Synchrotron techniques for materials characterization

X-ray generation, interaction and detection

Berit Zeller-Plumhoff

Data-Driven Analysis and Design of Materials

Universität Rostock

Open position(s) for student assistants / theses projects

1. **Design and implementation of online lecture „Synchrotron techniques for materials characterization“**

2. Modelling of chronic inflammation in skin pathologies

3. Modelling of angiogenesis near biodegradable implants

4. (Data-driven) Modelling of biofouling and anti-fouling strategies

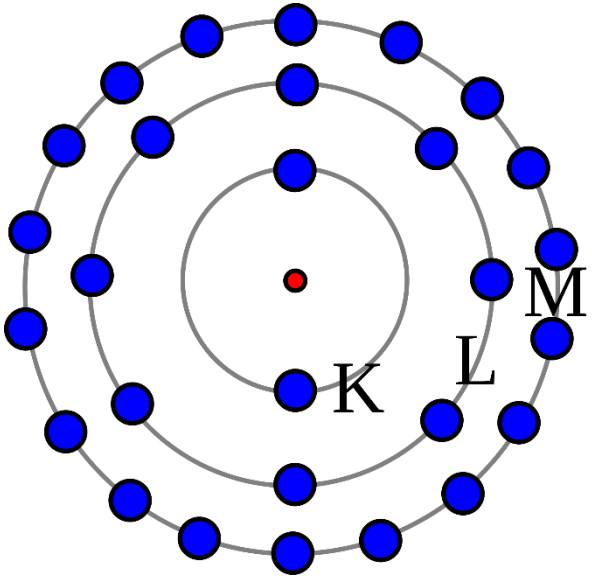
Learning goals

At the end of the lecture you will

- Know the principles of X-ray generation
- Be familiar with the main components of a synchrotron and their function
- Understand in which manner X-rays can interact with matter
- ~~Understand the requirements for X-ray detection~~

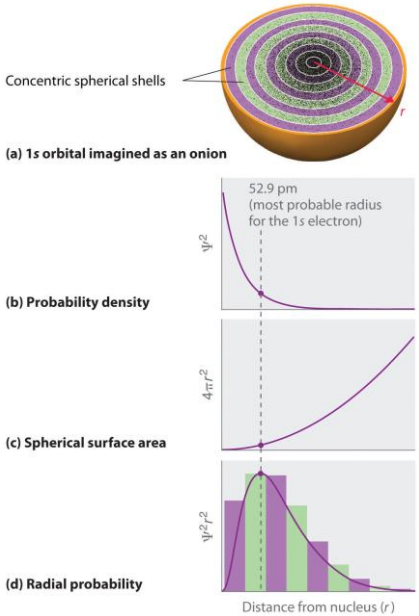
Atoms

Bohr model (1921)



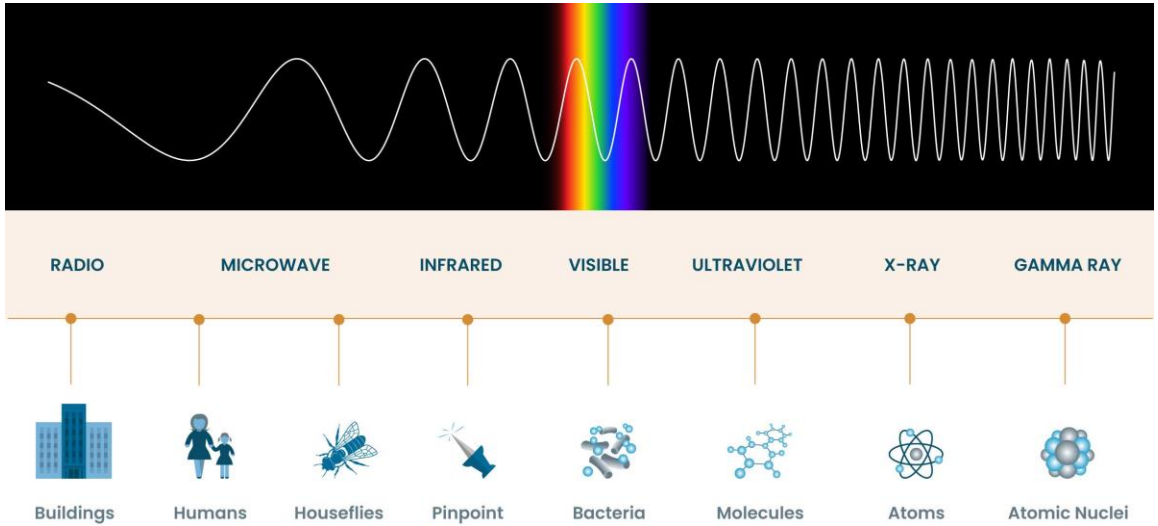
https://en.wikipedia.org/wiki/Bohr_model

Atomic orbitals (quantum mechanics)



https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Organic_Chemistry_(Morsch_et_al.)/01%3A_Structure_and_Bonding/1.02%3A_Atomic_Structure_-_Orbitals

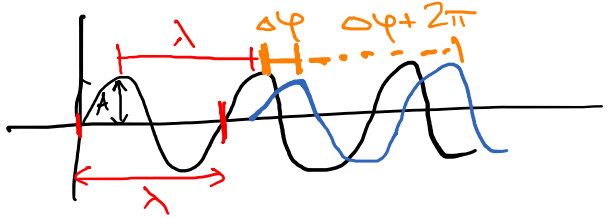
X-rays



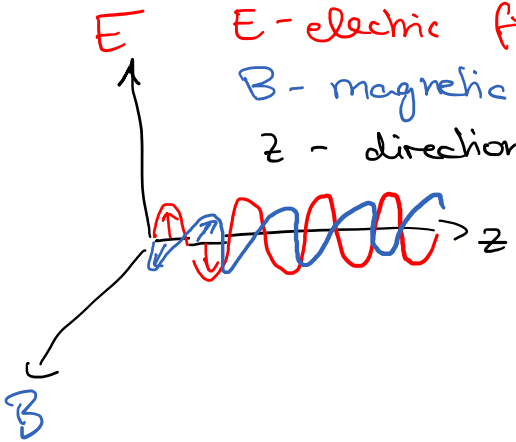
Wavelength / m	10^{3}	10^{-2}		10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

https://hubblesite.org/contents/articles/the-electromagnetic-spectrum

X-rays



Δφ - phase difference
λ - wavelength
A - amplitude



E - electric field
B - magnetic field
z - direction of propagation

wavelength unit $[\lambda] = \text{Å}$ (Ångström)
$= 10^{-10}\,m = 0.1\,nm$

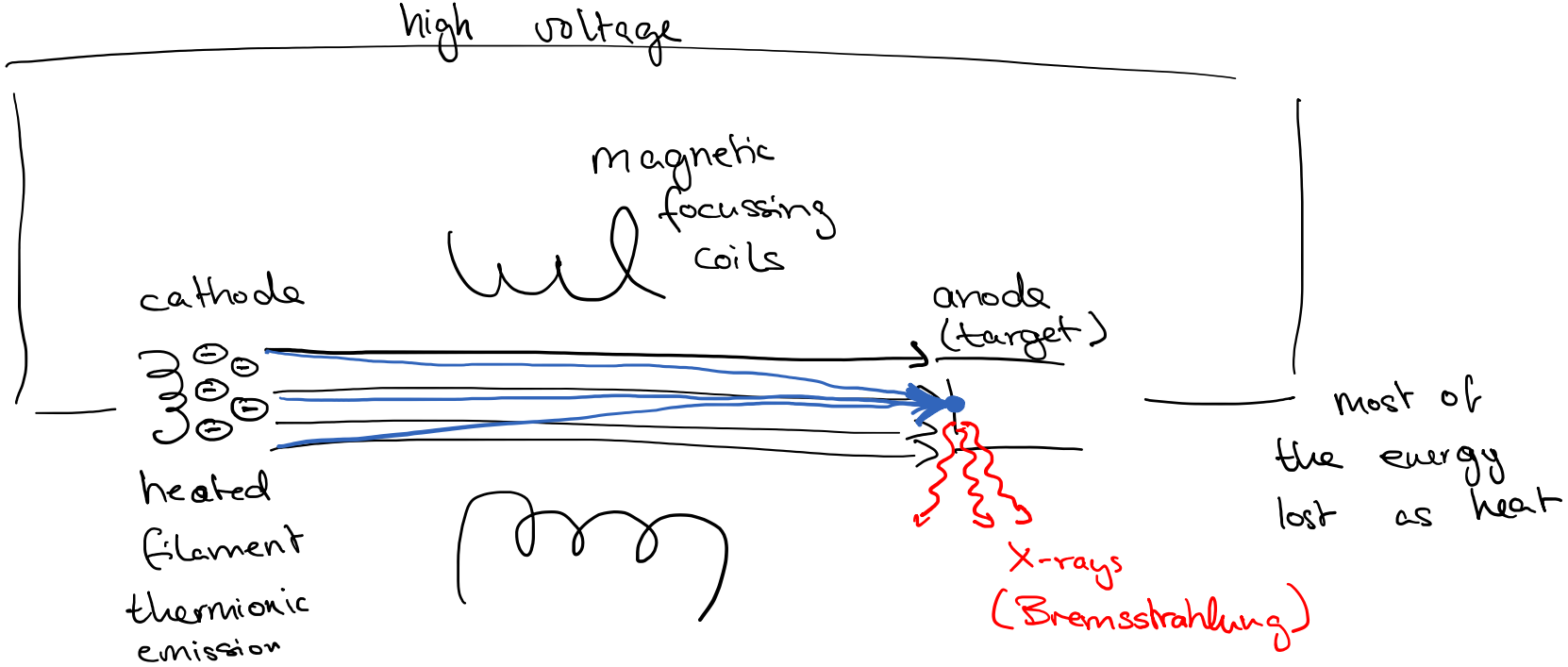
$$\lambda = \frac{hc}{E_{ph}}$$

h - Planck's constant
c - speed of light
E_{ph} - photon energy

X-ray history

- 1895: Wilhelm Conrad Röntgen discovered X-rays in Würzburg
- until mid 1970 steady and slow progress
  → main limitation X-ray source
- mid 1970: storage rings for high energy physics
  → generation of synchrotron radiation
- dedicated construction of synchrotrons
  → nowadays 3rd – 4th generation of synchrotron sources

How does a laboratory X-ray source work?



X-ray sources

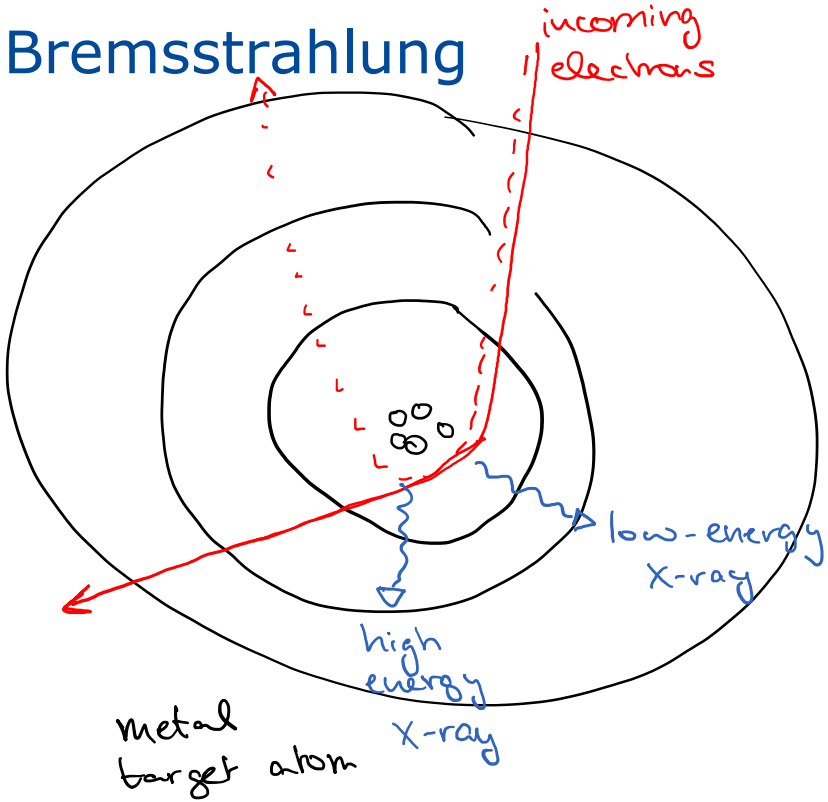
Coolidge universal X-ray tube (1923-1926)

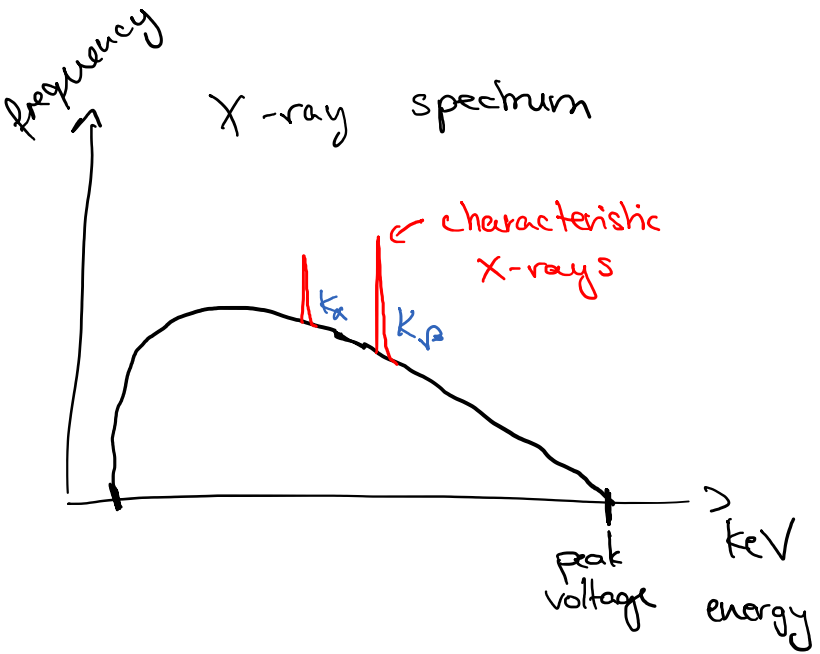
https://www.orau.org/health-physics-museum/collection/x-ray-coolidge/universal/victor-x-ray-corp-universal-x-ray-tube.html

Modern tube in micro computed tomography scanner

https://www.bristol.ac.uk/earthsciences/research/palaeobiology/facilities/xtm-facility/

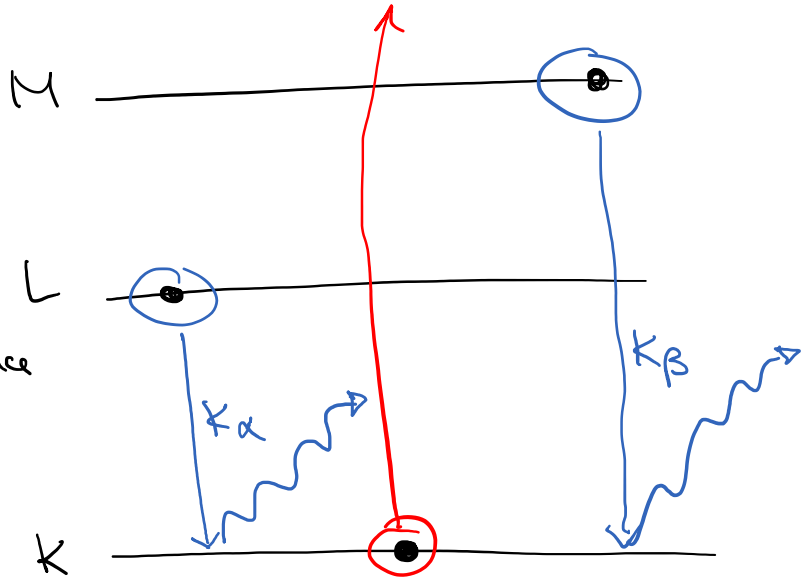
Bremsstrahlung



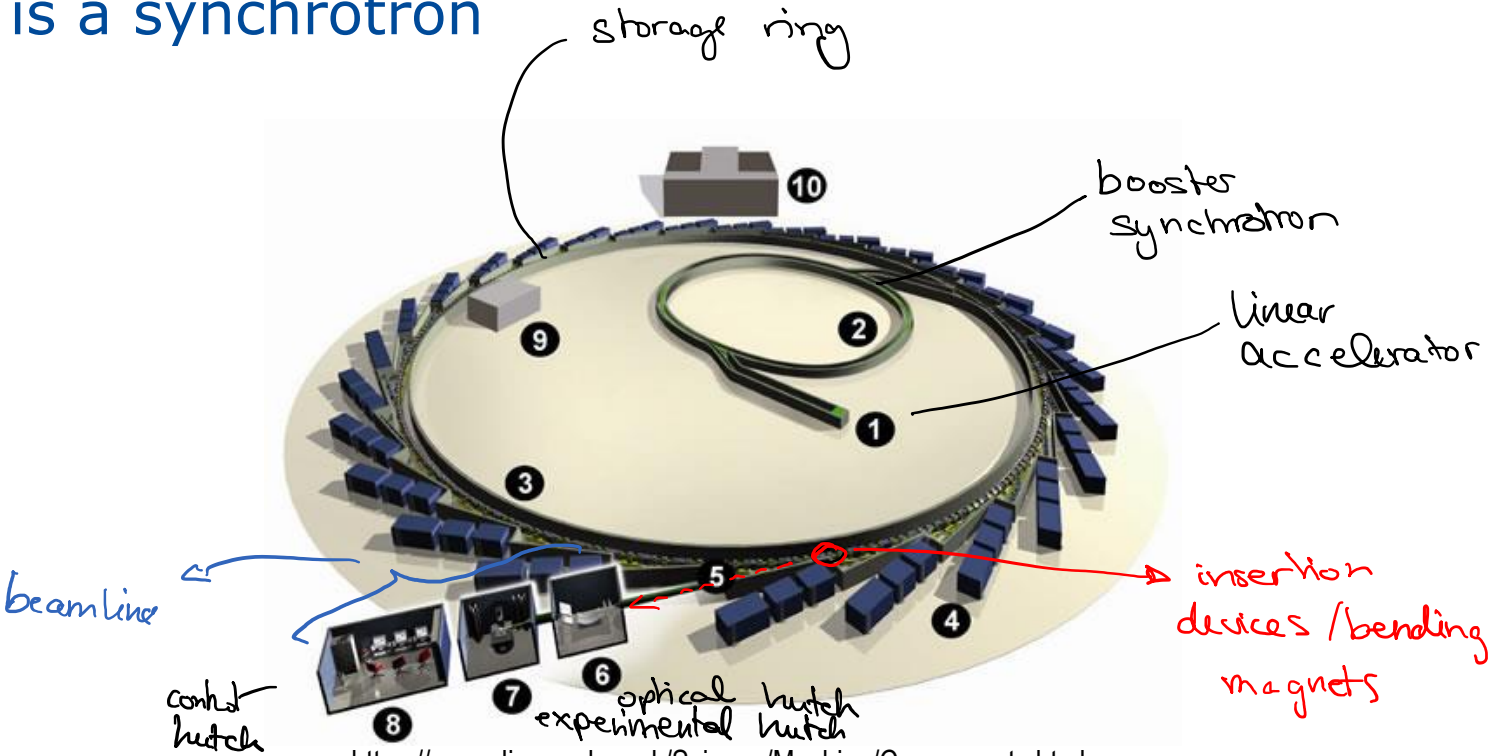


Characteristic X-rays

- interaction of incoming electron with (inner shell) electron from target atom
  → vacancy
- relaxation of outer shell electron into vacancy
  → producing characteristic X-rays with energy equal to the difference in binding energies of shells
- target dependent (W, Ag, Mo, Cu)



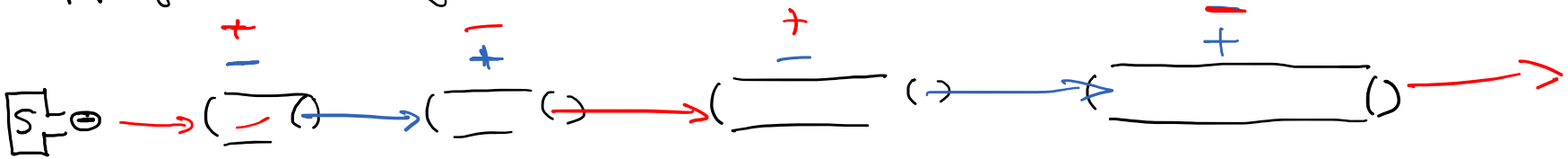
What is a synchrotron



https://www.diamond.ac.uk/Science/Machine/Components.html

Linear accelerator

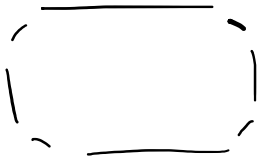
- hollow pipe vacuum chamber
  - → no air interaction
  - → ultra-high vacuum 10^{-11} bar
- ~ 10 m long
- particle source → charged particles
  - → cathode for electrons
  - → ion source for positrons
- series of open-ended cylindrical electrodes → radiofrequency (RF) cavity
  - length increases with distance from source
- apply oscillating voltage



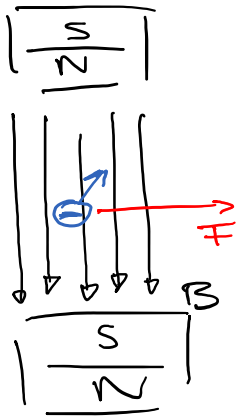
- final energy ~ 0.1 GeV

Booster synchrotron

- athletics track design



- straight section: RF cavities for acceleration → 3 – 6 GeV
- corners: dipole bending magnet



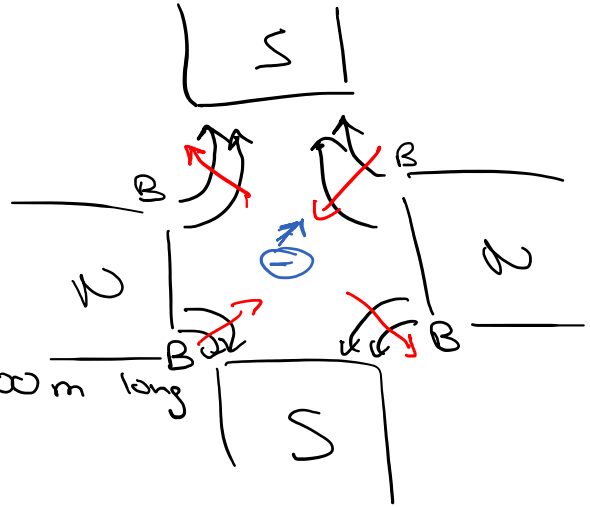
B - magnetic field

F - Lorentz force

- increase magnetic field strength as particle energy increases

Storage ring

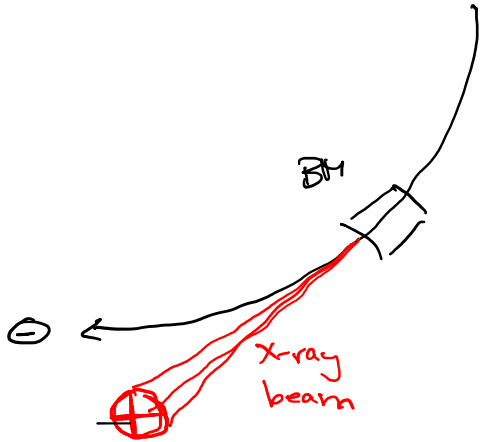
- bending magnets
- quadrupole magnets
  → multiple



- Petra III → 2.3 km long
  Canadian light source → 200 m long
- straight section:
  insertion devices (wigglers and undulators)

Bending magnet

- decelerating electron bunches due to change in direction
  → emission of radiation
  - intensity
  - beam collimation



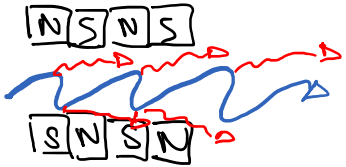
$$\varnothing = \frac{1}{\gamma} \qquad \gamma = \frac{E}{E_0}$$

E: electron energy, E_0: rest energy, γ: Lorentz factor

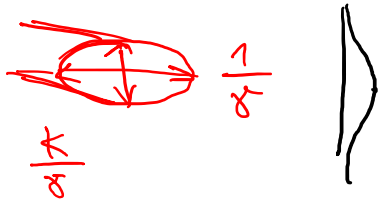
$E_0 = 0.511$ MeV

$E = 4.5$ GeV $= 4500$ MeV $\Rightarrow \gamma \sim 9000$

Wigglers and undulators



- N dipole magnets → number of periods
- $I_{wiggler} = N \cdot I$



- undulator: constructive interference of X-rays

$I_{undulator} = N^2 \cdot I$

collimation

- energy spectrum of X-rays adjusted by adjusting magnetic field strength