▪

Methoden moderner Röntgenphysik II: Streuung und Abbildung

Lecture 3

Vorlesung zum Haupt/Masterstudiengang Physik

SS 2013

G. Grübel, M. Martins, E. Weckert

Location: Hörs AP, Physik, Jungiusstrasse

Tuesdays 12.45 – 14.15

Thursdays 8:30 – 10.00

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 4, 2013

Tuesdays 14:30 – 16:00: *Tutorials/Übungen*
Organisation-1st meeting: April 9, 2013 in SemRm 4
First Tutorial: April 16 in SemRm 4

Methoden moderner Röntgenphysik II: Streuung und Abbildung

Gerhard Grübel (GG), Thomas Schneider (TS), Oliver Seeck (OS),
Stephan Roth (SR), Hermann Franz (HF)

4.4. – 16.5.	Basics of X-ray physics	(GG)
14.5.	Site Visit	
28.5.-13.6.	Surfaces and Interfaces	(OS)
18.6.-27.6.	Biology	(TS)
2.7.-11.7.	Soft Matter	(SR)

Site Visit: May 14, 2 pm at the DESY/Bahrenfeld site
Building 25f (Cafeteria)

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,..

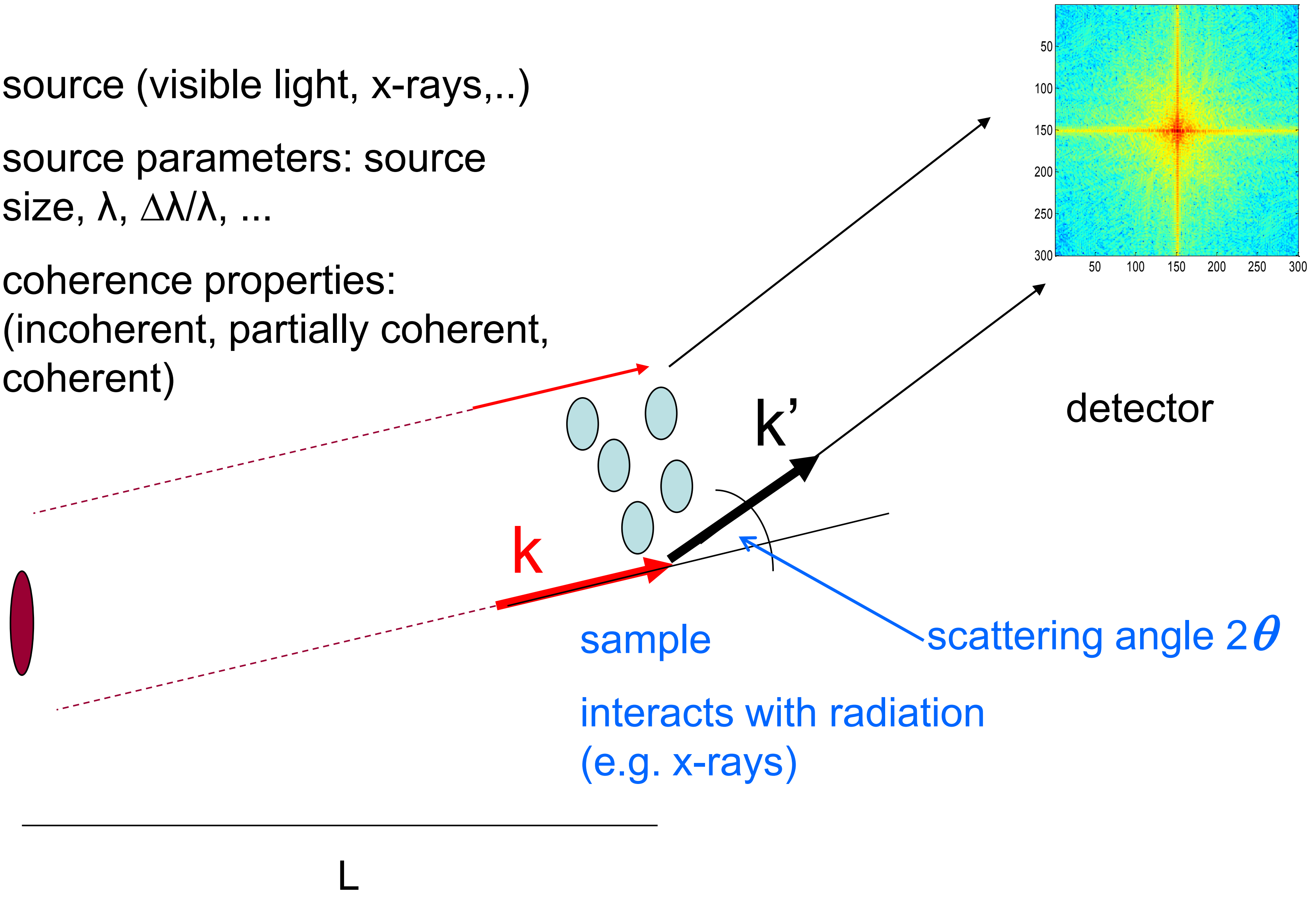
Kinematical Diffraction (II)
Diffraction from a crystal, reciprocal lattice, structure factor,..

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

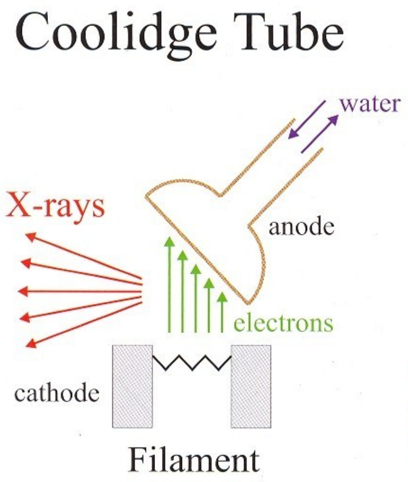
sample

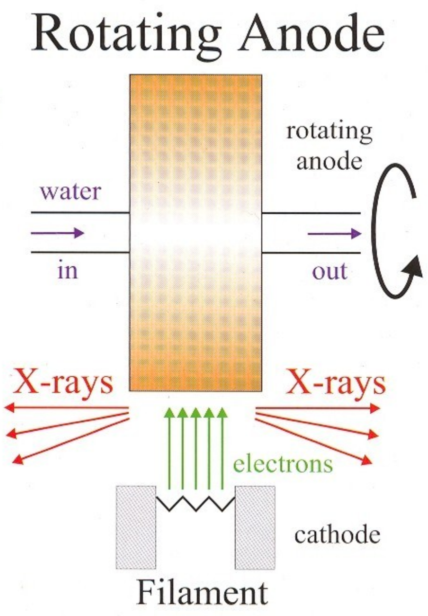
scattering angle 2θ

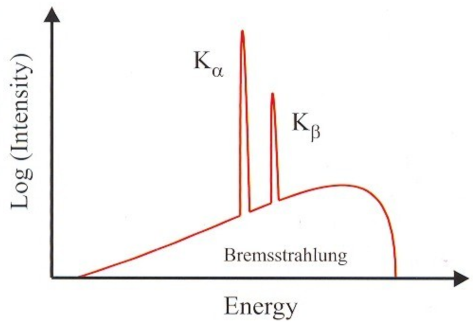
interacts with radiation (e.g. x-rays)

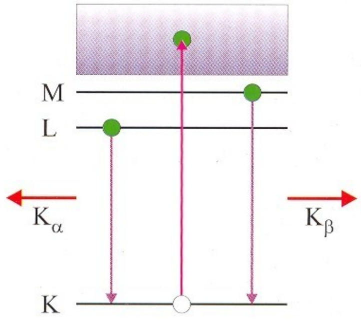
Sources of X-Rays

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)

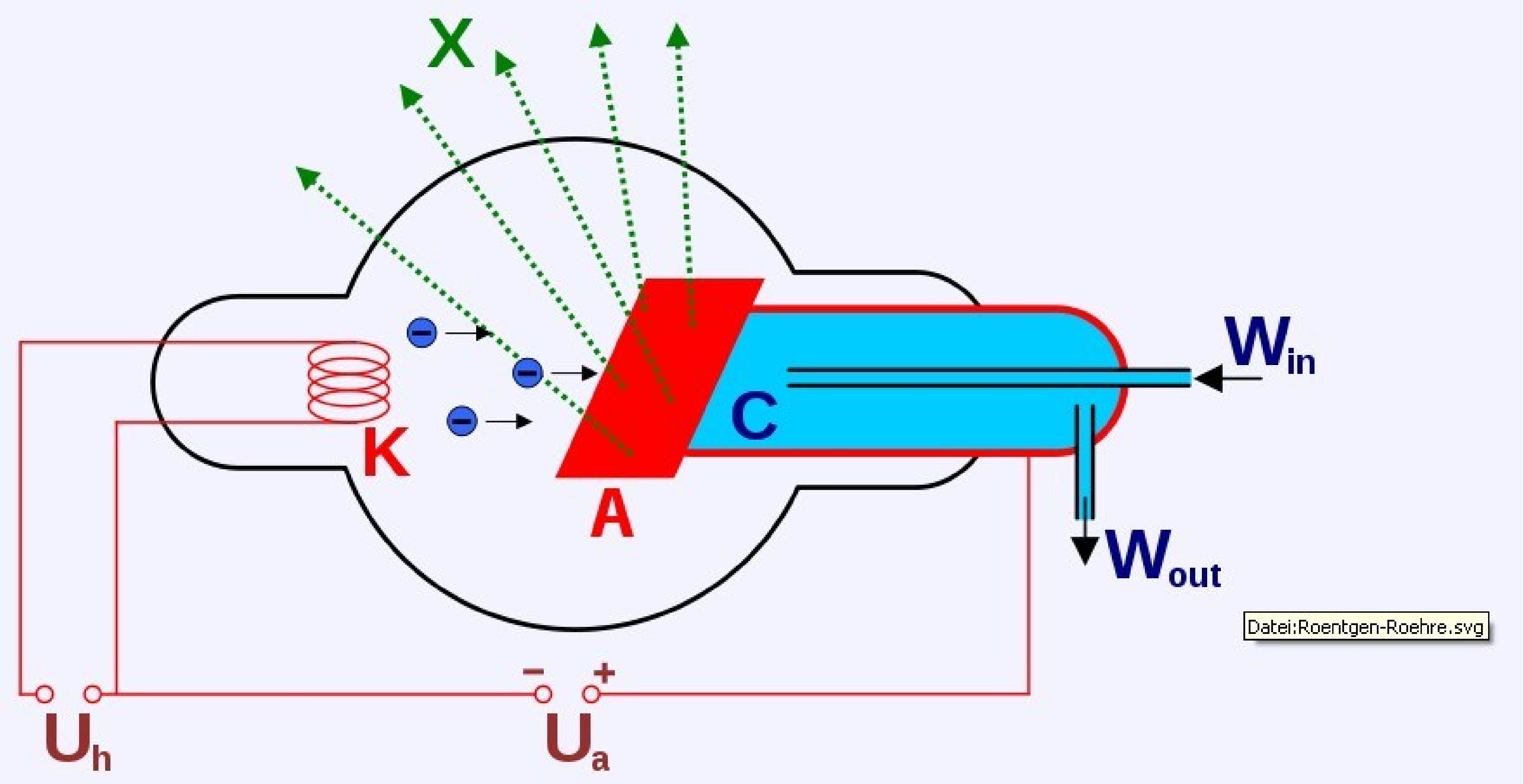




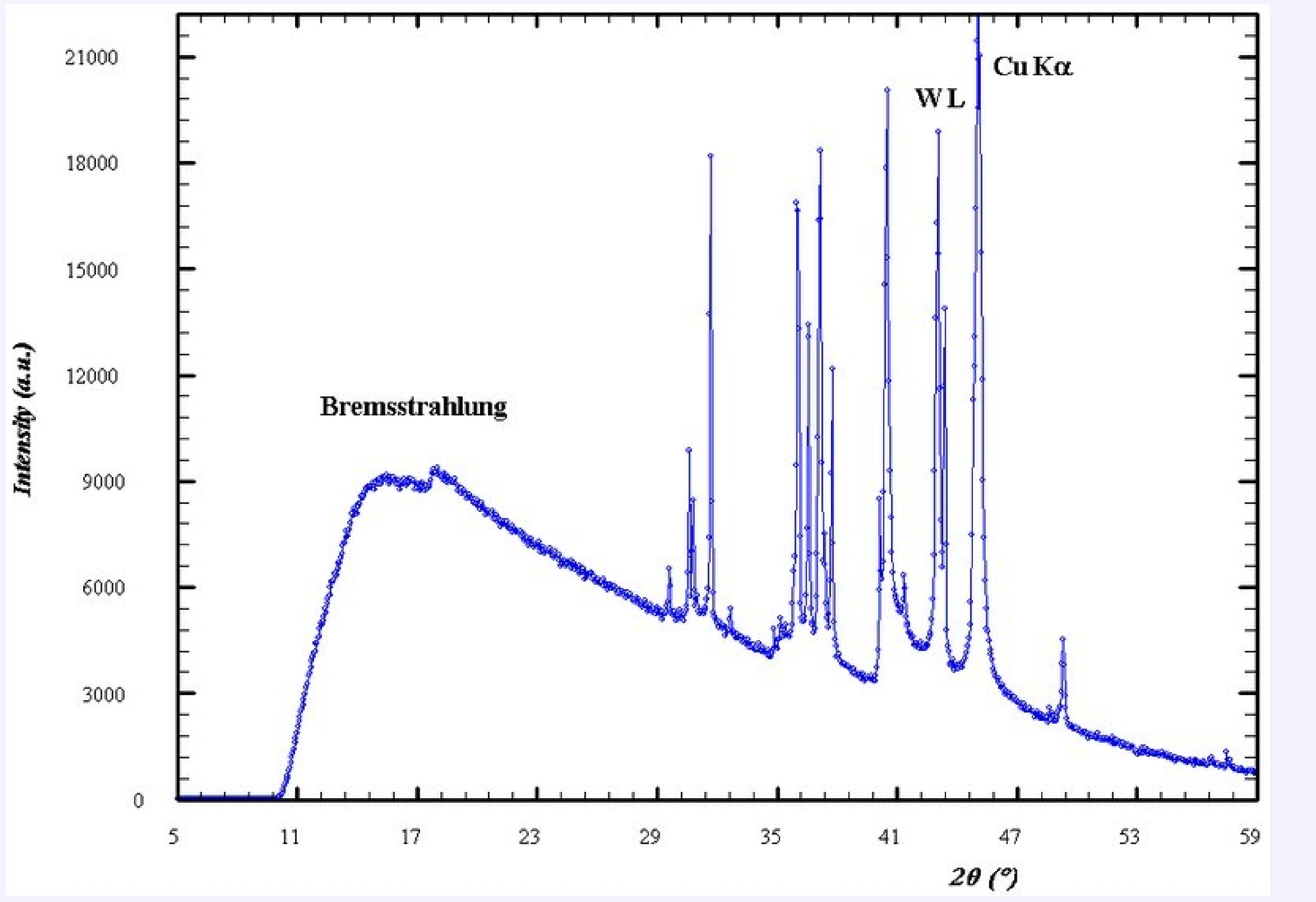




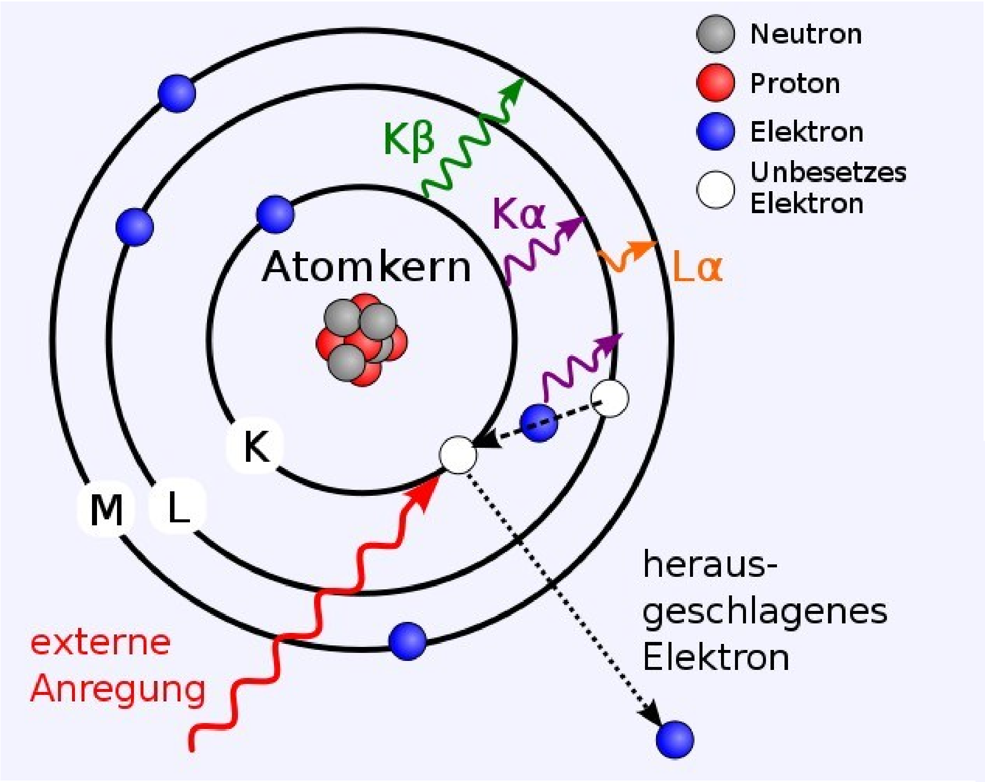
X-ray Tube



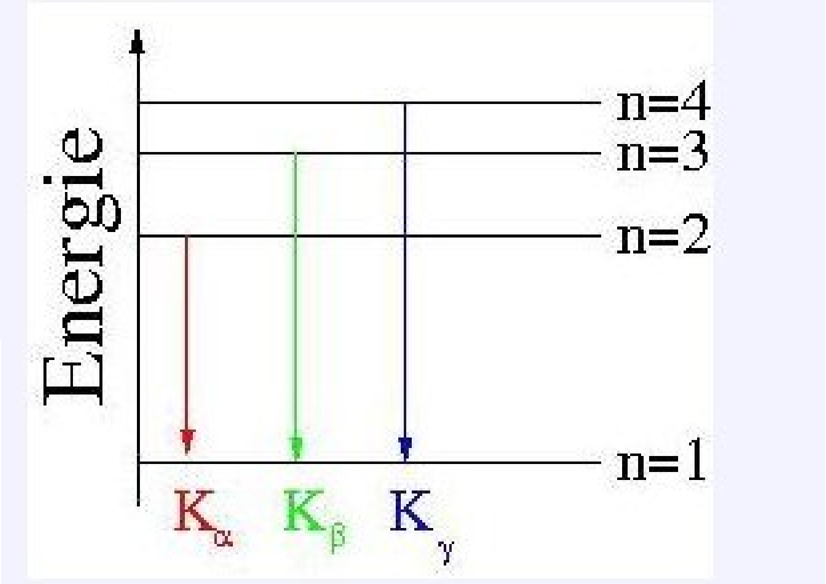
- X-ray Tube


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

X-ray Tube

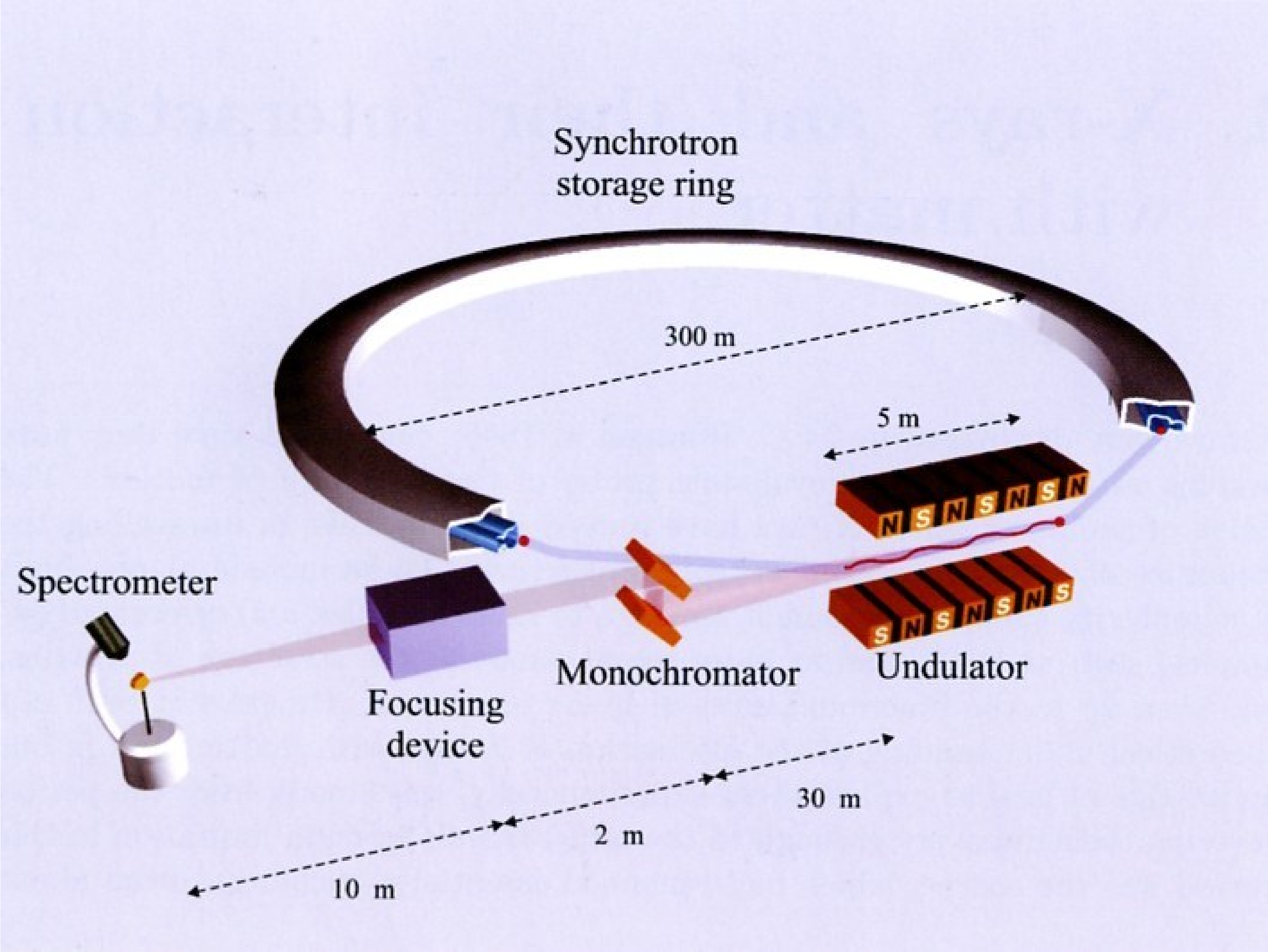


Neutron
Proton
Elektron
Unbesetzes Elektron
Kβ
Kα
Lα
Atomkern
K
L
M
externe Anregung
heraus-geschlagenes Elektron



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

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

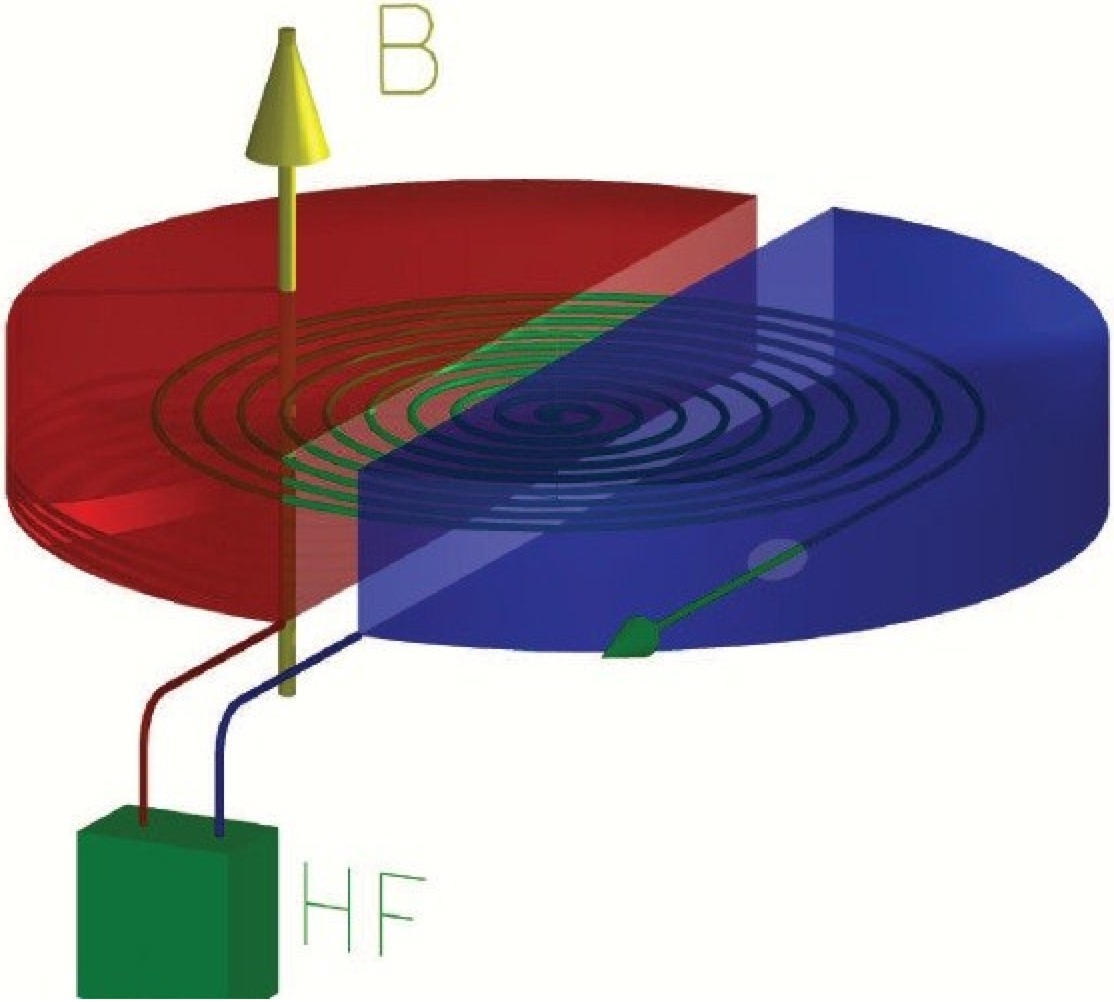
$$\omega_c = (e/m)\ B_z$$

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

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

- o 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

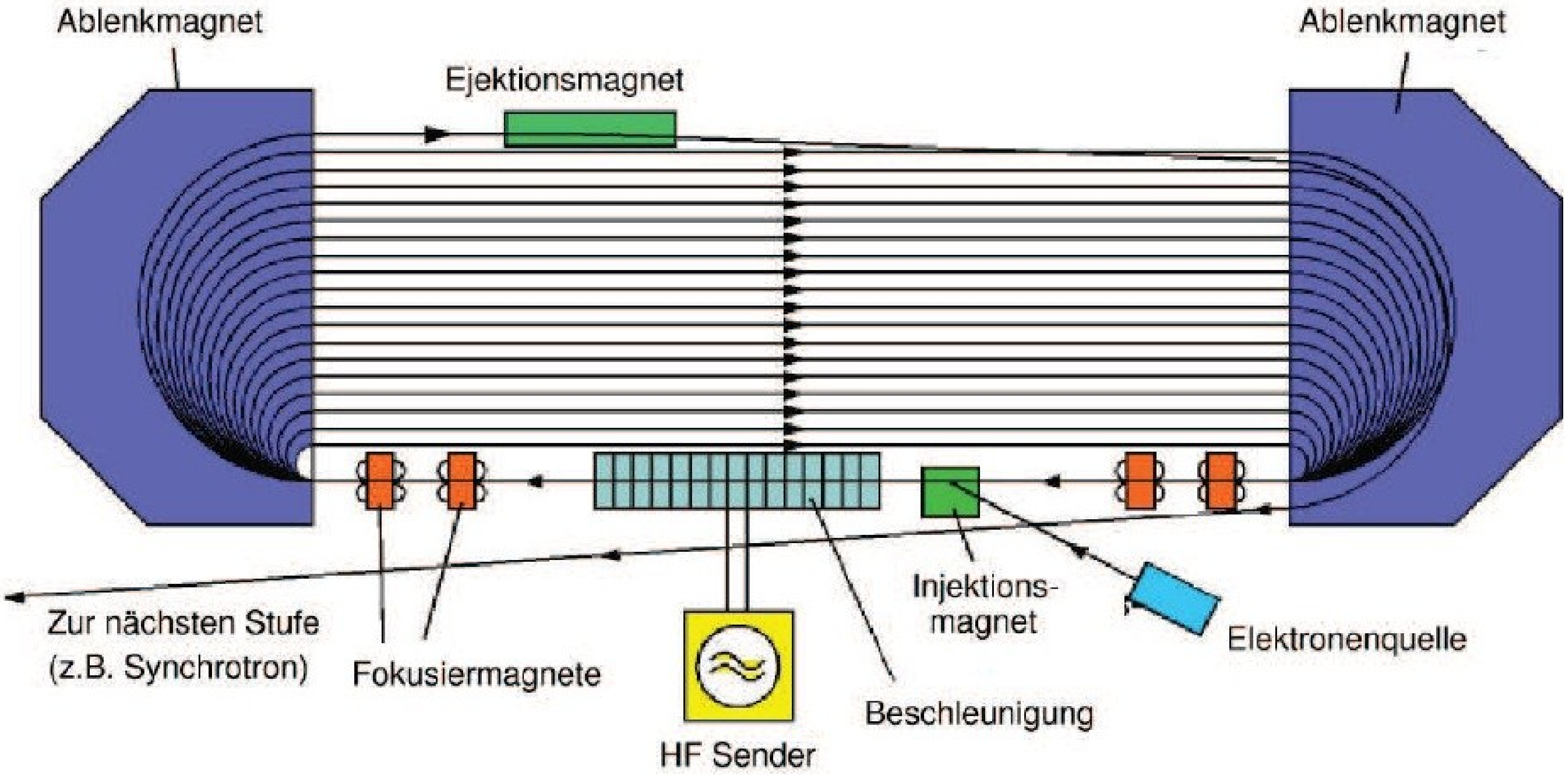
$$evB = m\,v^2/R$$

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

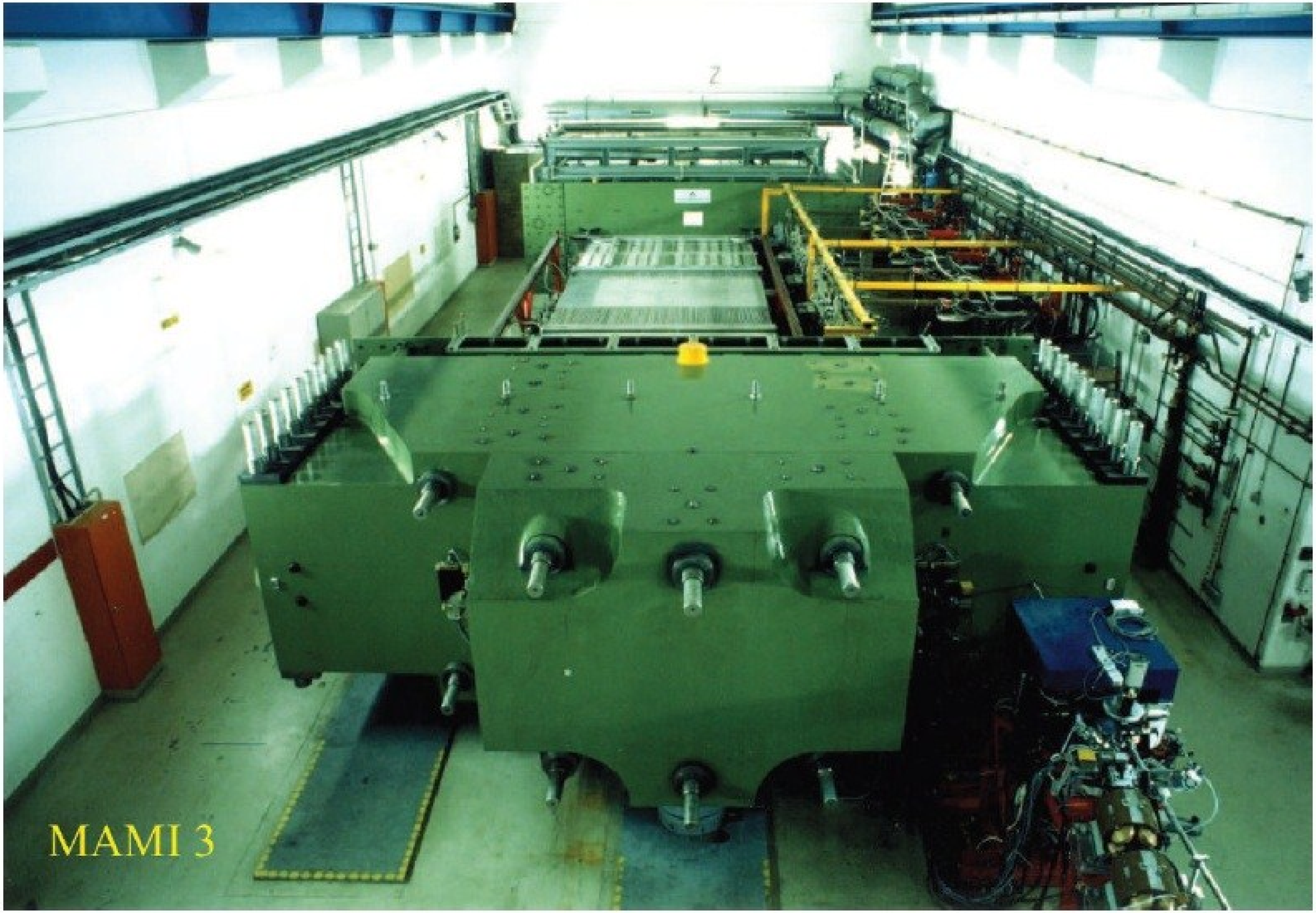
- Acceleration such that electrons are in phase with RF field
- Energies up to 100 MeV can be reached

Example: BESSY II

- # Microtron


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

- # 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.

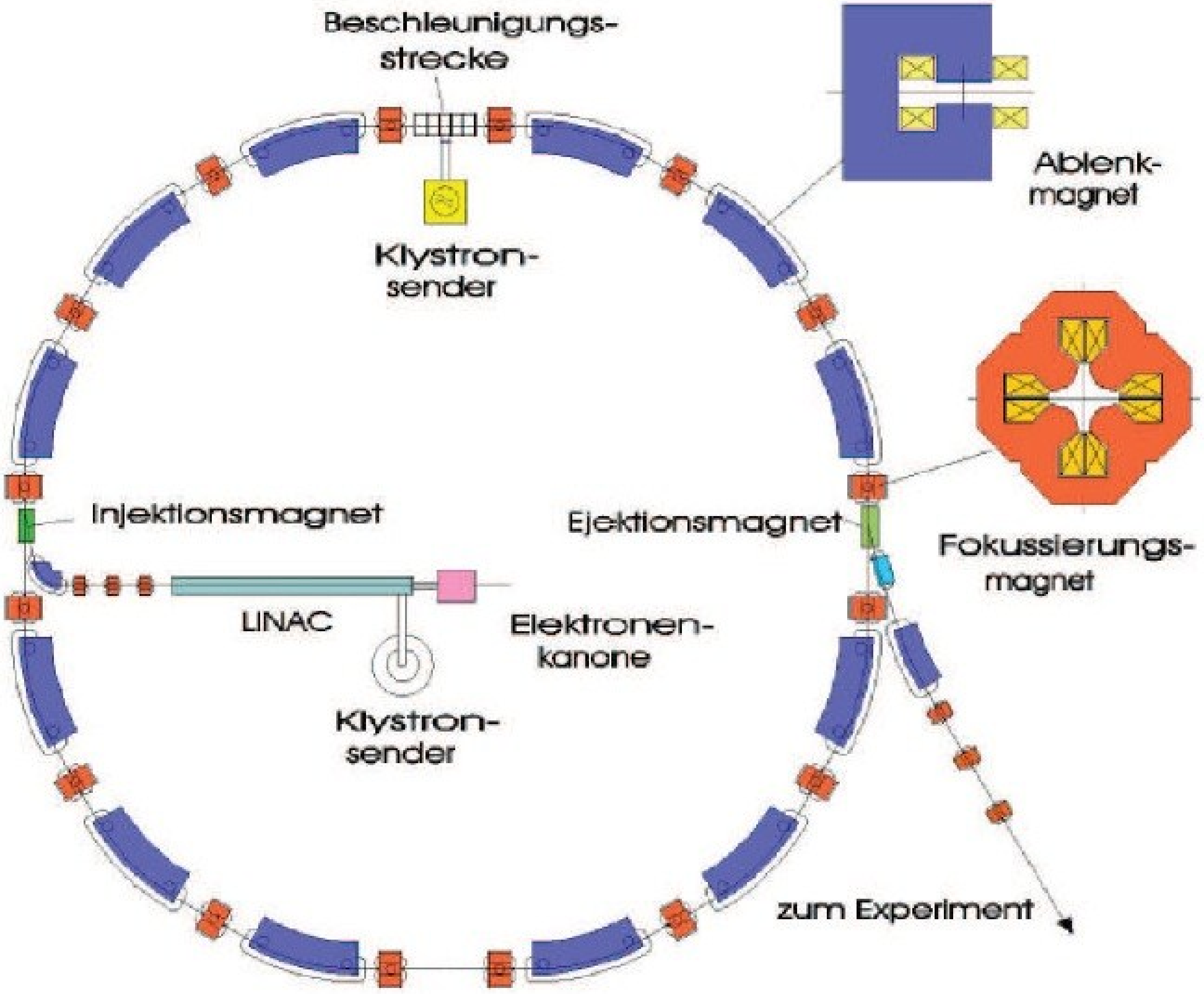
o Enforce trajectory with constant radius.

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.

$\Rightarrow$ Use LINAC or Microtron as pre-accelerator
Use synchrotron to reach the final energy E
Use storage ring to keep electrons at energy

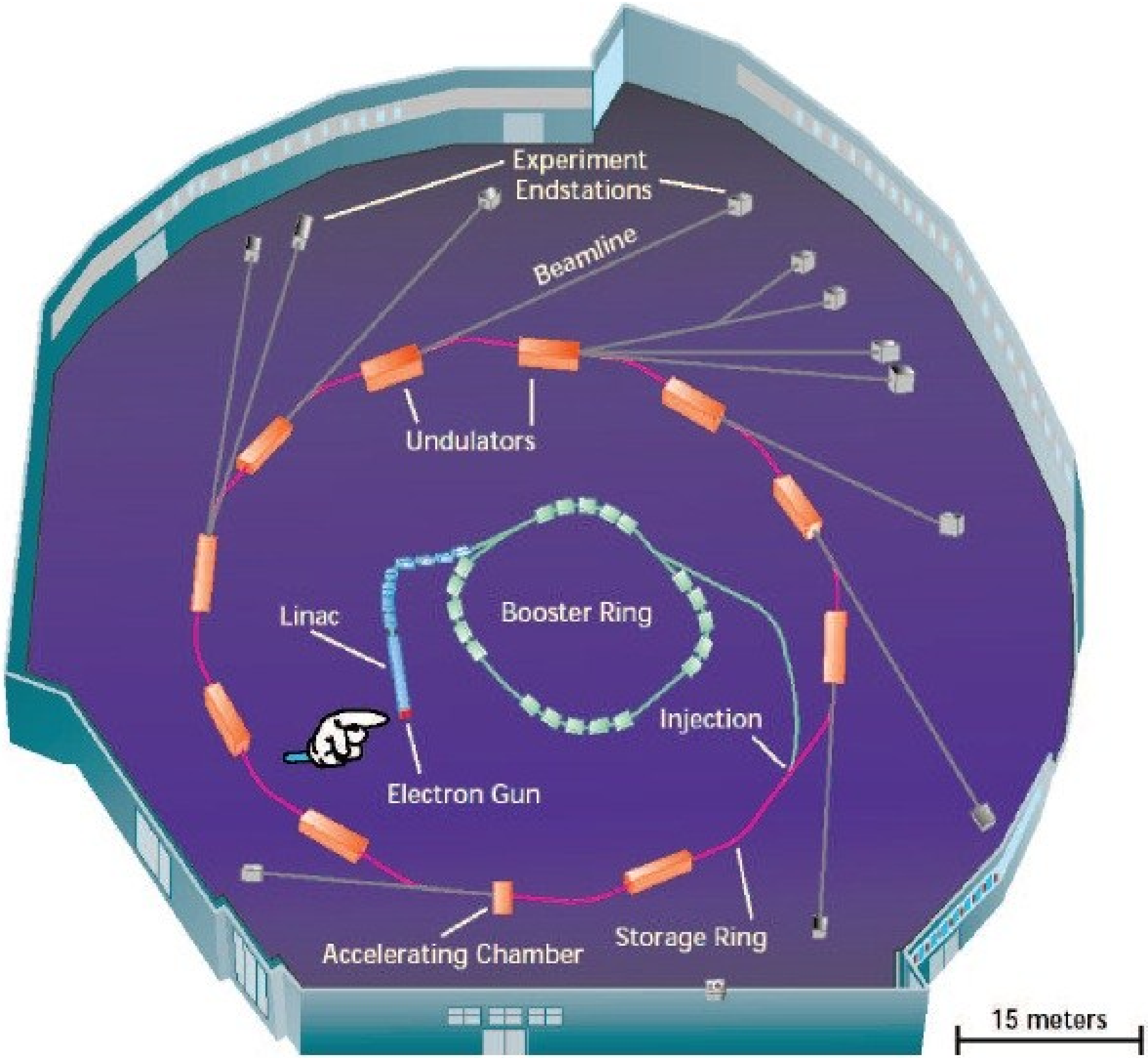
o The storage ring supplies the energy lost by radiation in each turn.

o Typical parameters: Lifetime: up to 30 h
Current: 100 – 500 mA

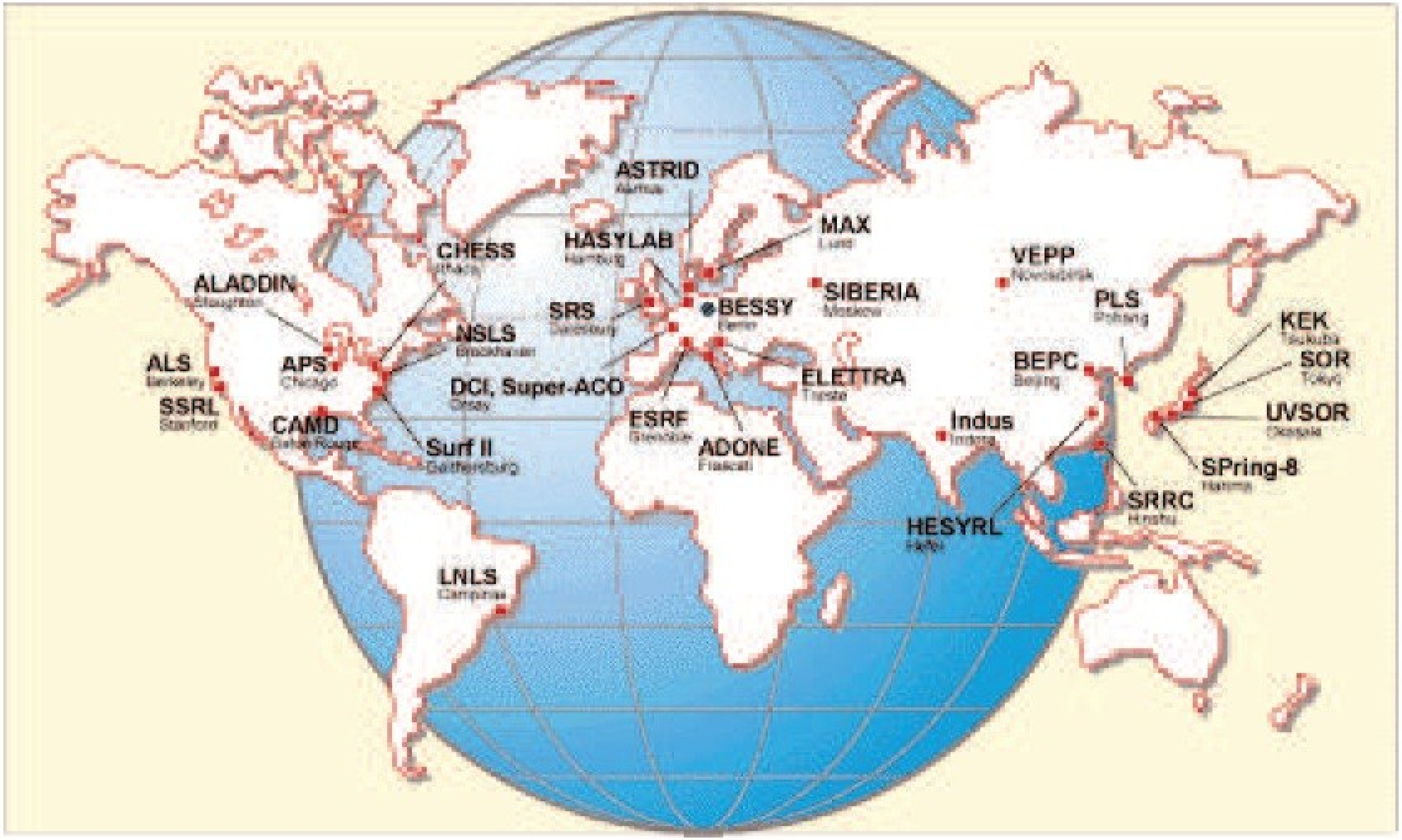
o Current losses through interaction with residual gas $\Rightarrow$ UHV

o Current supplied in bunches.

- # Storage Rings



Storage Rings



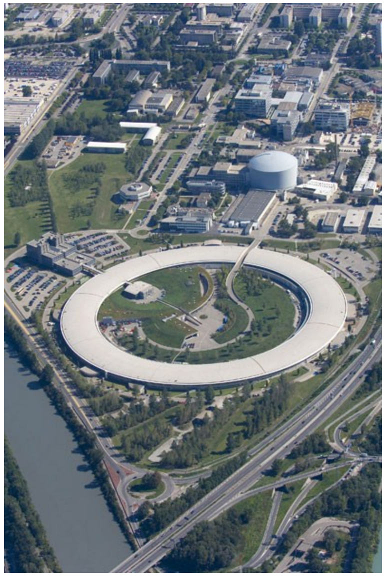
Photos machines

The three largest and most powerful synchrotrons in the world

APS, USA

ESRF, Europe-France

Spring-8, Japan



Synchrotron Radiation Primer

Radiation of a non-relativistic, accelerated particle:

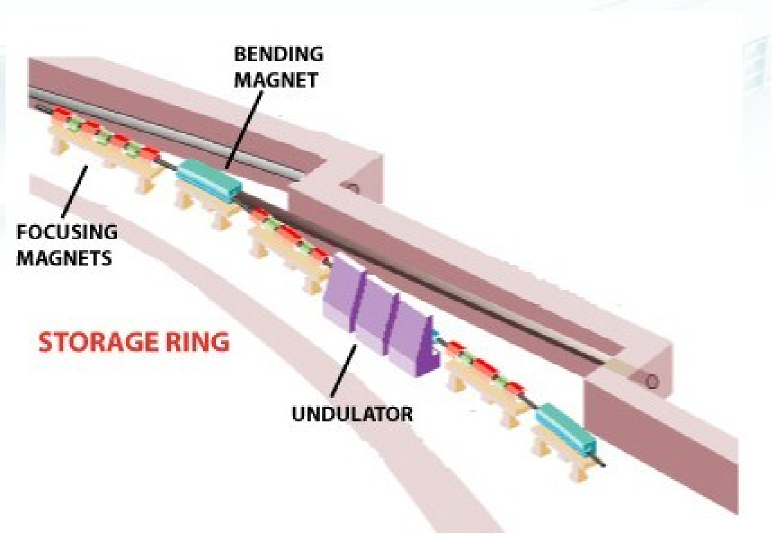
$$P = (e^2/6\pi\varepsilon_0 m_0{}^2 c^3) \ (dp/dt)^2$$

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

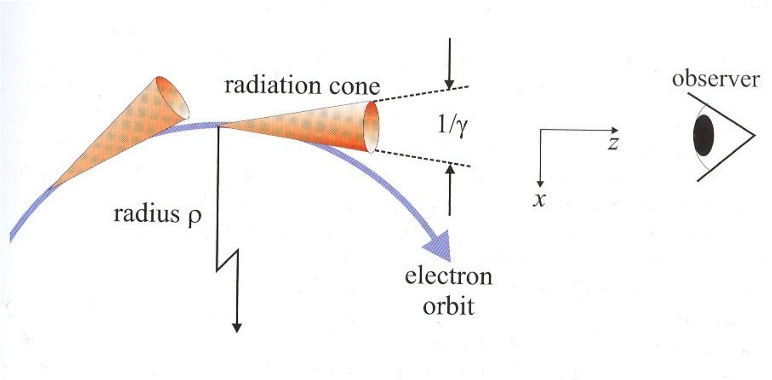
Synchrotron Radiation Primer



<u>Energy E_e of an electron at speed v:</u>

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

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



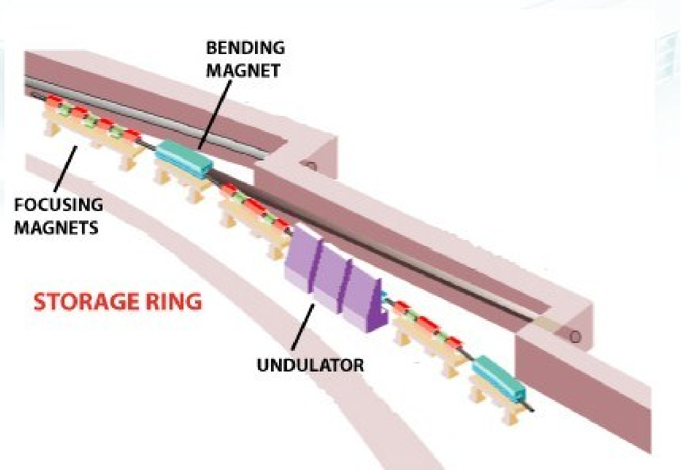
<u>Centrifugal=Lorentz force yields for radius:</u>

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

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

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

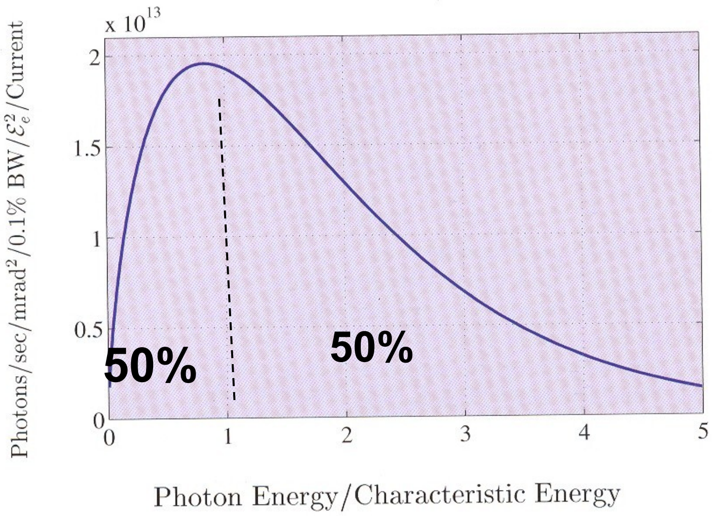
▪ Bending magnets



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

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

Flux ~ E^2



Energy loss by synchrotron radiation per turn:

ΔE [keV] = 88.5 E^4[GeV]/ρ[m]

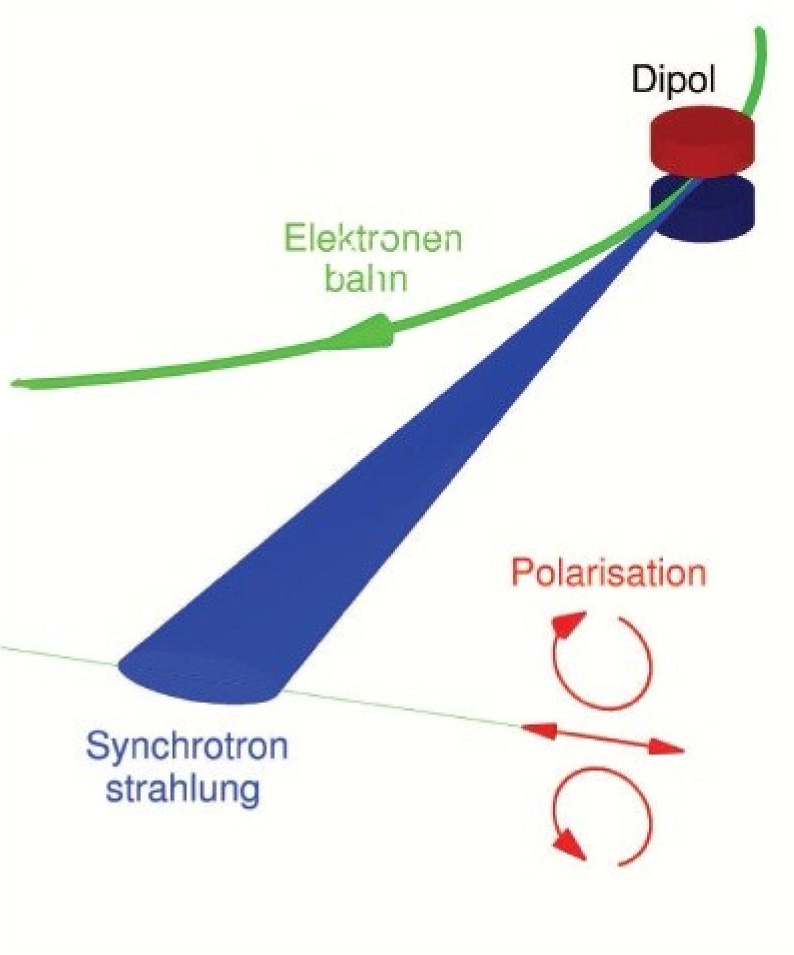
For 1 GeV and ρ=3.33 m: ΔE =26.6 keV/turn

For I=500 mA ≡ 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



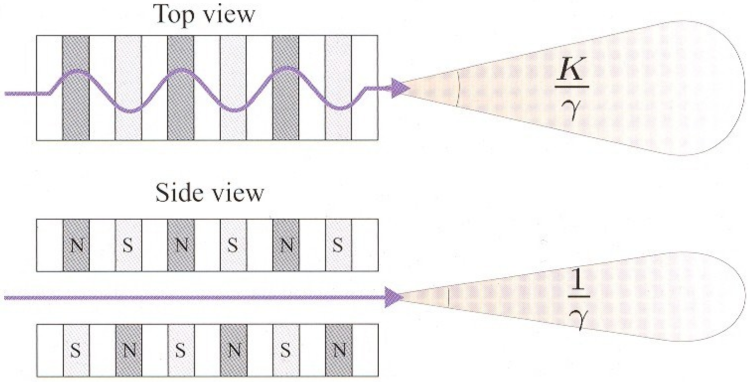
- Synchrotron radiation is polarised linearly in the plane of the orbit.

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

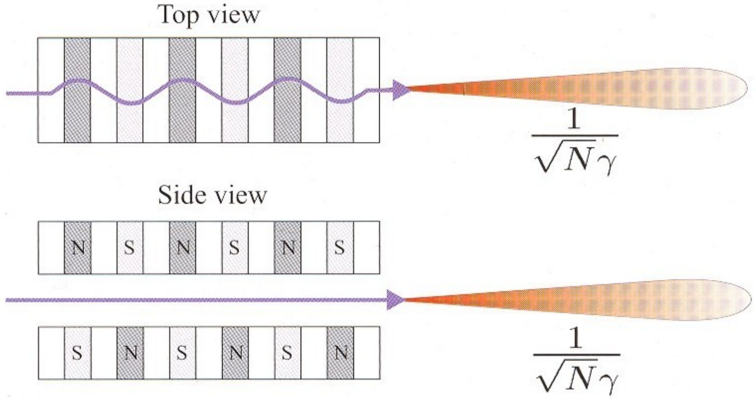
- Important applications for magnetic X-ray scattering.

Insertion Devices (wigglers and undulators)

(a) Wiggler



(b) Undulator



Wiggler:

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

Flux ~ $E^2 \times N$

N: number poles

Undulator:

$k = eB / mc \quad k_u = 0.934\ \lambda_u\ [cm]\ Bo[T]$

with λ_u undulator period

undulator fundamental:

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

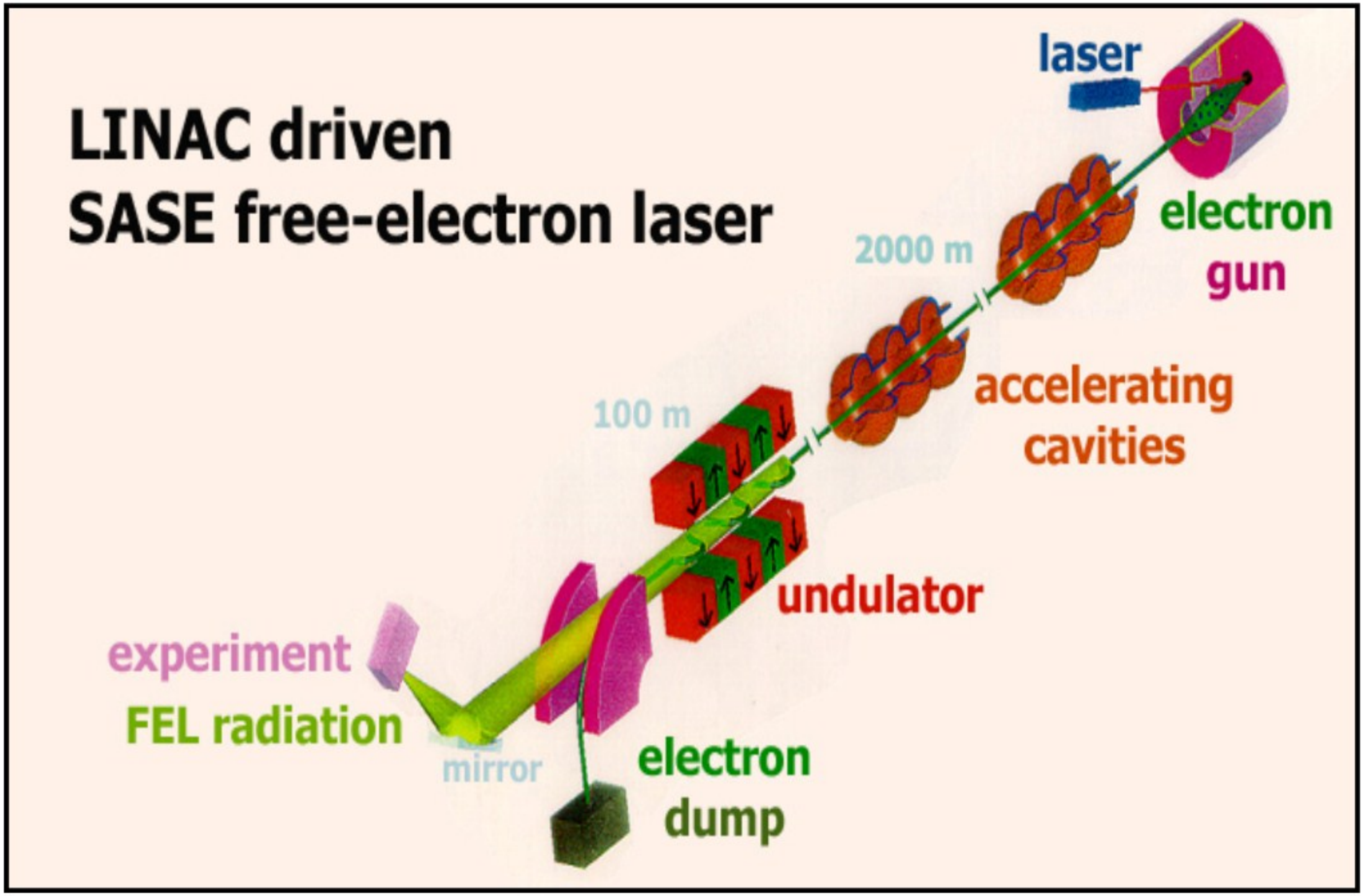
on axis

Flux ~ $E^2 \times N^2$

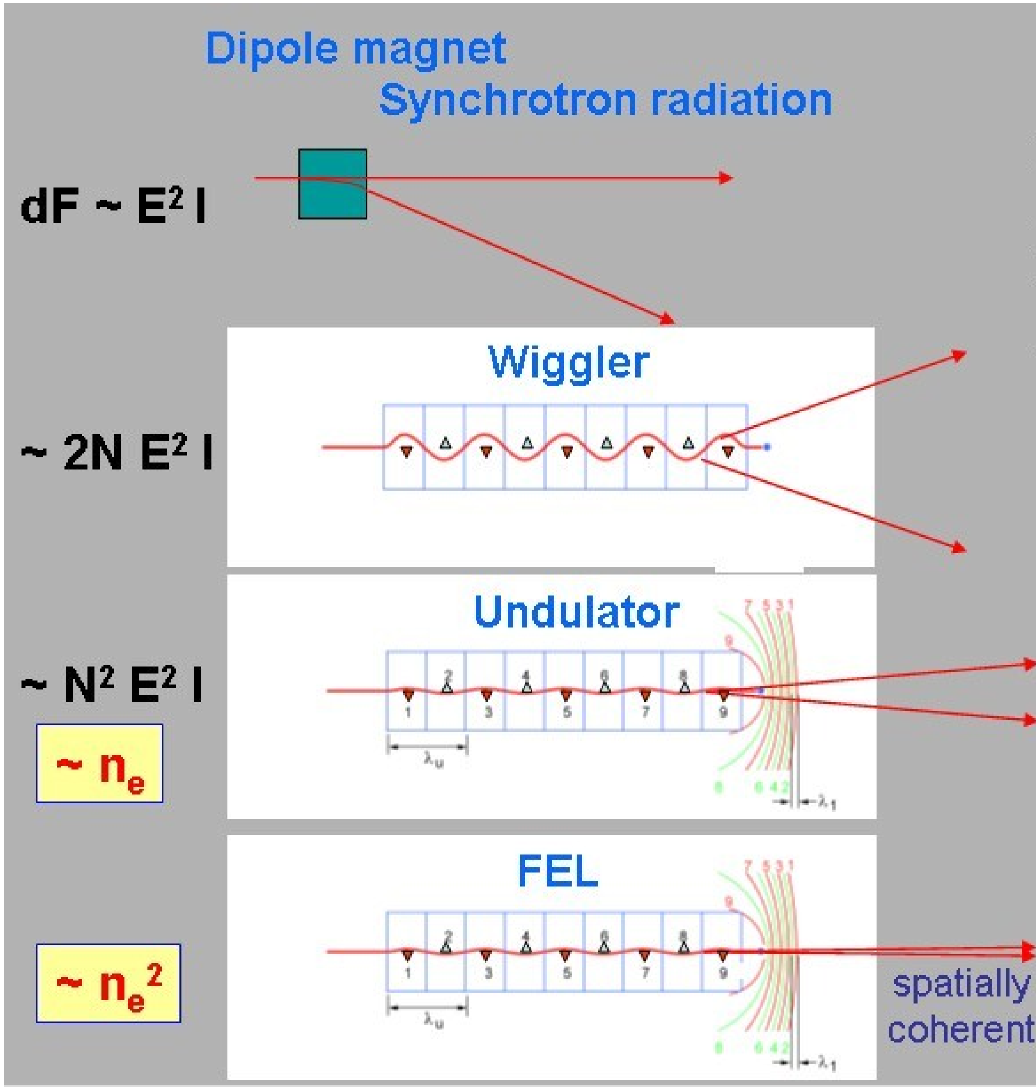
bandwidth:

$\Delta\lambda/\lambda \sim 1/nN$

Free Electron Lasers (FELs)



Synchrotron and FEL sources



Dipole magnet

Synchrotron radiation

$dF \sim E^2 I$

Wiggler

$\sim 2N\ E^2\ I$

Undulator

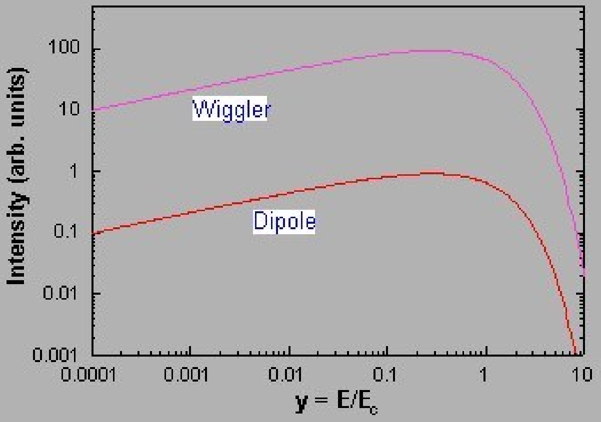
$\sim N^2\ E^2\ I$

$\sim n_e$

FEL

$\sim n_e^{\ 2}$

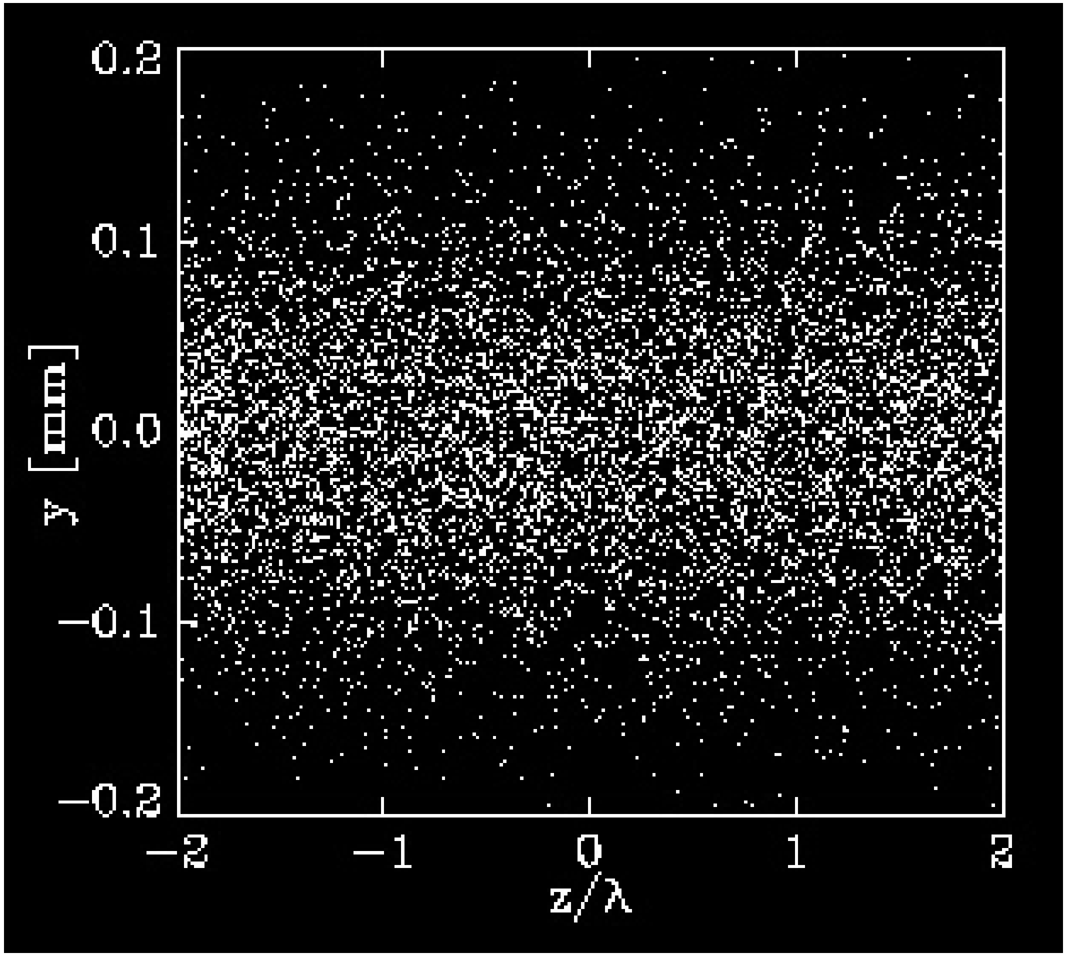
spatially coherent



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.

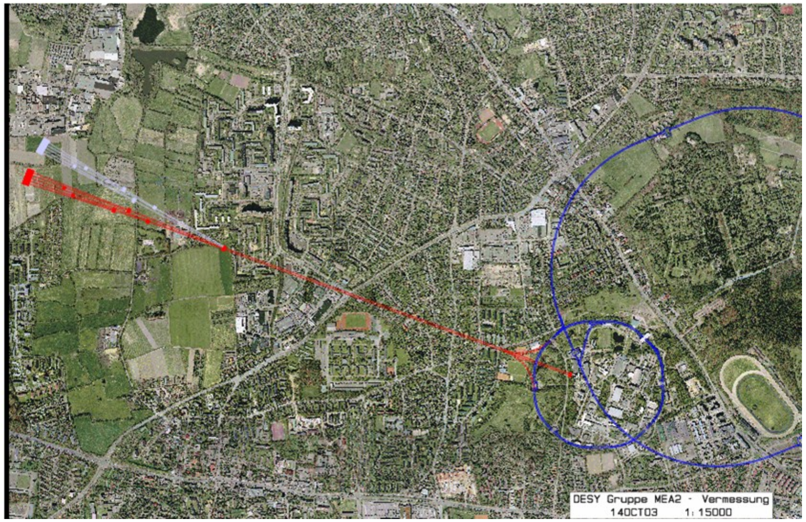
- # Electron bunching

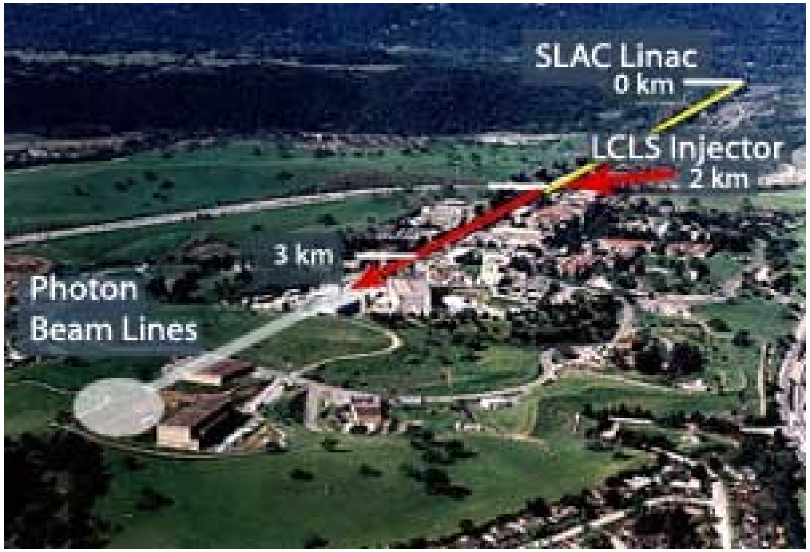


GENESIS – simulation for TTF parameters

Courtesy Sven Reiche (UCLA)

VUV and X-Ray FELs





- # Brilliance

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