

Methoden moderner Röntgenphysik II: Streuung und Abbildung

Lecture 3	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2017 G. Grübel, A. Philippi-Kobs, O. Seeck, T. Schneider, L. Frenzel, M. Martins, W. Wurth		
Location	Lecture hall AP, Physics, Jungiusstraße		
Date	Tuesday	12:30 - 14:00	(starting 4.4.)
	Thursday	8:30 - 10:00	(until 13.7.)



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, ...

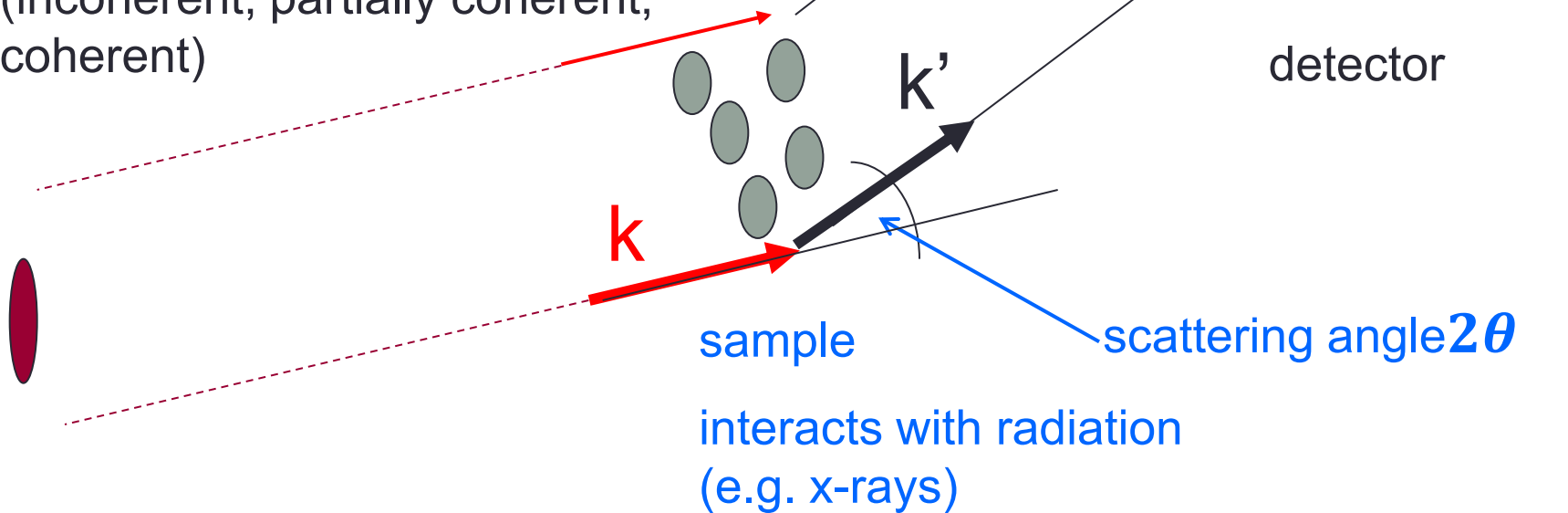
Set-up for Scattering Experiments

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

source parameters: source

size, λ , $\frac{\Delta\lambda}{\lambda}$...

coherence properties:
(incoherent, partially coherent,
coherent)

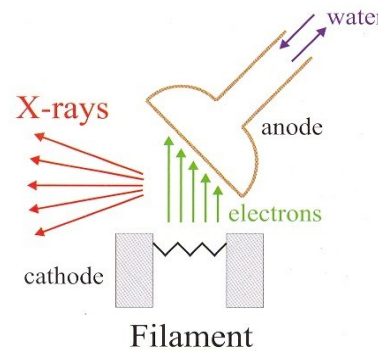


Source of X-Rays

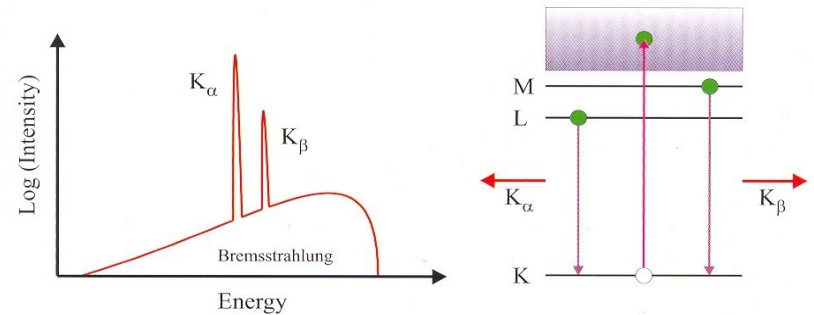
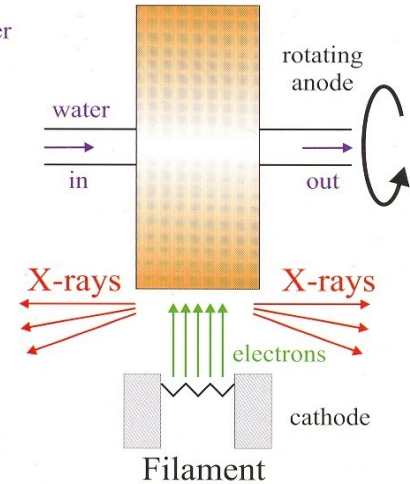
- 1895 Discovered by W.C. Röntgen
- 1912 First diffraction experiment (v. Laue)
- 1912 Coolidge tube (W.D. Coolidge, GE)
- 1946 Radiation from electrons in a synchrotron, GE, Physical Review, 71,829 (1947)



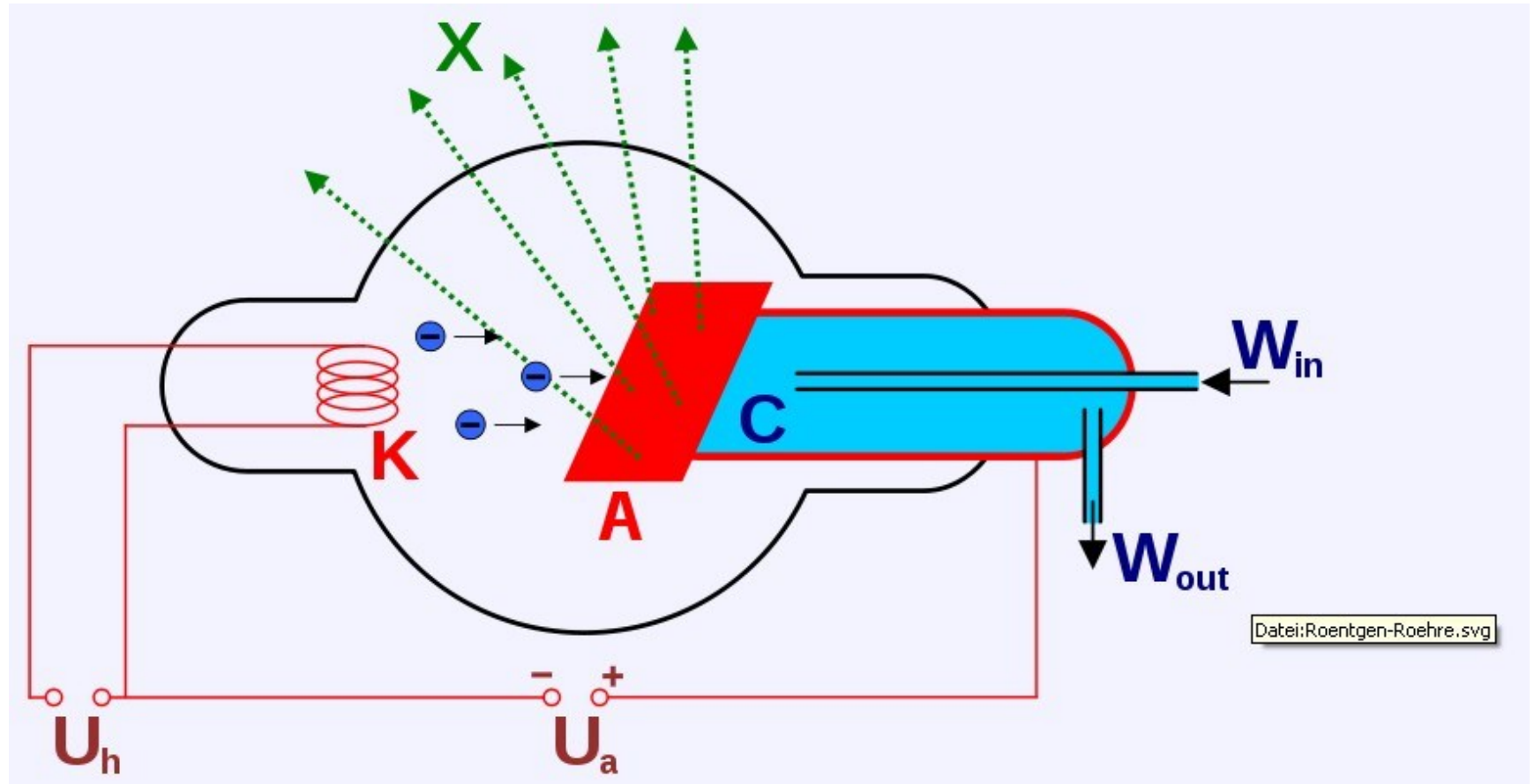
Coolidge Tube



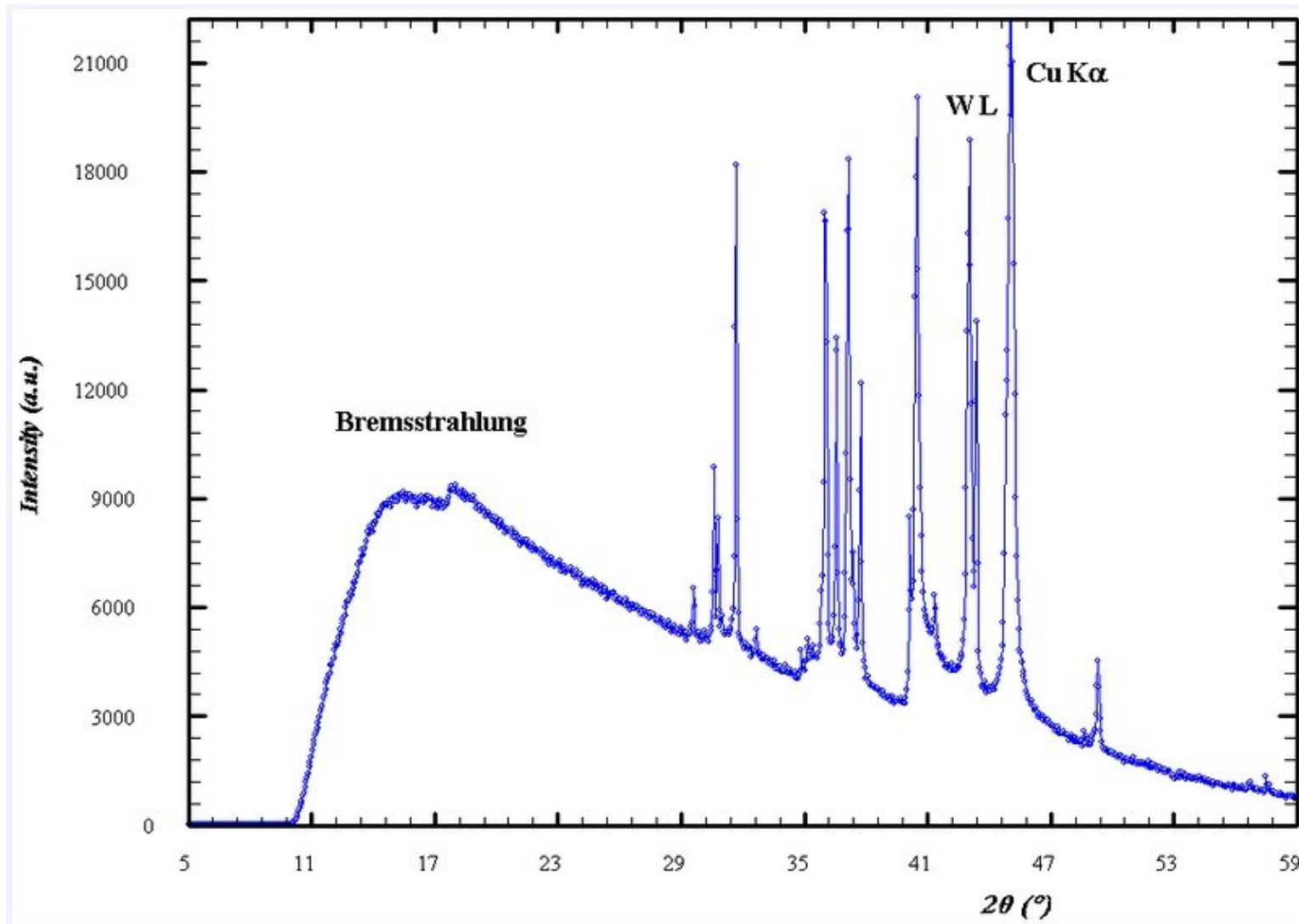
Rotating Anode



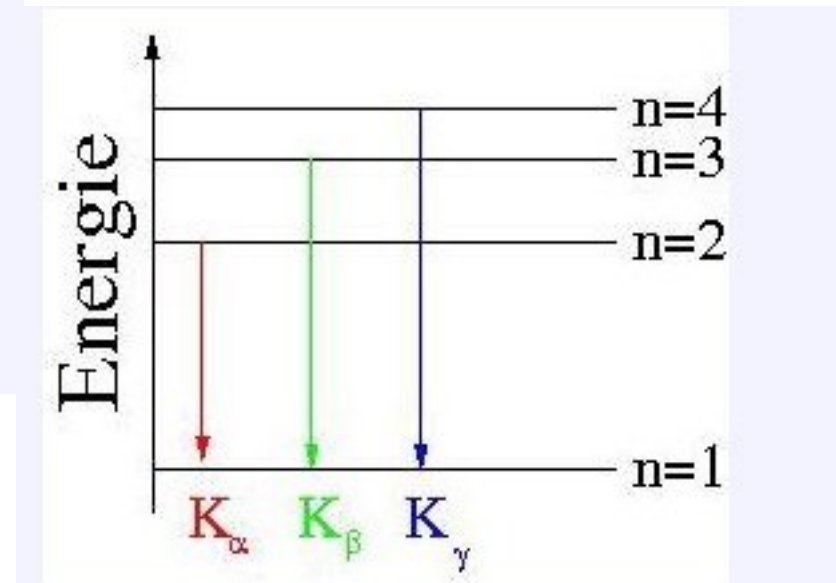
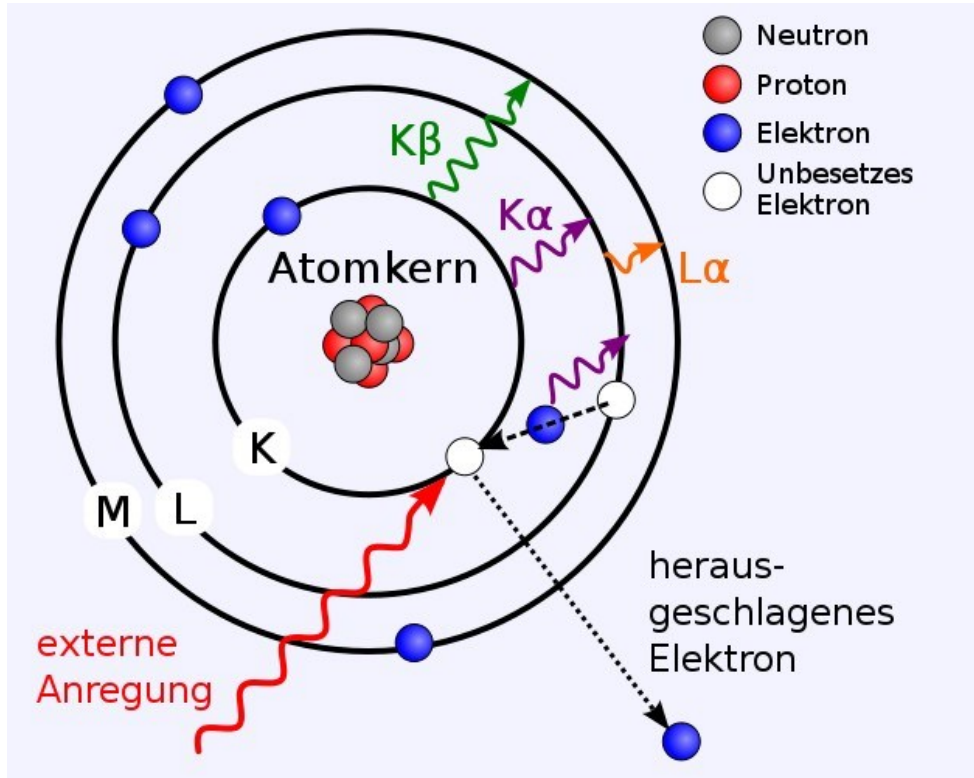
X-Ray Tube



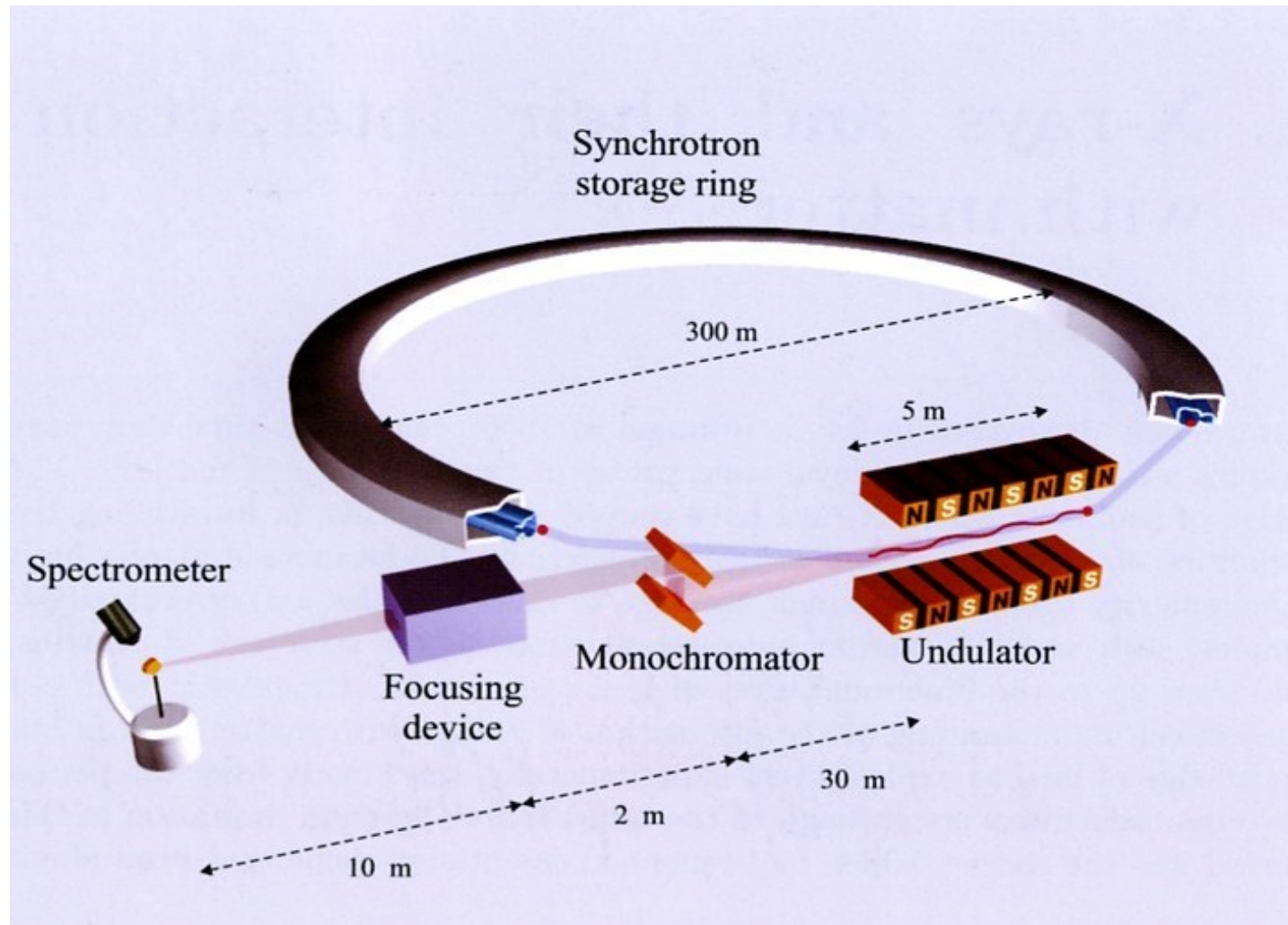
X-Ray Tube



X-Ray Tube



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

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

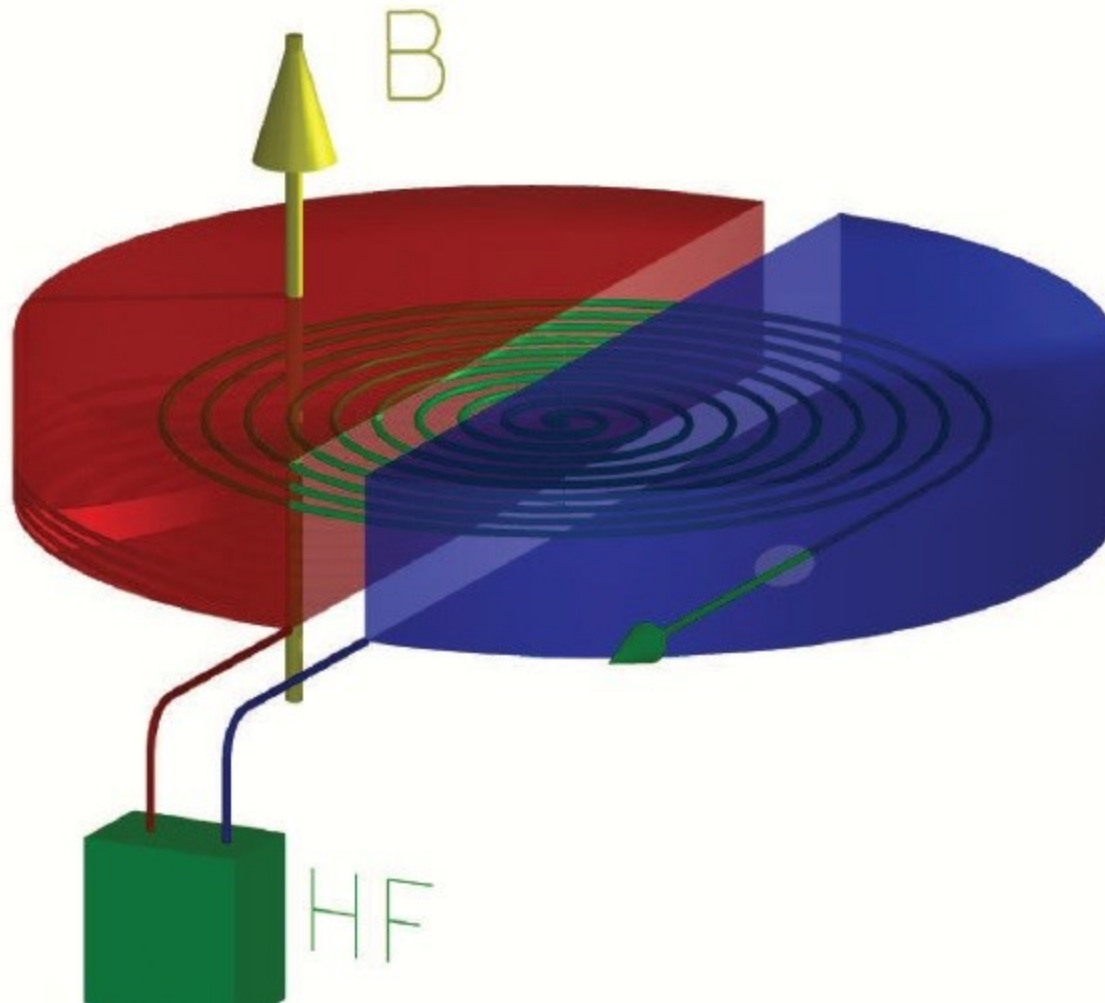
- At high energies the mass changes and the frequency of the field needs to be adapted.

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

- 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

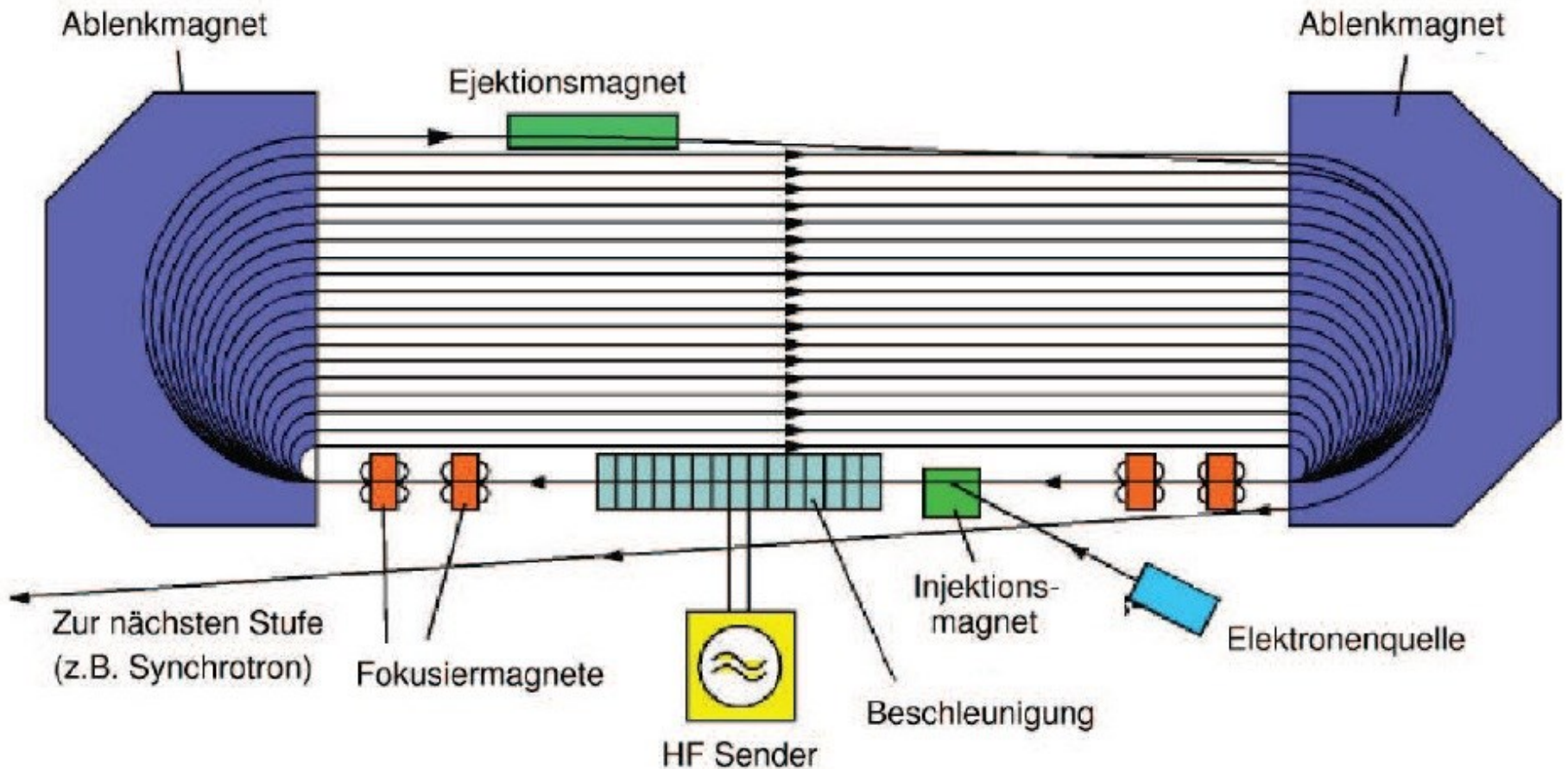
$$evB = m \frac{v^2}{R}$$

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

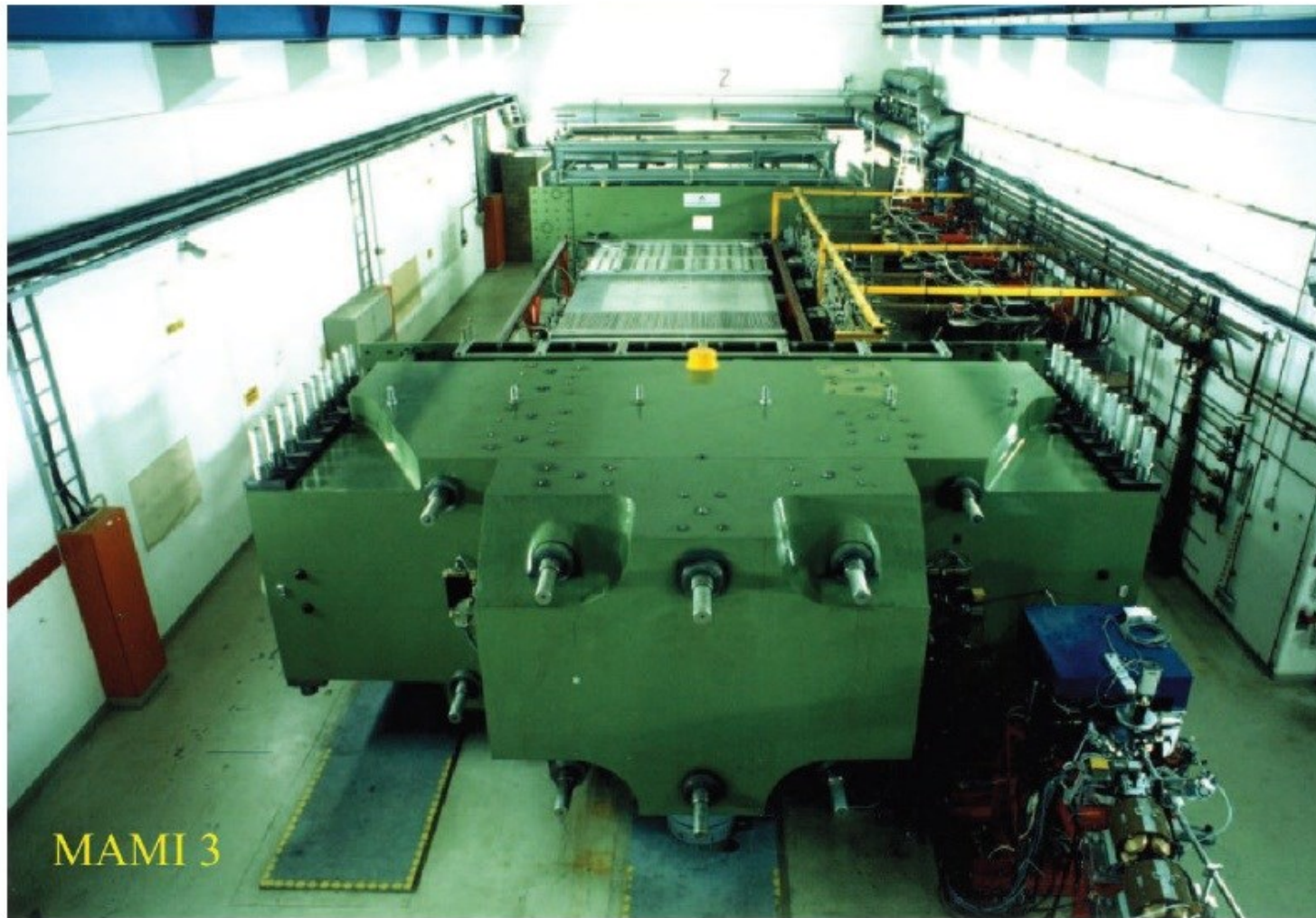
- Such Acceleration that electrons are in phase with RF field
- Energies up to 100 MeV can be reached

Example: BESSY II

Microtron



Microtron



Synchrotron

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

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

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

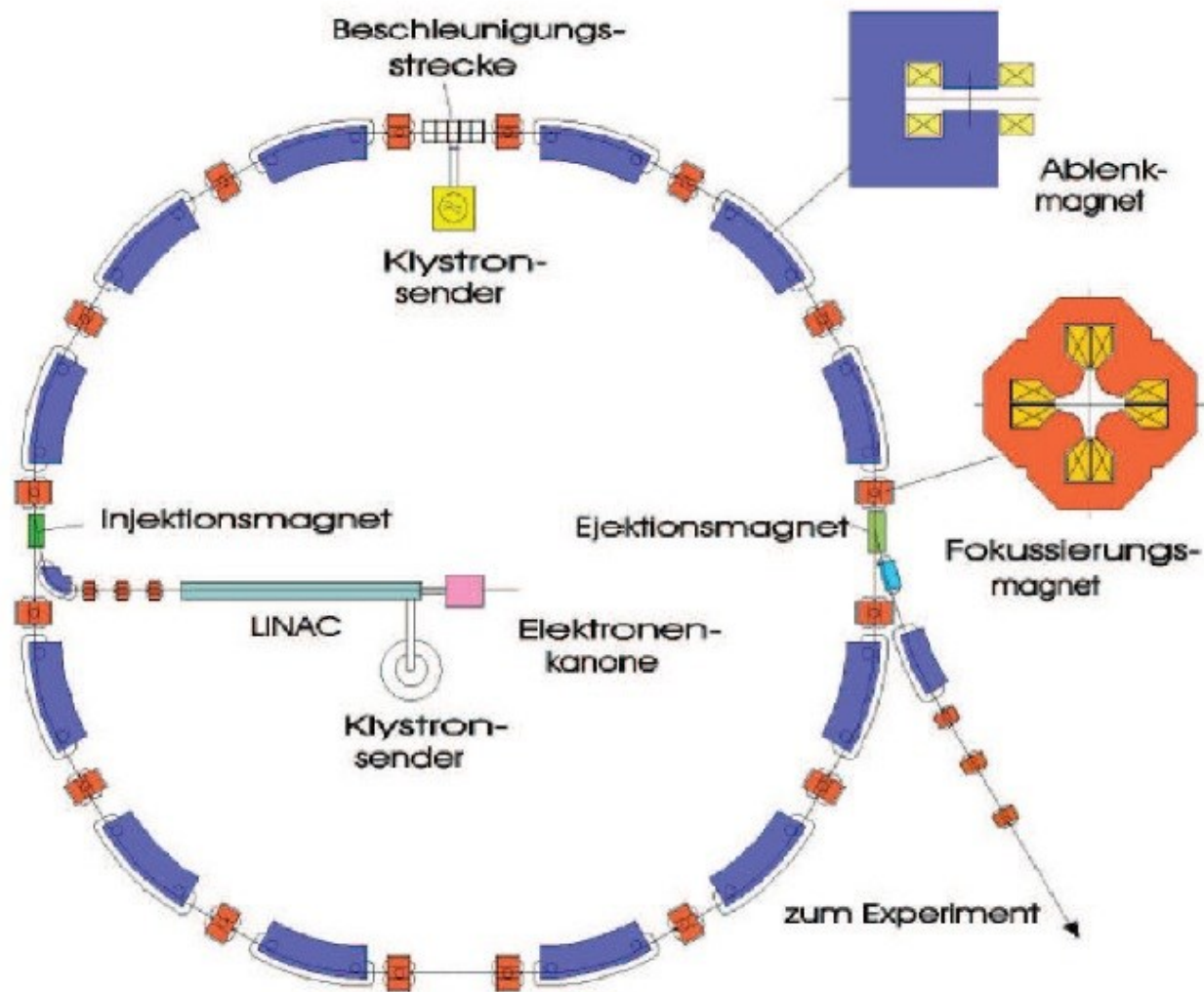
Bends in small , local magnets

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

\Rightarrow Synchrotron



Synchrotron

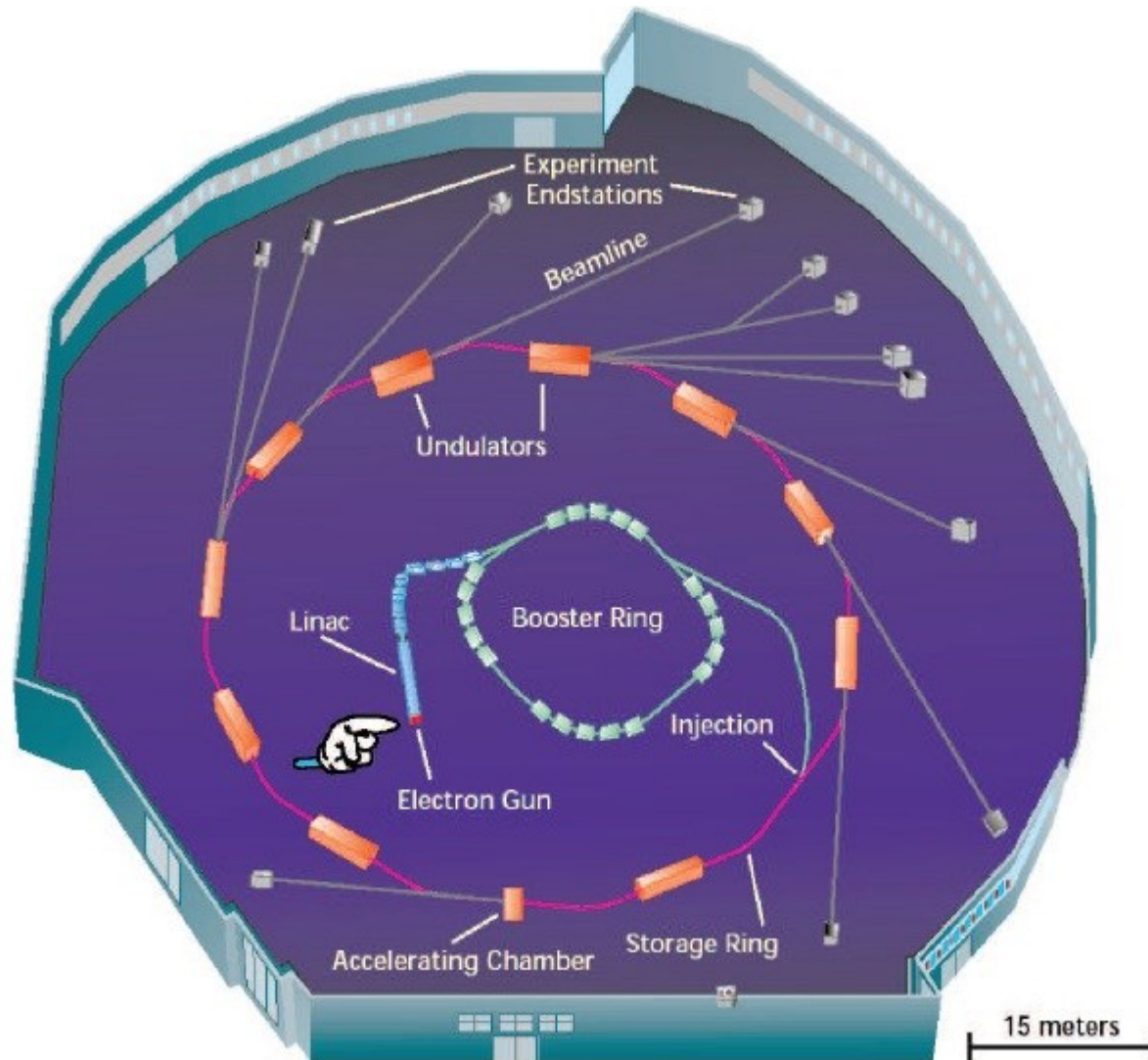


Synchrotron

- Modern synchrotron radiation sources are built as storage rings
- Synchrotron cannot operate at $E=0$ since it requires $B \neq 0$.
 - ⇒ 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:

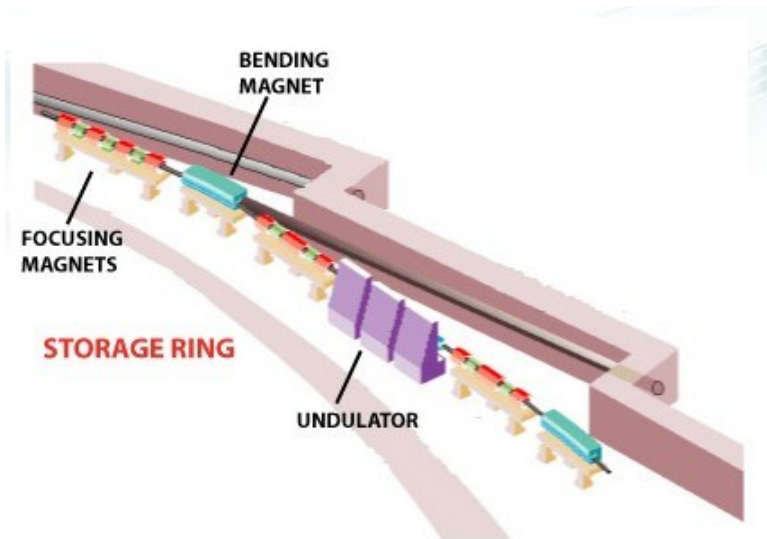
$$P = \left(\frac{e^2}{6\pi\epsilon_0 m_0^2 c^3} \right) \left(\frac{dp}{dt} \right)^2$$

Angular distribution resembles the one of a Hertz dipole:

$$\left(\frac{dP}{d\Omega} \right) = \left(\frac{e^2}{16\pi^2 \epsilon_0 m_0^2 c^3} \right) \left(\frac{dp}{dt} \right)^2 \sin^2(\Psi)$$

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 :

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

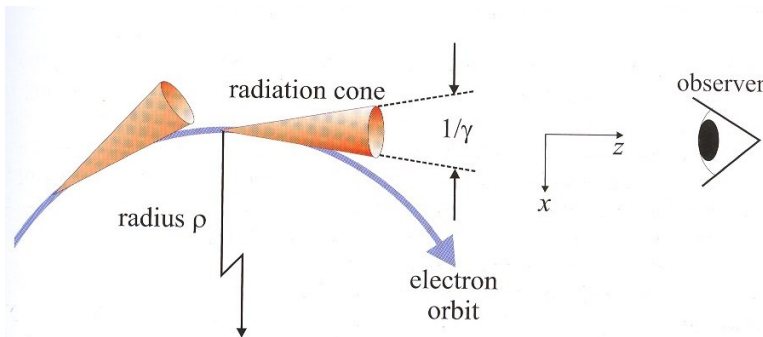
For 5GeV and $mc^2=0.511$ MeV get $\gamma \approx 10^4$

Centrifugal=Lorentz force yields for radius:

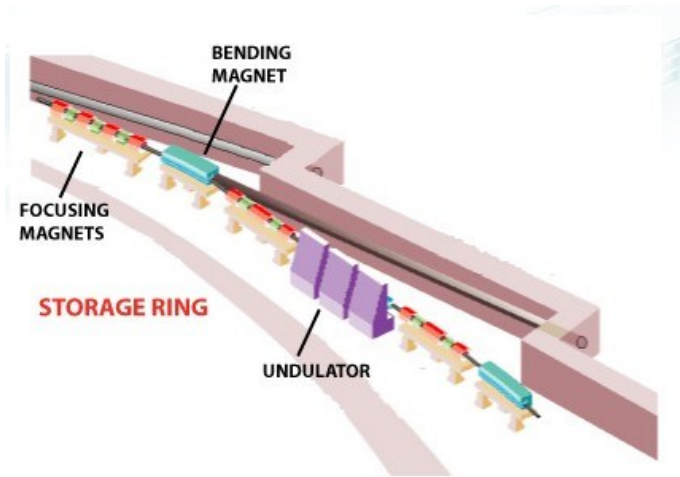
$$\rho = \frac{\gamma mc}{eB} = \frac{3.3 E [\text{GeV}]}{B[\text{T}]} \approx 25 \text{ m}$$

$$E_e = 6 \text{ GeV}, \quad B = 0.8 \text{ T}$$

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



Bending Magnets



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

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

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

Energy loss by synchrotron radiation per turn:

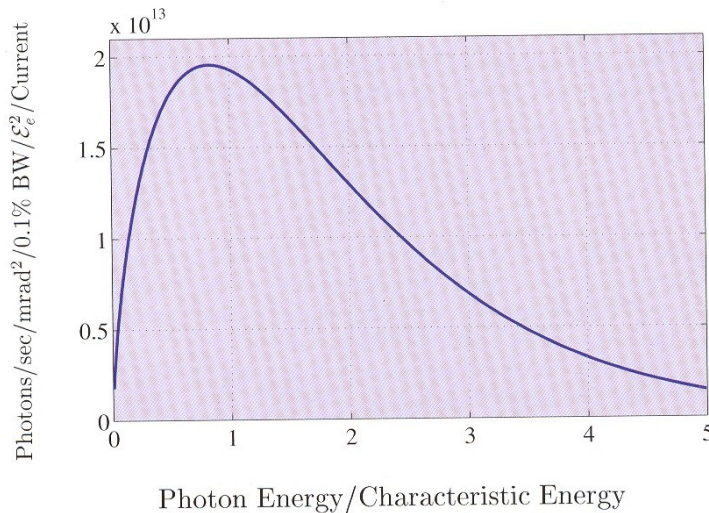
$$\Delta E[\text{keV}] = \frac{88.5 E^4[\text{GeV}]}{\rho[\text{m}]}$$

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

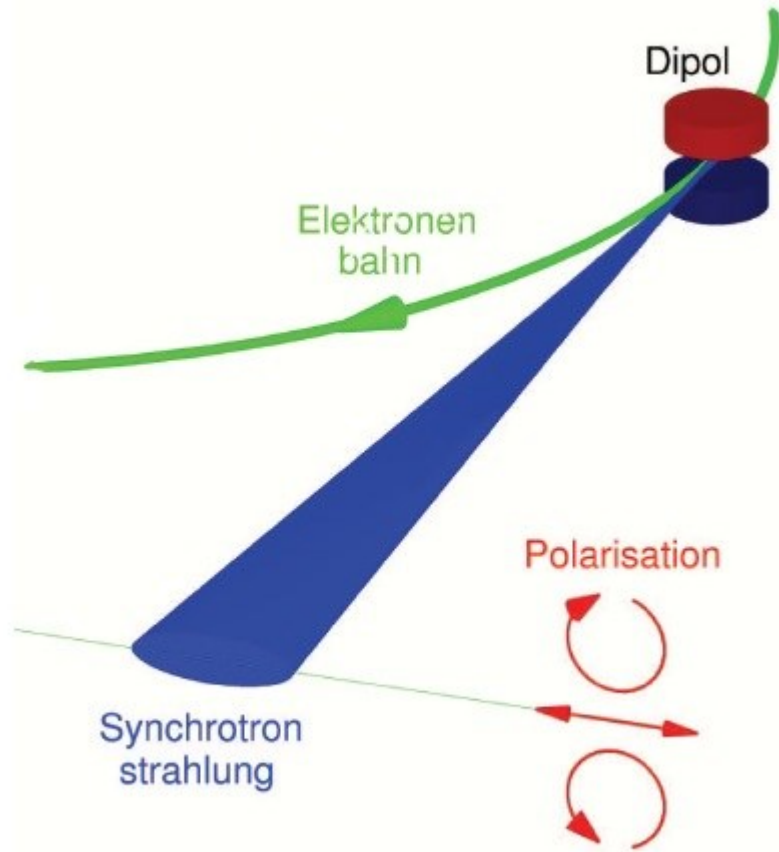
$$\text{For } I = 500 \text{ mA} \equiv 0.5 \frac{\text{Cb}}{\text{s}} = 0.5 \times 6.25 \times 10^{18} \frac{e^-}{\text{s}}$$

$$\rightarrow P = 0.5 \times 6.25 \times 10^{18} \frac{e^-}{\text{s} \times 26.6 \text{ keV}}$$

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



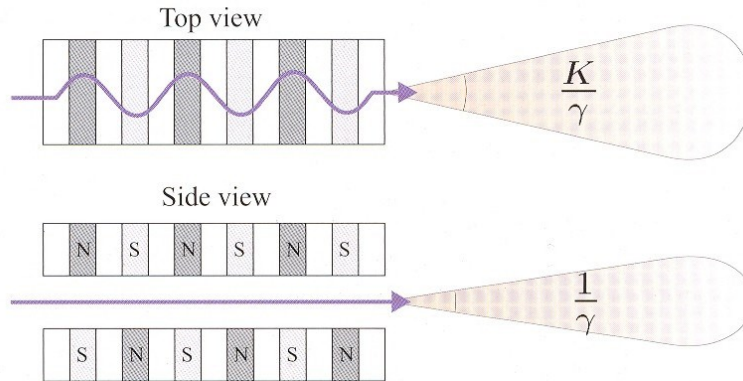
Polarization



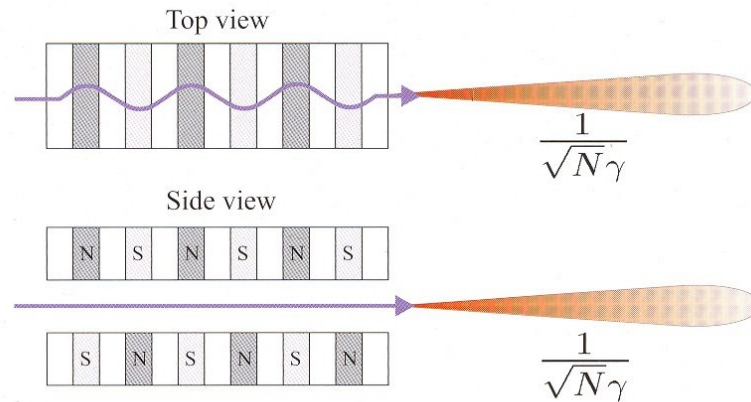
- Synchrotron radiation is polarized linearly in the plane of the orbit
- Above and below the orbital plane of the polarization is circular
- Important applications for magnetic x-ray scattering

Insertion Devices (Wigglers and Undulators)

(a) Wiggler



(b) Undulator



Wiggler:

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

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

N: number poles

Undulator:

$$k = eB / mc \quad k_u = 0.934 \lambda_u [\text{cm}] B_0 [\text{T}]$$

with λ_u undulator period

~~undulator fundamental:~~

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

on axis

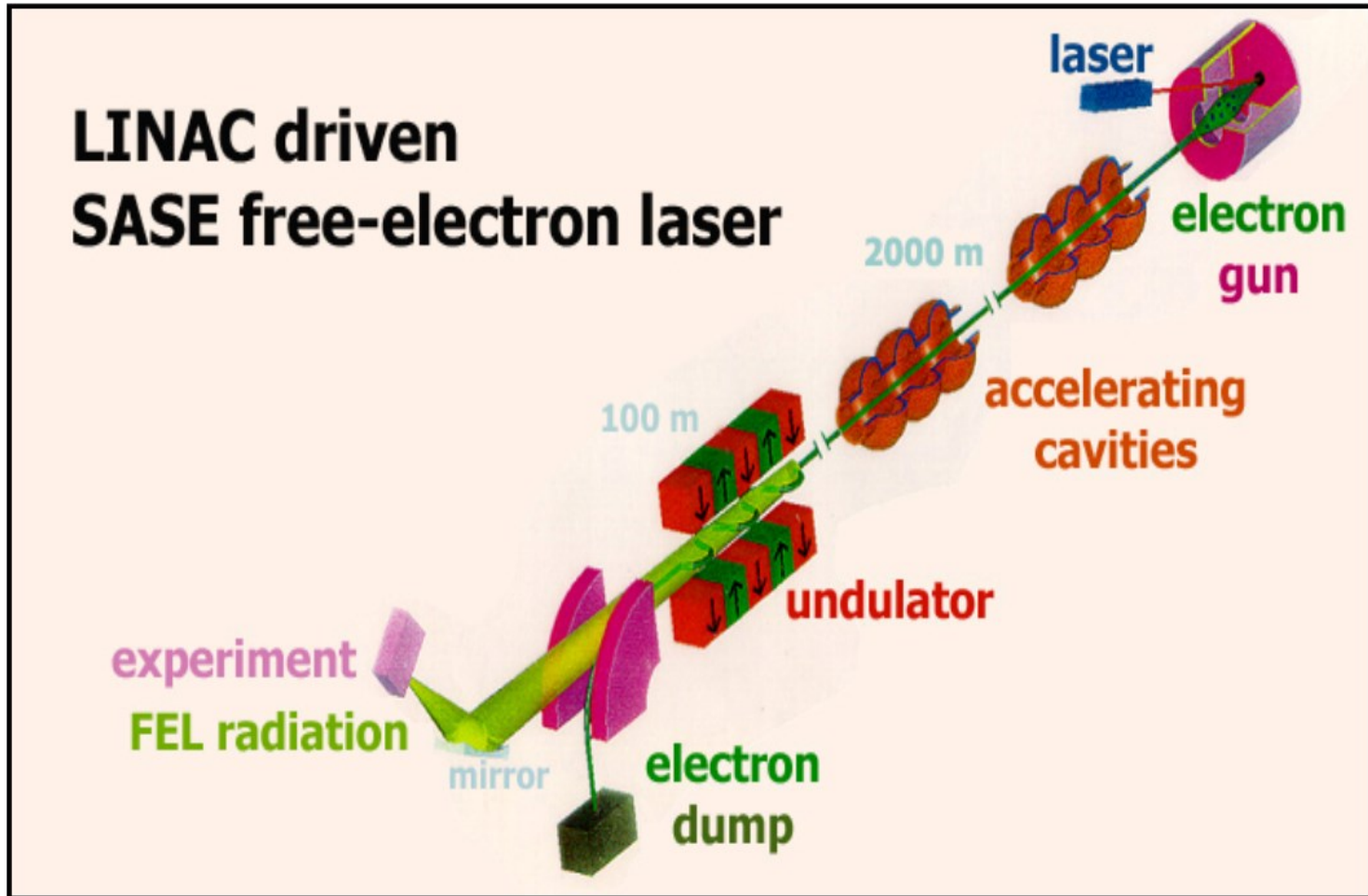
$$\text{Flux} \sim E^2 \times N^2$$

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

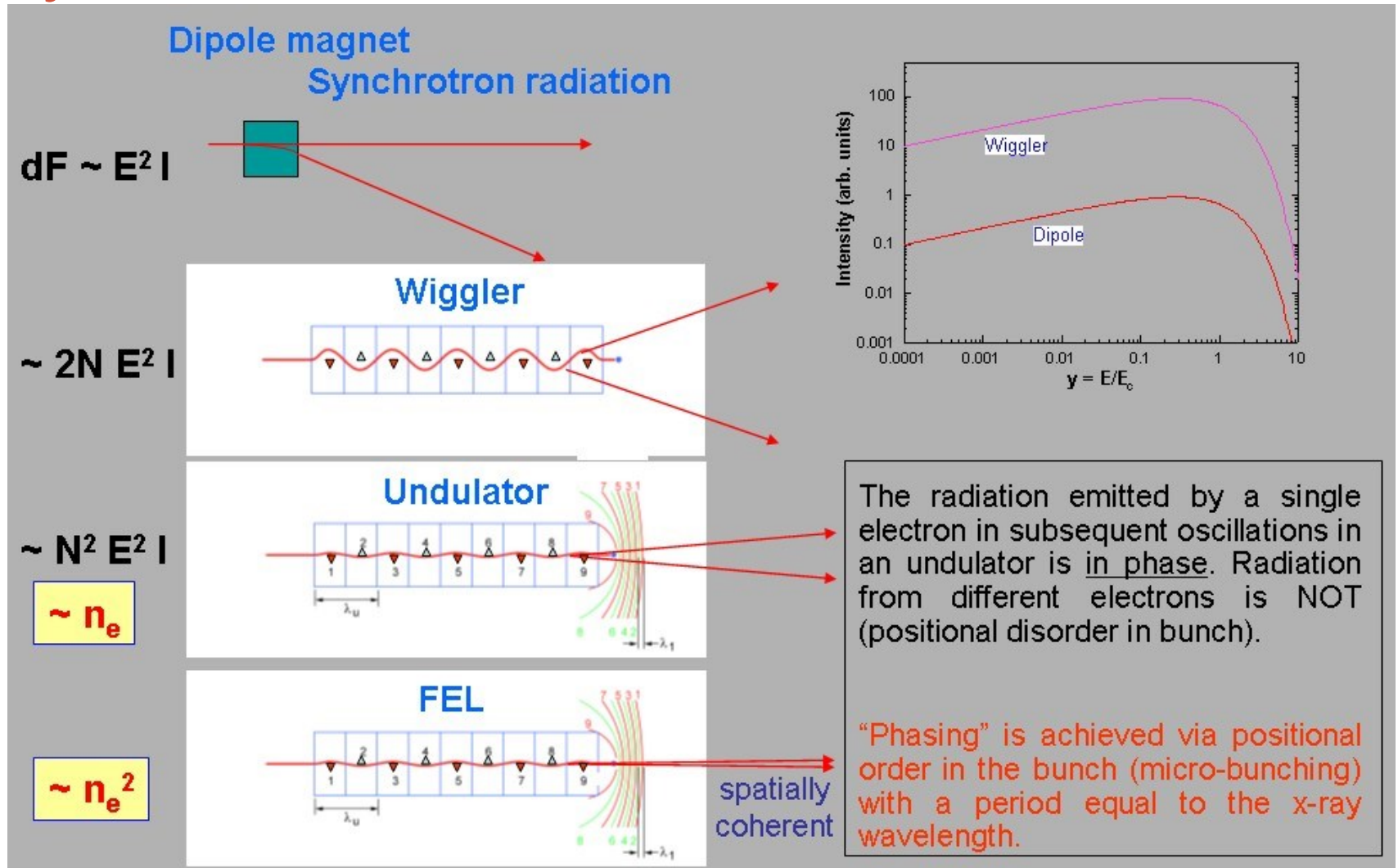
Towards Diffraction Limited Light Sources: MAX IV (Lund)



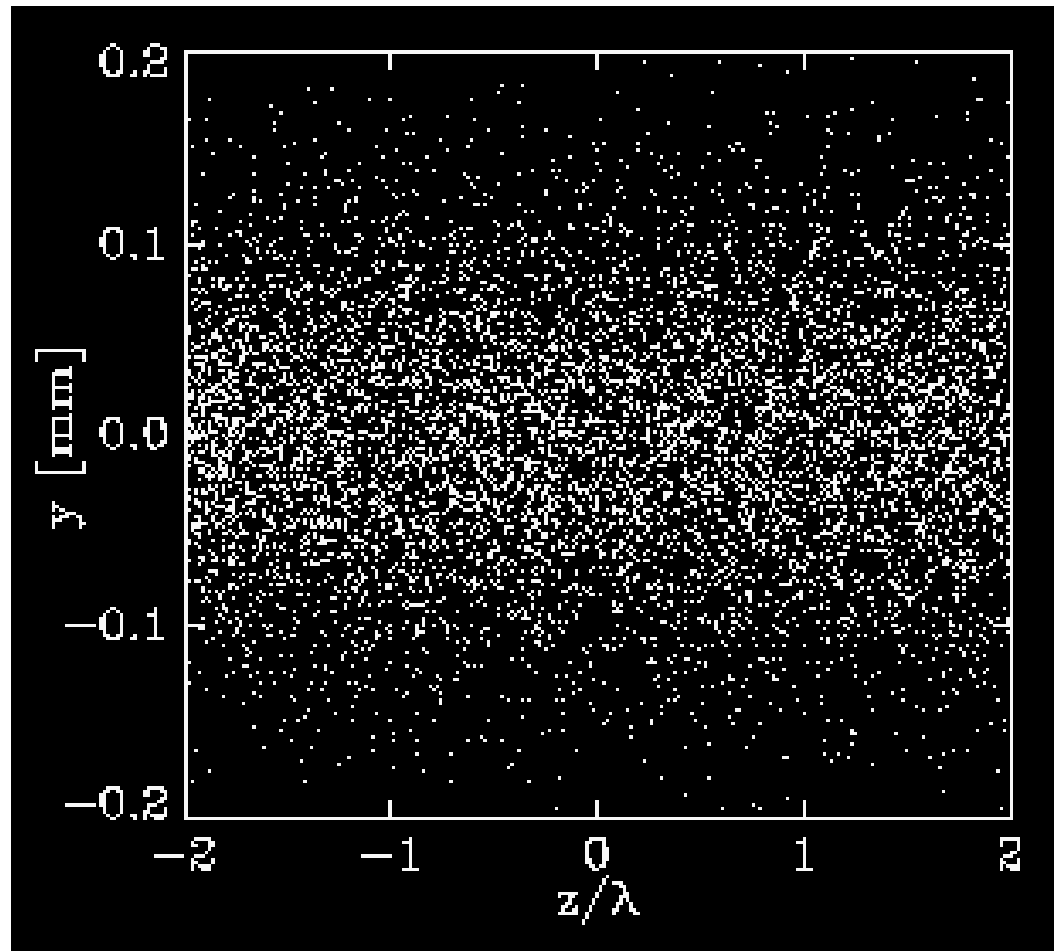
Free Electron Lasers (FELs)



Synchrotron and FEL Sources



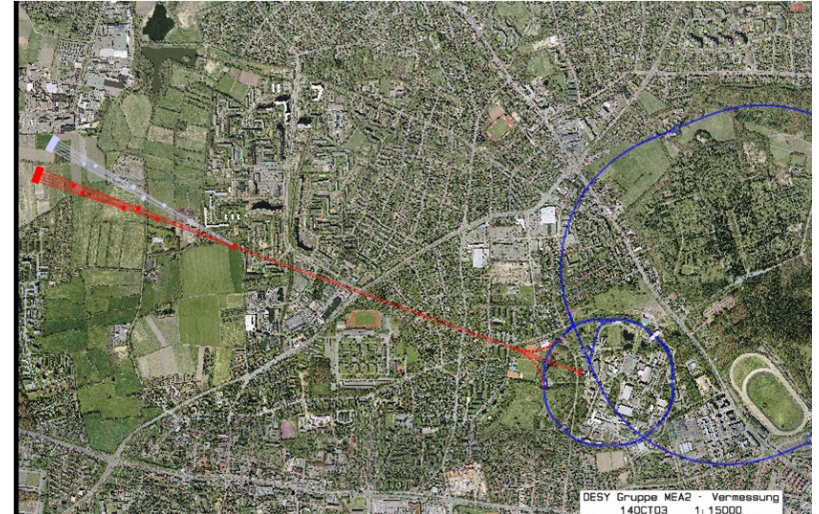
Electron Bunching



GENESIS – simulation for TTF parameters

Courtesy Sven Reiche
(UCLA)

VUV and X-Ray FELs



Brilliance

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

