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Methoden moderner Röntgenphysik II: Streuung und Abbildung

Lecture 3

Vorlesung zum Haupt/Masterstudiengang Physik

SS 2014

G. Grübel, M. Martins, E. Weckert

Location:	Hörs AP, Physik, Jungiusstrasse
	Tuesdays 12.45 – 14.15
	Thursdays 8:30 – 10.00

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Methoden moderner Röntgenphysik II: Streuung und Abbildung

Vorlesung:	4 SWS: Dienstag und Donnerstag
Übungen:	2 SWS: Dienstag (wenn vereinbart)
Proseminar:	*für Batchelor Studierende*

8 Leistungspunkte für dieses Modul im Masterstudiengang

Tuesdays 12.45 – 14.15:
Thursdays 8.30 – 10.00: starting April 1, 2014

Tuesdays 14:30 – 16:00: *Tutorials/Übungen*

First Tutorial: ***April 15 in SemRm 4***

▪ Methoden moderner Röntgenphysik II: Streuung und Abbildung

Introduction
Overview, Introduction to X-ray scattering

X-ray Scattering Primer
Elements of X-ray scattering

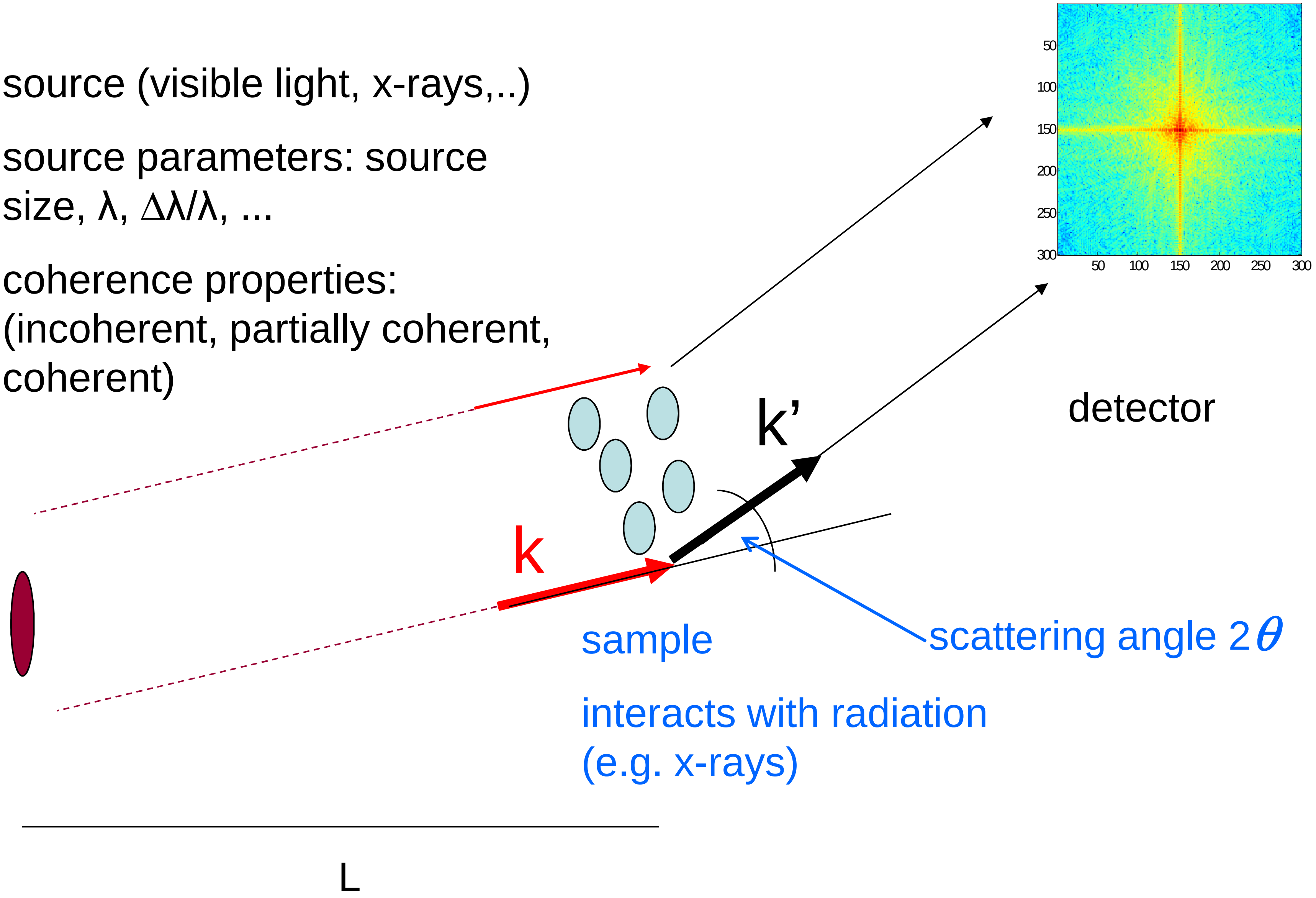
Sources of X-rays, Synchrotron Radiation Laboratory sources, accelerator bases sources

Reflection and Refraction
Snell’s law, Fresnel equations,

Kinematical Diffraction (I)
Diffraction from an atom, molecule, liquids, glasses,..

Kinematical Diffraction (II)
Diffraction from a crystal, reciprocal lattice, structure factor,..

Experimental Set-Up for Scattering Experiments



source (visible light, x-rays,..)

source parameters: source size, λ, Δλ/λ, ...

coherence properties: (incoherent, partially coherent, coherent)

detector

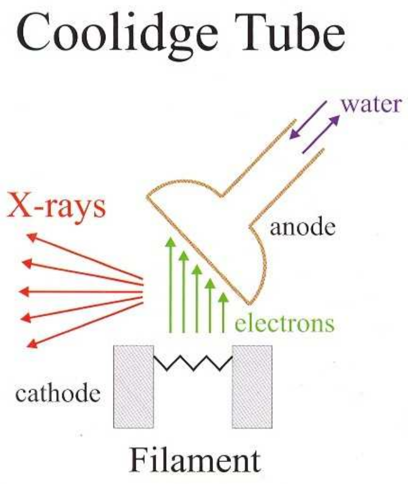
sample

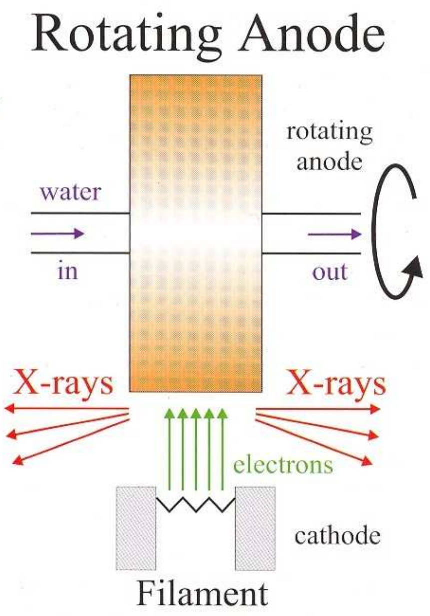
interacts with radiation (e.g. x-rays)

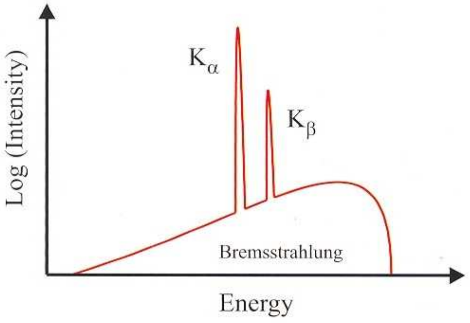
scattering angle 2θ

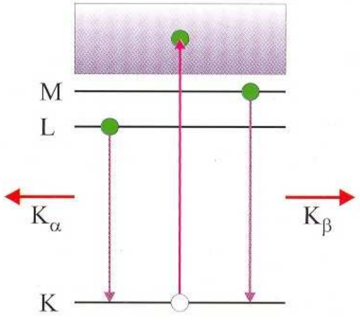
Sources of X-Rays

1895	discovered by W.C. Röntgen
1912	First diffraction experiment (v. Laue)
1912	Coolidge tube (W.D. Coolidge,GE)
1946	Radiation from electrons in a synchrotron, GE, Physical Review, 71,829(1947)

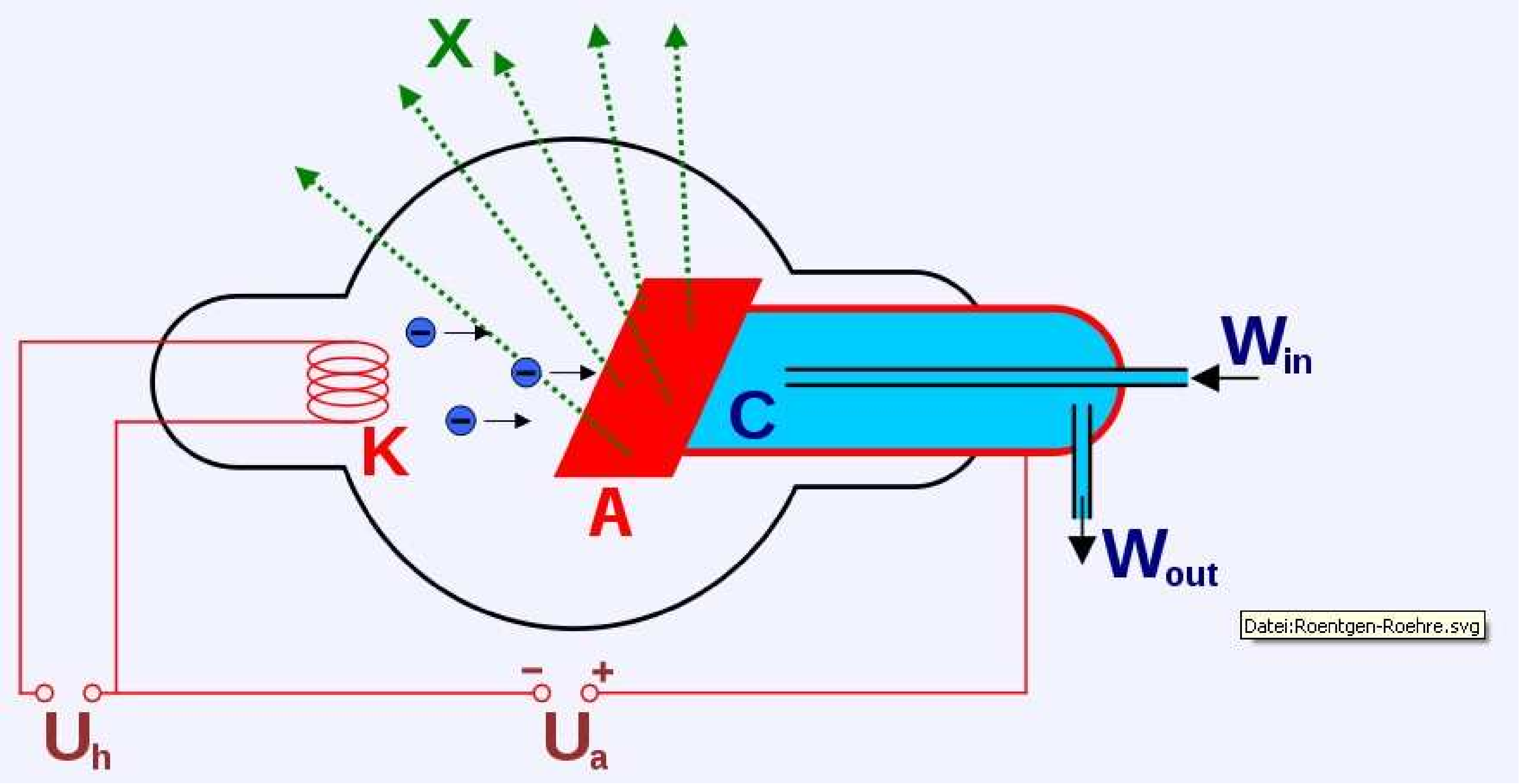




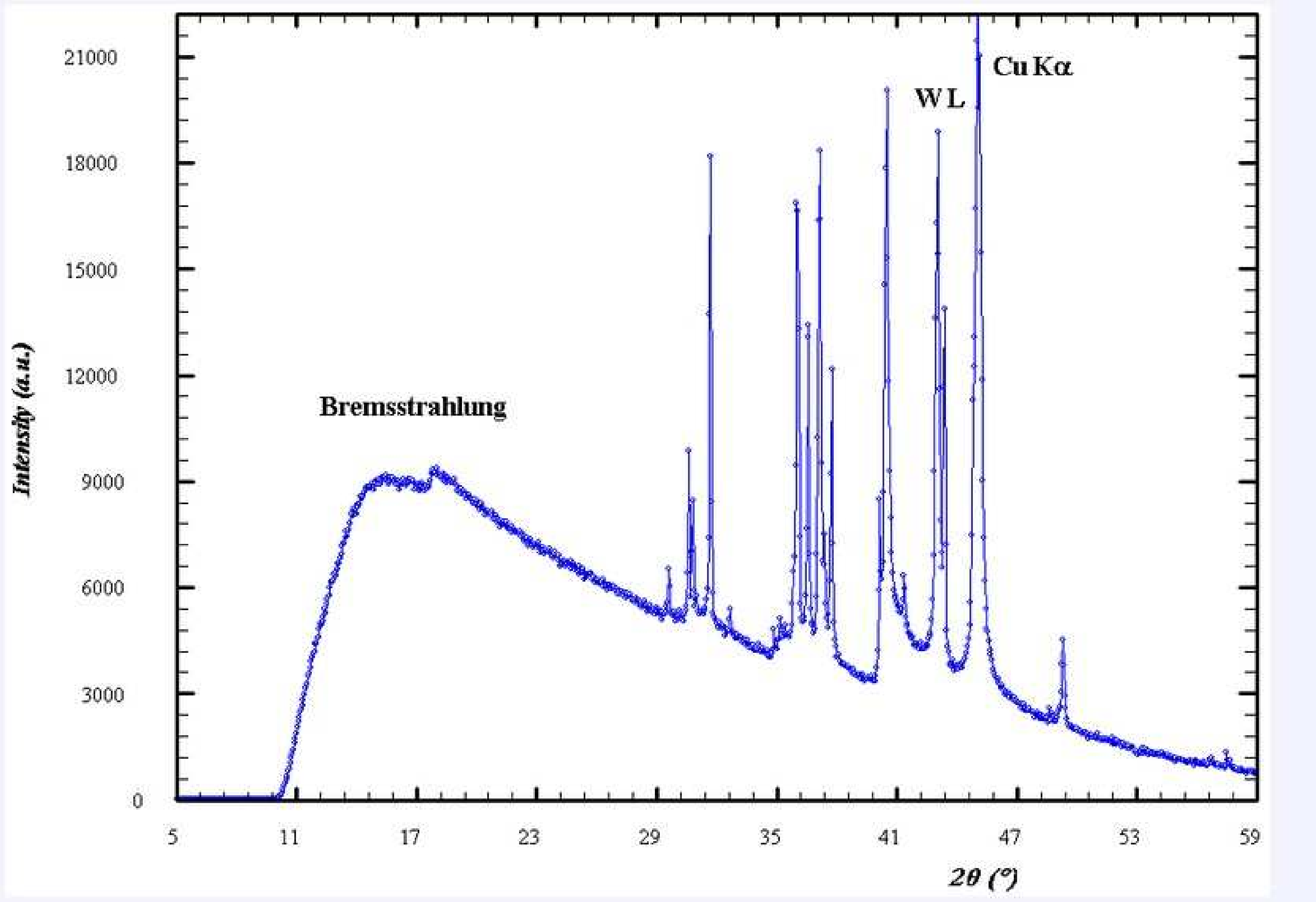




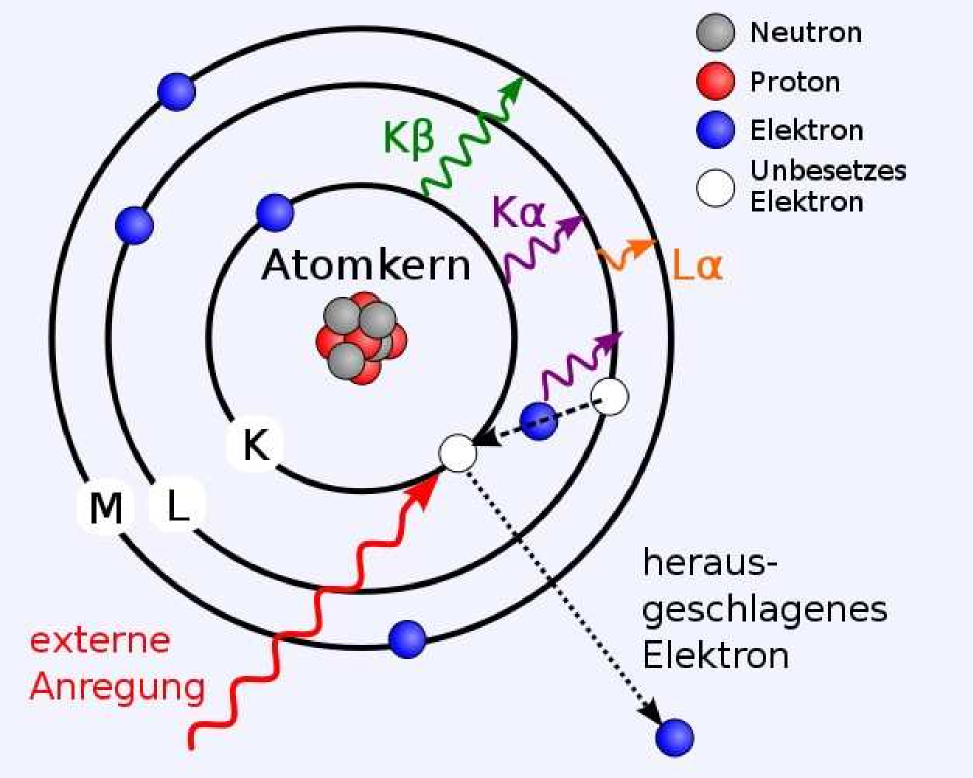
- X-ray Tube

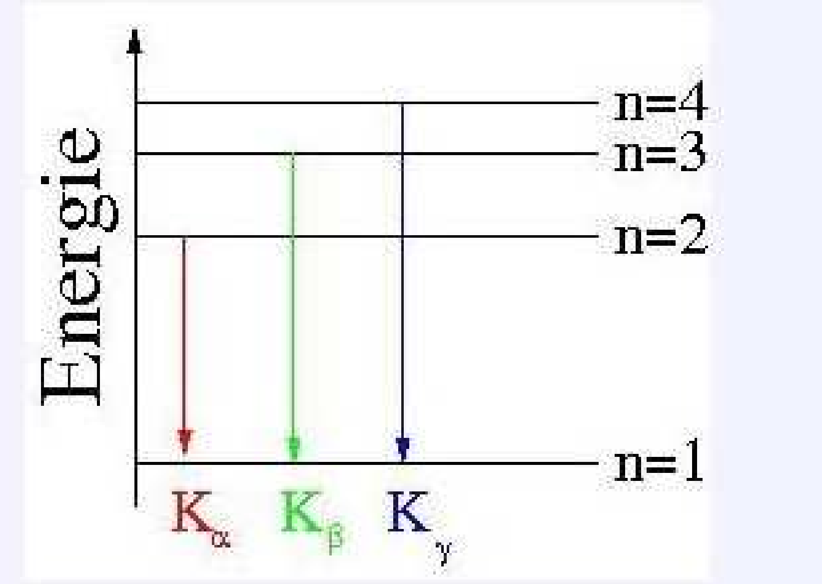


X-ray Tube

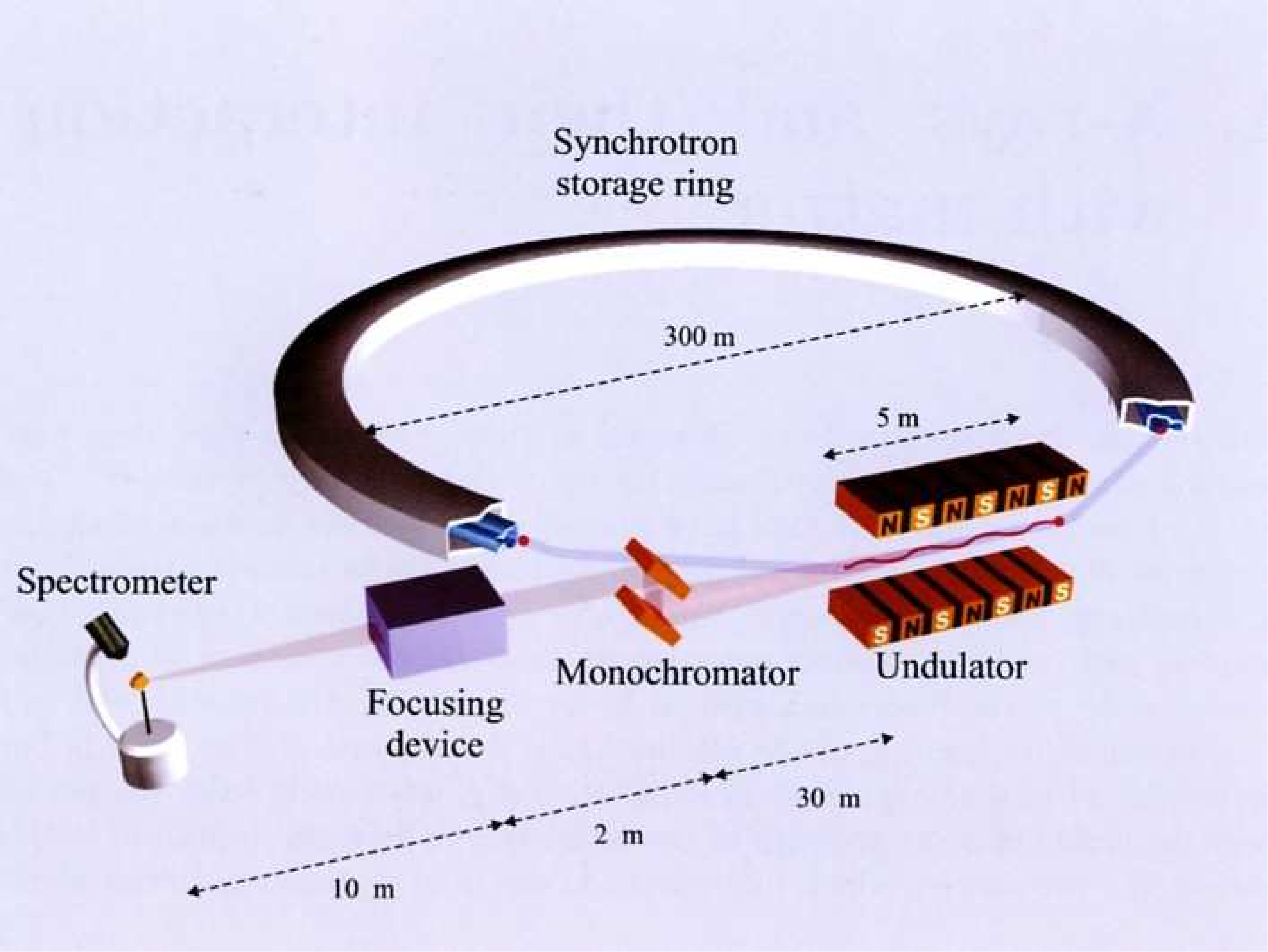

Intensity (a.u.)
21000
18000
15000
12000
9000
6000
3000
0
Bremsstrahlung
W L
Cu Kα
5
11
17
23
29
35
41
47
53
59
2θ (°)

X-ray Tube


Neutron
Proton
Elektron
Unbesetzes Elektron
Kβ
Kα
Lα
Atomkern
K
L
M
externe Anregung
heraus-geschlagenes Elektron


Energie
n=4
n=3
n=2
n=1
K_α
K_β
K_γ

Synchrotron Radiation Storage Ring



- Circular Accelerators

Cyclotron
Microtron
Synchrotron
Storage Ring

Cyclotron

- Proposed in 1930 by E.O. Lawrence
- Electrons cirulate in a homogeneous magnetic field B
- Frequency for one cycle is given by

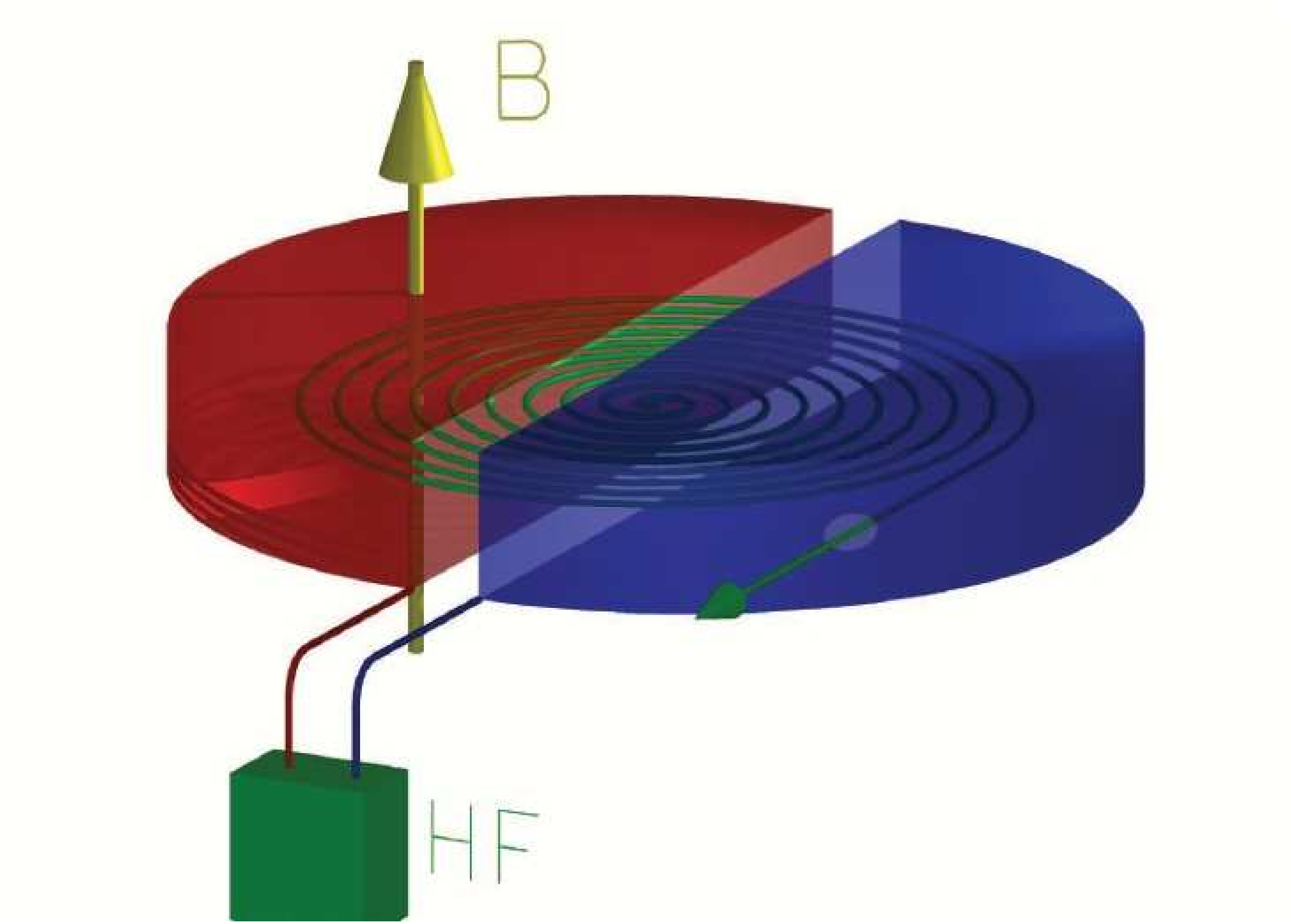
$$\omega_c = (e/m)\ B_z$$

- For non-relativistic electrons ω_c is independent of the velocity v (v/c < 0.15)
- At high energies the mass changes and the frequency of the field needs to be adapted.

Example: E_{kin}=10keV = eU = $m_e v_e^2/2 \Rightarrow\ v_e/c = 0.2$!

- Electrons at 10 keV are already relativistic!

- Cyclotron



- Cyclotron

Zyklotron der Uni Bonn

- # Microtron

  - Acceleration with a linear accelerator
  - Circular bend similar to a cyclotron
  - Bending radius R in magnetic field B for relativistic particles

    Lorentz Force = Radial Force

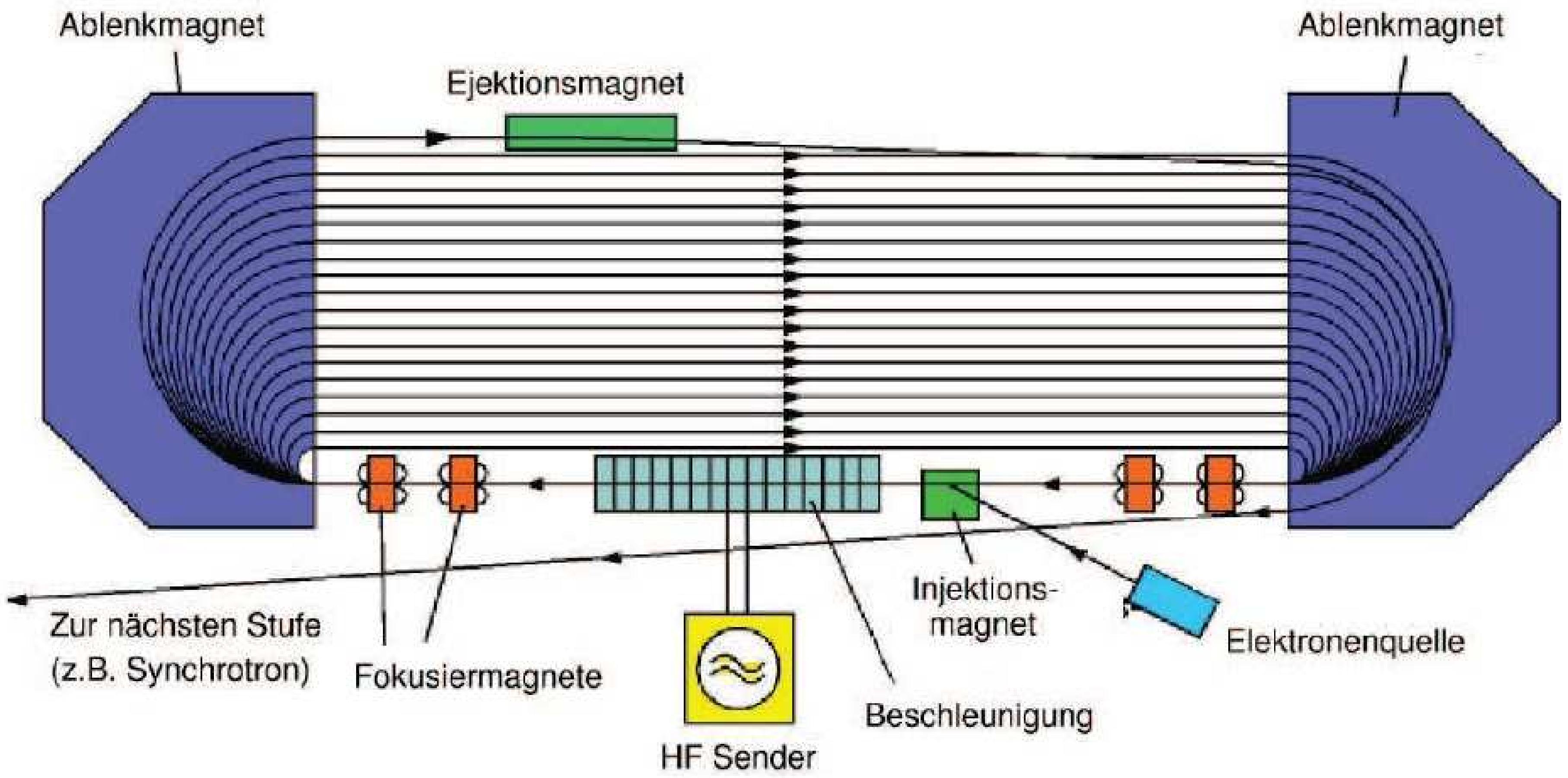
    $$evB = m v^2/R$$

    $$\Rightarrow R = mv/eB = vmc^2/ec^2B = (v/ec^2B)\ E$$

  - Acceleration such that electrons are in phase with RF field
  - Energies up to 100 MeV can be reached

    Example: BESSY II

- Microtron


Ablenkmagnet
Ablenkmagnet
Ejektionsmagnet
Injektions-magnet
Elektronenquelle
Zur nächsten Stufe
(z.B. Synchrotron)
Fokusiermagnete
HF Sender
Beschleunigung

- Microtron

- # Synchrotron

o For relativistic particles $v \cong c$ in a B field the radius is given by

$$R = E/ecB$$

o For E > 1 GeV and B = 5 T: R > several meter.

o Technically difficult.

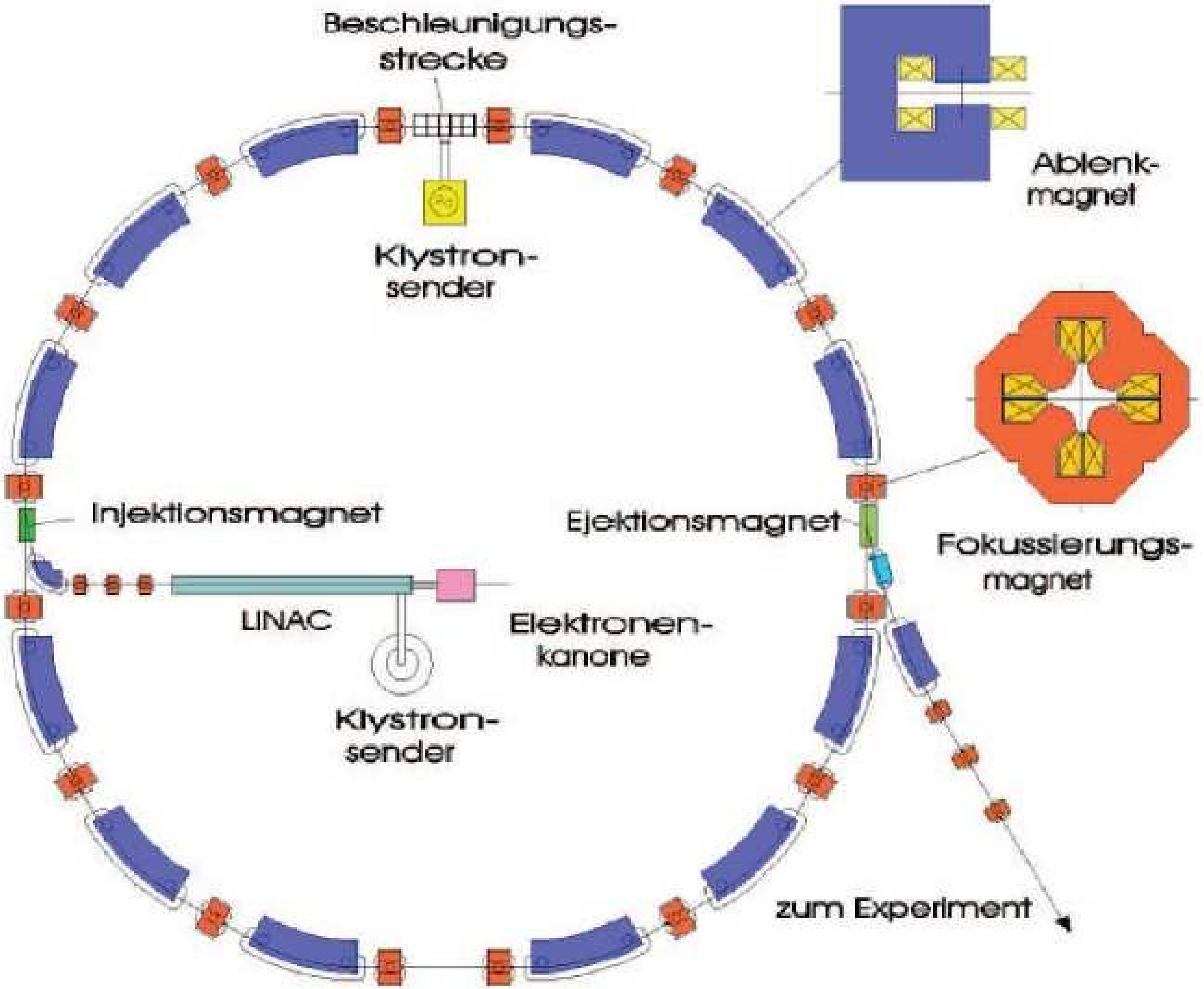
o Enforce trajectory with constant radius.

Bends in small, local magnets.

E/B = const. ⇒ synchroneous ramping of E and B

⇒ Synchrotron

- Synchrotron



Storage Rings

o Modern synchrotron radiation sources are built as storage rings

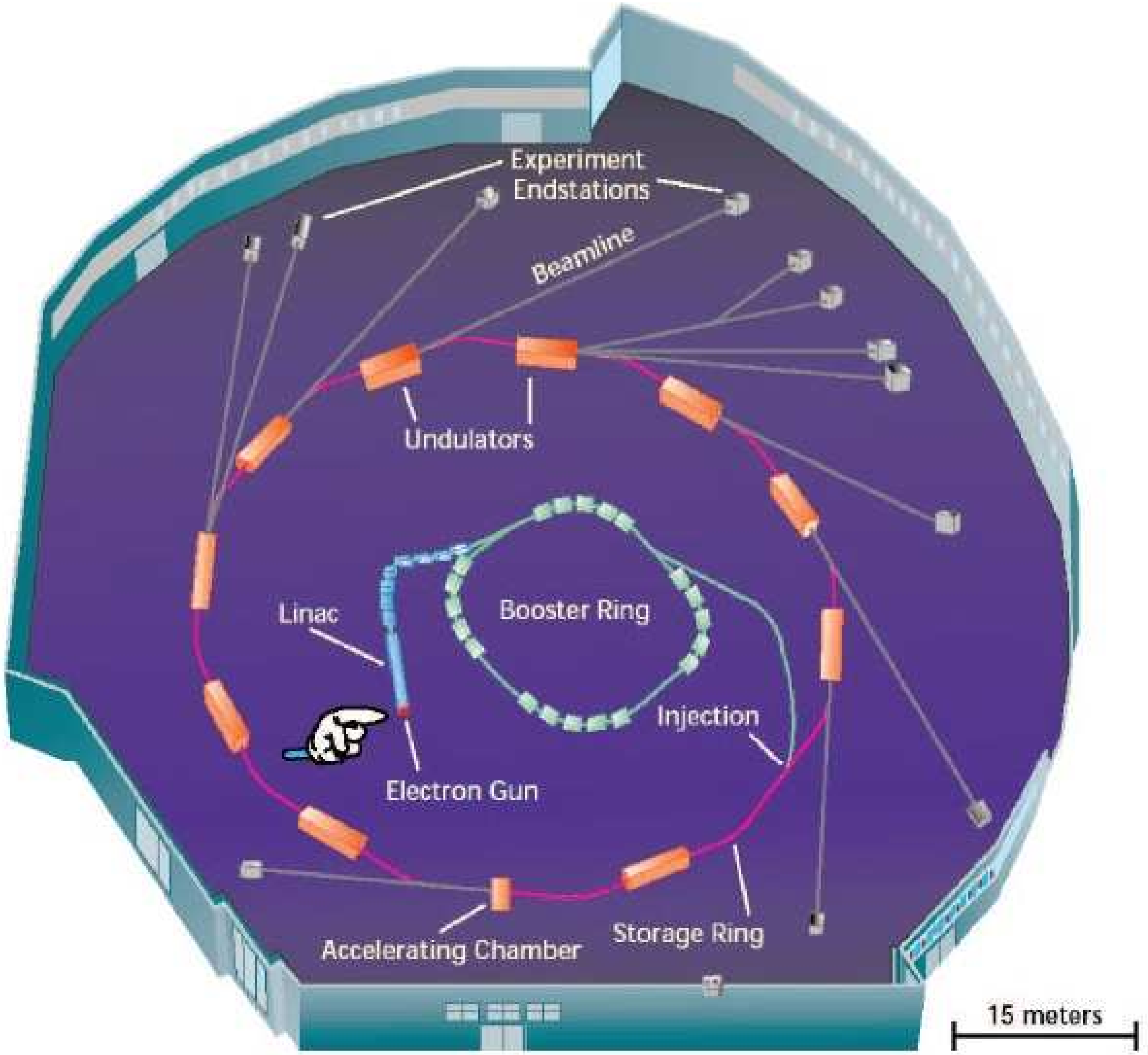
o Synchrotron cannot operate at E=0 since it requires B=0.
⇒ Use LINAC or Microtron as pre-accelerator
Use synchrotron to reach the final energy E
Use storage ring to keep electrons at energy

o The storage ring supplies the energy lost by radiation in each turn.

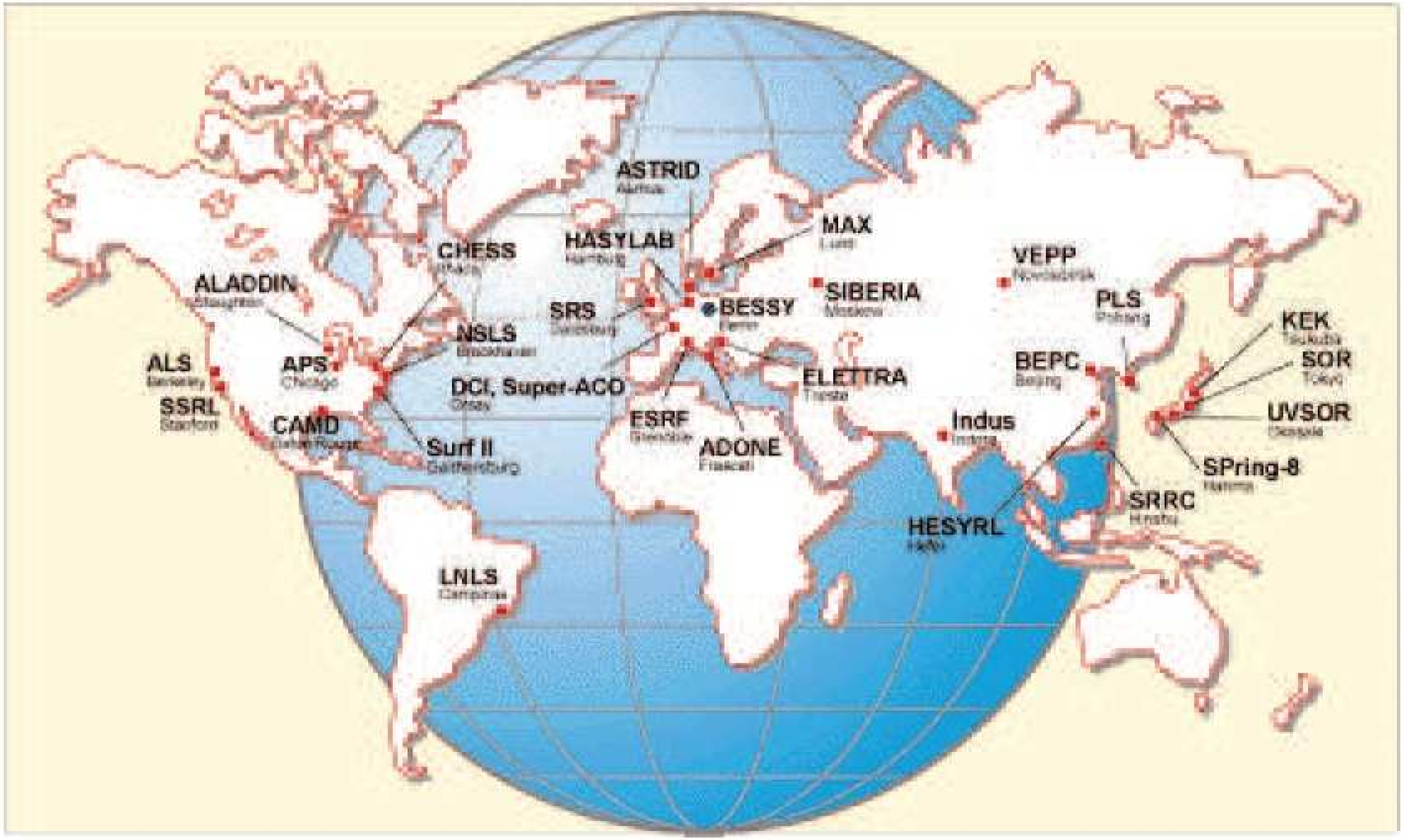
o Typical parameters: Lifetime: up to 30 h Current: 100 – 500 mA
o Current losses through interaction with residual gas ⇒ UHV

o Current supplied in bunches.

- Storage Rings



- ## Storage Rings



- # Photos machines

four

The ~~three~~ largest and most powerful synchrotrons in the world

APS, USA

ESRF, Europe-France

Spring-8, Japan

PETRA III (DESY)

- # Synchrotron Radiation Primer

Radiation of a non-relativistic, accelerated particle:

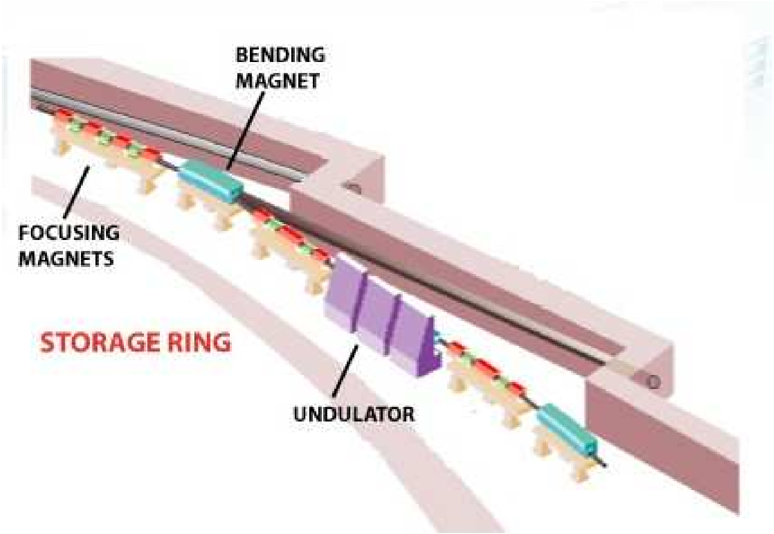
$$P = (e^2/6\pi\varepsilon_0 m_0^2 c^3)\ \ (dp/dt)^2$$

Angular distribution resembles the one of a Hertz dipol:

$$(dP/d\Omega) = (e^2/16\pi^2\varepsilon_0 m_0^2 c^3)\ \ (dp/dt)^2\ \sin^2(\psi)$$

Radiation is emitted (similar to the dipole) in the direction perpendicular to the acceleration

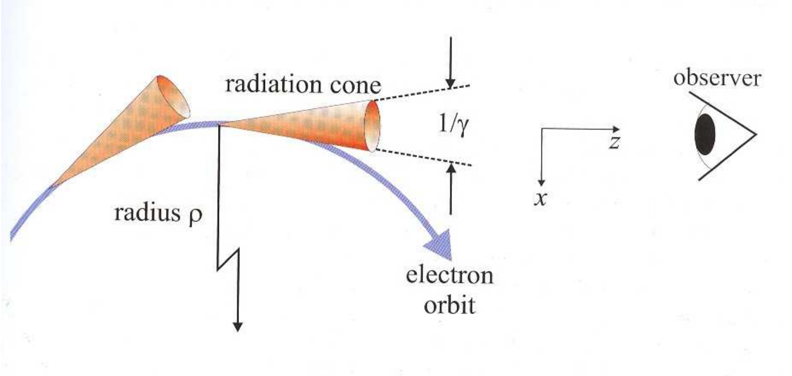
Synchrotron Radiation Primer



Energy E_e of an electron at speed v:

$$E_e = mc^2/\text{sqrt}\{(1-(v/c)^2\} = \gamma\, mc^2$$

For 5GeV and mc^2=0.511 MeV get $\gamma \approx 10^4$



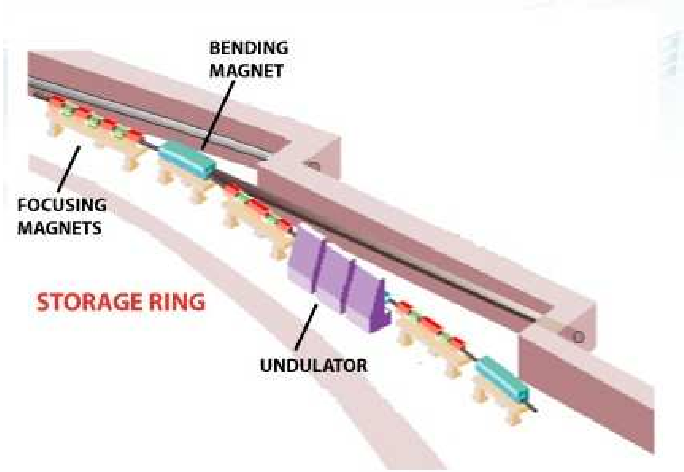
Centrifugal=Lorentz force yields for radius:

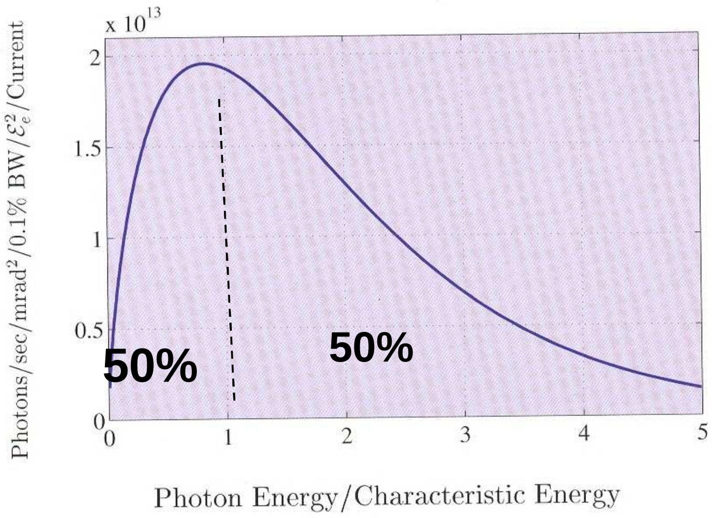
$\rho = \gamma mc / eB = 3.3\ E[\text{GeV}]/B[\text{T}] \approx 25$ m

$E_e \approx 6$ GeV, B=0.8 T

Opening angle is of order $1/\gamma \approx 0.1$ mrad

▪ Bending magnets





Characteristic energy $\hbar\omega_c$ for bend or wiggler:

$\hbar\omega_c$ [keV] = 0.665 E_e^2[GeV] B(T) $\approx$20 keV

Flux ~ E^2

Energy loss by synchrotron radiation per turn:

ΔE [keV] = 88.5 E^4[GeV]/ρ[m]

ρ : radius of curvature

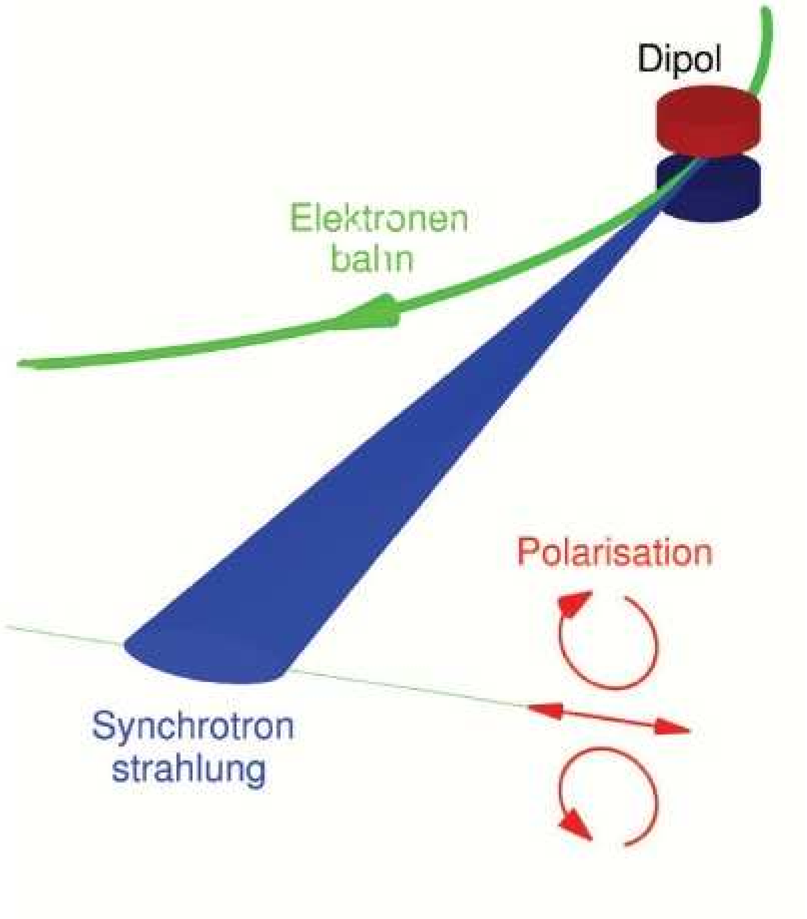
For 1 GeV and ρ=3.33 m: ΔE =26.6 keV/turn

For I=500 mA $\equiv$ 0.5 Cb/s =0.5x6.25x10^{18} e^-/s

➔P= 0.5x6.25x10^{18} e^-/sx26.6 keV

=8.3125x10^{22}x1.6x10^{-19} = 13.3 KJ/s =13.3 KW

▪



Polarisation

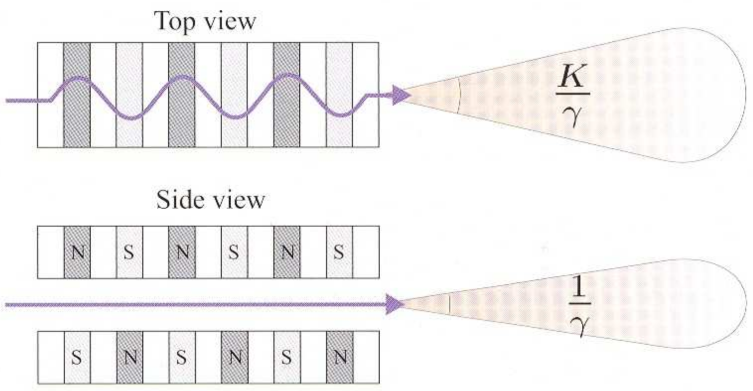
- Synchrotron radiation is polarized nearly in the plane of the orbit.

- Above and below the orbital plane the polarization is circular.

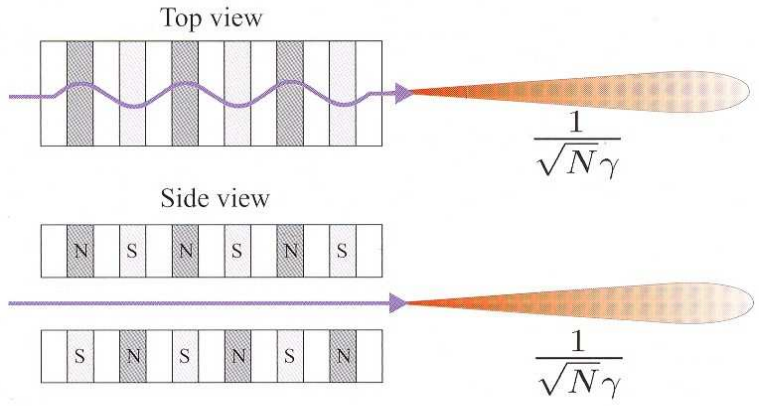
- Important applications for magnetic X-ray scattering.

Insertion Devices (wigglers and undulators)

(a) Wiggler



(b) Undulator



k : so-called K-parameter of undulator

<u>Wiggler:</u>

P[kW] = $0.633E_e^2$[GeV] B^2[T] L[m] I[A]

Flux ~ E^2 x N

N: number poles

<u>Undulator:</u>

k = eB / mc k_u = 0.934 λ_u [cm] Bo[T]

with λ_u undulator period

<u>undulator fundamental:</u>

$\lambda_0 = \lambda_u/2\gamma^2 \{(1+ k^2/2 + \cancel{(\gamma\theta)})\}$

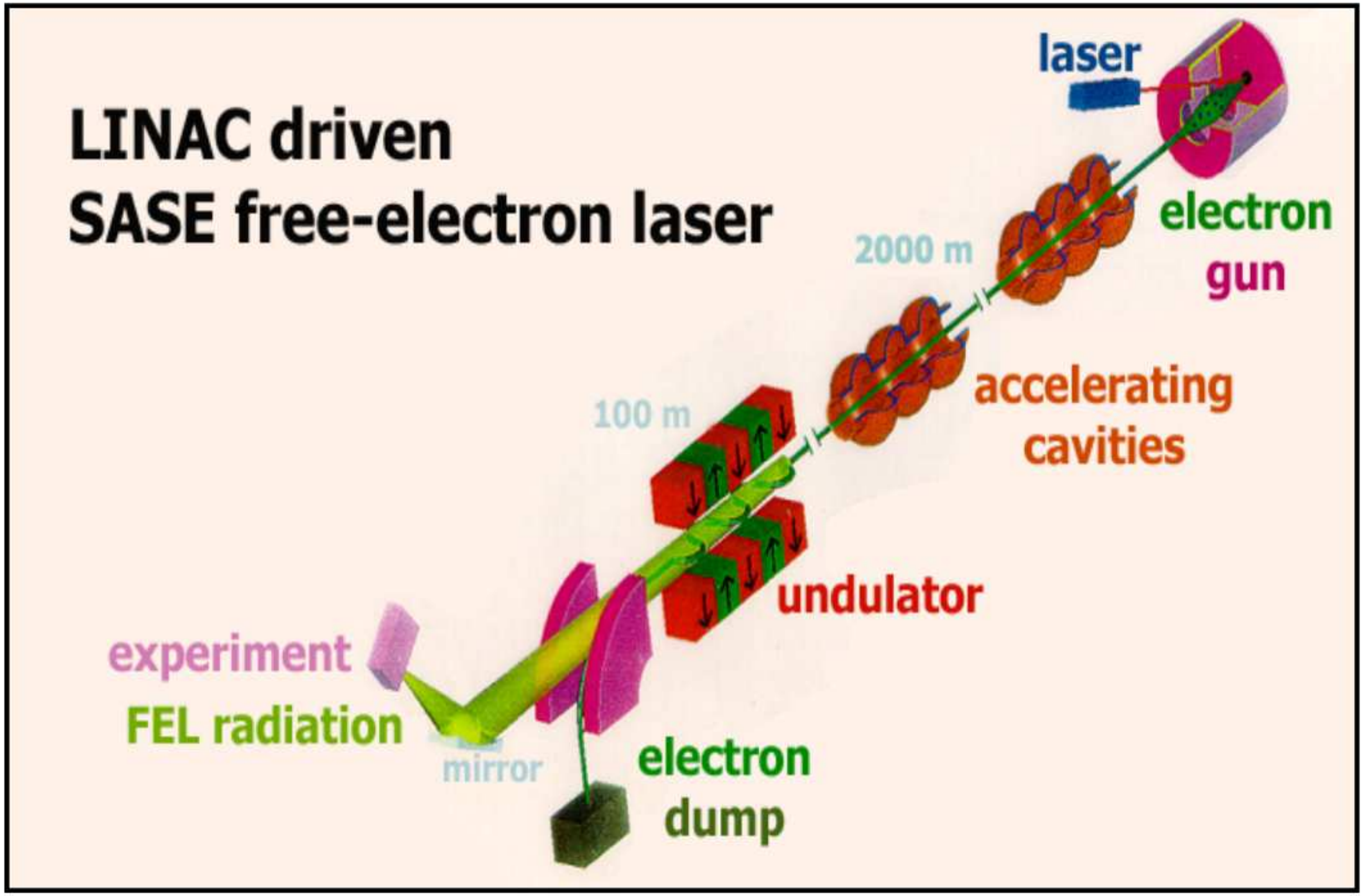
on axis

Flux ~ E^2 x N^2

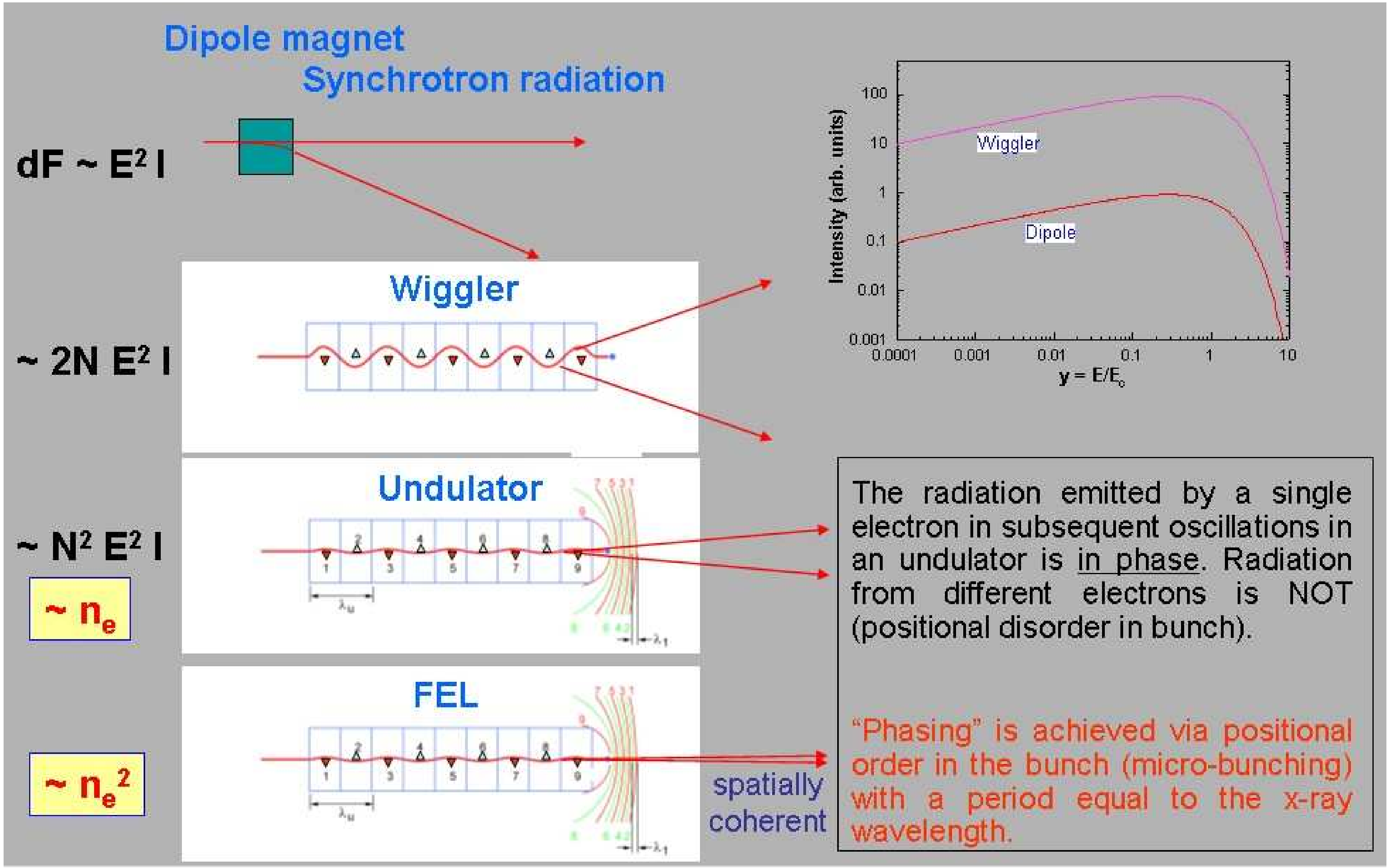
<u>bandwidth:</u>

$\Delta\lambda/\lambda$ ~ 1/nN

- Free Electron Lasers (FELs)



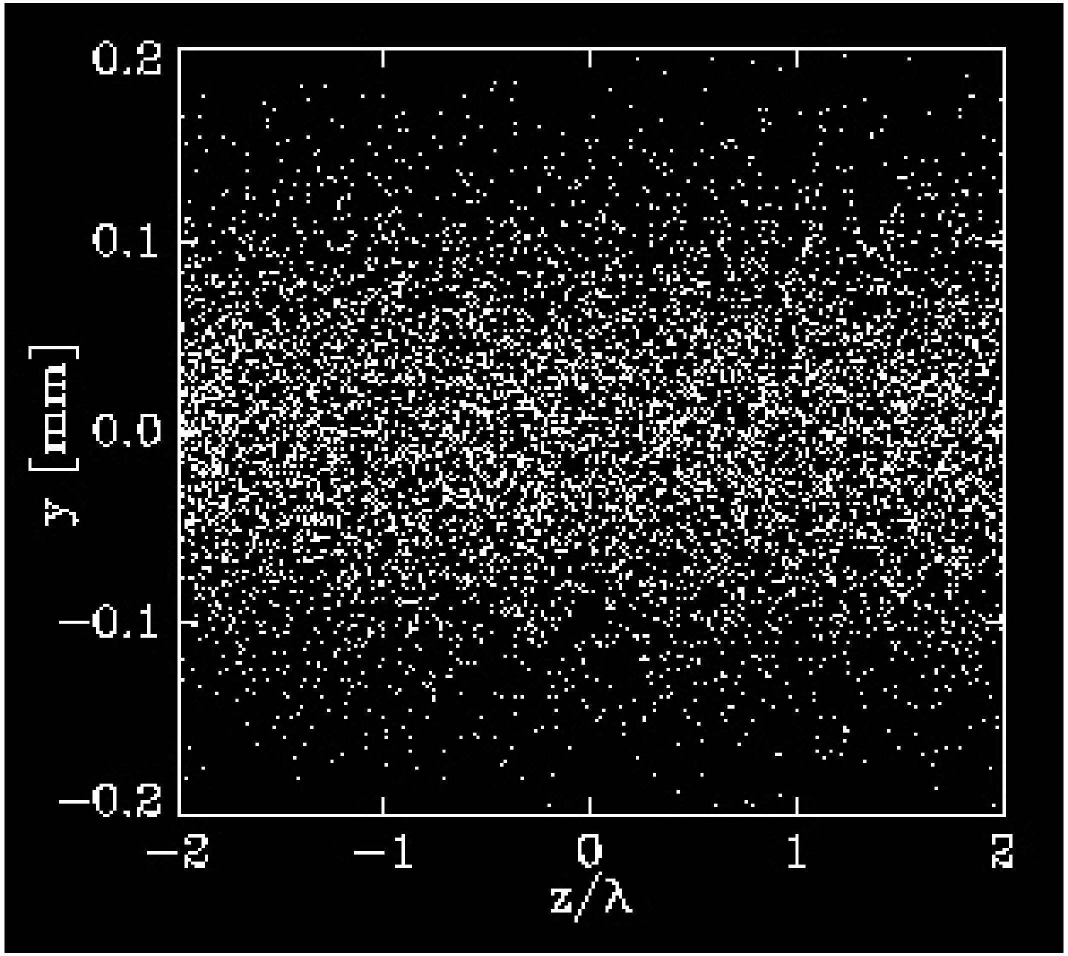
Synchrotron and FEL sources



The radiation emitted by a single electron in subsequent oscillations in an undulator is in phase. Radiation from different electrons is NOT (positional disorder in bunch).

“Phasing” is achieved via positional order in the bunch (micro-bunching) with a period equal to the x-ray wavelength.

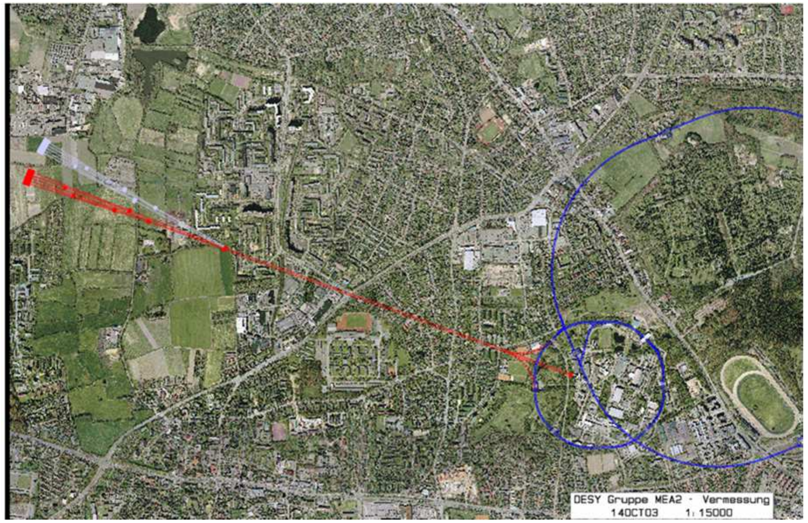
- Electron bunching

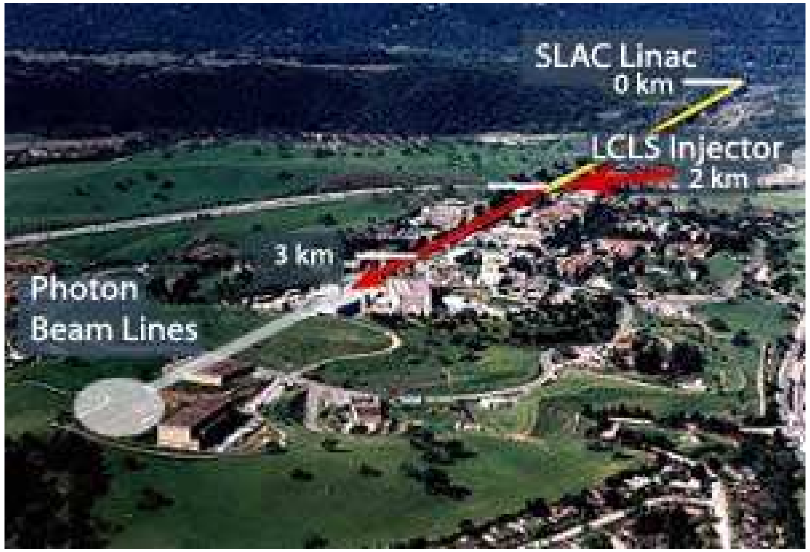


GENESIS – simulation for TTF parameters

Courtesy Sven Reiche (UCLA)

- # VUV and X-Ray FELs





Brilliance

$$B = \frac{\text{photons}}{\text{s mm}^2\ \text{mrad}^2\ 0.1\%\ \text{BW}}$$