Introduction to
Synchrotron Radiation

What is?

How is produced?

Which are its properties?

Where is produced?

How and why is used?

What is foreseen for the future?

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References

Handbook of Synchrotron Radiation

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"Synchrotron light"

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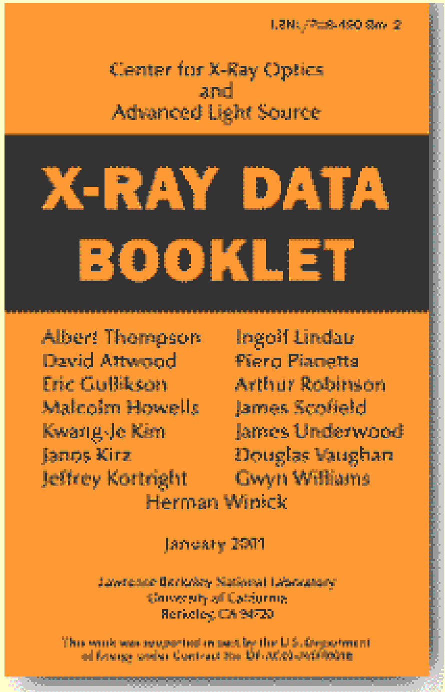
http://www.lightsources.org

http://xdb.lbl.gov/



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Center for X-Ray Optics
and
Advanced Light Source

X-RAY DATA
BOOKLET

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1. **G. K. Green, "Spectra and Optics of Synchrotron Radiation," in *Proposal for National Synchrotron Light Source*, Brookhaven National Laboratory, Upton, New York, BNL-50595 (1977).**
2. **H. Winick, "Properties of Synchrotron Radiation," in H. Winick and S. Doniach, Eds., *Synchrotron Radiation Research* (Plenum, New York, 1979), p. 11.**
3. **S. Krinsky, "Undulators as Sources of Synchrotron Radiation," *IEEE Trans. Nucl. Sci.* NS-30, 3078 (1983).**
4. **D. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge Univ. Press, Cambridge, 1999); see especially Chaps. 5 and 8.**

Synchrotron Radiation

Electromagnetic Radiation Emitted by an accelerated charge moving with relativistic a speed v ~ c

Today: radiation emitted by relativistic electrons (positrons) in a storage ring

Today/Future: coherent radiation emitted by relativistic electrons in a linear accelerator (LINAC)

Synchrotron Radiation Properties

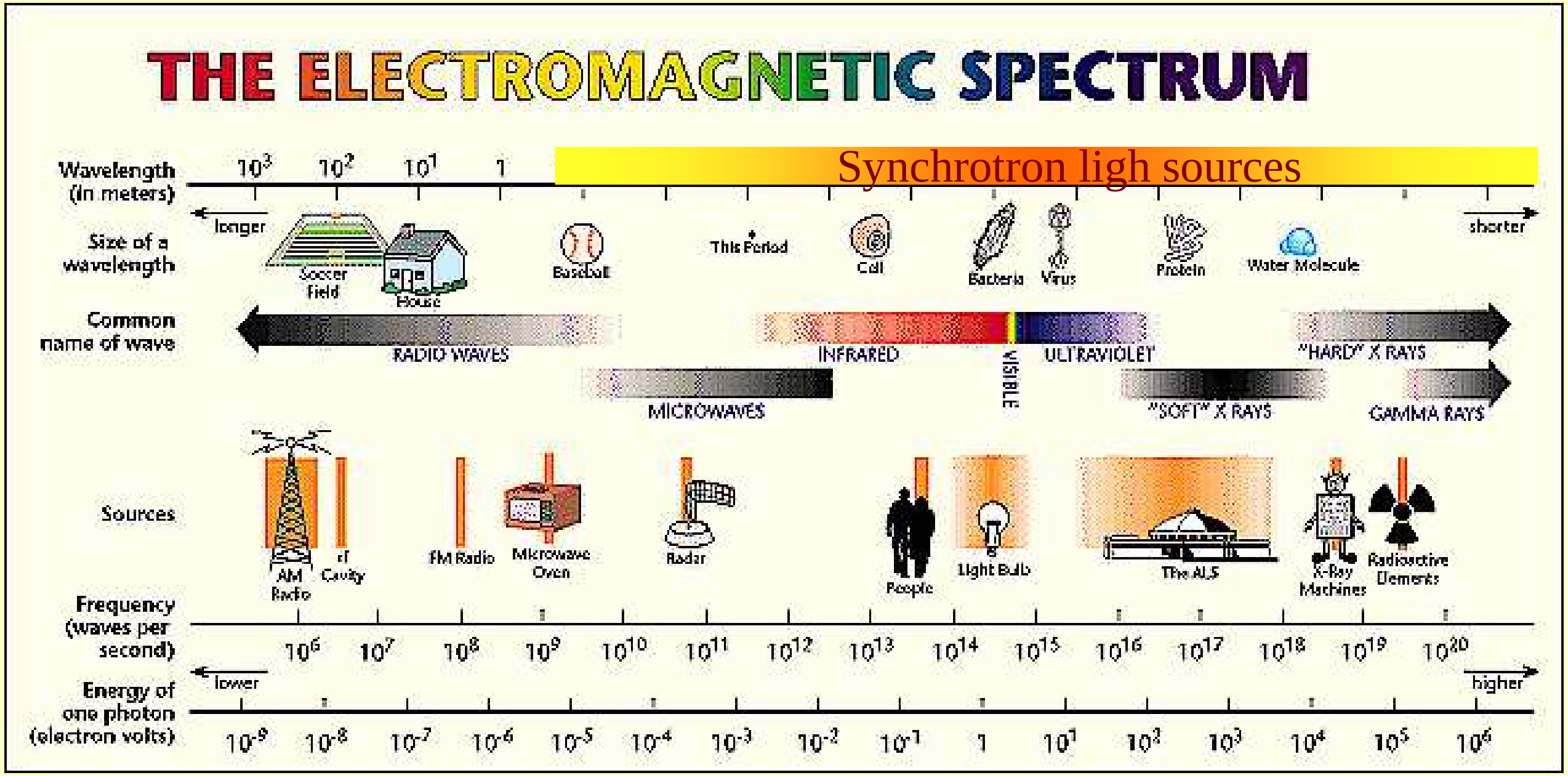
1. ***Continuous spectrum from infrared to hard X-ray***
2. ***High intensity***
3. ***Narrow angular collimation***
4. ***High degree of polarization***
5. ***Pulsed time structure***
6. ***Partially coherent (for the moment)***
7. ***Quantitative evaluable.***

} → ***High Brilliance***

Storage Ring: rather large installations

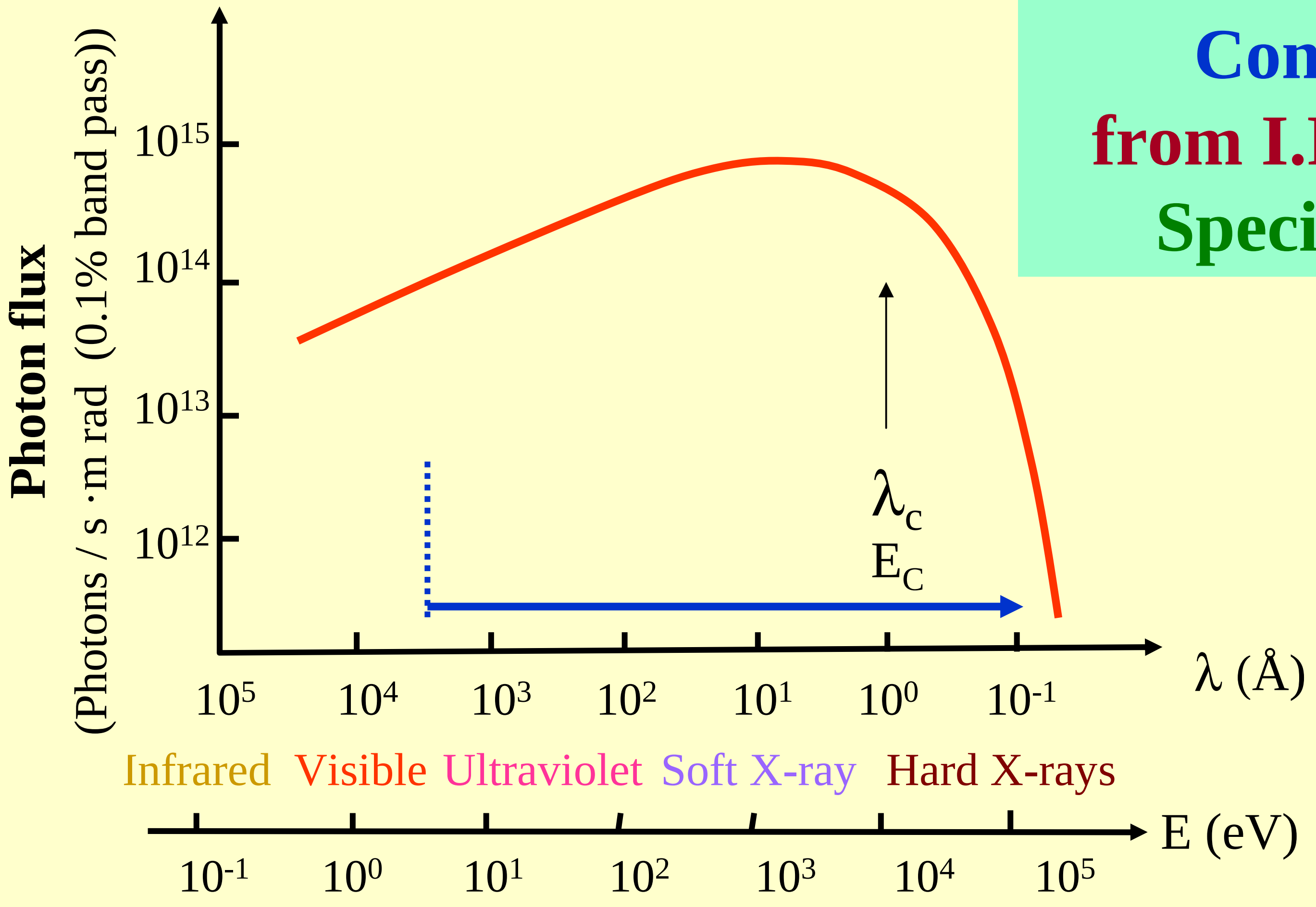
Ultra-high vacuum environment

Synchrotron Radiation: Energy Range



Synchrotron ligh sources

Spectral distribution of synchrotron radiation



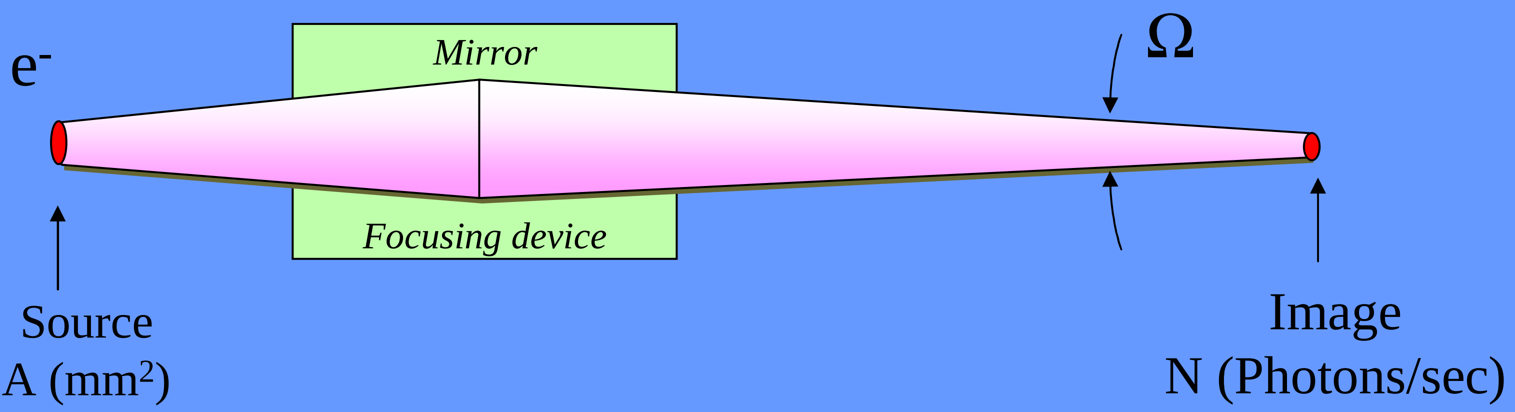
Continuous

from I.R. to X-ray

Specific shape

E_c critical energy= $3h\gamma^3c/4\pi R$

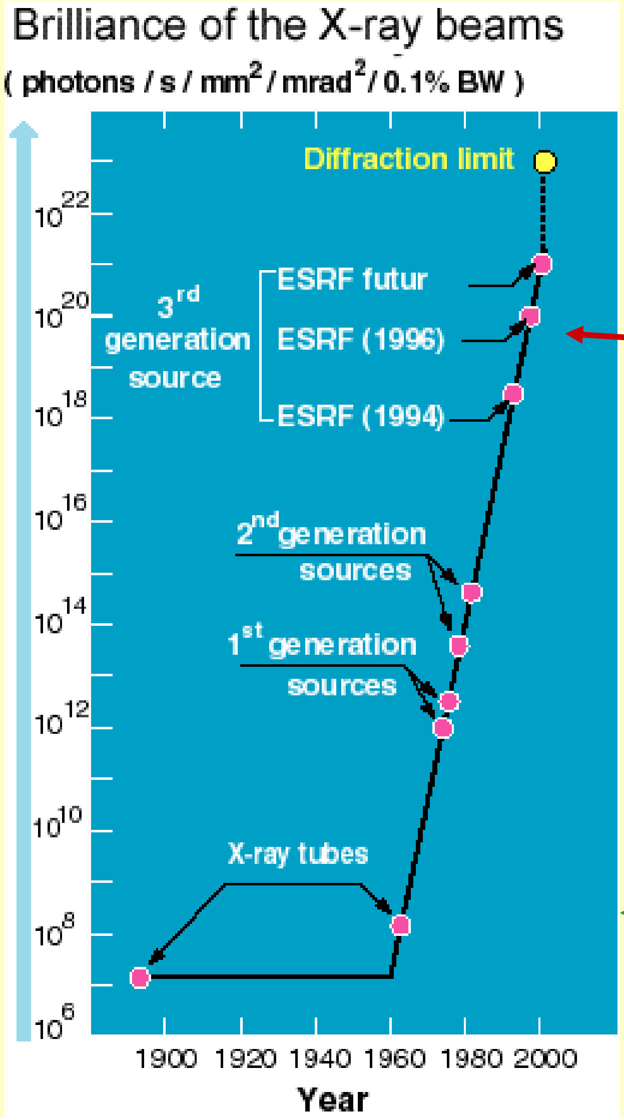
Brilliance



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

Brilliance of synchrotron radiation

Comparison between the average brilliance of storage rings of different generations.



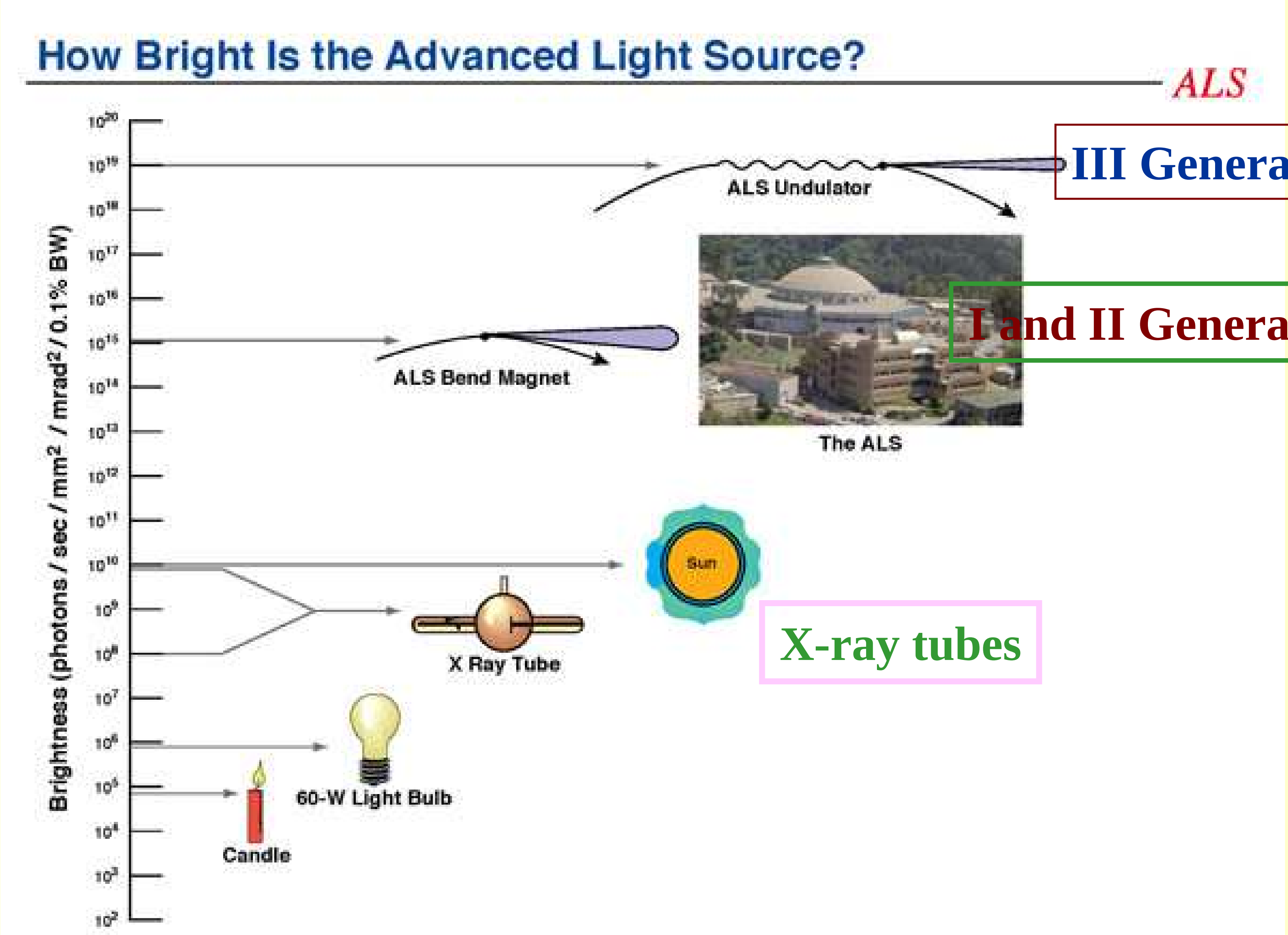
XFEL

III Generation

I and II Generation

X-ray tubes

Brilliance of synchrotron radiation



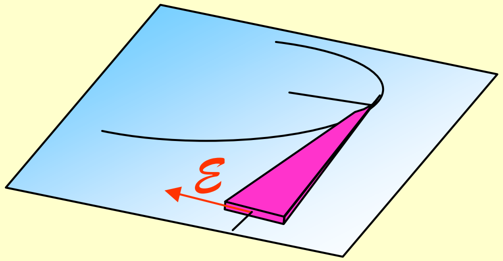
III Generation

I and II Generation

X-ray tubes

Polarization

Mainly linear
In the plane of
the orbit

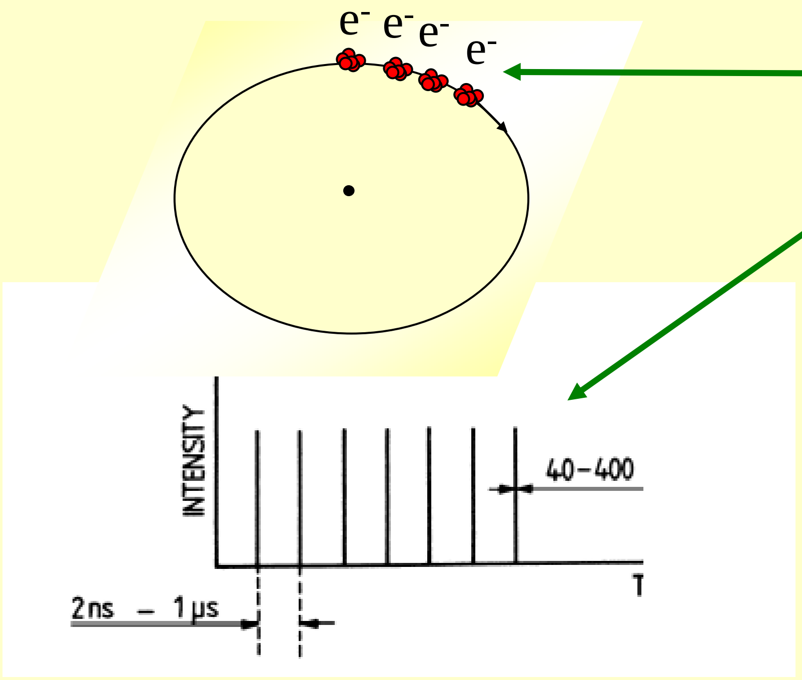


There is a second component
perpendicular to
the orbit

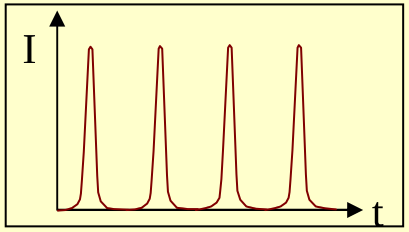
Two polarization component
±π/2 out of phase

Left and right circular polarization

Time Structure



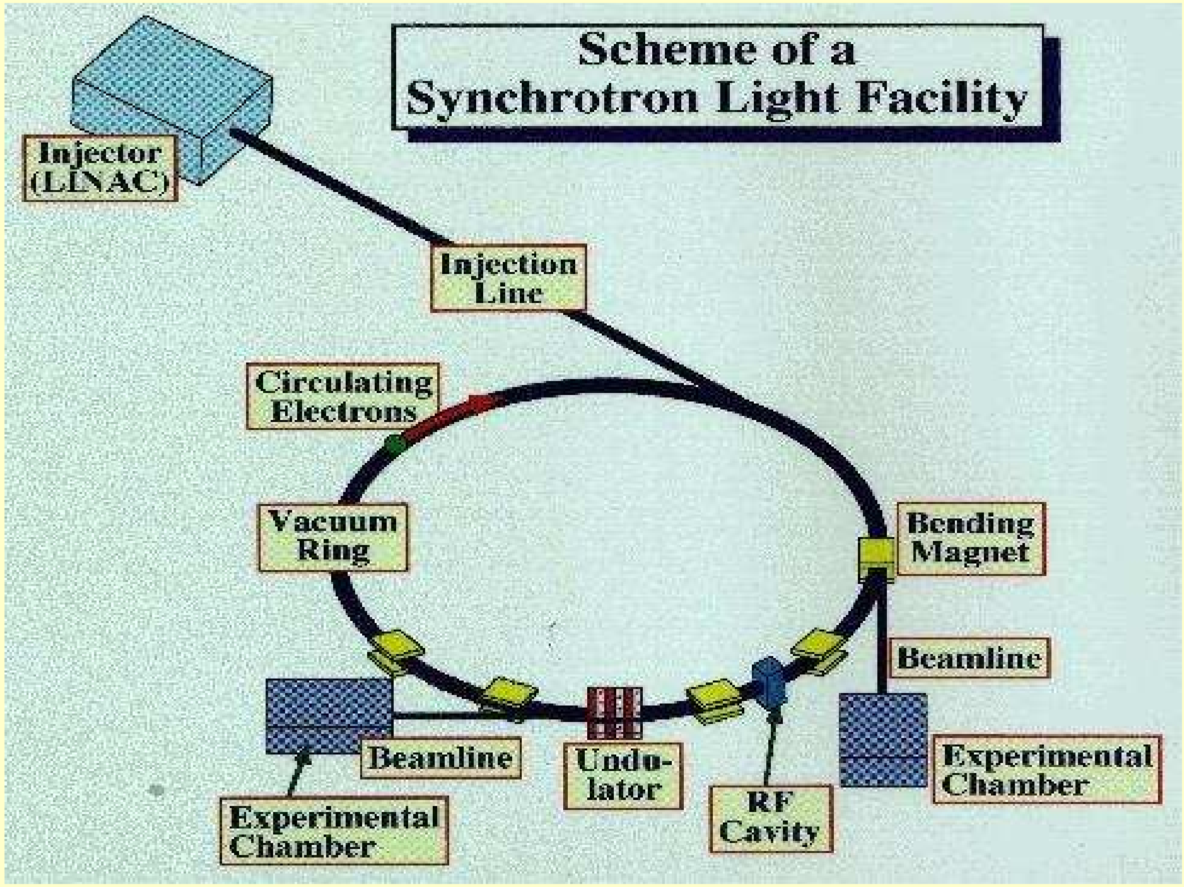
bunches



Bunch time length
10 – 100 ps

Repetition rate: **Maximum time distance = period of the orbit**
Minimum time distance = period of the RF

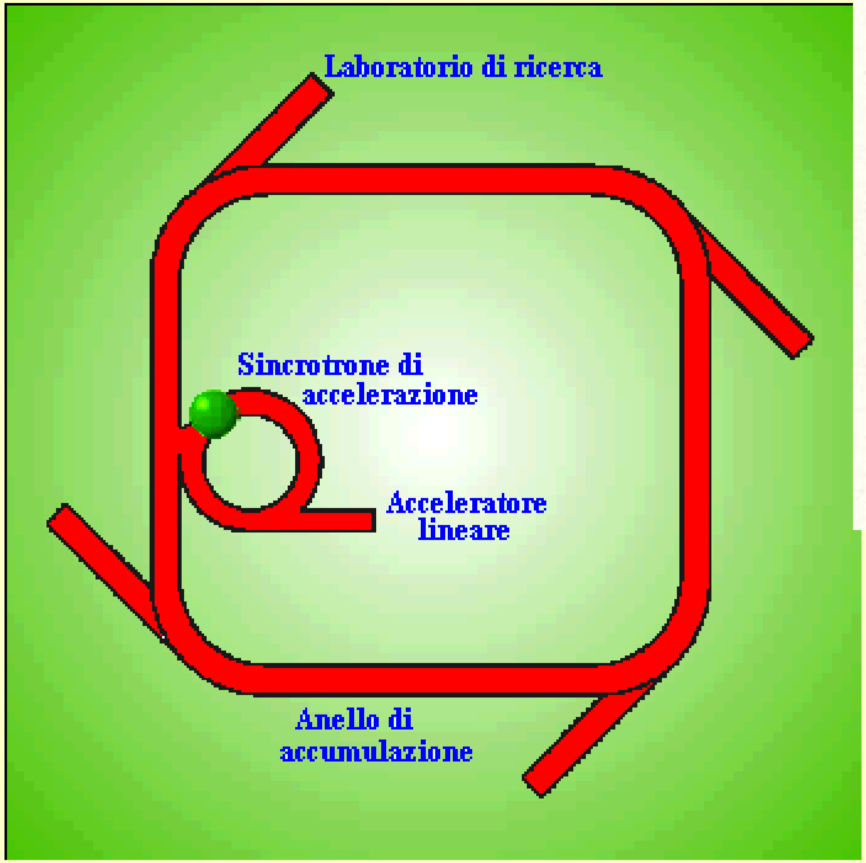
Schematic view of a Storage Ring



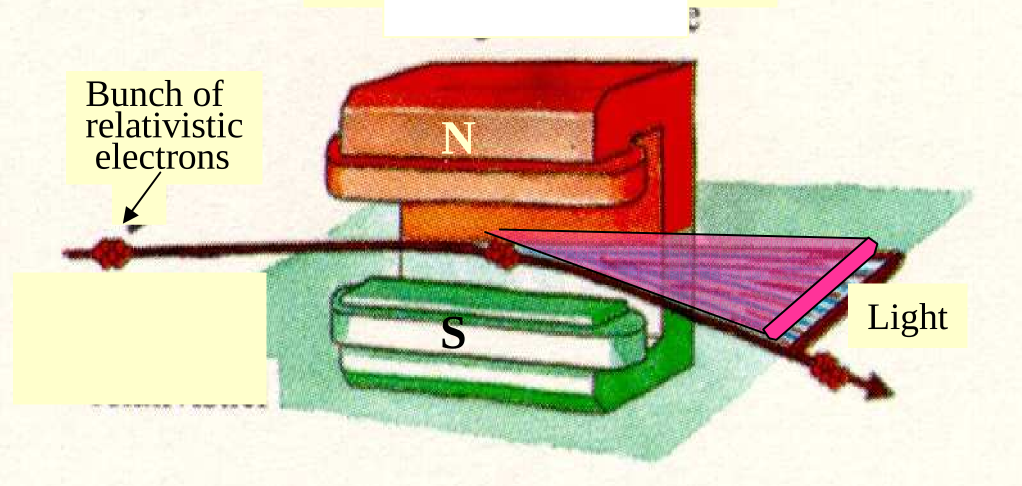
SR sources

- Bending magnets
- Insertion devices (undulator/wiggler)

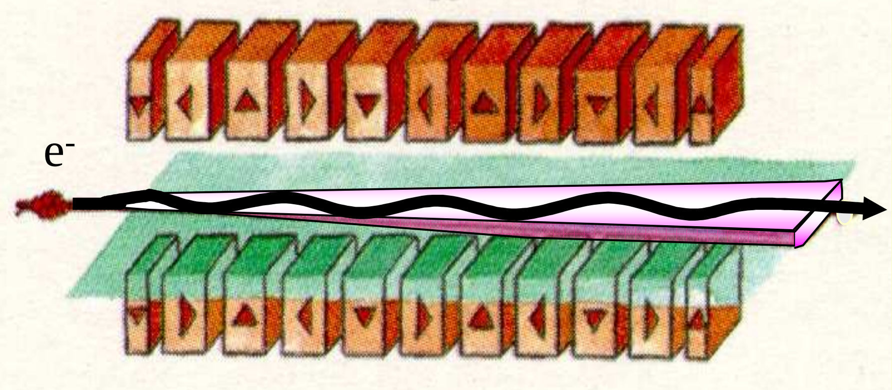
Synchrotron Radiation Sources



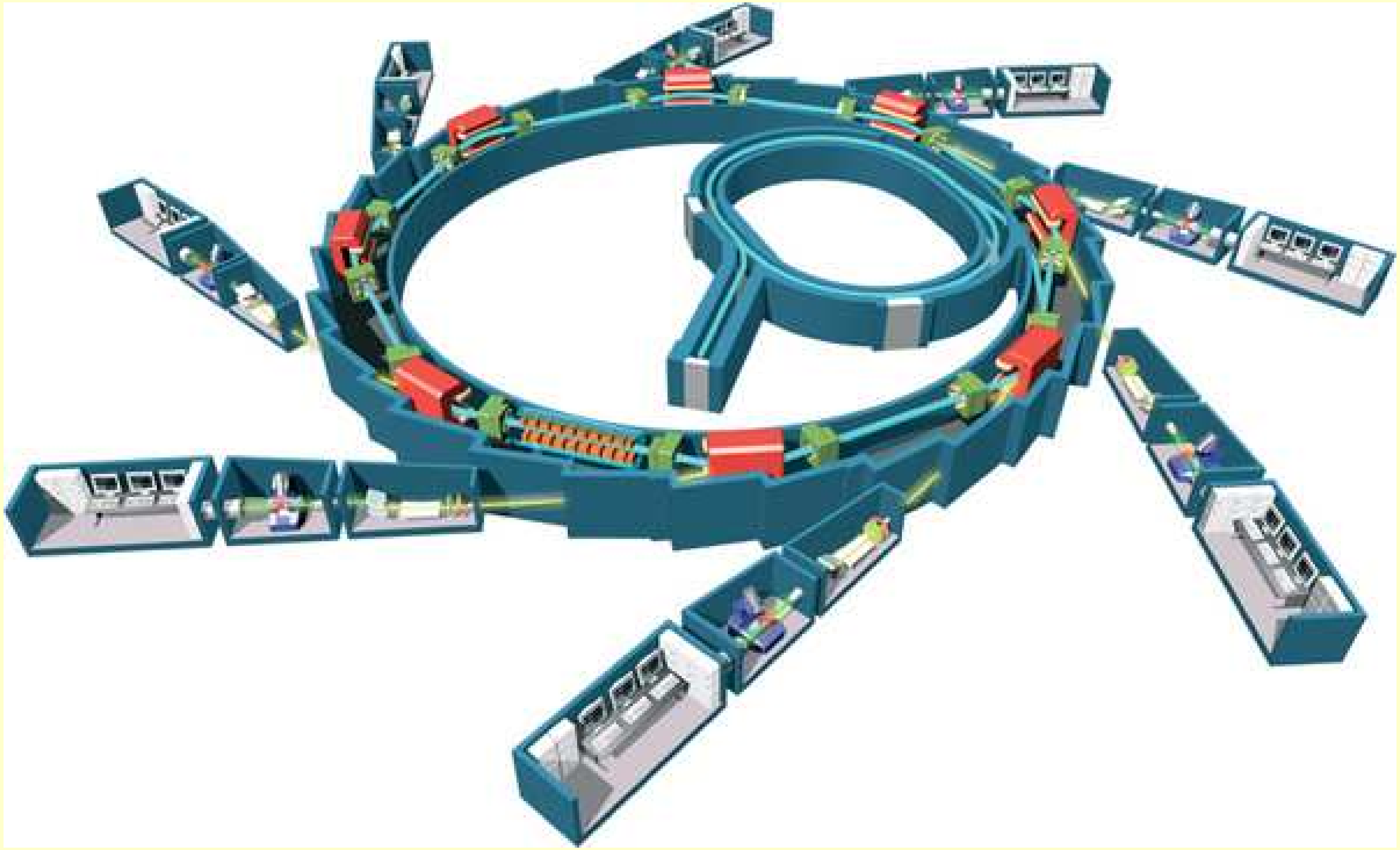
Bending magnet



Insertion device

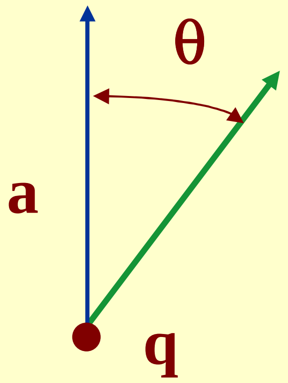


Synchrotron light from a storage ring



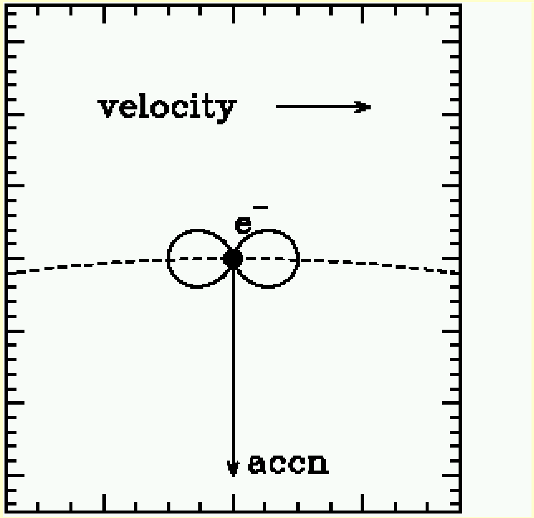
Origin of Synchrotron Radiation: Larmor Formula

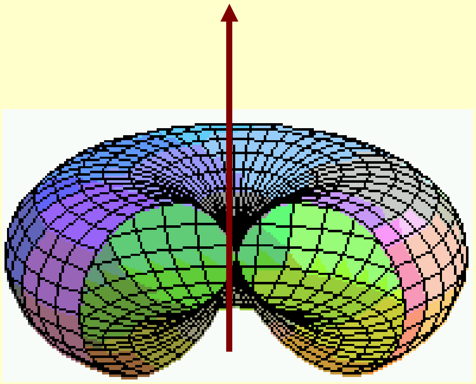
A classical accelerated charge emits e.m. radiation symmetrically with respect to the acceleration according to the Larmor formula



$$\frac{dP}{d\Omega} = \frac{1}{4\pi}\frac{q^2 a^2}{c^3}\sin^2\theta$$

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

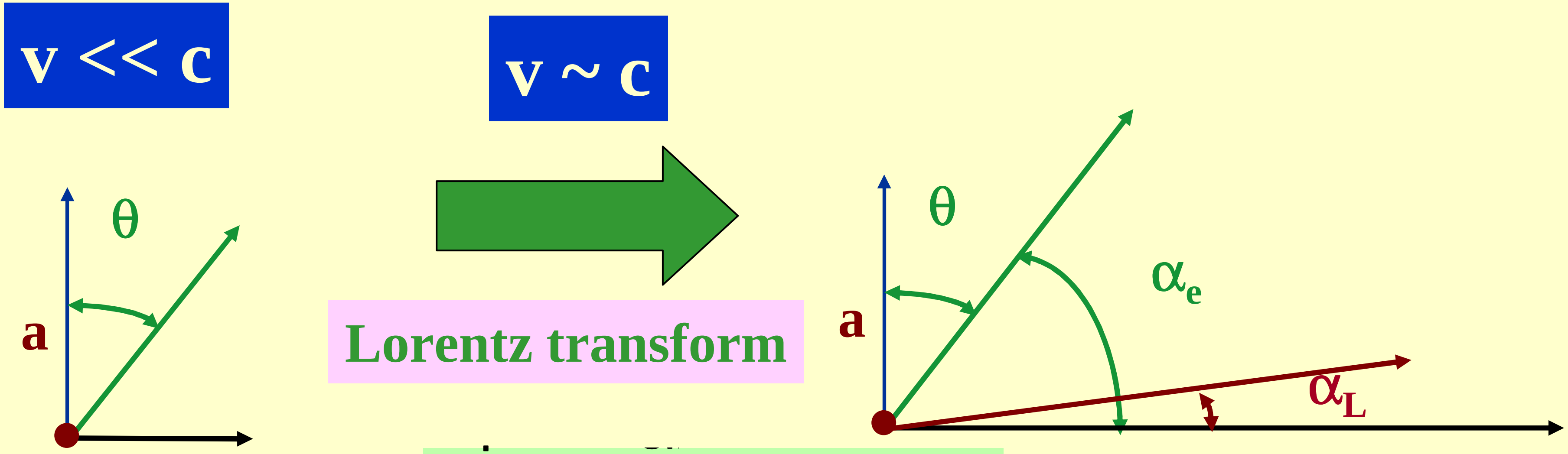




v << c

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

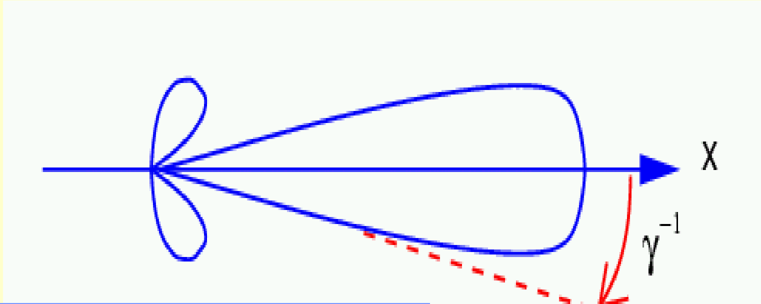
Origin of Synchrotron Radiation: Lorentz transformation



Lorentz transform

$$\sin\alpha_L = \frac{\sin\alpha_e}{\gamma(1+\beta\cos\alpha_e)}$$

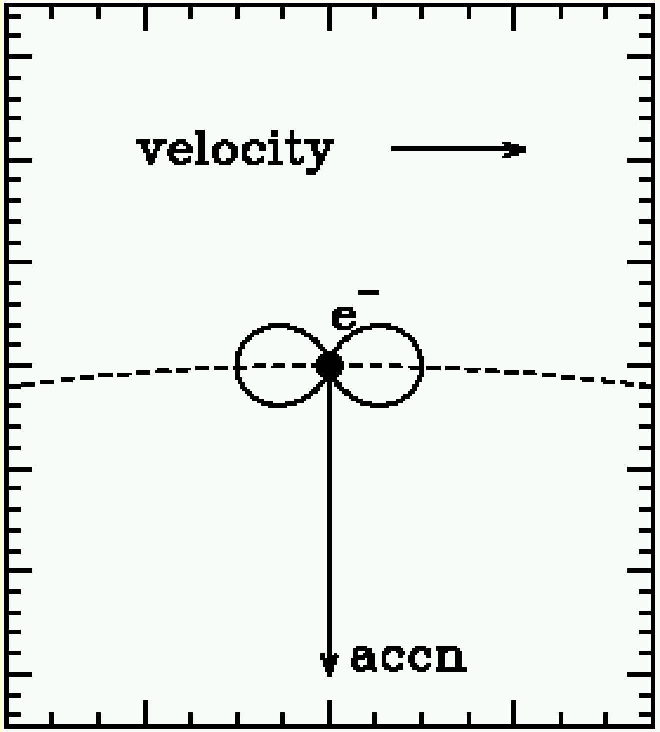
$\alpha_L \sim 0$ for $\alpha_e = 0$ $(\theta = \pi/2)$
$\alpha_L \sim 1/\gamma$ for $\alpha_e = \pi/2$ $(\theta = 0)$

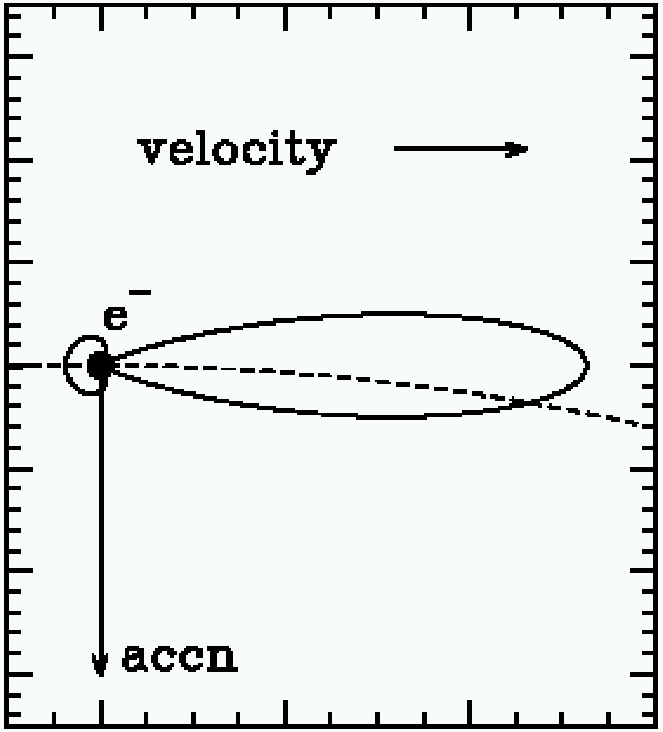


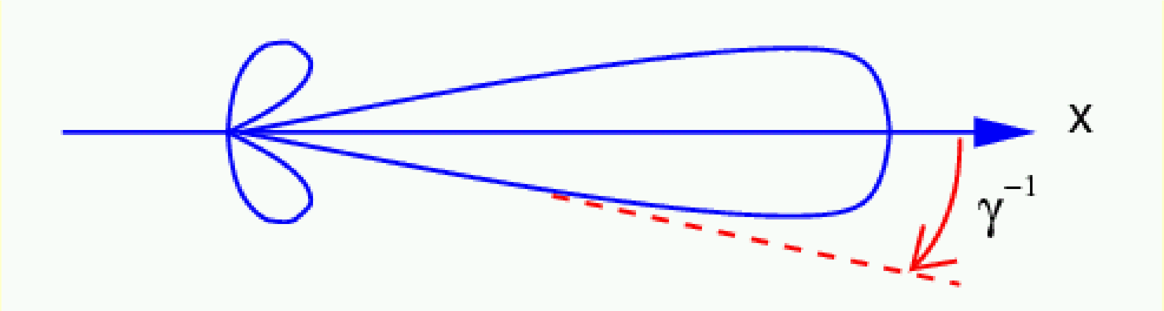
$$\gamma = \frac{E_k}{mc^2} \approx 10^4 \Rightarrow \frac{1}{\gamma} \approx 10^{-4}\,\mathrm{rad}$$

Synchrotron Radiation Angular Distribution

$$\frac{dP}{d\Omega} = \frac{1}{4\pi}\frac{q^2 a^2}{c^3}\frac{\left[\left(1-\beta\cos\theta\right)^2 - \left(1-\beta^2\right)\sin^2\theta\cos^2\varphi\right]}{\left(1-\beta\cos\theta\right)^5}$$

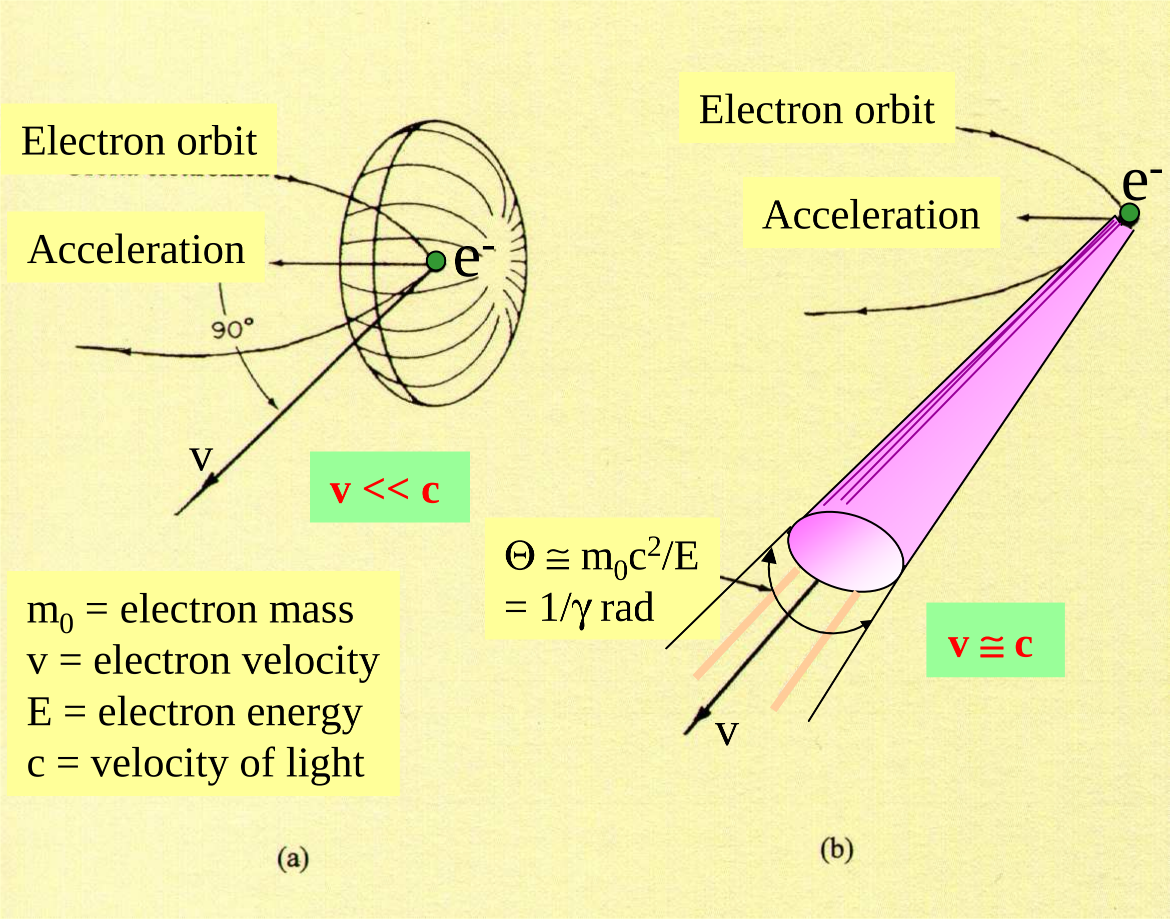






Angular distribution

A relativistic accelerated charge emits radiation mainly into the direction of the speed



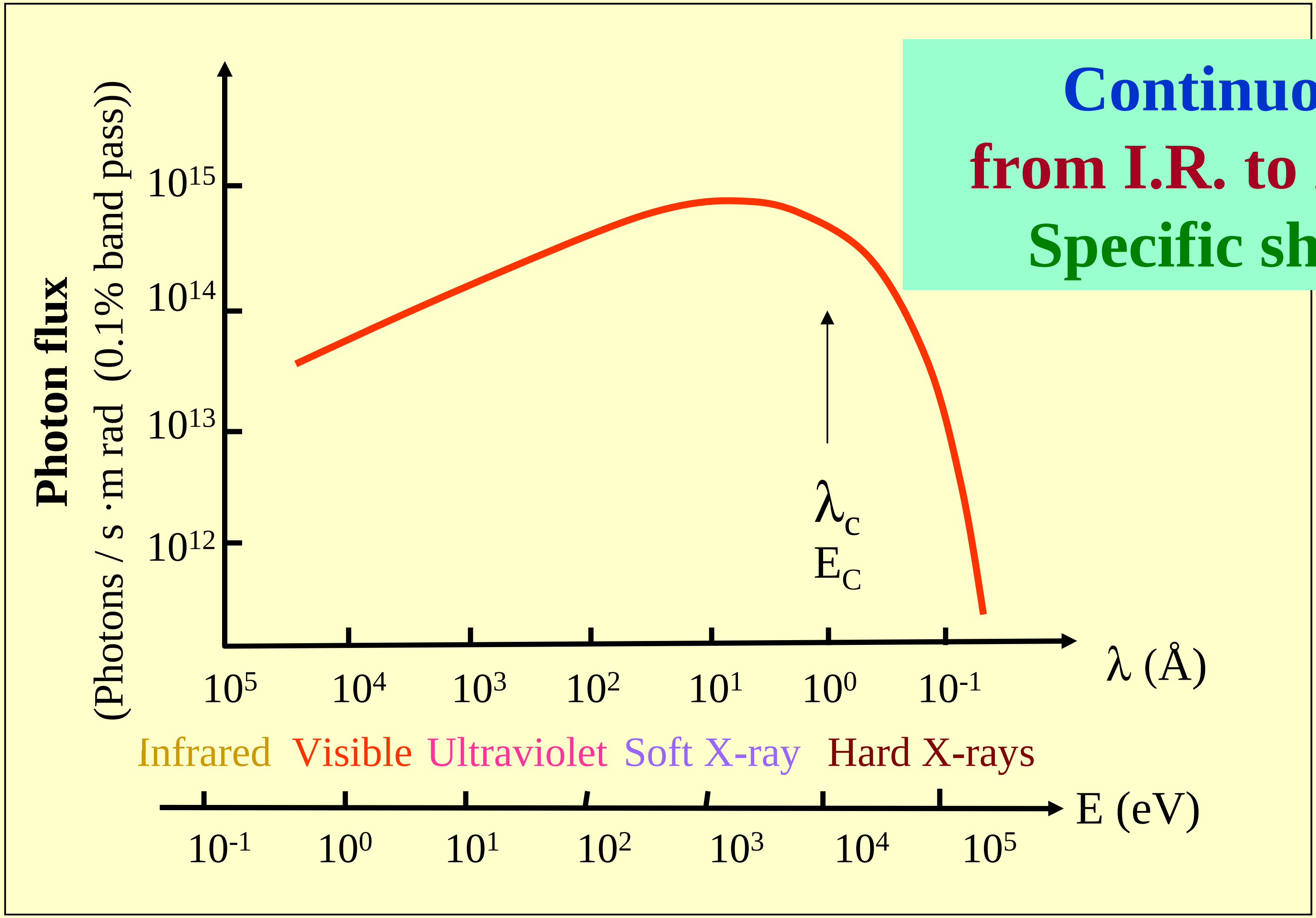
$\Theta \cong m_0c^2/E$
$= 1/\gamma$ rad

m_0 = electron mass
v = electron velocity
E = electron energy
c = velocity of light

Cone aperture

$$\frac{1}{\gamma} = \frac{m_0 c^2}{E} \cong \text{mrad}$$

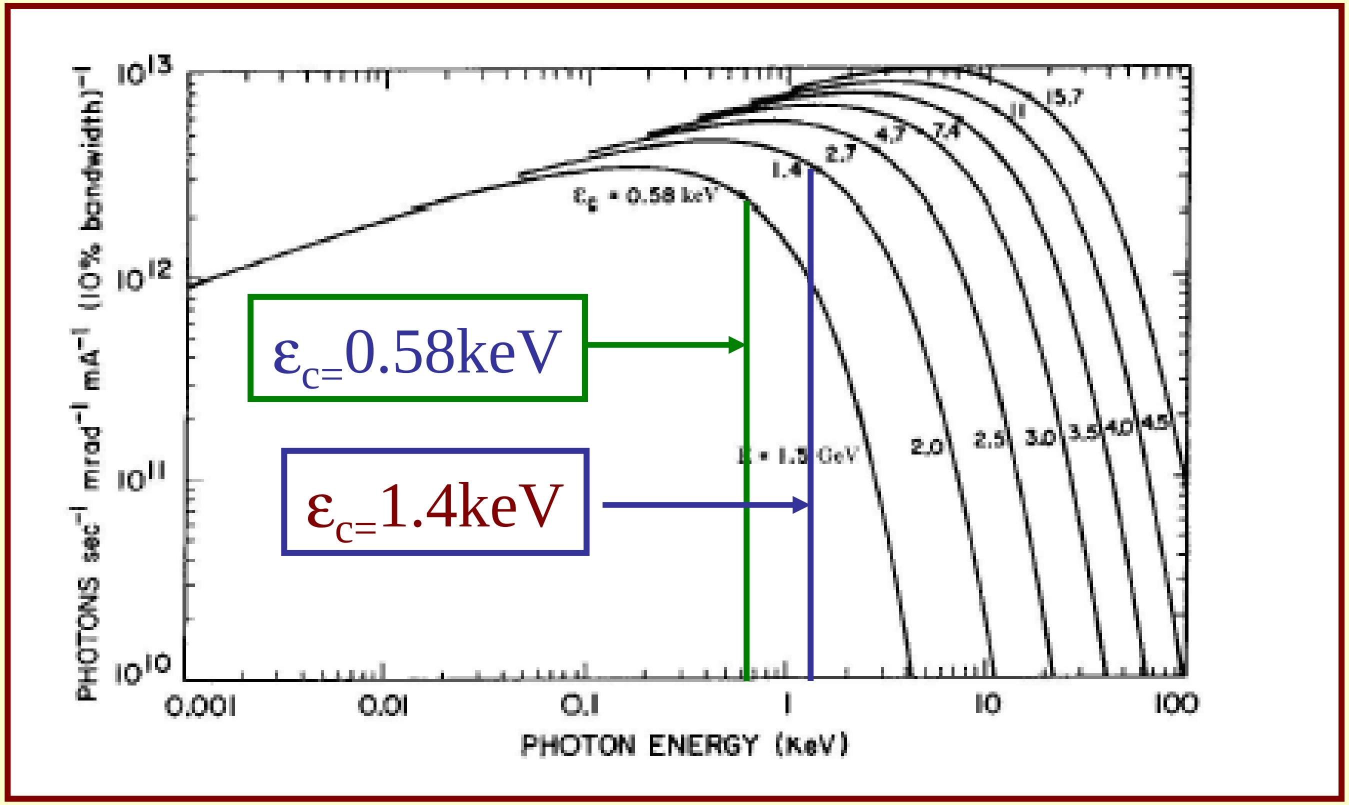
Spectral distribution of synchrotron radiation



Continuous
from I.R. to X-ray
Specific shape

E_c critical energy = $3h\gamma^3c/4\pi R$ = kE^3/R

Spectral distribution of synchrotron radiation as a function of the critical energy of the storage ring.



$\varepsilon_{c=}0.58$keV

$\varepsilon_{c=}1.4$keV

$$\varepsilon_c = 3h\gamma^3 c/4\pi R$$

$$\lambda_c = 4\pi R/3\gamma^3$$

The power emitted at wavelengths lower than λ_c is equal to the power emitter at wavelengths higher than λ_c

Origin of the broad spectral distribution

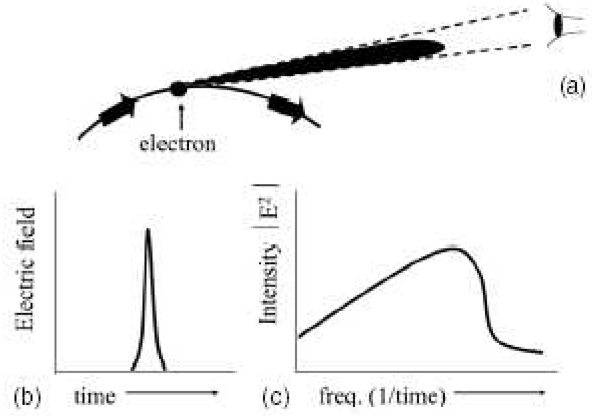
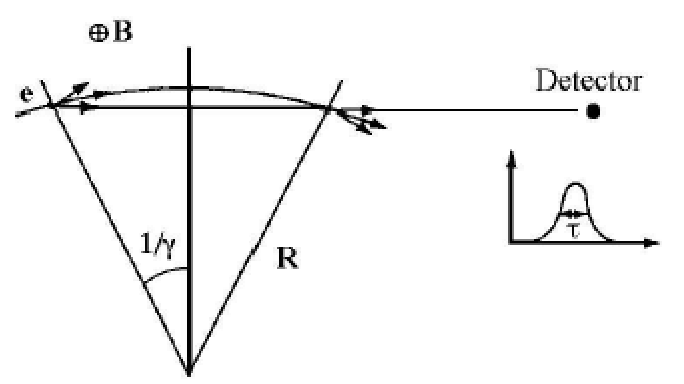


Figure 3. Schematic showing the physics of synchrotron radiation generation. An observer of an electron travelling in an arc in (*a*), 'sees' an electric field pulse (*b*), whose power spectrum is given by the Fourier transform (*c*).



A point detector receives the radiation for a very short time

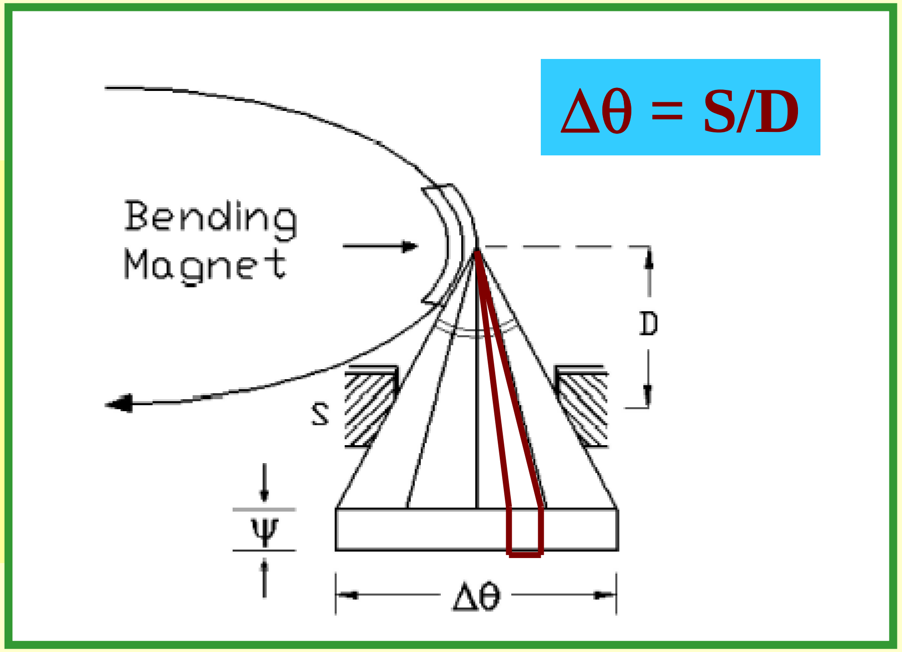
The detector records the radiation emitted along the arc 2/γ

→

the duration of the pulses is non zero (τ)

Angular emission from a Bending magnet

- The orbit is circular
- The radiation is emitted tangentially
- It is collected in a horizontal slit (S) of width, *w*, at a distance, *D*.



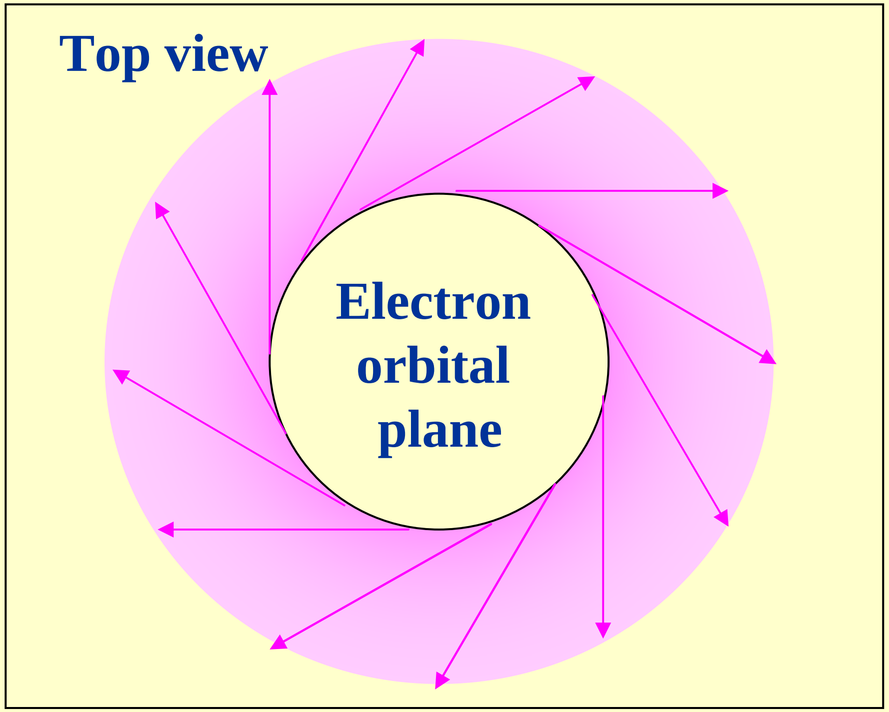
$\Delta\theta = S/D$

In the vertical direction the natural collimation preserved

In the horizontal direction the natural collimation is lost

Insertion Devices

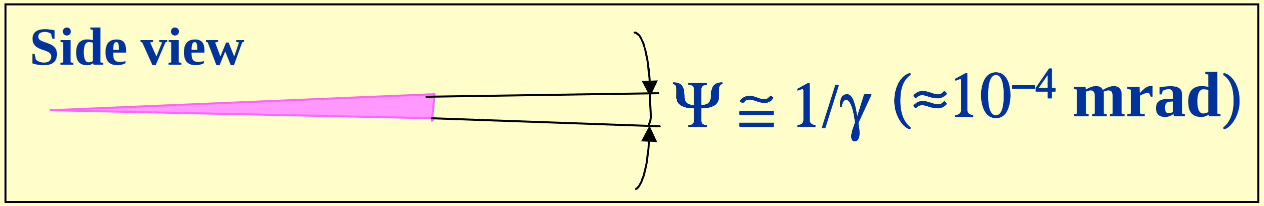
Emission view



Top view

Electron orbital plane

Vertical aperture



Side view

$\Psi \cong 1/\gamma$ (≈10^{-4} mrad)

Angular and wavelength distribution of synchrotron radiation

The power radiated by one electron in a unit wavelength interval centred at λ in a unit vertical angular cone centred at ψ is:

$$I(\lambda,\psi) = \frac{27}{32\pi^3}\,\frac{e^2c}{R^3}\left(\frac{\lambda_c}{\lambda}\right)^4\gamma^8\left[1+(\gamma\psi)^2\right]^2\left[K_{2/3}^2(\xi)+\frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}^2(\xi)\right] \qquad (2).$$

1. ***R*** **is the bending radius of the electron orbit**
2. **$K_{1/3}$ and $K_{2/3}$ are modified Bessel functions of the second kind**
3. **λ_c is the so called critical wavelength**

$\lambda_c\,(\text{Å}) = 4/3\,\pi R\,\gamma^3$

$\xi = (\lambda_c/2\lambda)\,[1+(\gamma\psi)^2]^{3/2}$

In pratical units:

$\lambda_c = 5.59\ R(\text{m})\ E^3\ (\text{GeV})$

Angular and wavelength distribution of S.R.

$$I(\lambda,\psi) = \frac{27}{32\pi^3}\frac{e^2 c}{R^3}\left(\frac{\lambda_c}{\lambda}\right)^4 \gamma^8\left[1+(\gamma\psi)^2\right]^2\left[K_{2/3}^2(\xi)+\frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}^2(\xi)\right] \qquad (2)$$

$\lambda_c = 4/3\,\pi R\,\gamma^3$

$\xi = (\lambda_c/2\lambda)\,[1+(\gamma\psi)^2]^{3/2}$

$\lambda_c(\text{Å}) = 5.59\,R(m)\,E^3\,(\text{GeV})$

Note that:

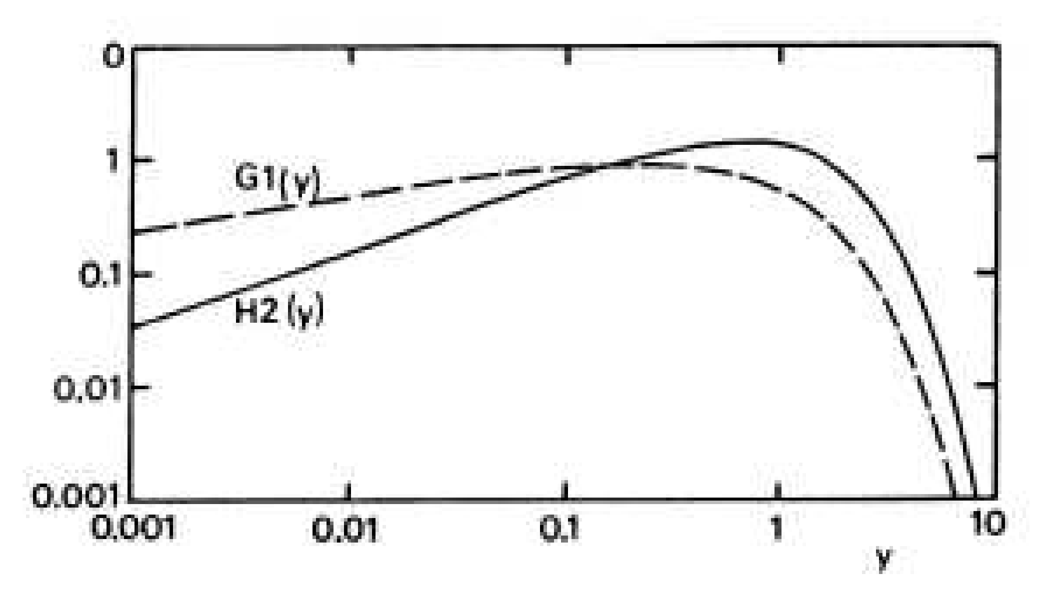
- **the wavelength dependence is only on the ratio λ_c/λ**
- **the angular dependence is only on the product $\gamma\psi$**

Wavelength distribution of S.R. in the horizontal direction

At ψ=0 → ξ= (λc/2λ)

$$I(\lambda,\psi)\Big|_{\psi=0} = \frac{27}{32\pi^3}\frac{e^2c}{R^3}\underbrace{\gamma^8\left(\frac{\lambda_c}{\lambda}\right)^4 K^2_{3/2}}$$

$H_2(\lambda_c/\lambda)$

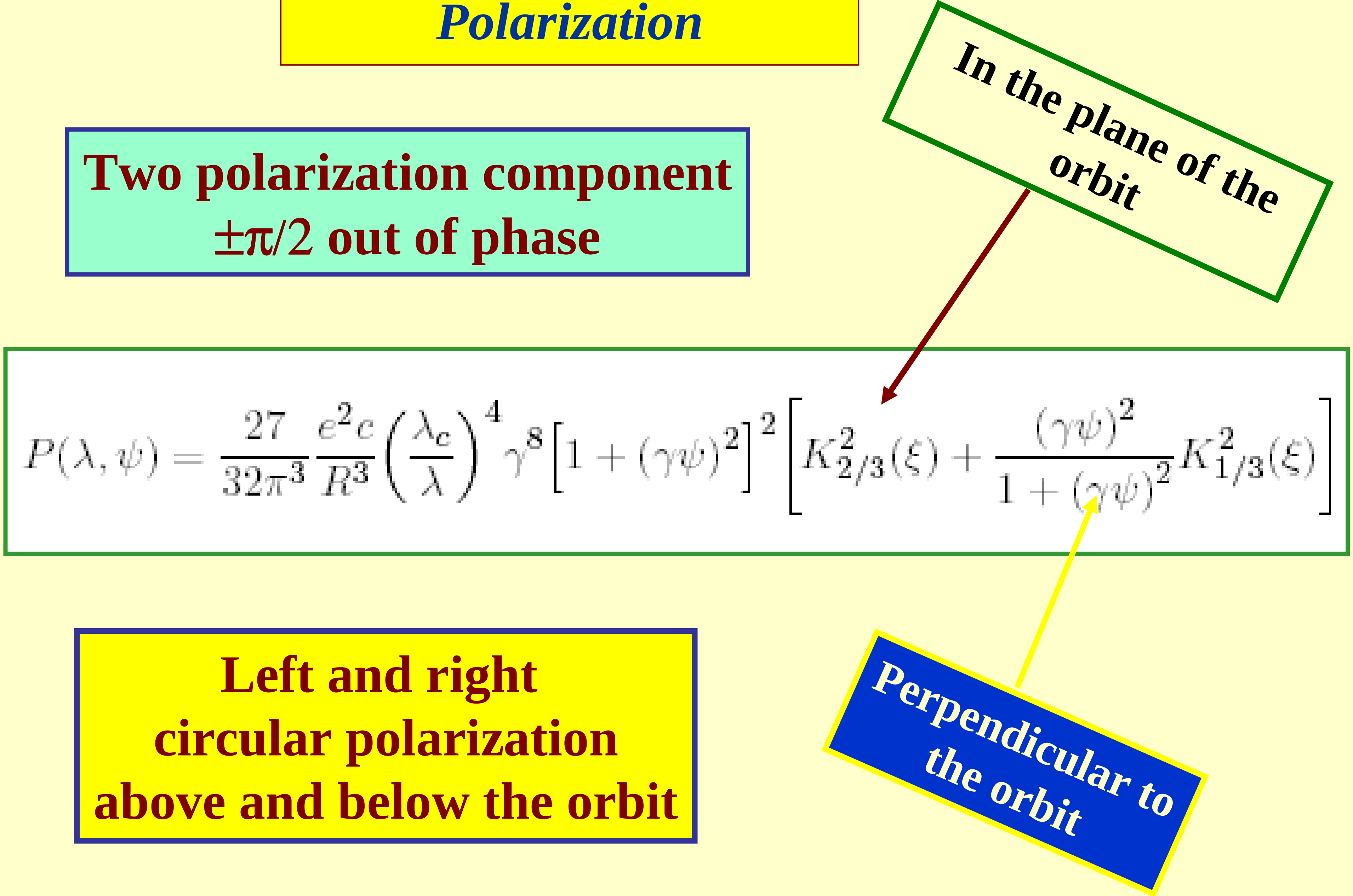


Integration over ψ

$$I(\lambda) \propto \underbrace{\frac{\lambda_c}{\lambda}\int_{\lambda_c/\lambda}^{\infty} K^2_{5/3}\, d\left(\frac{\lambda_c}{\lambda}\right)}_{G_1(\lambda_c/\lambda)}$$

Polarization

Two polarization component ±π/2 out of phase



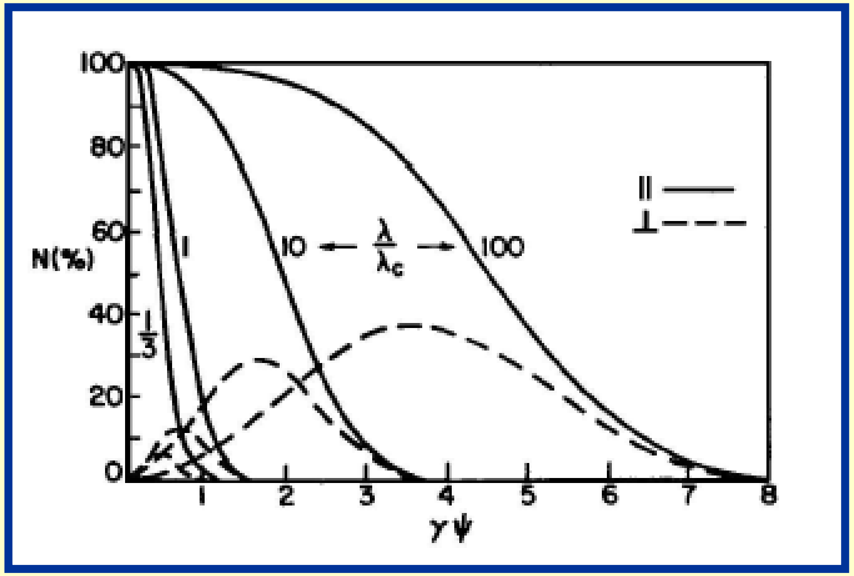
In the plane of the orbit

$$P(\lambda,\psi)=\frac{27}{32\pi^3}\frac{e^2c}{R^3}\left(\frac{\lambda_c}{\lambda}\right)^4\gamma^8\left[1+(\gamma\psi)^2\right]^2\left[K^2_{2/3}(\xi)+\frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K^2_{1/3}(\xi)\right]$$

Perpendicular to the orbit

Left and right circular polarization above and below the orbit

Behavior of the parallel and perpendicular component for different λ/λ_c



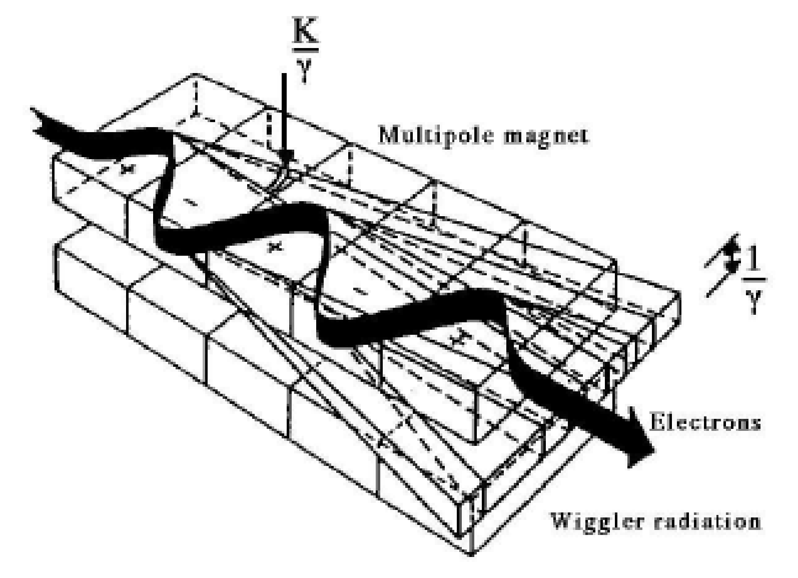
The integration over all wavelengths gives:

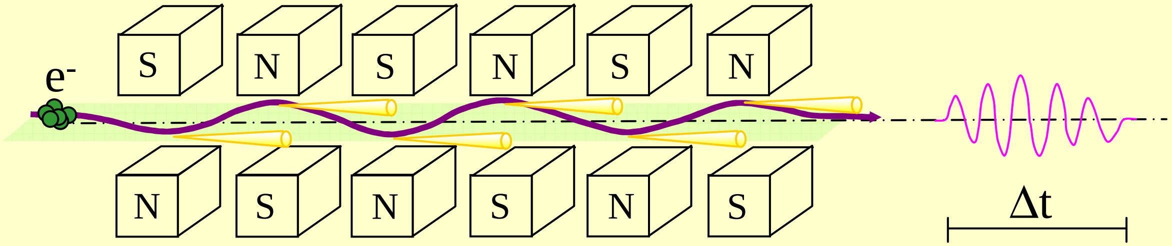
$I_{//} = 7/8\ I_{total}$

$I_{\perp} = 1/8\ I_{total}$

Insertion devices

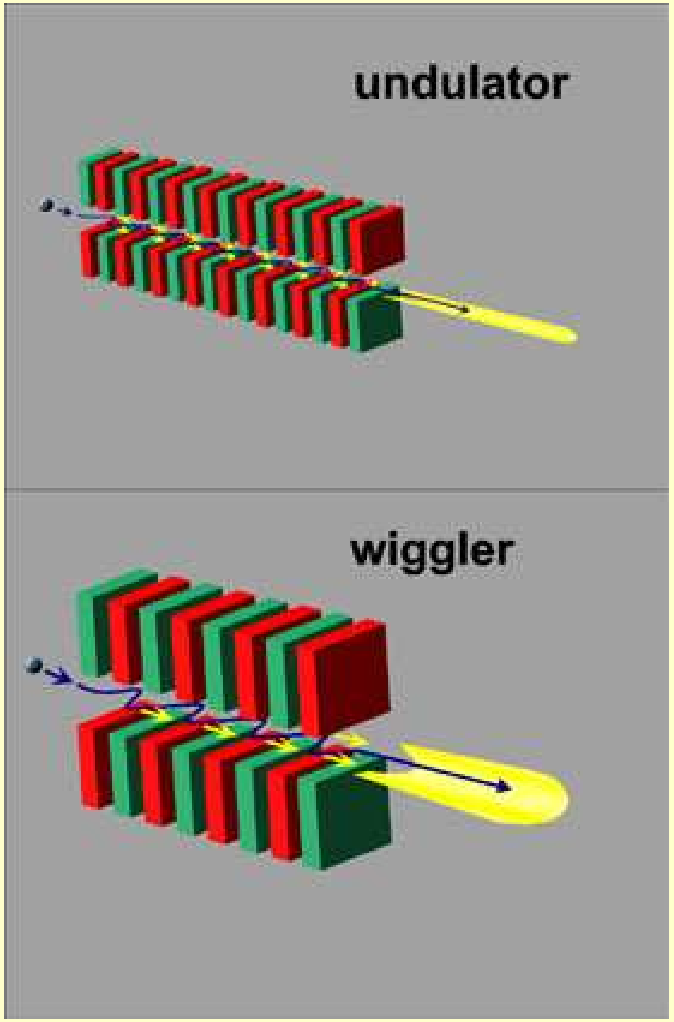
Magnetic field structures
Force the electrons to move along particular orbits





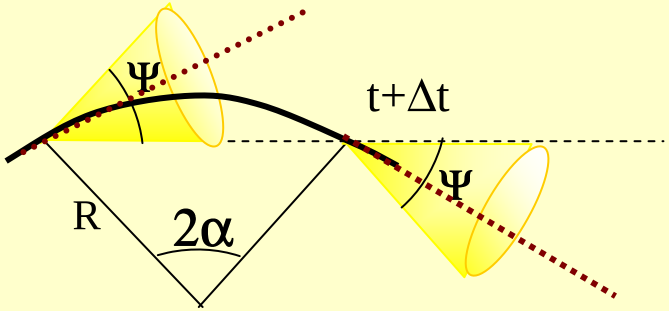
Wigglers
Undulators

Insertion devices



**Magnetic field structures
Force the electrons to move
along particular orbits**

$\Delta\Psi = 1/\gamma$



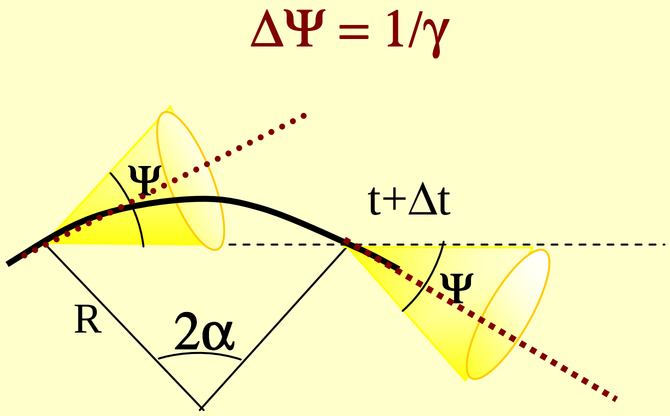
Wiggler Condition

Dimensionless parameter K

$$K = \frac{\alpha}{1/\gamma} = \frac{e}{2\pi mc}\lambda_u B = 0.934\,\underset{[\mathrm{cm}]}{\lambda_u}\,\underset{[\mathrm{T}]}{B}$$

In a wiggler K>>1

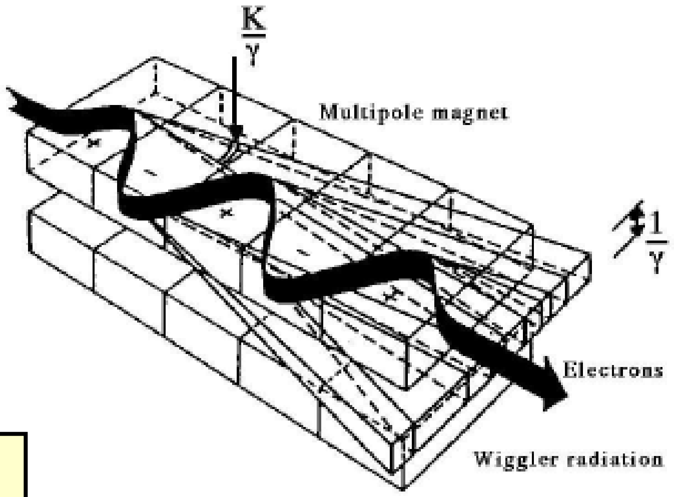
In a wiggler the angular oscillations of the electrons $\alpha=K/\gamma$ are much wider than the natural opening angle $\Delta\psi=1/\gamma$

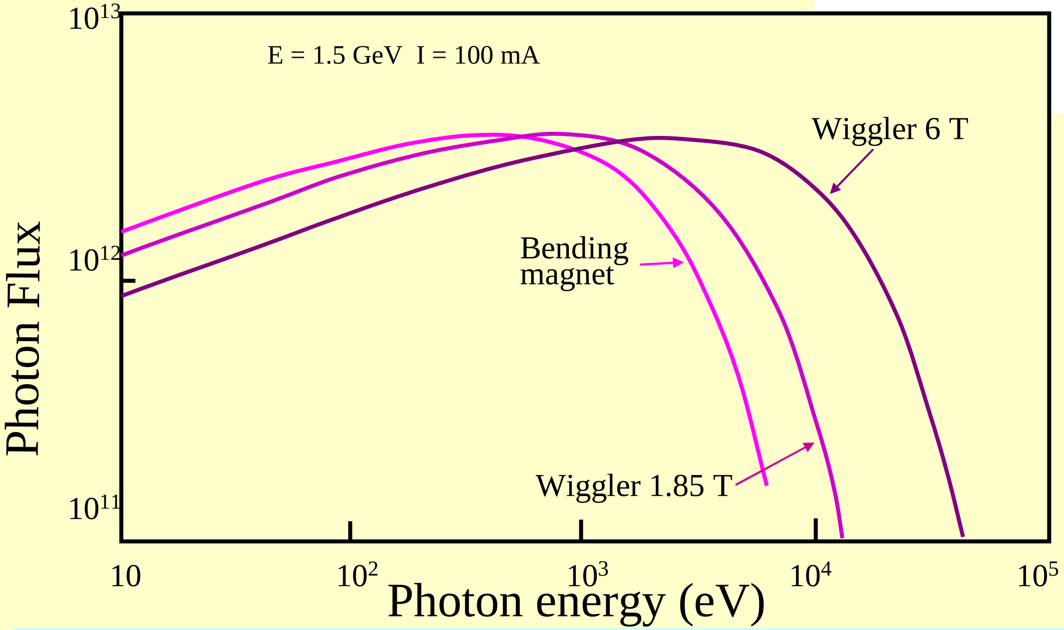


- **No interference between the emission from different poles**
- **Total emission is the sum of the emission from each pole**

Wigglers Emission

Multipole magnet made up of a periodic arrangement of *N* magnets whose magnetic field forces electrons to wiggle around the orbit



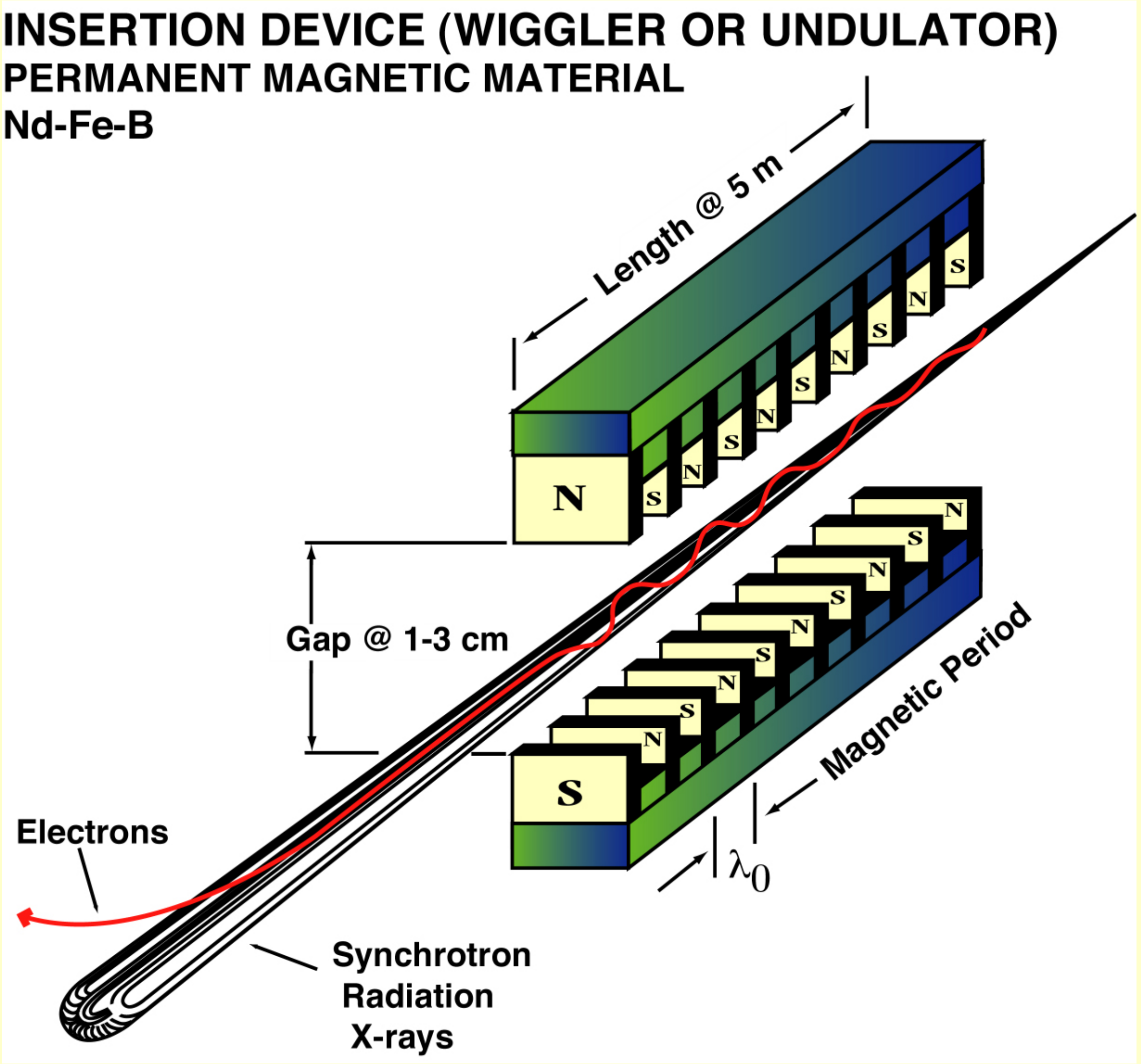


Higher magnetic field → higher critical energy

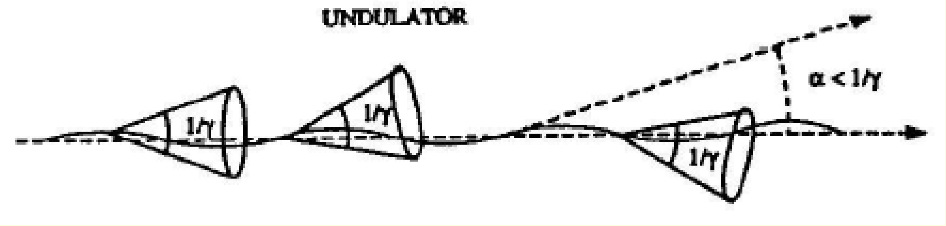
Radiation from the poles increases the total emission

Wigglers have higher critical energy → enhance the X-ray emission

Undulator


INSERTION DEVICE (WIGGLER OR UNDULATOR)
PERMANENT MAGNETIC MATERIAL
Nd-Fe-B
Length @ 5 m
N
S
Gap @ 1-3 cm
Magnetic Period
λ_0
Electrons
Synchrotron Radiation X-rays

Undulators condition



An undulator is similar to a wiggler with a K < 1

→

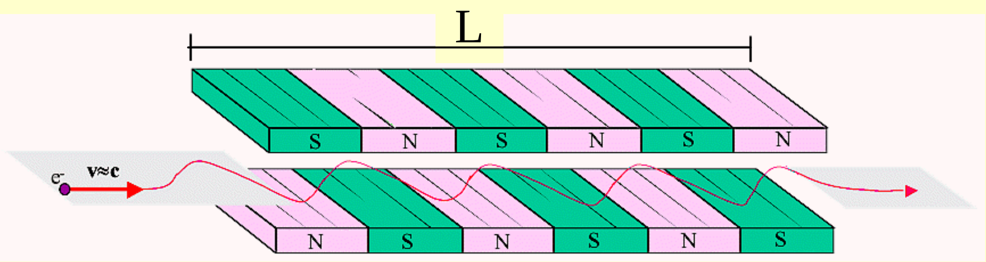
The wiggling angle is smaller than the photon natural emission angle *1/γ*

Interference effects are important

Observing the radiation at an angle θ from the axis constructive interference occur at the wavelengths

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

Undulator fundamental frequency

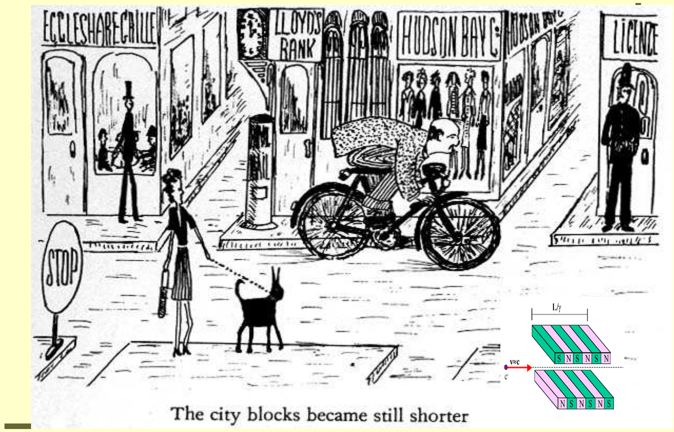


An undulator as seen in the laboratory reference system

$$\lambda_0 = L/n$$

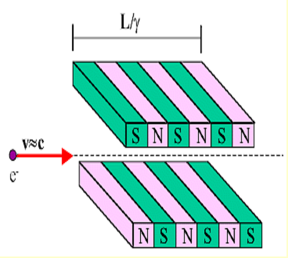
Magnetic pole periodicity

n = number of periods



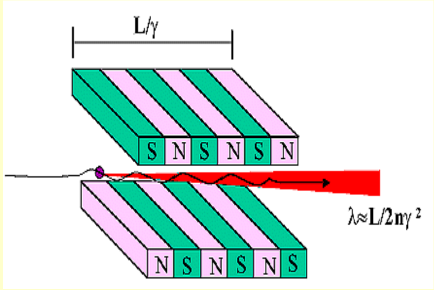
The city blocks became still shorter

Relativistic contraction



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

The undulator as seen from the electron



Doppler shift

$$\lambda = \frac{\lambda_0}{\gamma}\frac{1}{2\gamma} = \frac{\lambda_0}{2\gamma^2}$$

Further reduction of the light periodicity due to the Doppler effect

Spectrum

Undulator harmonics

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

Also harmonics λ/n are emitted

On the axis (θ=0) only odd harmonics are emitted

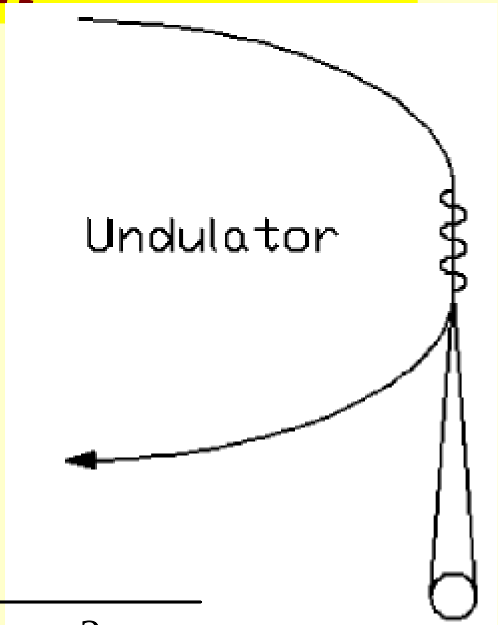
The radiated field adds coherently →

The intensity increases as N^2

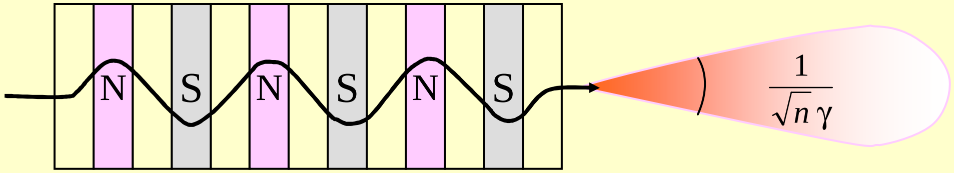
while in a wiggler it increase as 2N

Undulator angular emission

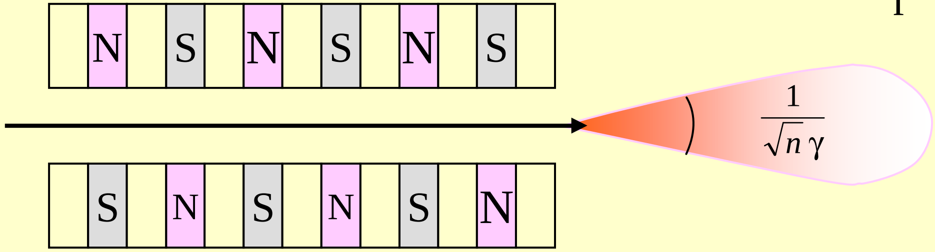
The angular distribution is concentrated in a narrow cone both in horizontal and vertical directions



Top view



Side view



$$\sigma_r = \sqrt{\frac{3}{4\pi}\frac{1+K^2/2}{\gamma^2 nN}} \approx \frac{1}{\gamma}\frac{1}{\sqrt{nN}}$$

Radiation from an undulator: typically N = 50

The natural emission cone is always smaller than 1/γ

Undulator bandwidth

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

$$\sigma_r \approx \frac{1}{\gamma}\frac{1}{\sqrt{nN}}$$

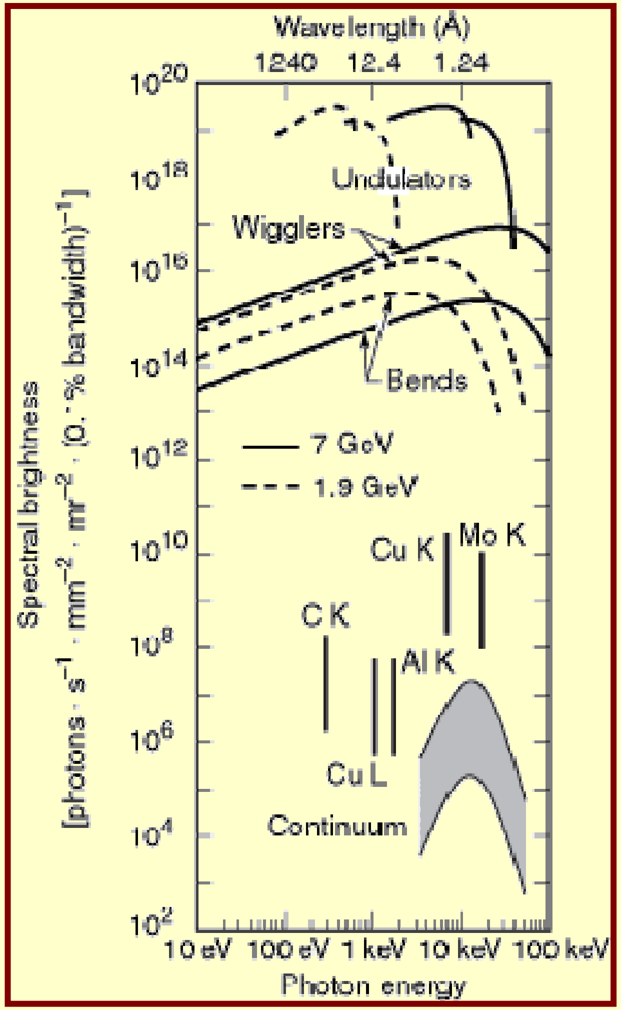
$$\frac{\Delta\lambda}{\lambda} = \frac{1}{nN}$$

Numbers: $\lambda_u \approx 0.1$ m
N = 50
$\gamma = 4000 - 10000$

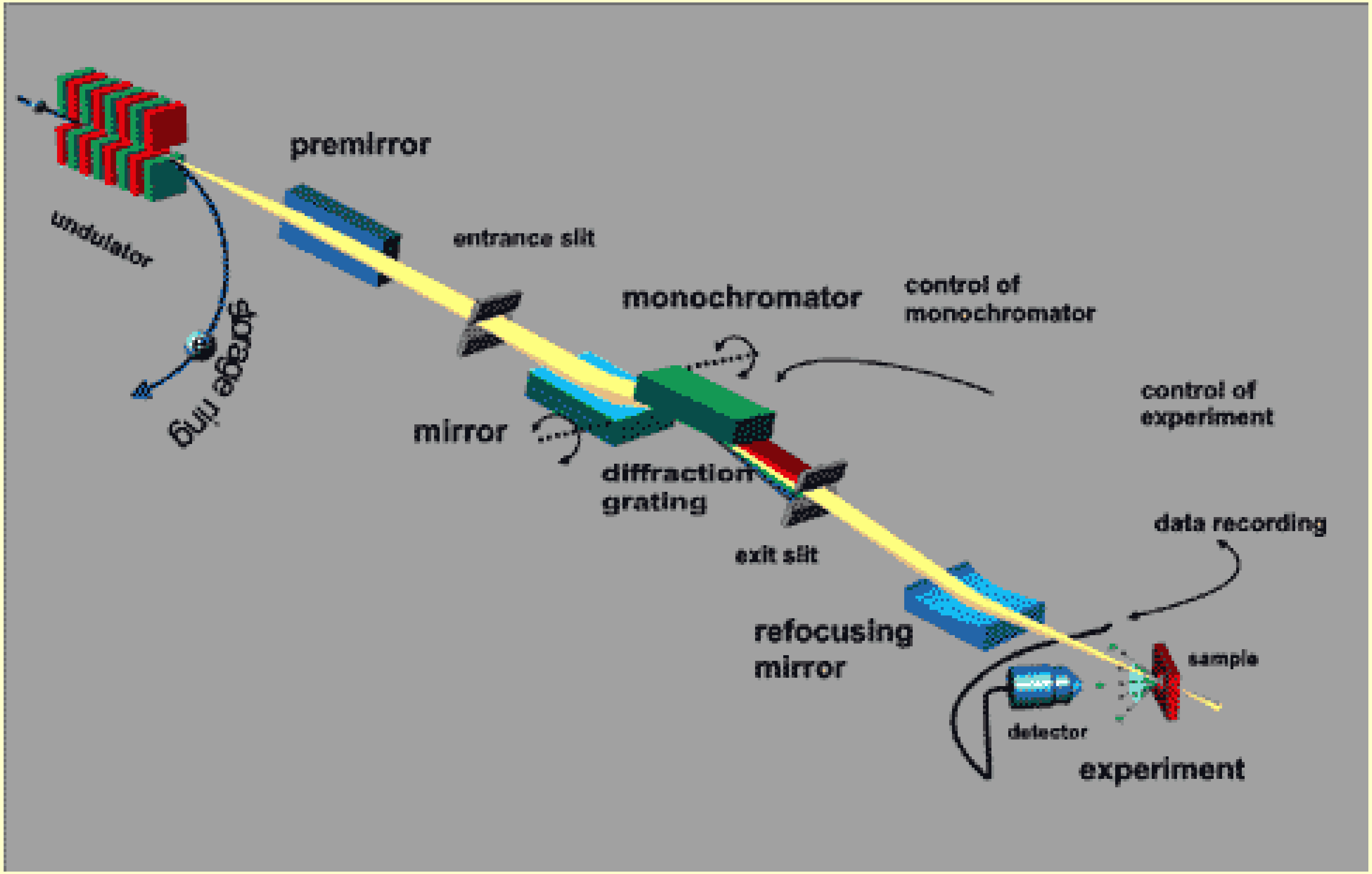
$\lambda_{Fund.} \approx 1 - 10$ Å
$\sigma_{Fund.} \approx 14 - 30$ μrad
$\Delta\lambda/\lambda \approx 2\ 10^{-2}$

Spectral brilliance

For experiments that require a small angular divergence and a small irradiated area, the figure of merit is the beam brilliance B which is the photon flux per unit phase space volume, often given in units of photons$\cdot s^{-1}\cdot mr^{-2}\cdot mm^{-2}\cdot$ (0.1% bandwidth)$^{-1}$



Beamlines


undulator
storage ring
premirror
entrance slit
monochromator
control of monochromator
mirror
diffraction grating
control of experiment
exit slit
data recording
refocusing mirror
sample
detector
experiment

Synchrotron Radiation Facilities around the world

71 facilities in the world:

18 in America
24 in Asia
26 in Europe
2 in Middle East
1 in Oceania

The twenty-five synchrotron light sources around the world which entered operation in the past 15 years

Synchrotron Radiation Facilities in Europe

26 Facilities, most dedicated, few parasitic

III Generation Facilities
Policy in Europe

ELETTRA in Italy
BESSYII in Germany
SLS in Switzerland
DIAMOND in UK
SOLEIL in France
ALBA in Spain

At home: Medium energy (~ 2GeV) S.R.
High brilliance in soft X-ray
Brilliance in hard X-ray

Germany (Hamburg)
DORIS III and PETRA II/III

European Synchrotron Radiation Facility ESRF in Grenoble
For High Brilliance in the hard X-ray region

European Synchrotron Radiation Facility -ESRF

European Synchrotron Radiation Facility -ESRF

Members' Contribution to the budget:

27.5%	**France**
25.5%	**Germany**
15%	**Italy**
14%	**United Kingdom**
4%	**Spain**
4%	**Switzerland**
6%	**Benesync (Belgium&Netherlands)**
4%	**Nordsync (Denmark, Finland,Norway, Sweden)**

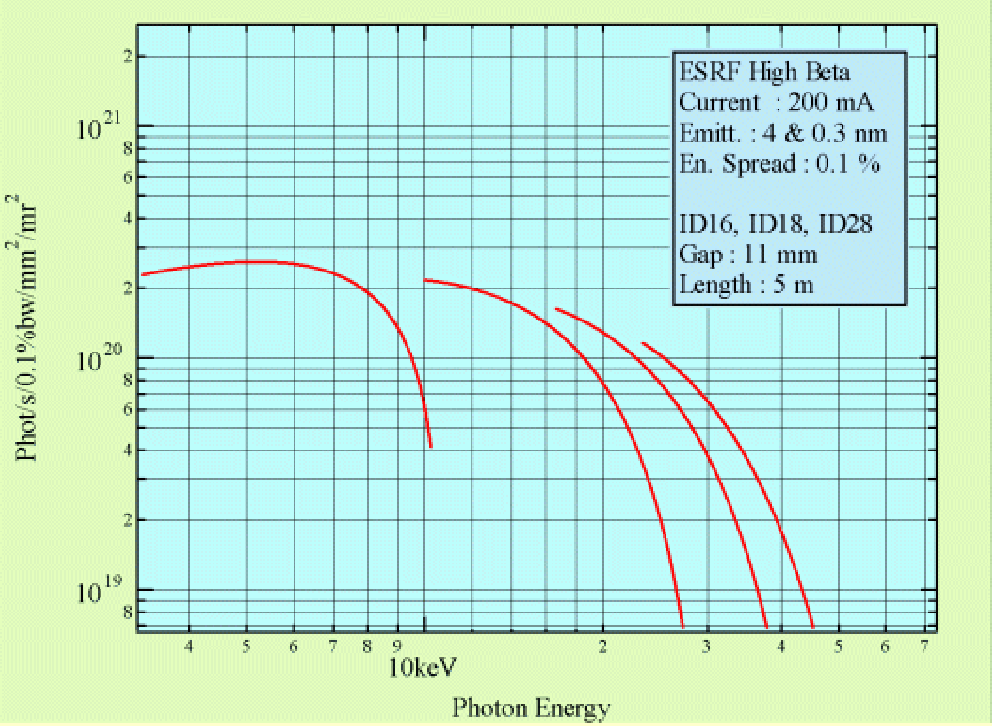
Additional contributions

1%	**Portugal**
1%	**Israel**
1%	**Austria**
1%	**Poland (from July 2004)**
1.05%	**Centr. Synch (Czech Republic,Hungary,Slovakia)**

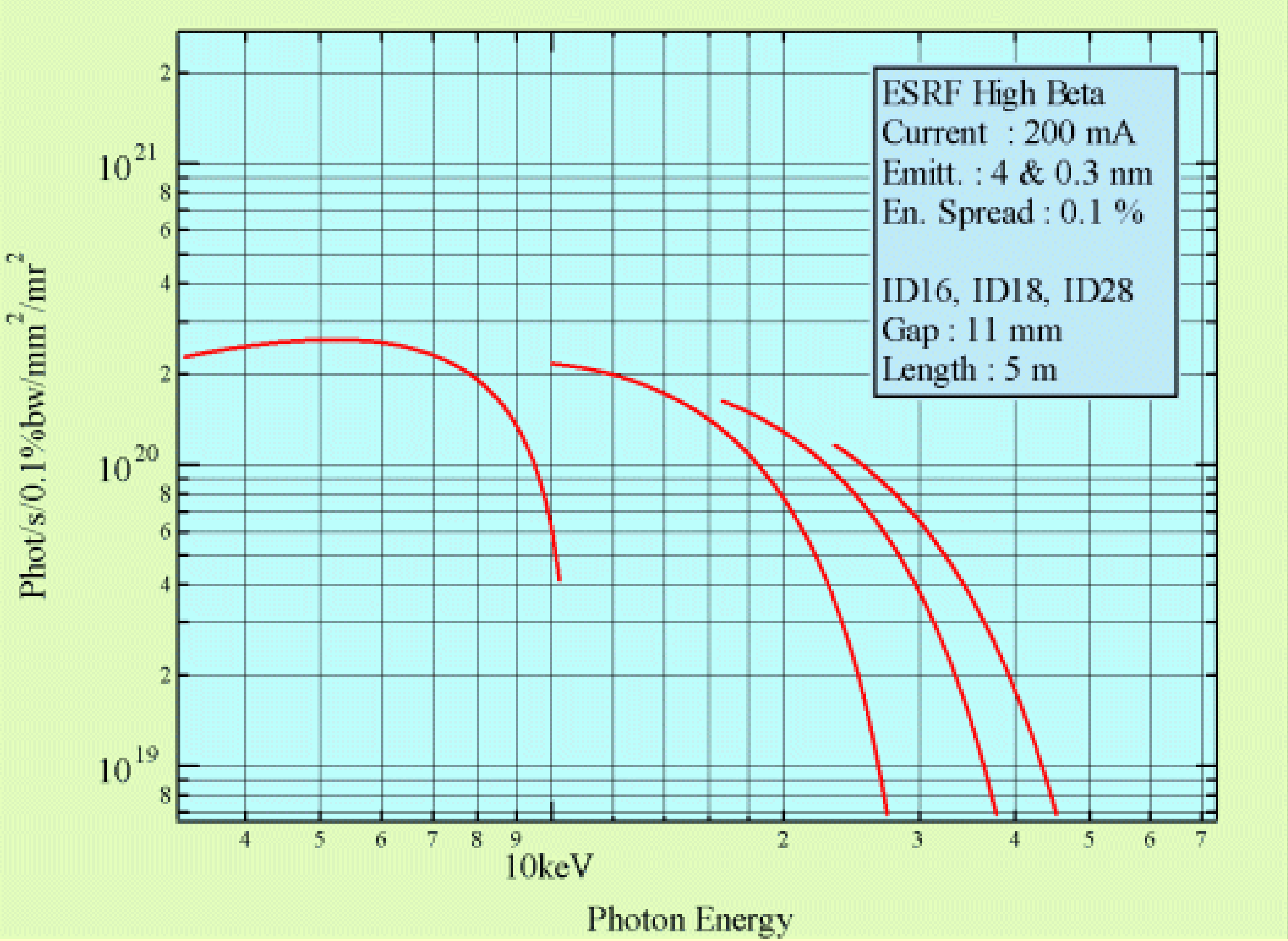
Parameters of the ESRF

Energy	**6GeV**
Circumference	**844m**
Current	**200 mA**
Bending Magnet Radius	**24.95m**
RF frequency	**352.2MHz**
Harmonic number	**992**

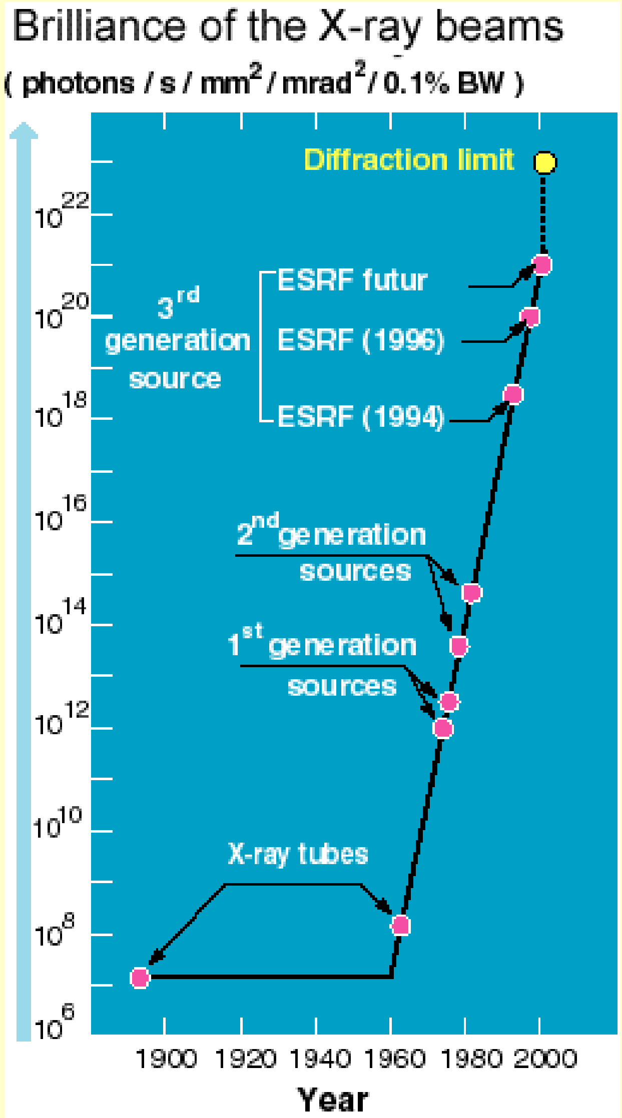
Critical Energy	**19.6 KeV**
Undulator 1st Harmonic	**14 KeV**



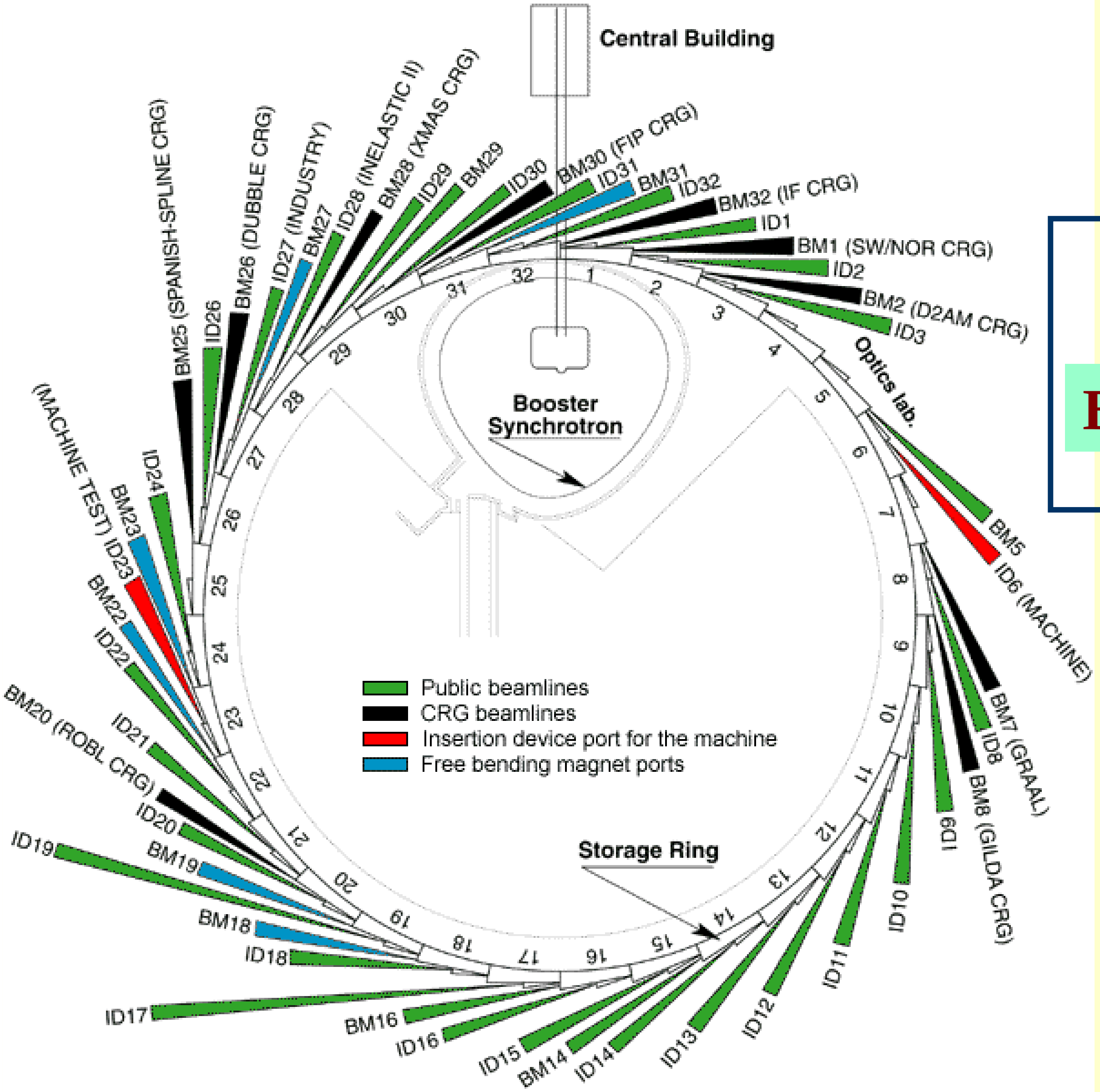
ESRF Achieved Brilliance



ESRF Brilliance



ESRF Experimental Hall



Undulator BL 34

Bending Magnet BL 3

Collaborating Research group Beamlines 13

Science at ESRF

Magnetism:

Separation of S and L contribution
Contribution of different electronic shells

Surfaces:

Structure of surfaces and overlayers
Surface magnetism

X-ray Inelastic Scattering:

Lattice dynamics &Electronic States

Life Science:

Protein Crystallography
Time resolved crystallography

Chemistry:

High resolution crystallography
Microcrystals
Catalysis

High Pressure:

Phase diagram up to 150 Gpa

Imaging:

Phase Contrast Imaging
Speckel

Medicine:

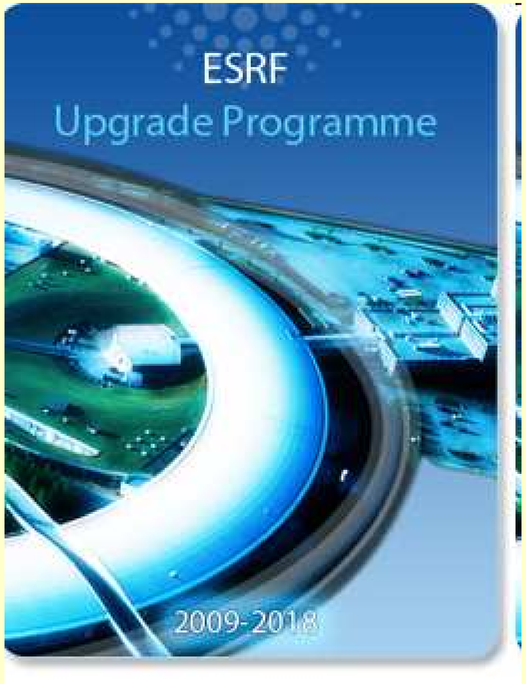
Microbeam therapy
Tomography
Angiography

Industrial:

High resolution strain (10μ 10^{-5} strain)
Trace element analysis (LLD 10^{6} at/cm^{2})

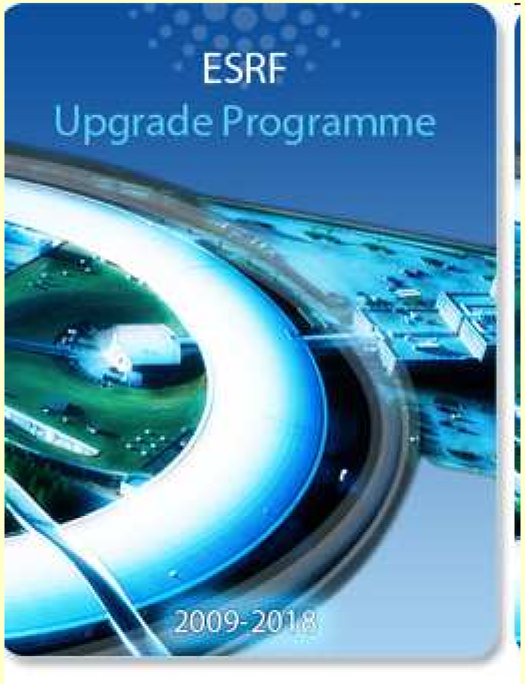
ESRF Upgrade programme

Demand for high-brilliance X-ray beams is continually growing, with user communities requiring ever increasing levels of performance along with ease of access to and use of the light sources.
At the ESRF, the user communities are specifically demanding smaller nanosized beams with higher brilliance, improved facilities on the beamlines and not least more beamtime.



The ESRF Upgrade Programme is serving this demand with the additional objective to maintain the ESRF's role as the leading European provider of hard X-ray light.

ESRF Upgrade programme



An X-ray vision

In 2008, the Council of the ESRF launched the ESRF Upgrade Programme 2009-2018 an ambitious ten-year project serving a community of more than 10,000 scientists.

Funding for a first phase of the Upgrade (from 2009 to 2015) has been secured to deliver:

- Eight new beamlines unique in the world
- Refurbishment of many existing beamlines to maintain them at world-class level
- Continued world leadership for X-ray beam availability, stability and brilliance
- Major new developments in synchrotron radiation instrumentation

ELETTRA

ELETTRA

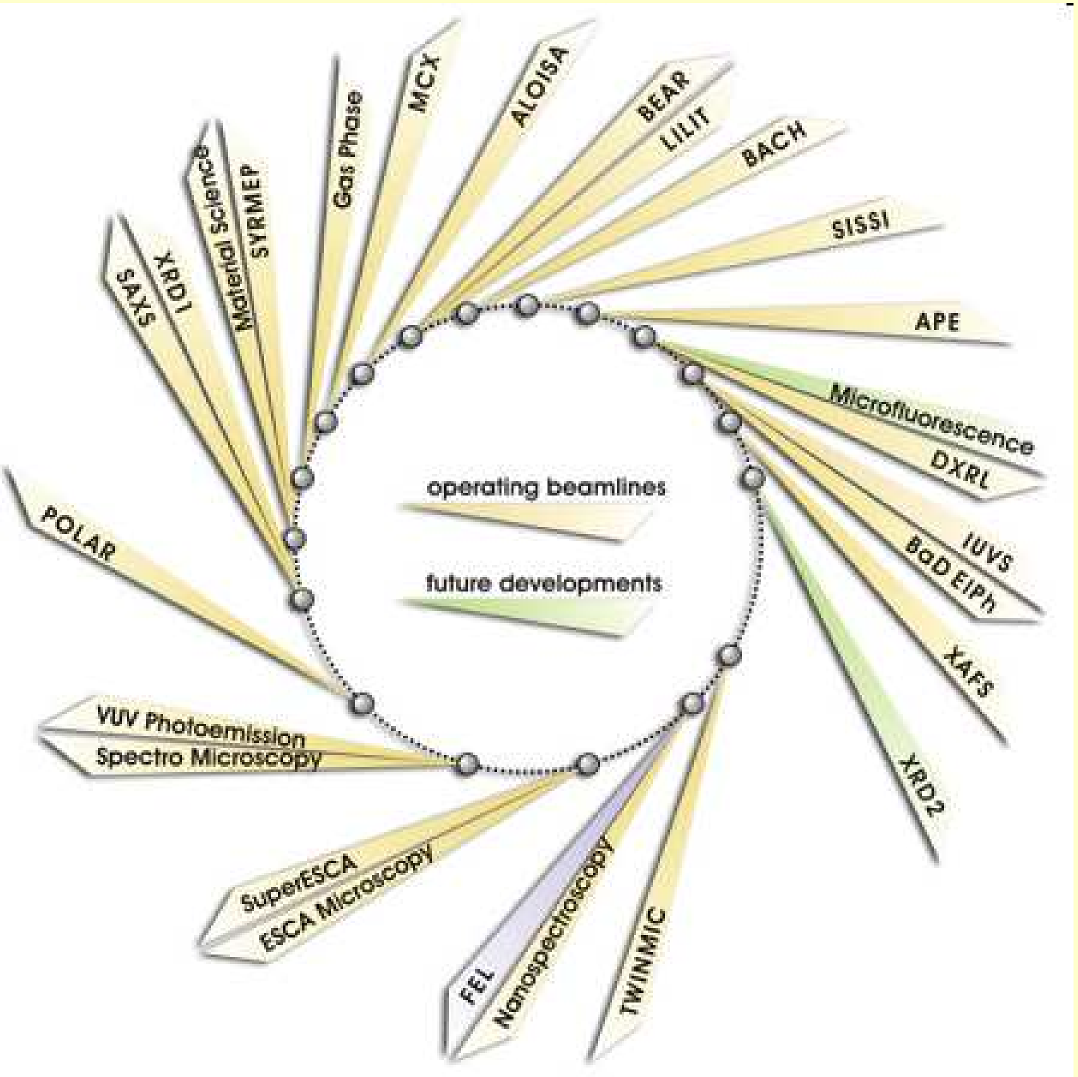
Energy: 2 – 2.4 GeV
Current: 300 mA
Critical Energy: 3.2 KeV

Spectral Range: 10 eV – 10 KeV

Undulator first Harmonic: 200 – 800 eV

Brilliance: 10^{19} photons/s/mm^2/mrad^2/0.1%bw

Beamlines at ELETTRA

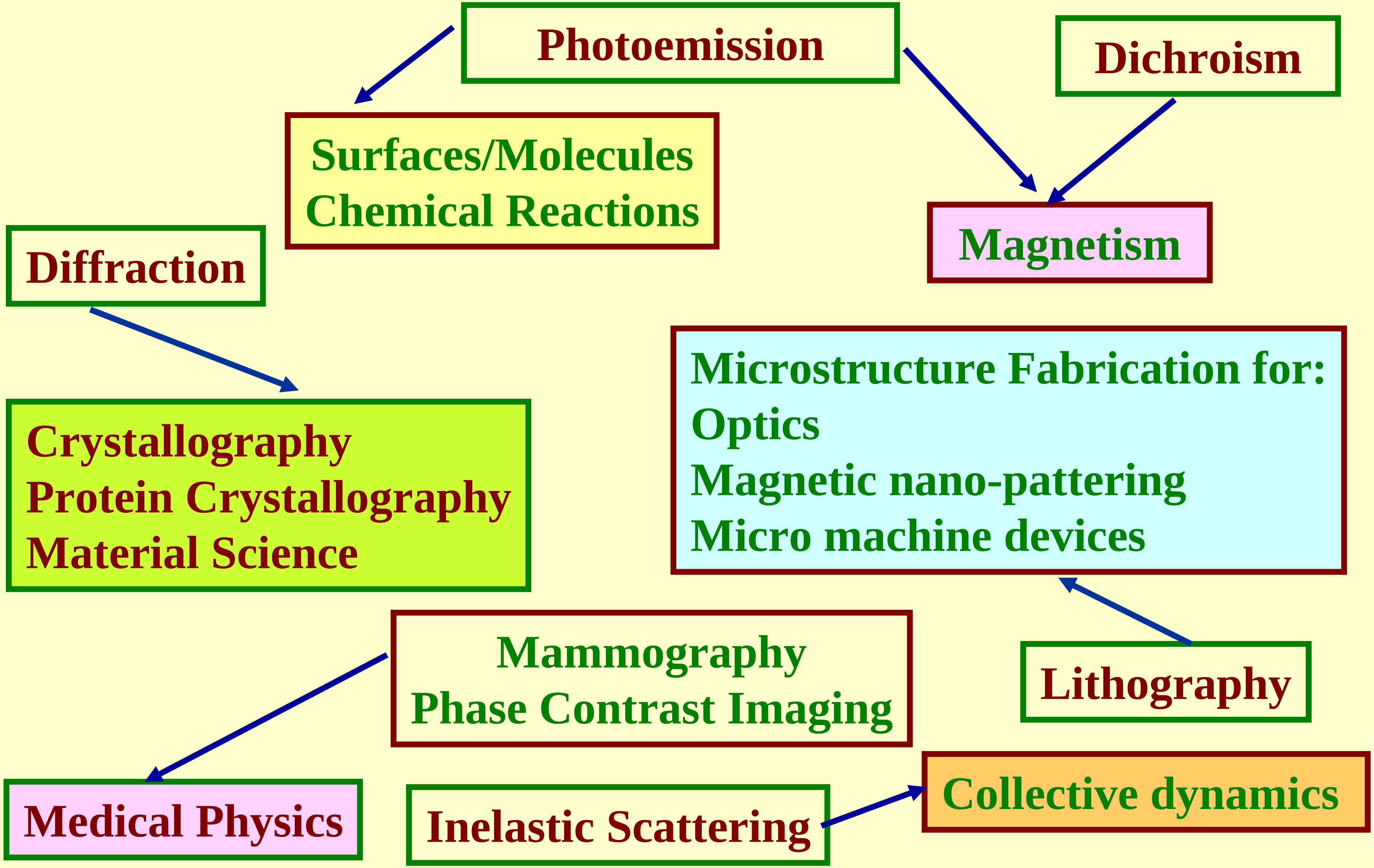


17 Operating Beamlines

24 Experimental Stations

2 More in the future

Science at ELETTRA



Photoemission

Surfaces/Molecules
Chemical Reactions

Dichroism

Magnetism

Diffraction

Crystallography
Protein Crystallography
Material Science

Microstructure Fabrication for:
Optics
Magnetic nano-pattering
Micro machine devices

Mammography
Phase Contrast Imaging

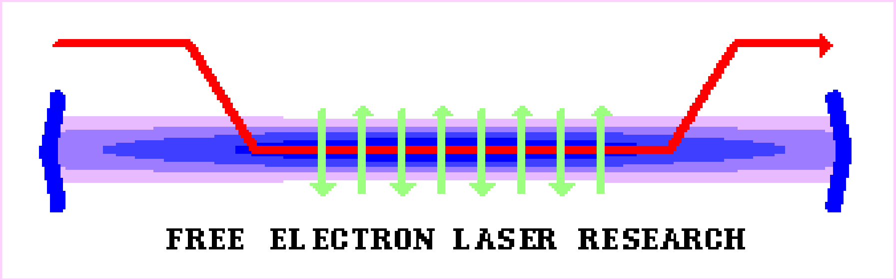
Lithography

Medical Physics

Inelastic Scattering

Collective dynamics

Free Electron Laser



FEL are tunable, coherent, high power radiation, currently spanning wavelengths from millimeter to visible up to ultraviolet and potentially to x-ray.

It is based on the stimulated photon emission: an electron is accelerated by an existing photon field and therefore irradiate additional photons in phase to the exiting ones.

First laser: Madey 1977-78 at Stanford(10μm)

Standard Linac

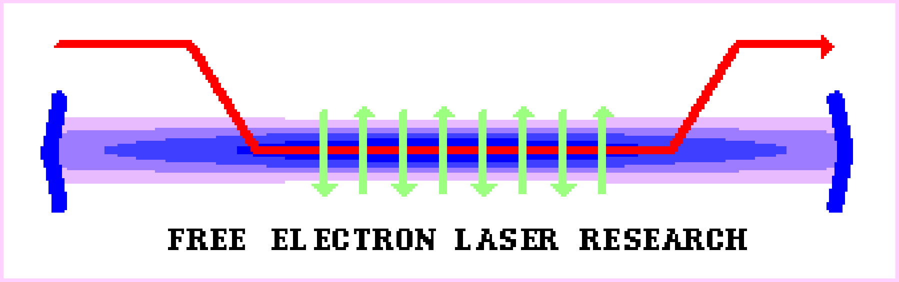
Existing Facilities/Experiments: (about 20)

mainly in IR 1- 100 μm

few in visible - UV

S.R.

Free Electron Laser



To-day interest: Estention toward soft and hard X-ray

Two main approaches:

Seeding **FERMI@ELETTRA**

SASE (Self Amplified Spontaneous Emission)

Self Amplified Spontaneous Emission Free Electron Laser

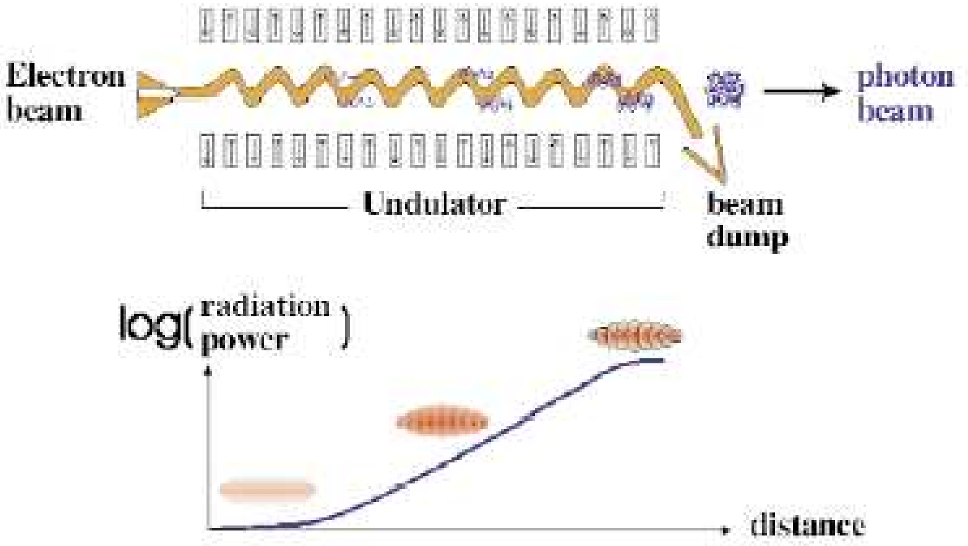
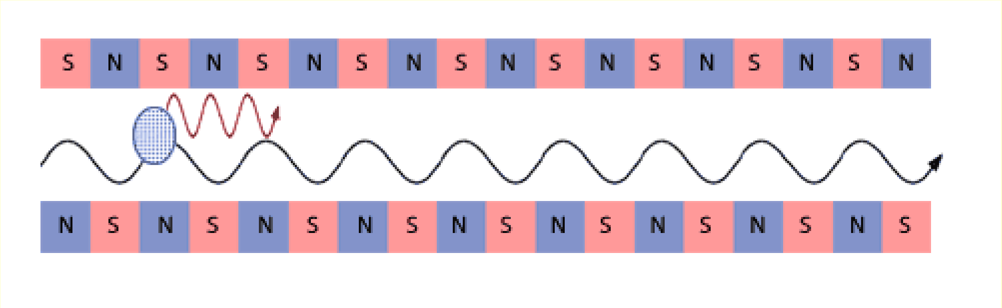


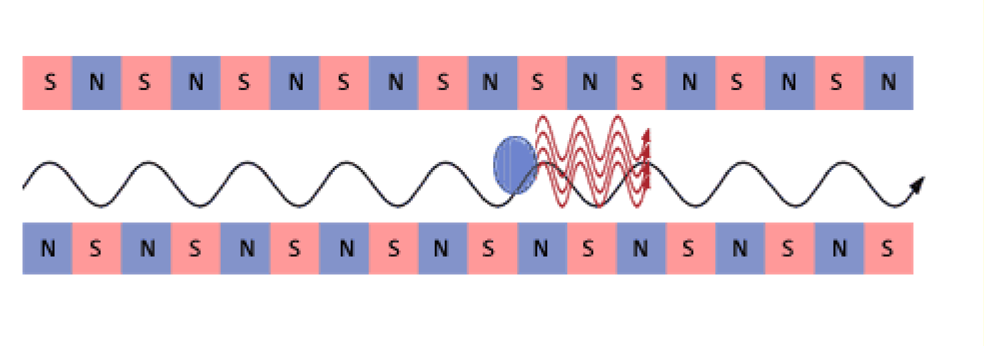
Figure 2: Principle of Self Amplified Spontaneous Emission. As the power grows during the propagation of the beam in the undulator, a longitudinal bunching of the beam takes place. (From the TESLA TDR Report).

In a long undulator the SR emission is self amplified
In a very long undulator saturation may be reached
At a level 7 order of magnitude above the S.R. level

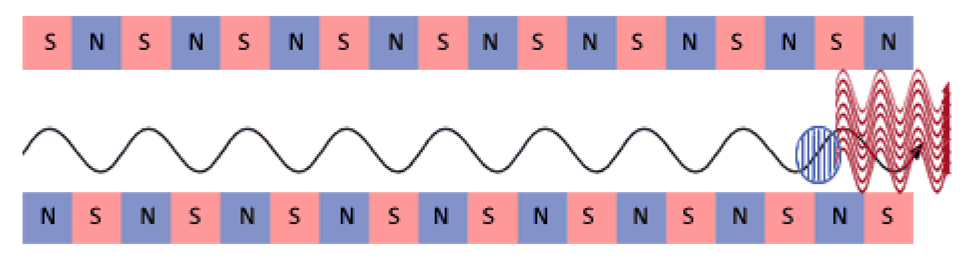
Key points: **electron beam emittance**
undulator characteristics

More on SASE Free Electron Laser Scheme



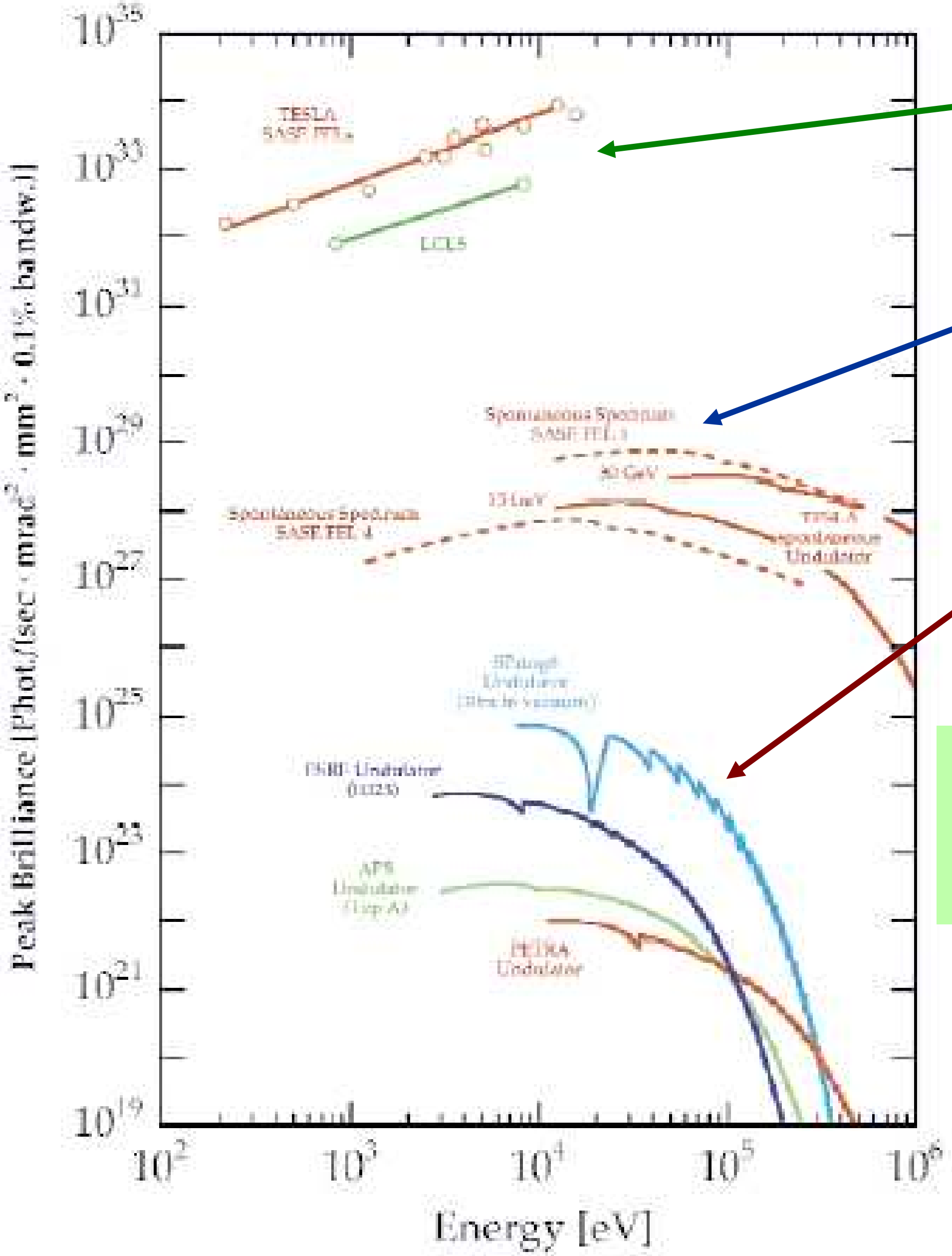


The electron beam and this synchrotron radiation travelling with it are so intense that the electron motion is modified by the electromagnetic fields of its own emitted synchrotron light.
Under the influence of both the undulator and its own synchrotron radiation, the electron beam begins to form micro-bunches, separated by a distance equal to the wavelength of the emitted radiation.



These micro-bunches begin to radiate as if they were single particles with immense charge.
The process reaches saturation when the micro-bunching has gone as far as it can go.

FEL Radiation Properties



Peak Brilliance

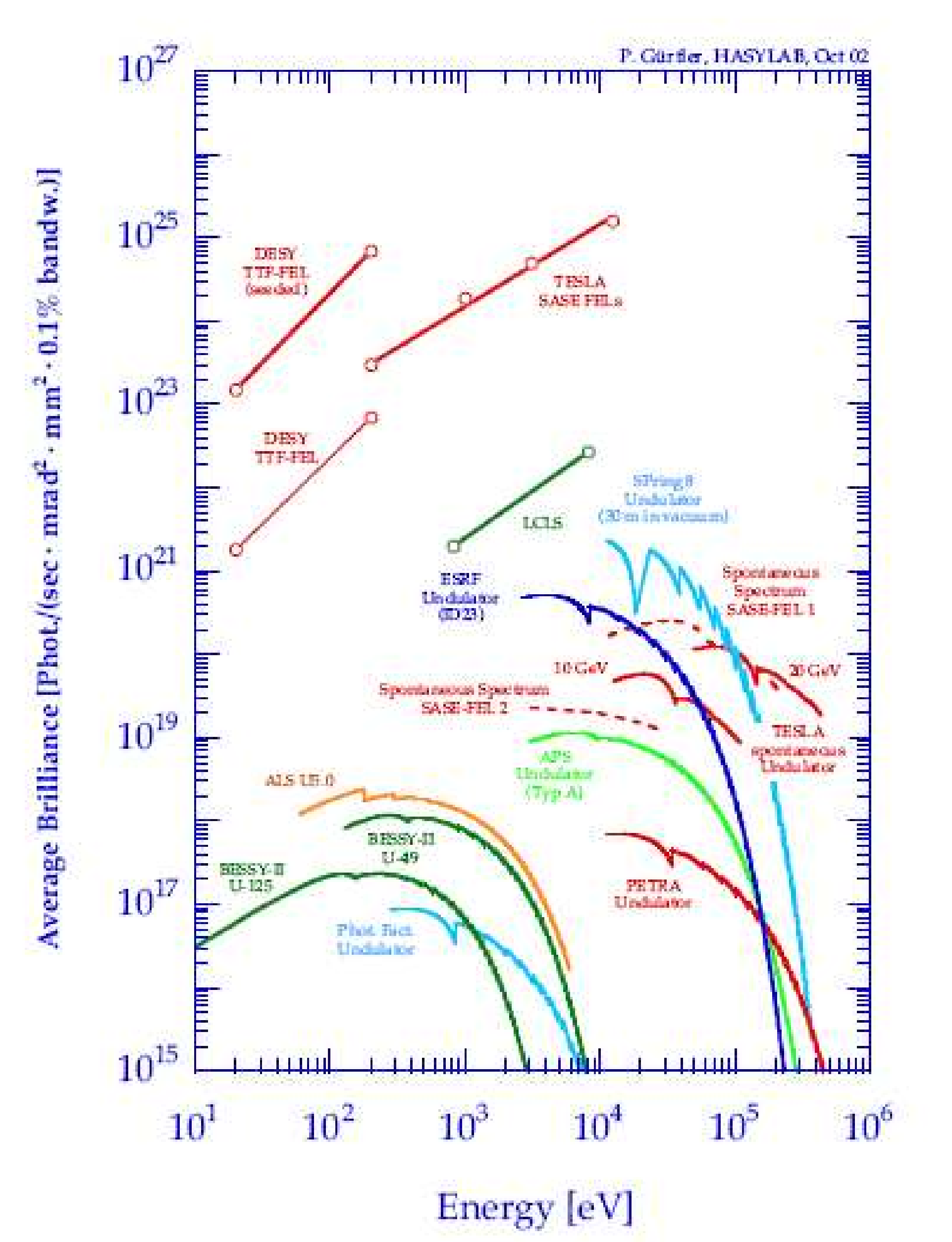
FEL Spontaneous Emission

Existing Undulators

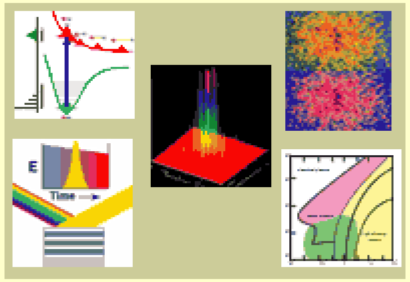
Coherent Radiation

Pulse length: tens of femtosecond

FEL Radiation Average Brilliance



X- FEL Science



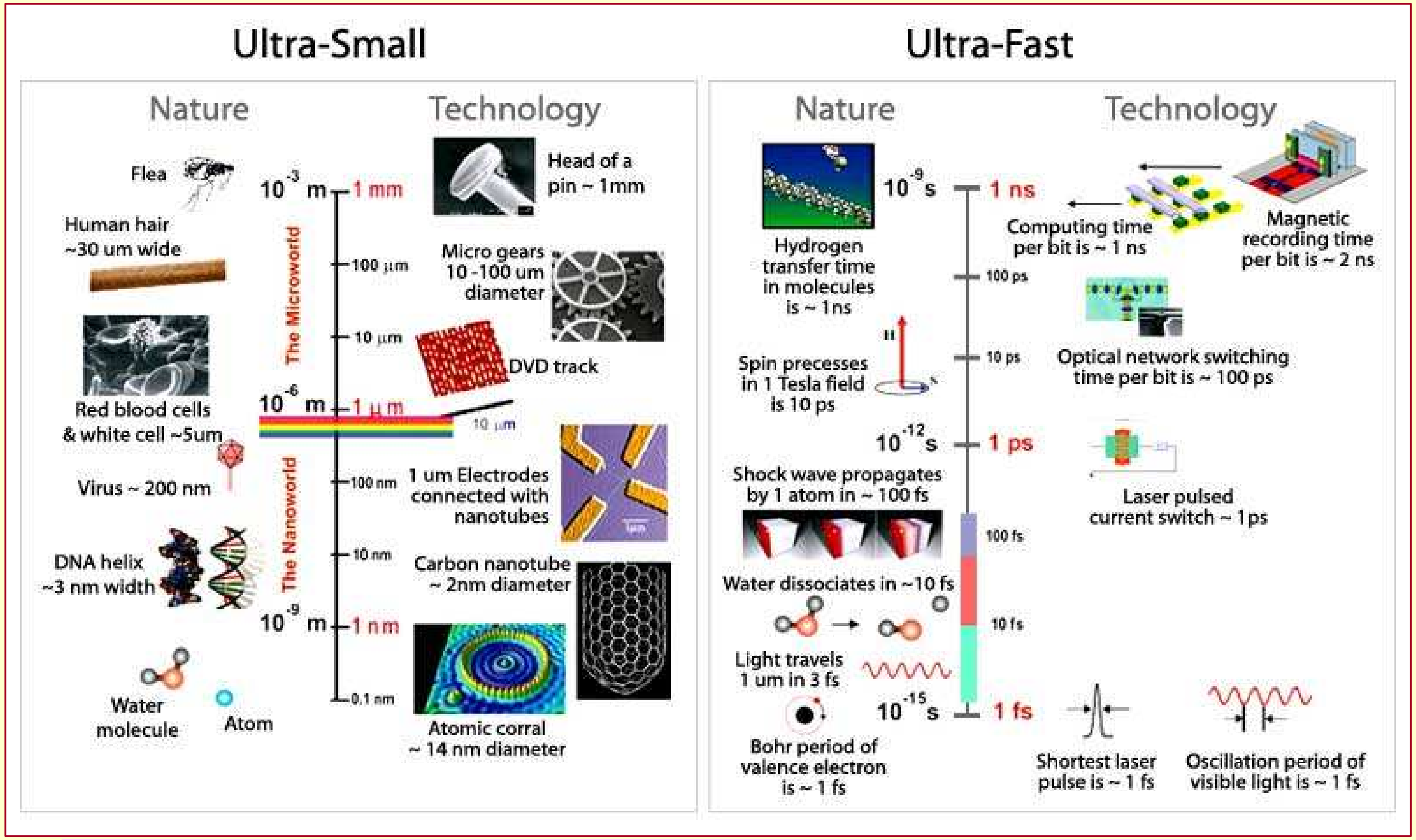
The investigation of structural changes on ultra short time scales will become possible, thus complementing femtochemistry with optical lasers.

Investigation of molecular structures without the need of crystallization. This will give access to a vast number of biomolecules yet impossible to crystallize.

A new, and may be most important domain will be the non-linear interaction of X-rays and matter, leading, e.g., to multiphoton processes in atoms and molecules
which can not be studied with the present radiation sources.

And last not least, by focusing the X-rays to μm^2 and below, one will generate plasmas at still totally unexplored temperatures and pressures.

X- FEL Science

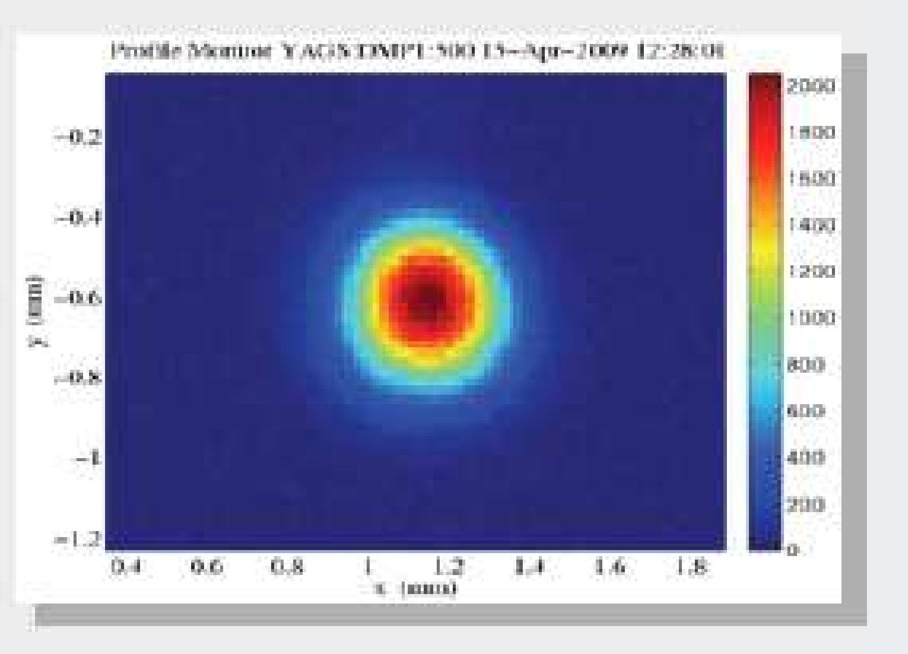


"Can we see the electron dynamics in the bonds?“
"Can we see how matter forms and changes?",
"Can we take pictures of single molecules?“
"Can we make a movie of a chemical reaction?“
"Can we study the vacuum decay in a high field?

FEL in the X-ray regime

Linear Coherent Light Source at Stanford

Image of the FEL spot at 1.5 Å



Main X-ray projects under development in Europe:
FLASH at Hamburg (HASYLAB)

European X-FEL (Hamburg)

A working FEL in Italy: FERMI @ ELETTRA

FLASH Facility @ DESY

Bird's eye view of the 260-meter-long FLASH user facility:
the experimental hall (left),
the FLASH tunnel (middle, between the ponds)
the FEL hall (right)

FLASH Facility @ DESY

Design wavelength range of the fundamental: 6.5 - 47 nm

Pulse duration 10-50 fs

Peak brilliance: 10^{29}-10^{30} [photons/(s mrad^2 mm^2 0.1% BW)]

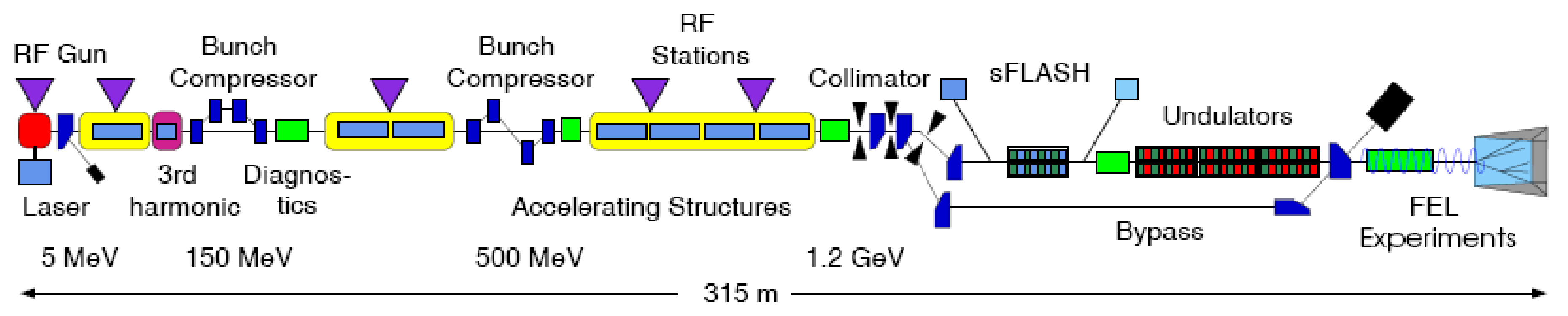
The FLASH experimental hall starts 30 meters behind the last dipole magnet that separates the electron bunches and the photon beam emerging from the long undulator in the accelerator tunnel. The photon beam transport system in the hall delivers the FEL pulses – as short as 10 fs – to the experimental stations.

FLASH Facility @ DESY

Design wavelength range of the fundamental: 6.5 - 47 nm

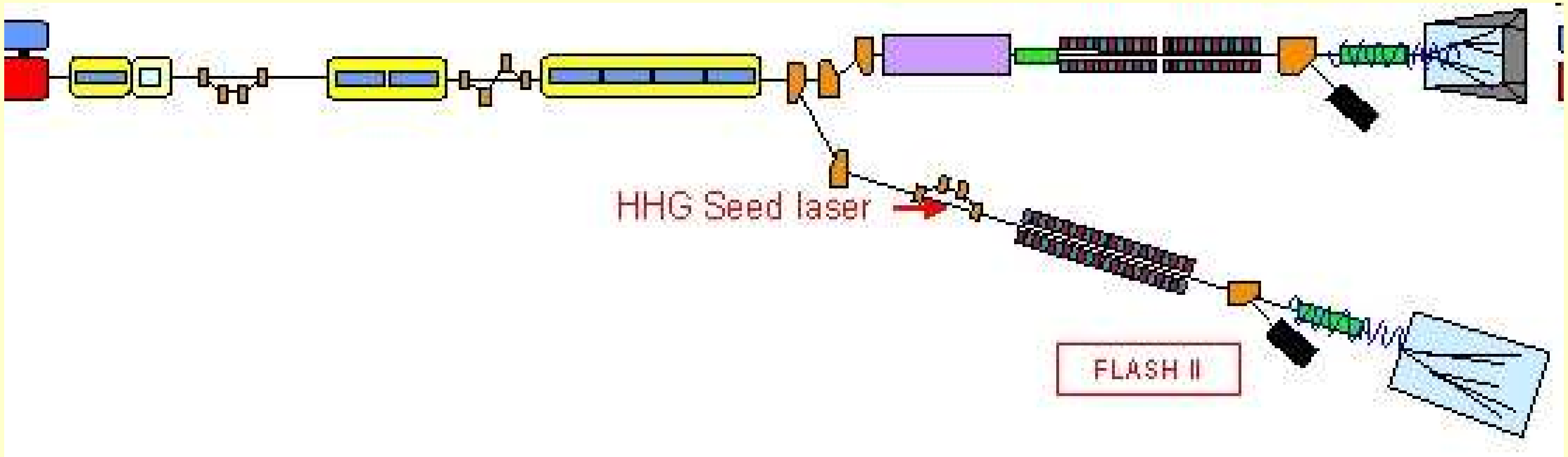
Pulse duration 10-50 fs

Peak brilliance: 10^{29}-10^{30} [photons/(s mrad^2 mm^2 0.1% BW)]



4.12 nm achieved: water window available

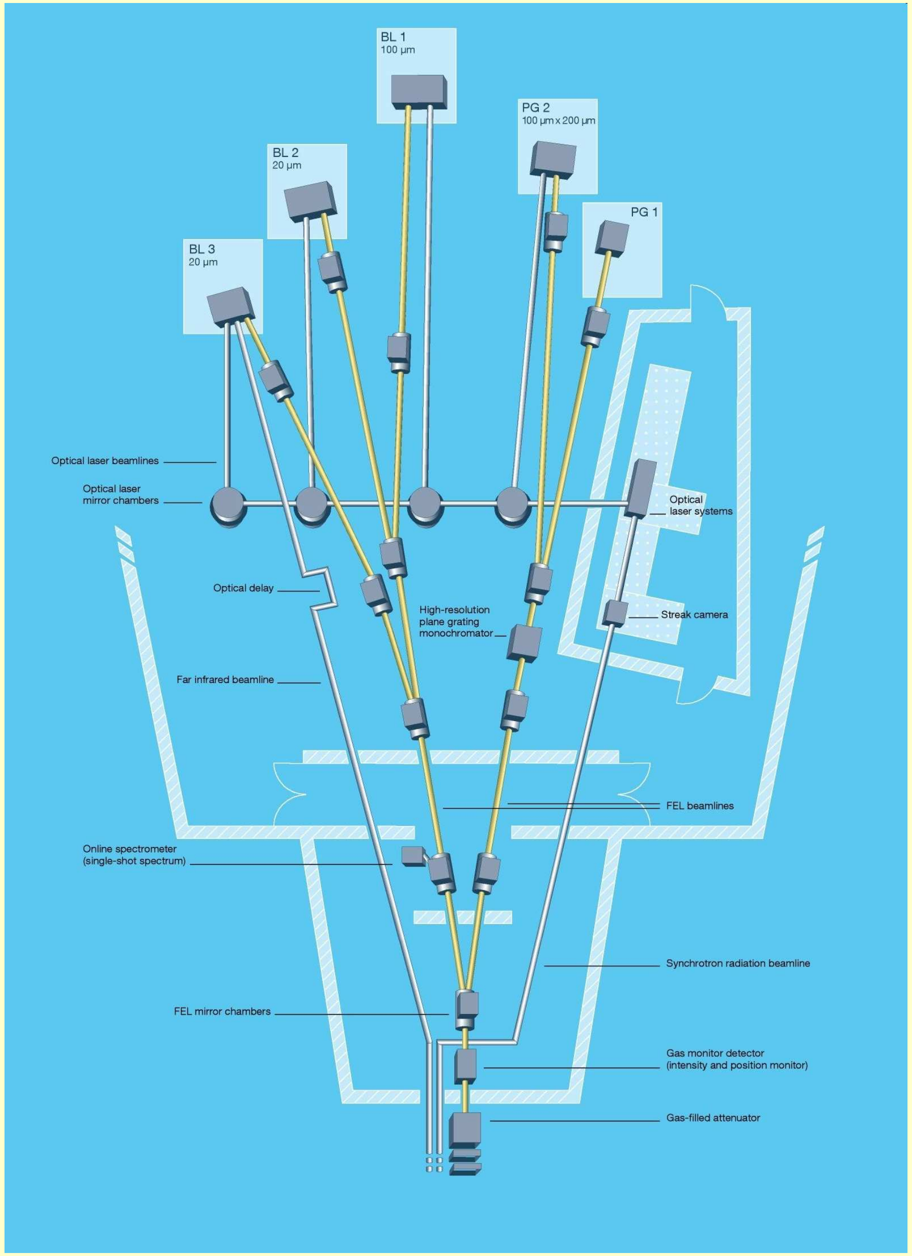
FLASH II Facility @ DESY



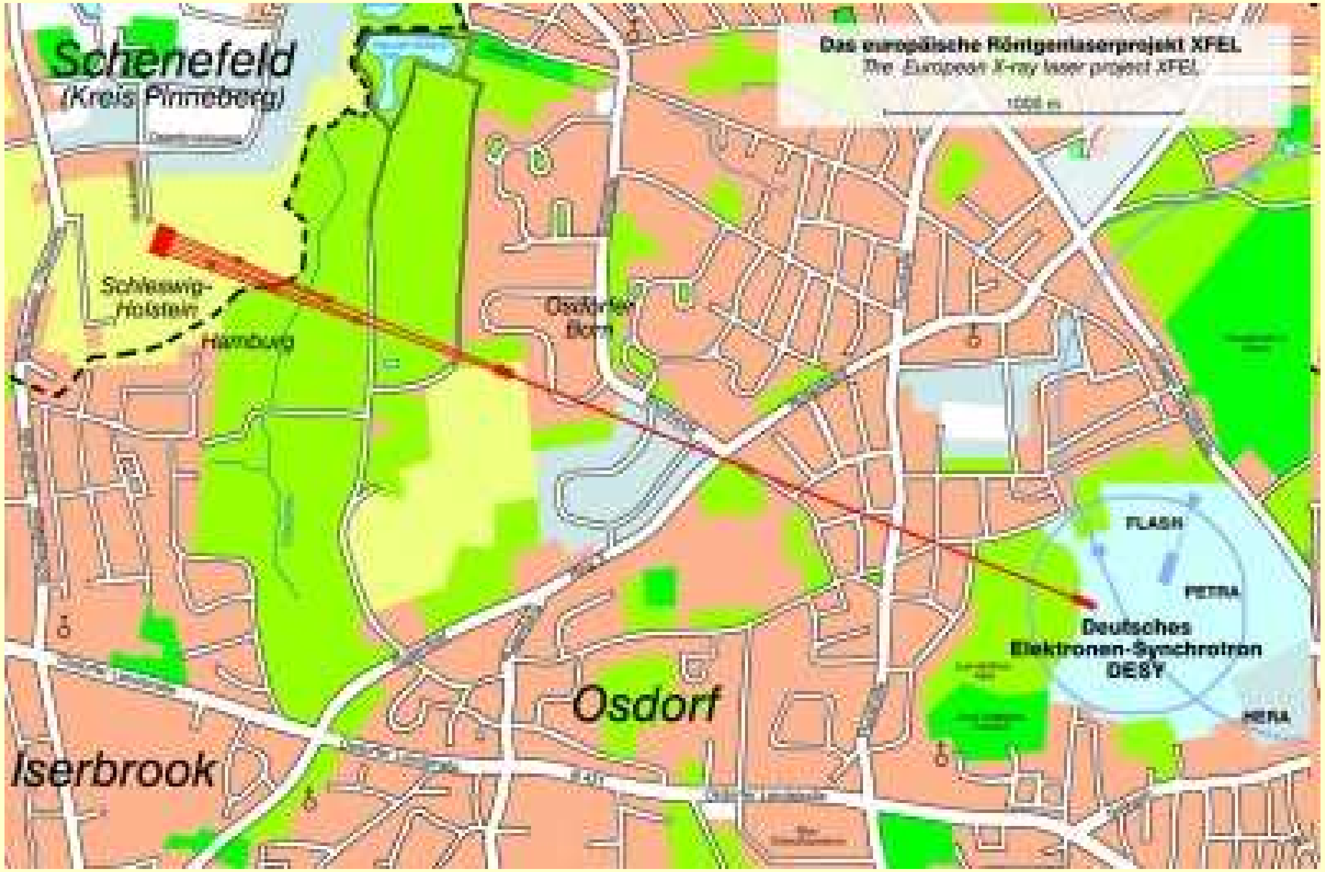
Schematic layout of the FLASH facility.
The electron gun is on the left, the experimental hall on the right.
Behind the last accelerating module, the beam is switched between FLASH I, which is the present undulator line, and FLASH II, which is the upgrade.
Behind the extraction point, space is reserved for an additional laser system for seeding.

0.8 nm on the fifth harmonic expected

FLASH Facility @ DESY: Five Beamline Scheme



European X-FEL @ Hamburg



The X-ray laser is an 3.4-km-long facility which runs essentially underground and comprises three sites above ground. It will begin on the DESY site in Hamburg-Bahrenfeld and runs mostly underground to the XFEL research site south of the town of Schenefeld (Pinneberg district, Schleswig-Holstein)

European X-FEL @ Hamburg

Wavelength:	**0.05 to 6 nanometres**
Flashes per second:	**27.000**
Pulse width:	**100 fs**
Peak brilliance:	**10^{33} ph/s/mm^2/mrad 0.1%Bw**
Average Brilliance:	**10^{25} ph/s/mm^2/mrad 0.1%Bw**

Partecipating countries: 12

Denmark, France, Germany, Greece, Hungary, Italy, Poland, Russia, Slovakia, Spain, Sweden and Switzerland

Total cost: 1 Geuro

Germany 54%, Russia 23%, other countries 1-3.5%

Time schedule: 2009 – 2014

Start of user operation: 2015

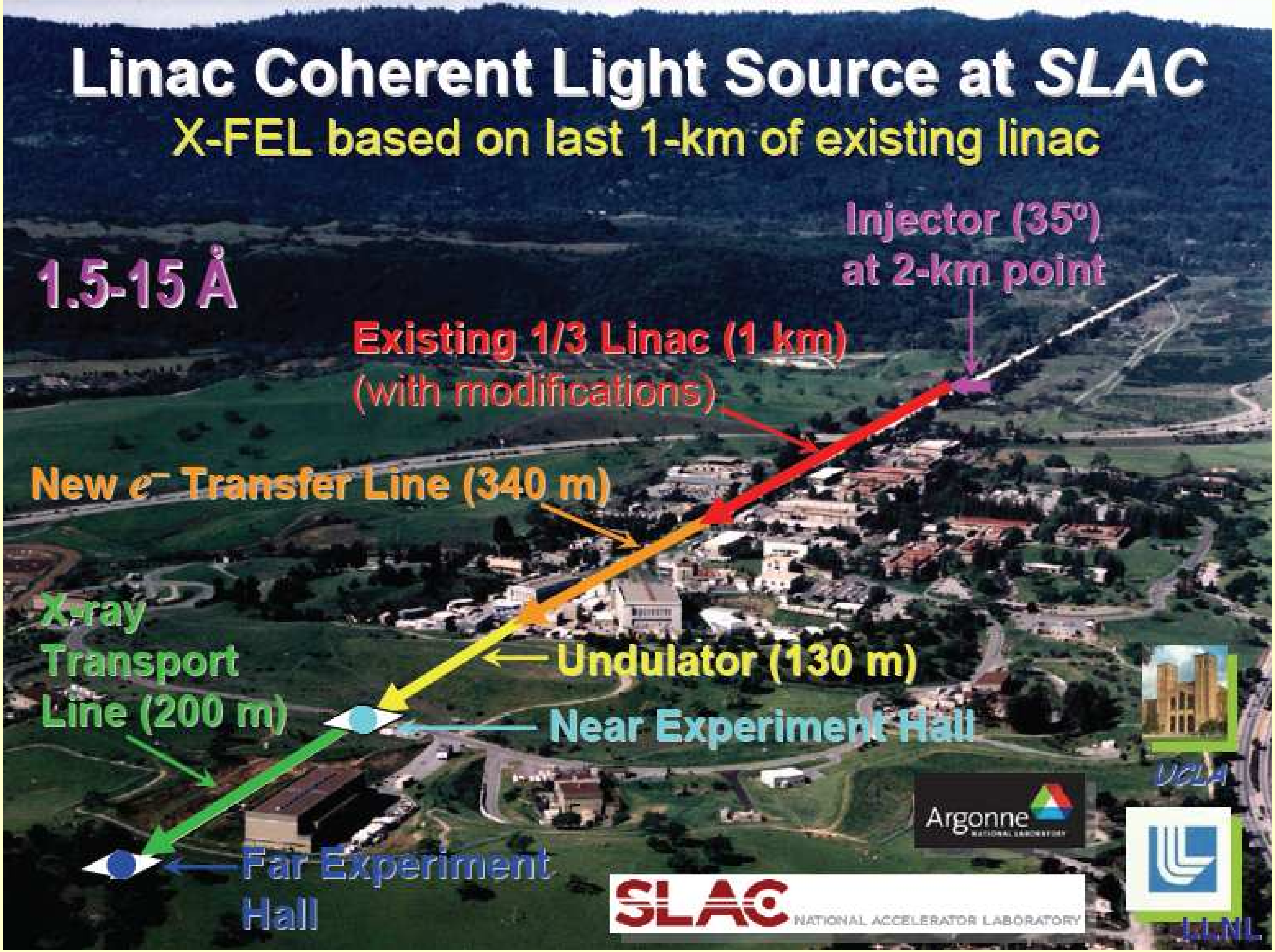
Introduction to Synchrotron Radiation

Thanks for your attention

Prof. Settimio Mobilio
Department of Physics “E. Amaldi”
University Roma TRE - Rome

Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing linac



1.5-15 Å

Injector (35°)
at 2-km point

Existing 1/3 Linac (1 km)
(with modifications)

New e^- Transfer Line (340 m)

X-ray
Transport
Line (200 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment
Hall

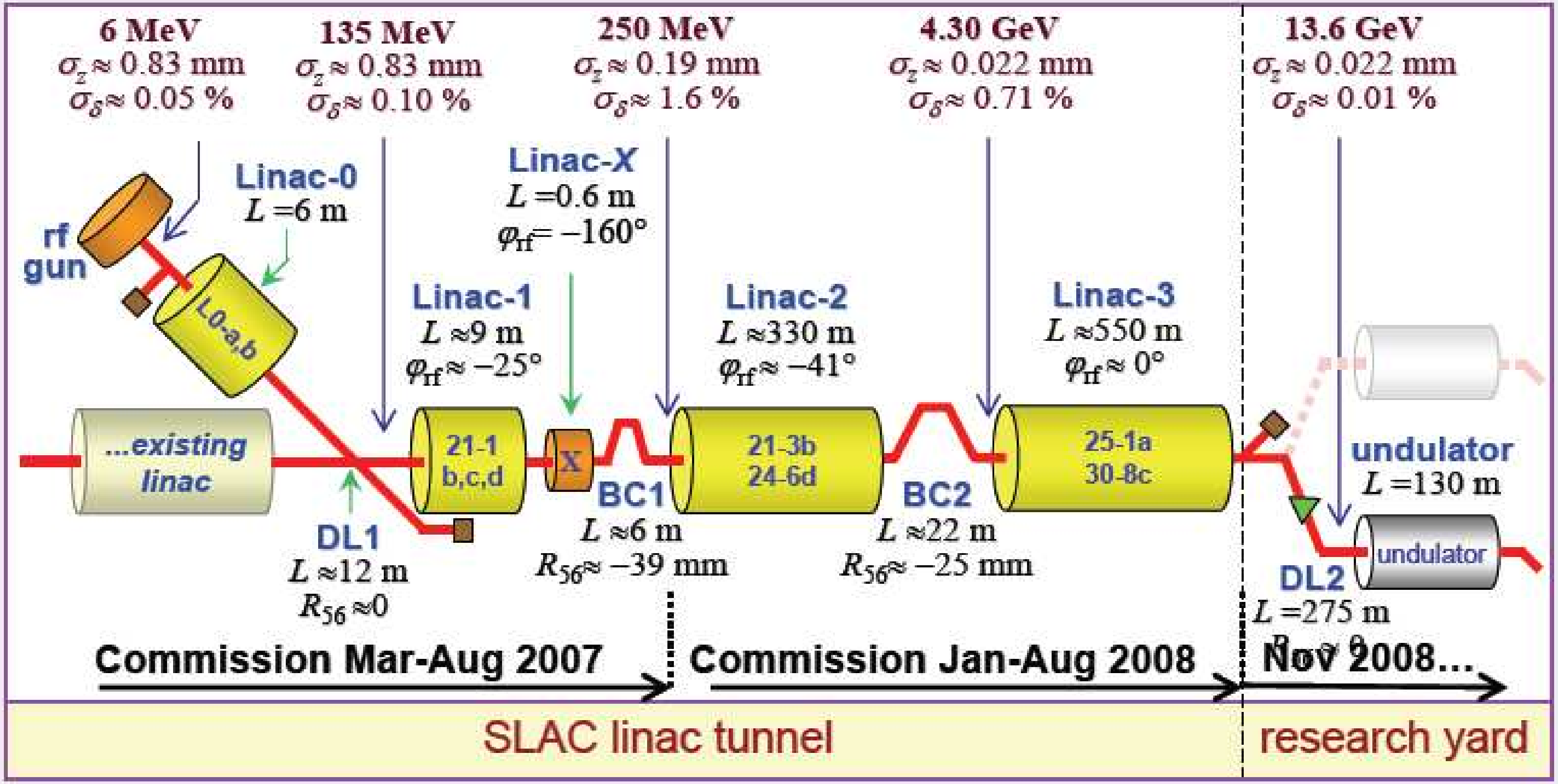
Argonne NATIONAL LABORATORY

SLAC NATIONAL ACCELERATOR LABORATORY

UCLA

LLNL

LCLS Accelerator Layout



6 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.05$ %

135 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.10$ %

250 MeV
$\sigma_z \approx 0.19$ mm
$\sigma_\delta \approx 1.6$ %

4.30 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.71$ %

13.6 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.01$ %

rf gun

Linac-0
$L = 6$ m

Linac-X
$L = 0.6$ m
$\varphi_{rf} = -160°$

Linac-1
$L \approx 9$ m
$\varphi_{rf} \approx -25°$

Linac-2
$L \approx 330$ m
$\varphi_{rf} \approx -41°$

Linac-3
$L \approx 550$ m
$\varphi_{rf} \approx 0°$

DL1
$L \approx 12$ m
$R_{56} \approx 0$

BC1
$L \approx 6$ m
$R_{56} \approx -39$ mm

BC2
$L \approx 22$ m
$R_{56} \approx -25$ mm

undulator
$L = 130$ m

DL2
$L = 275$ m
$R_{56} \approx 0$

Commission Mar-Aug 2007

Commission Jan-Aug 2008

Nov 2008…

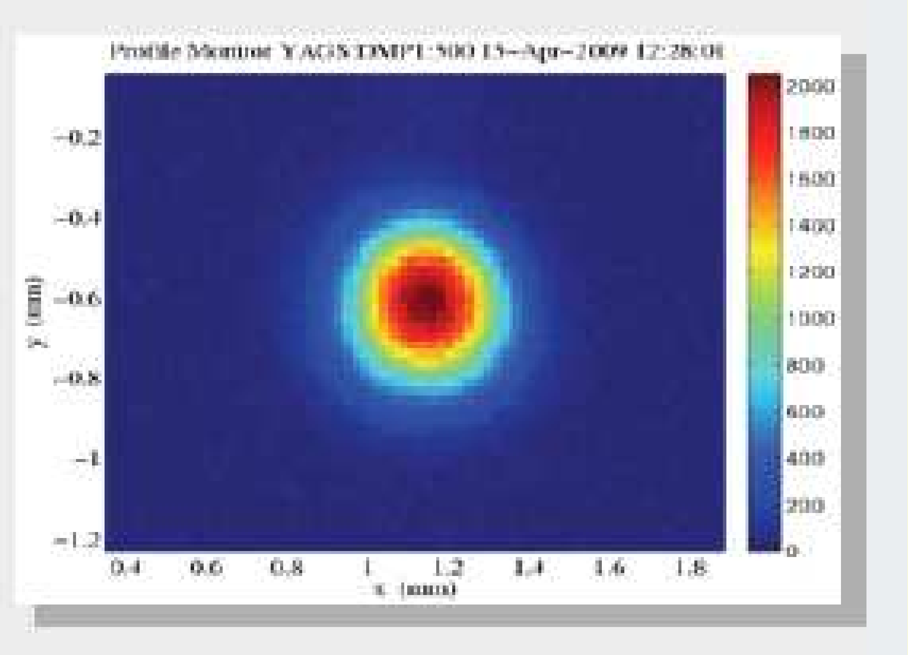
SLAC linac tunnel

research yard

First lasing at 1.5 Å: April 10, 2009 (first try!)

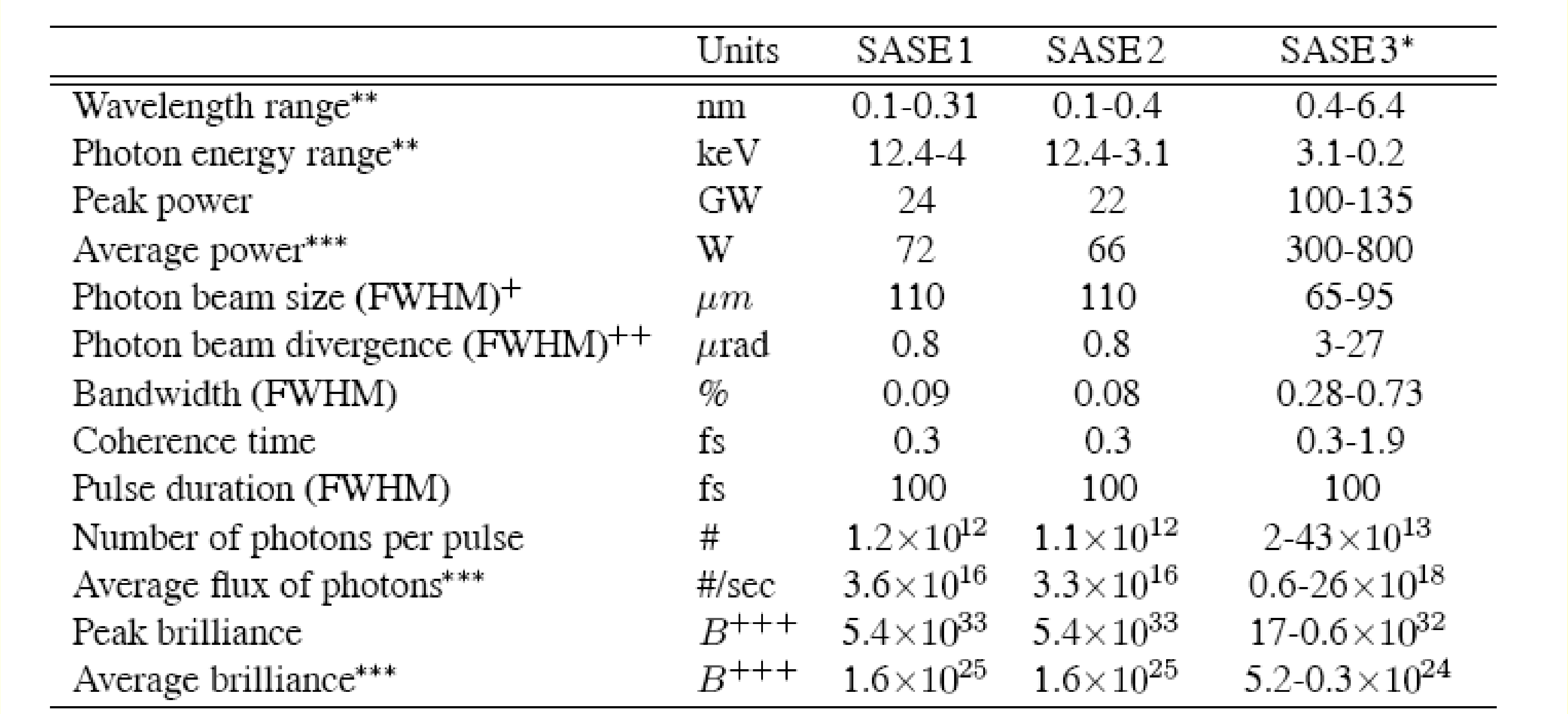
LCLS Stanford

Image of the FEL spot at 1.5 Å



http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx

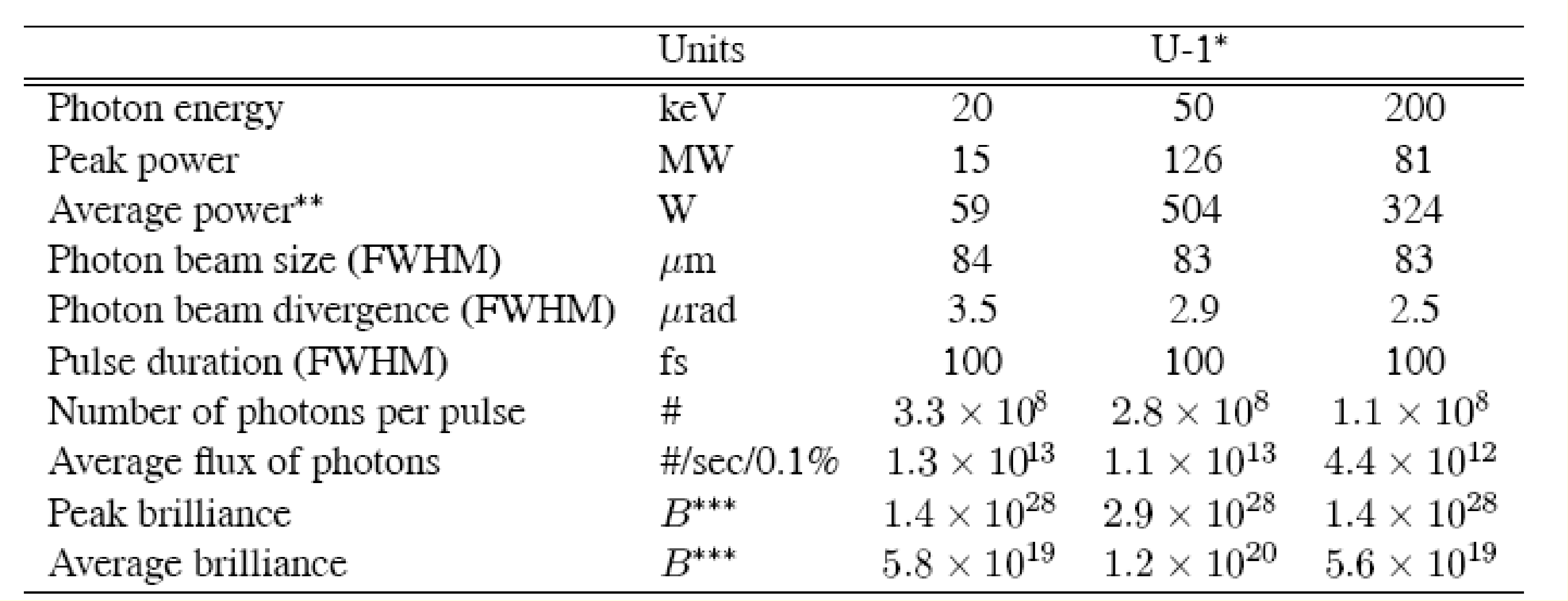
European X-FEL @ Hamburg



	Units	SASE 1	SASE 2	SASE 3*
Wavelength range**	nm	0.1-0.31	0.1-0.4	0.4-6.4
Photon energy range**	keV	12.4-4	12.4-3.1	3.1-0.2
Peak power	GW	24	22	100-135
Average power***	W	72	66	300-800
Photon beam size (FWHM)$^+$	μm	110	110	65-95
Photon beam divergence (FWHM)$^{++}$	μrad	0.8	0.8	3-27
Bandwidth (FWHM)	%	0.09	0.08	0.28-0.73
Coherence time	fs	0.3	0.3	0.3-1.9
Pulse duration (FWHM)	fs	100	100	100
Number of photons per pulse	#	1.2×10^{12}	1.1×10^{12}	$2\text{-}43\times10^{13}$
Average flux of photons***	#/sec	3.6×10^{16}	3.3×10^{16}	$0.6\text{-}26\times10^{18}$
Peak brilliance	B^{+++}	5.4×10^{33}	5.4×10^{33}	$17\text{-}0.6\times10^{32}$
Average brilliance***	B^{+++}	1.6×10^{25}	1.6×10^{25}	$5.2\text{-}0.3\times10^{24}$

European X-FEL @ Hamburg

Spontaneous emission



	Units	U-1*		
Photon energy	keV	20	50	200
Peak power	MW	15	126	81
Average power**	W	59	504	324
Photon beam size (FWHM)	μm	84	83	83
Photon beam divergence (FWHM)	μrad	3.5	2.9	2.5
Pulse duration (FWHM)	fs	100	100	100
Number of photons per pulse	#	3.3×10^8	2.8×10^8	1.1×10^8
Average flux of photons	#/sec/0.1%	1.3×10^{13}	1.1×10^{13}	4.4×10^{12}
Peak brilliance	B***	1.4×10^{28}	2.9×10^{28}	1.4×10^{28}
Average brilliance	B***	5.8×10^{19}	1.2×10^{20}	5.6×10^{19}