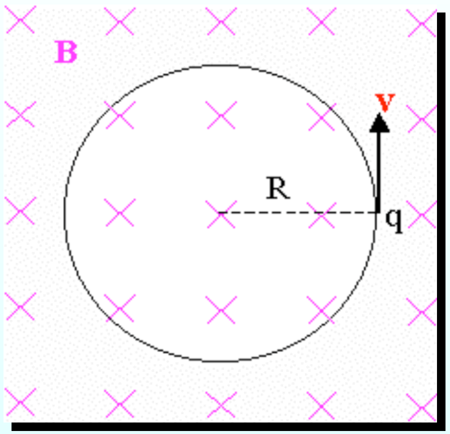

16
14
12
10
8
6
4
2
0
0
.2
.4
.6
.8
1.0
1.2
1.2
λ (Å)
Relative absorption intensity
18
16
14
12
10
8
6
4
2
0
0
.2
.4
.6
.8
1.0
1.2
1.2
to 37.2
Mo
Kα
Mo
Kβ
λ (Å)
Zr filter
White beam
monochromatized beam

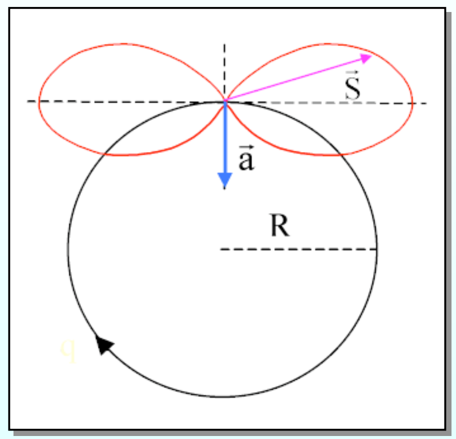
Charged particles moving in circular motion radiate

Larmor Formula

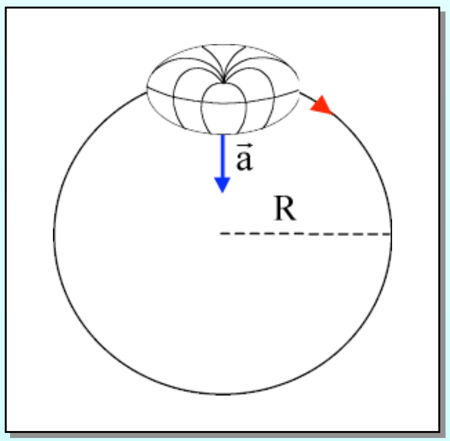
$$P = \frac{q^2 a^2}{6 \pi \varepsilon_0 c^3}$$

P = Electromagnetic power
q = charge
a = centripetal acceleration





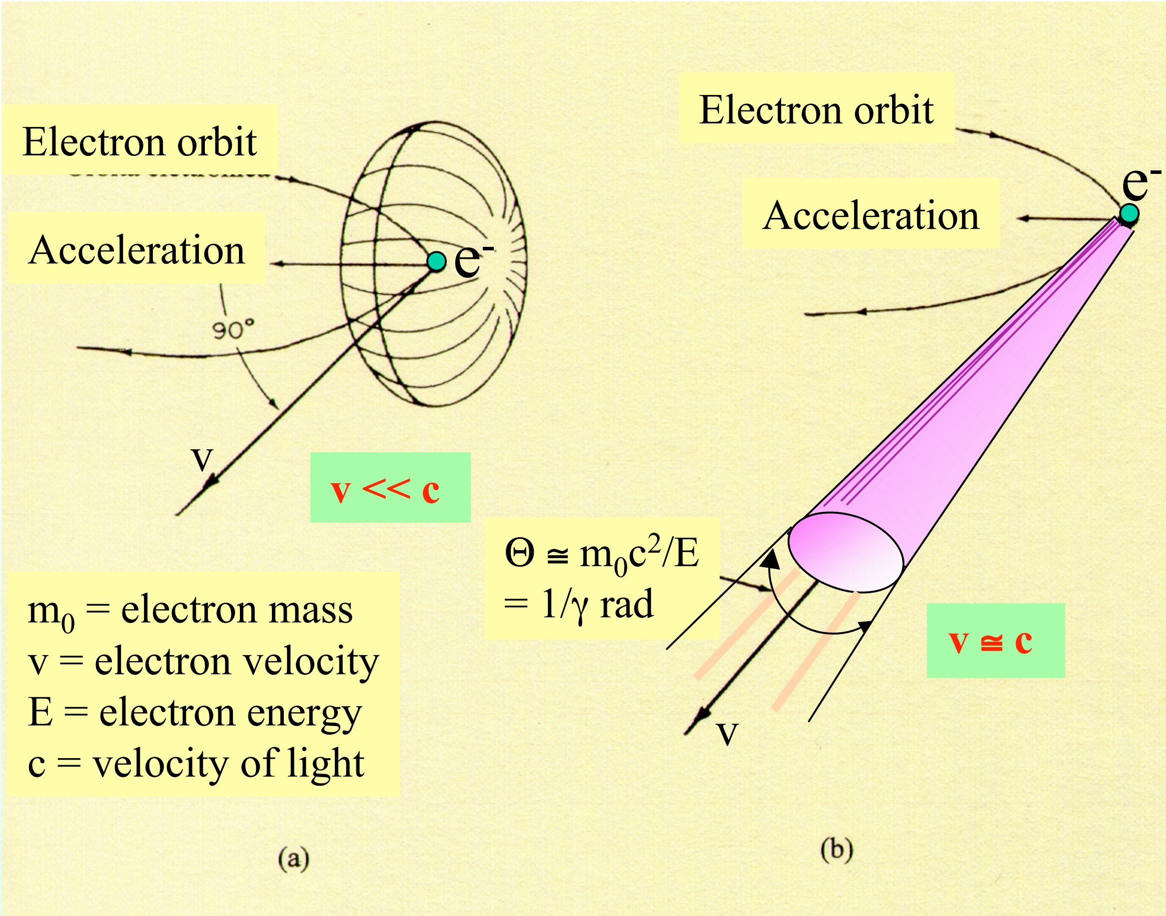
S = Pointing vector



v << c

The radiation angular distribution of non-relativistic electrons has the shape of a tire orbiting at the same velocity of the electron bunch

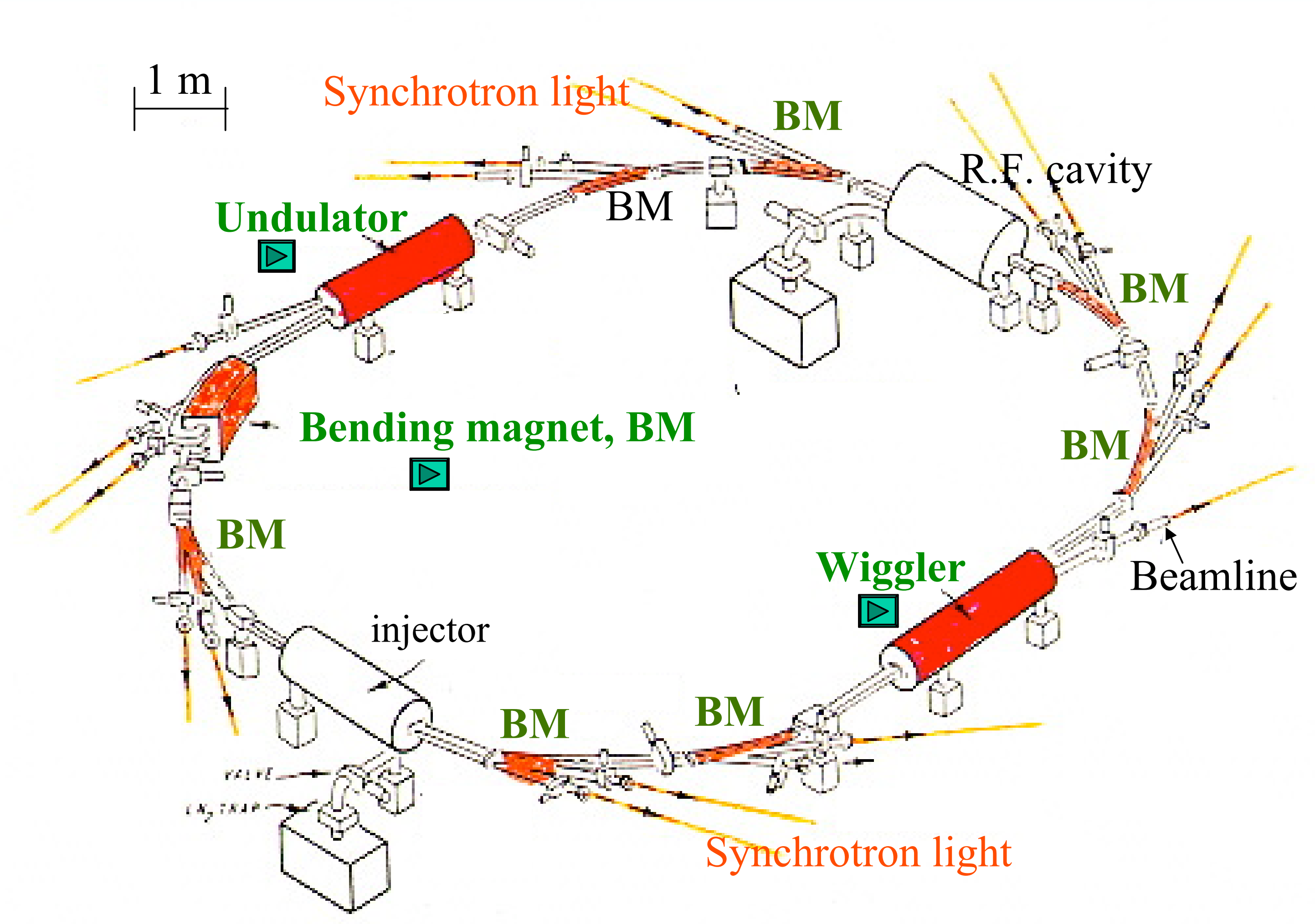
Synchrotron radiation angular distribution



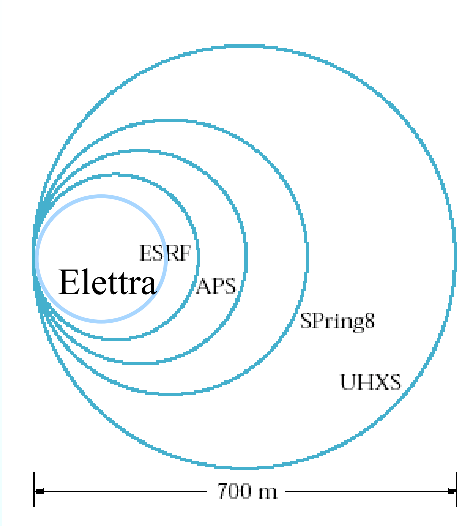
Top view

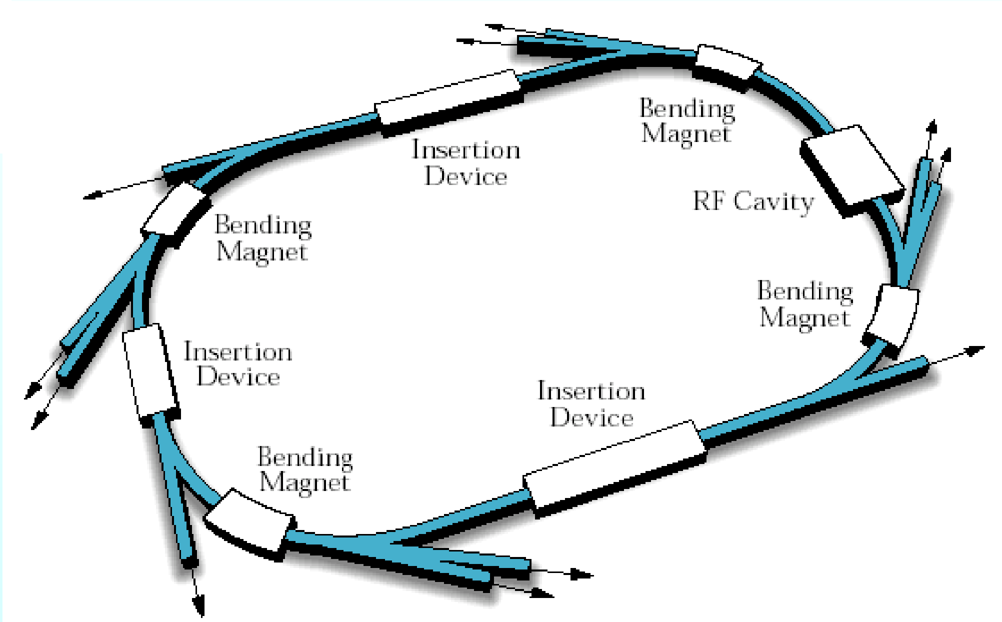
Radiation angular distribution (a) electrons travelling at low speed
(b) electrons travelling at relativistic speed ($\gamma = (1-v^2/c^2)^{-1/2} \cong 10000$ at ESRF)

Synchrotron light from a storage ring



Animation *Three types of magnetic systems*

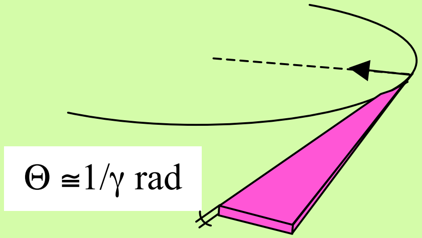

ESRF
Elettra
APS
SPring8
UHXS
700 m


Bending Magnet
Insertion Device
RF Cavity
Bending Magnet
Insertion Device
Bending Magnet
Insertion Device
Bending Magnet

Properties of synchrotron radiation

High collimation

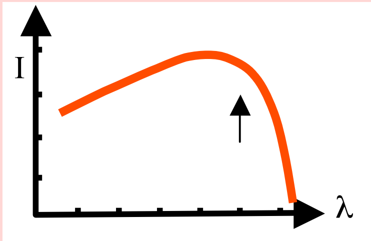
?



Bending Magnets
Wigglers
Undulators

High flux

Wide spectrum

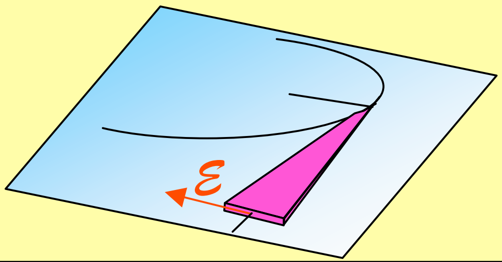


BM

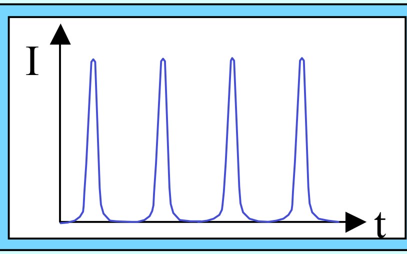
ID

Brillance

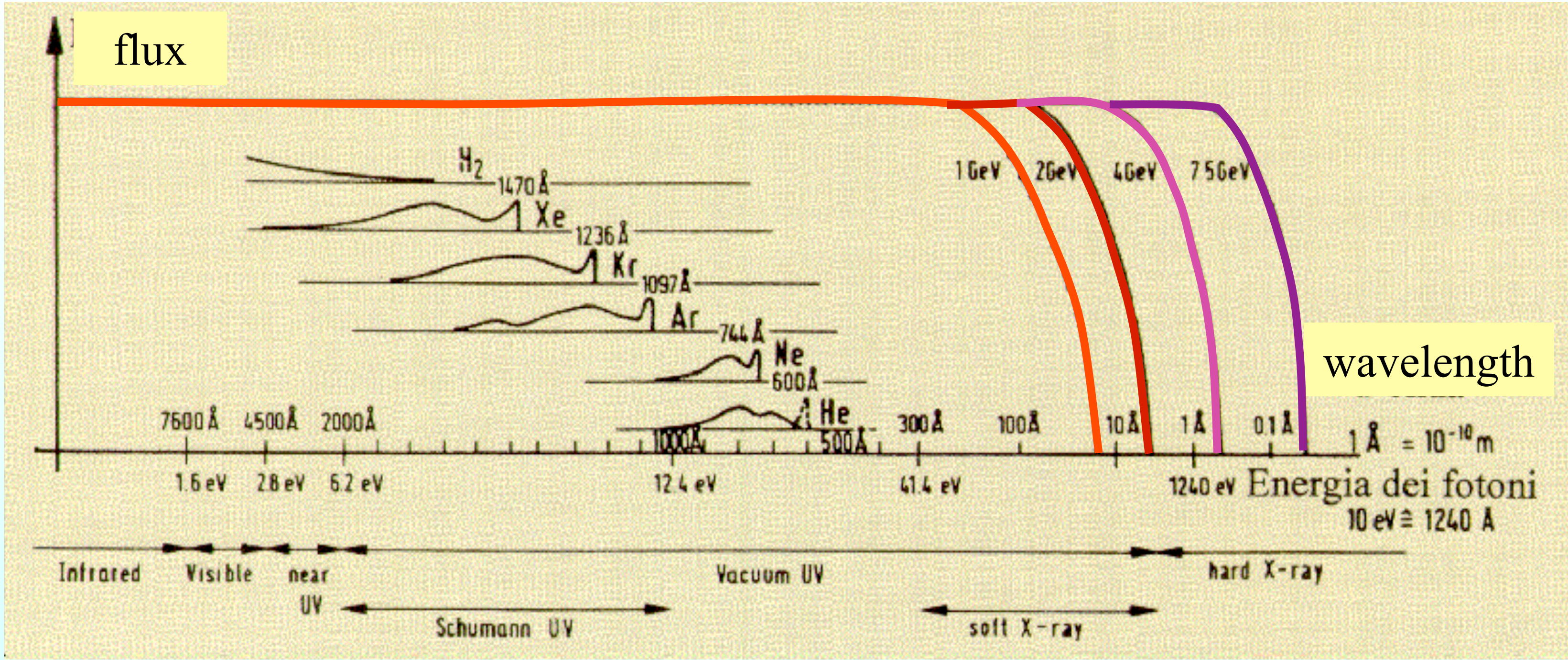
Polarization



Temporal structure

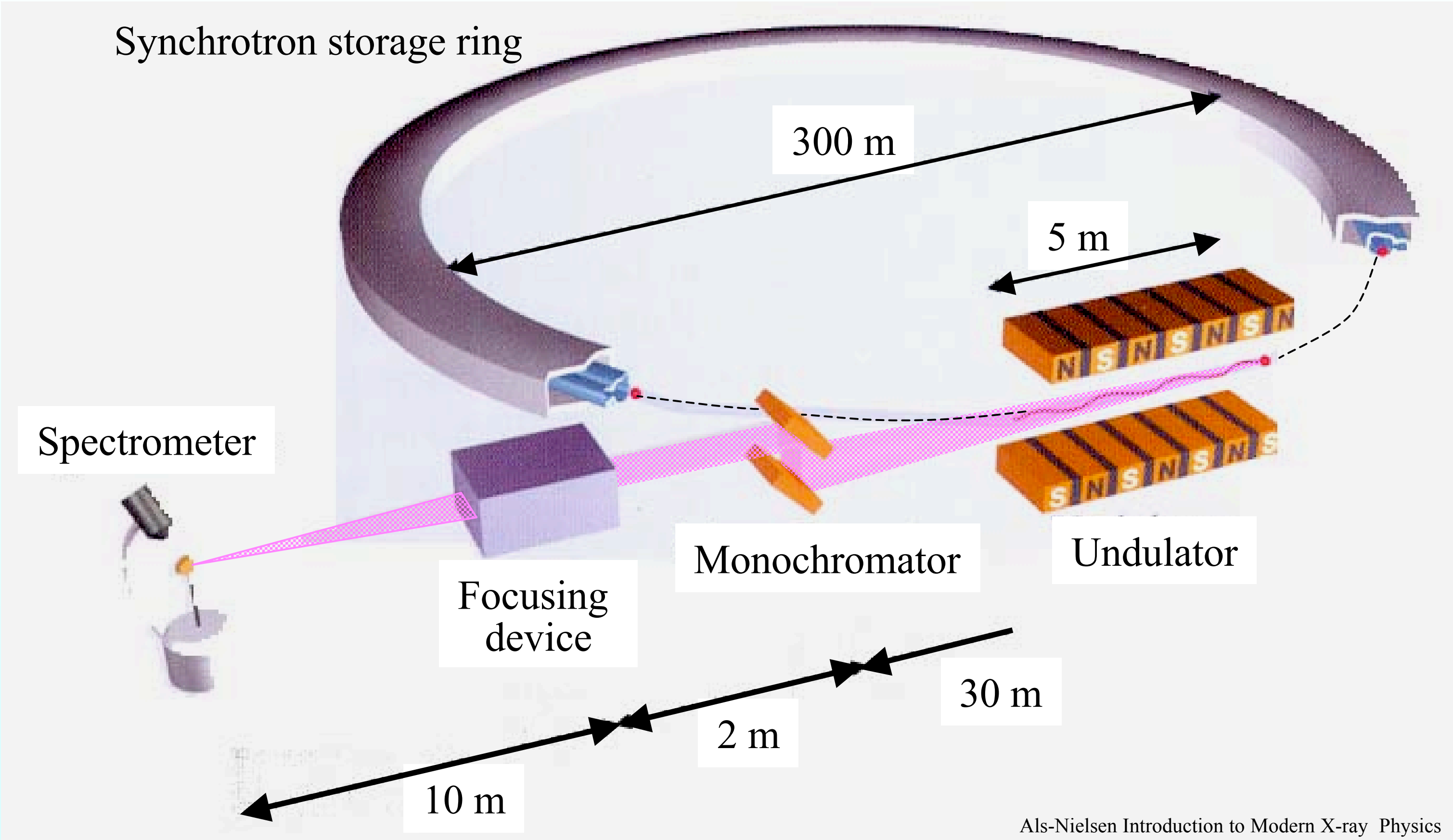


Spectral distributions of different sources



Intensity and spectral range of synchrotron radiation sources are several order of magnitude greater than those of rare gas discharge lamps.

From the magnetic device to the experimental station

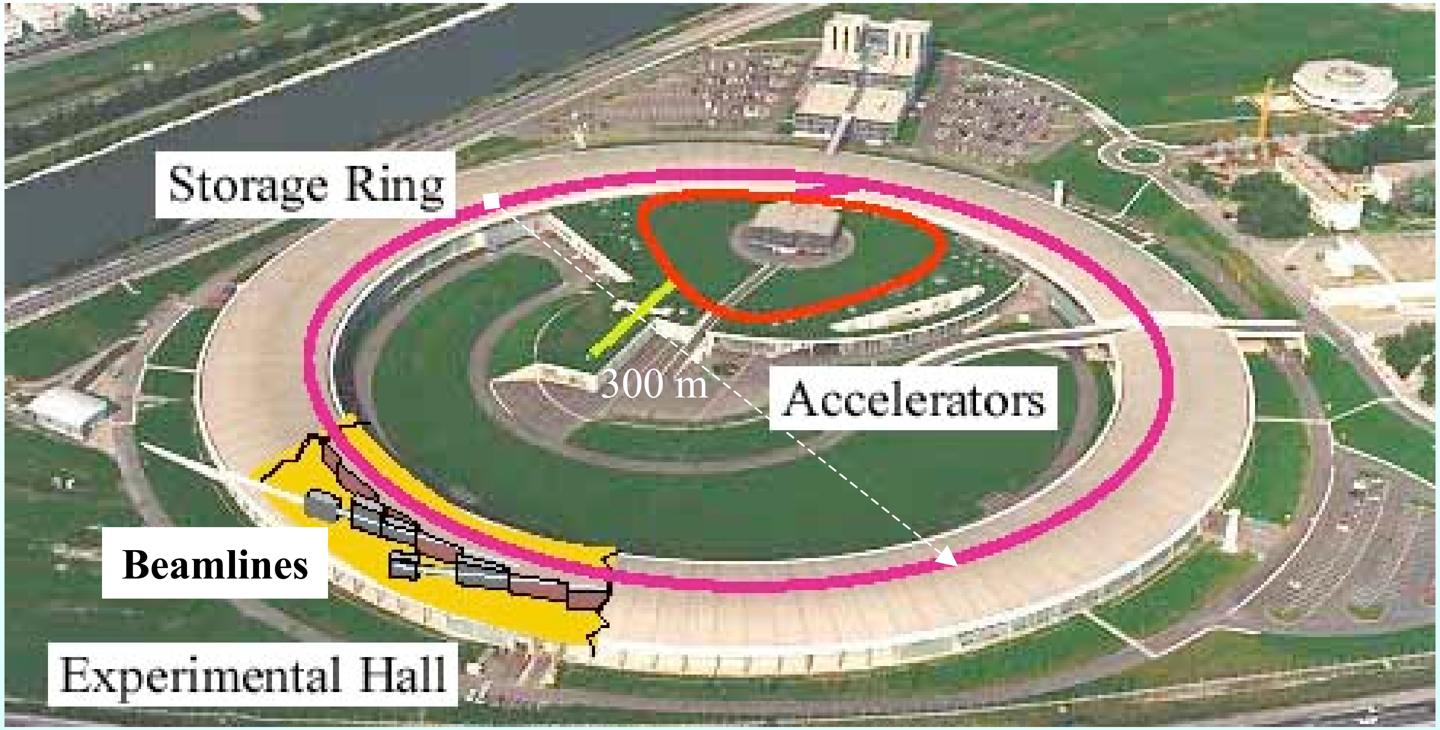


Als-Nielsen Introduction to Modern X-ray Physics

ESRF - Grenoble

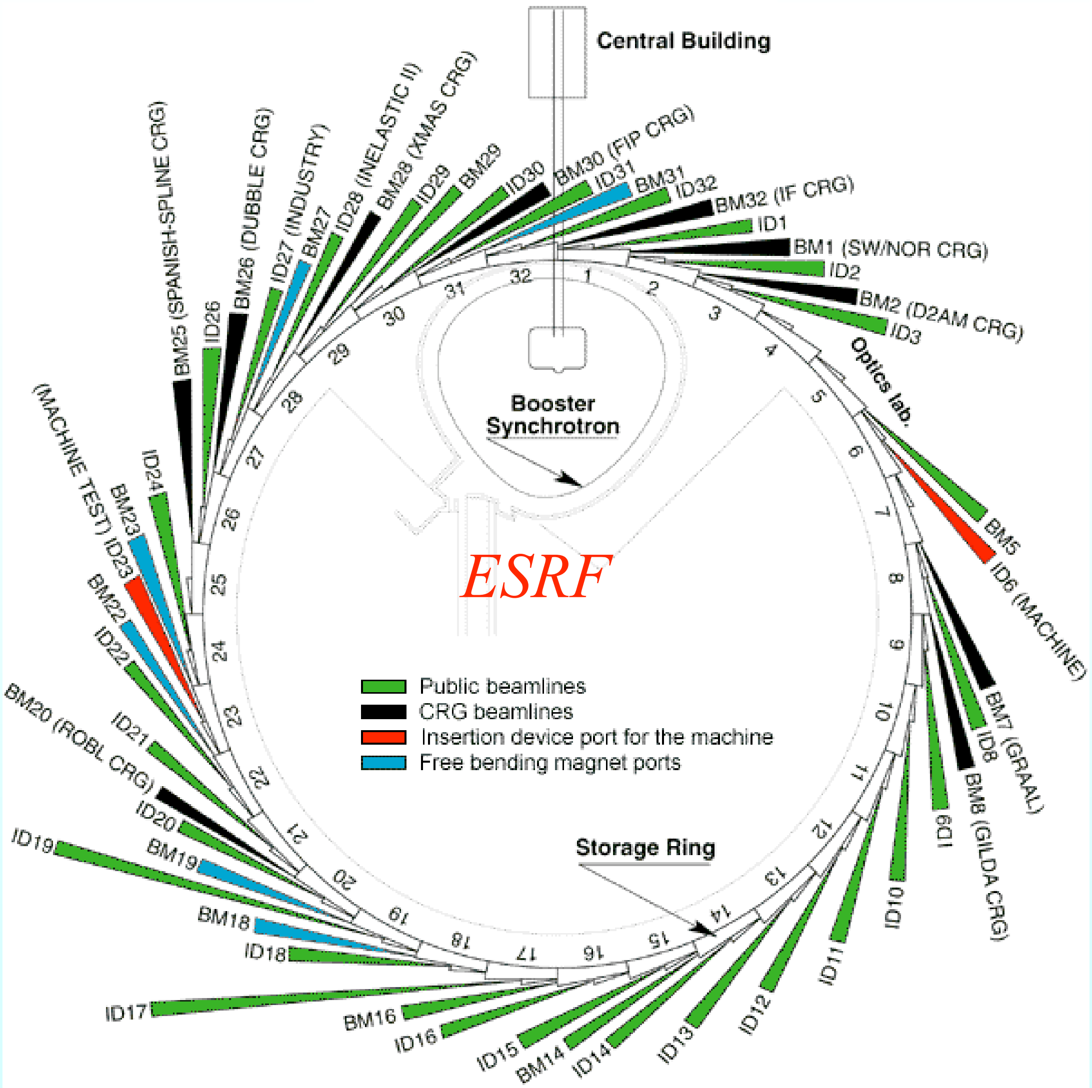
The greatest concentration of laboratories in matter Physics in Europe

The Grenoble machine

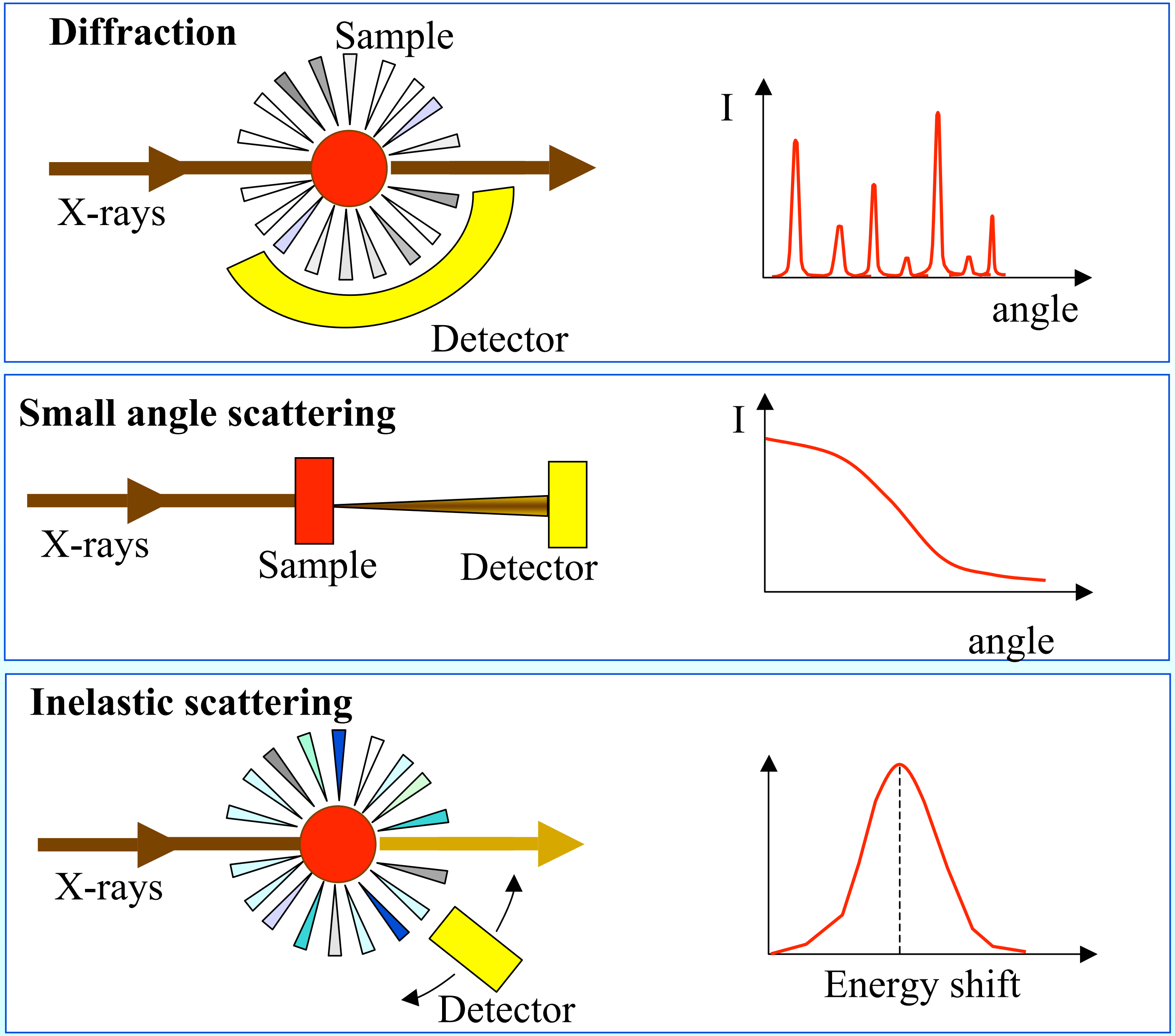


The European Synchrotron Radiation Facility (ESRF)

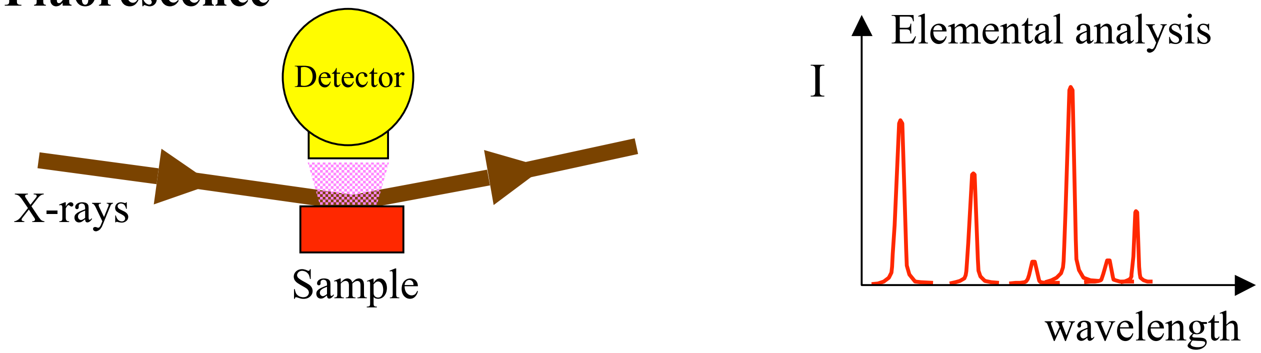
ESRF beamlines



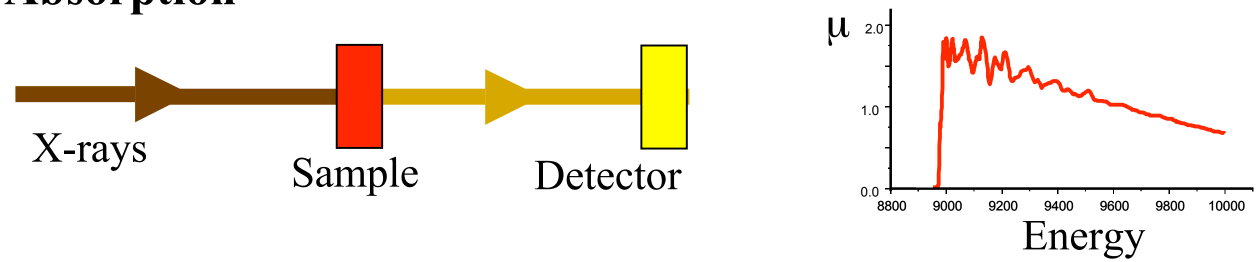
Each beamline hosts one or more specialized experimental stations


Diffraction
Sample
X-rays
Detector
I
angle
Small angle scattering
X-rays
Sample
Detector
I
angle
Inelastic scattering
X-rays
Detector
Energy shift

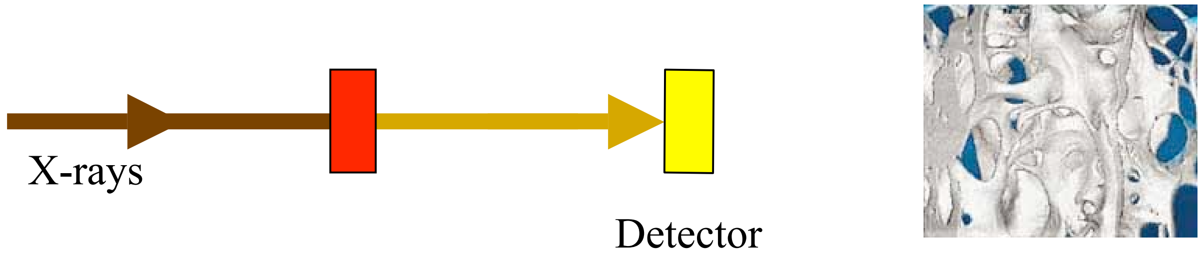
Fluorescence



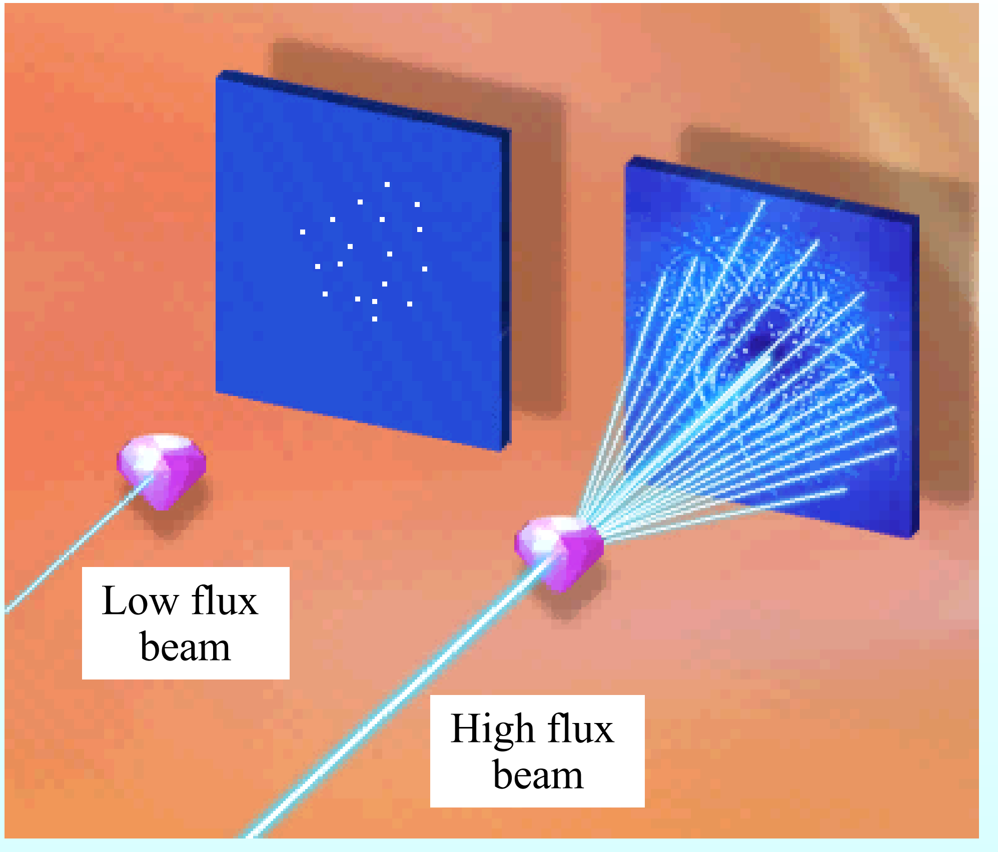
Absorption



Imaging

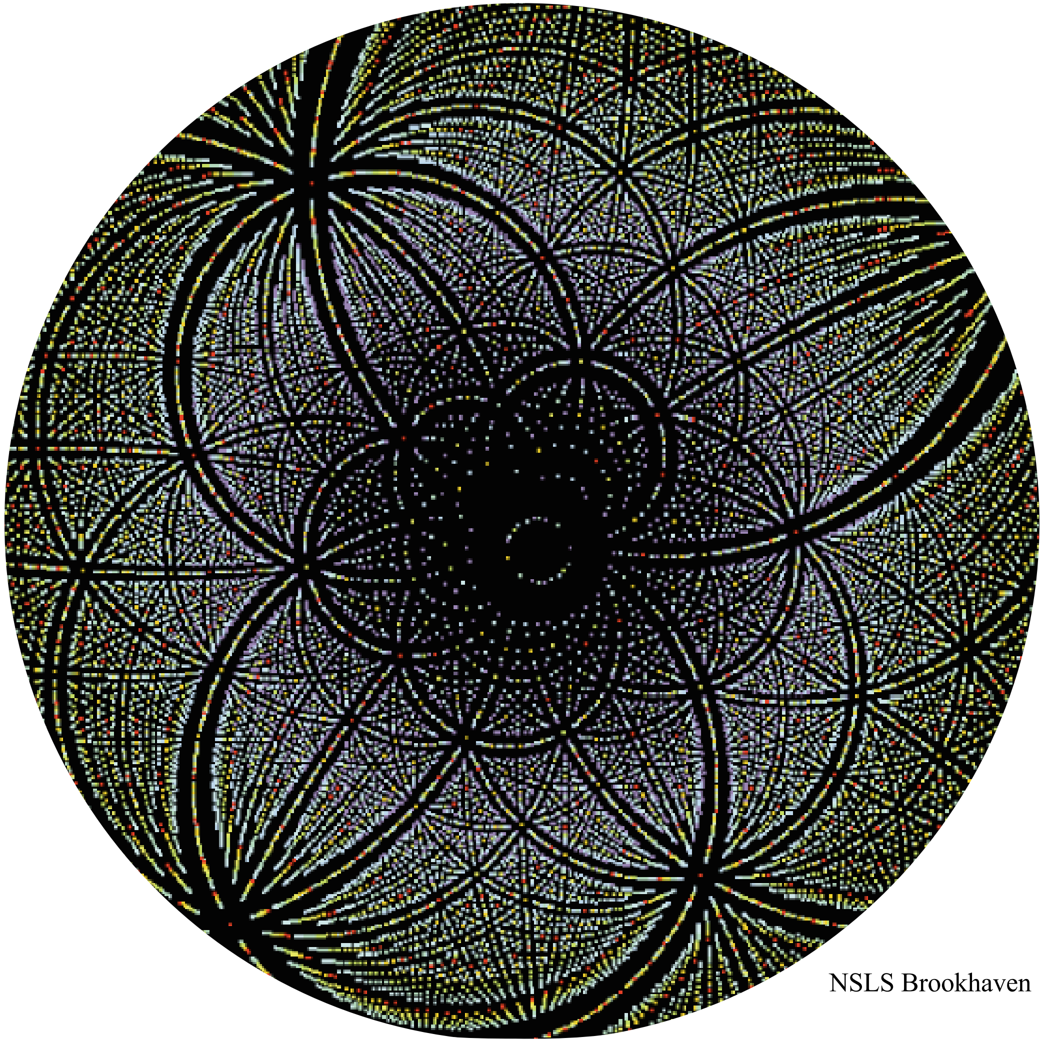


Laue Diffraction



Synchrotron light, Springer-Verlag Compact Disk 2000

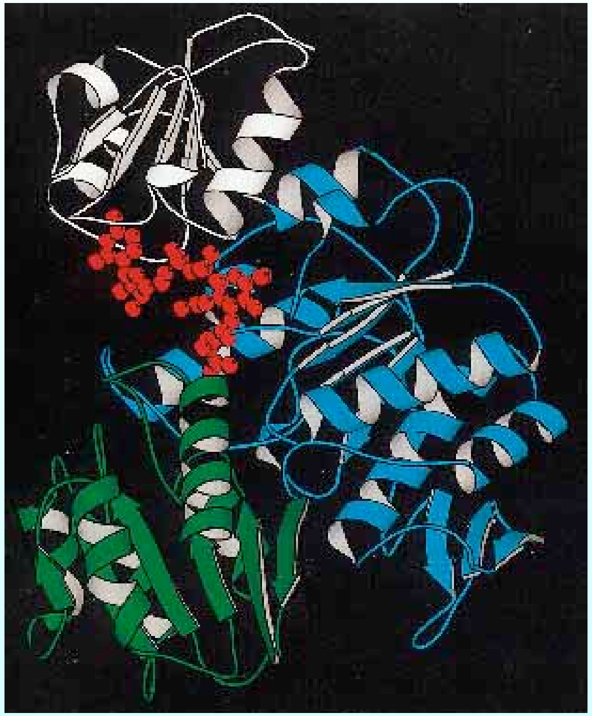
Laue pattern of a crystal of metabolic enzyme isocitrate deydrogenase

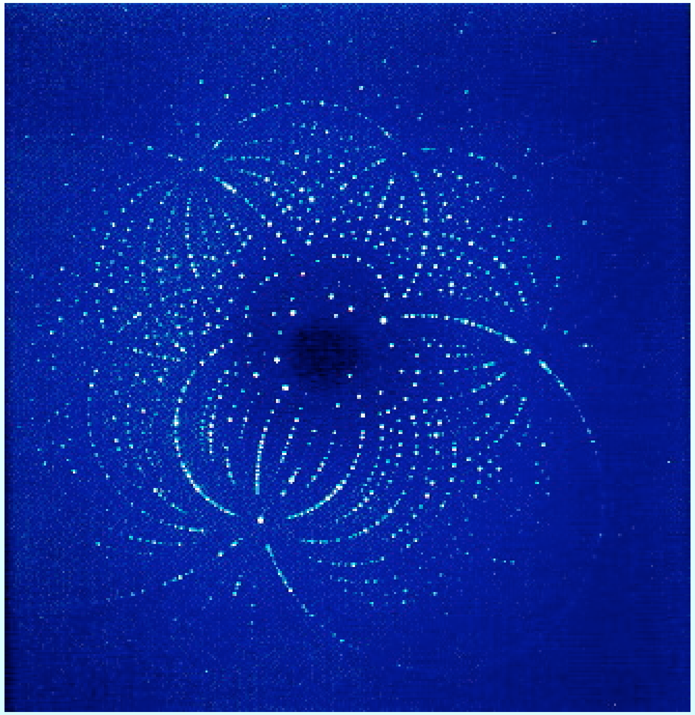

NSLS Brookhaven

Time resolved crystallography: Exposure time: 10 ms

Biology

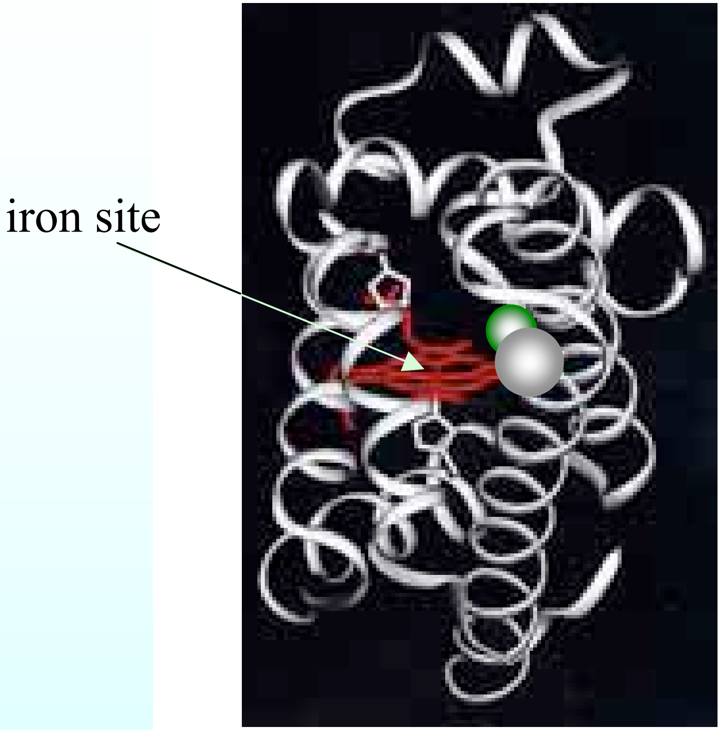
The functions of the life molecules, like proteins and nucleic acids, depend on three-dimensional atomic structure. For instance the knowledge of viruses has allowed the preparation of anti-viruses compounds to be prepared





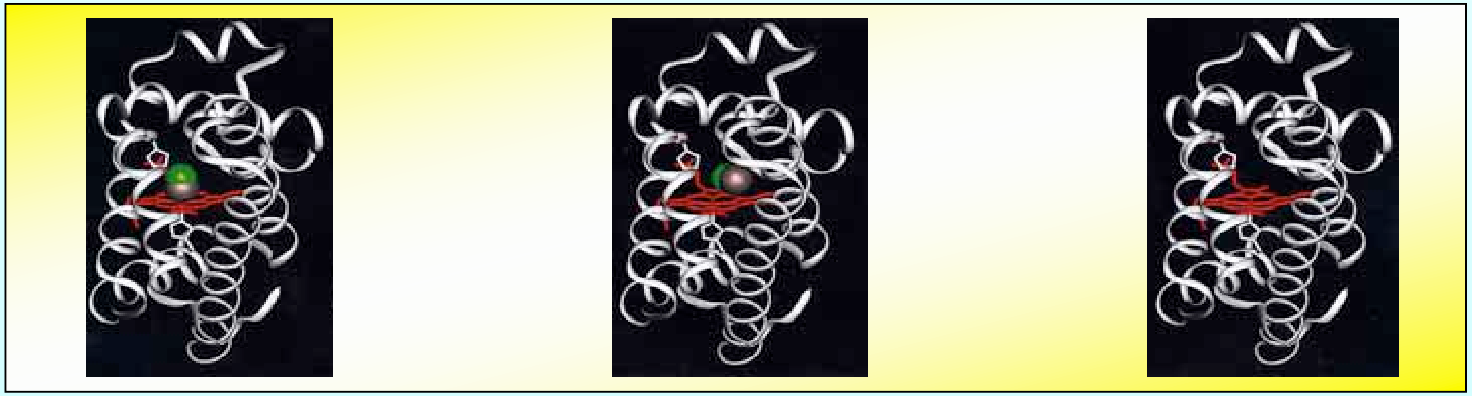
Diffraction is the technique to study the molecular structure of biological systems

Film of molecular process



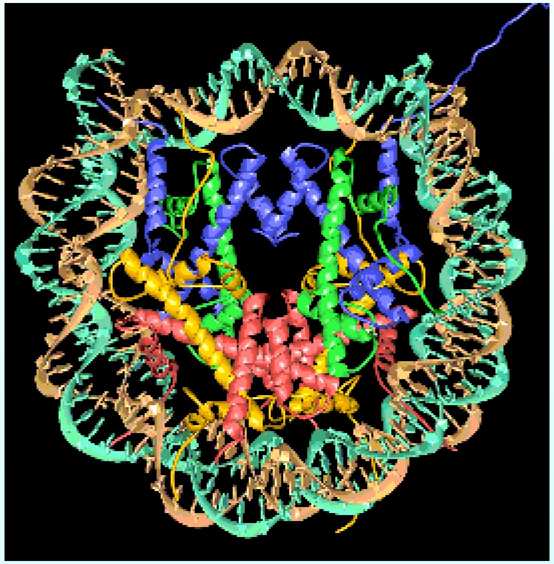
The myoglobine molecule

a CO molecule interacting with a myoglobine molecule



The life construction plan reported by the genetic code

The collection of precise information on the molecular structure of chromosomes and their components can improve the knowledge of how the genetic code of DNA is maintained and reproduced



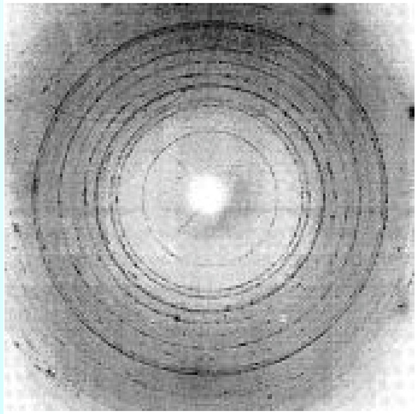
Reconstruction of the molecular structure of nucleosome with a resolution of .2 nm

Study o materials under extreme conditions

High pressures and temperatures

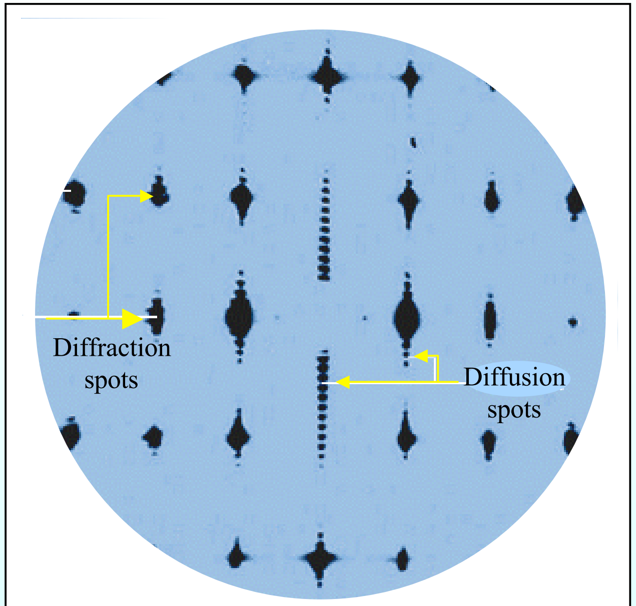
Cella di diamante

In laboratory it is possible to reach pressures of some milions of atm (100 Gpa) comparable with those present in the Earth nucleus



Iron is the dominant element present in the nucleus of the Earth. The knowledge of iron properties at high temperature and pressure is fundamental for Earth science. At ESRF a new orthorombic phase of Fe has been discovered at 45 GPa and 2100 K

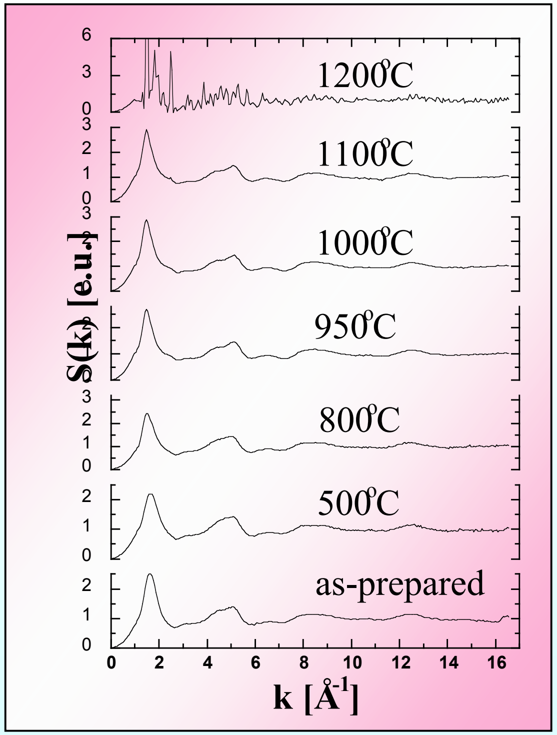
Diffuse scattering in crystalline materials



Synchrotron light - Springer Verlag

Unexpected diffusion peaks appear in a diffraction pattern of a non perfect crystalline structures.

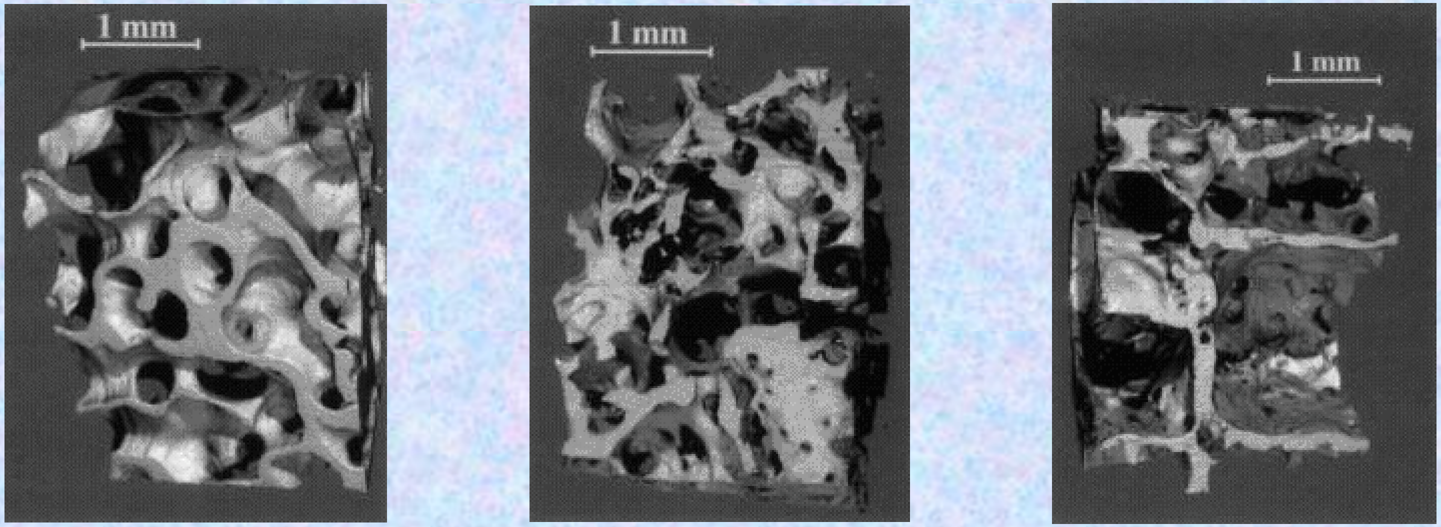
Diffuse scattering in amorphous materials



The structure factors for pure silica gel samples treated at different temperatures starting from the as-prepared to 1200°C.

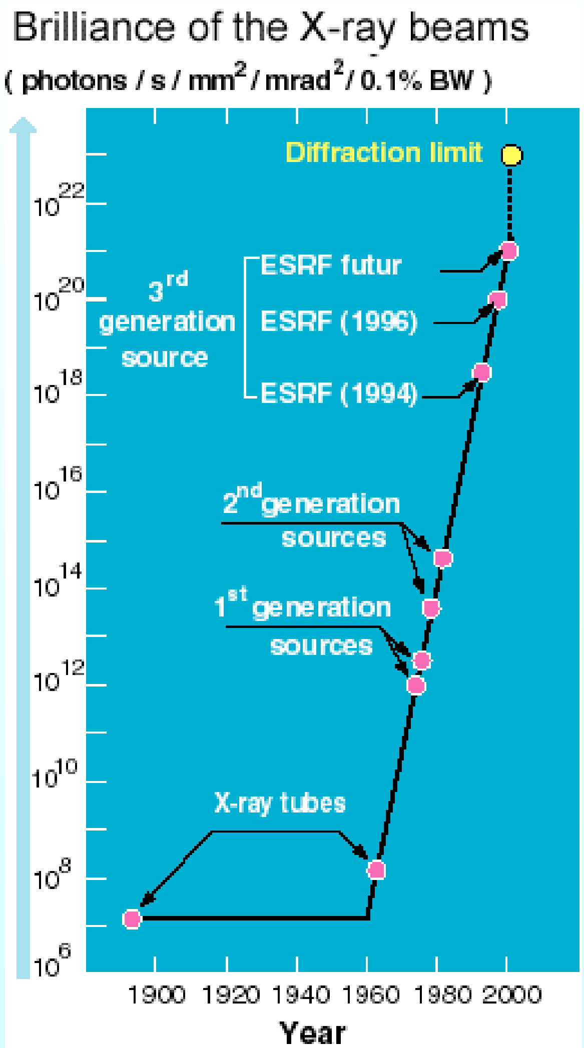
WAXS measurements can be carried out in short time at various conditions of temperature and pressure.

X-ray ray micro-tomography

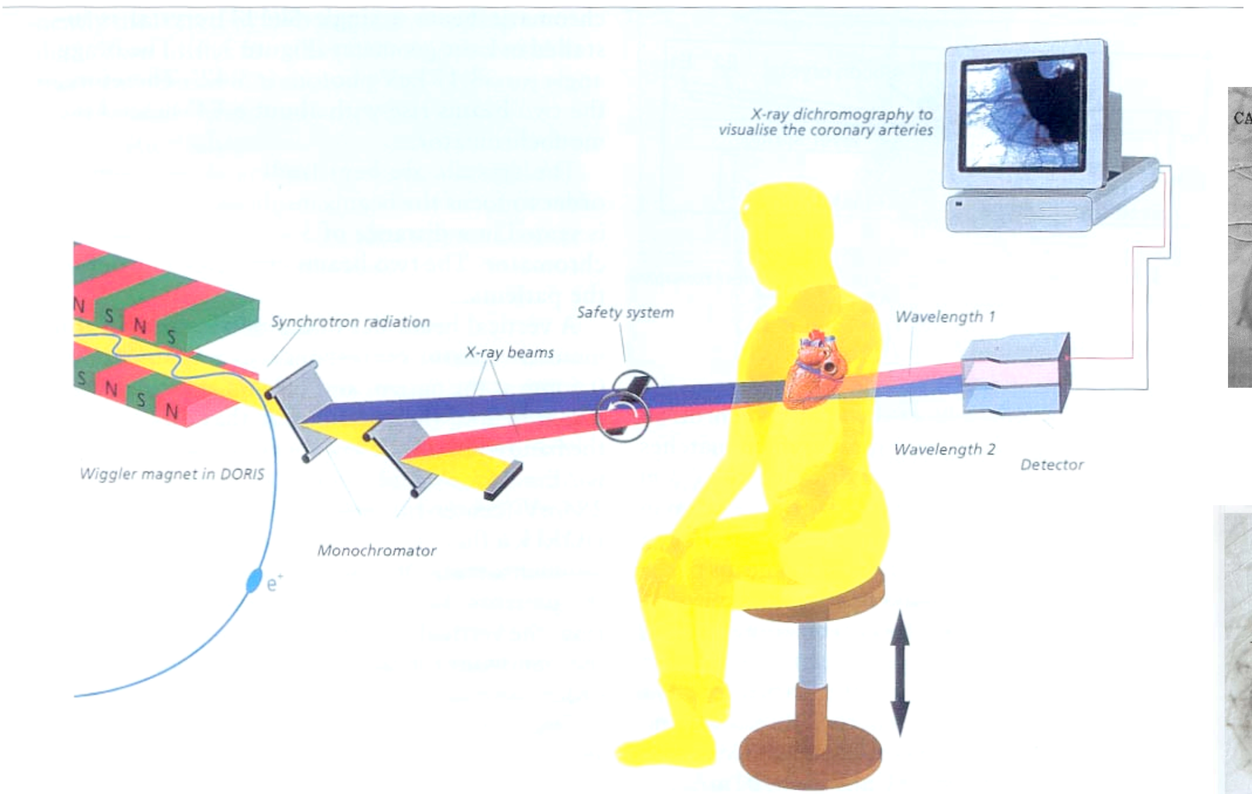


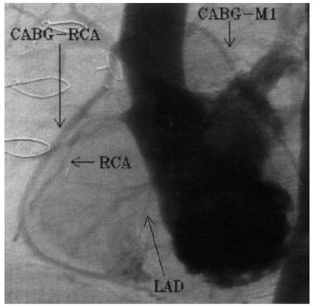
Micro tomogram of iliac crest bone from a female patient undergoing haemodialysis. The three images are of biopsies taken at three ages, 24, 27 and 32 years. The severe loss of bone mass is apparent.
The ratios of bone volume to total volume fell from 29.6% to 23.7% between the ages of 24 and 32

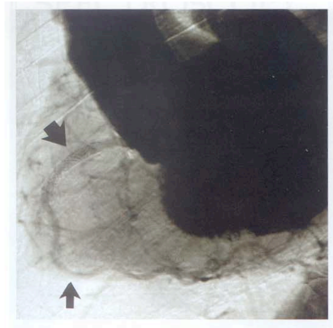
The brilliance versus time



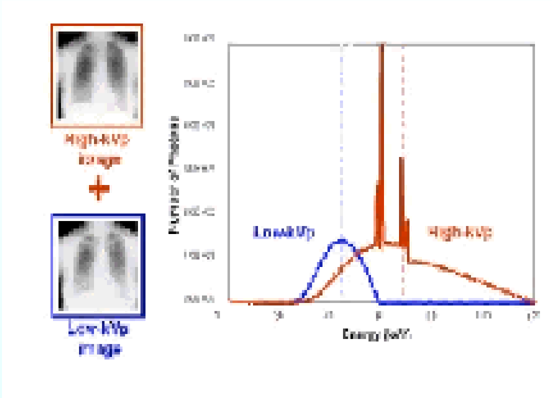
Coronaric angiography

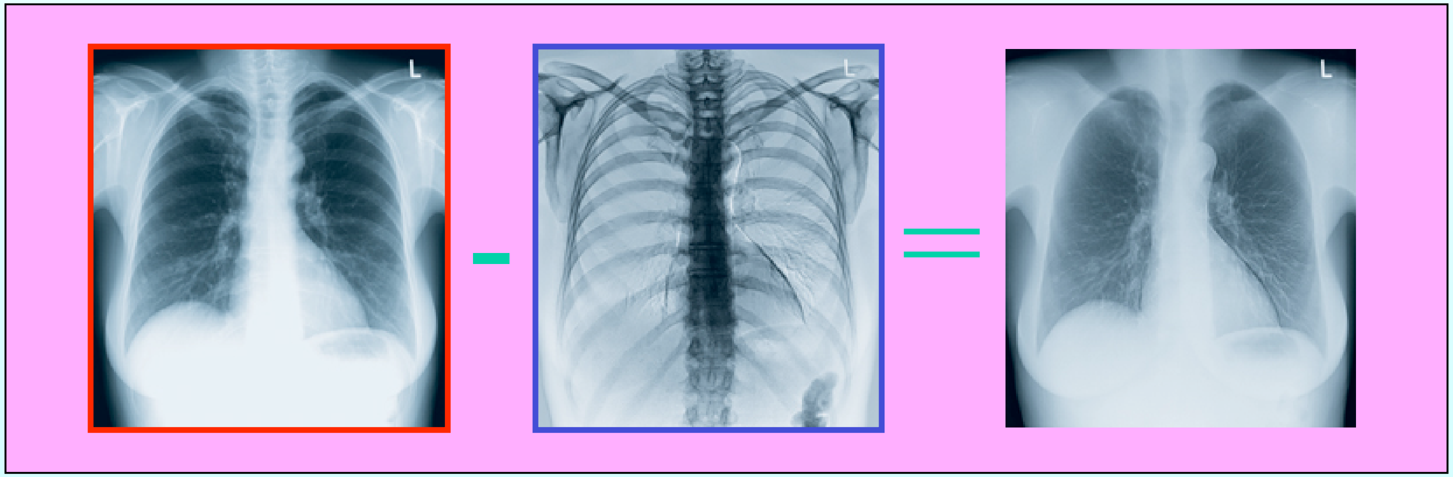




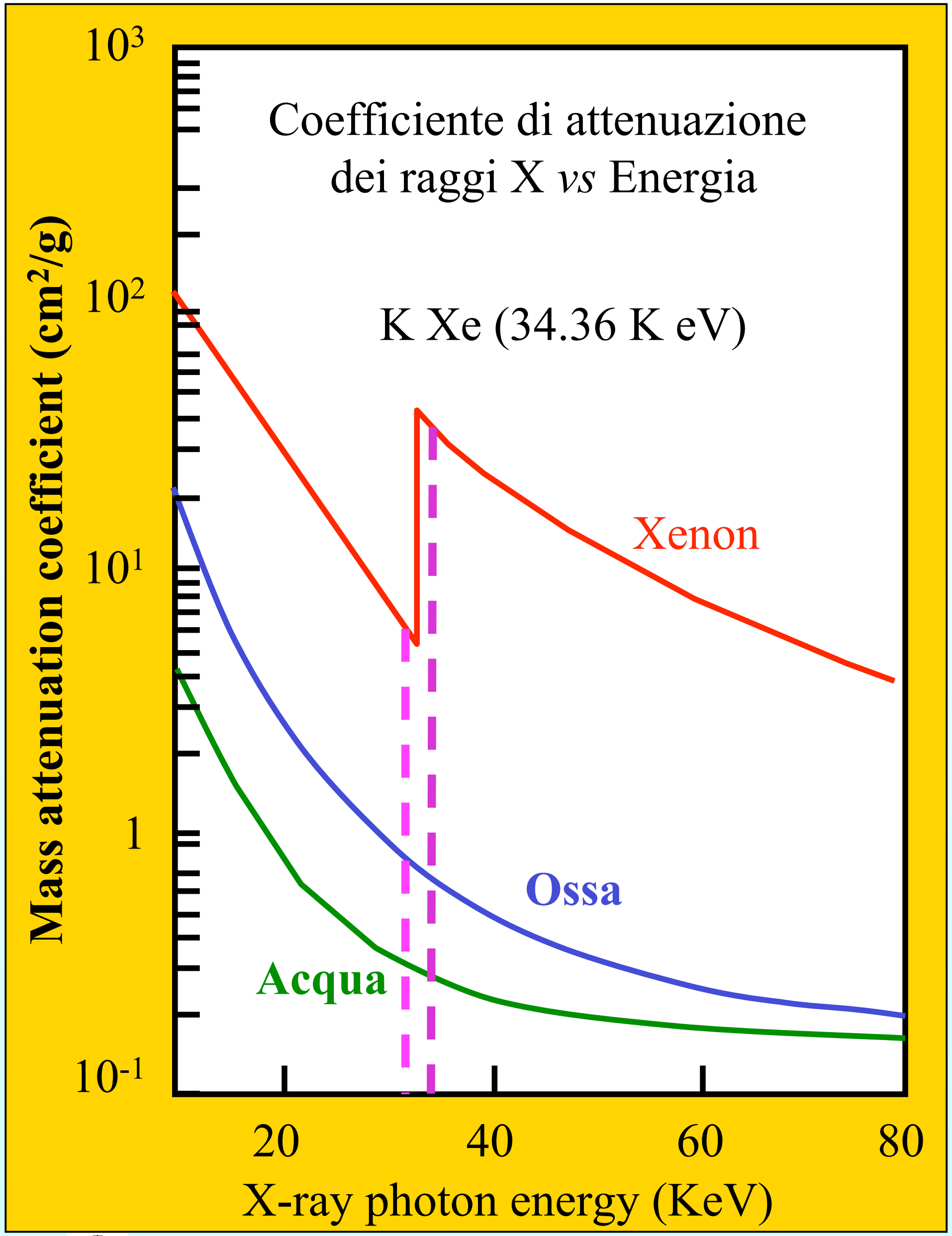


Dual Energy Subtraction Radiography





Dual Energy Subtraction with contrast element



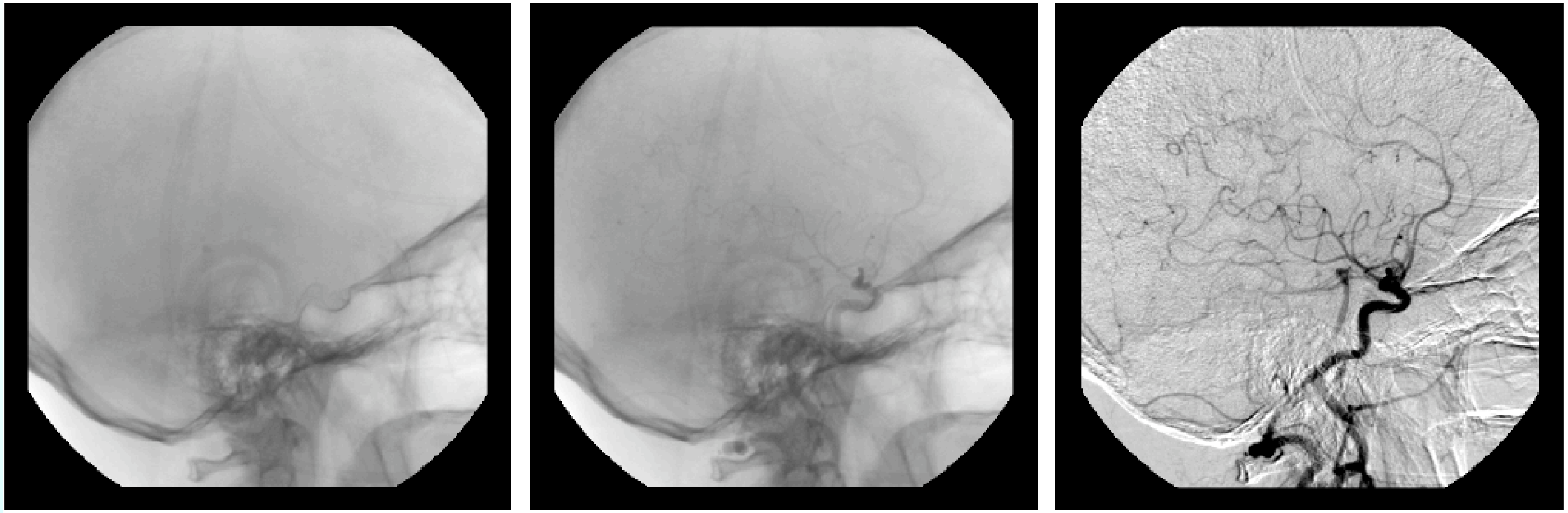
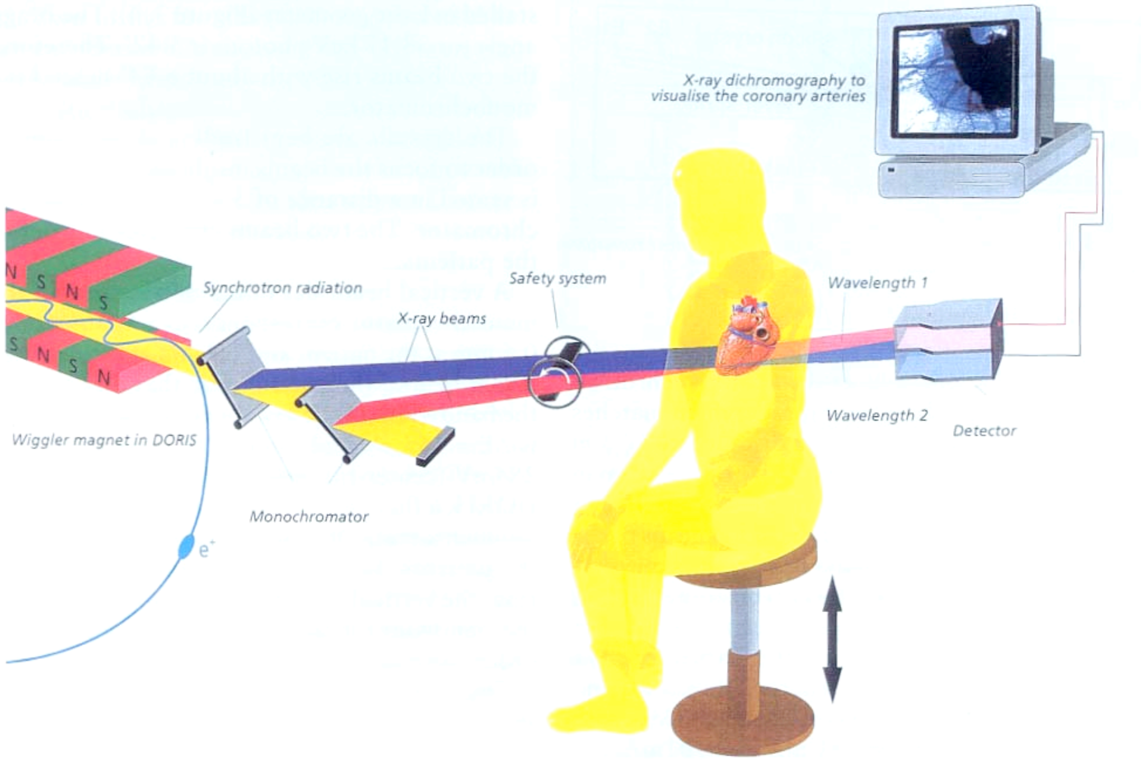
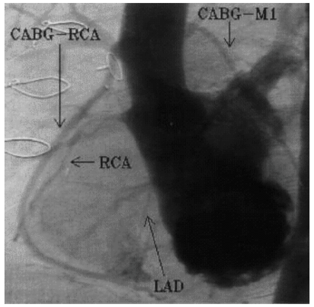
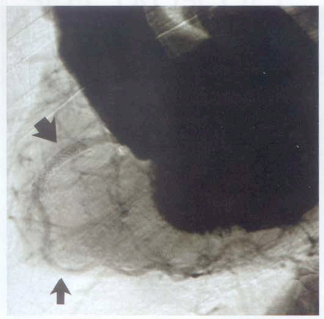


Figure 1: An example of motion artifacts in a cerebral DSA image (right), obtained by subtraction of the mask image (left) from the contrast image (middle), and subsequent image-contrast enhancement. The artifacts appear as black and white structures.

Coronary Angiography







BRONCHOGRAPHY

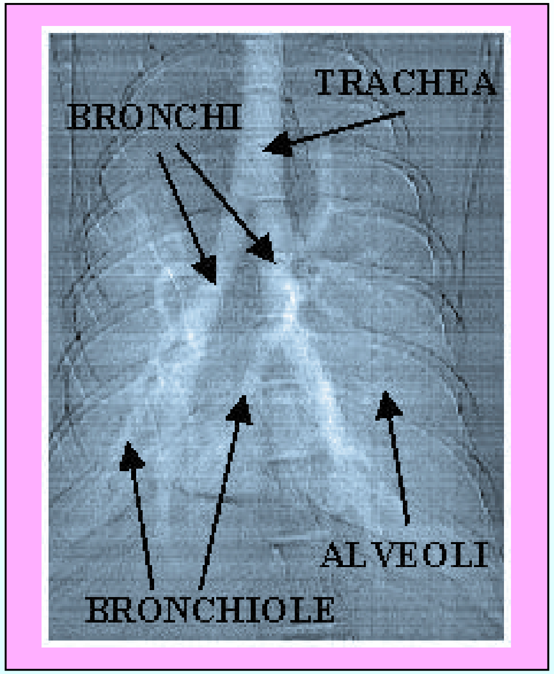
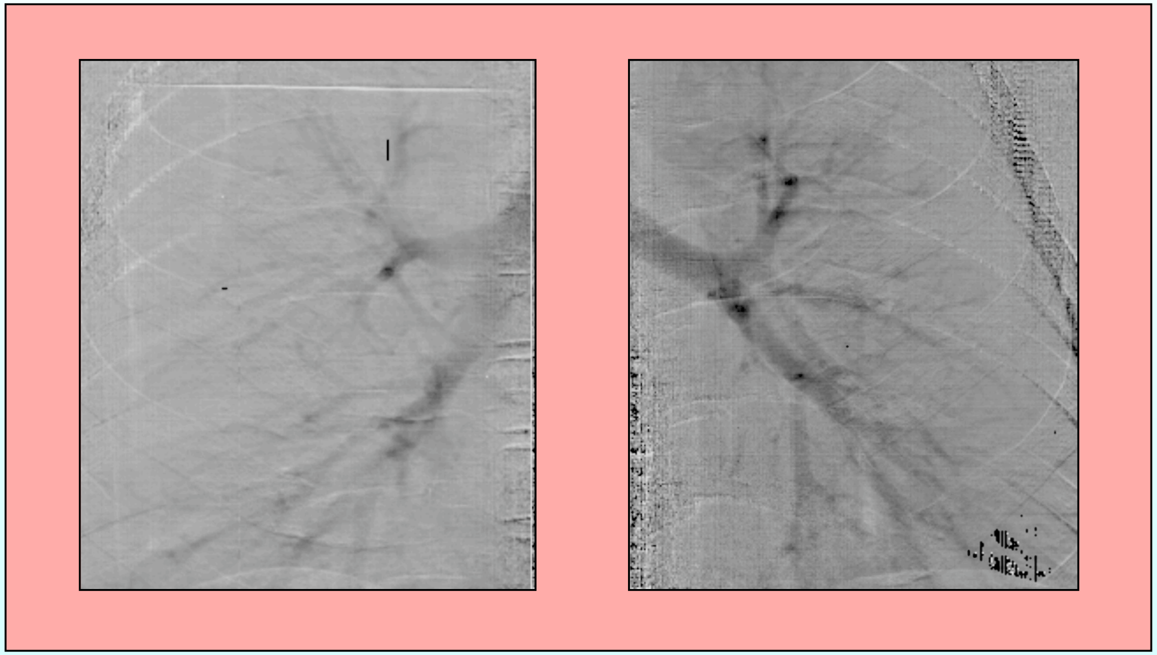
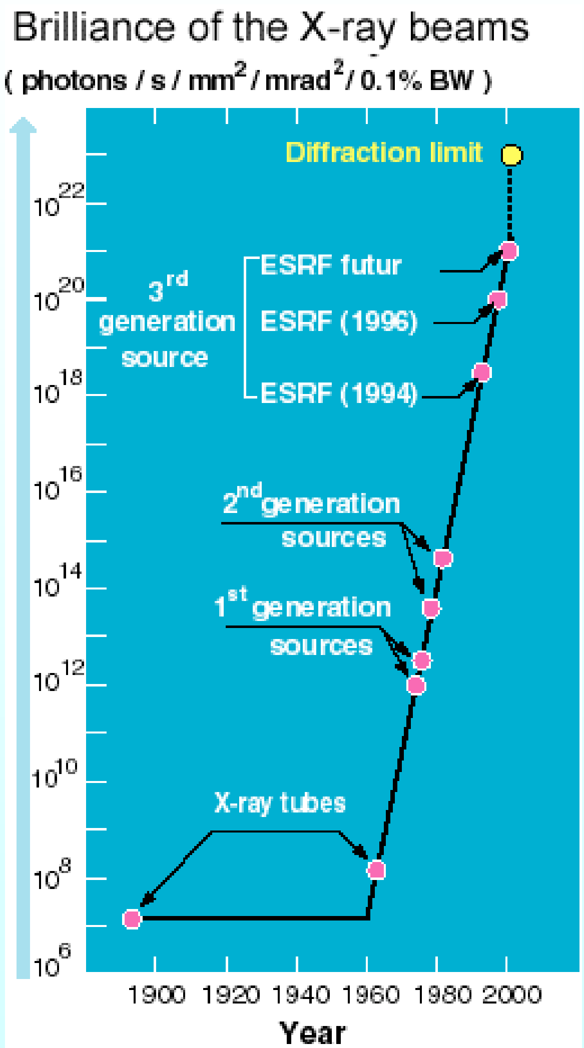


Immagine *in vivo* ottenuta mediante sottrazione digitale dei polmoni di un topo mostrante la distribuzione dell'agente di contrasto, Xenon, nell'albero bronchiale.

L'obiettivo è di vedere I dettagli morfologici dei bronchi ed il riempimento degli alveoli Durante il ciclo respiratorio in presenza di xenon nelle vie respiratorie.



The brilliance versus time



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100 anni di Raggi X, 2001, P. Fornasini, Università dgli Studi di Trento Dipartimento di Fisica, Compact Disk, 2001

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http://www. sesame.htm

http://www.esrf.fr (web site of European Synchrotron Radiation Facility, Grenoble, France)

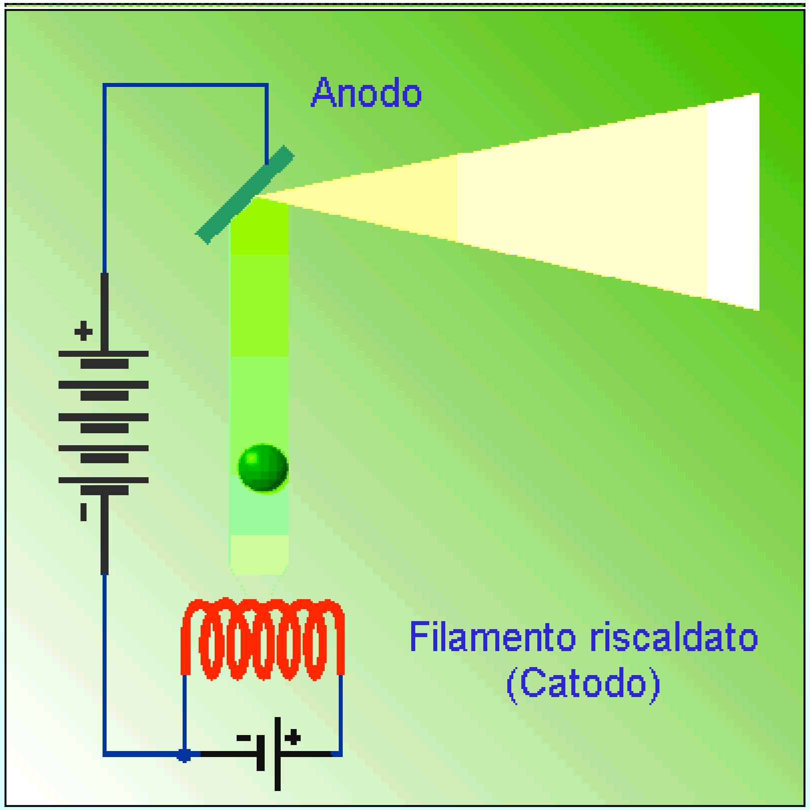
http://www.lbl.gov/MicroWorlds/ALSTool/ (web site of theAdvanced Light Source)

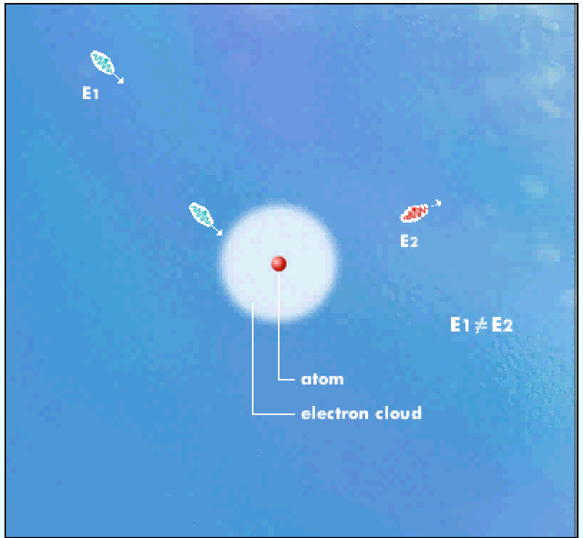
Time Resolved Macromolecular Crystallography, Physics Today, 54 (2001) 33.
Mr. Tompkins in paperback by G. Gamow

J Als-Nielsen, Des McMorrow *Elements of modern X-ray Physics* Wiley

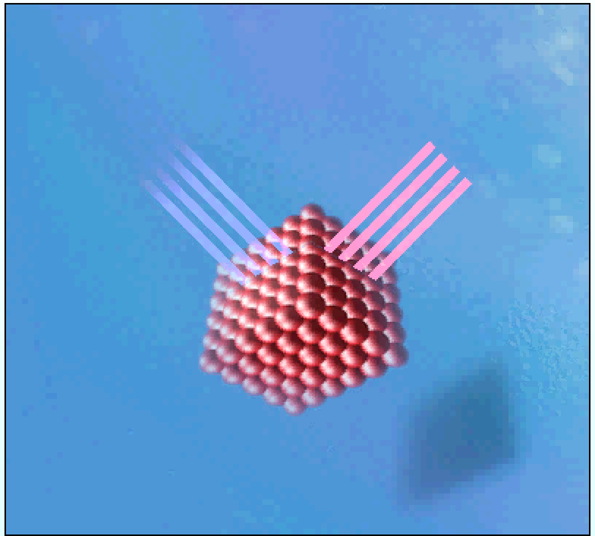

Trento
Trieste
Milan
Venice
Florence
Italy
Rome
Naples
Sardinia
Cagliari
Palermo
Sicily

Emission from an x-ray tube



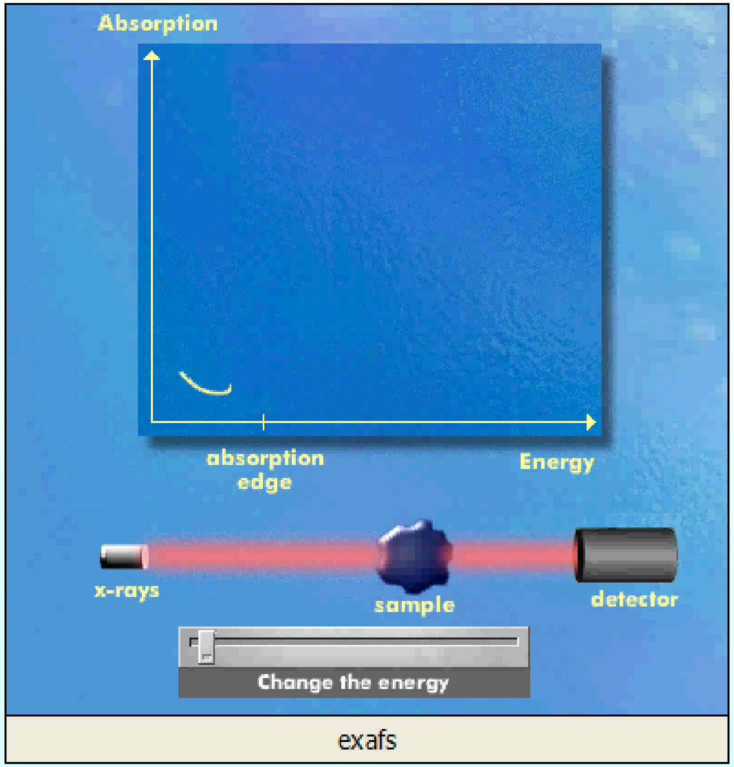


inelastic_scattering



inelastic scattering1

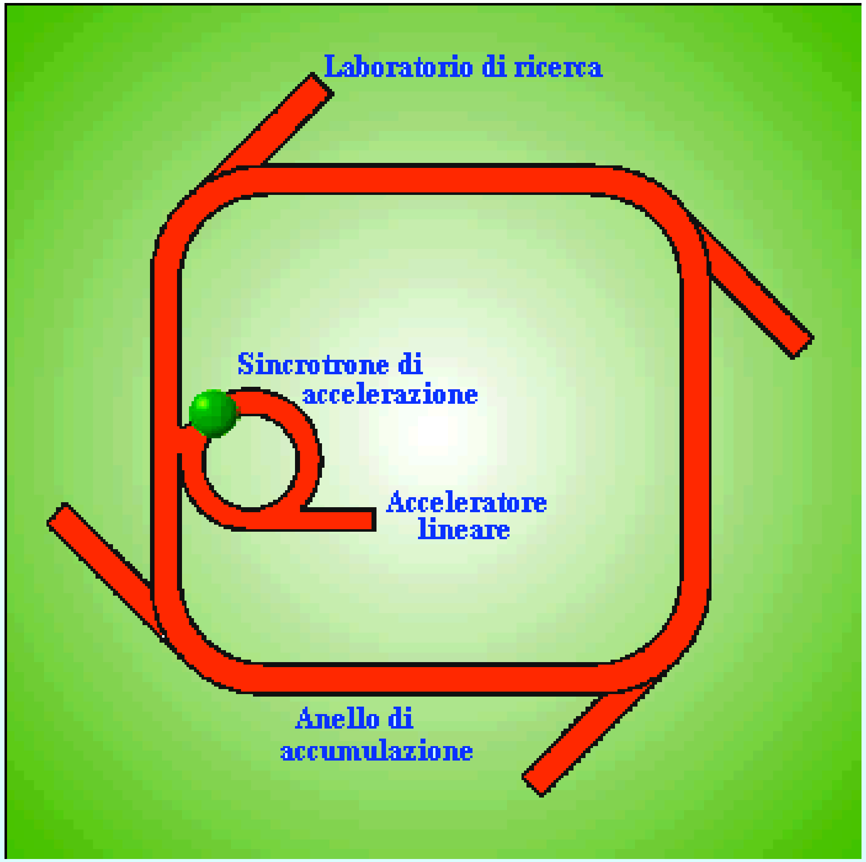
Synchrotron light, Springer-Verlag Compact Disk 2000



Synchrotron light, Springer-Verlag Compact Disk 2000

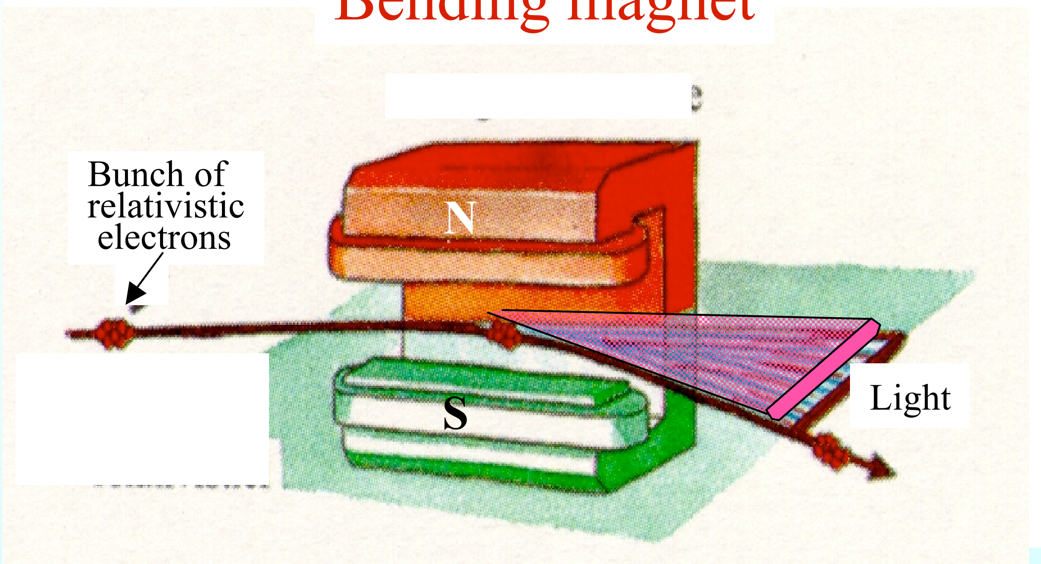
Giuseppe Dalba, University of Trento, Italy

Charged particles in accelerated motion radiate



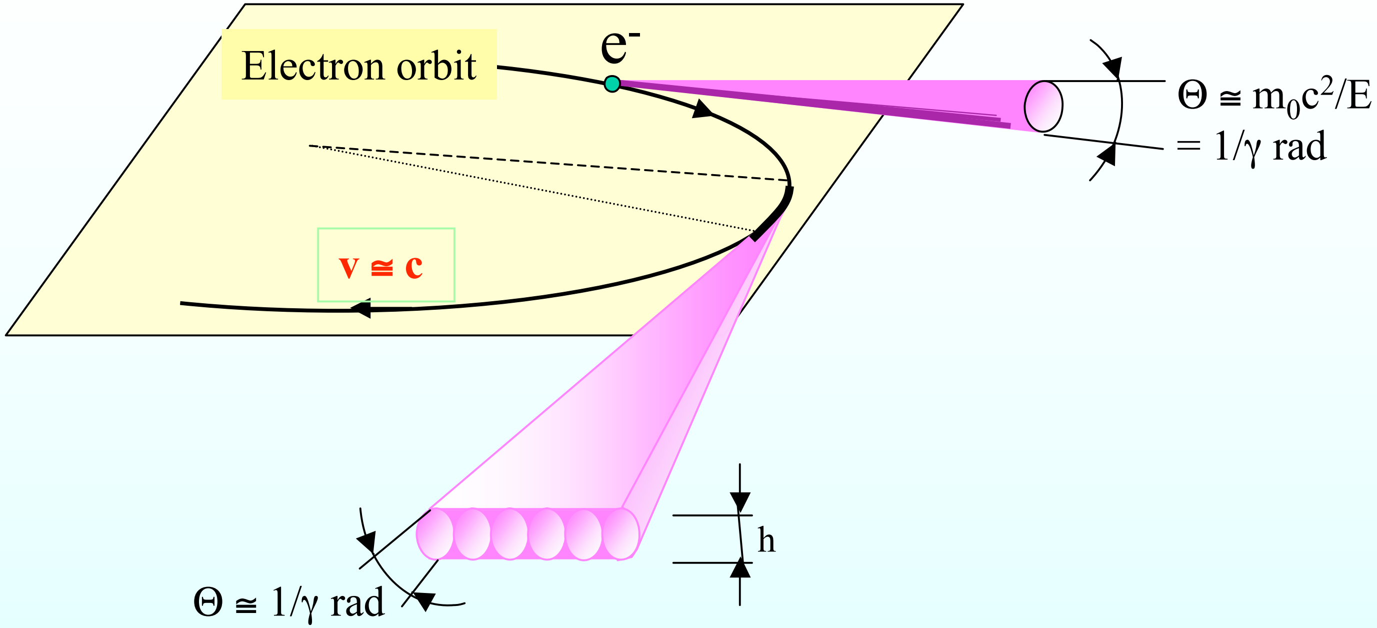
Storage ring

Bending magnet



Storage ring

Angular divergence

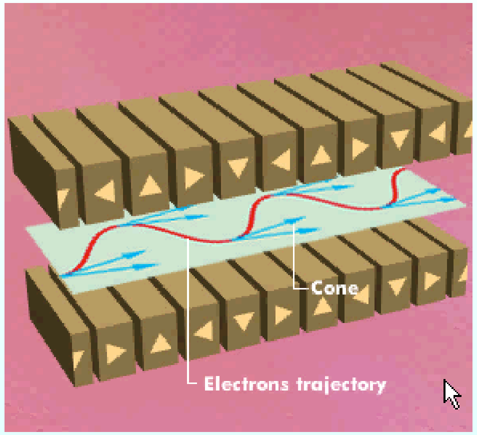


The beam collimation is defined as the photon opening angle $\Theta \cong 1/\gamma$ rad.
For GeV electrons Θ can be smaller than 0.1 m rad. It means that at 100 m from the source the vertical dimension of the beam, h, is 1 cm.

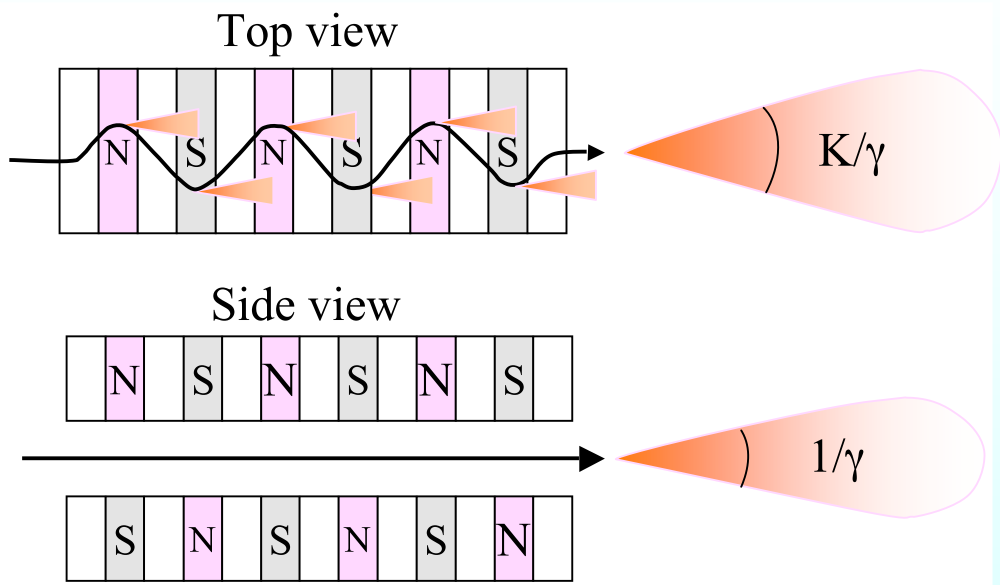
Horizontally the beam opens as a fan. A very thin sheet of light spreads out from the orbit on the orbital plane.

Properties

Wiggler



Synchrotron light, Springer-Verlag Compact Disk 2000

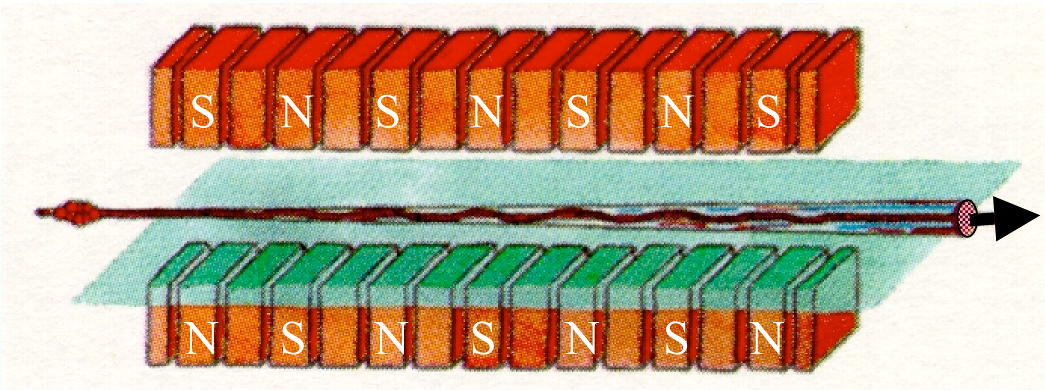


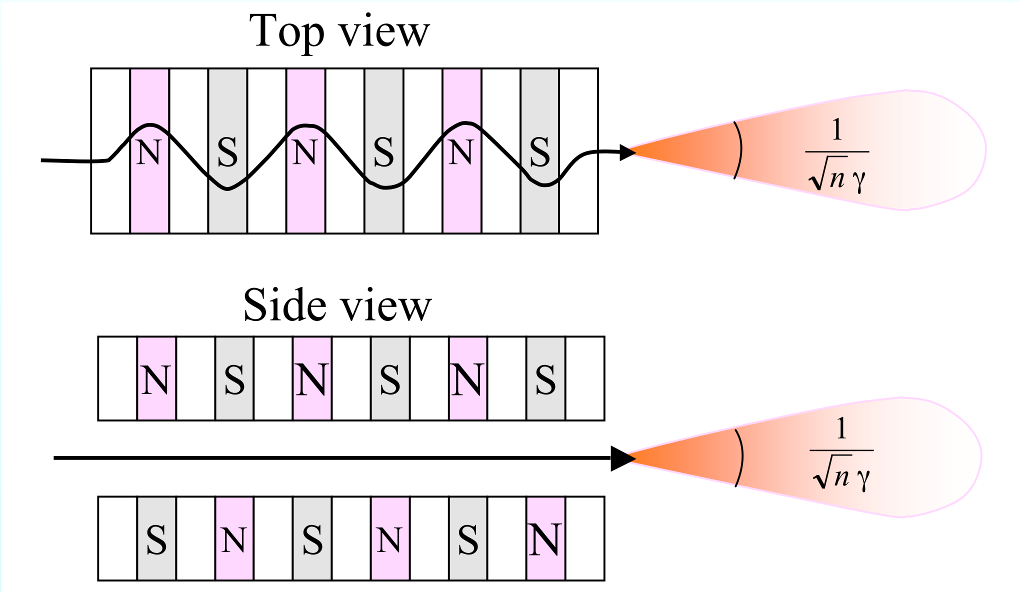
Storage ring

Properties

Radiation from a wiggler: the horizontal opening is higher than the vertical one: K is around 20 for a wiggler

Undulator





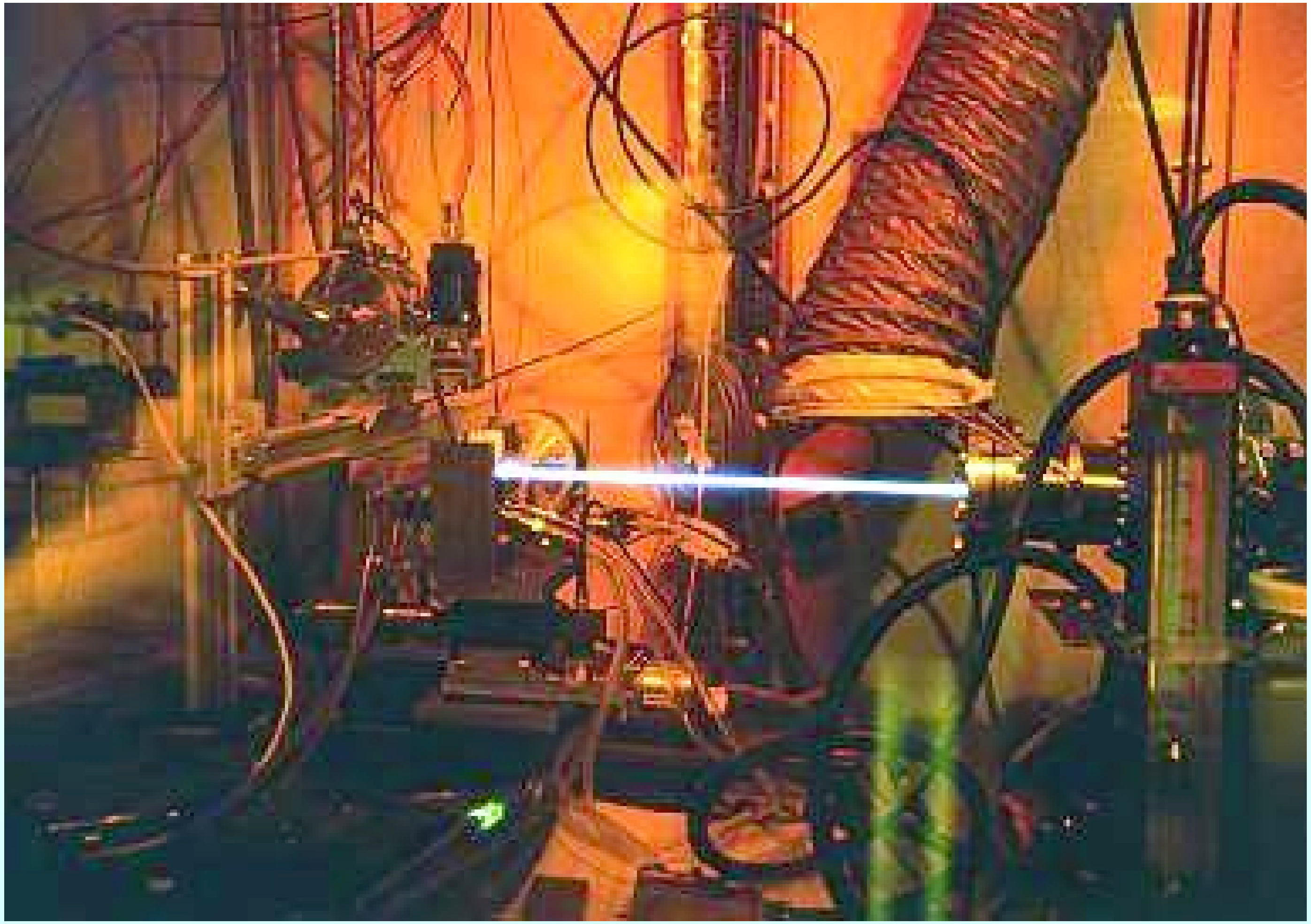
Collimation, Why?

Storage ring

Properties

Radiation from an undulator: typically N = 50

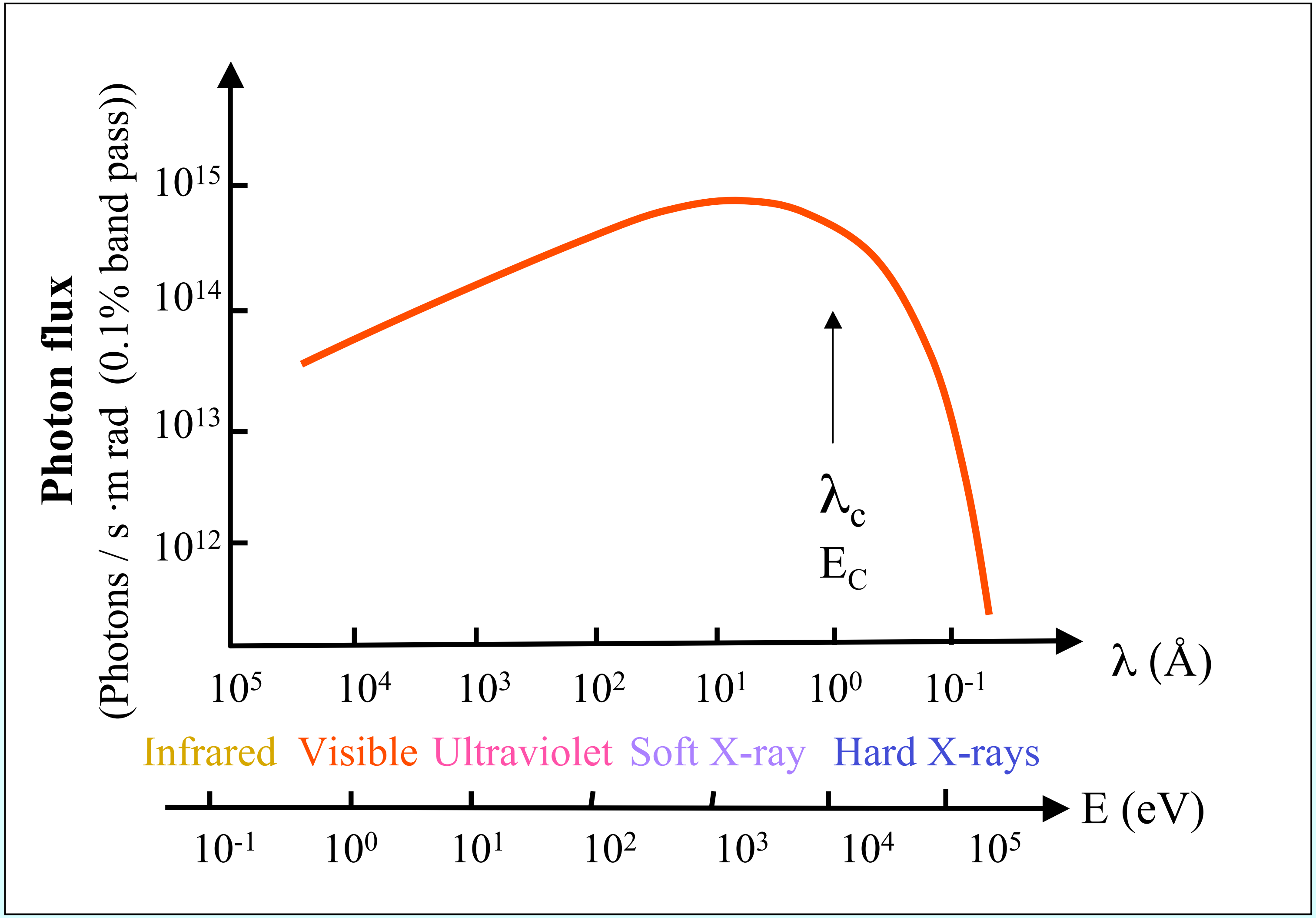
An X-ray beam at the ESRF facility



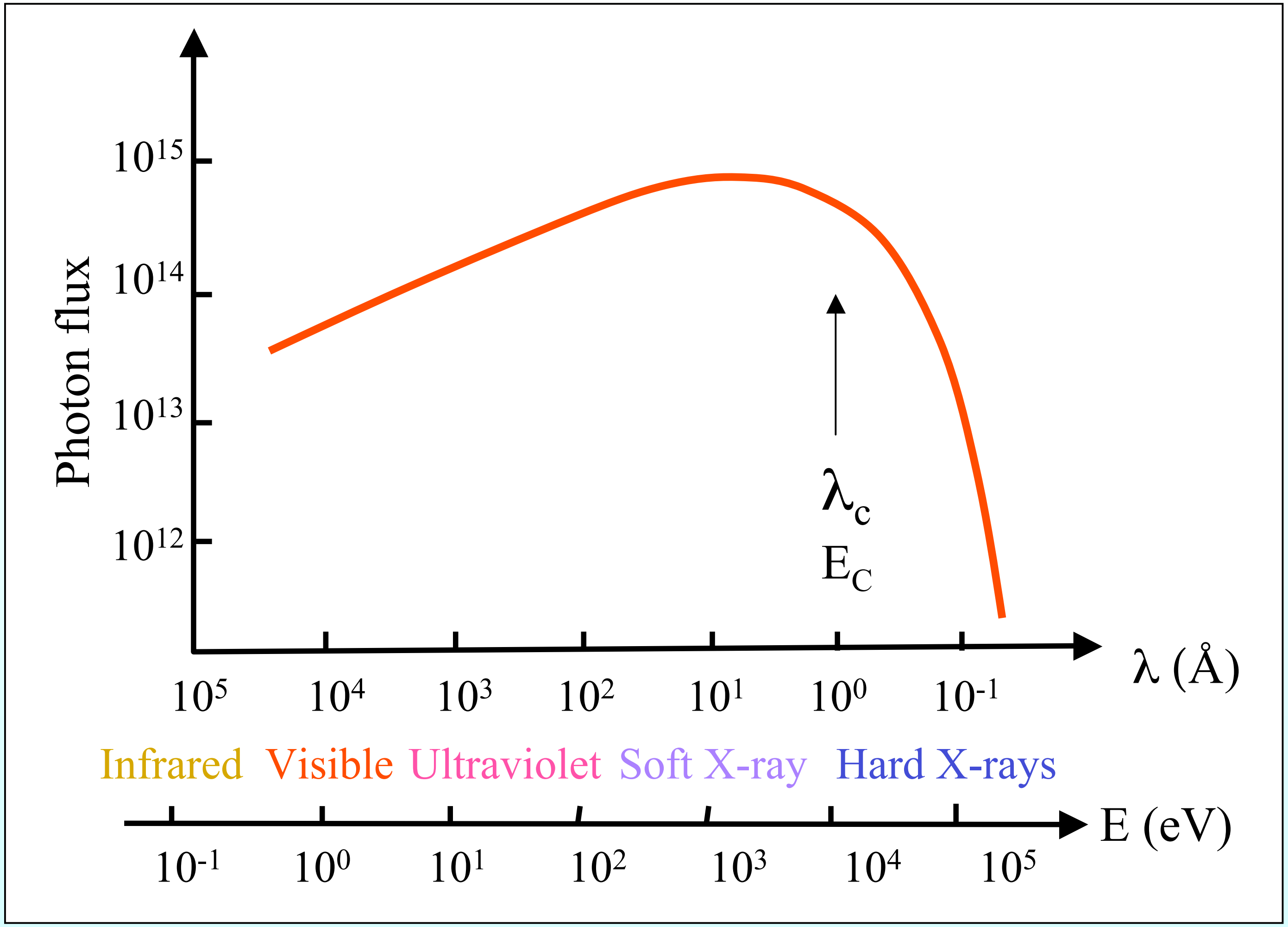
Are X-rays visible?

Properties

Flux of synchrotron light .



Spectral distribution of synchrotron light .

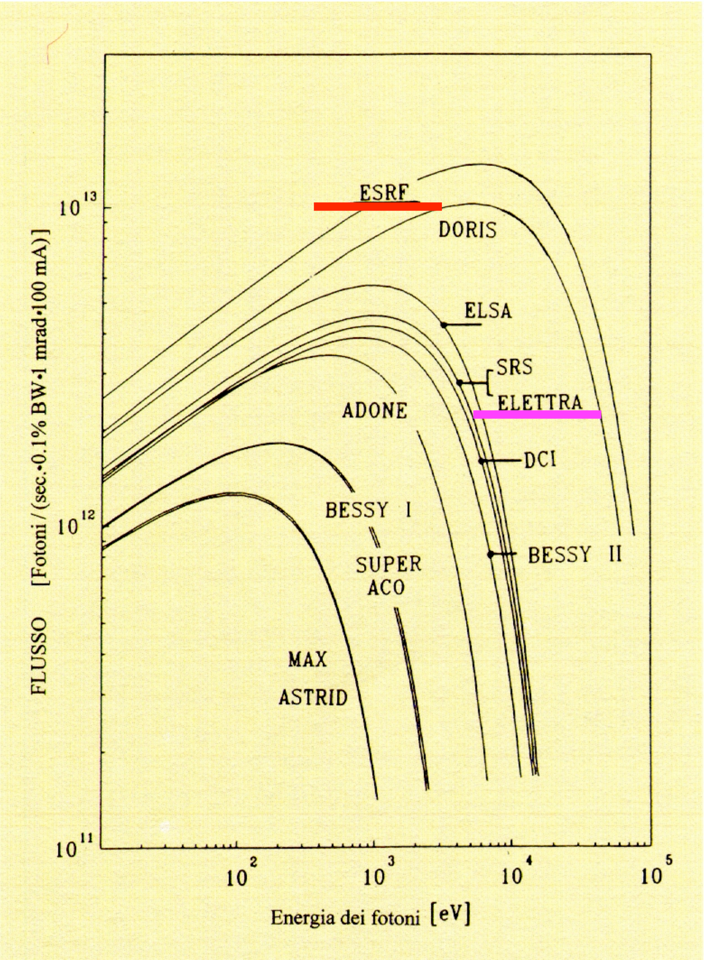


$$\lambda_C = \frac{5.6\,R}{E^3} = \frac{18.6}{B \cdot E^2}$$

?

Spectra

Spectral distribution curves from bending magnets of some synchrotron light facilities

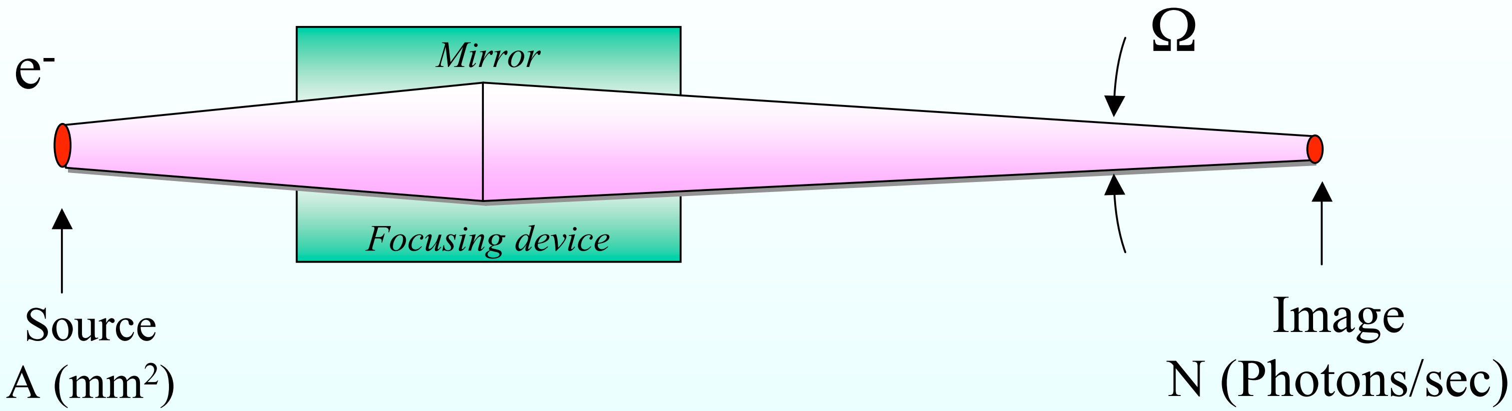


Properties

Critical energy

ESRF is the European facility located in Grenoble, ELETTRA, the Italian facility is located in Trieste.

Definition of Brilliance

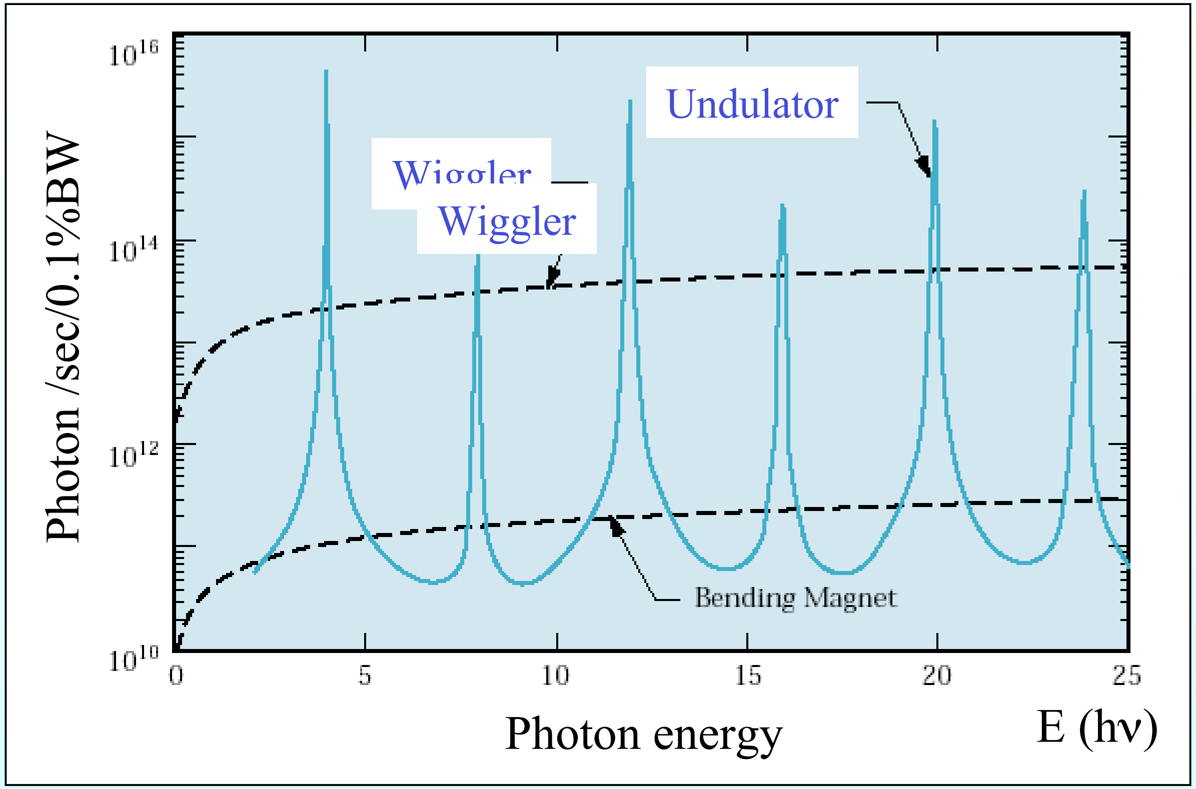


$$Brilliance = \frac{N}{A \cdot \Omega} \qquad \left(\frac{Photons\,/\,sec}{mm^2 \, . (m\,rad)^2 \, (0.1\%\,ban)} \right)$$

The brilliance represents the largest number of photons per second in a given band pass that can be focused by a perfect optics onto the unit area at the sample

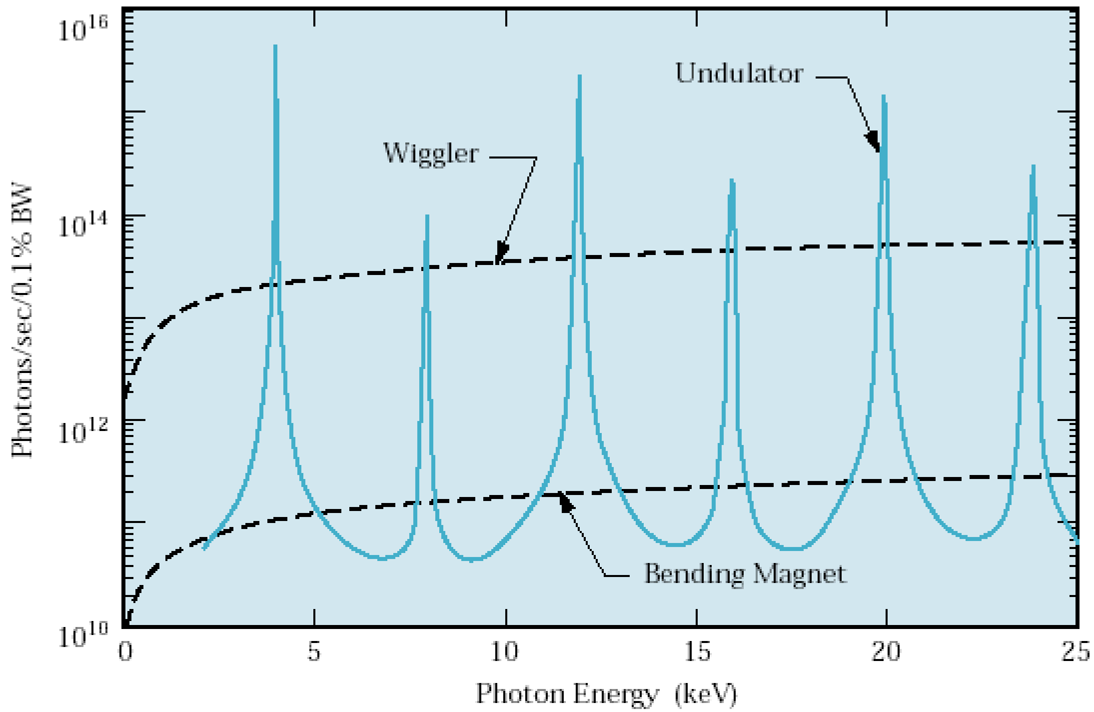
Spectra

Spectral radiation distribution



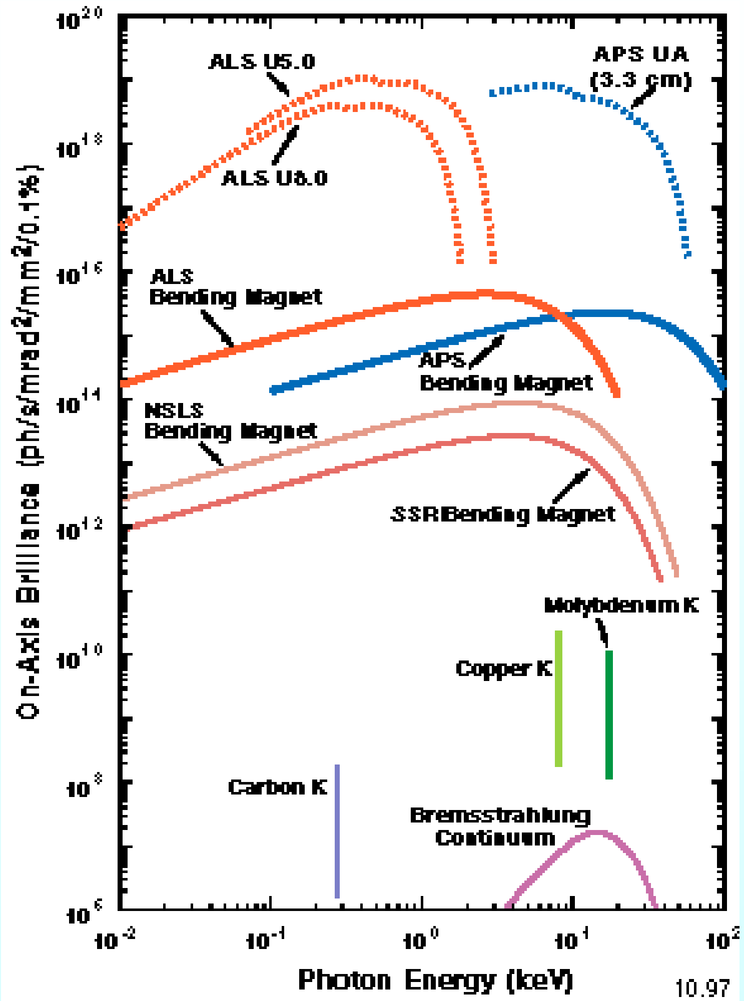
Properties

UHXS Stanford (US)



Comparison of spectra produced by an undulator, a wiggler, and a bending magnet type of source installed on the UHXS. The collection aperture is located at a distance of 50 m from the source. The flux is collected over an aperture of 0.5×0.5 mm^2. The bending magnet and wiggler type sources present continuous spectra while the undulator presents a series of intense peaks. The peaks are harmonically related starting from the fundamental around 4 keV. The photon energy of each peak can be tuned by changing the undulator field. The collection of high flux through such a narrow aperture reduces the power to a few hundred watts.

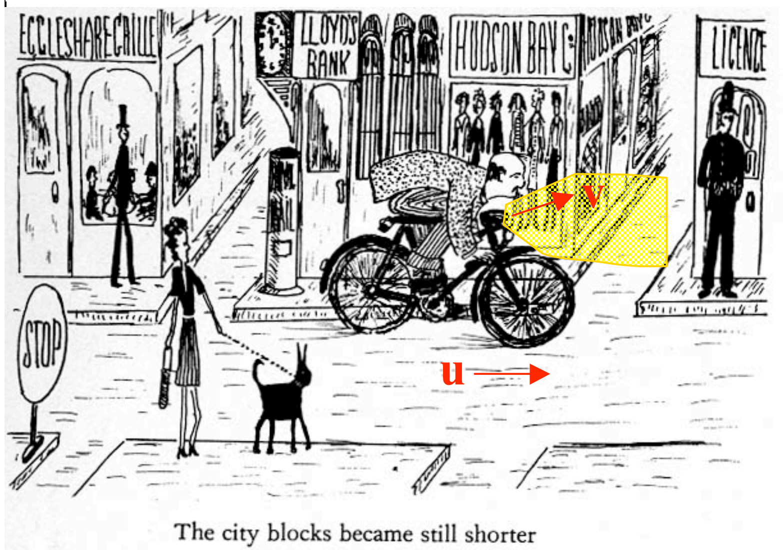
Brilliance



Properties

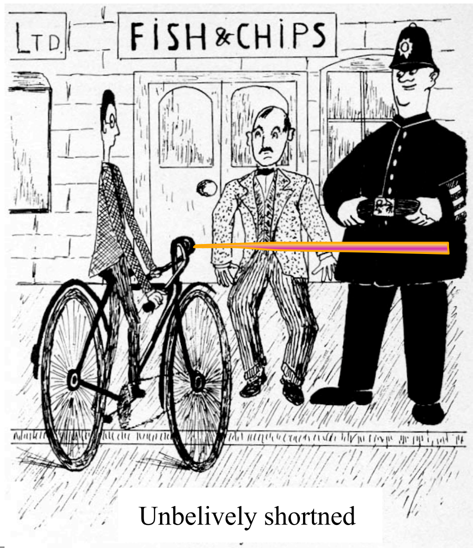
Comparison of brilliances between synchrotron and conventional x-ray sources

The world as seen from the moving reference frame...



The city blocks became still shorter

...and from the laboratory reference frame



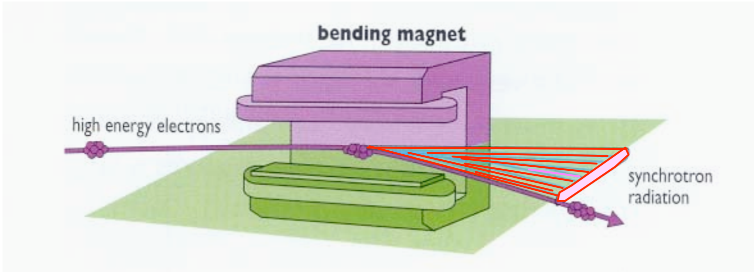
Unbelively shortned

The relativistic effect on the vertical opening of the light beam

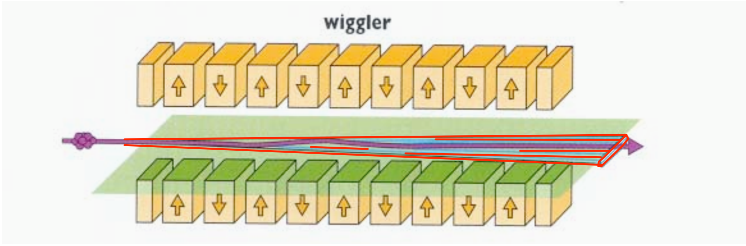
Properties

Insertion devices

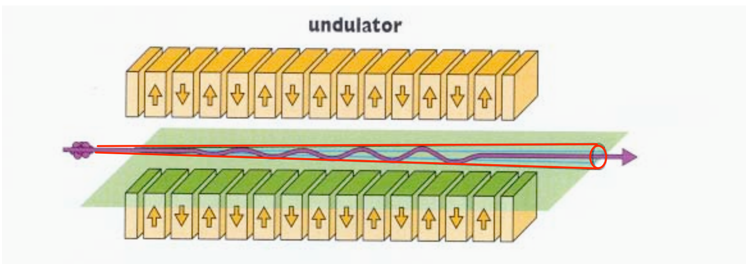
Bending magnets



Wigglers



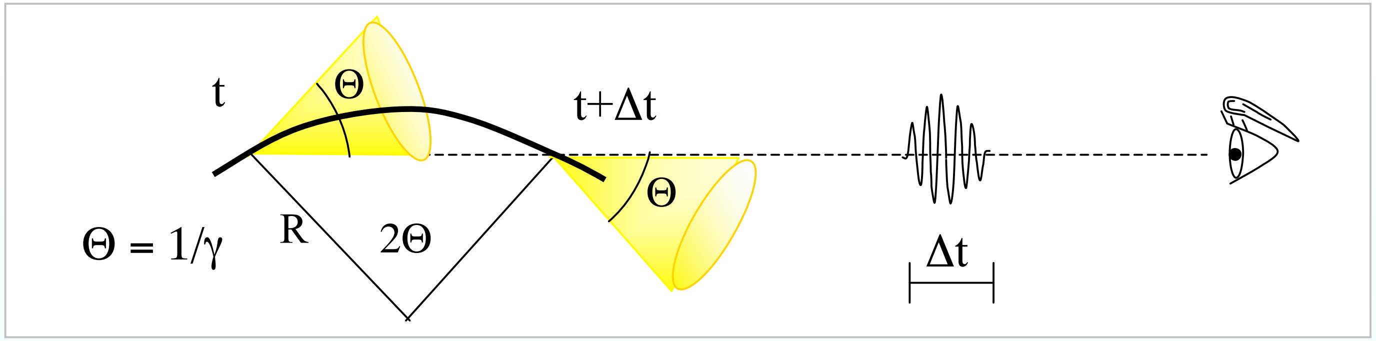
Undulators



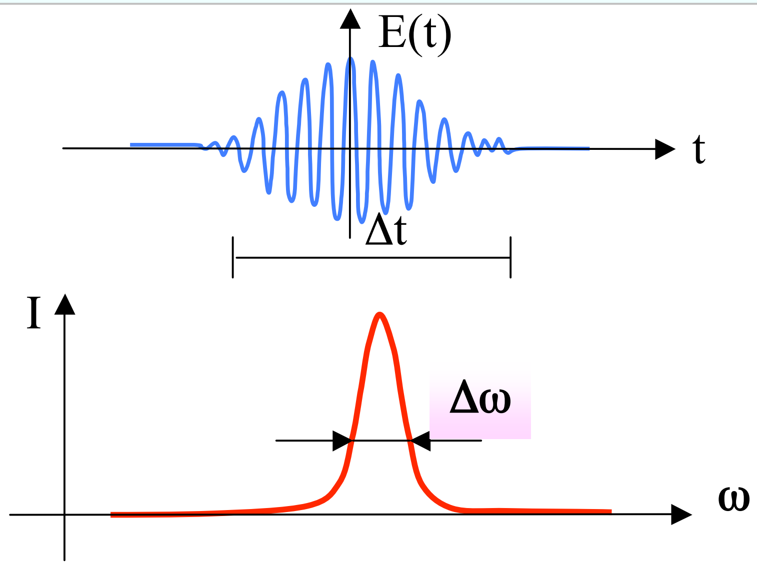
Electron bunches, their trajectory and synchrotron radiation in three different magnetic devices: bending magnets, wigglers, undulators

Storage ring

Why a so wide emission spectrum?



Fourier relationship: $\Delta t \cdot \Delta\omega \cong 2\pi$



$\Delta t \approx 10^{-19}$ sec

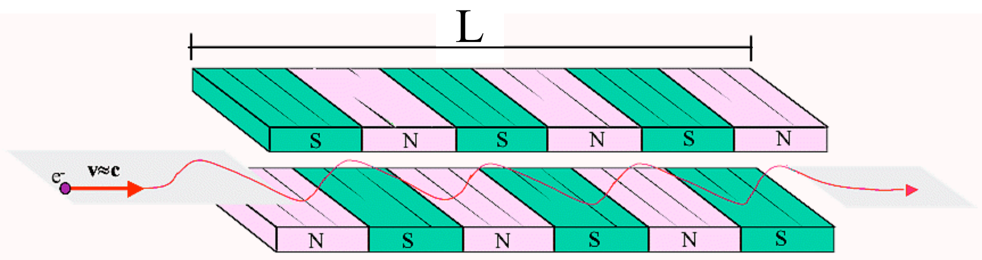
$\Downarrow$

$\Delta\omega \cong 10^{19}$ sec^{-1}

A cosinusoidal wave train modulated by a Gaussian envelope along with its gaussian transform

?

Low wavelengths



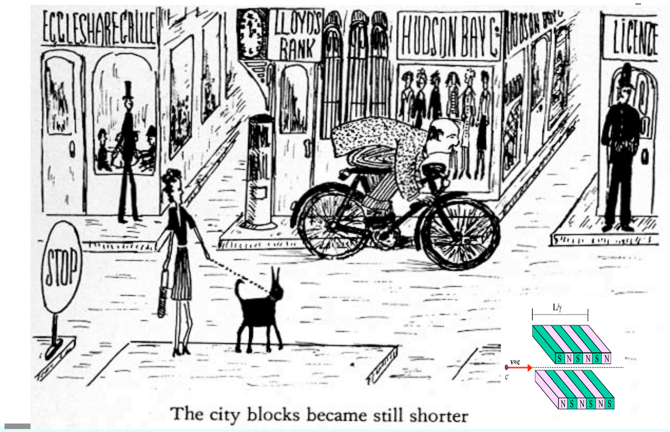
An undulator as seen in the laboratory reference system

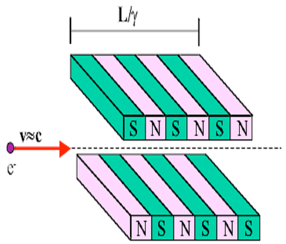
$$\lambda_0 = L/n$$

Magnetic pole periodicity

n = number of periods

Relativistic contraction

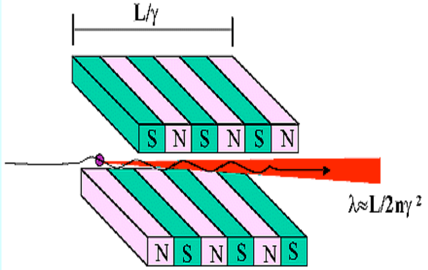




$$\lambda'_0 = L/n\gamma = \lambda_0/\gamma$$

The undulator as seen from the electron

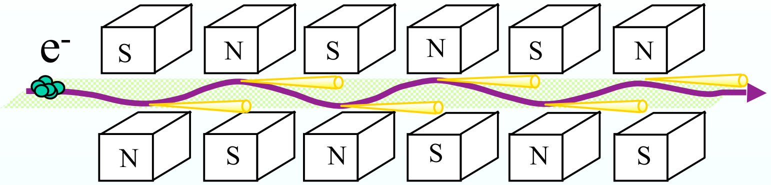
Doppler shift

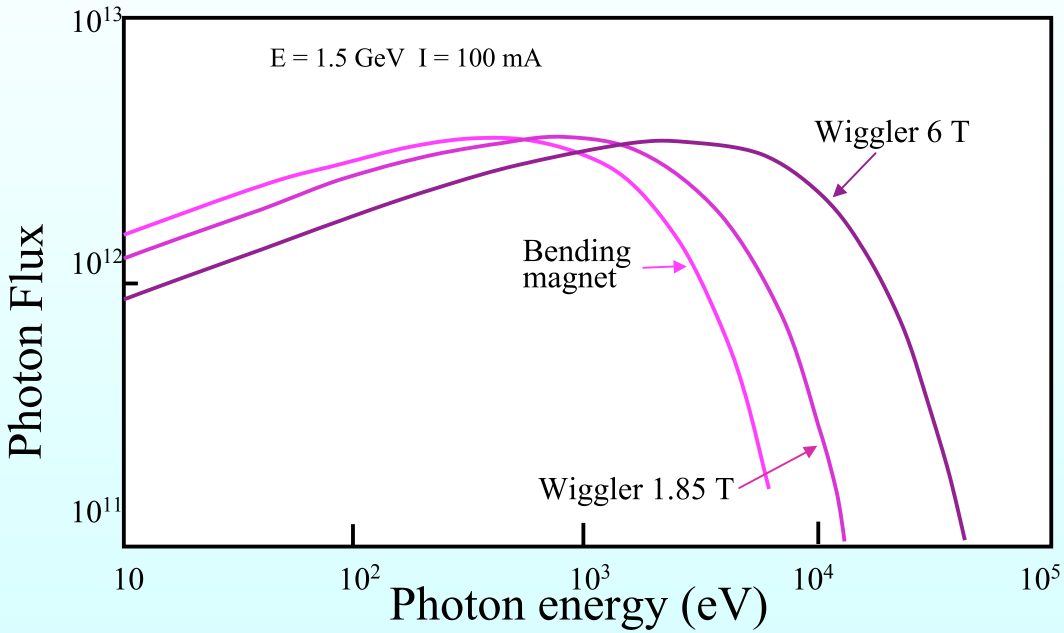


$$\lambda = L/2n\gamma^2$$

Further reduction of the light periodicity due to the Doppler effect

Spectrum



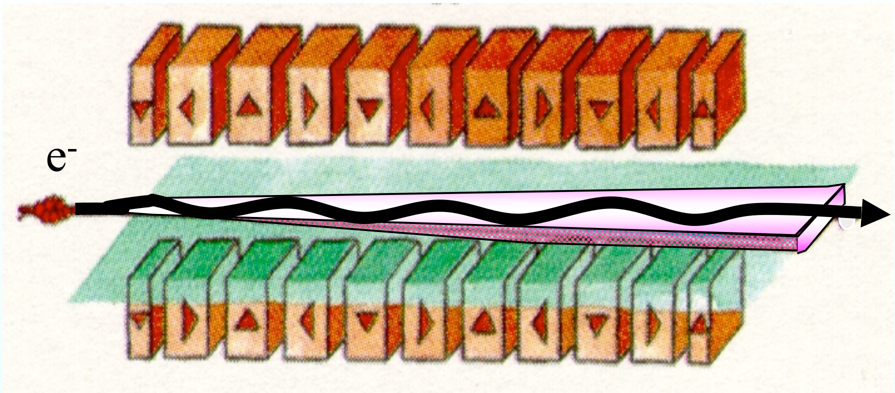


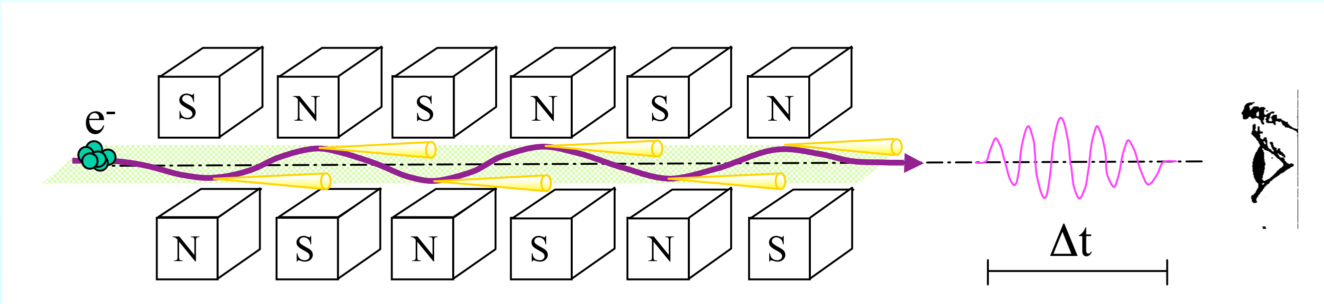
$$R = \frac{E(GeV)}{B(T)}$$

$$Ec = k/R$$

ID comparison

By decreasing the curvature radius of the electron trajectory the spectrum shifts to higher photon energies


e-


e-
S
N
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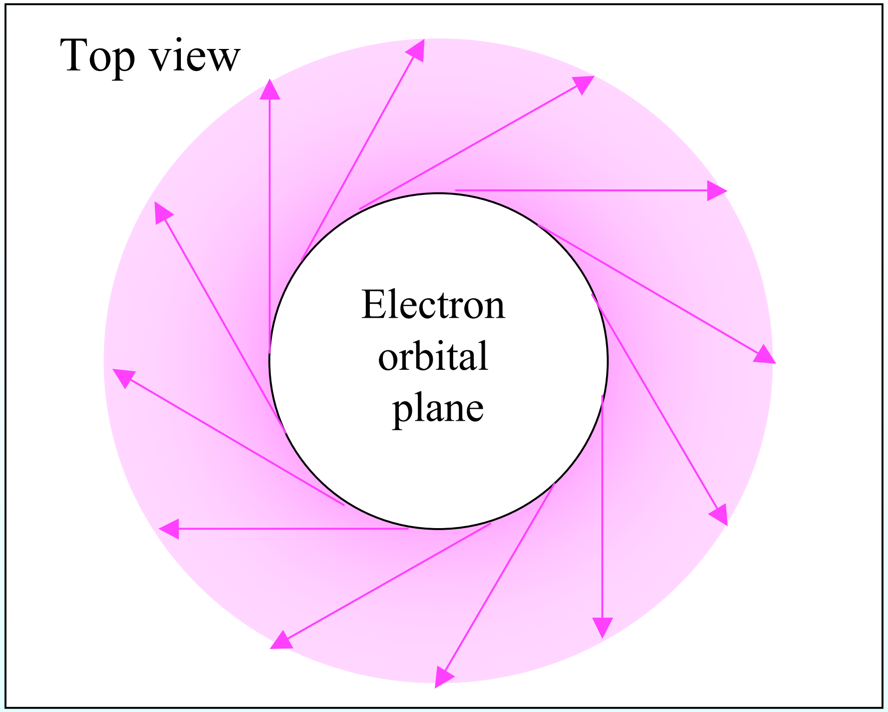
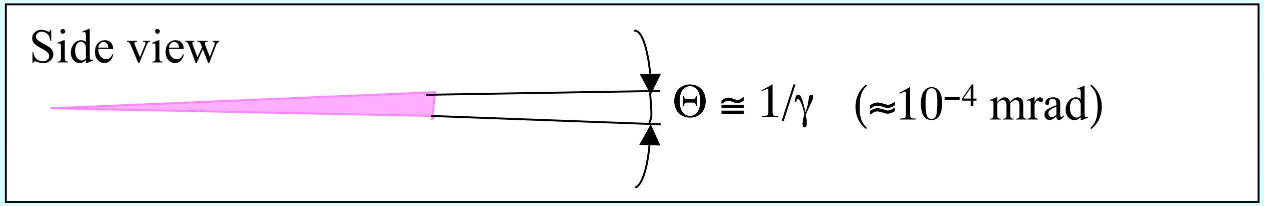
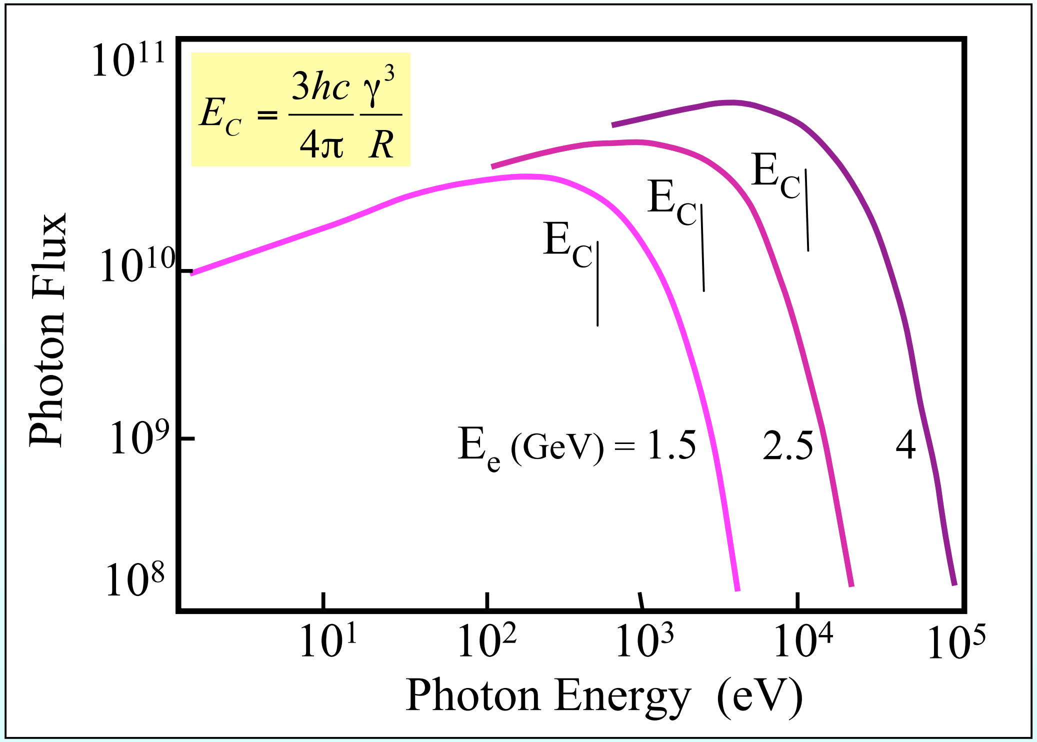
S
N
S
N
S
Δt





Synchrotron light is spread on the orbital plane as a very thin sheet

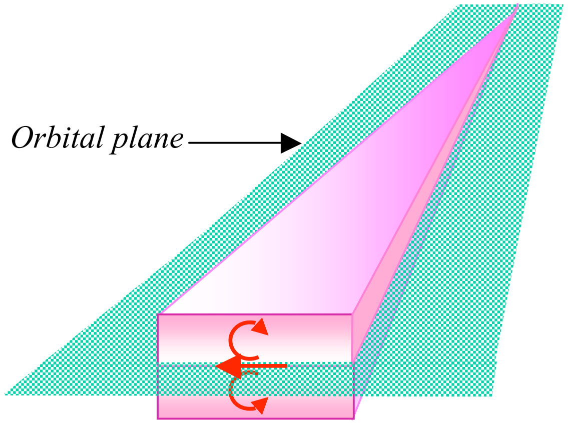
Angular distribution



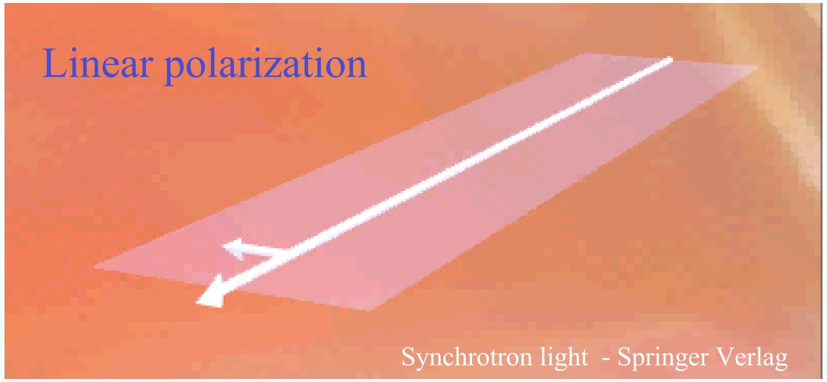
Dependence of the critical photon energy on the electron energy

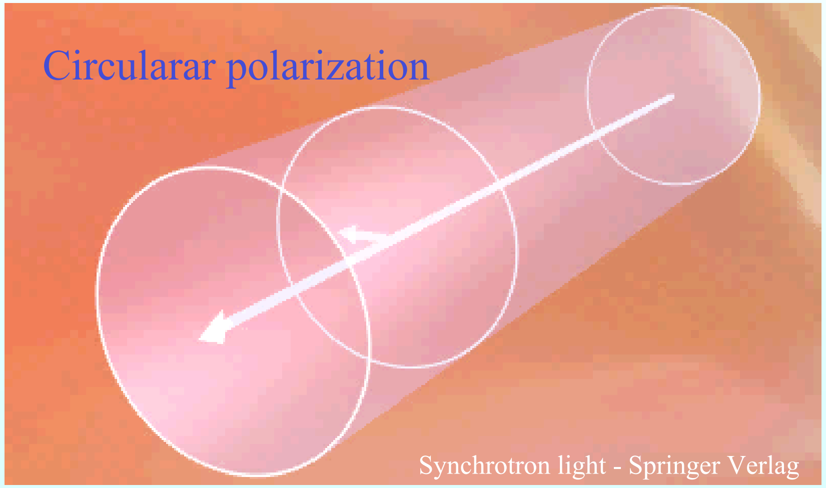
Polarization

The on-axis synchrotron light is polarized in the orbital plane



The synchrotron light out of the orbital plane has circular components with opposite helicities above and below the horizontal plane.

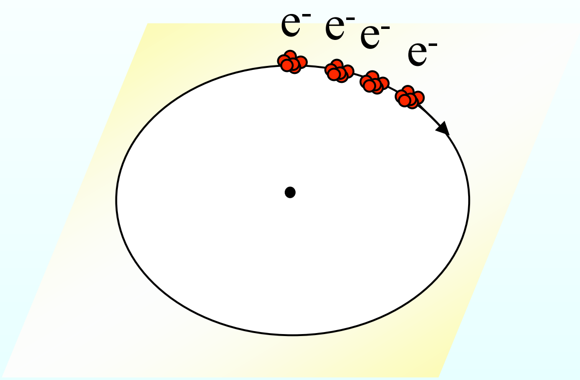


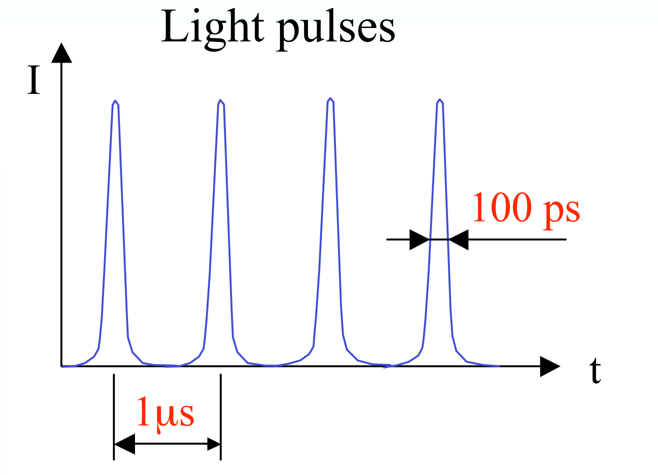


Polarization is exploited for studying magnetic interactions. The difference in absorption in left and right hand circularly polarised light by a solid can be directly related to the ferromagnetic magnetization density (circular dichroism).

Properties

Time structure





Time pulsed emission is interesting for studying rapid reactions

Properties

SESAME

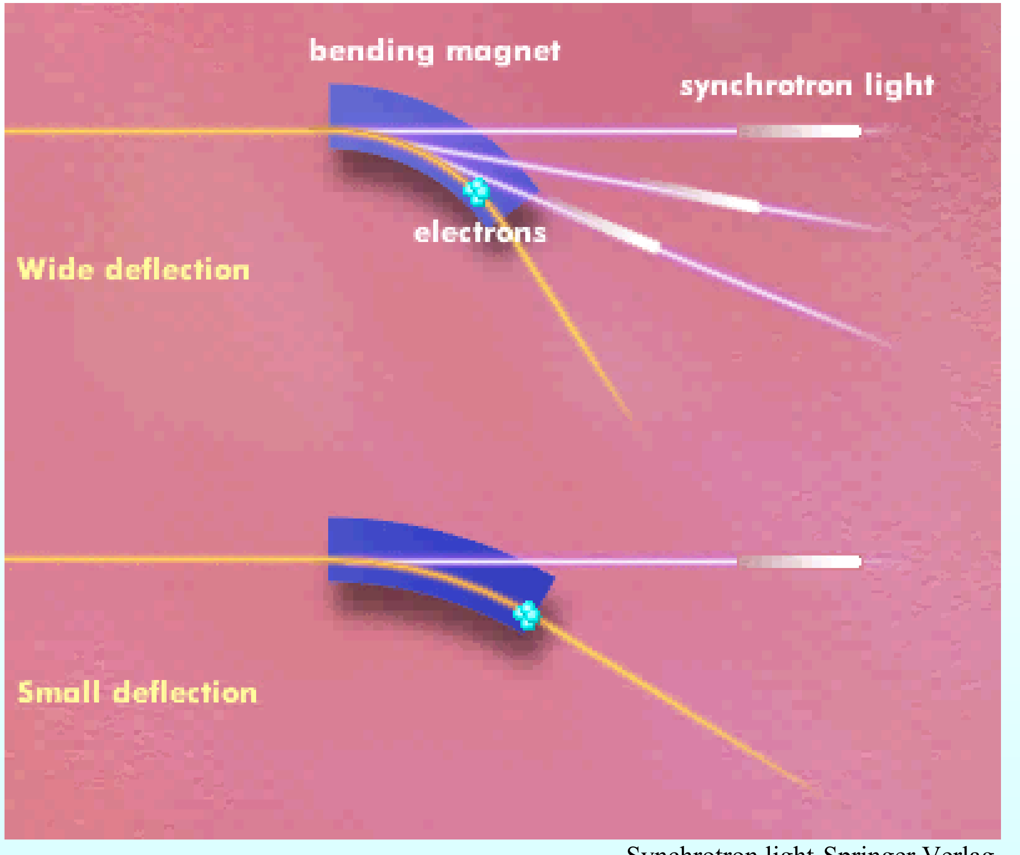
Synchrotron-light for Experimental Science and Applications in the Middle East

The SESAME Project aims to establish the Middle East's first major international research center as a cooperative venture by the scientists of the region

SESAME will have as its centerpiece a synchrotron radiation source based on a gift from Germany of the 0.8 GeV BESSY I storage ring and injector system which stopped operation at the end of November 1999.

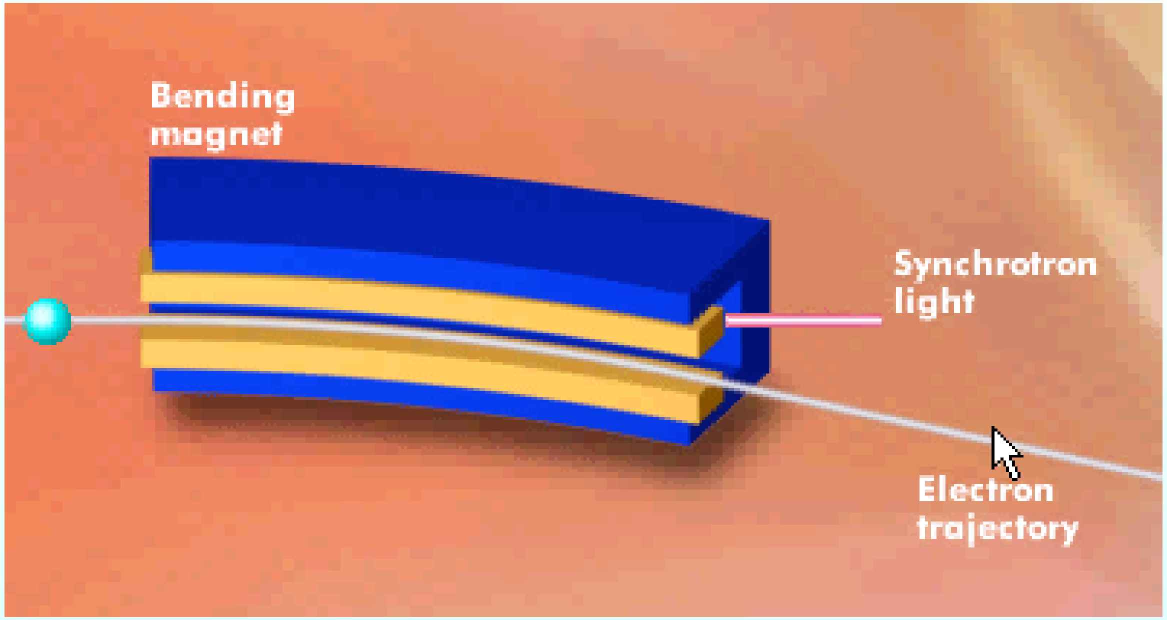
Eleven countries have so far joined the project. These are: Armenia, Cyprus, Egypt, Greece, Iran, Israel, Jordan, Morocco, Oman, Palestinian Authority, and Turkey.

The project is being developed under the umbrella of UNESCO and will be located in Allaan, Jordan (30 km from Amman and 30 km from the King Hussein/Allenby Bridge crossing of the Jordan River.



Synchrotron light Springer Verlag

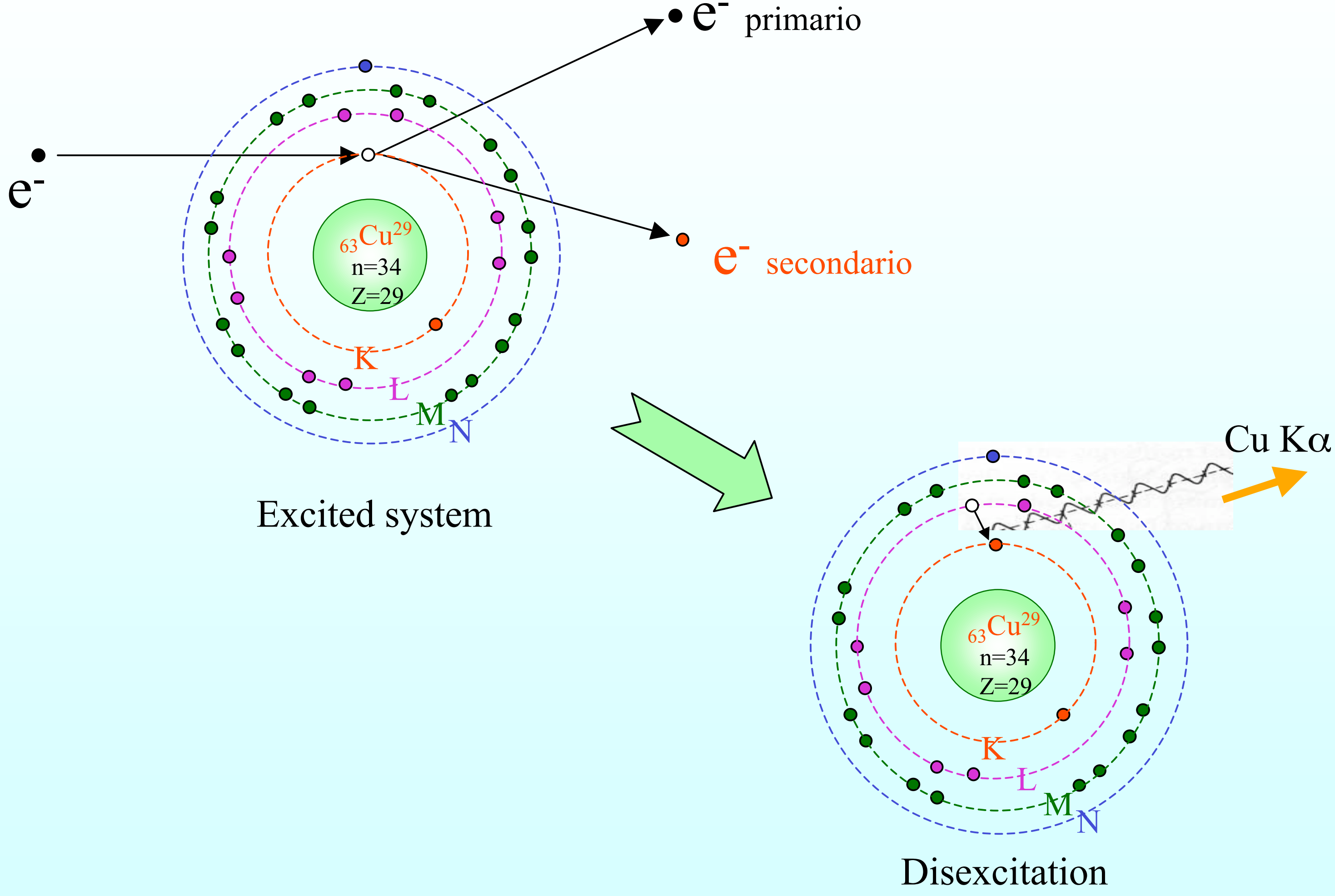
Principle of operation of a bending bending magnet



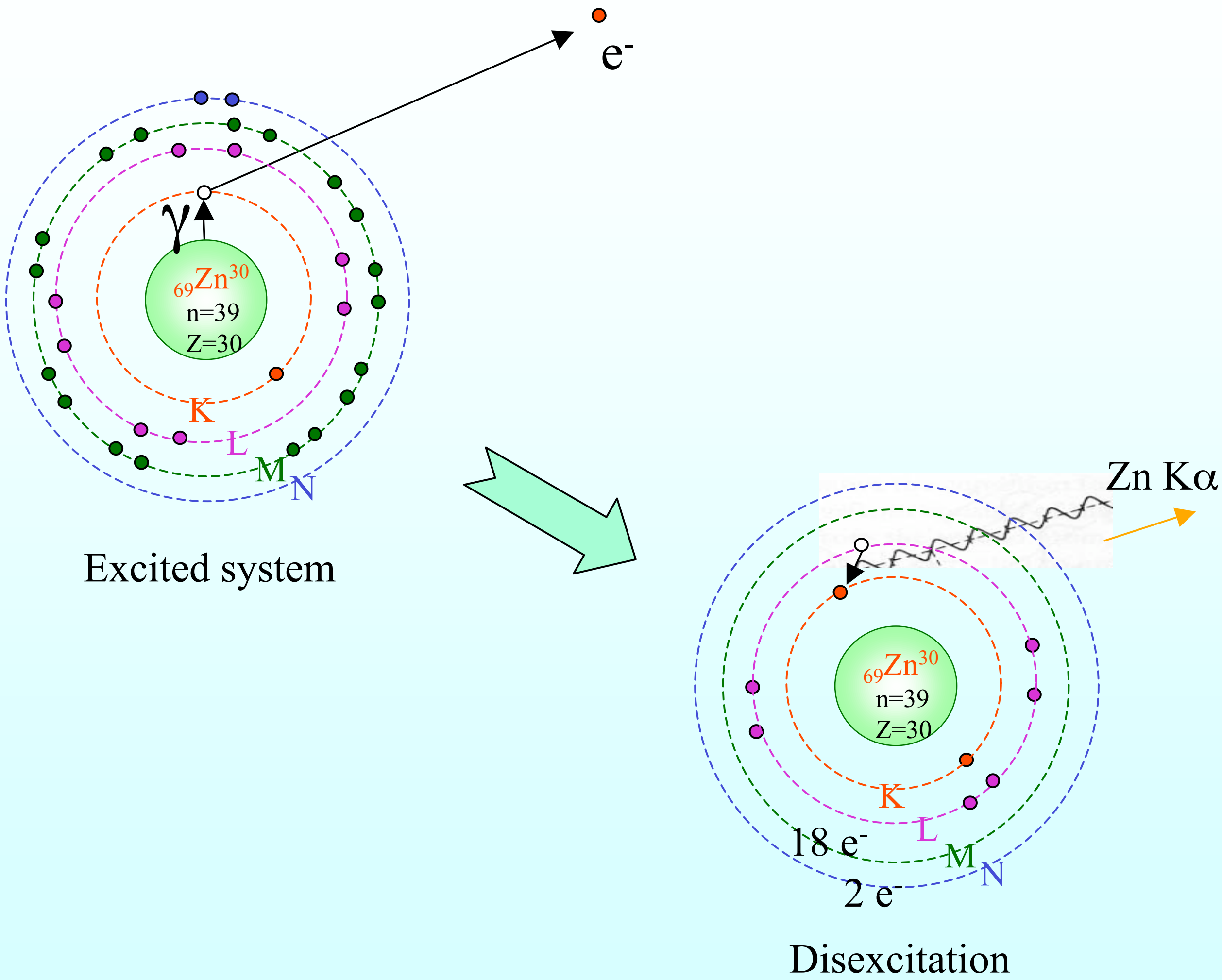
Synchrotron light, Springer-Verlag Compact Disk 2000

Principle of operation of a bending magnet

Kα excitation

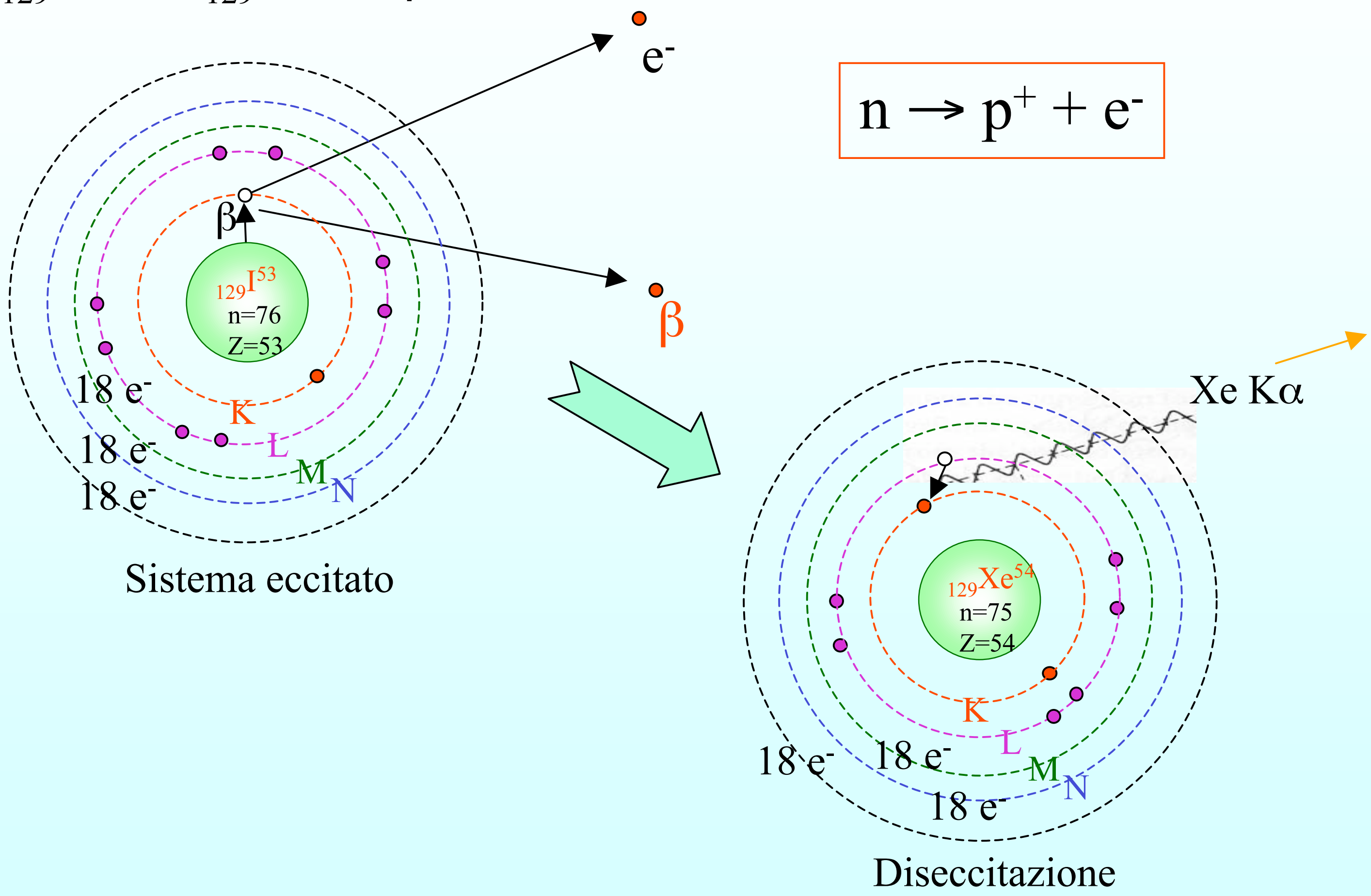


Internal γ conversion



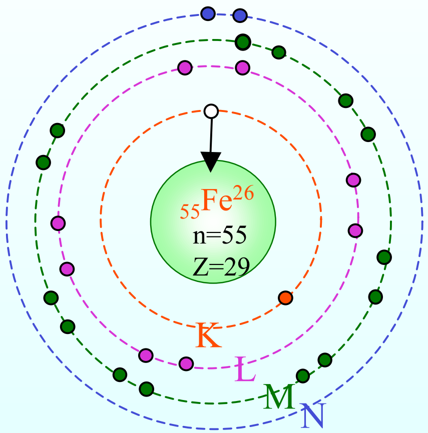
Internal β conversion

$_{129}I^{53} \rightarrow {}_{129}Xe^{54} + \beta^-$



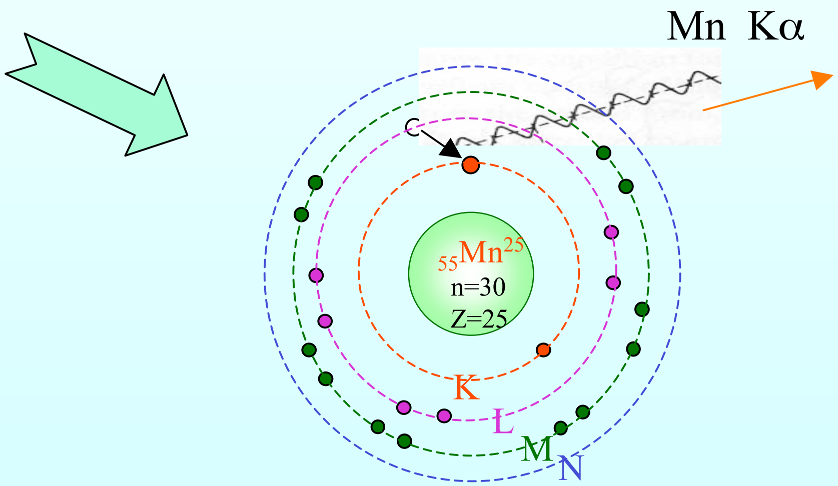
Core electron capture

$_{55}Fe^{26}$ —Cattura K→ $_{55}Mn^{25}$



Sistema eccitato

$$p^{+} + e^{-} \rightarrow n$$



Sistema diseccitato