X-ray and neutron sources

Paolo Fornasini
Department of Physics
University of Trento
Italy

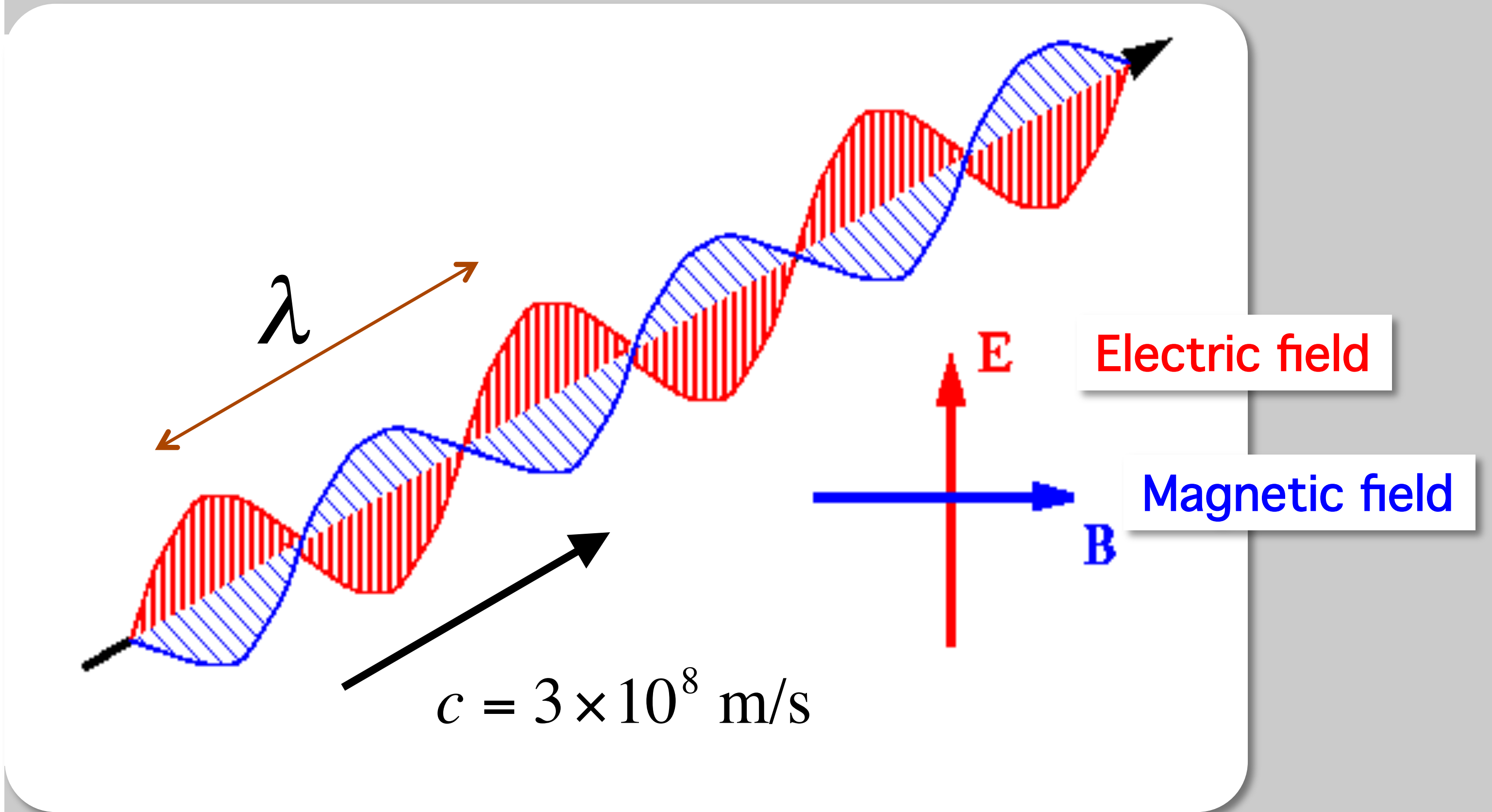
Overview

1. Mechanisms of X-ray production
2. Laboratory X-ray sources
3. Synchrotron Radiation
   - SR sources
   - SR from bending magnets
   - SR from insertion devices
4. Neutron sources

Mechanisms of X-ray production

X-rays are electromagnetic radiation

Paolo
Fornasini
Univ. Trento



Superposition
of sinusoidal waves

X-rays

$$\lambda \approx 0.01 \div 10 \text{ Å}$$

$$\nu \approx 10^{17} \div 10^{20} \text{Hz}$$

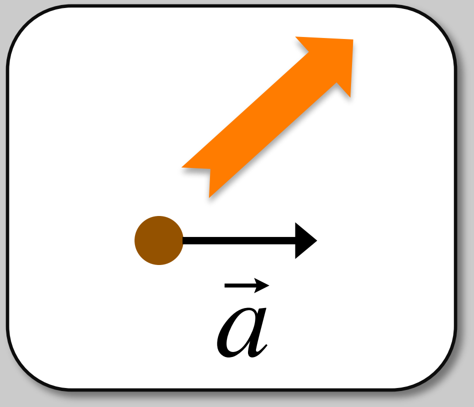
$$E \approx 1 \div 400 \text{ keV}$$

Two mechanisms ...

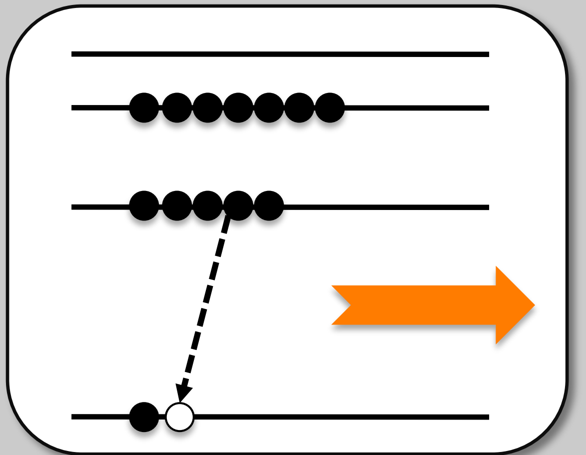
Paolo
Fornasini
Univ. Trento

... of production of electromagnetic radiation

1. Emission from accelerated electric charges

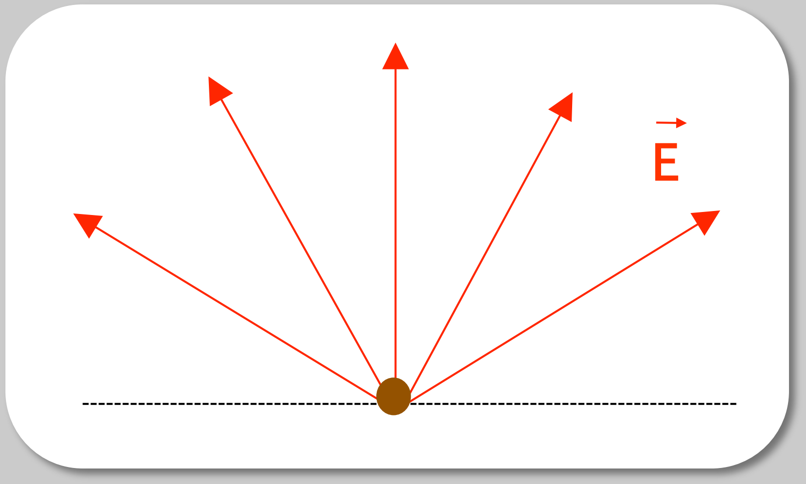


2. Emission as effect of quantum transitions

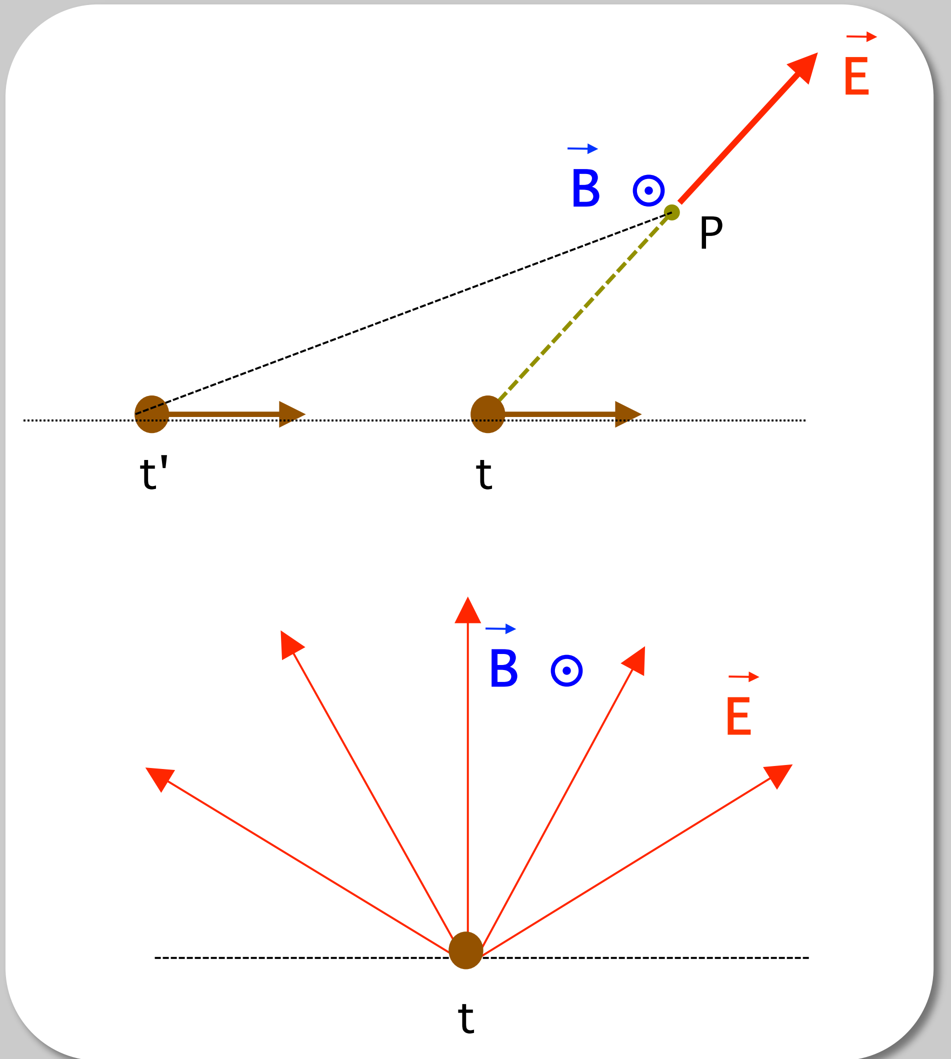


Non-accelerated charges

Charge at rest



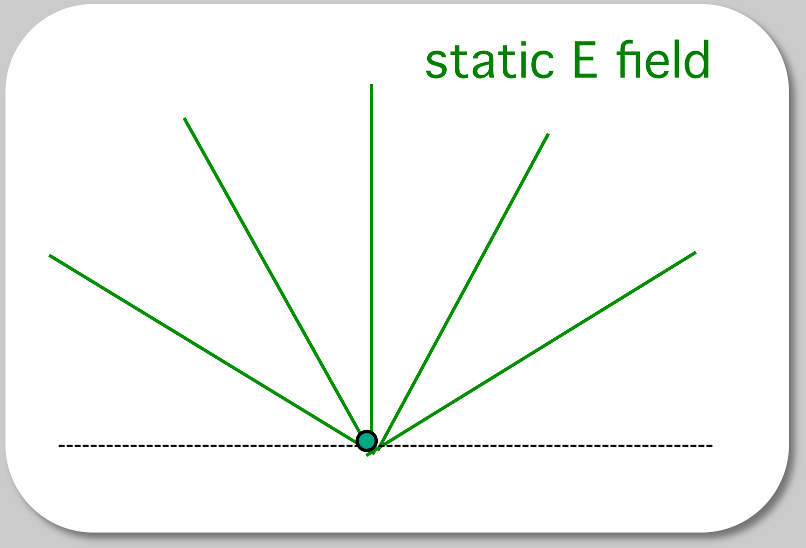
Constant velocity

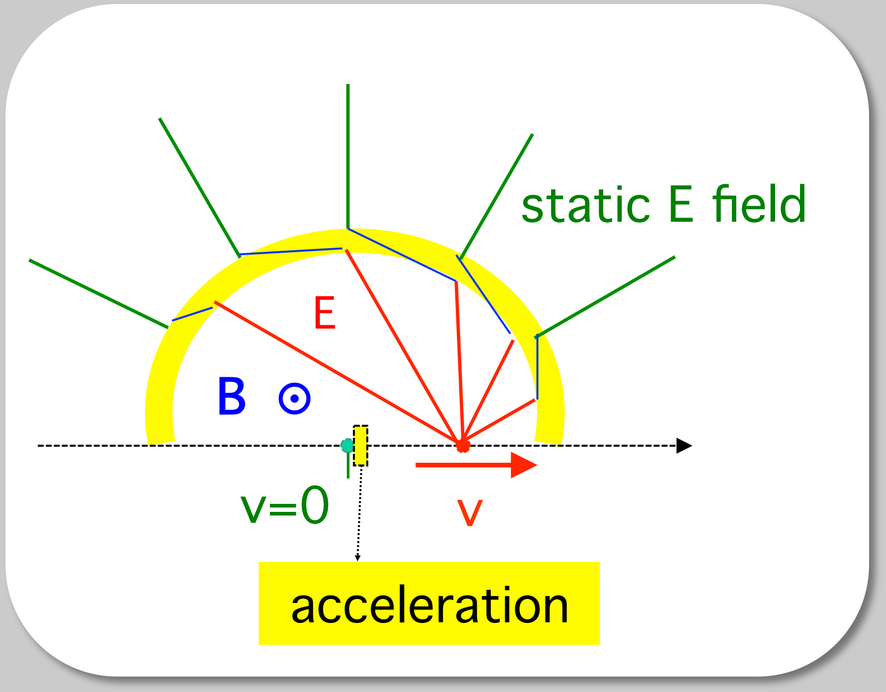


No power is emitted
as electromagnetic radiation

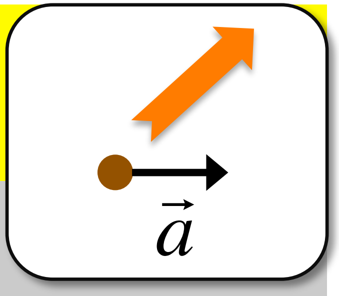
Accelerated charge: a tutorial example (a)

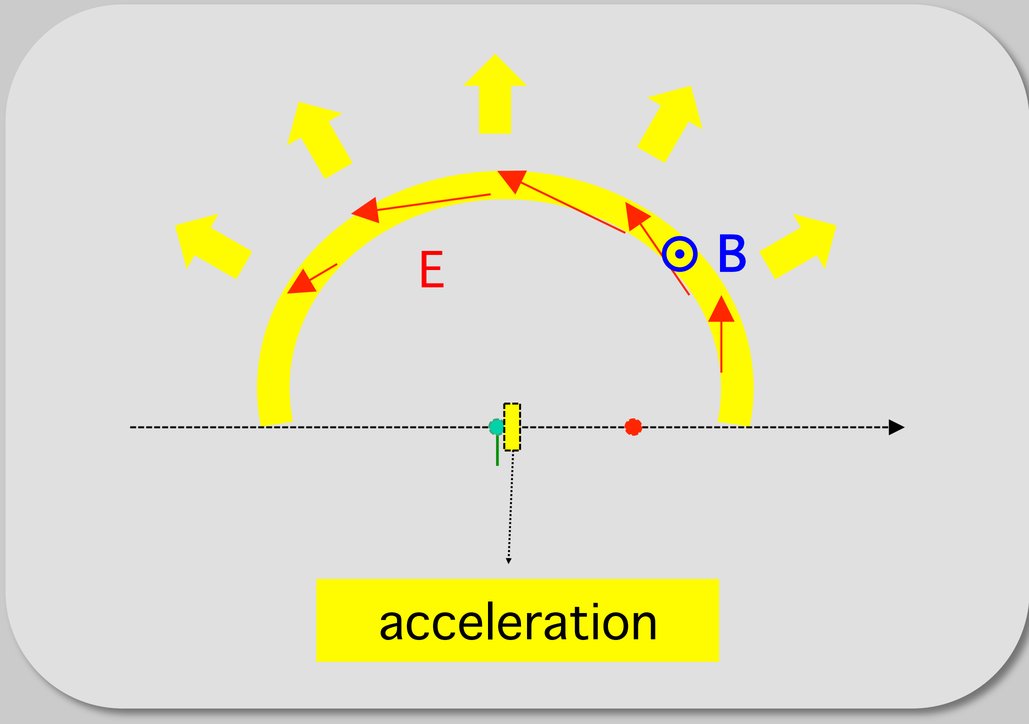
Charge at rest → Short acceleration → Constant velocity





Accelerated charge: a tutorial example (b)



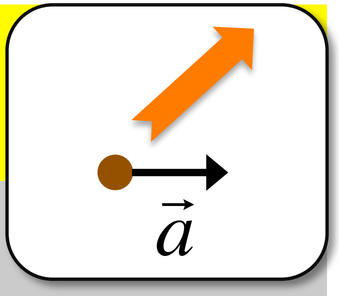


Acceleration

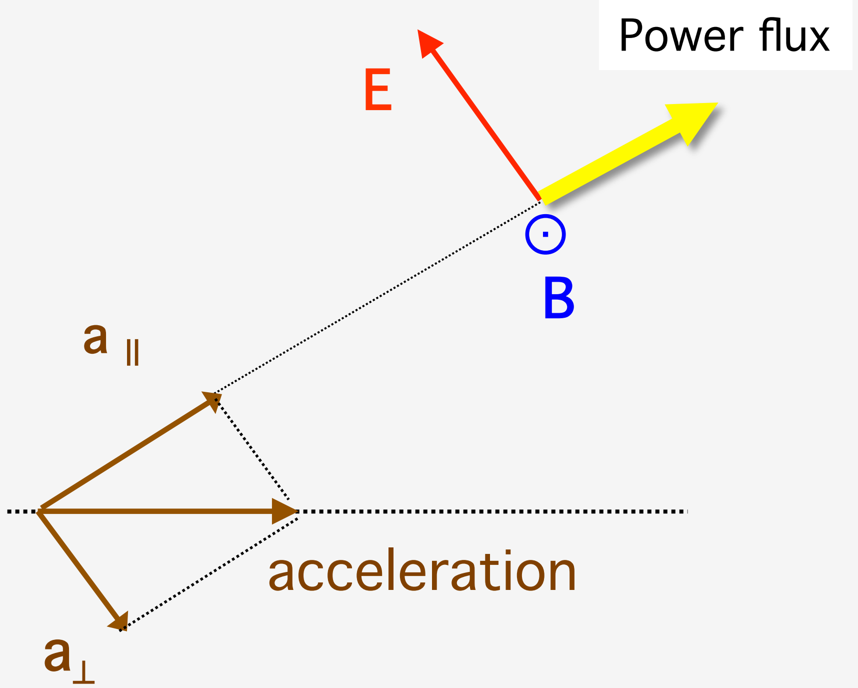
Perturbation
of static fields

- Electro-magnetic field
- Propagating with velocity $c = 3 \times 10^8$ m/s
- Carrying energy

Dipole approximation



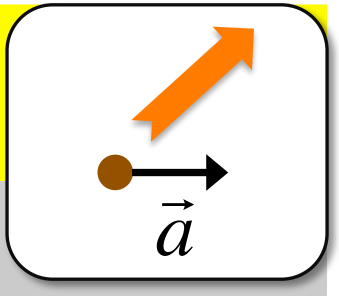
• charge velocity:	**v << c**
• charge size:	d << λ
• observer distance:	r >> λ



$$\vec{E}(\vec{r},t) = -\frac{q\,\vec{a}_\perp(t')}{4\pi\varepsilon_0\, r\, c^2}$$

$$\vec{B}(\vec{r},t) = \frac{\hat{r}\times\vec{E}(\vec{r},t)}{c}$$

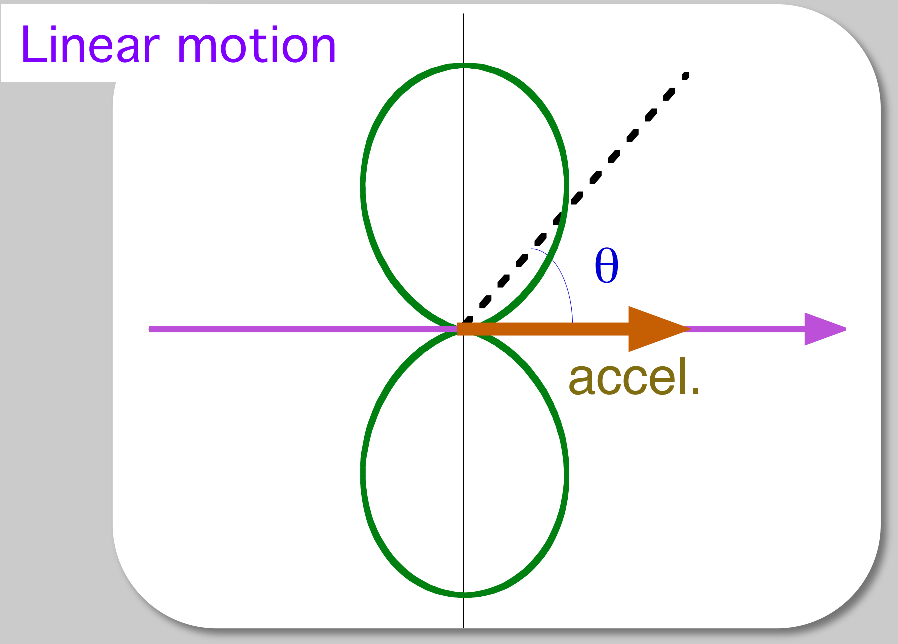
Dipole approximation: radiated power

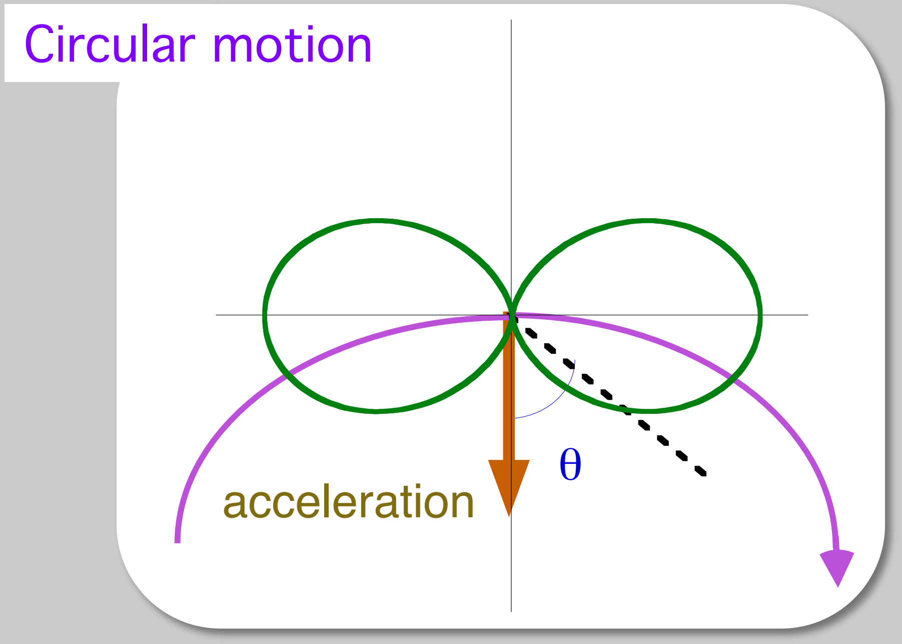


The emitted power is:

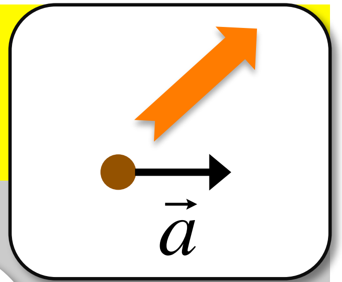
- Zero in the direction of acceleration
- Maximum in the perpendicular plane

Angular emission profiles

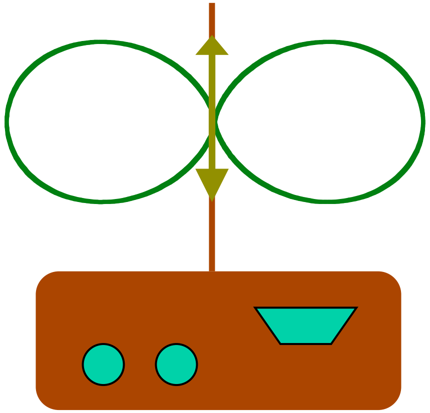




Examples

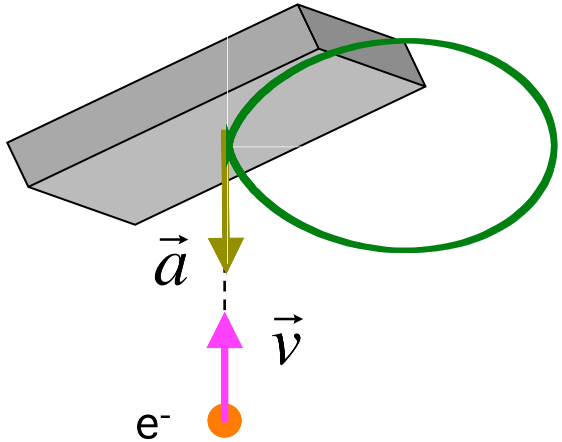


Oscillating motion



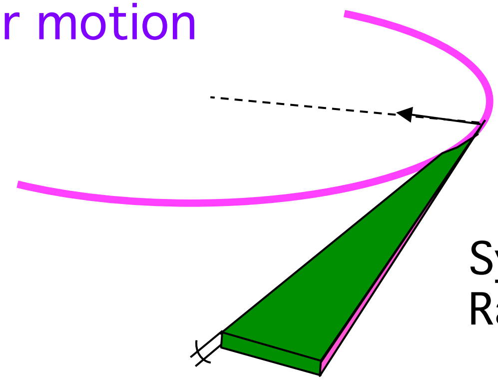
Broadcasting antenna

Average linear deceleration



Bremsstrahlung
in X-ray tubes

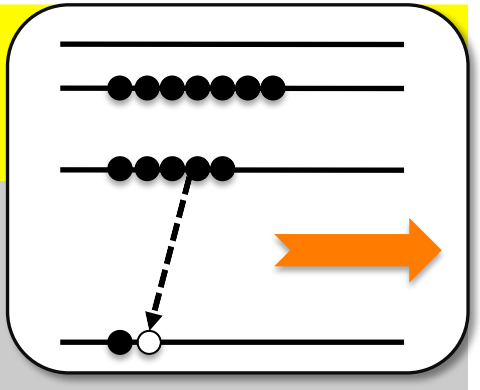
Relativistic circular motion

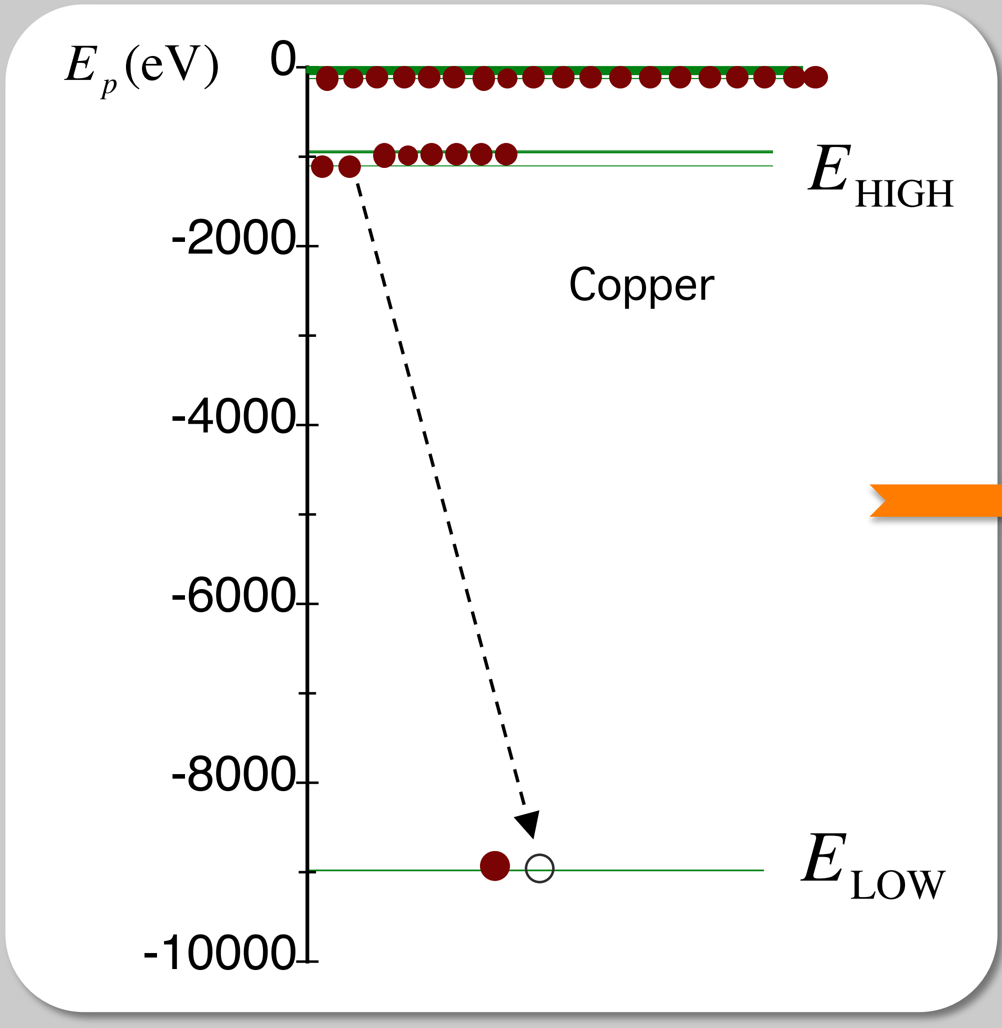


Synchrotron
Radiation

No dipole approximation
Relativistic treatment necessary

Quantum transitions



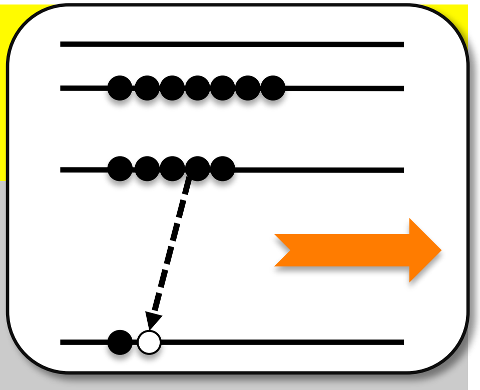


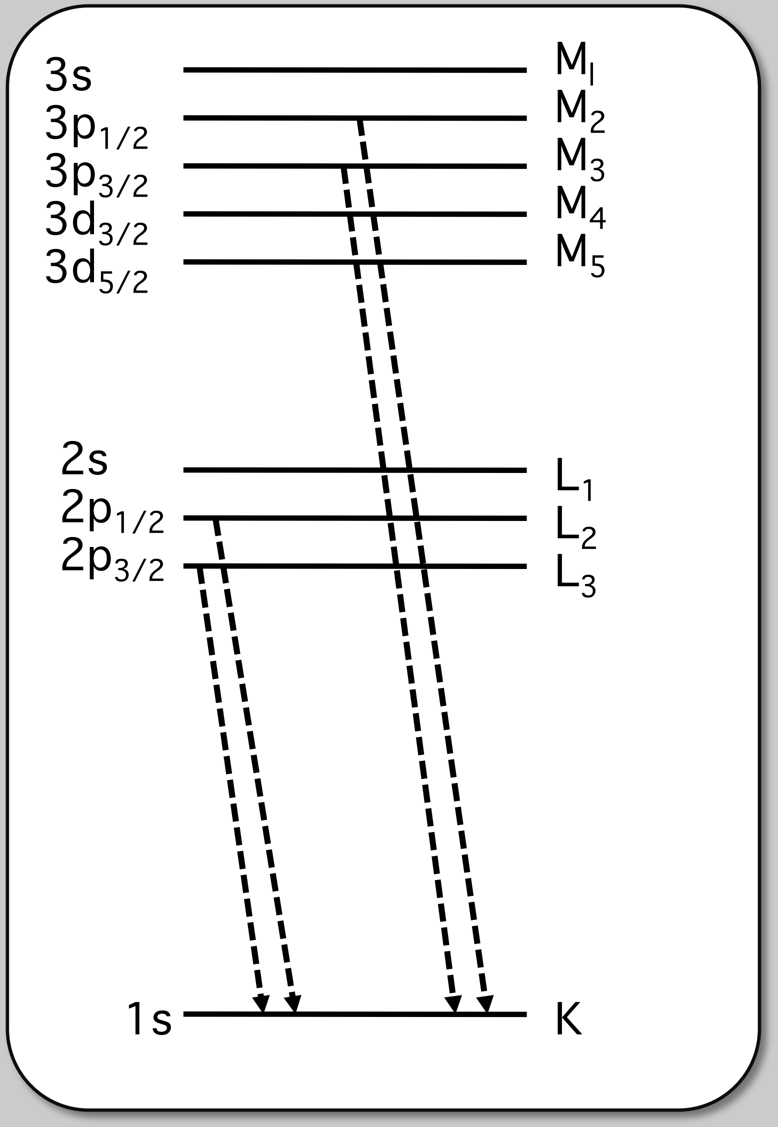
$$\hbar\omega = E_{\mathrm{HIGH}} - E_{\mathrm{LOW}}$$

Atomic X-ray transitions

$$\hbar\omega \approx 0.4 \div 100 \text{ keV}$$

Characteristic lines





Transitions and X-ray lines

$K - L_3$	$K\alpha_1$	$K\alpha$
$K - L_2$	$K\alpha_2$	
$K - M_3$	$K\beta_1$	$K\beta$
$K - M_2$	$K\beta_3$	

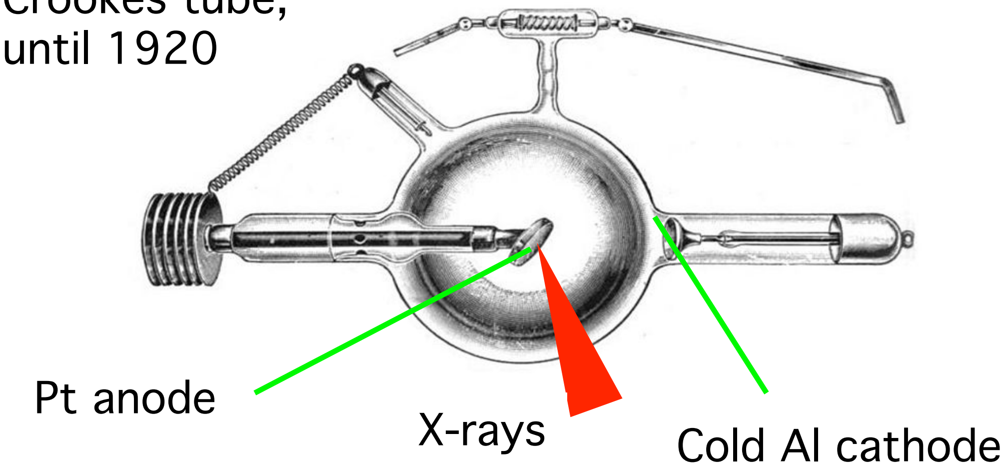
(Electric-dipole allowed transitions)

Laboratory X-ray sources

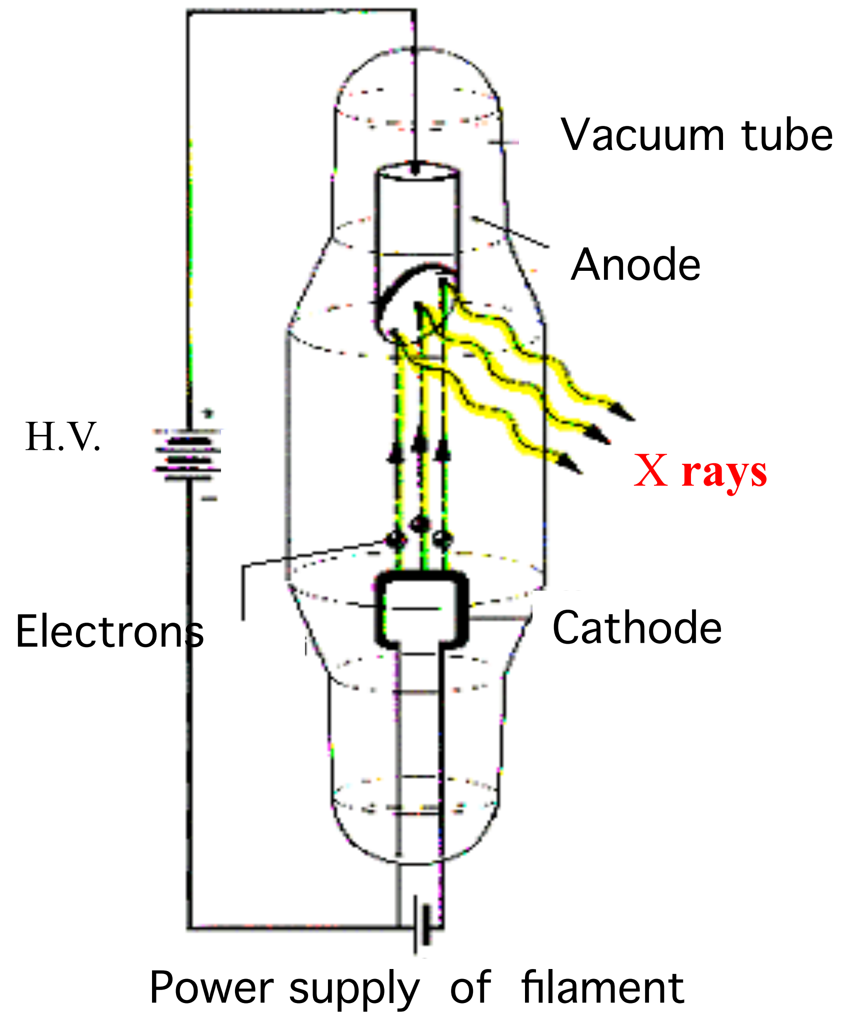
X-ray tubes

Paolo
Fornasini
Univ. Trento

Crookes tube,
until 1920

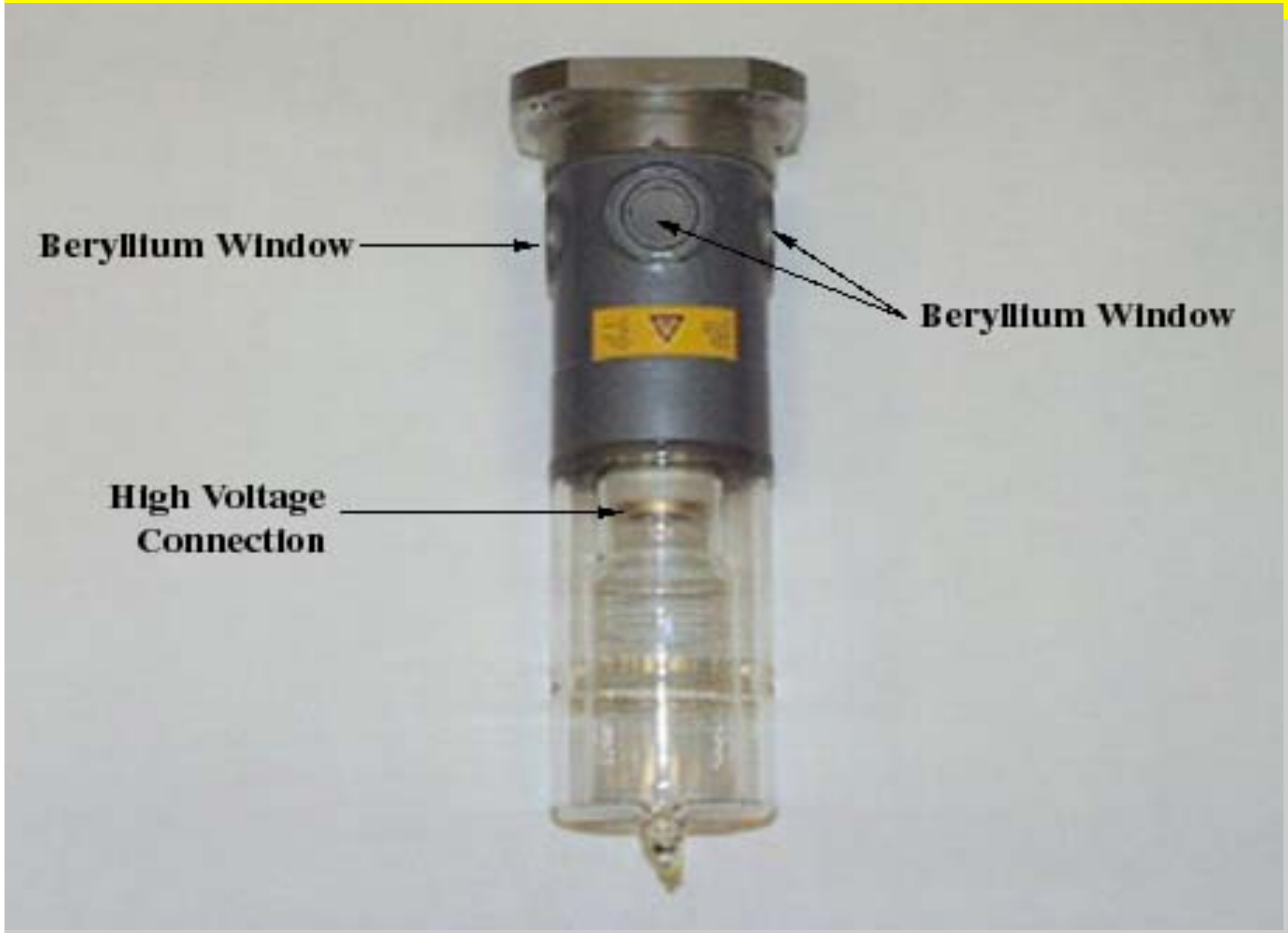


Hot cathode Coolidge's tube (1913)



Present-day laboratory tubes

Paolo
Fornasini
Univ. Trento



High vacuum sealed tubes

Independent control of I and V

Accelerating voltage < 100 kV

Different anode metals:
Cr, Cu, Mo, W, ...

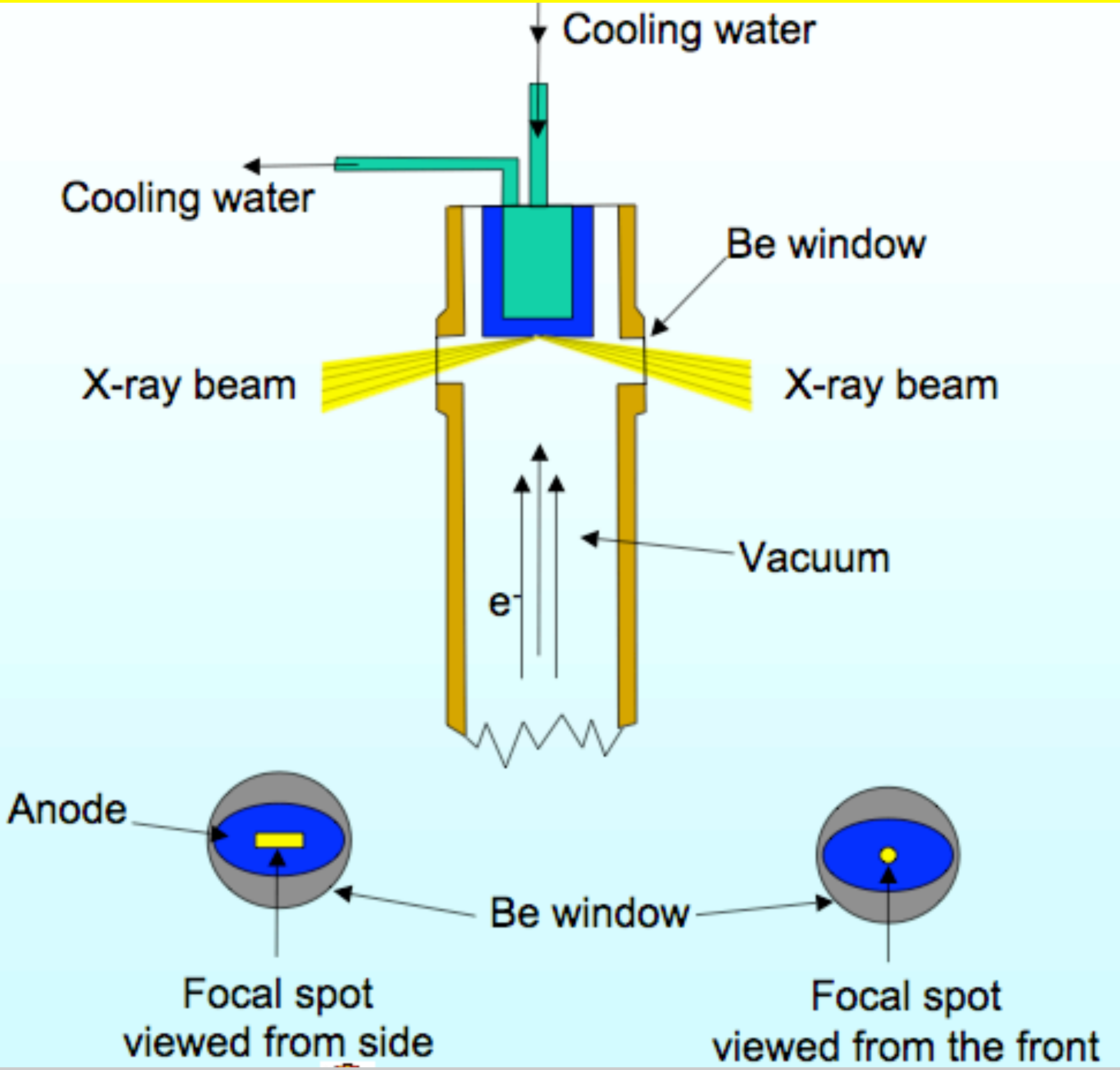
Power: 1 - 4 kW

~ 1 % X-ray production
~99 % anode heating

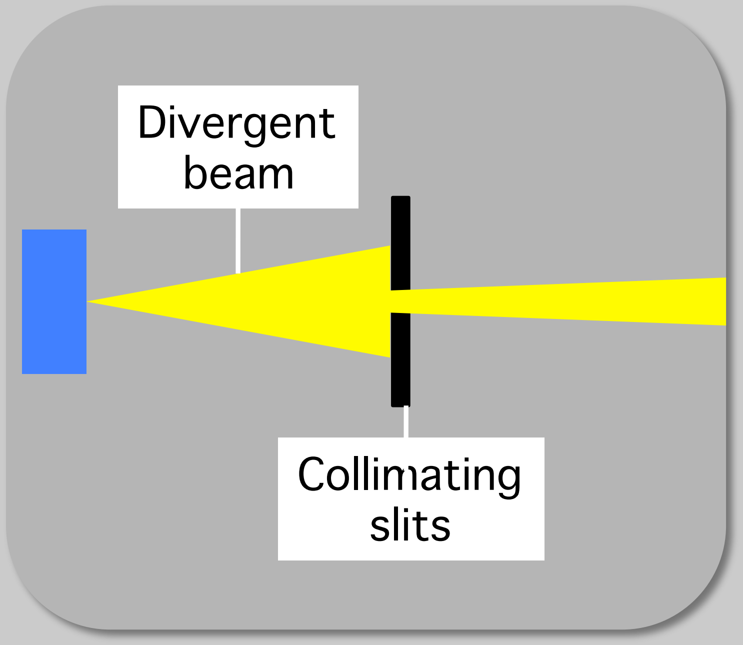
➔ water cooling

X-ray emission

Paolo
Fornasini
Univ. Trento

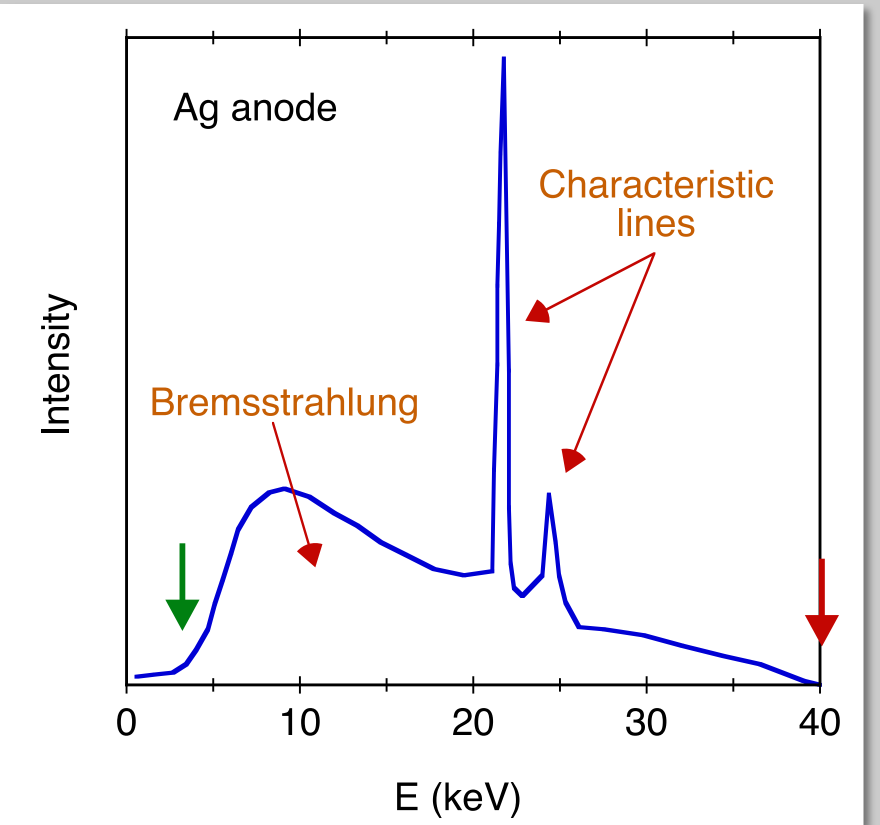


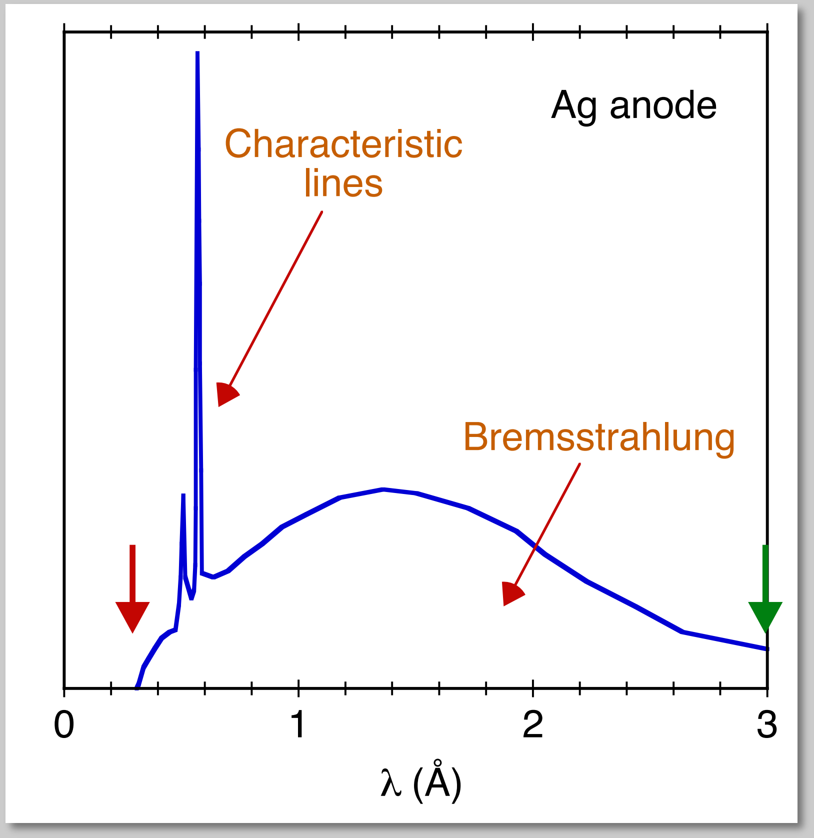
Un-polarized X-rays



Emission spectrum

Paolo
Fornasini
Univ. Trento

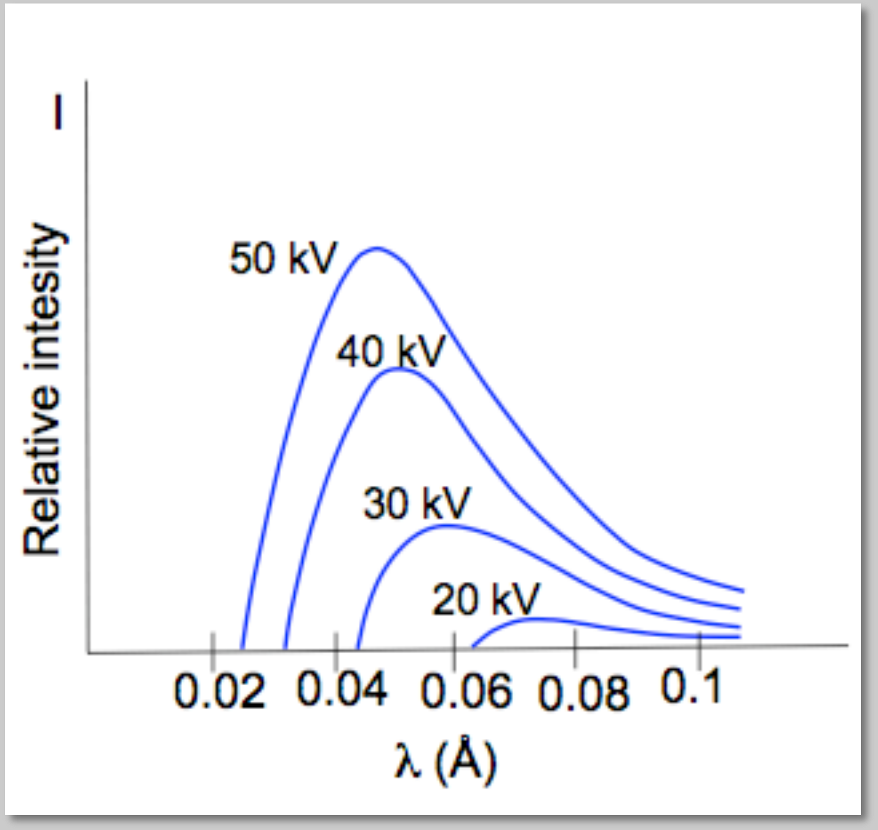




$$\lambda\,[\text{Å}] = \frac{12.4}{E\ [\text{keV}]}$$

Continuous bremsstrahlung spectrum

Paolo
Fornasini
Univ. Trento

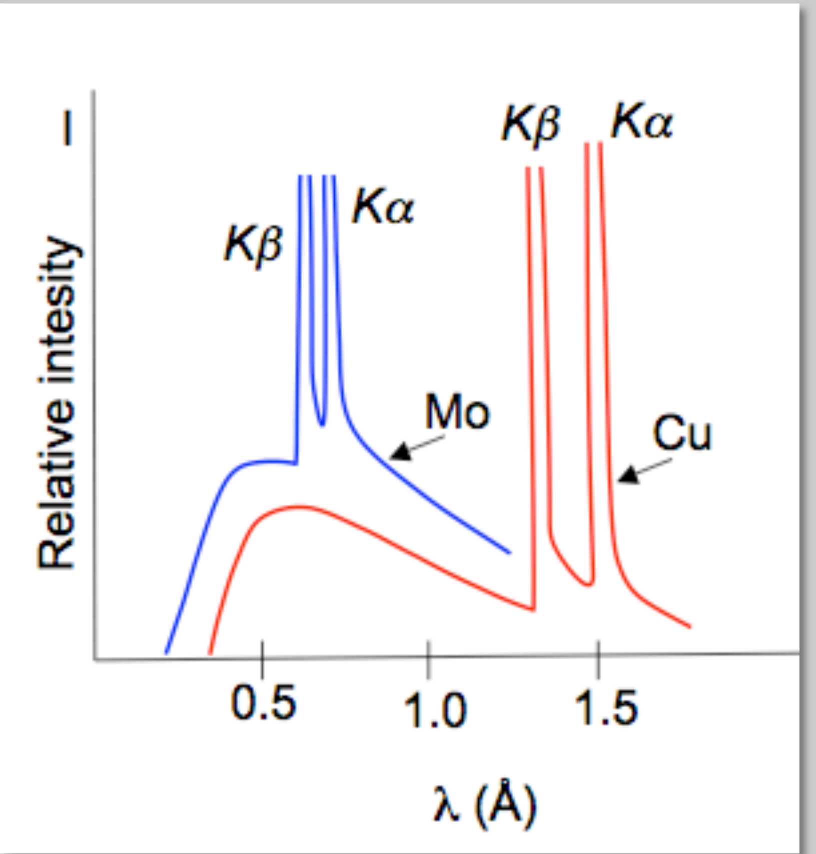


Electrons accelerating voltage:

- Maximum energy (minimum λ)
- Total intensity

Characteristic lines

Paolo
Fornasini
Univ. Trento

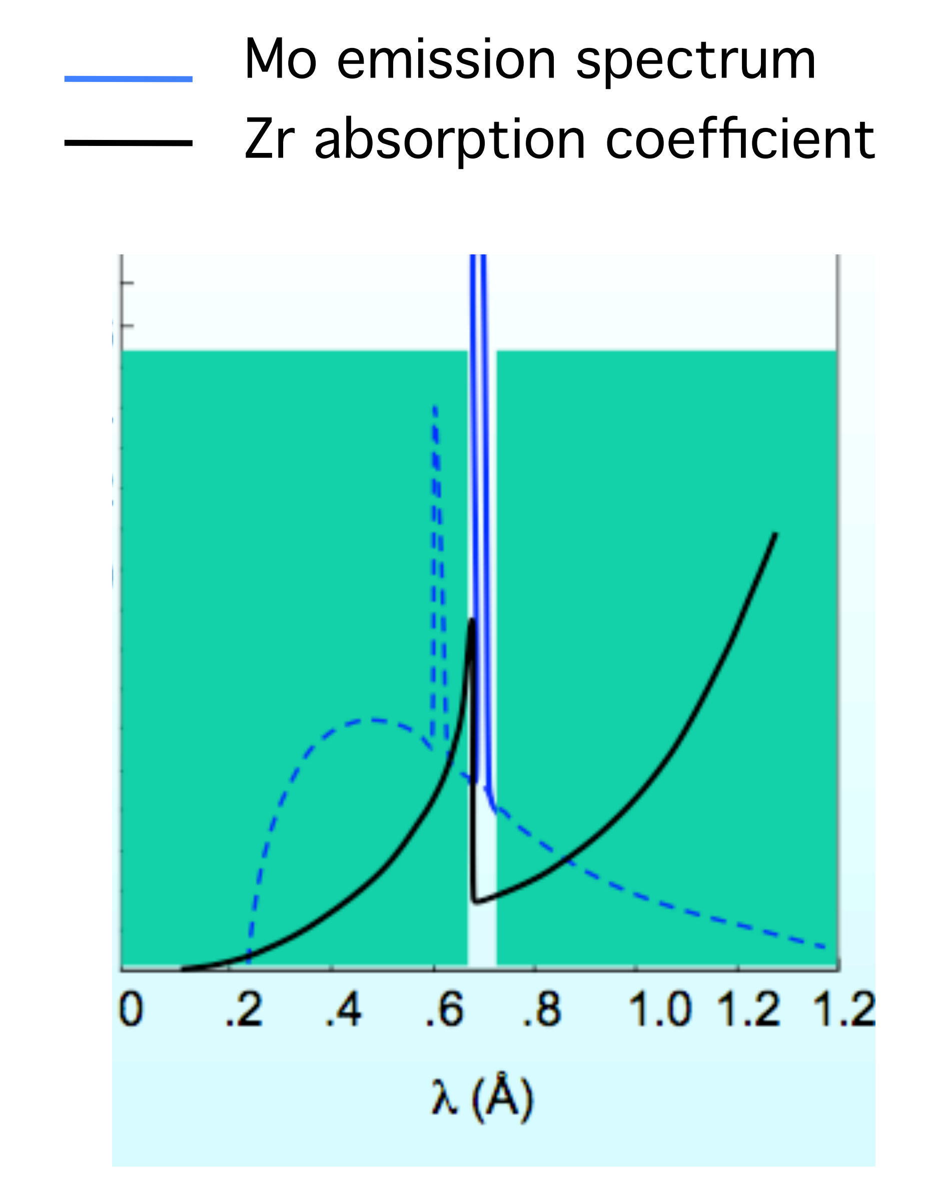


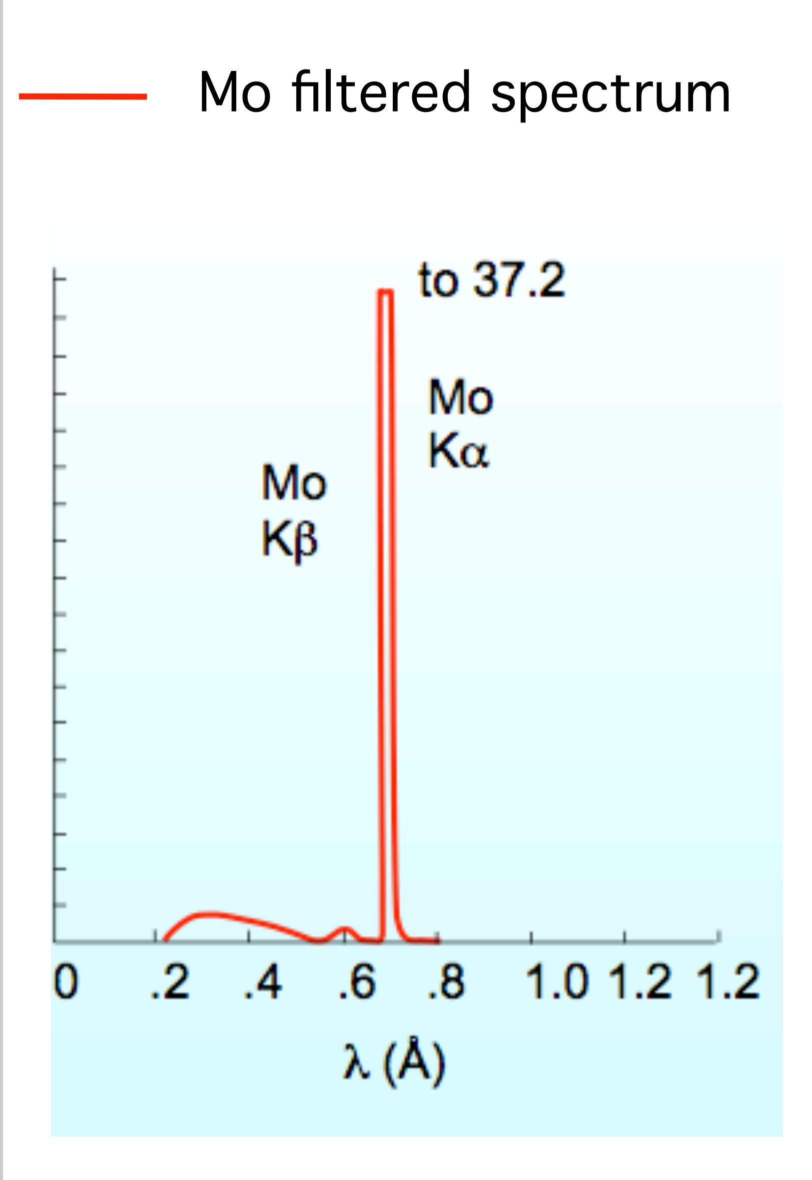
Moseley law $\lambda \propto \frac{1}{Z^2}$

		Cr	Cu	Mo
$K\alpha$	$K\alpha_1$	2.2897	1.5406	0.7093
	$K\alpha_2$	2.2936	1.5444	0.7136
$K\beta$		2.0849	1.3922	0.6323

Filters

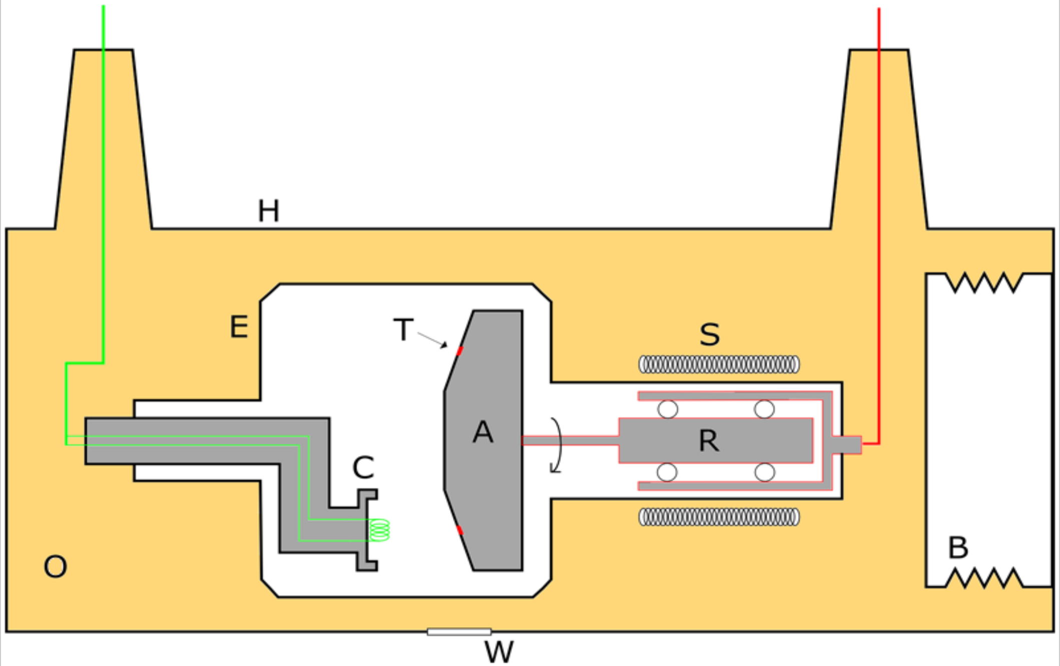
Paolo
Fornasini
Univ. Trento





Rotating-anode tubes

Paolo
Fornasini
Univ. Trento



Snapshot emission:
no liquid cooling

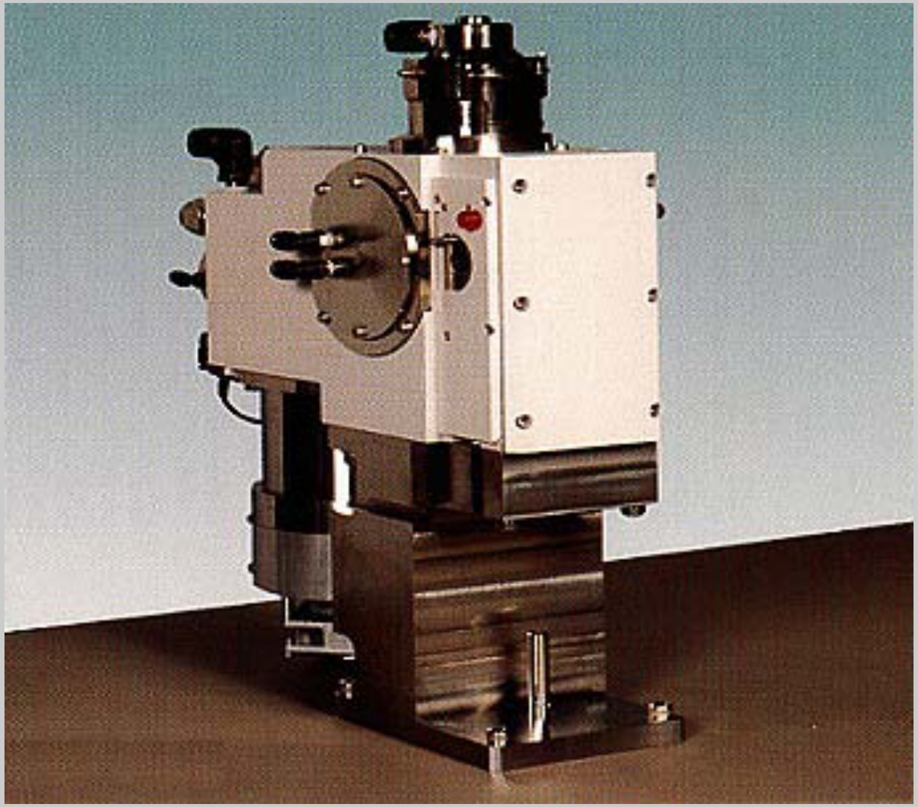
Power ratings up to 100 kW

Anode rotated by
electromagnetic induction

Almost all medical tubes
are rotating anode tubes
(exception: dental tubes)

Liquid cooled rotating-anode sources

Paolo
Fornasini
Univ. Trento



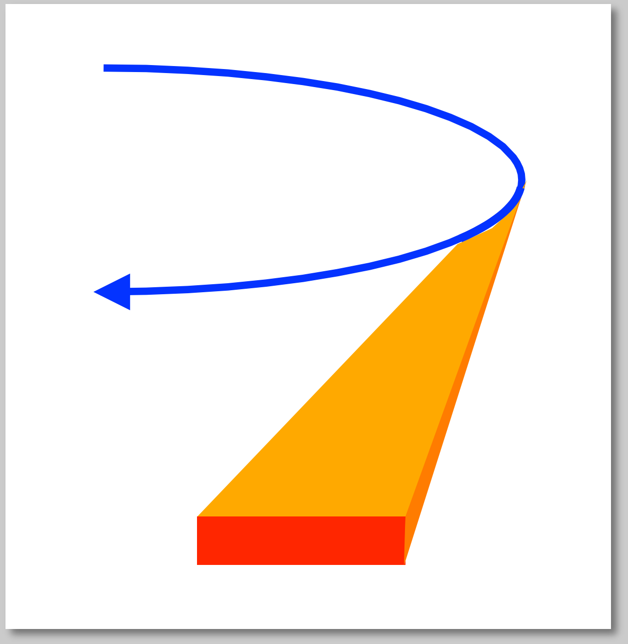
Power ratings 12 – 18 kW

For non-snapshot applications: diffraction, tomography, etc.

Synchrotron Radiation

Synchrotron radiation

Electromagnetic radiation
emitted by centripetally accelerated electrons
moving at relativistic speed



Storage rings

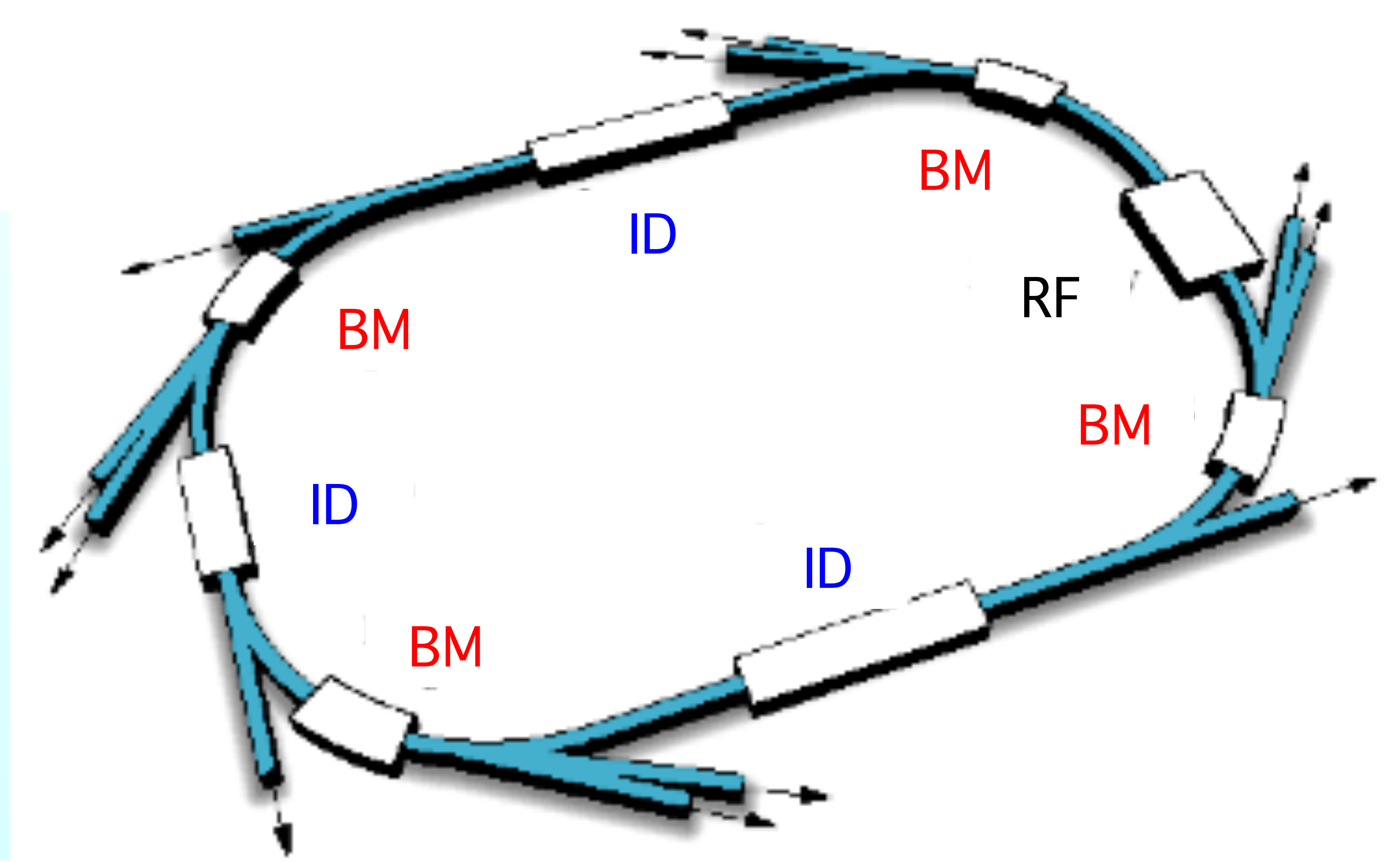
Relative velocity $\beta = \dfrac{v}{c} \approx 1$

Electron energy $W \cong 1 \div 10 \text{ GeV}$

A key parameter
$$\gamma = \left(1 - v^2/c^2\right)^{-1/2} = W/m_0c^2 \approx 2000 \div 20000$$

Storage rings as S.R. sources

Paolo
Fornasini
Univ. Trento



Basic components

BM = bending magnets

ID = insertion devices

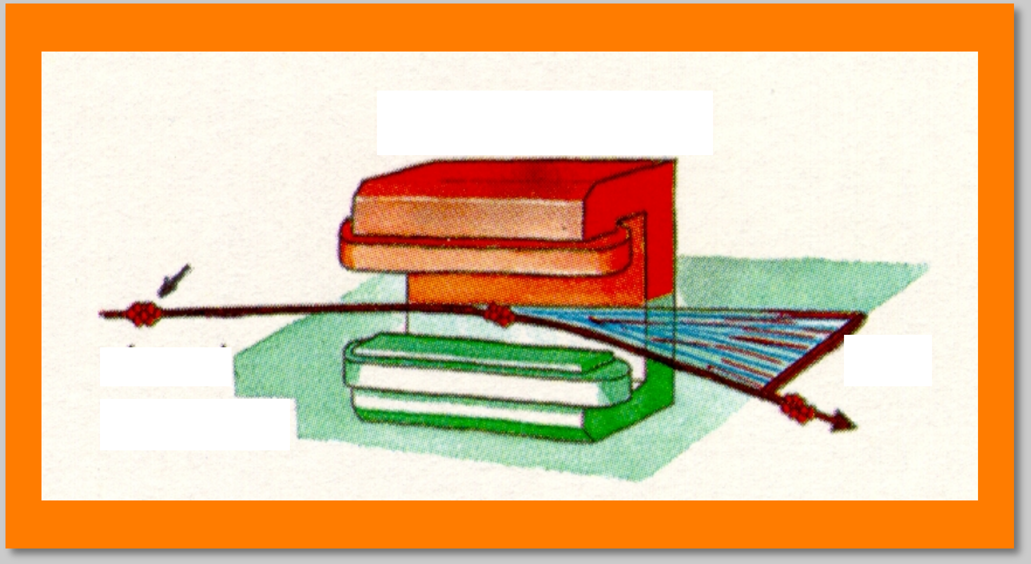
RF = radiofrequency cavity

Synchrotron Radiation from:

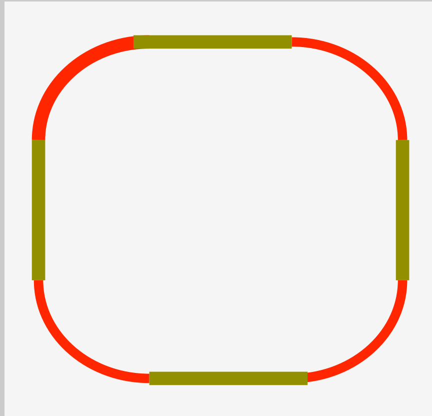
- Bending magnets
- Insertion devices ...
  - wigglers
  - undulators

Bending magnets and insertion devices

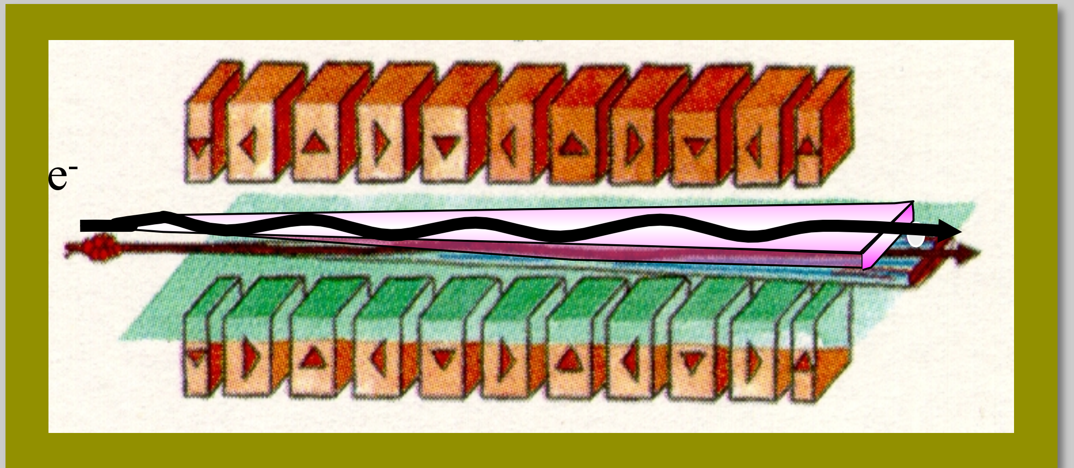
Paolo
Fornasini
Univ. Trento



Bending magnet

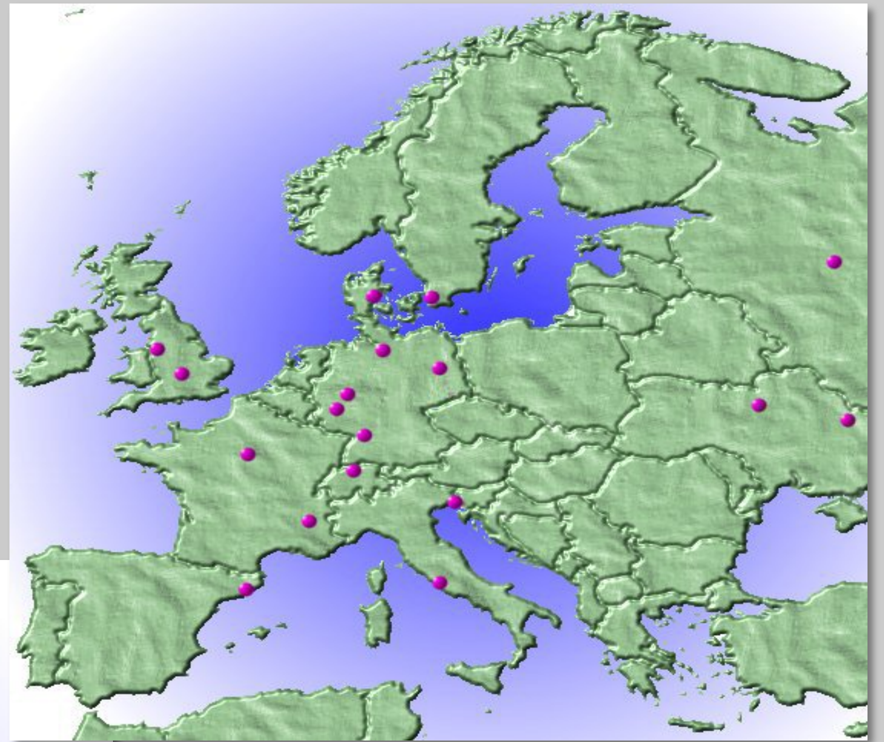


Insertion device



S.R. Facilities - map

Paolo
Fornasini
Univ. Trento



S.R. Facilities

Paolo
Fornasini
Univ. Trento

Name	Site	Year	E (GeV)
SPring8 Super Photon ring 8 GeV	Hyogo (Japan)	1997	8
APS Advanced Photon Source	Argonne, IL (USA)	1996	7
ESRF European S. R. Facility	Grenoble (France)	1994	6

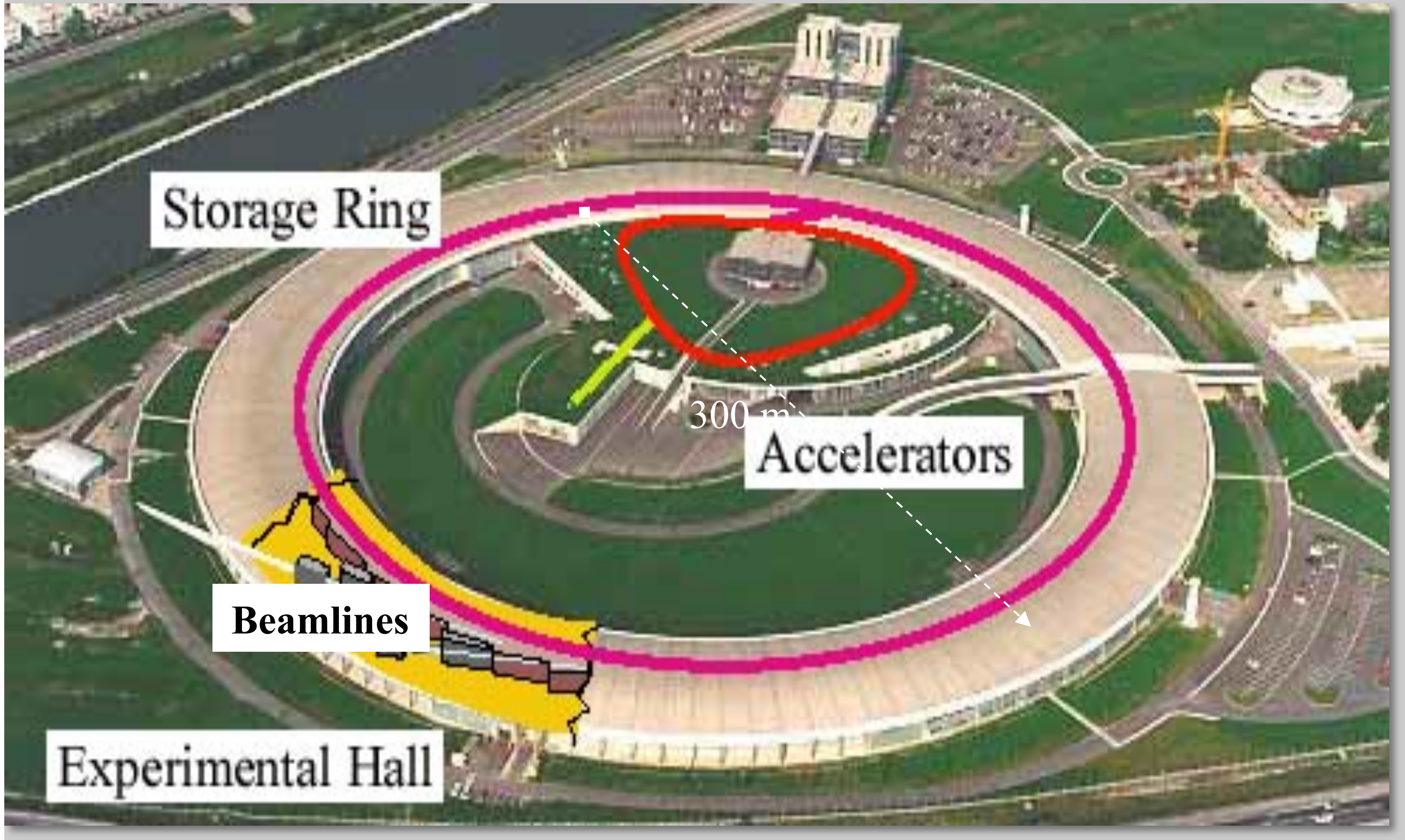
Large

Europe

Name	Site	Year	E (GeV)
PETRA III	Hamburg (D)	2009	6
DORIS III	Hamburg (D)	1980	4.45
Diamond	Didcot (UK)	2007	3
Soleil	S.Aubin (F)	2006	2.75
Elettra	Trieste (I)	1994	2.4
ALBA	Barcelona (E)	2012	3.0
SLS	Villigen (CH)	2001	2.4

E.S.R.F = European Synchrotron Radiation Facility

Paolo
Fornasini
Univ. Trento



Electron energy

W = 6 GeV

γ = 12000

Diameter

300 m

32 bending magnets
32 straight sections

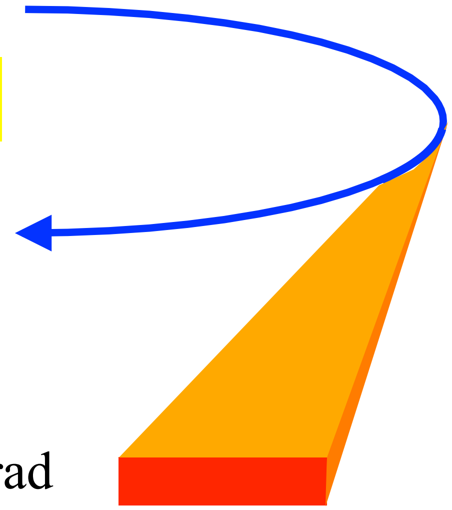
15 BM beamlines
32 ID beamlines

S. R. from bending magnets

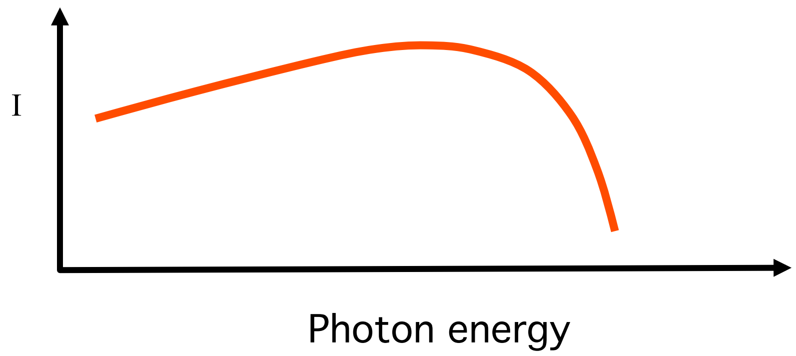
Properties of Synchrotron Radiation

Paolo
Fornasini
Univ. Trento

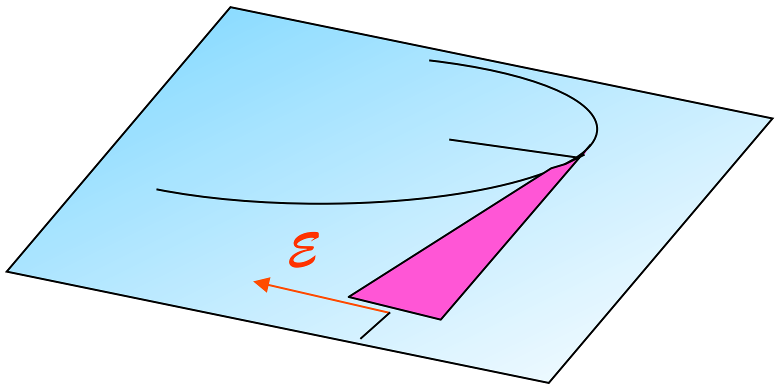
Collimation



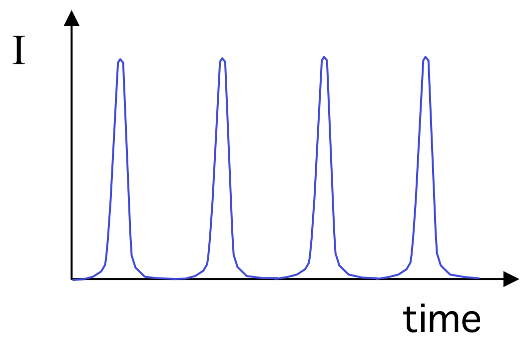
$\Theta \cong 1/\gamma$ rad



High intensity continuous spectrum



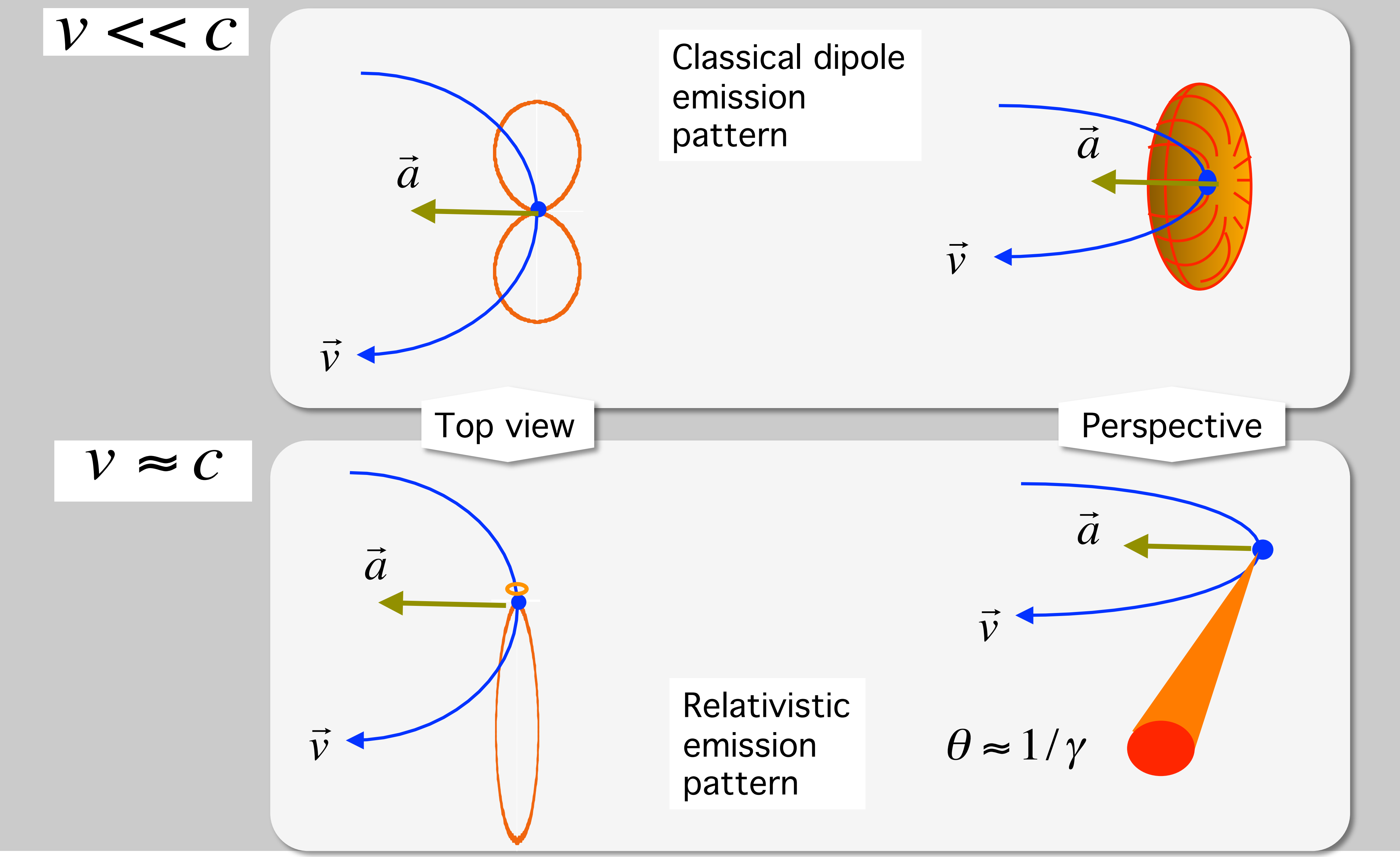
Polarisation



Time structure

S.R. angular distribution (a)

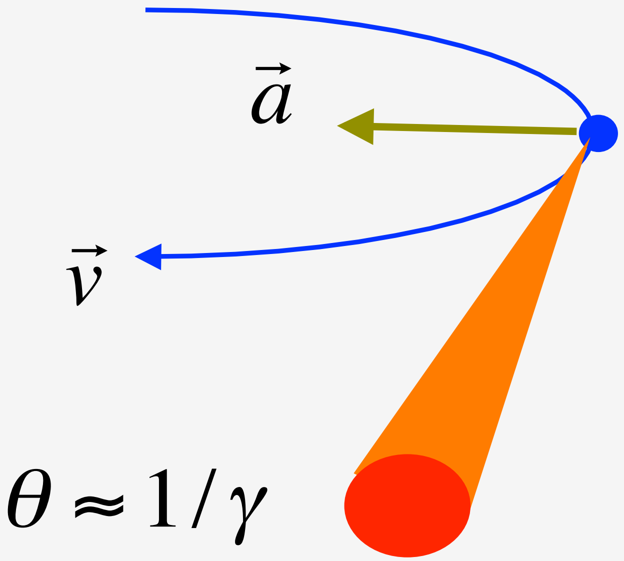
Paolo
Fornasini
Univ. Trento



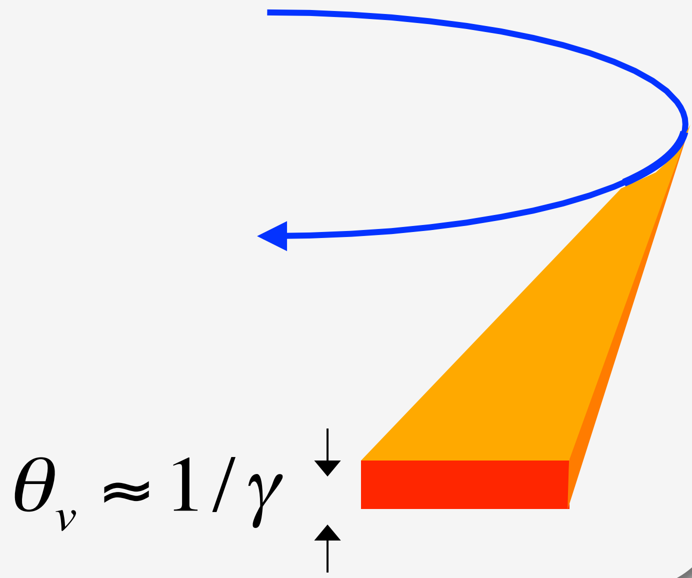
S.R. angular distribution (b)

Paolo
Fornasini
Univ. Trento

Instantaneous emission from one electron



Electron beam in bending magnet



ESRF:

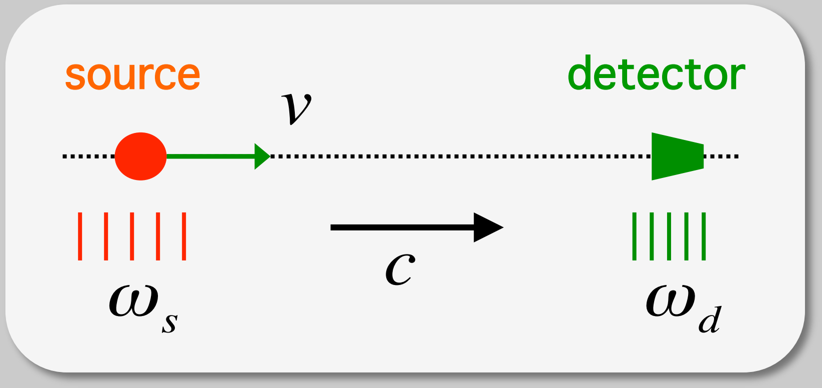
$$W = 6\ \text{GeV}$$

$$\gamma = \frac{W}{m_0 c^2} \approx 12000$$

$$\theta \approx \frac{1}{\gamma} \approx 10^{-4}\ \text{rad} \approx 0.005^\circ$$

Relativistic Doppler effect

Paolo
Fornasini
Univ. Trento



v = approaching velocity (detector .vs. source)

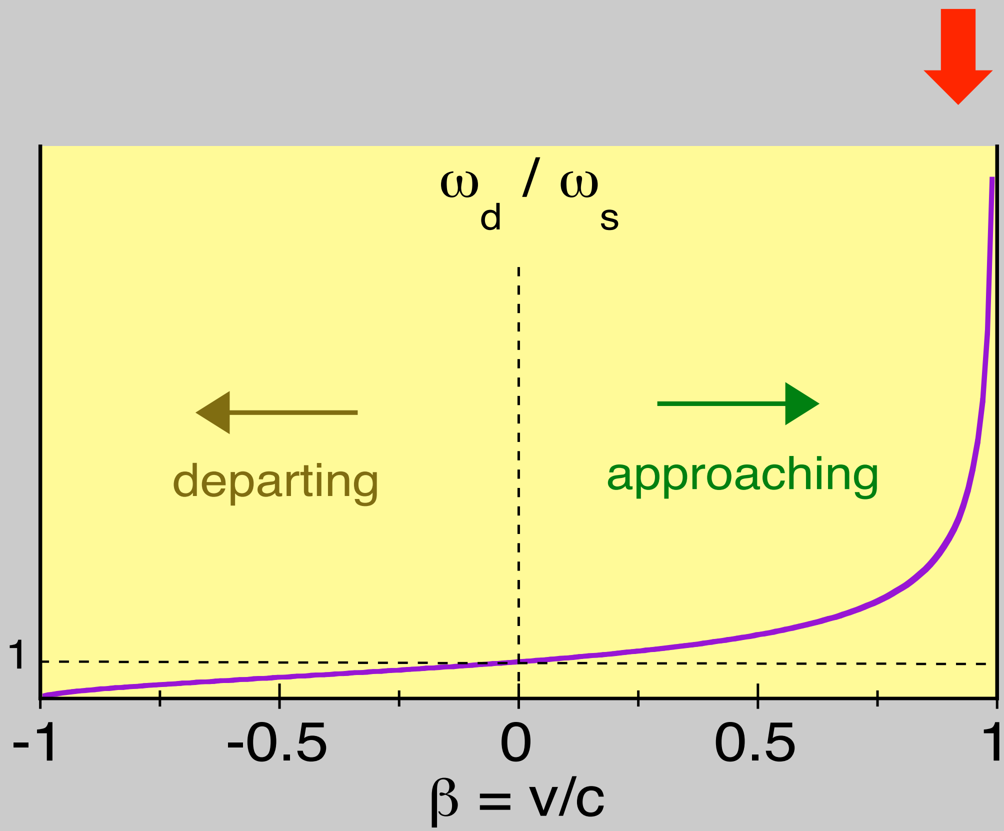
c = electrom. wave velocity (indep. of reference)

Lorentz-invariance

$$kx - \omega t = k'x' - \omega' t'$$

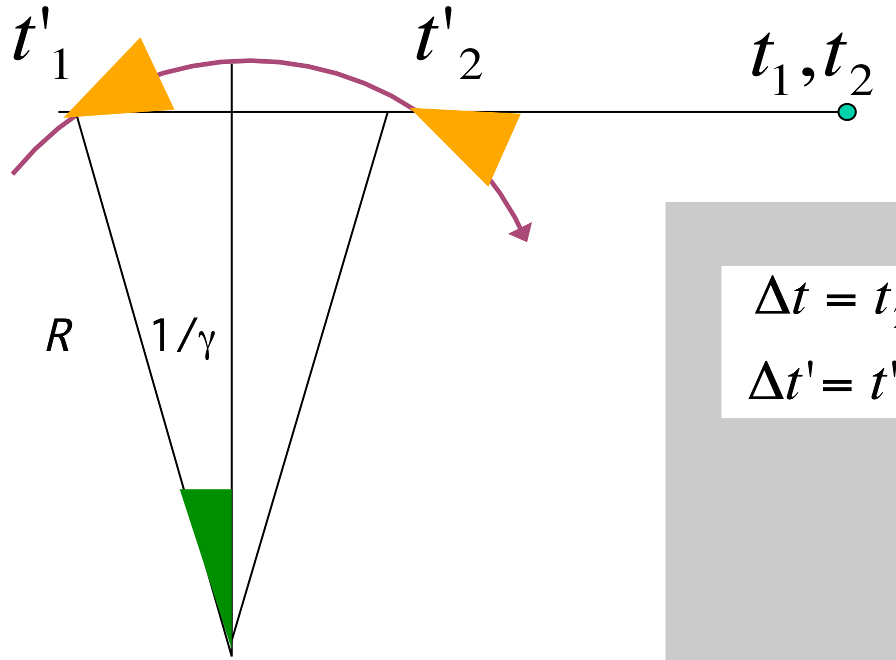
Frequency (energy) shift

$$\omega_d = \omega_s \sqrt{\frac{1+v/c}{1-v/c}} = \omega_s \, \gamma \left(1 + v/c\right)$$



S.R. spectral properties (a)

Paolo
Fornasini
Univ. Trento



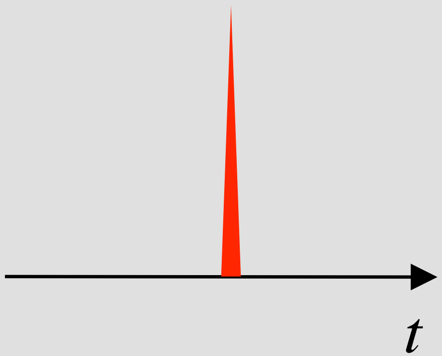
$\Delta t = t_2 - t_1$ emission time

$\Delta t' = t'_2 - t'_1$ detection time

Time domain

Short time pulse

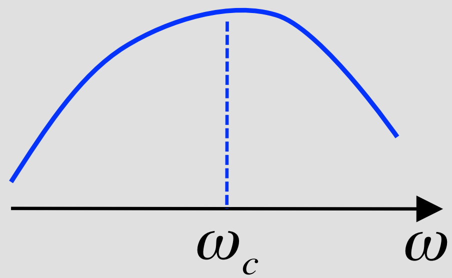
$$\Delta t \cong \frac{4}{3}\frac{R}{c\gamma^3}$$



Frequency domain

High frequencies

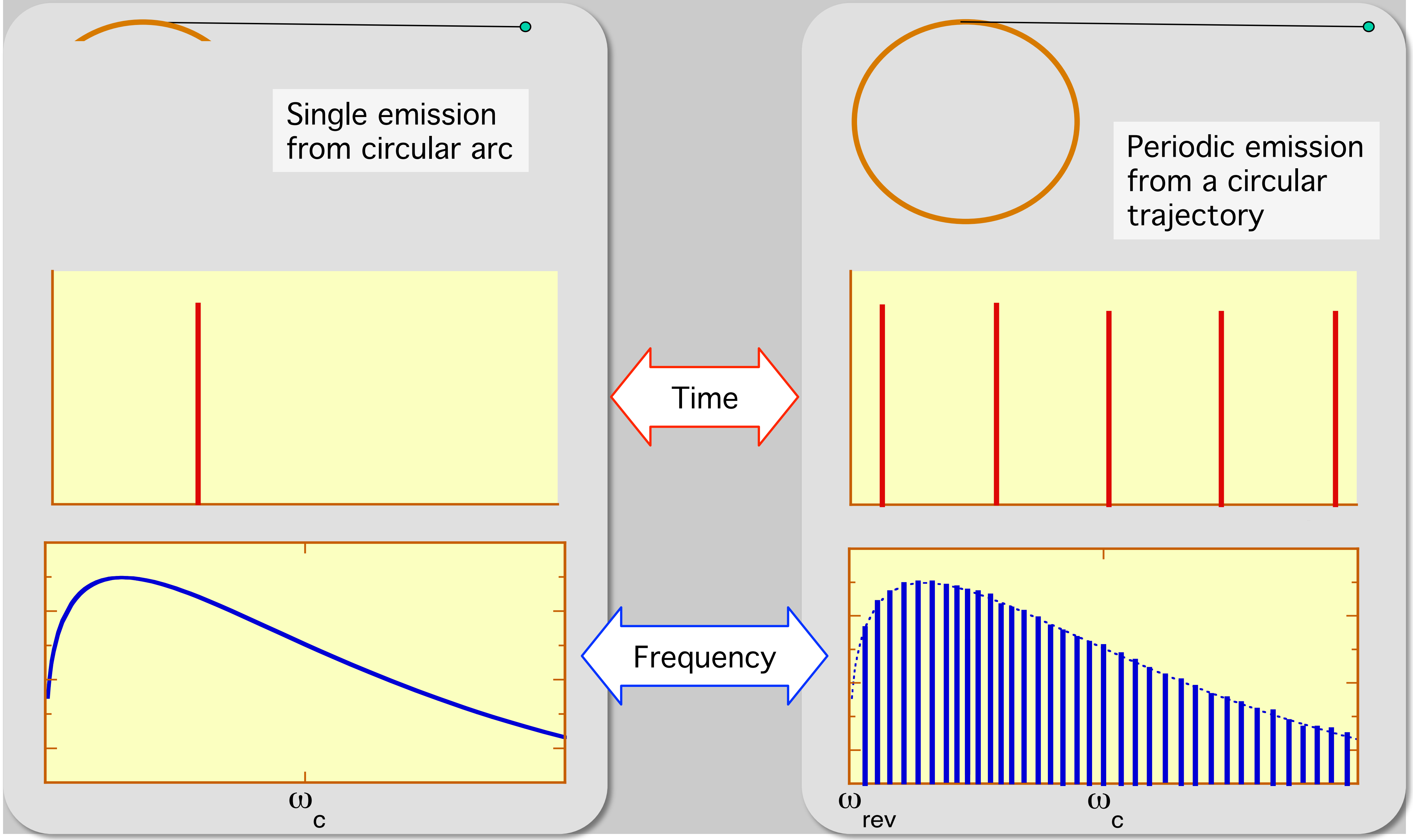
$$\omega_c \approx \frac{3c\gamma^3}{2R}$$



Broad spectrum

S.R. spectral properties (b)

Paolo
Fornasini
Univ. Trento



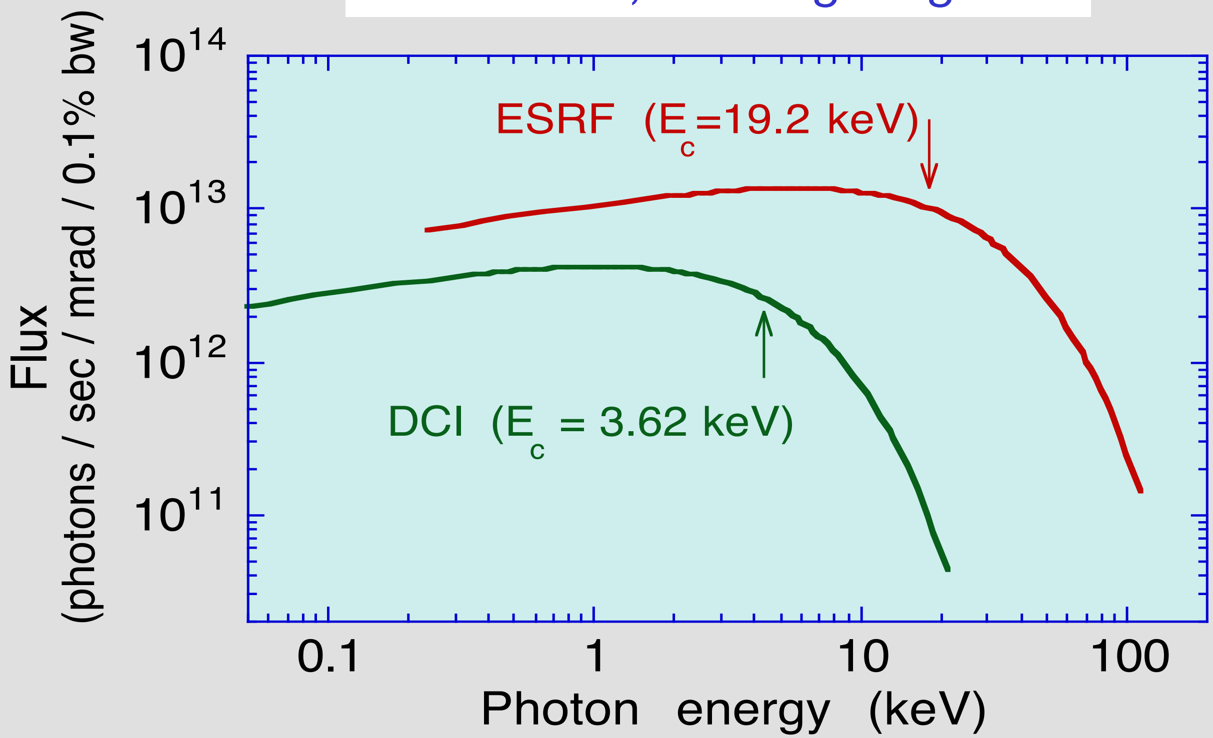
S.R. emission spectra

Paolo
Fornasini
Univ. Trento

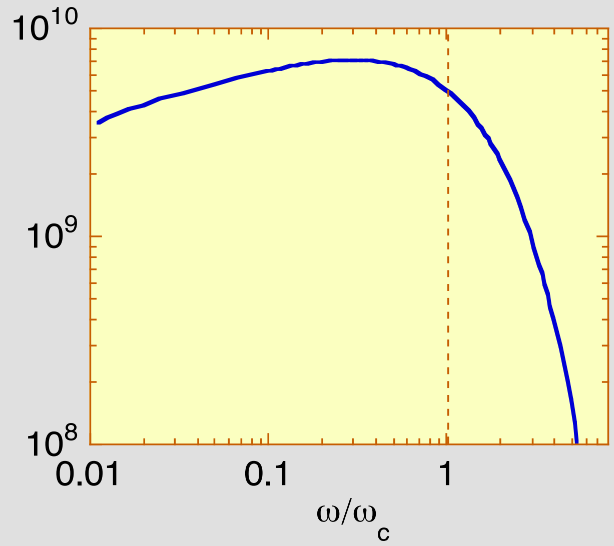
Photons/s/mrad/ 0.1% $\Delta\lambda/\lambda$

$$\mathrm{Flux} = I\ \gamma\ F_1$$

I=100 mA, bending magnets



F_1 = S.R. universal curve



S.R. polarization

Paolo
Fornasini
Univ. Trento

σ - Horizontal component (in the orbit plane)

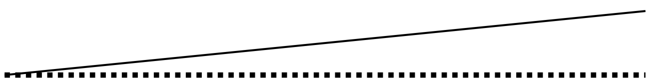
π - The vertical component:
increases with angle
decreases with photon energy

$\pm \frac{\pi}{2}$ dephasing

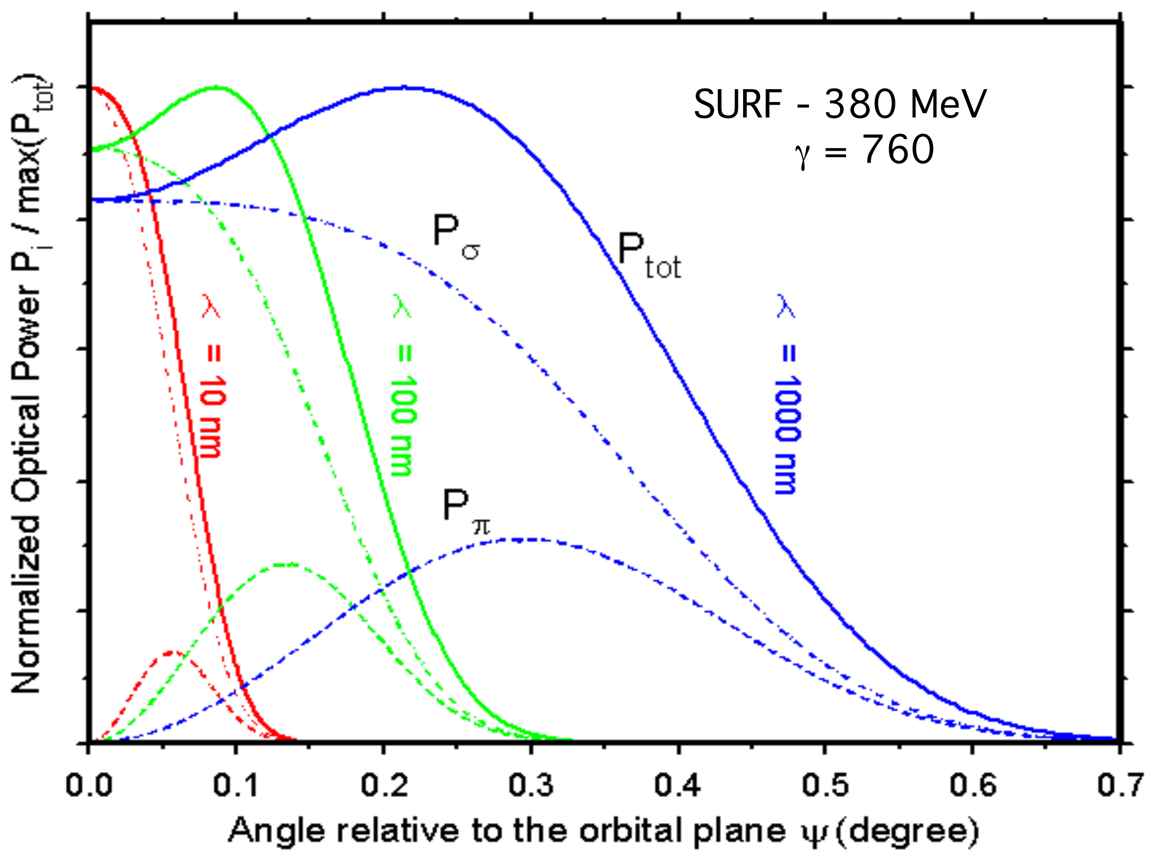
↓

Elliptical polarisation

Vertical divergence



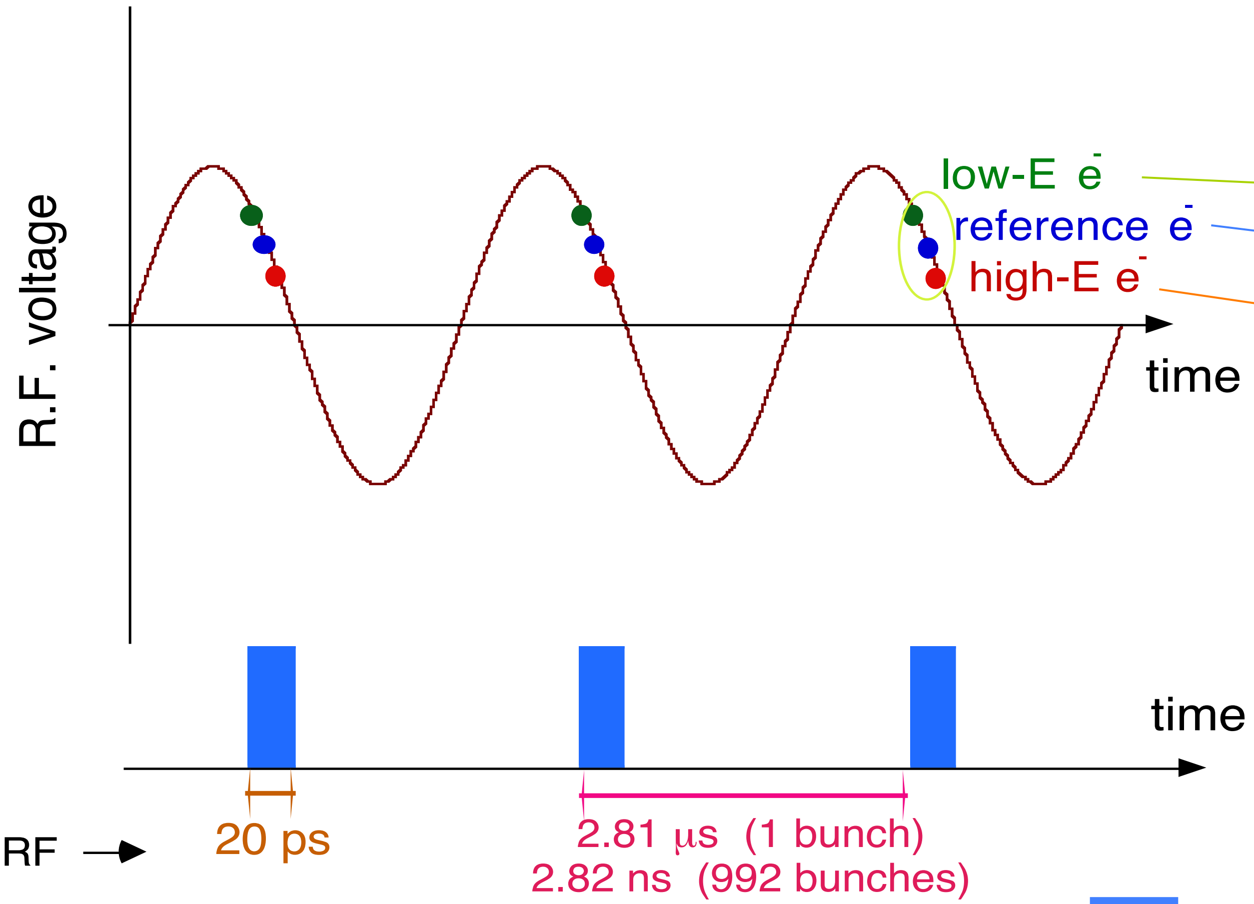
$$\psi \approx \frac{1}{\gamma} \quad \text{for} \quad E = E_c$$



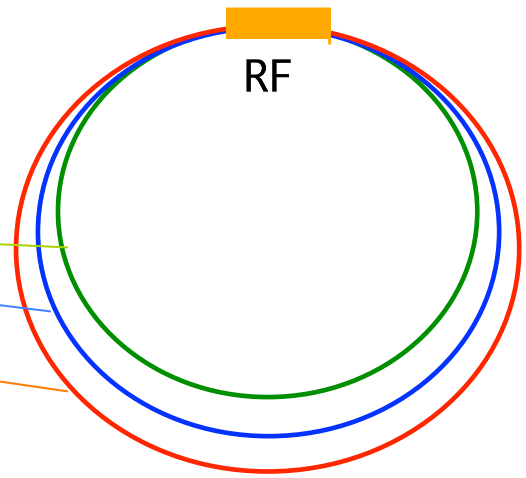
S.R. time structure

Paolo
Fornasini
Univ. Trento

Phase-focussing in RF cavities



Orbits



$$v \approx c\,; \quad \rho = \frac{m_0 c}{eB}\gamma$$

Bunched structure:

- of electron beam
- of S.R. emission

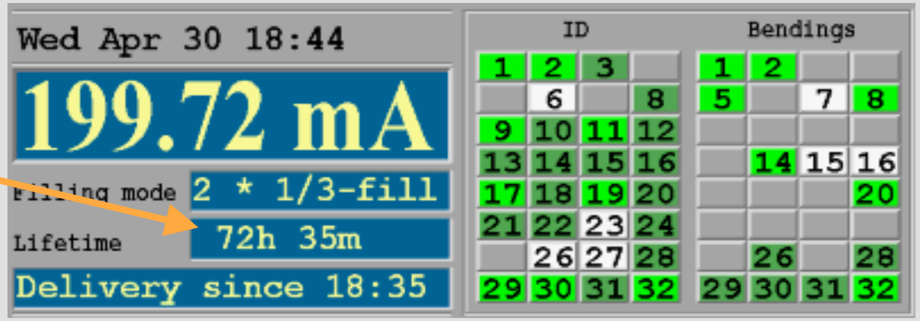
$e^{\pm}$ beam lifetime

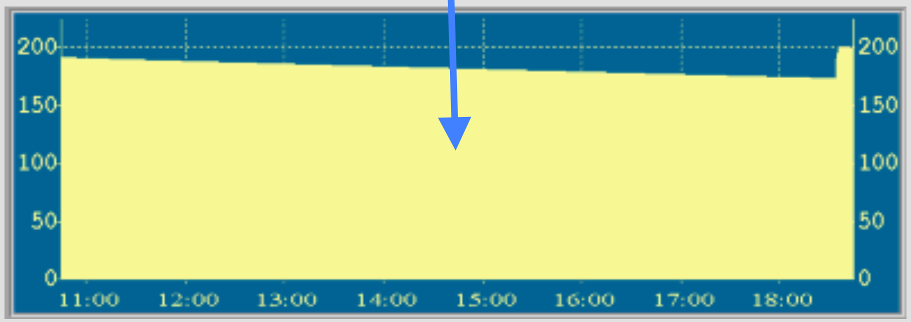
Paolo
Fornasini
Univ. Trento

- Collisions with residual gas (photon-stimulated desorption)
- Occasional large energy losses through S.R. emission
- Non-linear resonances (anharmonic betatron oscillations)
- Toushek effect (e-e scattering inside each bunch)

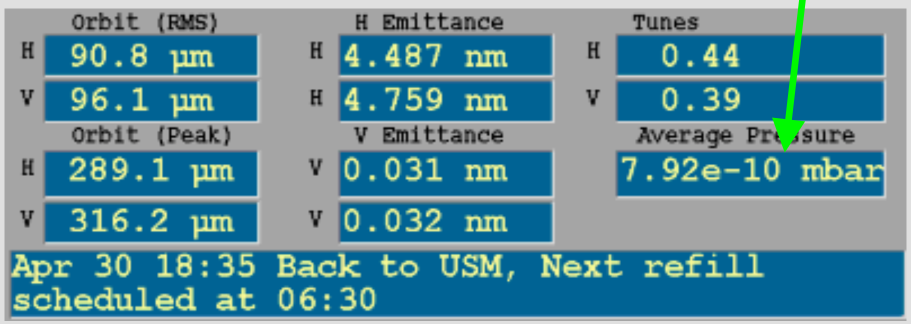
$$\tau = \frac{I(t)}{dI/dt}$$

$$I(t) = I_0 \exp[-t/\tau]$$





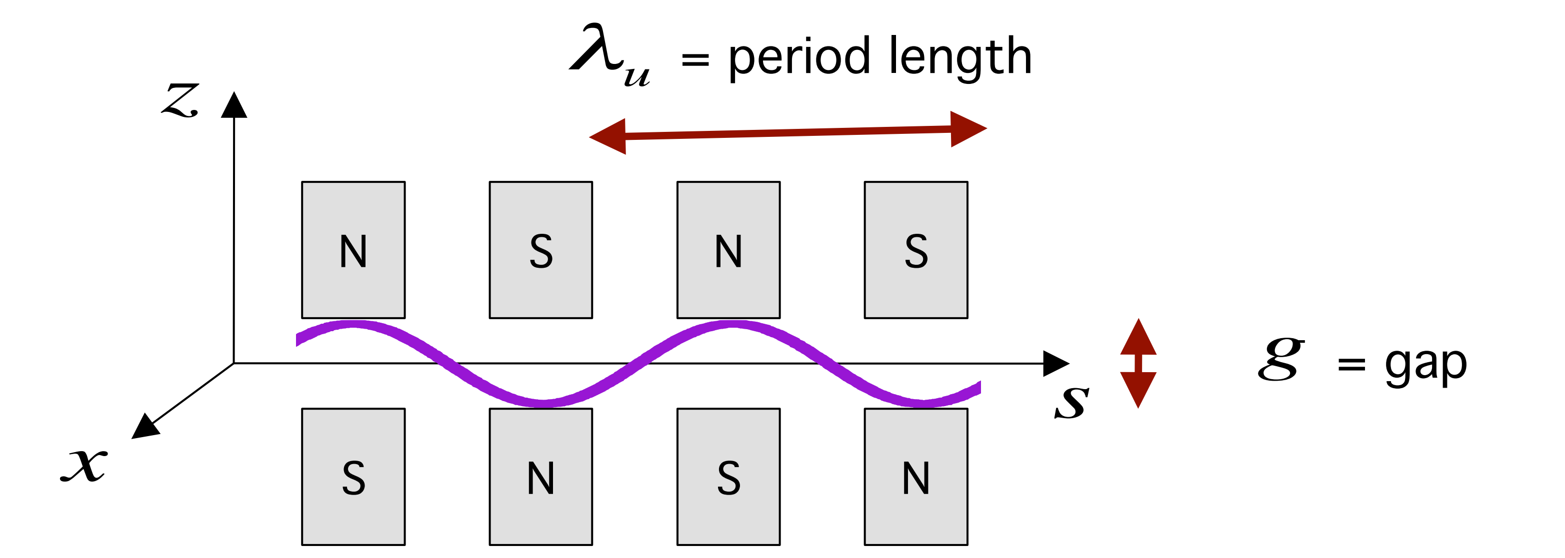
ESRF



S. R. from insertion devices

Alternating magnetic fields

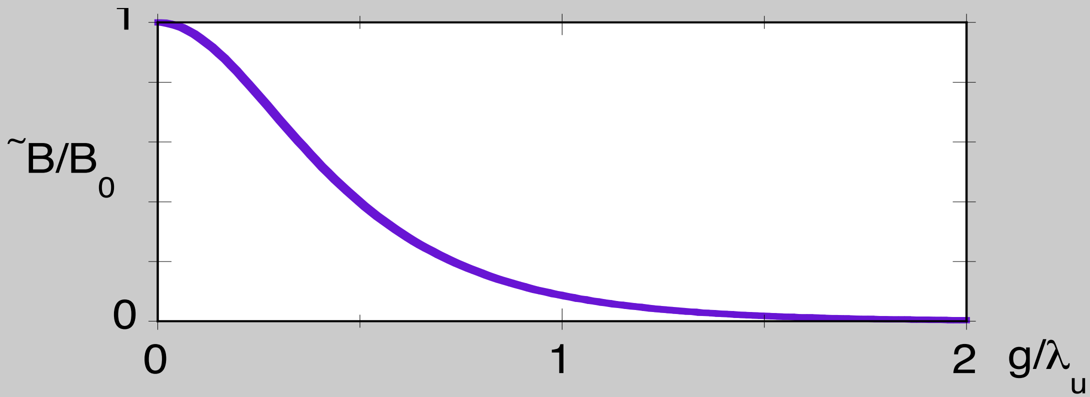
Paolo
Fornasini
Univ. Trento



Vertical magnetic field

$$B_z(s) = \frac{B_0}{\cosh(\pi g/\lambda_u)}\cos(k_u s) = \tilde{B}\cos(k_u s)$$

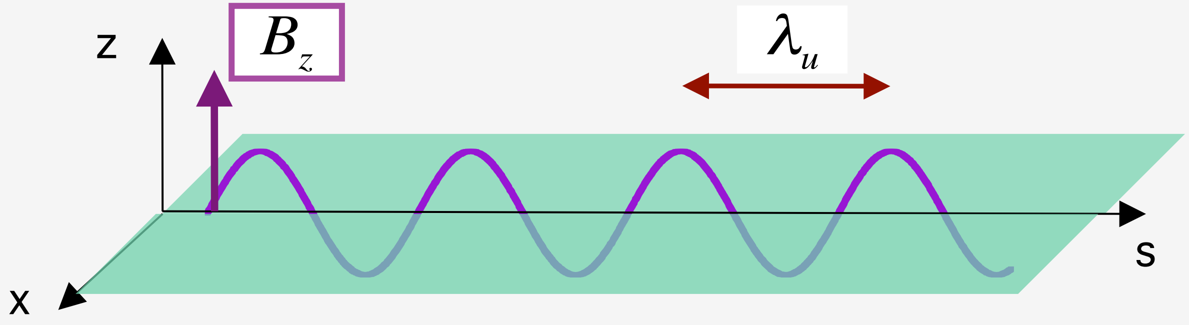
Gap-period relation



$$k_u = \frac{2\pi}{\lambda_u}$$

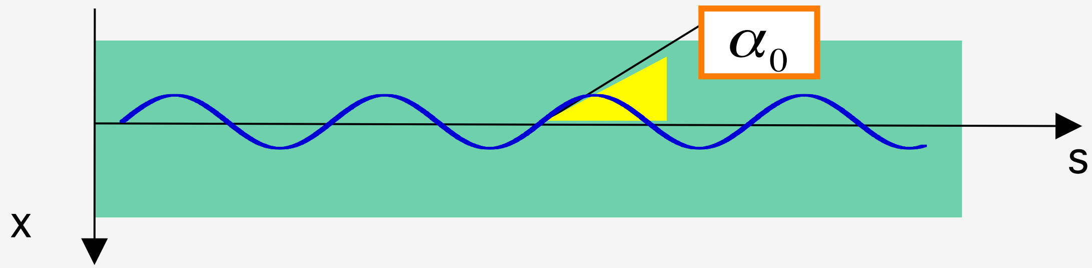
Magnetic field effects

Paolo
Fornasini
Univ. Trento



Oscillating vertical magnetic field

$$\vec{F} = e\vec{v} \times \vec{B}$$



Transverse beam oscillation

$$\alpha_0 = K \frac{1}{\gamma}$$

Wiggler/undulator parameter

$$K = \frac{eB\lambda_u}{2\pi c m_e}$$

The K parameter

W/U properties

SR divergence

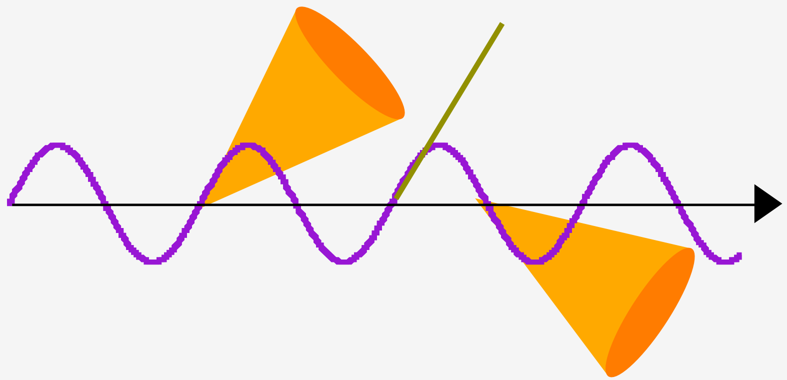
$$\alpha_0 = K \frac{1}{\gamma}$$

$$K = \frac{eB\lambda_u}{2\pi c m_e} = 0.934 \times B[\mathrm{T}] \times \lambda_u[\mathrm{cm}]$$

$$K > 1, \quad \alpha_0 > \frac{1}{\gamma}$$

High-K devices

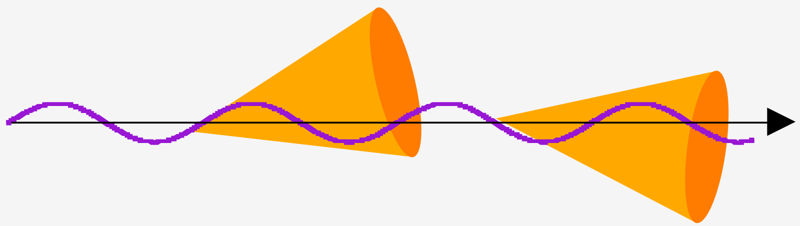
WIGGLERS



$$K \leq 1, \quad \alpha_0 \leq \frac{1}{\gamma}$$

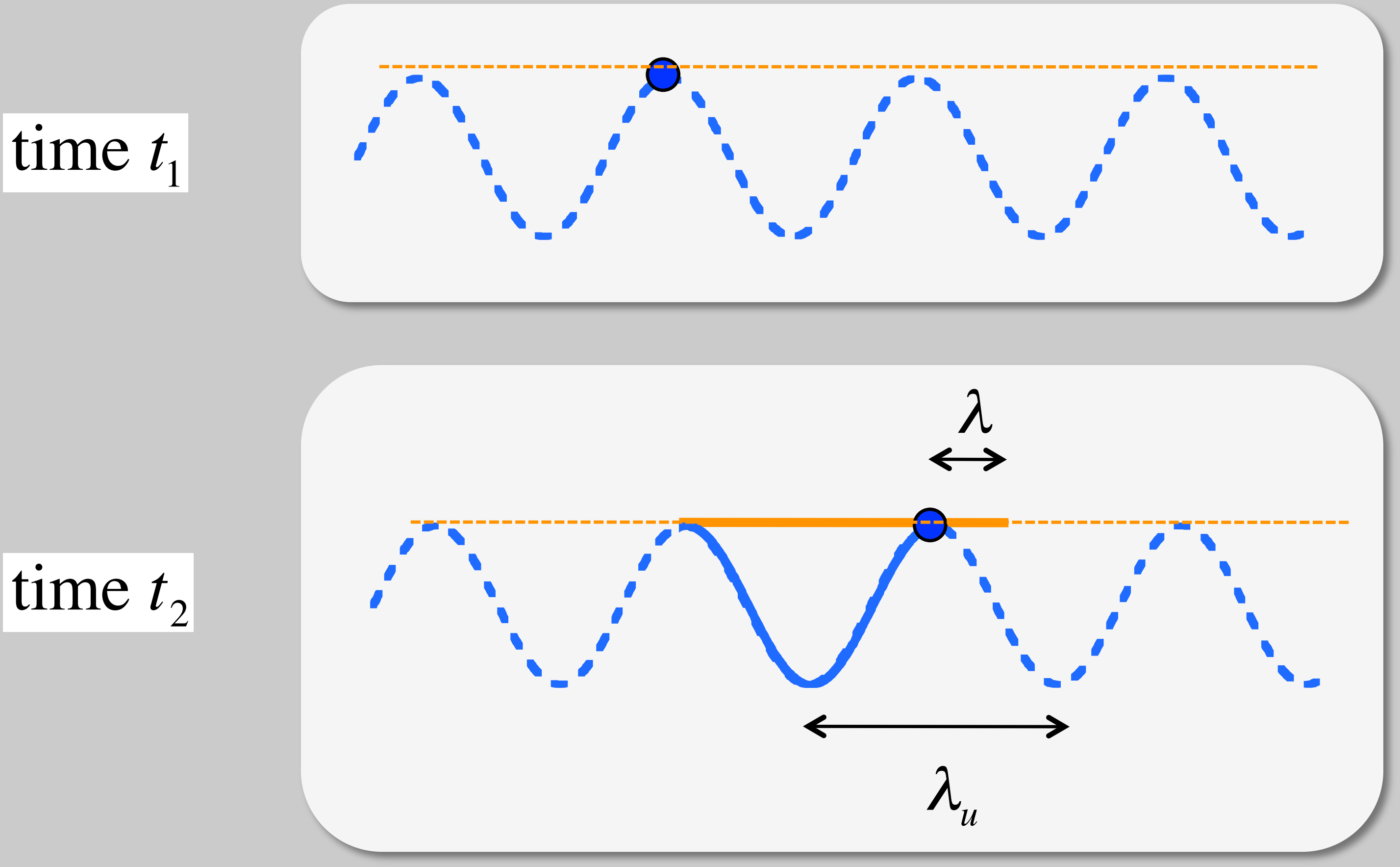
Low-K devices

UNDULATORS



Undulator: interference effect

Paolo
Fornasini
Univ. Trento

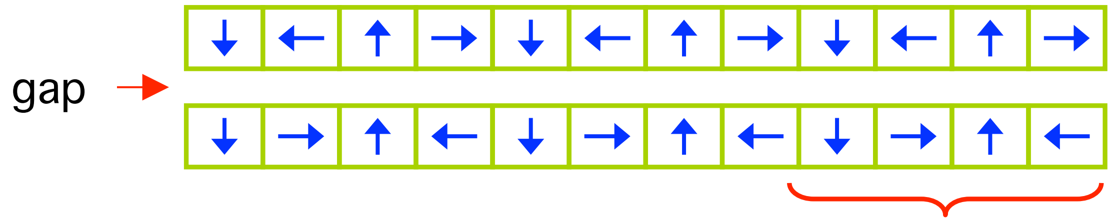


Constructive interference for

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

Properties of undulator radiation (a)

Paolo
Fornasini
Univ. Trento



$$\lambda_u \approx 20 \div 40 \text{ mm}$$

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

tunability:
gap ⇒ B ⇒ K

Angular
red-shift

- Large N
- K<1

⇒ Interference
(monochromatic
radiation)

Properties of undulator radiation (b)

Paolo
Fornasini
Univ. Trento

- Interference ➔ Flux $\propto N^2$ (in forward direction)

N = number of wiggles

- Electron motion not perfectly sinusoidal ➔ higher order harmonics

$$\omega_1 \approx \frac{4\pi c\gamma^2/\lambda_u}{1+K^2/2+\gamma^2\theta^2}$$

$$\omega_n = n\omega_1$$

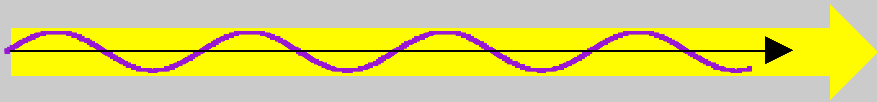
- Finite wave-train of radiation emitted by each electron ➔ bandwidth

$$\frac{\Delta\omega_n}{\omega_n} \approx \frac{\gamma^2\delta(\theta^2)}{1+K^2/2}$$

$$\frac{\Delta\omega_n}{\omega_n} \approx \frac{1}{nN}$$

Low-K .vs. high-K devices

Low-K



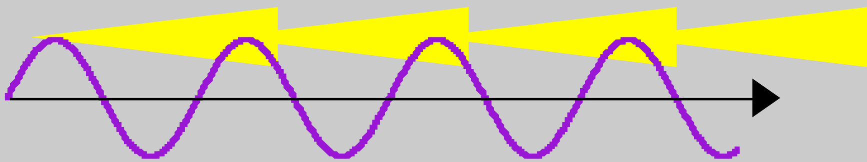
Coherent superposition
Interference

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

Increasing K:

- λ increases
- relevance of harmonics
- interference effects reduced
- broader spectrum

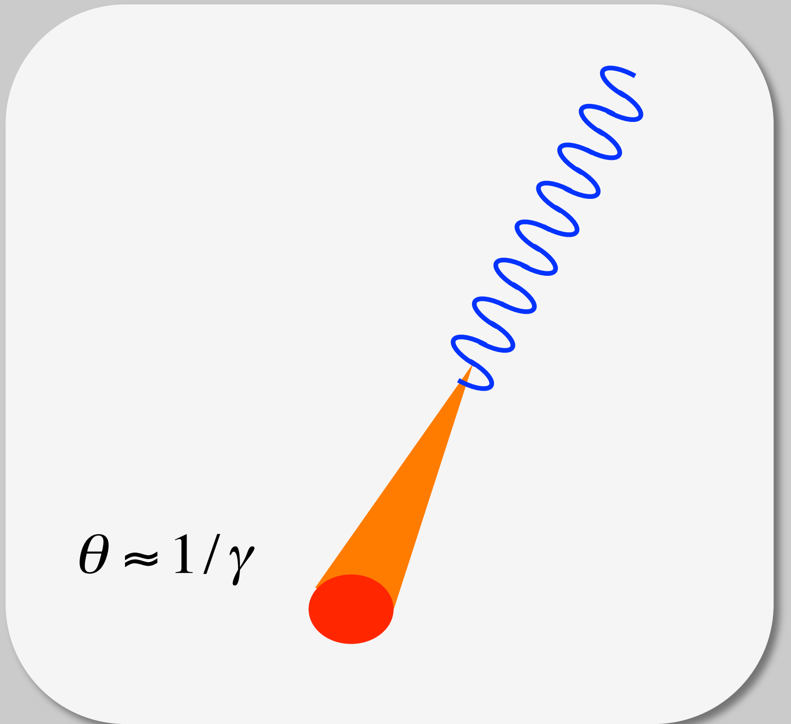
High-K



Inoherent superposition
Continuous spectrum

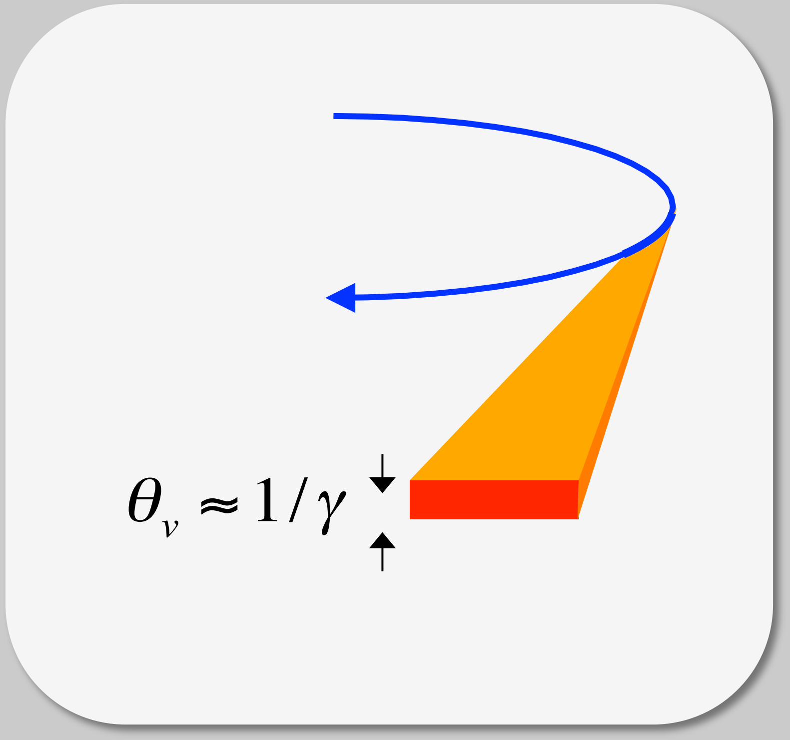
Undulators .vs. bending magnets (a)

Undulator



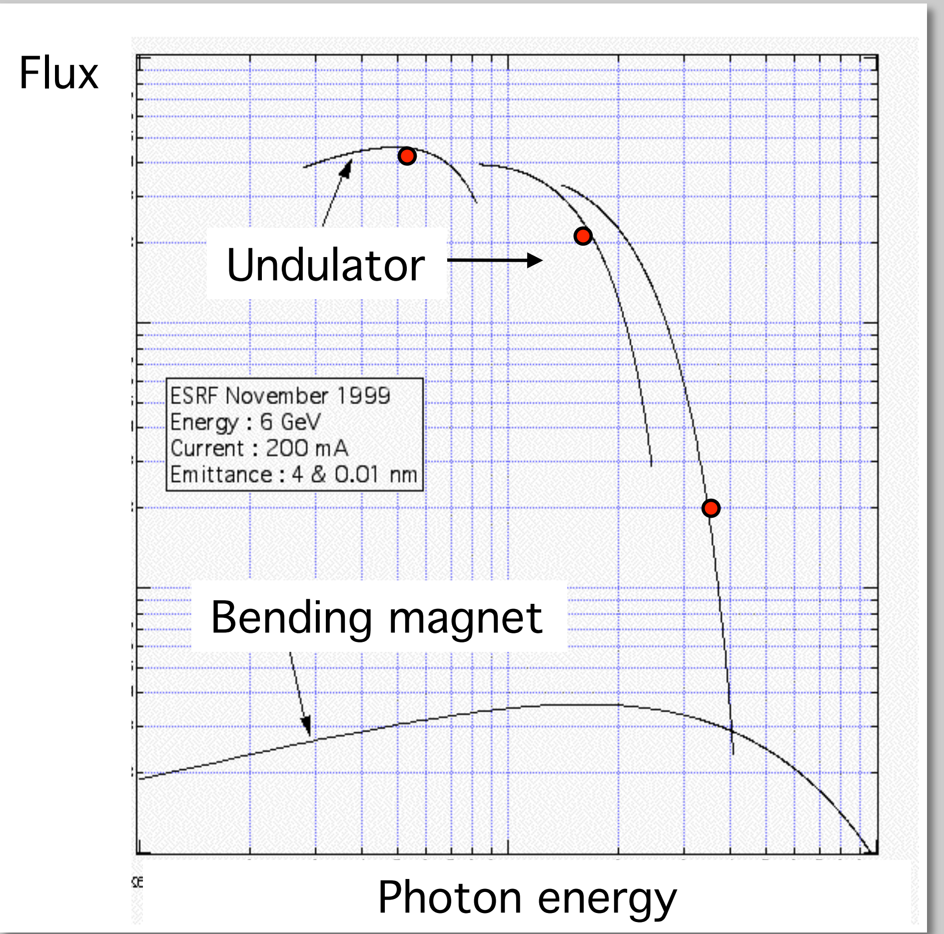
Vertical and horizontal collimation

Bending magnet, wiggler



Vertical collimation

Undulators .vs. bending magnets (b)



Undulator

Strong emission at discrete energies (fundamental + harmonics)

Tunability by varying the gap

Bending magnet, wiggler

Emission over a continuous spectrum

Brilliance of S.R.sources

Photon beam properties

e-beam size $\sigma_{x,y}(s)$ + e-beam divergence $\sigma'_{x,y}(s)$ + SR divergence $\theta \approx 1/\gamma$ = **Photon beam properties**

ESRF

	Horizontal		Vertical	
	σ_x [μm]	σ'_x [μrad]	σ_y [μm]	σ'_y [μrad]
Even I.D.	415	51	8.6	2.9
Odd I.D.	10.3	108	8.6	2.9

S.R. divergence $\theta \approx 1/\gamma \approx 100\ \mu\text{rad}$

Photon beam parameters

Paolo
Fornasini
Univ. Trento

Brilliance

$$\frac{\text{photons}}{\text{s mm}^2\ \text{mrad}^2\ \text{bandwidth}}$$

source size — solid angle — $0.1\%\ \Delta\lambda/\lambda$

Integrating over source size

Brightness

$$\frac{\text{photons}}{\text{s}\cdot\text{mrad}^2\cdot\text{bandwidth}}$$

+

Integrating over vert. angle

$$\frac{\text{photons}}{\text{s}\cdot\text{mrad}\cdot\text{bandwidth}}$$

+

Integrating over horiz. angle

Spectral flux

$$\frac{\text{photons}}{\text{s}\cdot\text{bandwidth}}$$

+

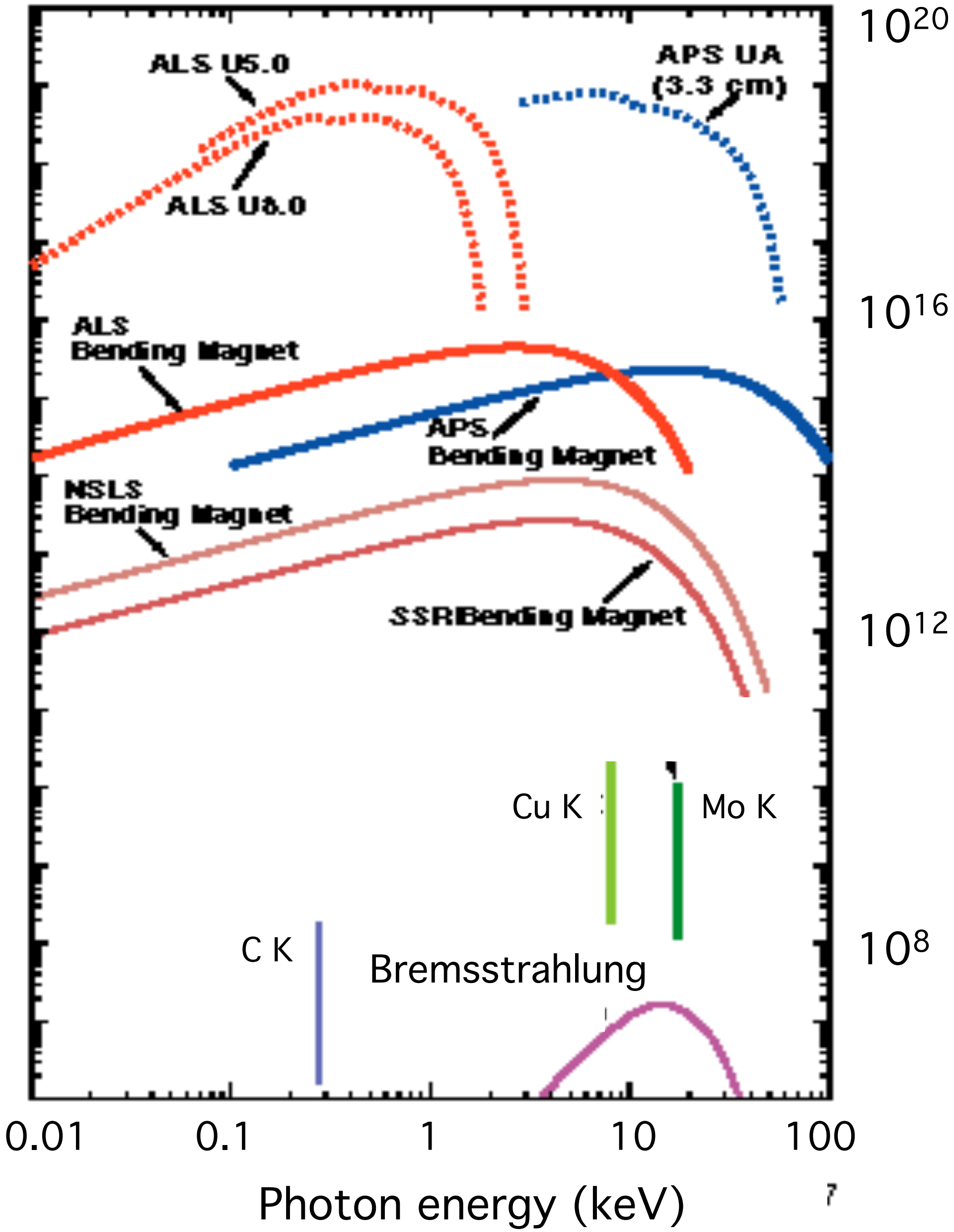
Integrating over bandwidth

Total flux

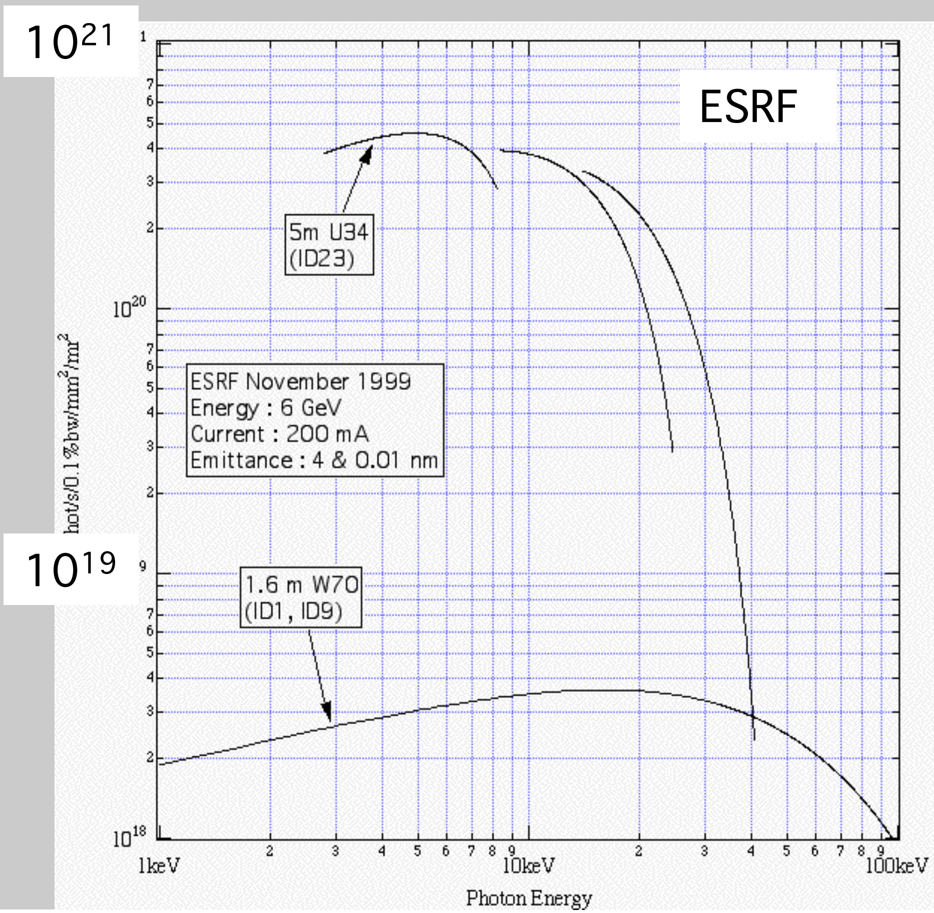
$$\frac{\text{photons}}{\text{s}}$$

Brilliance: comparisons

Paolo
Fornasini
Univ. Trento



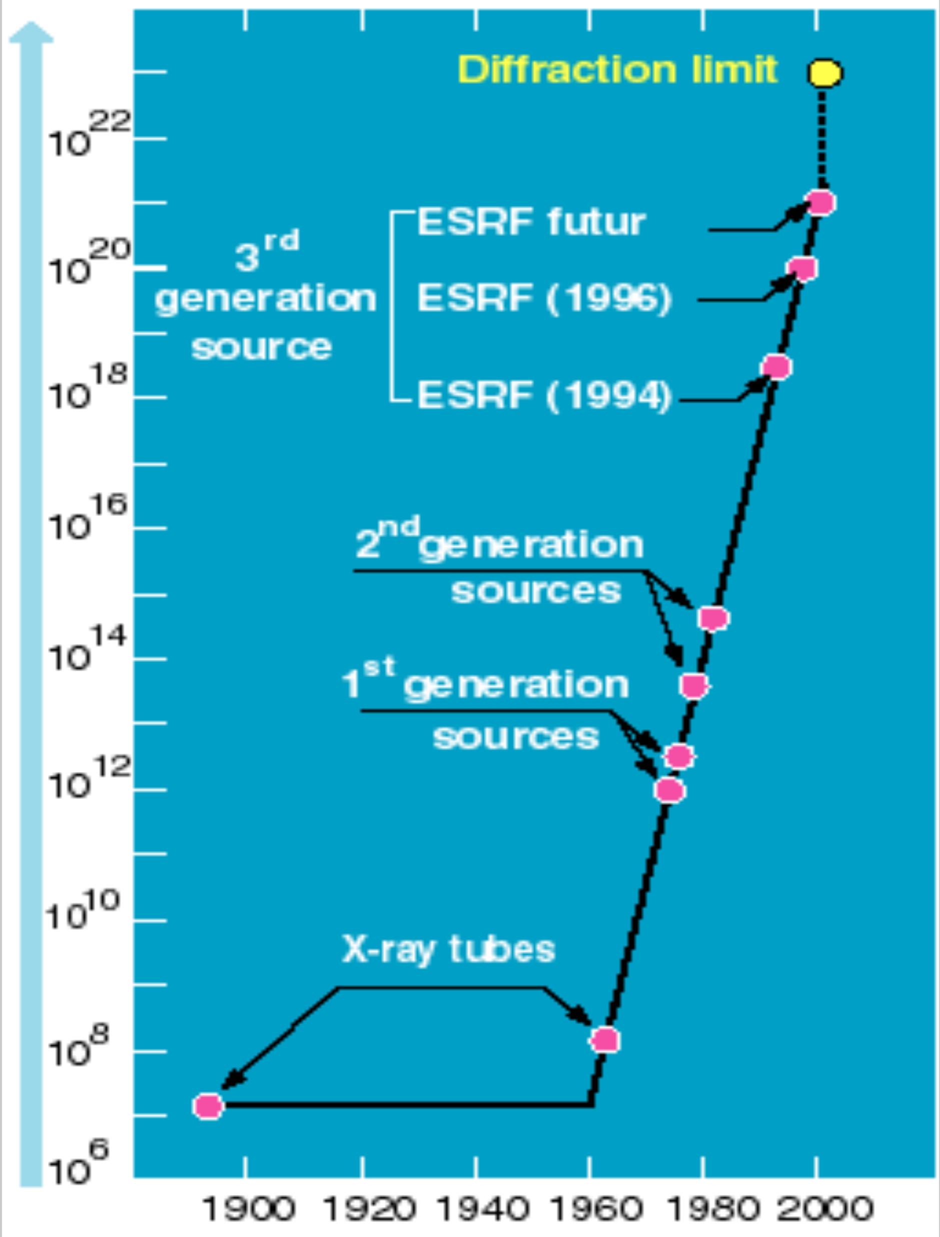
$$\frac{\text{photons}}{\text{s mm}^2\ \text{mrad}^2\ \text{bandwidth}}$$



Brilliance: time evolution

Paolo
Fornasini
Univ. Trento

$$\frac{\text{photons}}{\text{s mm}^2\ \text{mrad}^2\ \text{bandwidth}}$$



Neutron sources

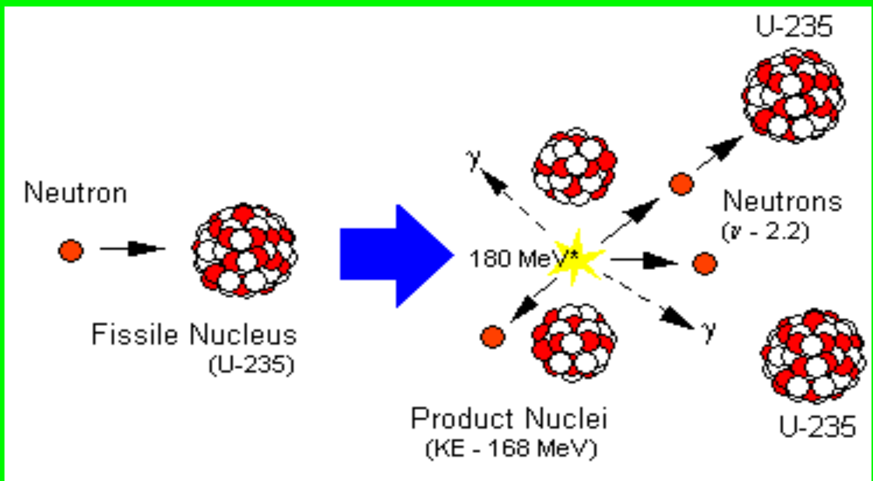
Neutron production

Paolo
Fornasini
Univ. Trento

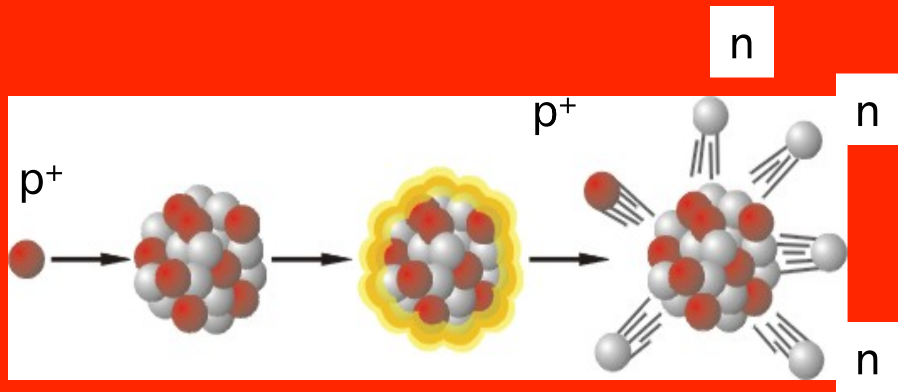
- Radioactive sources
- Neutrons from nuclear reactors
- Neutrons from pulsed accelerators
  - photofission
  - spallation

Most effective for solid state research:

Fission (reactors)

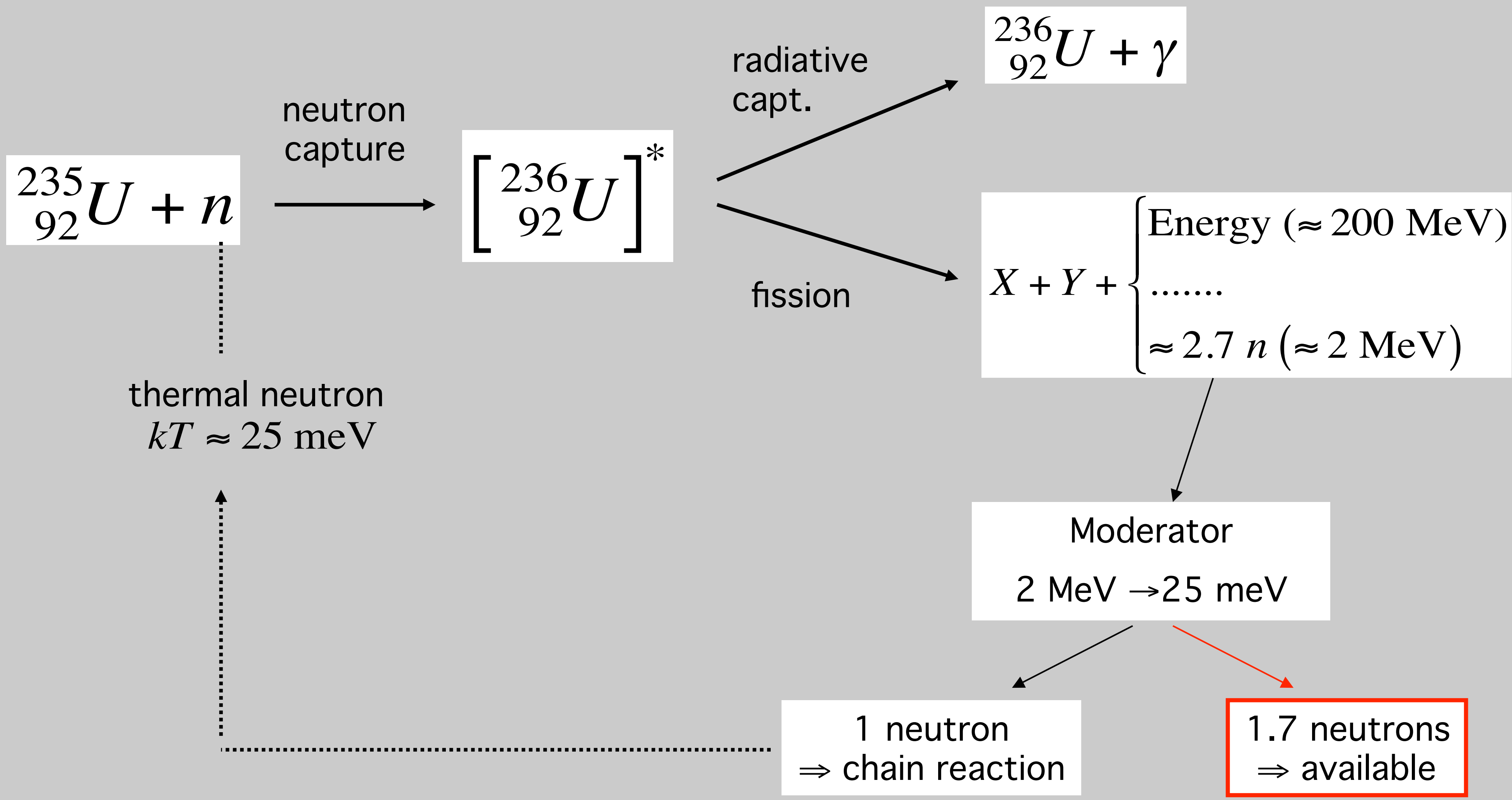


Spallation (accelerators)



Fission

Paolo
Fornasini
Univ. Trento



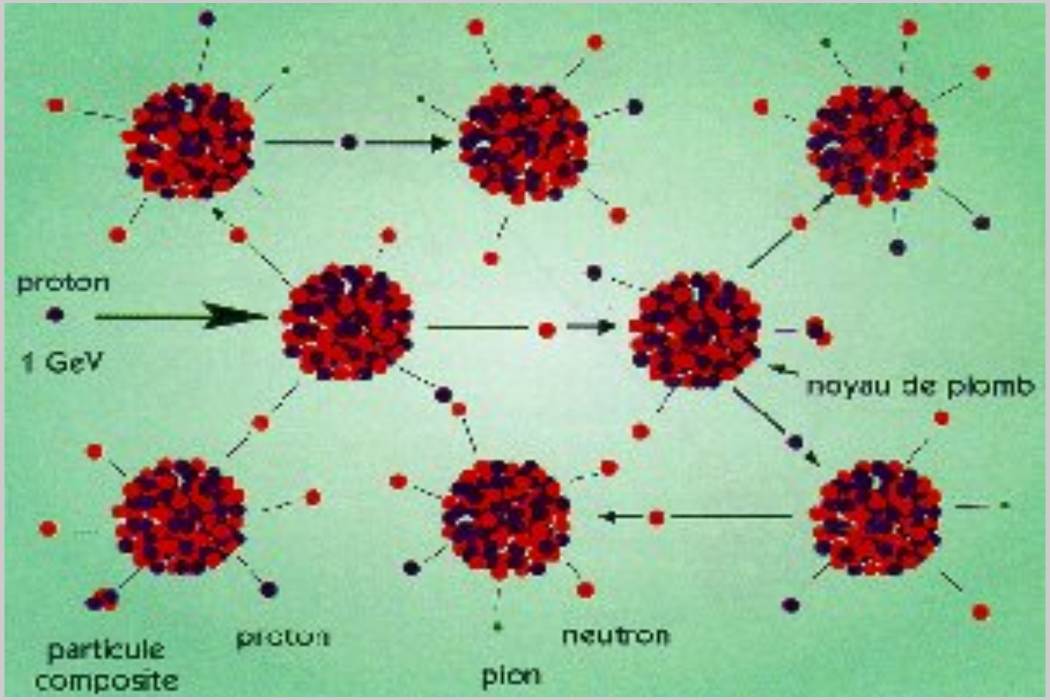
Spallation

Paolo
Fornasini
Univ. Trento

Proton accelerator

≈ 1 GeV proton

interaction
with nucleons



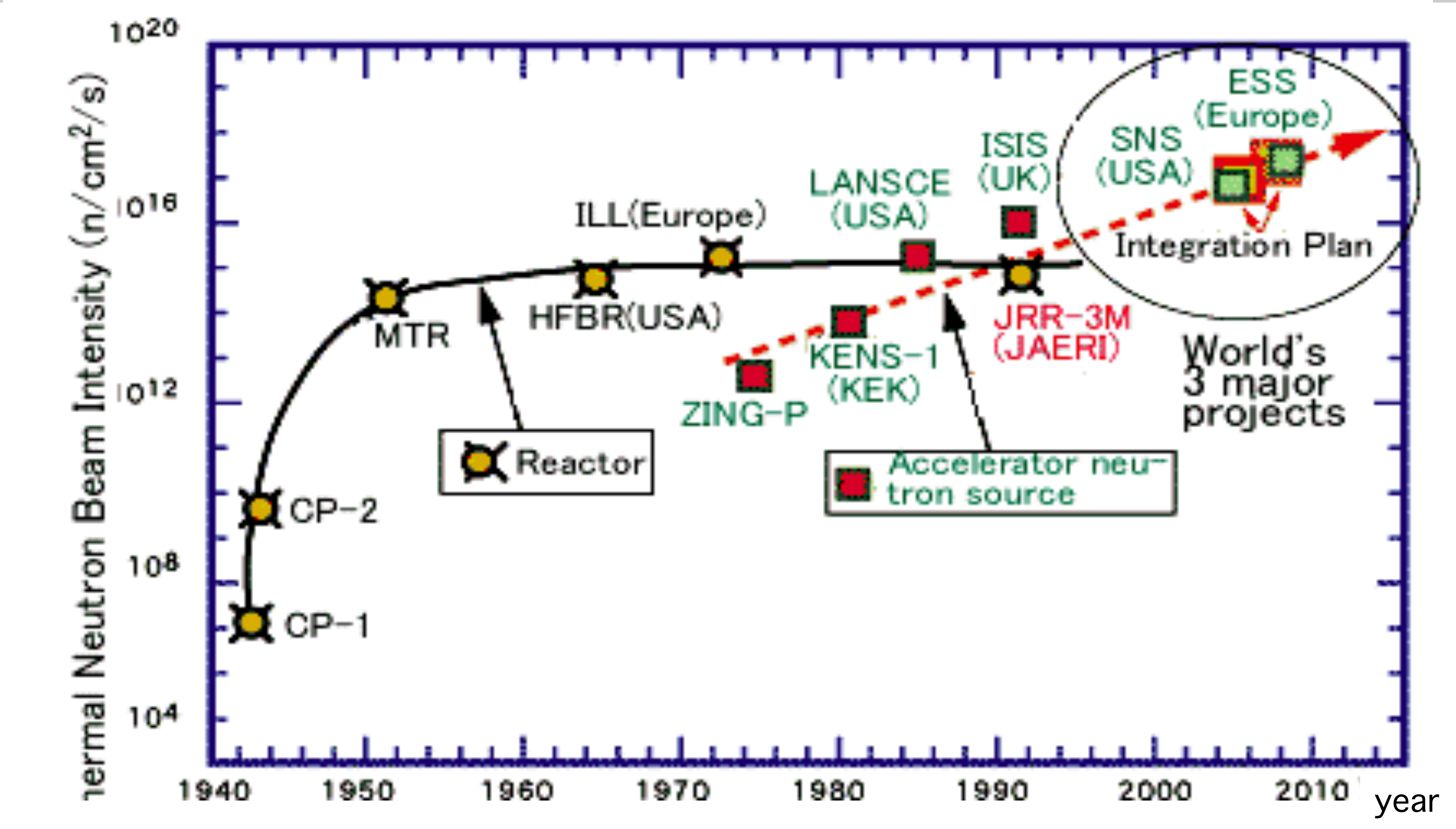
- high-energy particles
- chain-reactions
- excitations of nuclei
- de-excitation (evapor.)

20-40 neutrons
(≈55 MeV)

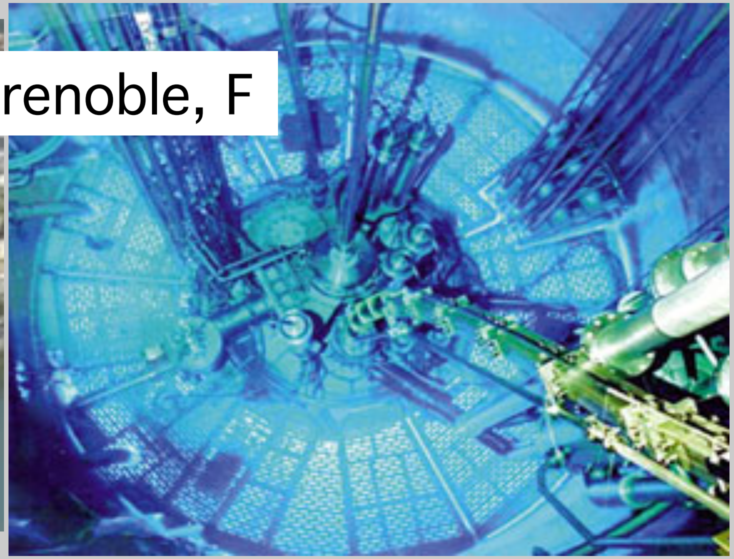
- Concentrated source ⇒ high flux
- Pulsed source

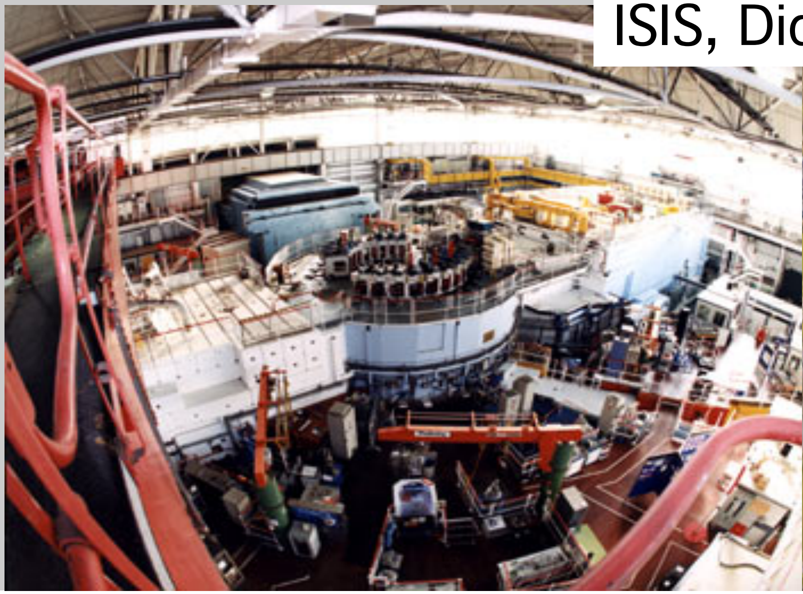
Neutron sources

Paolo
Fornasini
Univ. Trento



Largest European Neutron Labs

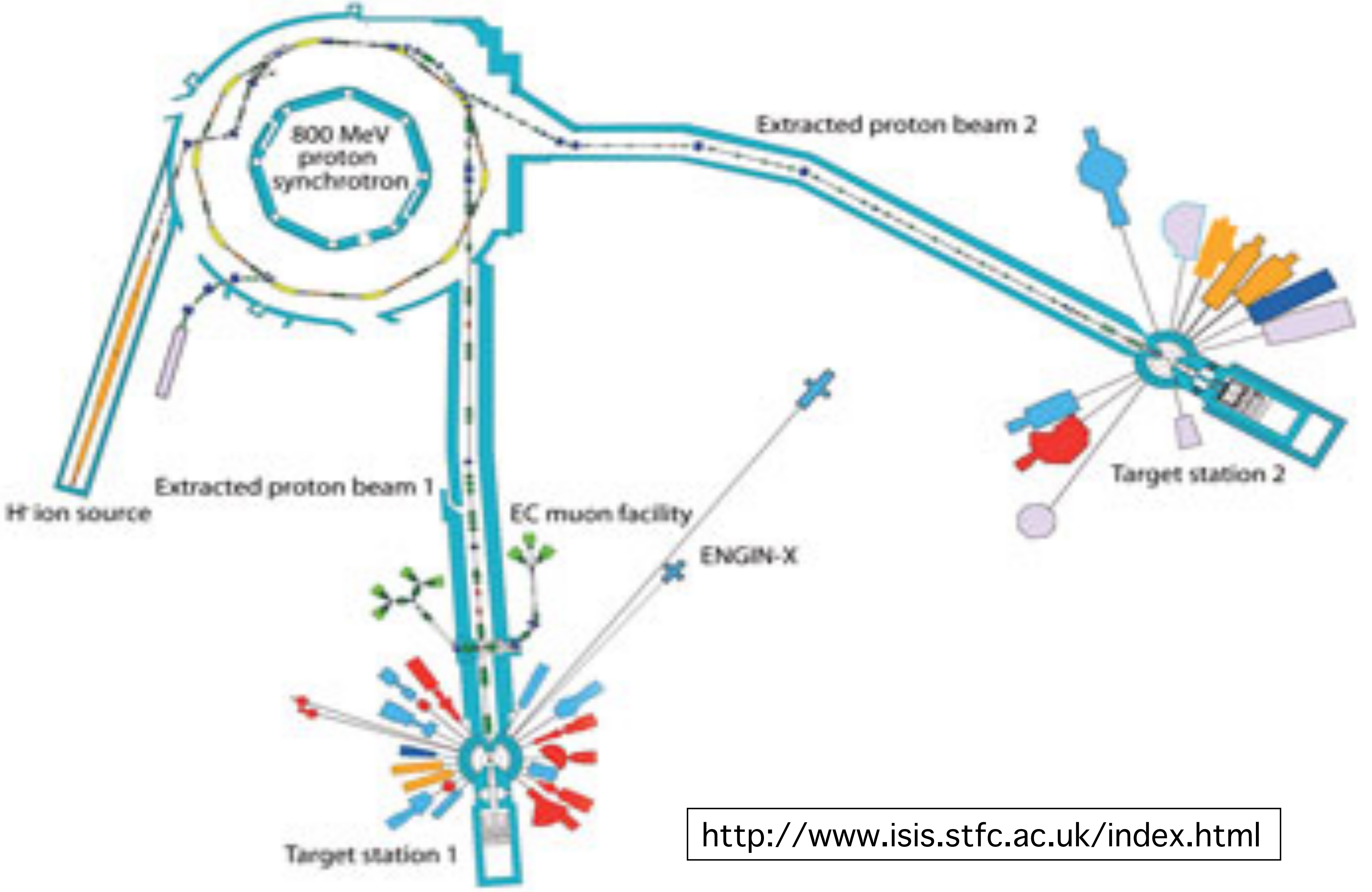




ILL reactor source

http://www.ill.eu/

ISIS spallation source



http://www.isis.stfc.ac.uk/index.html

Energy of neutrons

Paolo
Fornasini
Univ. Trento

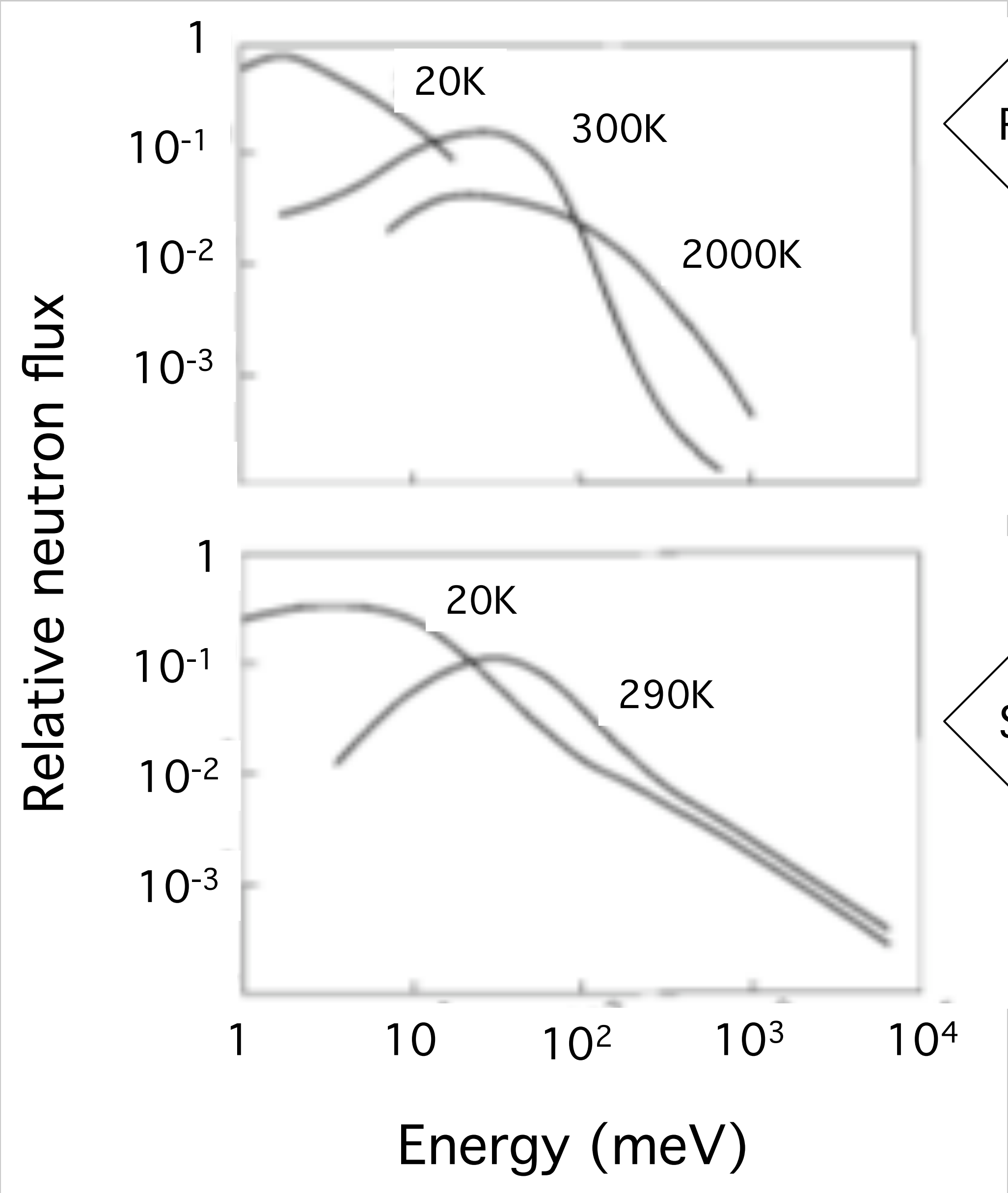
Moderation:

Neutrons are slowed down in moderators,
where they are brought to thermal equilibrium
through inelastic collisions with light atoms (H, D, Be)

The Table refers to the peak values of the Maxwell equilibrium distribution.

	Ultra-cold	Cold	Thermal	Hot	Epi-thermal
Energy (meV)	0.00025	1	25	250	1000
Temperature (K)	0.003	12	290	2900	12000
Wavelength (Å)	570	9	1.8	0.57	0.29
Velocity (m/s)	6.9	440	2200	6900	14000

Energy distribution of neutrons



Reactor sources

CONTINUOUS PRODUCTION
Energy selection
by crystal monochromators
(Bragg law)

Spallation sources

Higher energies available

PULSED PRODUCTION
Energy selection
by time-of-flight techniques

Neutrons and X-rays properties (b)

Paolo
Fornasini
Univ. Trento

	Thermal neutrons	X-rays (synchrotron)	X-rays (anodes)
Energy (eV)	10^{-1} eV	10^{4} eV	10^{4} eV
Wavelength (Å)	0.5 - 10	0.5 - 5	0.5 - 2
Flux (part./cm^2/s)	10^{10} - 10^{15}	10^{20} - 10^{25}	10^{16} - 10^{17}
Sample volume (mm^3)	1 - 10	10^{-5} - 10^{-1}	10^{-3} - 10^{-2}
Tunability	yes	yes	no
Beam divergence	5 mr	10^{-1} mr	5 mr
$\Delta\lambda/\lambda$	10^{-3}	10^{-5} - 10^{-4}	10^{-3}
Absorption	weak	medium	medium