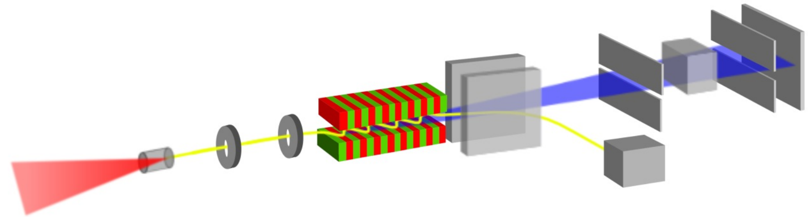
HelmholtzZentrum münchen
German Research Center for Environmental Health



Munich-Centre for
Advanced Photonics (MAP)

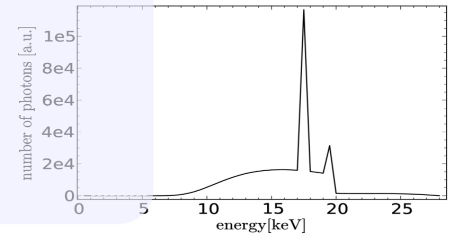
LAOLA
Laboratory for Laser- and beam-driven plasma Acceleration

Introduction into brillant X-ray sources for medical imaging

From X-ray tubes over large-scale synchrotrons to compact, laser-driven sources

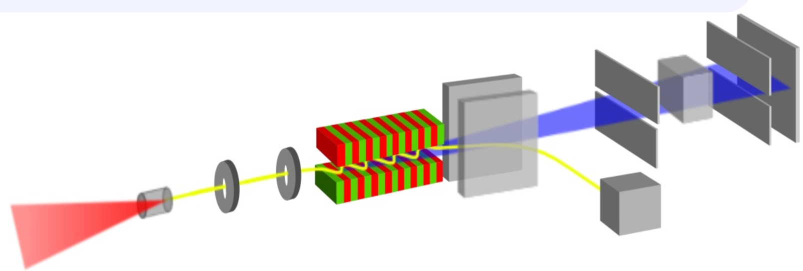
Ultimate goal: dose/contrast agent reduction

- **disadvantages of x-ray tubes:**
  - **polychromatic spektrum → low CNR/Dose**
  - **focal spot size → limited spatial resolution (especially for magnification)**

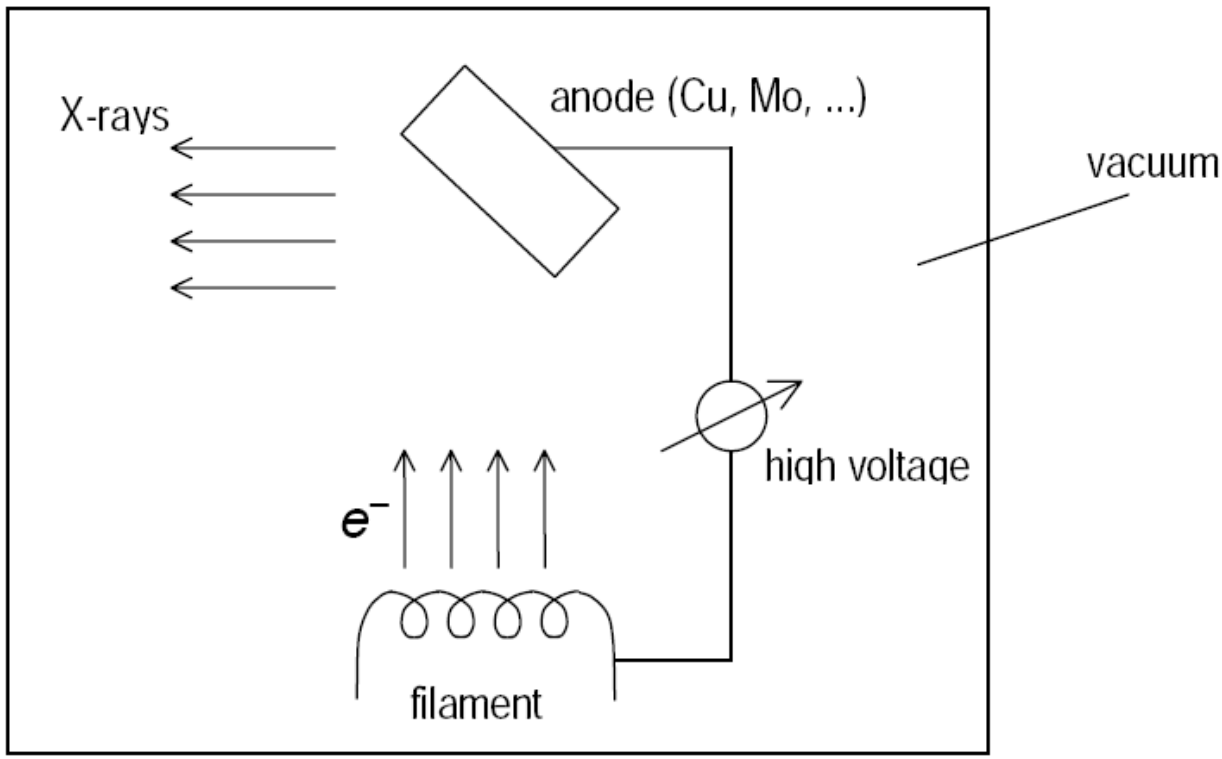


- **advantages of undulator sources:**
  - **quasi-monochromatic (few %) → high CNR/dose**
  - **laminar beam geometry → scatter reduction**
  - **low divergence → high spatial resolution**
  - **tunable energy**

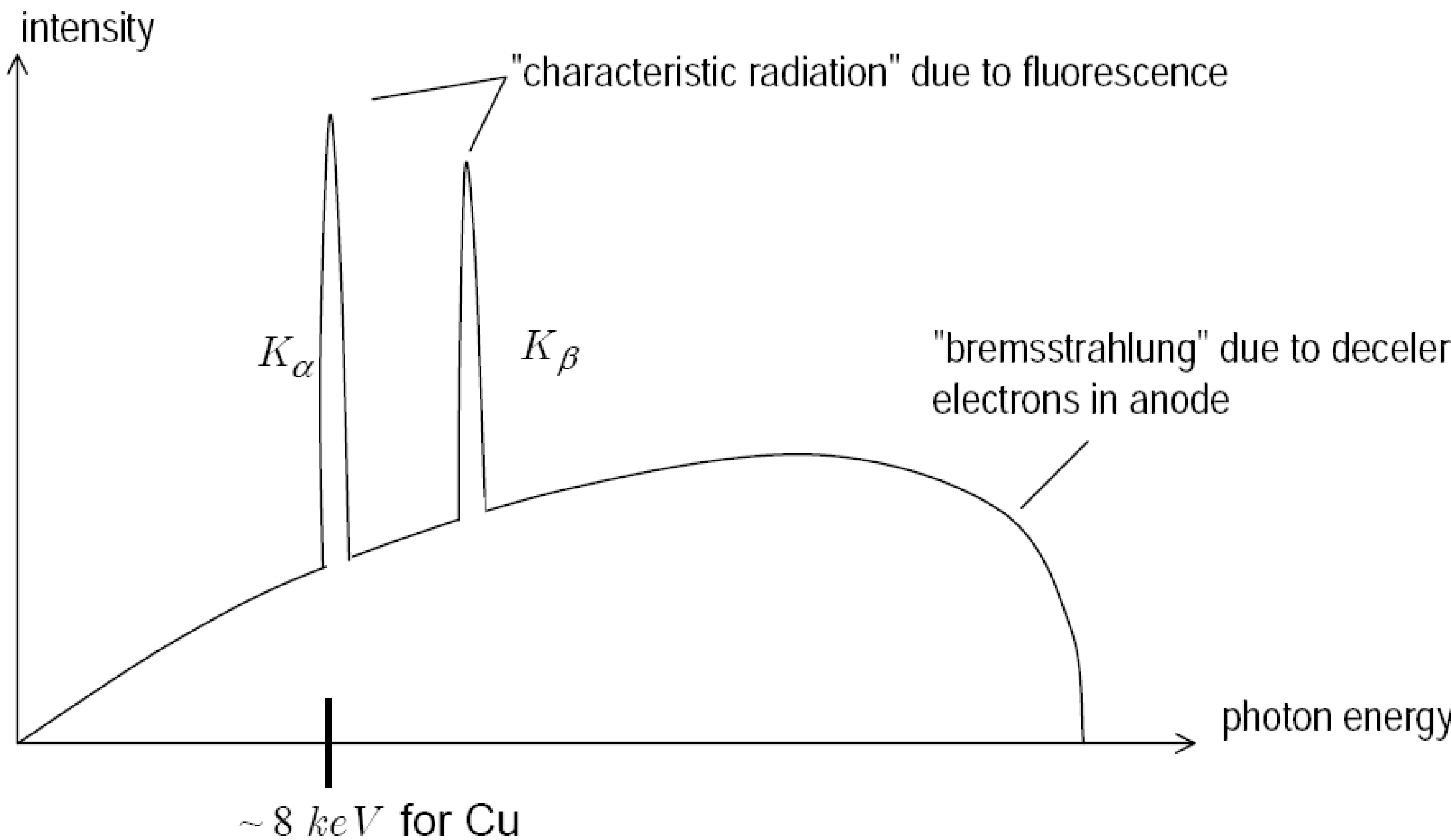
high brilliance (applies to the first three advantages)



Laboratory Source ("X-ray tube")



emitted spectrum:



Synchrotron

First constructed for high energy physics experiments since 1970's: dedicated synchrotron sources for condensed matter physics/chemistry/biology (esp. protein crystallography).

Figure of merit for many applications:

$$\text{brilliance} = \frac{\text{photons / sec}}{(mrad)^2\left(mm^2\ \text{source area}\right)(0.1\%\ \text{band width})}$$

$\uparrow$ 1 $\quad\uparrow$ 2 $\quad\uparrow$ 3

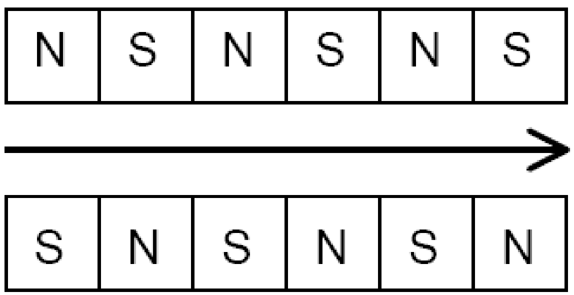
1 angular divergence of X-ray beam.
2 size of electron beam
3 determined by monochromator

Brilliance of synchrotron sources up to $\sim 10^{10}$ larger than X-ray tube, mostly due to much smaller angular divergence. This is important because many experiments use small samples (e.g. protein crystals!) that can use only a tiny fraction of radiation emitted by tube.

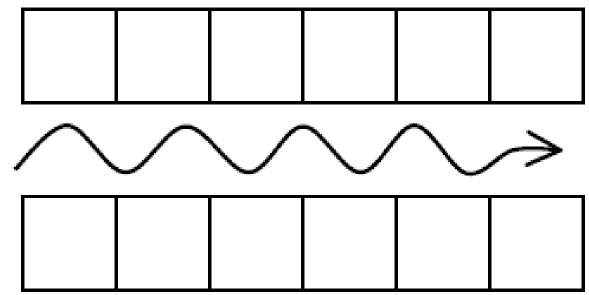
opening angle of synchrotron radiation: 1/gamma

➤ *Wiggler*

side view:



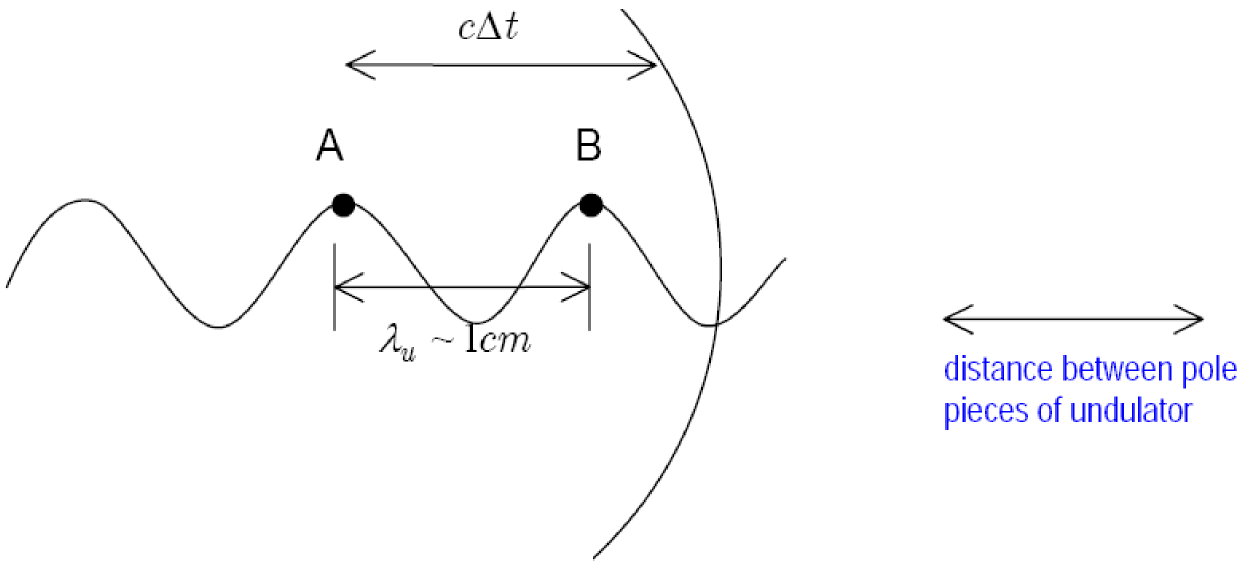
top view:



$N \sim 30$ segments of alternating B-field $\Rightarrow$ intensity enhancement by factor $\sim N$ compared to bending magnet.

► ***Undulator***

Similar to wiggler, but E-fields of wave fronts emitted in each segment are coherent, interfere constructively ⇒ intensity enhancement by factor $\sim N^2$.



Time for electron to get from A to B: $\Delta t = \frac{\lambda_u}{v}$

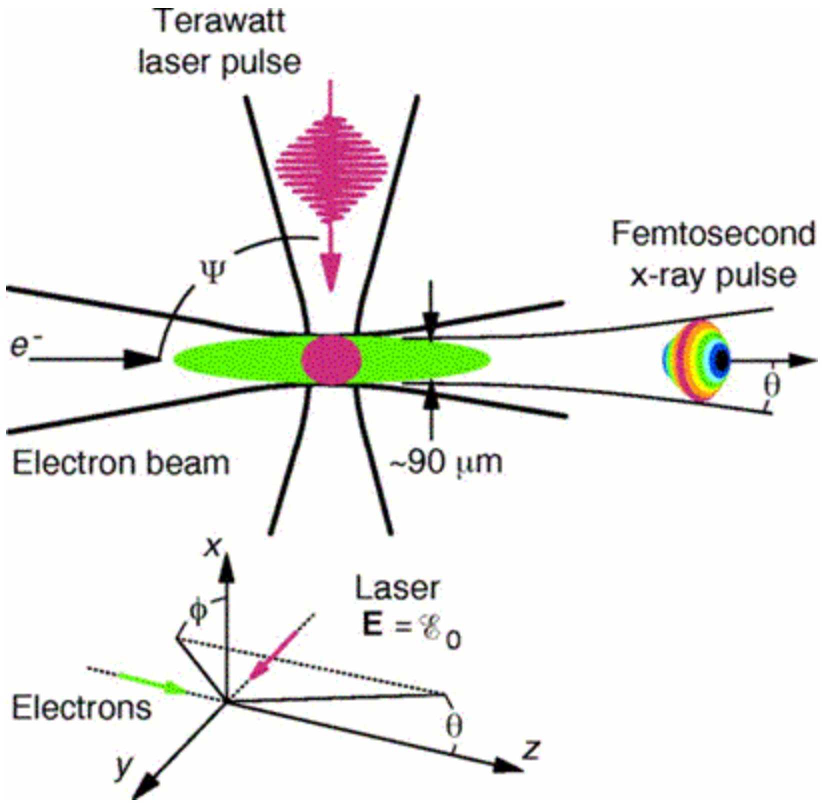
By this time, wave front emitted at A has progressed a distance $c\Delta t$.
Condition for constructive interference:

$$c\Delta t - \lambda_u = n\lambda$$

$$\Rightarrow \left(\frac{c}{v} - 1\right)\lambda_u = \left(\frac{1}{\beta} - 1\right)\lambda_u \approx \frac{\lambda_u}{2\gamma^2} = n\lambda$$

⇒ largest intensity at wavelengths $\lambda = \frac{\lambda_u}{2\gamma^2}\frac{1}{n} \sim \frac{1\mathring{A}}{n}$ (mostly use first harmonic, $n = 1$)

Laser Thomson scattering equivalent to undulator radiation



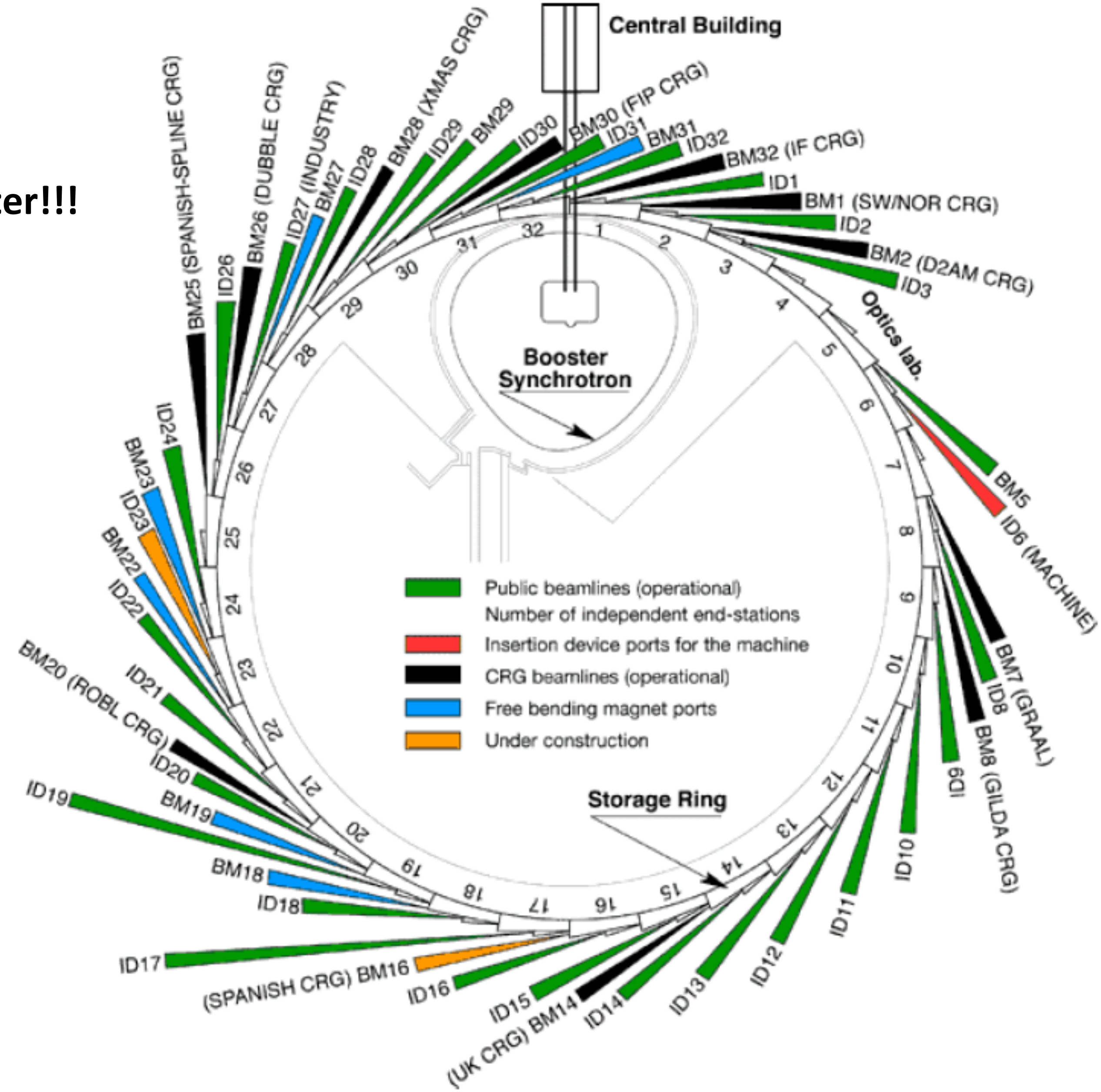
$$\lambda = \frac{\lambda_u}{2\gamma^2}$$

$\lambda_u \rightarrow \lambda_{laser}$

$2\gamma^2 \rightarrow 4\gamma^2$ as laser moves with v=–c, while undulator is at rest

typically: about 40 MeV electrons → 50 keV photons

600 m diameter!!!



Source: http://www.esrf.fr
For a list of the beamlines, see http://www.esrf.fr/beamline/

The "brightness" of a light source:

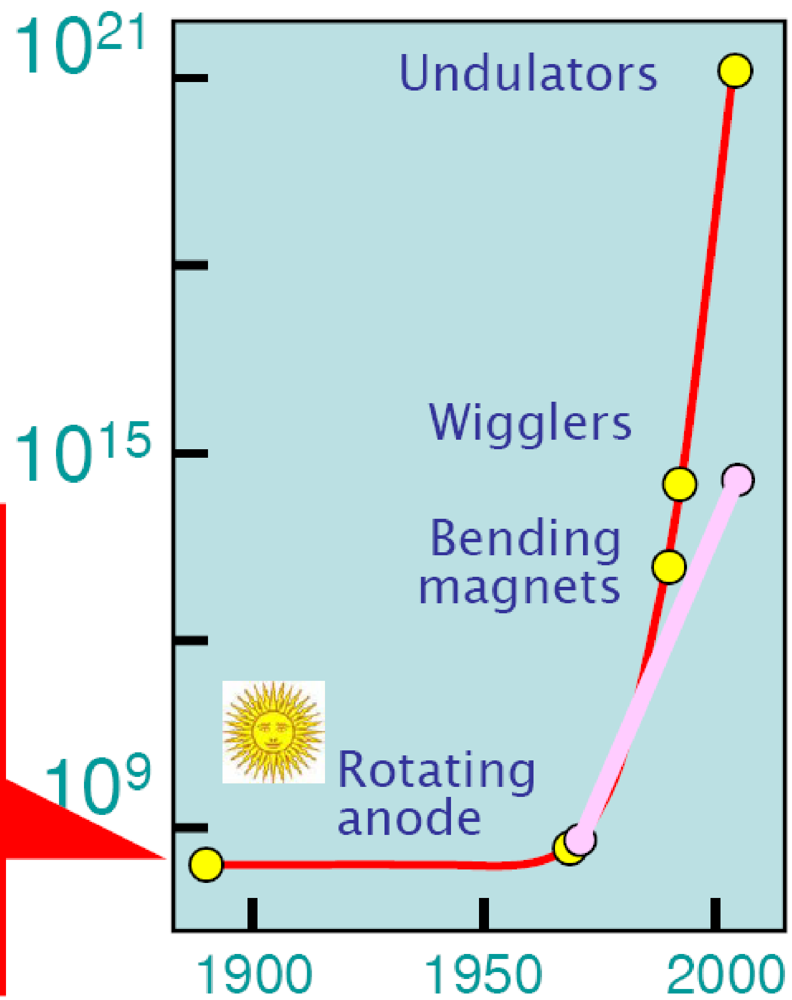
$$\textbf{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

Steep rise in brightness

the second wave

XFEL

SLS
SOLEIL (F)
DIAMOND (UK)
...
ESRF
SPring8
APS



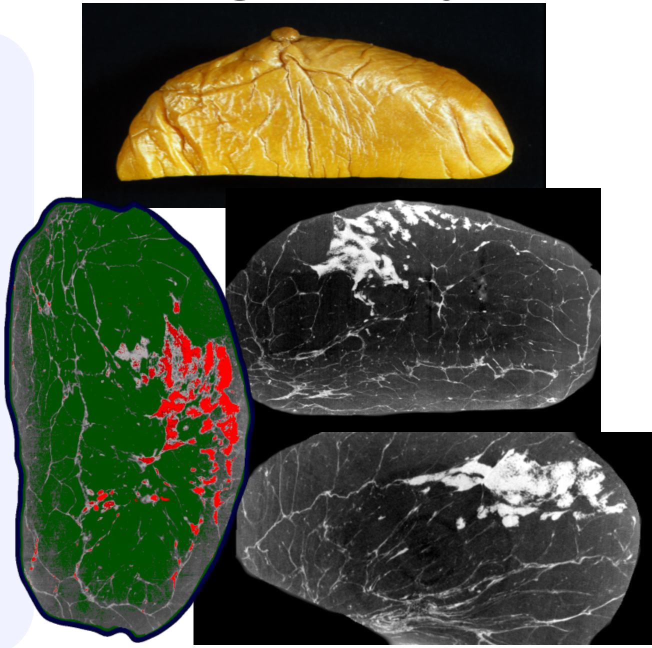
Moore's Law for semiconductors

Bertha Roentgen's hand
(exposure: 20 min)

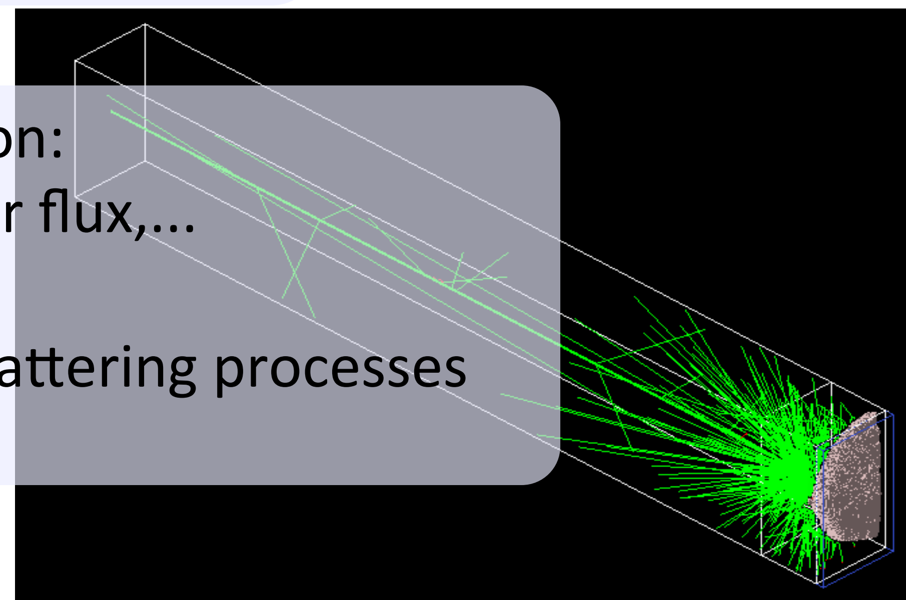
Third Generation Light Sources in Operation

Monte Carlo simulation of mammography

- high resolution voxemodels of breast
- created from CT-scans
  of anatomical breast specimens
- voxel size: 60 x 60 x 60 μm^3
- segmentation in different tissues:
  - adipose
  - glandular
  - skin

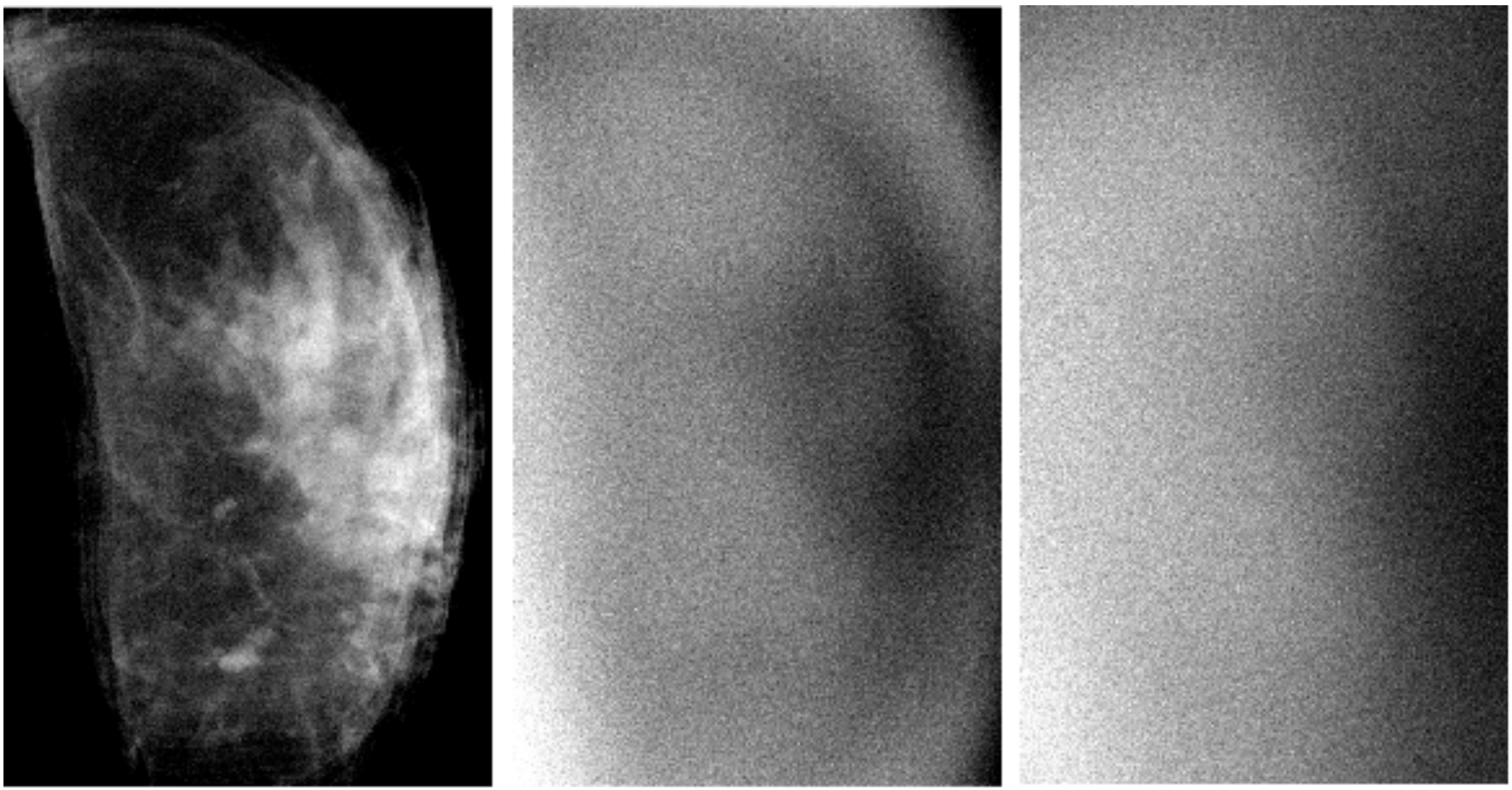


- using **brilliant** undulator radiation:
  beam geometry, spectral angular flux,...
- pulsed scanning geometry
- simulation of absorption and scattering processes
  with Geant4-Software-Toolkit



Simulation of mammography

0.2 mGy average glandular dose at ~10^{11} photons

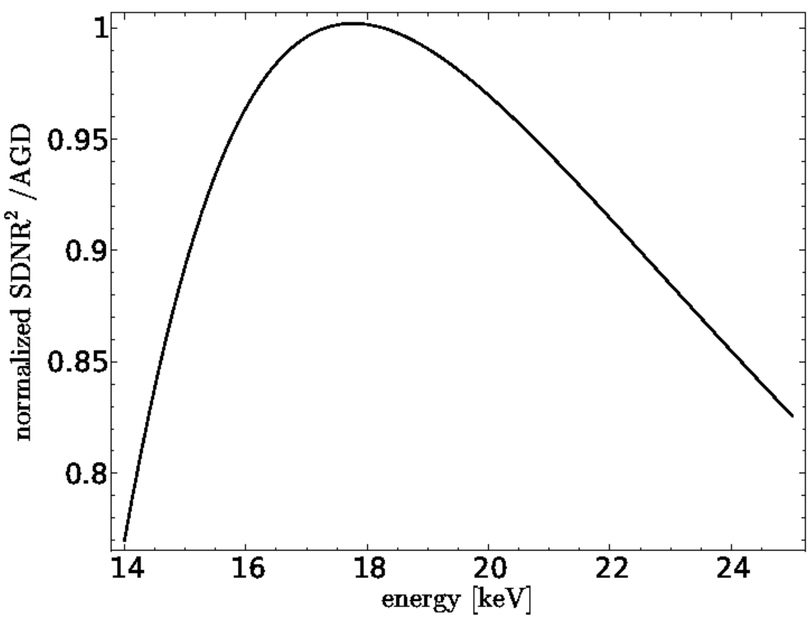


(a) primary

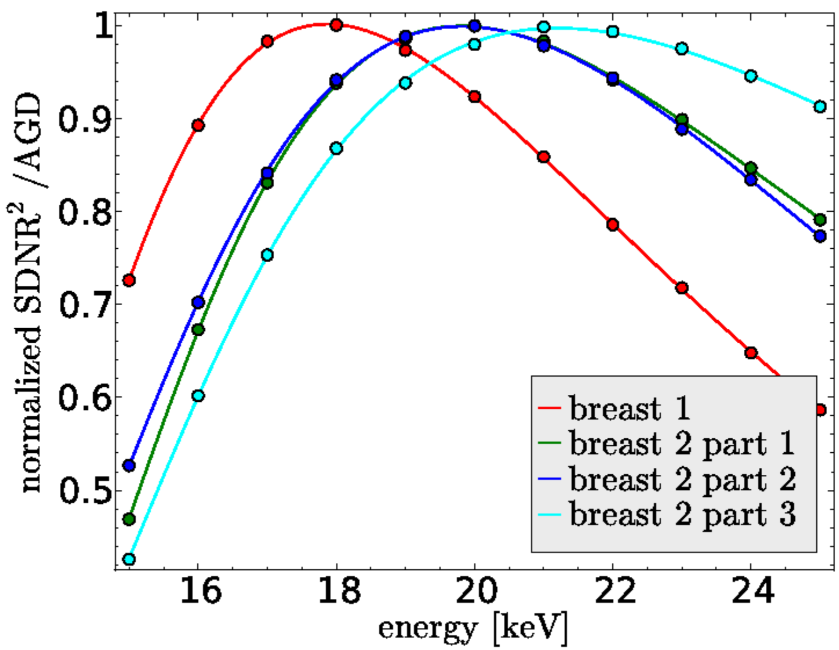
(b) Rayleigh

(c) Compton

optimal X-ray energy



analytical **model**

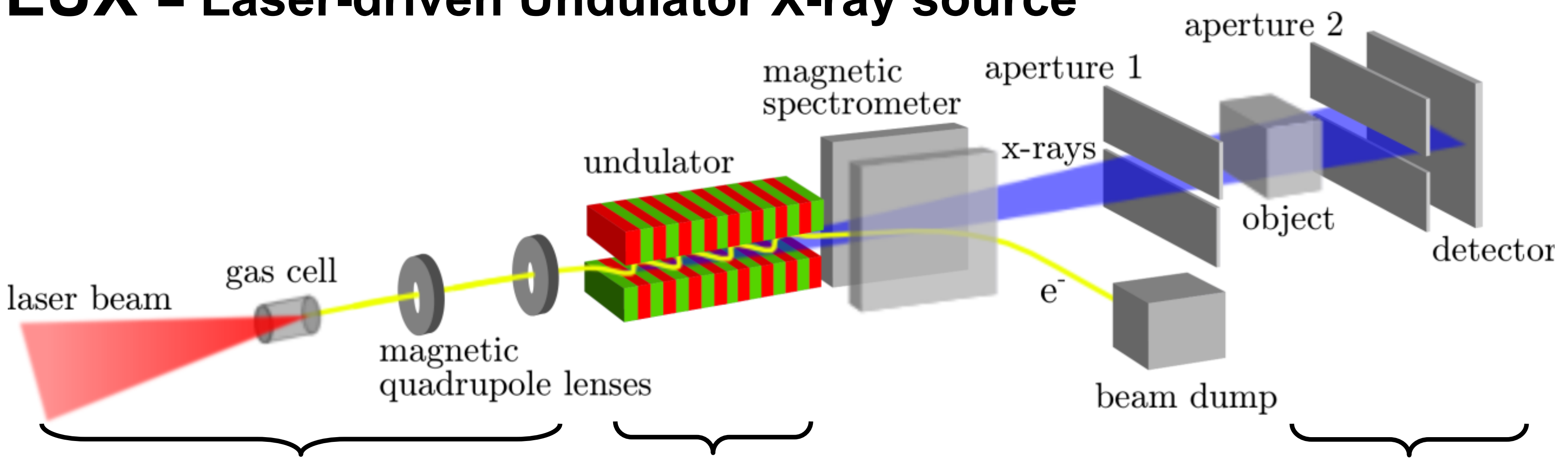


(b)

simulation for 3 different breast models

→ requires tunable source

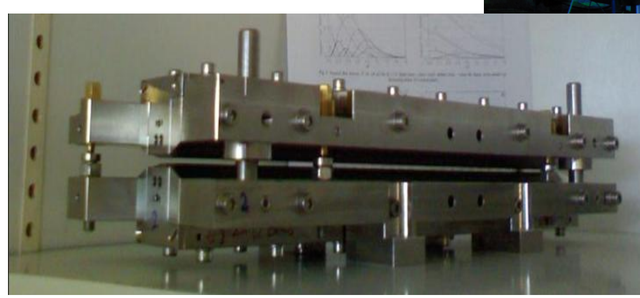
LUX = Laser-driven Undulator X-ray source

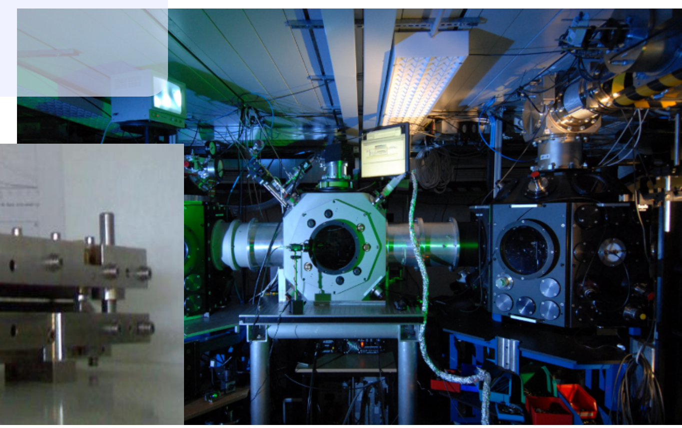


Electron acceleration:
- compact
- stability through band-pass property

Synchrotron radiation:
- narrow bandwidth
- low divergence

imaging





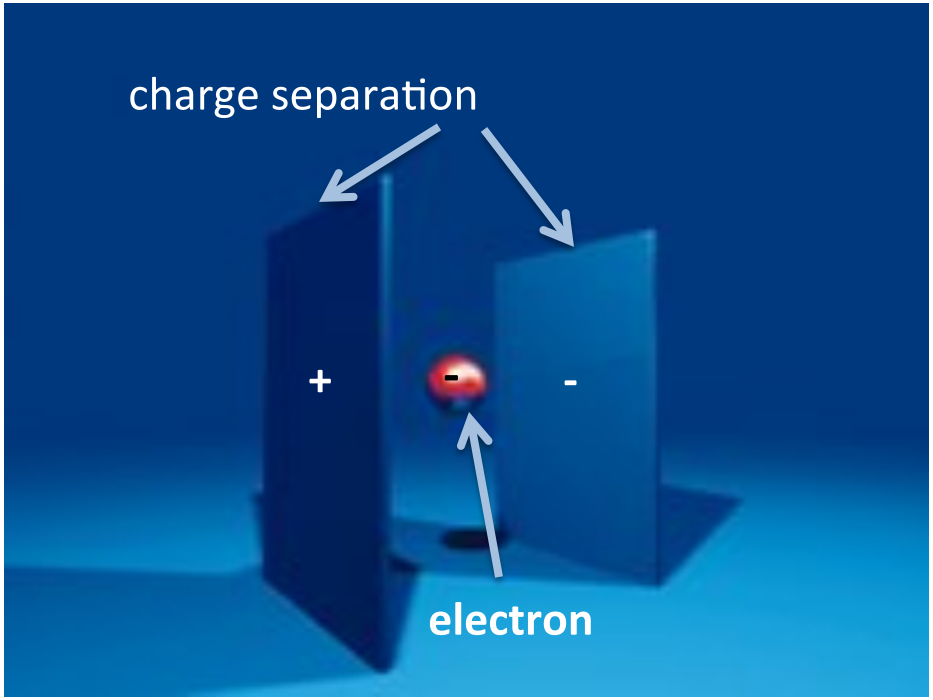
M. Fuchs et al., Laser-driven soft-X-ray undulator source, Nature Physics 5, 826 (2009)

okay up to 25 keV, above one needs Thomson scattering

basic principle of any accelerator

one needs an electric field…

…charged particles are then accelerated

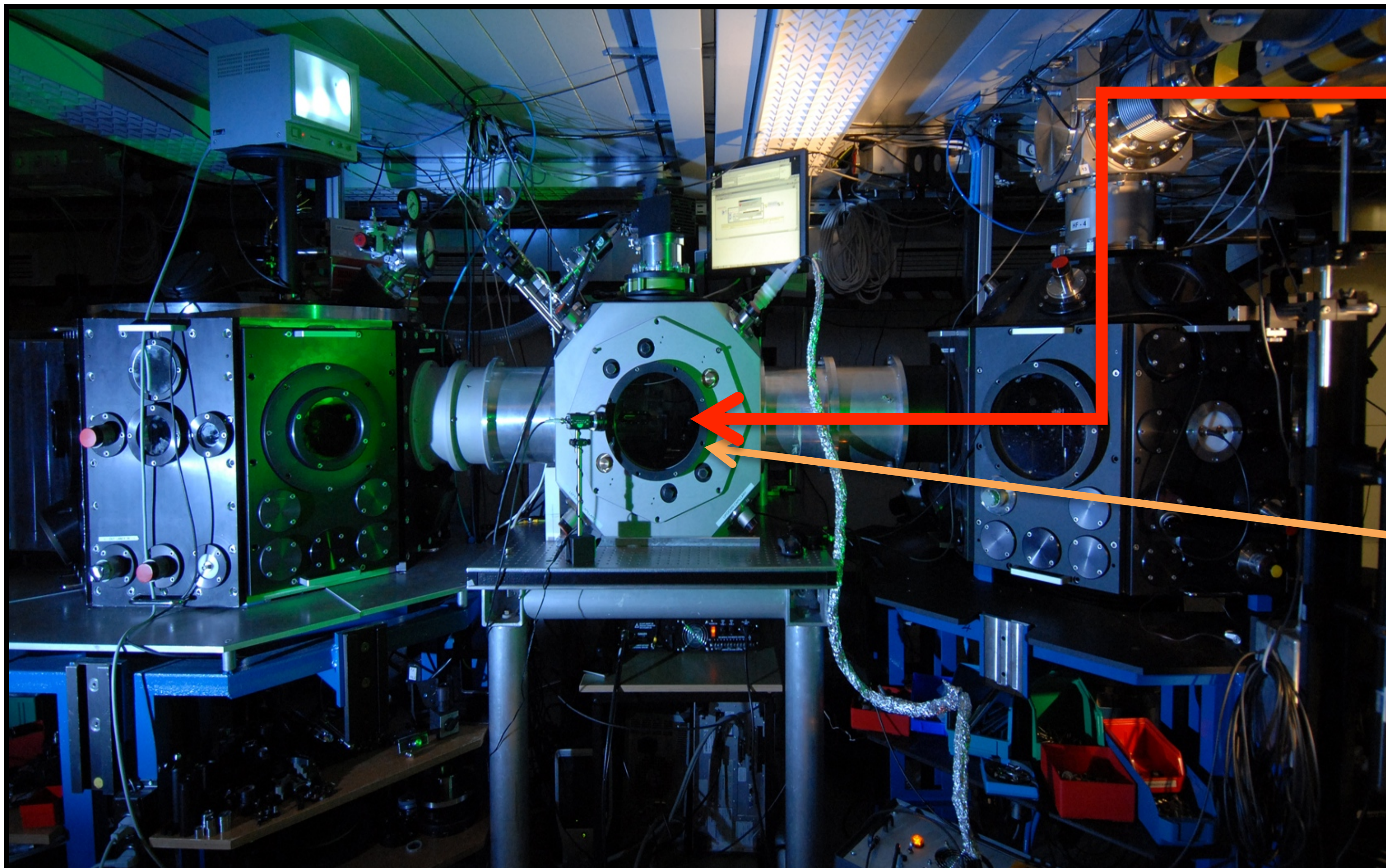


accelerators can be quite large…

kilometer long!!!!....

but also quite small…

lab setup of a Laser-Plasma-Accelerator at MPQ (S. Karsch et al.)



pulse of a high-Power laser

plasma cell:
cm short!!!!….

plasma wakefield acceleration