Methoden moderner Röntgenphysik: Streuung und Abbildung

Lecture 3	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2019 G. Grübel, L. Müller, O. Seeck, L. Frenzel, F. Lehmkühler, M. Martins, W. Wurth		
Location	Lecture hall AP, Physics, Jungiusstraße		
Date	Tuesdays	12:30 - 14:00	(starting 2.4.)
	Thursdays	8:30 - 10:00	(until 11.7.)

Methoden moderner Röntgenphysik: Streuung und Abbildung

Part I:

Basics of X-ray Physics

by Gerhard Grübel (GG)

[2.4.]	Organisation and Introduction
[4.4.]	X-ray Scattering Primer
[9.4.]	Sources of X-rays, Synchrotron Radiation
[11.4.]	Refraction and Reflection
[16.4.]	Kinematical Scattering Theory (I)
[18.4.]	Kinematical Scattering Theory (II), Applications
[23.4.]	Small Angle Scattering and Soft Matter
[25.4.]	Anomalous Scattering
[30.4.]	Introduction: Coherence I
[2.5.]	Coherence II; Applications of Coherent X-ray Beams

Methoden moderner Röntgenphysik II: Streuung und Abbildung

Part I:

Basics of X-ray Physics

by Gerhard Grübel (GG)

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 from Interfaces
Snell's Law, Fresnel Equations

Kinematical Diffraction (I)
Diffraction from an Atom, a Molecule, from Liquids, Glasses, …

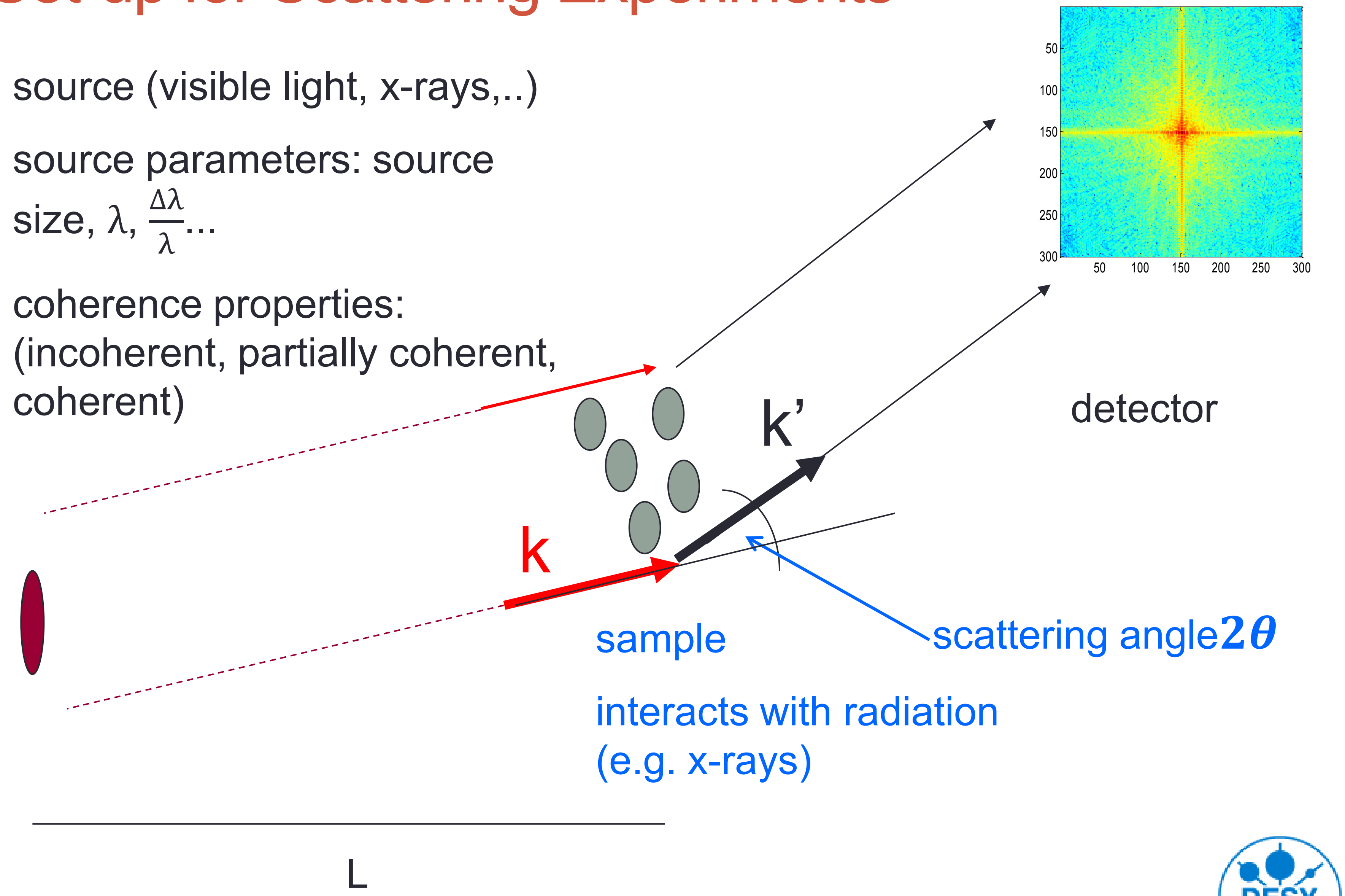
Kinematical Diffraction (II)
Diffraction from a Crystal, Reciprocal Lattice, Structure Factor, …

Set-up for Scattering Experiments

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

source parameters: source size, λ, $\frac{\Delta\lambda}{\lambda}$...

coherence properties: (incoherent, partially coherent, coherent)



detector

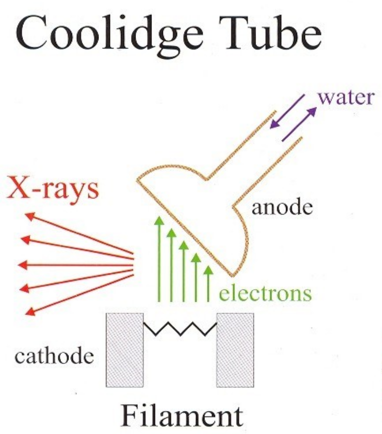
sample

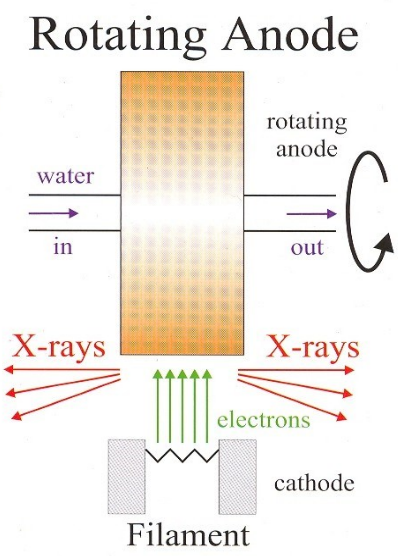
scattering angle 2θ

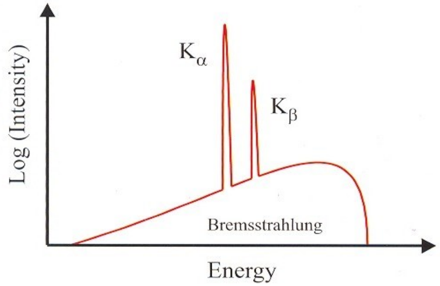
interacts with radiation (e.g. x-rays)

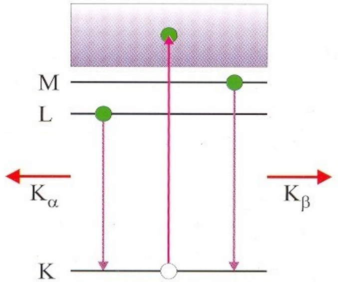
Source of X-Rays

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)

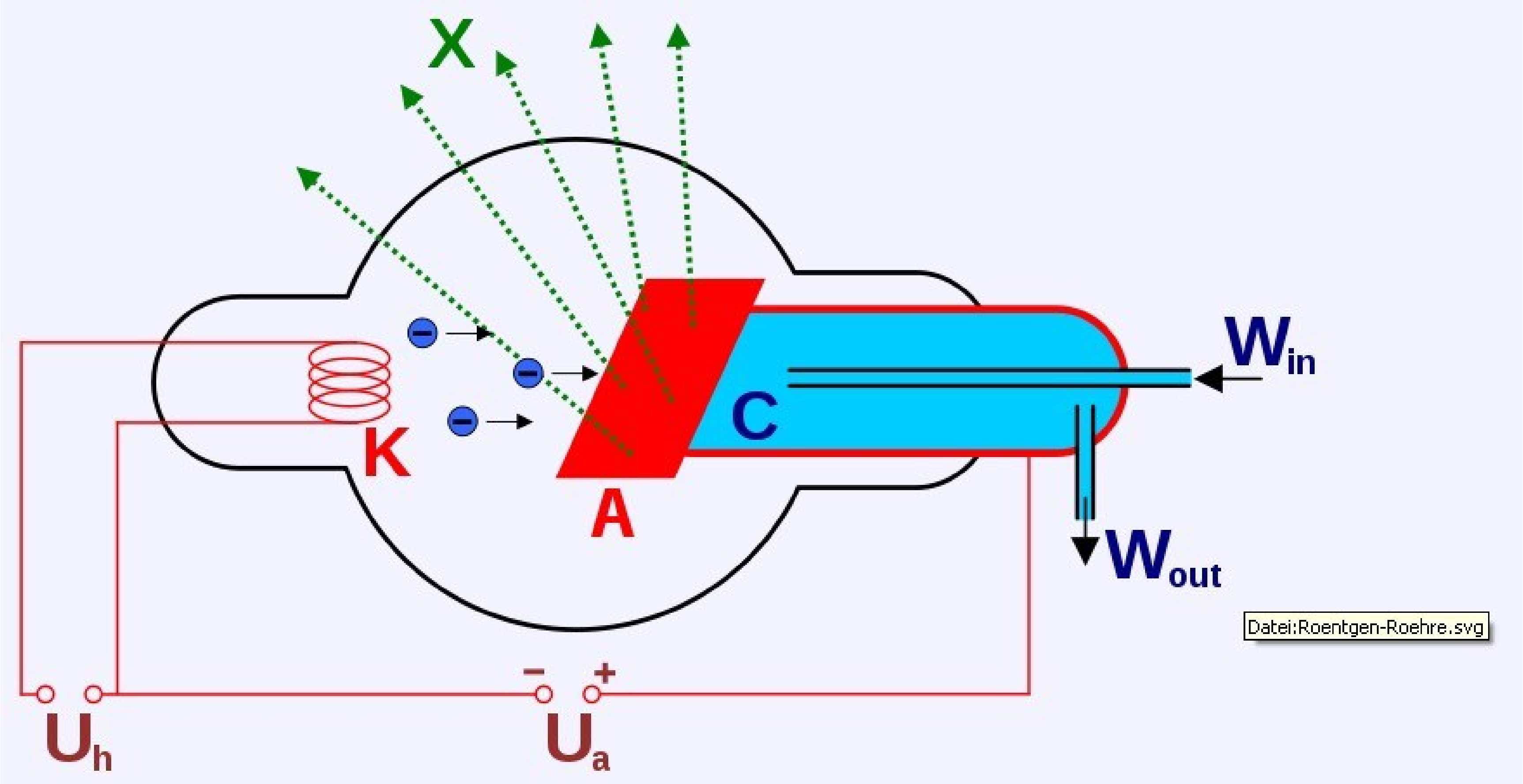








X-Ray Tube



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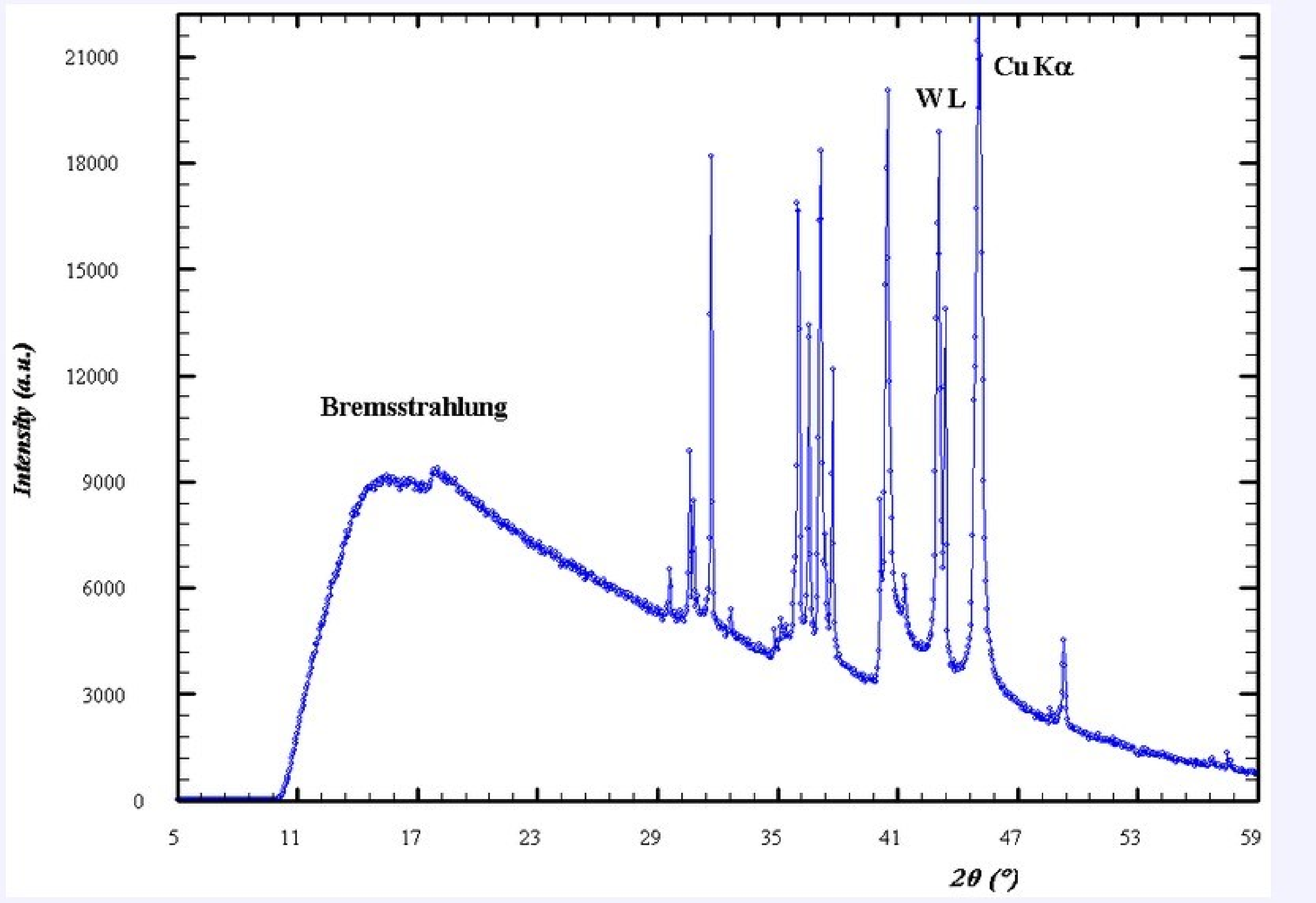
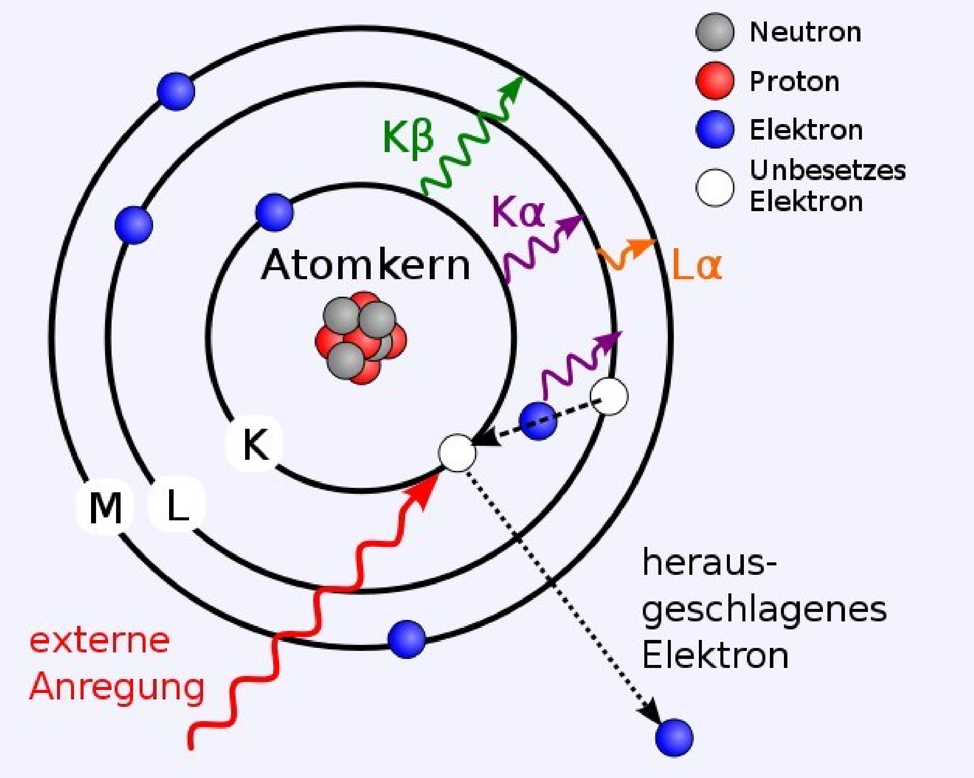
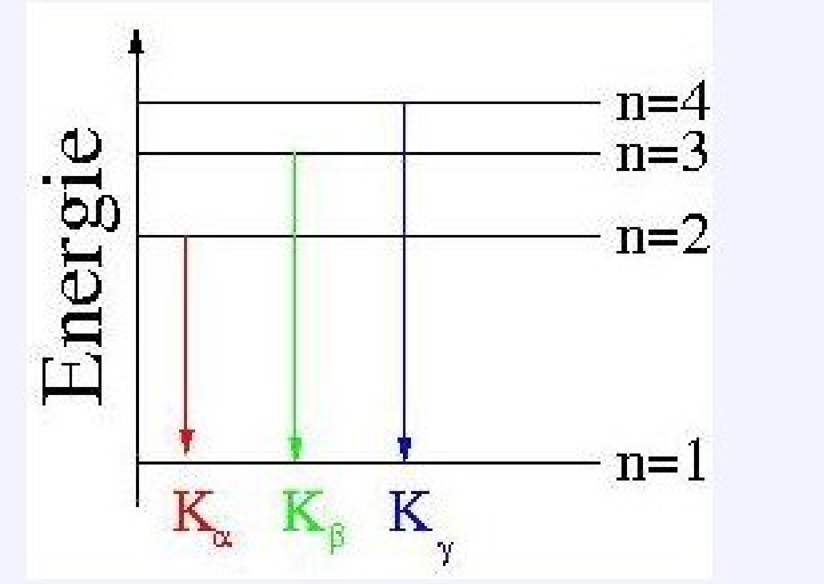
X-Ray Tube

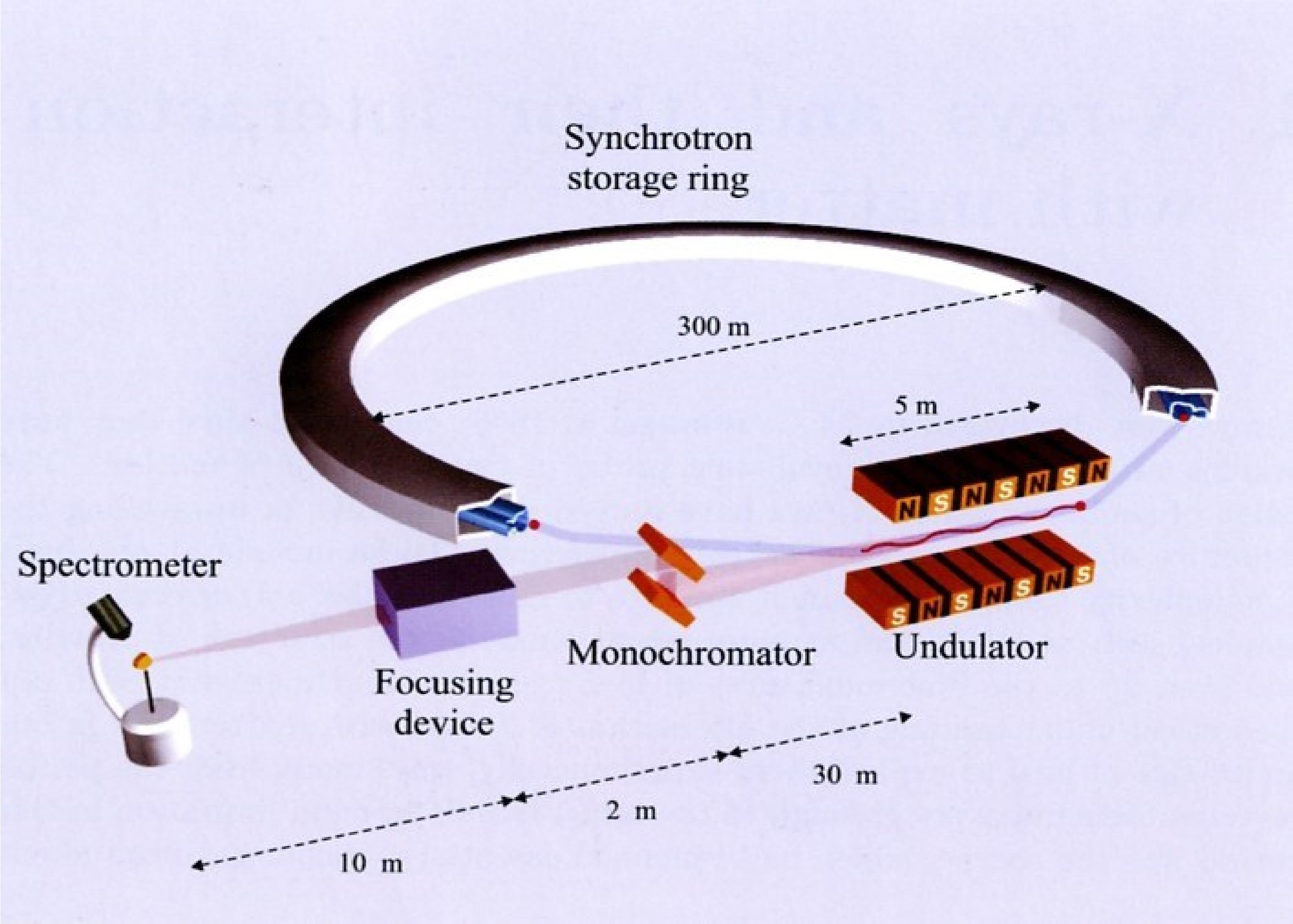

Intensity (a.u.)
21000
18000
15000
12000
9000
6000
3000
0
5
11
17
23
29
35
41
47
53
59
2θ (°)
Bremsstrahlung
W L
Cu Kα

X-Ray Tube


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


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 circulate in a homogeneous magnetic field B
- Frequency for one cycle is given by

$$\omega_c = \left(\frac{e}{m}\right) B_Z$$

- For non-relativistic electrons ω_c is independent of the velocity v

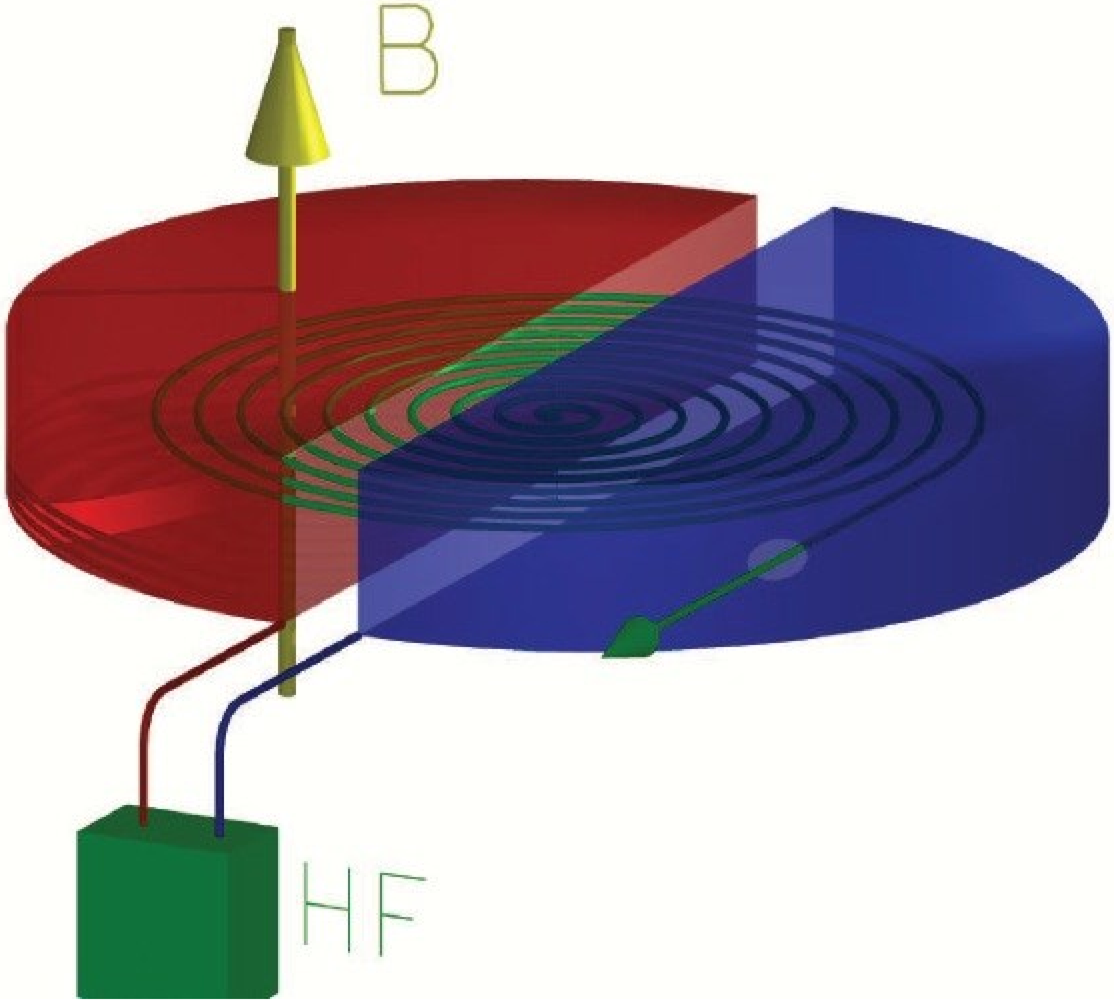
$$\left(\frac{v}{c} < 0.15\right)$$

- At high energies the mass changes and the frequency of the field needs to be adapted.

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

- Electrons at $10\ \mathrm{keV}$ 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

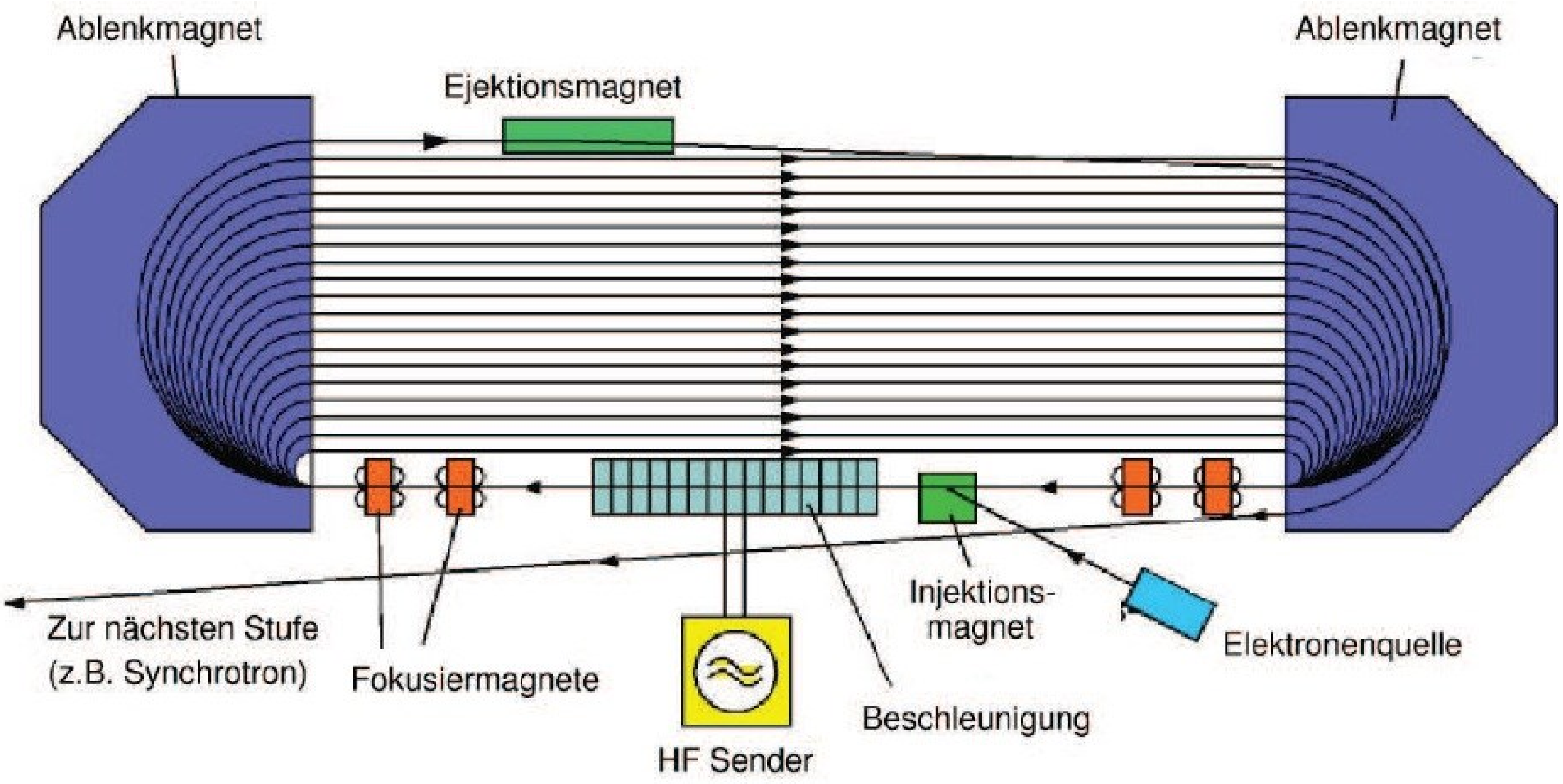
$$\mathrm{evB} = \mathrm{m}\frac{\mathrm{v}^2}{\mathrm{R}}$$

$$\Rightarrow \mathrm{R} = \frac{\mathrm{mv}}{\mathrm{eB}} = \frac{\mathrm{vmc}^2}{\mathrm{ec}^2\mathrm{B}} = \left(\frac{\mathrm{v}}{\mathrm{ec}^2\mathrm{B}}\right)\mathrm{E}$$

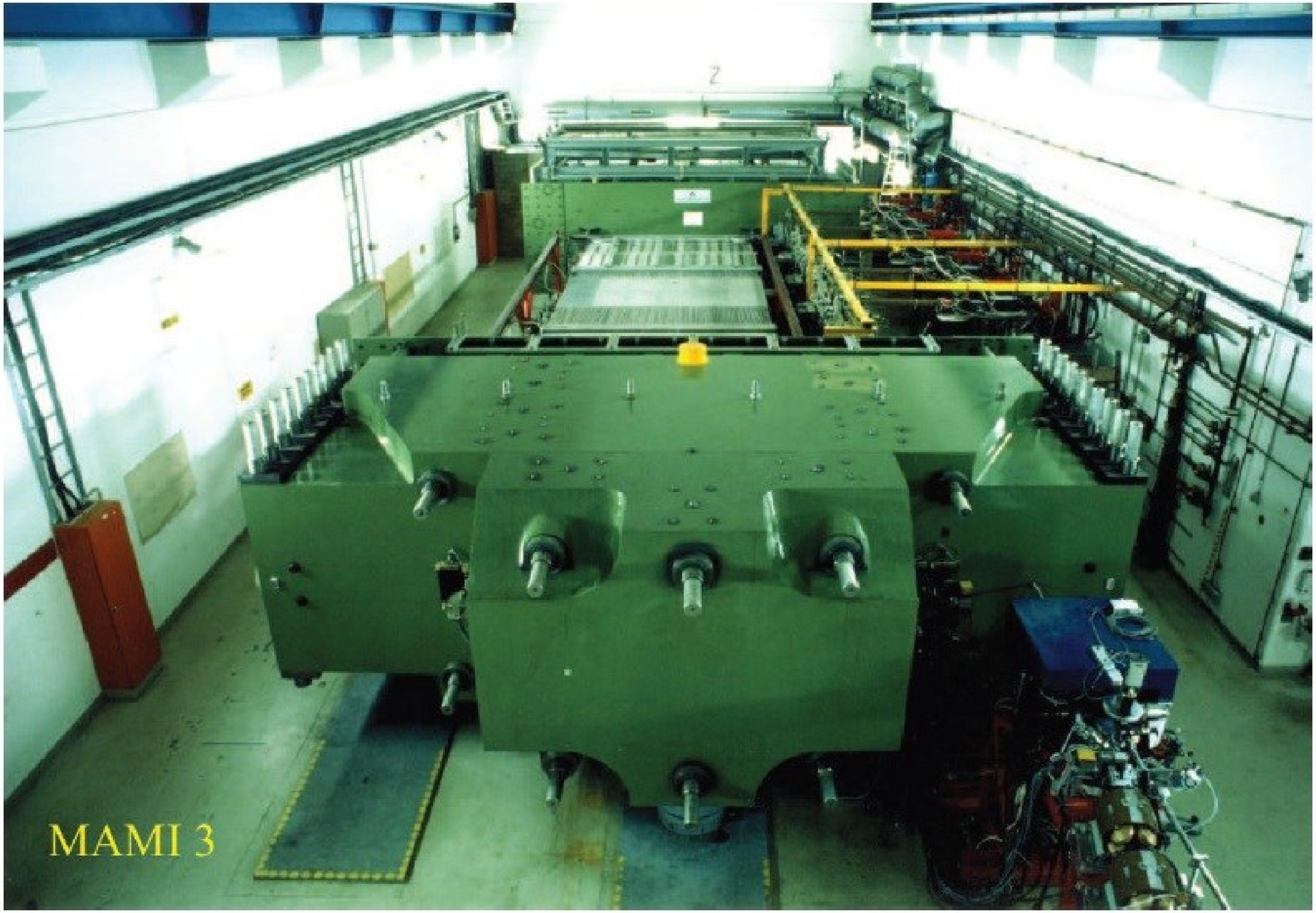
- Such Acceleration that electrons are in phase with RF field
- Energies up to 100 MeV can be reached

Example: BESSY II

Microtron


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

Microtron



Synchrotron

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

$$R = \frac{E}{ecB}$$

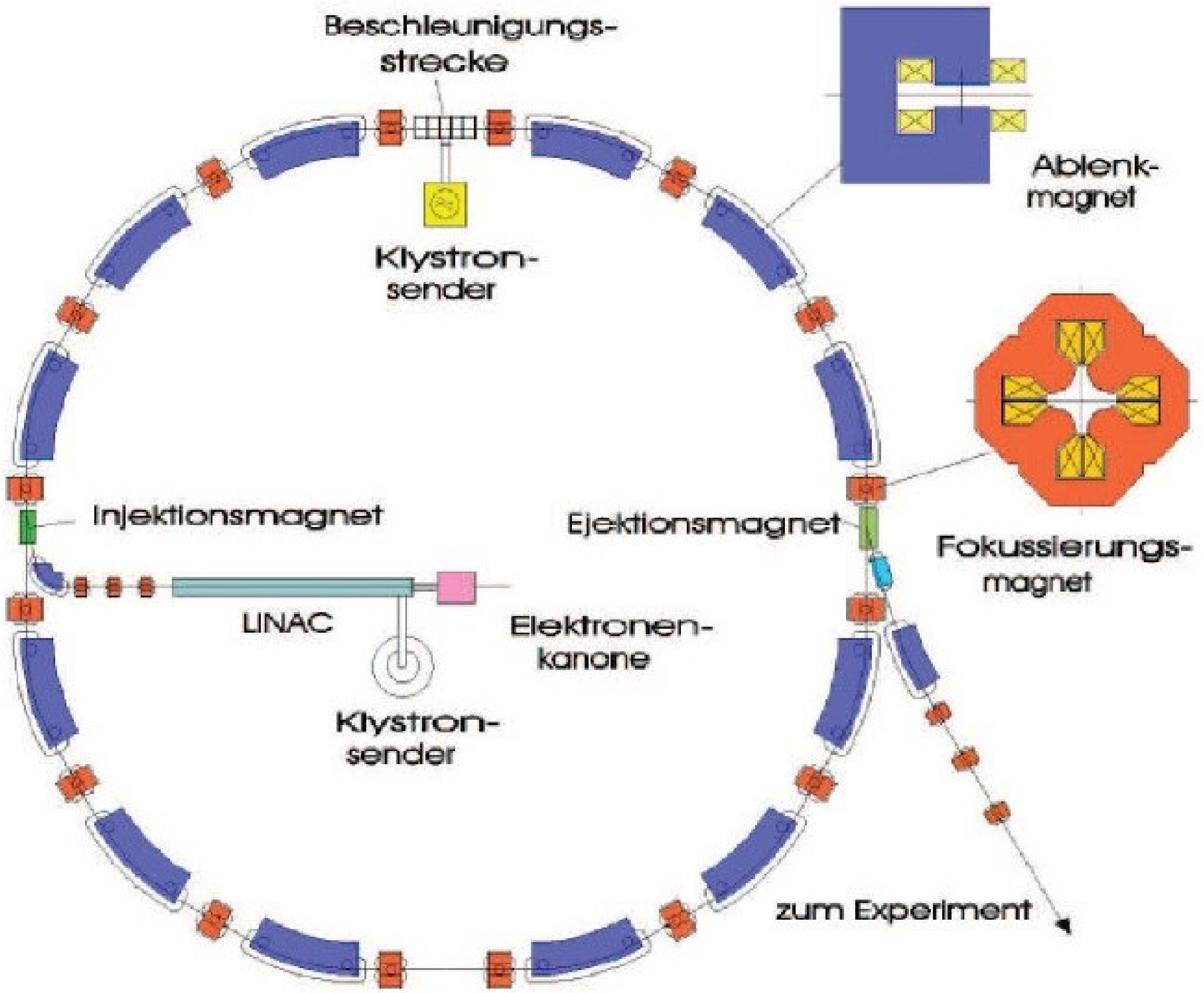
- For $E > 1\ \mathrm{GeV}$ and $B = 5T : R > \text{several meter}$
- Technically difficult
- Enforce trajectory with constant radius

Bends in small , local magnets

$\frac{E}{B} = \text{const.} \Rightarrow$ synchronous ramping of E and B

⇒ Synchrotron

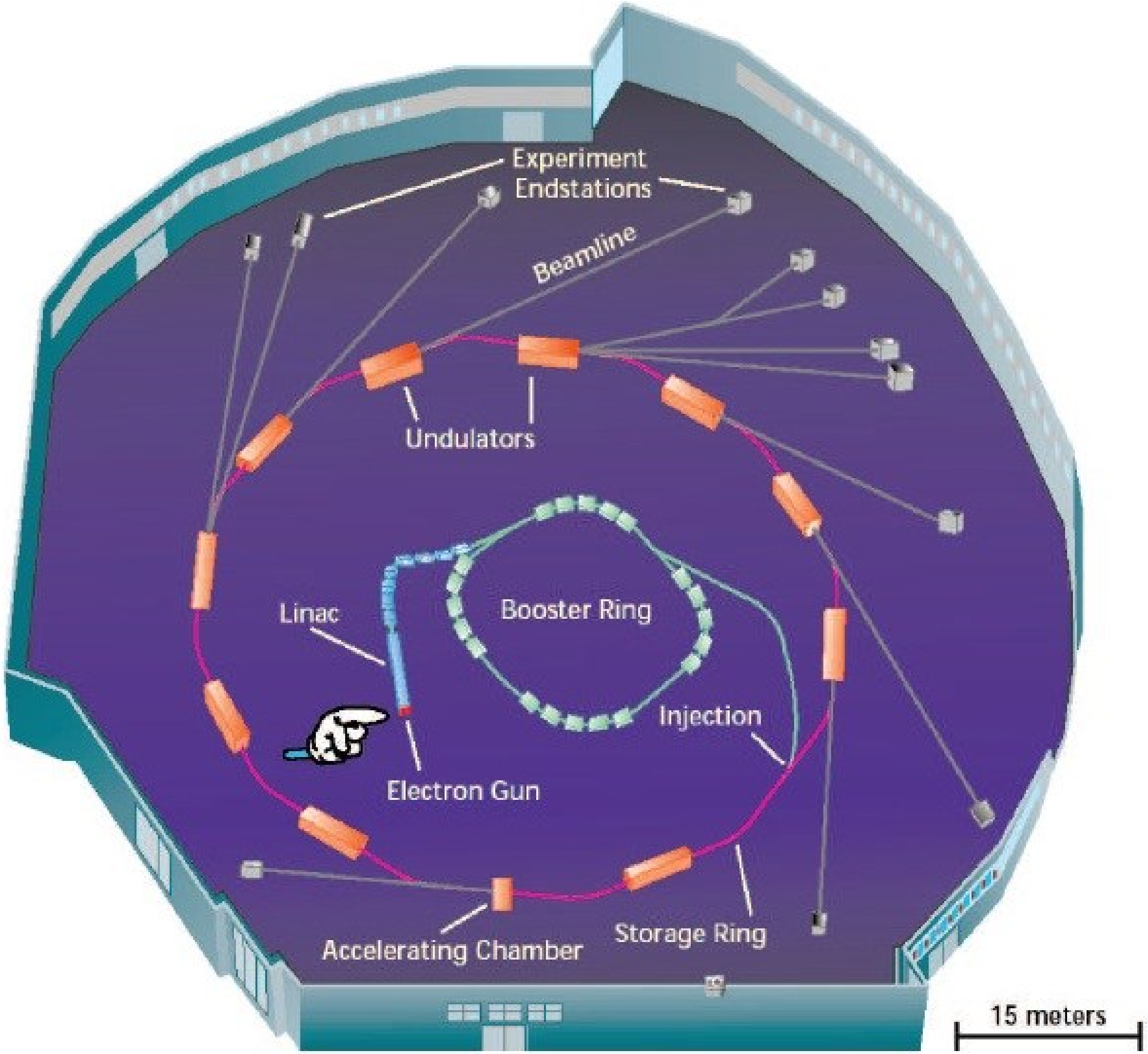
Synchrotron



Synchrotron

- Modern synchrotron radiation sources are built as storage rings
- 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
- The storage ring supplies the energy lost by radiation in each turn.
- Typical parameters: Lifetime: up to 30 h
  Current: 100 – 500 mA
- Current losses through interaction with residual gas ⇒ UHV
- Current supplied in bunches.

Storage Rings



Storage Rings

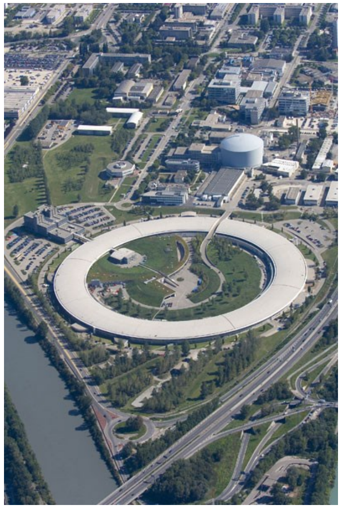
Photon Machines

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:

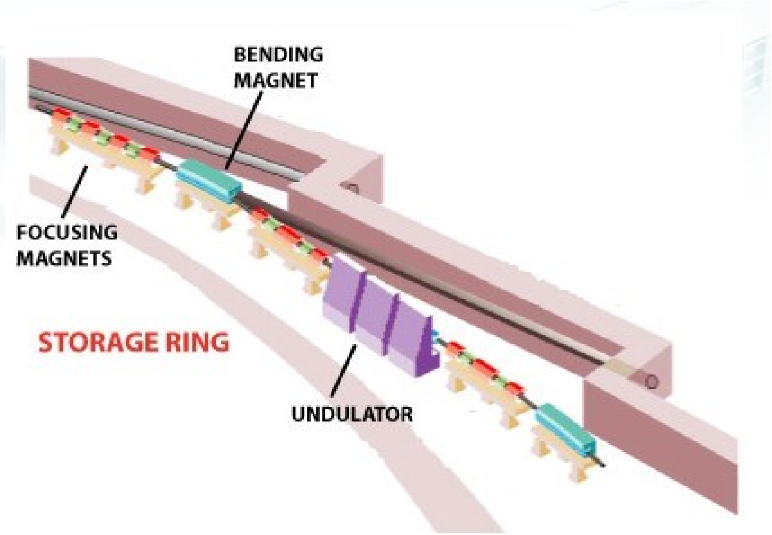
$$P = \left(\frac{e^2}{6\pi\varepsilon_0 m_0^2 c^3}\right) \left(\frac{dp}{dt}\right)^2$$

Angular distribution resembles the one of a Hertz dipole:

$$\left(\frac{dP}{d\Omega}\right) = \left(\frac{e^2}{16\pi^2\varepsilon_0 m_0^2 c^3}\right)\left(\frac{dp}{dt}\right)^2 \sin^2(\Psi)$$

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

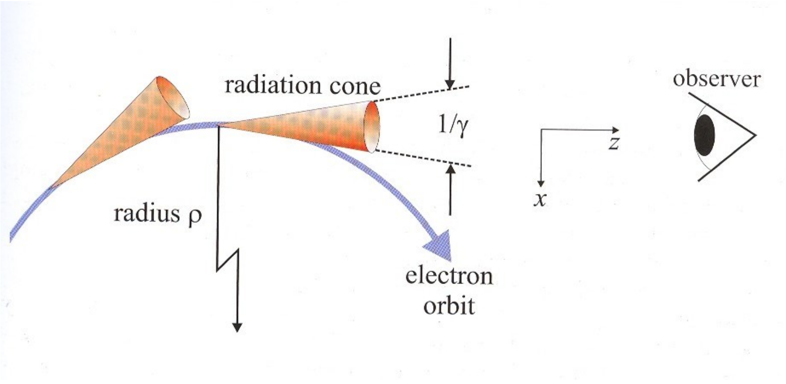
Synchrotron Radiation Primer



Energy E_e of an electron at speed v:

$$E_e = \frac{mc^2}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \gamma\, mc^2$$

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



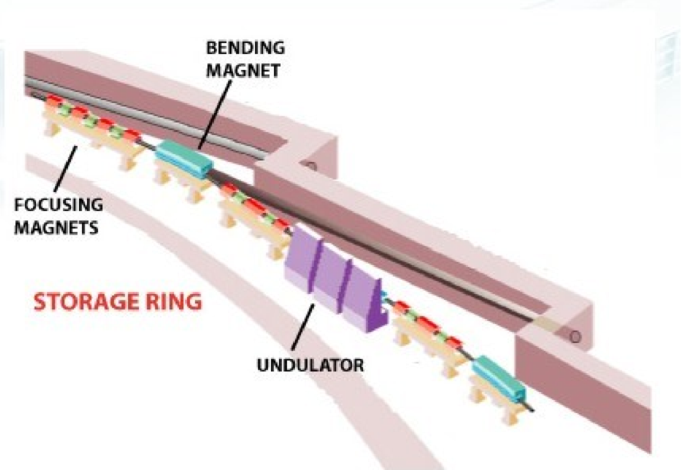
Centrifugal=Lorentz force yields for radius:

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

$$E_e = 6\ \mathrm{GeV}, \qquad B = 0.8\ \mathrm{T}$$

Opening angle is of order $\frac{1}{\gamma} \approx 0.1\ \mathrm{mrad}$

Bending Magnets

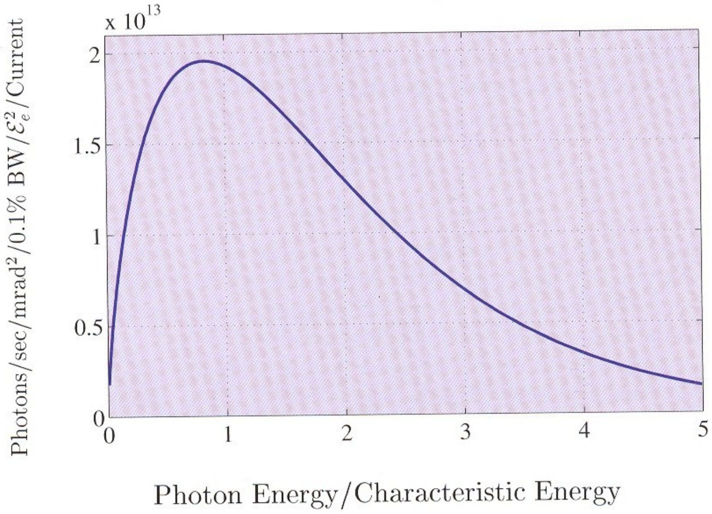


Characteristic energy $\hbar\omega_c$ for bend or wiggler:

$$\hbar\omega_c[\mathrm{keV}] = 0.665\mathrm{E}^2{}_{\mathrm{e}}\ [\mathrm{GeV}]\mathrm{B(T)} \approx 20\ \mathrm{keV}$$

$$\mathrm{Flux} \sim \mathrm{E}^2$$

Energy loss by synchrotron radiation per turn:



$$\Delta\mathbf{E}[\mathbf{keV}] = \frac{\mathbf{88.5\ E^4[GeV]}}{\boldsymbol{\rho}\mathbf{[m]}}$$

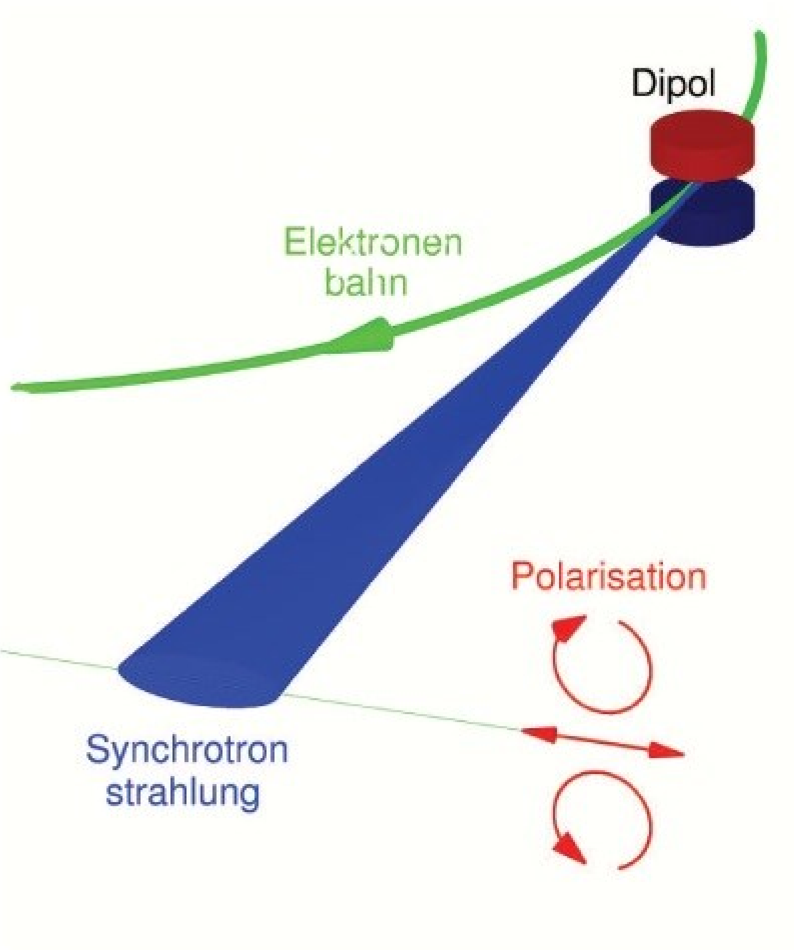
For 1 GeV and $\mathrm{p} = 3.33\ \mathrm{m}$: $\Delta\mathrm{E} = 26.6\ \mathrm{keV/turn}$

$$\mathrm{For I} = 500\mathrm{mA} \equiv 0.5\frac{\mathrm{Cb}}{\mathrm{s}} = 0.5 \times 6.25 \times 10^{18}\frac{\mathrm{e}^-}{\mathrm{s}}$$

$$\Rightarrow \mathrm{P} = 0.5 \times 6.25 \times 10^{18}\ \frac{\mathrm{e}^-}{\mathrm{s}\ x\ 26.6\ \mathrm{keV}}$$

$$= 8.3125 \times 10^{22} \times 1.6 \times 10^{-19} = 13.3\frac{\mathrm{kJ}}{\mathrm{s}} = 13.3\ \mathrm{KW}$$

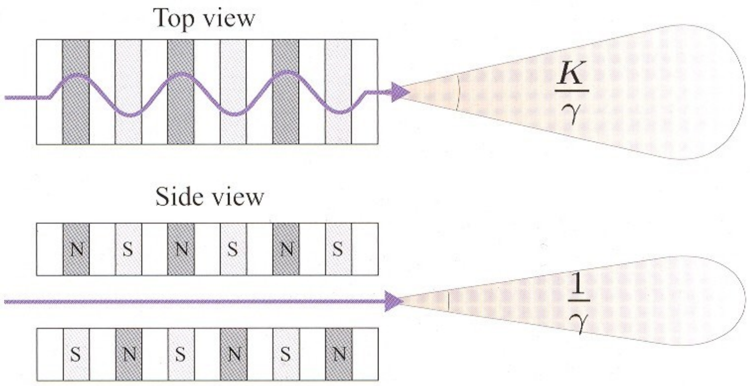
Polarization



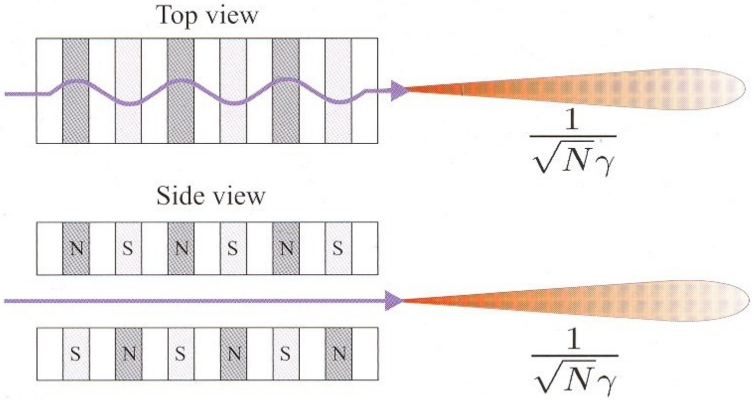
- Synchrotron radiation is polarized linearly in the plane of the orbit
- Above and below the orbital plane of the polarization is circular
- Important applications for magnetic x-ray scattering

Insertion Devices (Wigglers and Undulators)

(a) Wiggler



(b) Undulator



Wiggler:

$$P[\mathrm{kW}] = 0.633E^2_e\ [\mathrm{GeV}]\ B^2[\mathrm{T}]\ L[\mathrm{m}]\ I[\mathrm{A}]$$

$\mathrm{Flux} \sim E^2 \times N$

N: number poles

Undulator:

$k = eB / mc\ k_u = 0.934\ \lambda_u\ [\mathrm{cm}]\ Bo[\mathrm{T}]$

with λ_u undulator period

undulator fundamental:

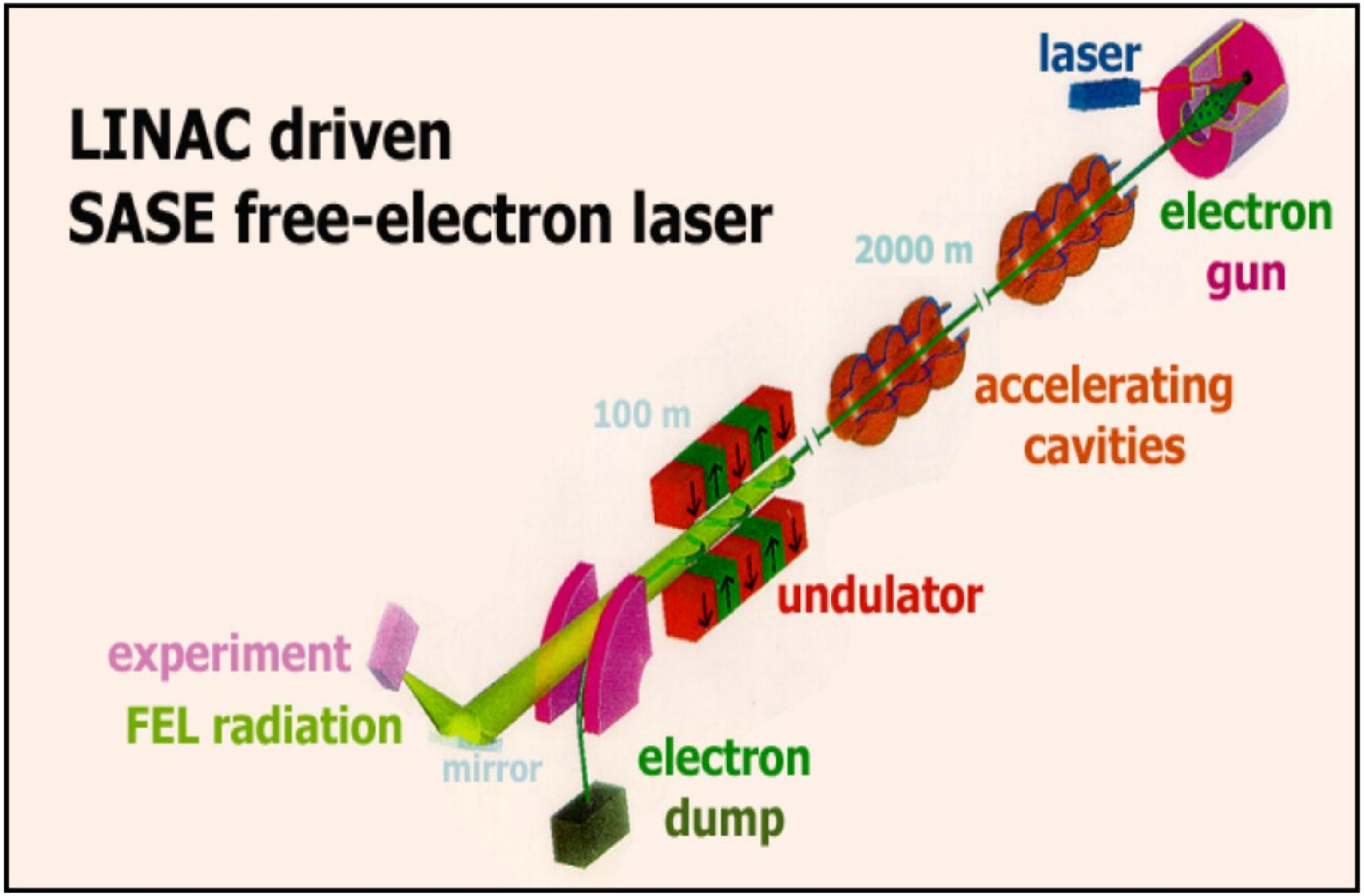
$$\lambda_0 = \frac{\lambda_u}{2_{\gamma^2}}\left(1 + \frac{k^2}{2} \cancel{+ \gamma\theta}\right)$$ on axis

$\mathrm{Flux} \sim E^2 \times N^2$

bandwidth: $\frac{\Delta\lambda}{\lambda} \sim \frac{1}{nN}$

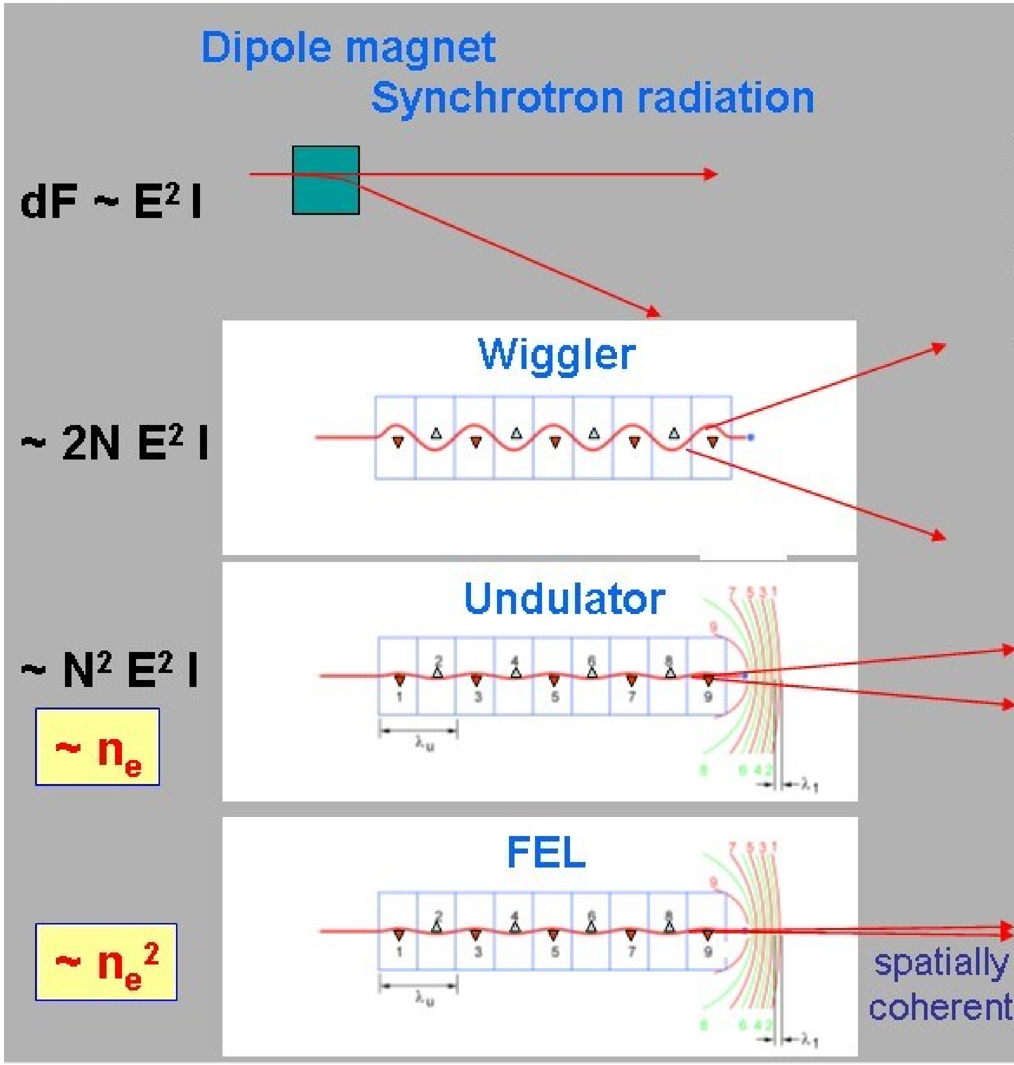
Towards
Diffraction Limited Light Sources: MAX IV (Lund)

Free Electron Lasers (FELs)



LINAC driven
SASE free-electron laser

Synchrotron and FEL Sources



Dipole magnet
Synchrotron radiation

$dF \sim E^2 I$

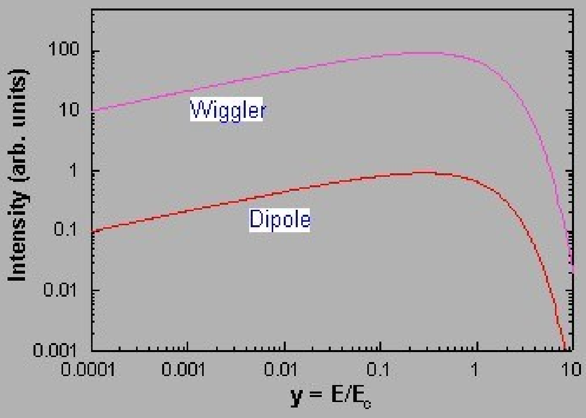
$\sim 2N\, E^2 I$

$\sim N^2 E^2 I$

$\sim n_e$

$\sim n_e^2$

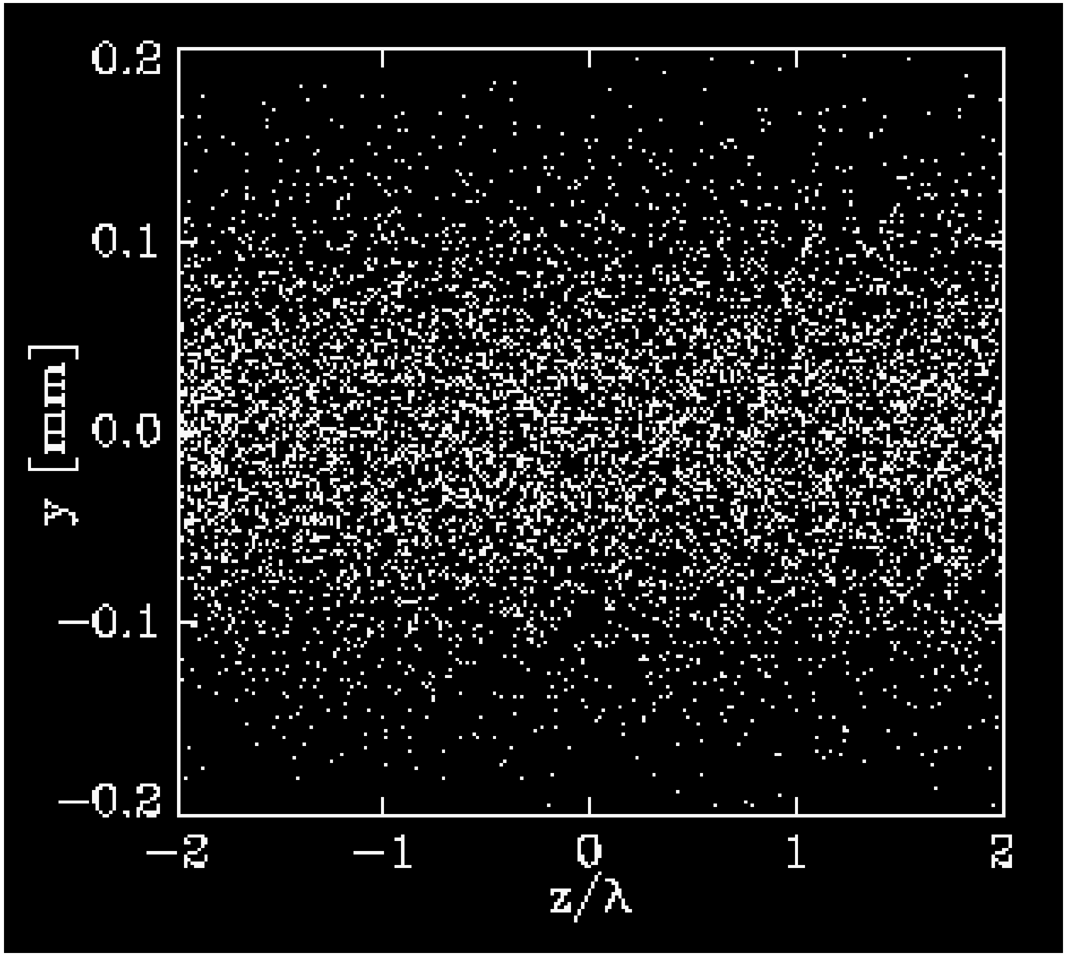
spatially coherent



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.

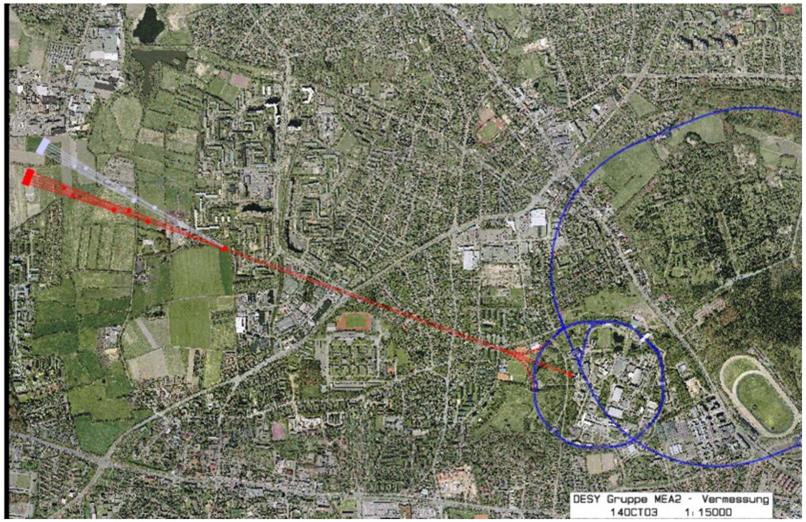
Electron Bunching

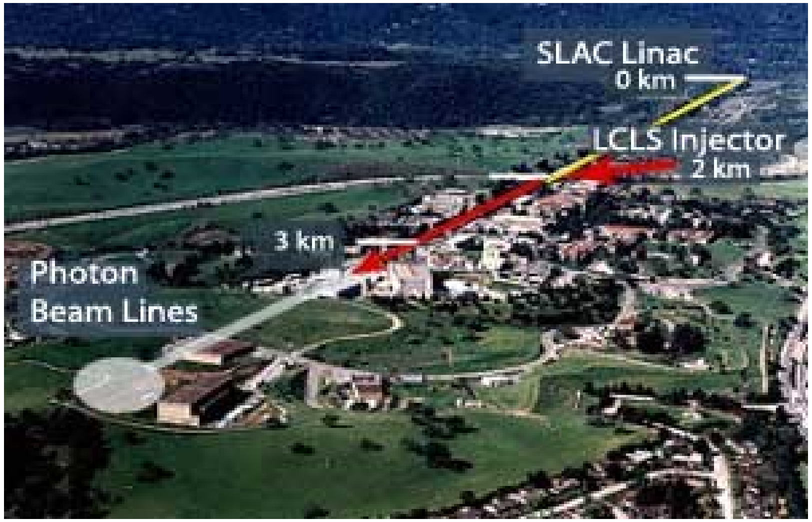


GENESIS – simulation for TTF parameters

Courtesy Sven Reiche (UCLA)

VUV and X-Ray FELs





Brilliance

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