UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Quantum dynamics with x-rays

Adriana Pálffy

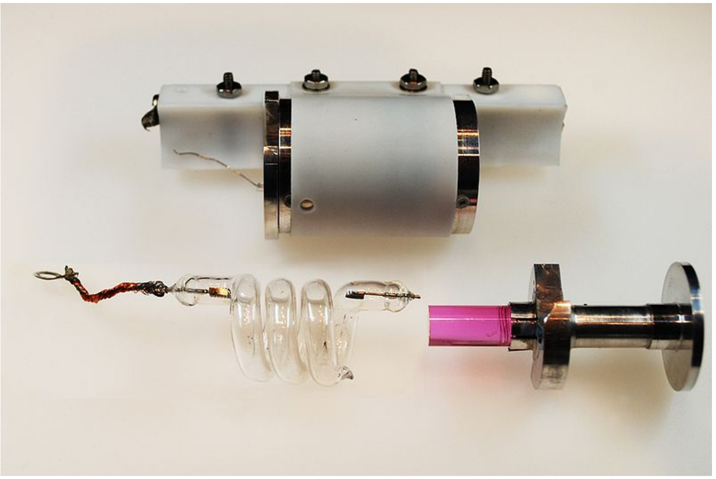
Max Planck Institute for Nuclear Physics, Heidelberg

palffy@mpi-hd.mpg.de

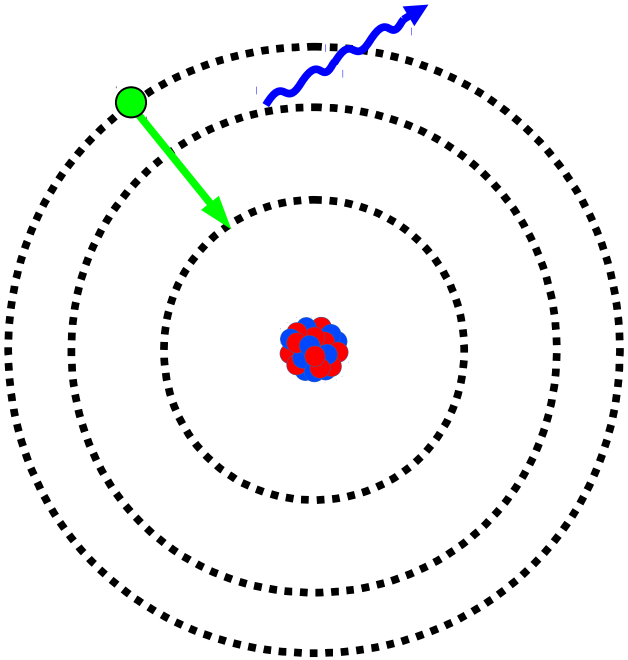
Graduate Days October 2018

Historical perspective

1960, T. Maiman, first successful laser



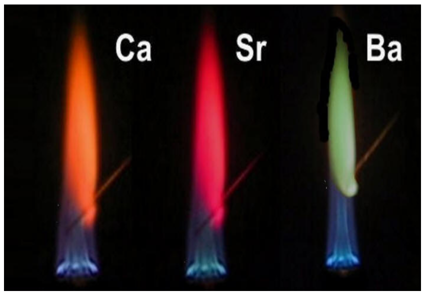
Optical, IR



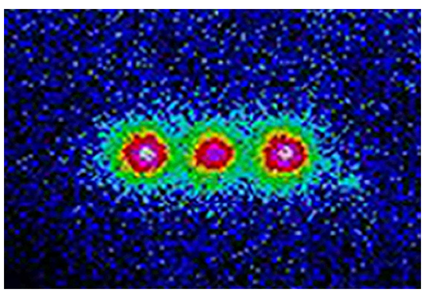
Mutual control of LASER LIGHT and ATOMS

Revolutionized atomic physics, technology and metrology!

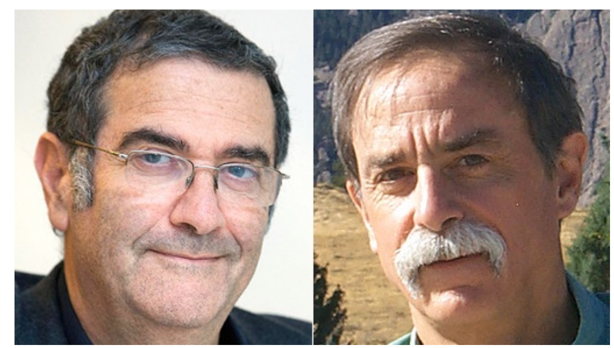
Historical perspective



Spectral analysis
à la Bundsen & Kirchhoff
(1859)



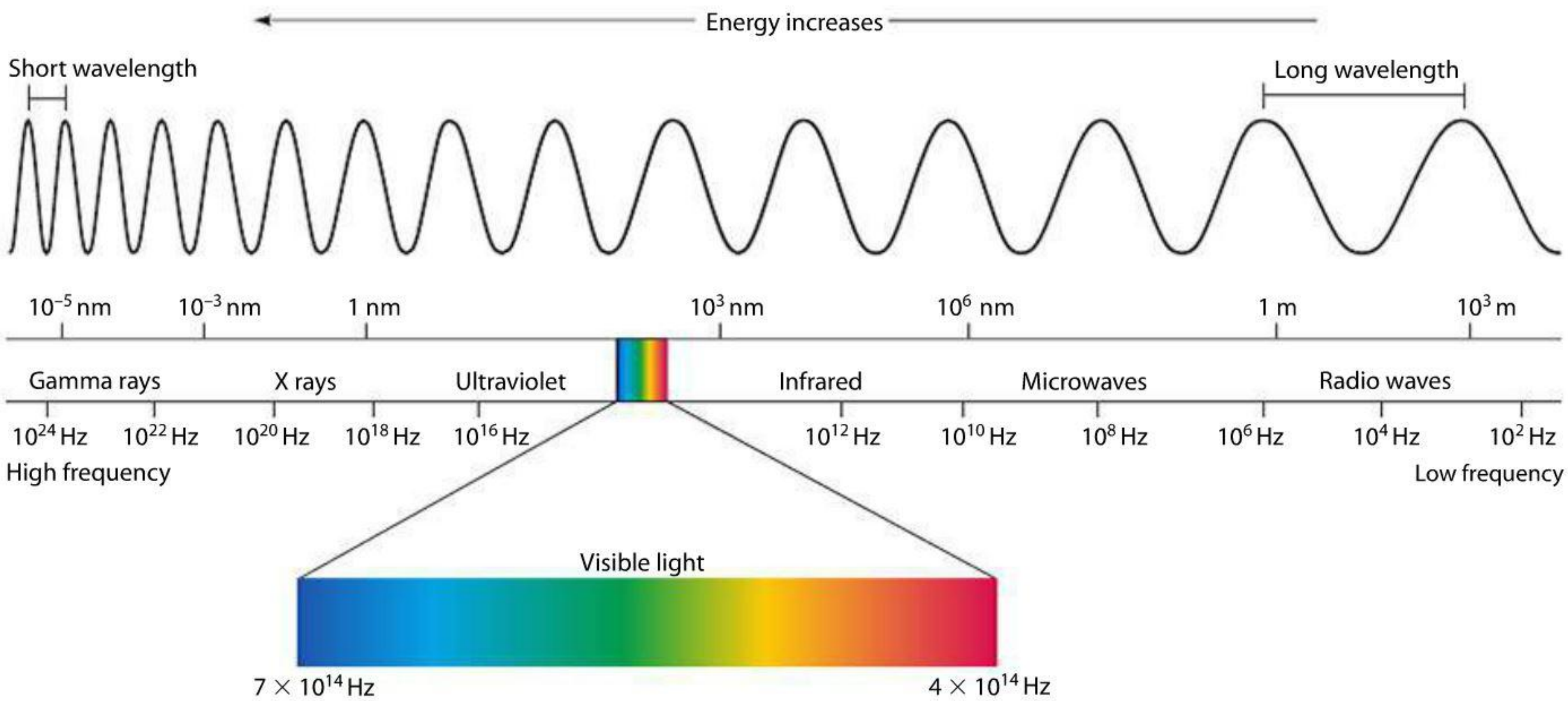
Full quantum control
à la Haroche & Wineland
(2012)



Mutual control of LASER LIGHT and ATOMS

Revolutionized atomic physics, technology and metrology!

The electromagnetic spectrum



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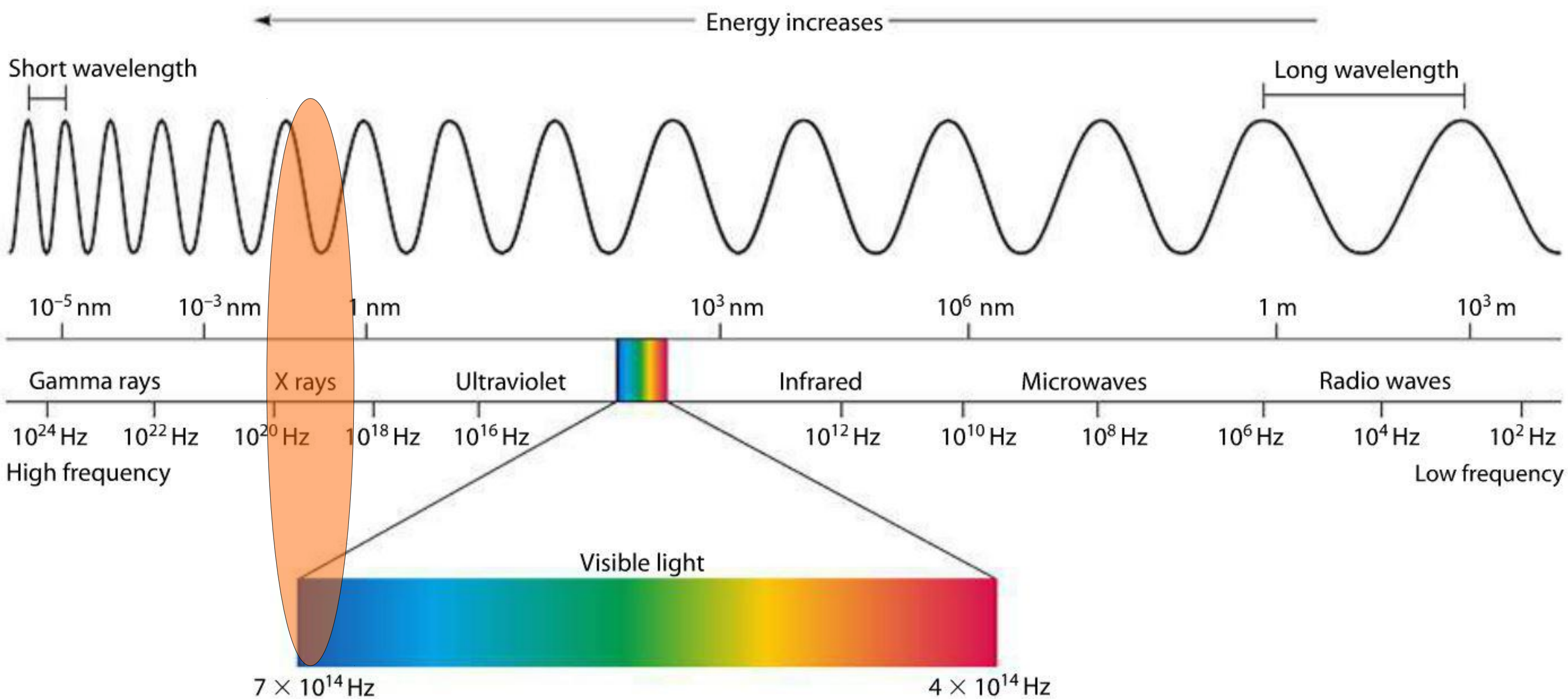


Mutual control of LASER LIGHT and ATOMS

Revolutionized atomic physics, technology and metrology!

Novel coherent sources

DESY Hamburg

LCLS Stanford

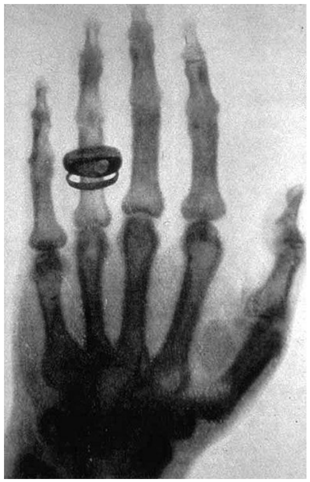
Higher frequencies:
x-, gamma-rays

SACLA Japan

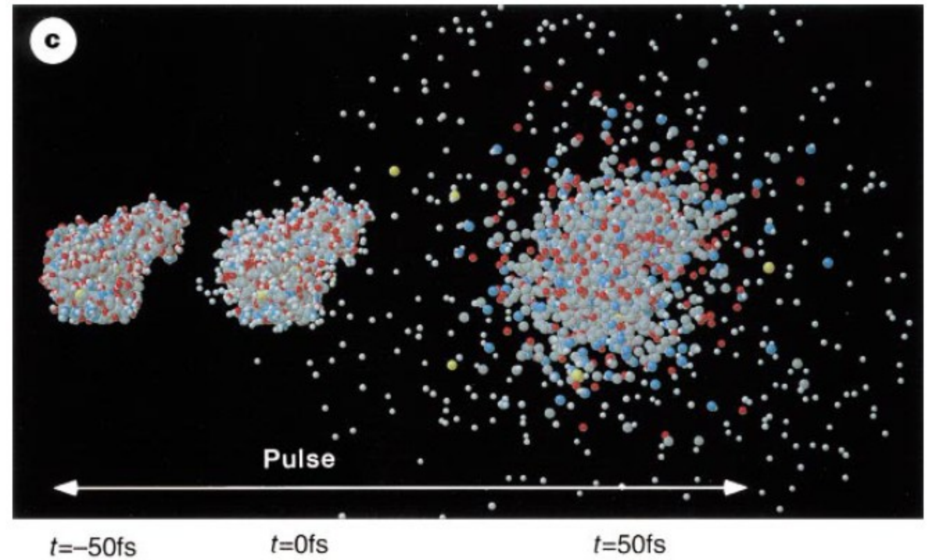
ELI NP Bucharest

What are x-rays good for?

Reveal structure and dynamics of matter with highest spatial and temporal resolution!



1896 W. Röntgen
starts the "business"

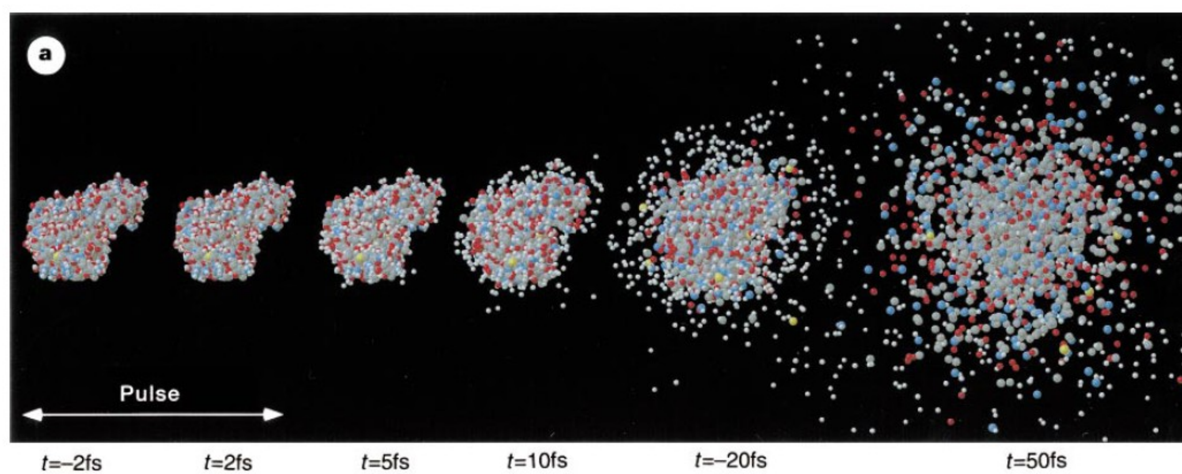


Potential for biomolecular imaging with femtosecond X-ray pulses

Richard Neutze*, Remco Wouts*, David van der Spoel*, Edgar Weckert†‡ & Janos Hajdu*

* *Department of Biochemistry, Biomedical Centre, Box 576, Uppsala University, S-75123 Uppsala, Sweden*
† *Institut für Kristallographie, Universität Karlsruhe, Kaiserstrasse 12, D-76128, Germany*

Nature 406, 752 (2000)



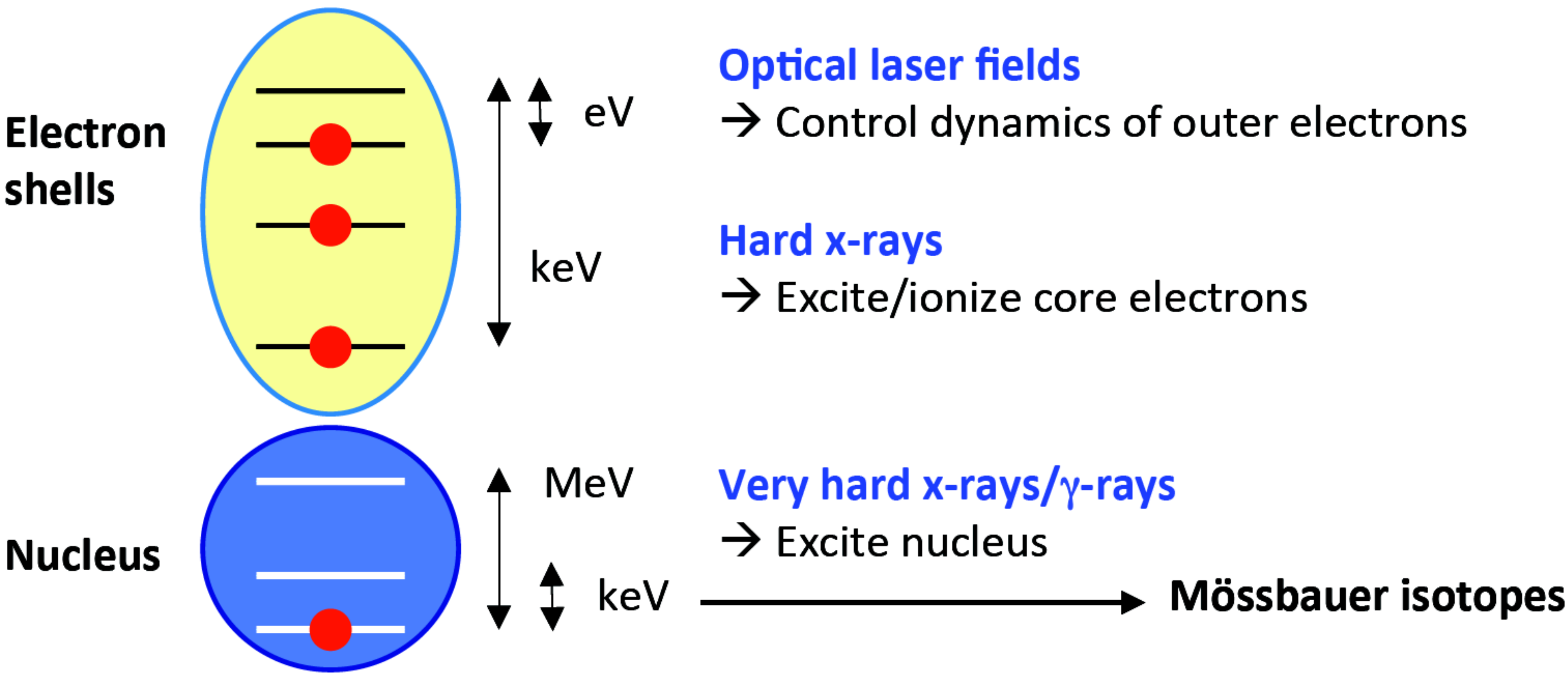
How do they interact with matter?

A free electron

↓

One atom

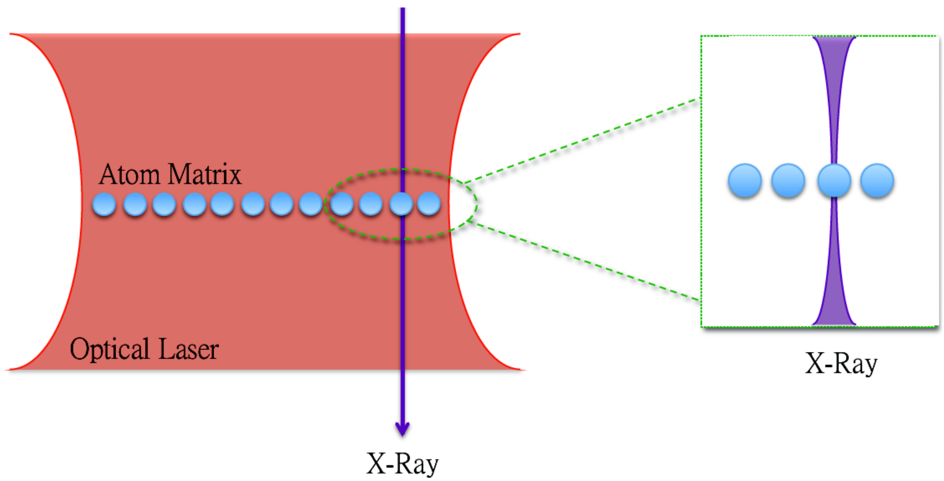
- The atomic form factor
- dispersion corrections
- atomic resonances: electronic and nuclear

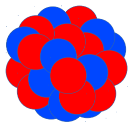


X-ray lasers are resonant to nuclear transitions

X-rays…

- Robustness, detection
- Deeper penetration
- Focusing- diffraction limit





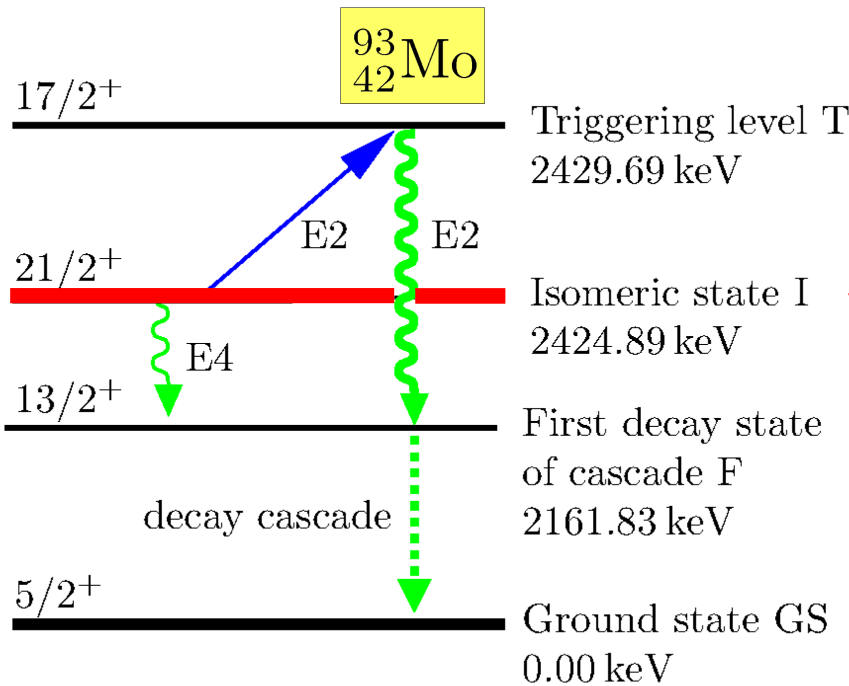
Match nuclear transitions!
Nuclei are very clean high-Q quantum optics systems – new platform!

TIMELY TO CONSIDER:

Are x-ray photons the information carriers of tomorrow?
Can we master the mutual control of x-rays and nuclei?

Special nuclear incentives

GAMMA-RAY LASERS
FREQUENCY STANDARDS
NUCLEAR ISOMERS



Nuclear isomers – metastable states that store energy over long periods of time

$\tau \simeq 7$ hours

Coherent control of nuclear transitions

→ population or depletion of the isomer i.e., "triggering"

Energy/Mass ratio (kWh/kg)

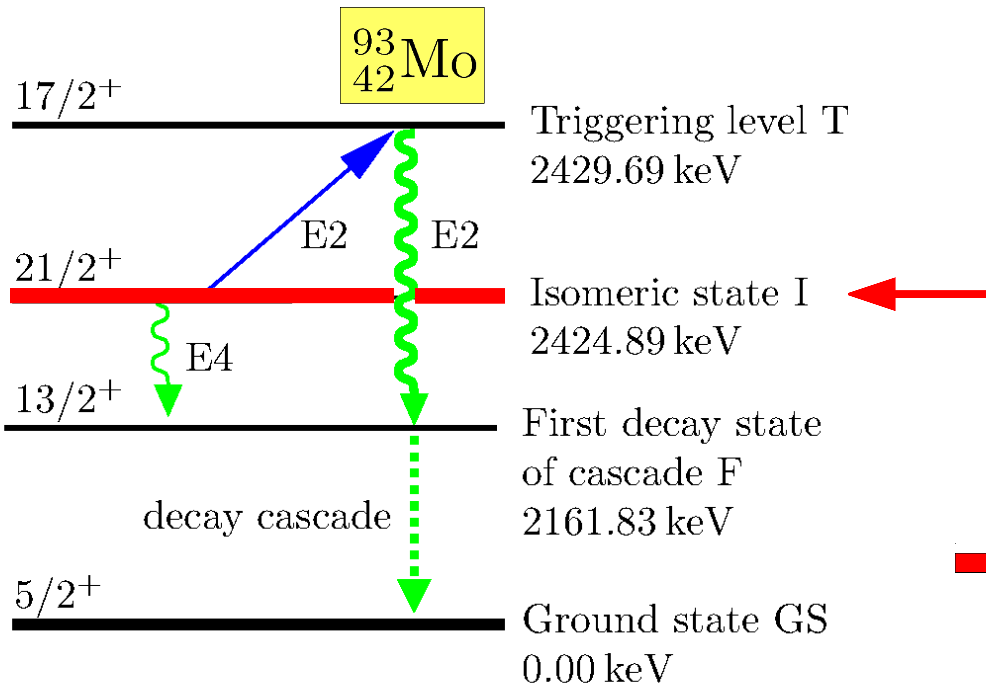
0.7

660 000

NUCLEAR ENERGY STORAGE

Special nuclear incentives

GAMMA-RAY LASERS
FREQUENCY STANDARDS
NUCLEAR ISOMERS



Nuclear isomers – metastable states
that store energy over long periods of time

Coherent control of nuclear transitions

→ population or depletion of the isomer
i.e., “triggering”

Energy/Mass ratio
(kWh/kg)

Lecture hall

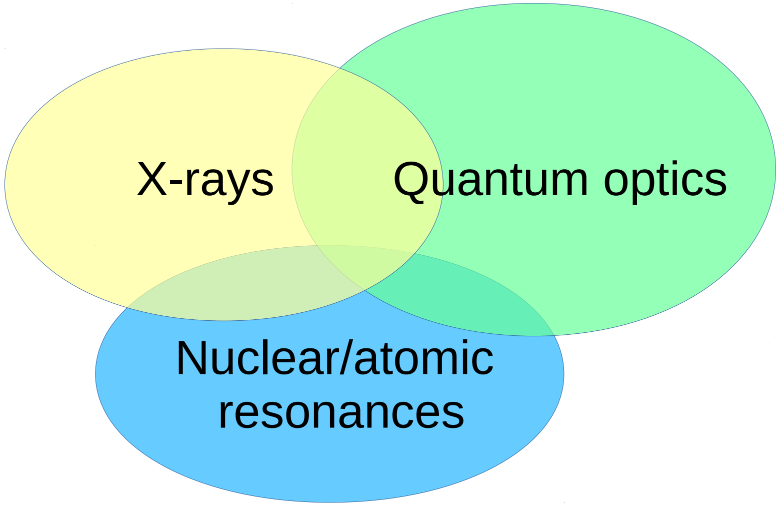
0.7

Earth's diameter

660 000

NUCLEAR ENERGY STORAGE

Quantum dynamics with x-rays



Goal: introduce basic concepts and experimental opportunities on quantum dynamics with x-rays

Contents:

X-ray sources

Imaging, scattering, diffraction

Light-matter interaction

Resonant interactions

Basics of quantum optics

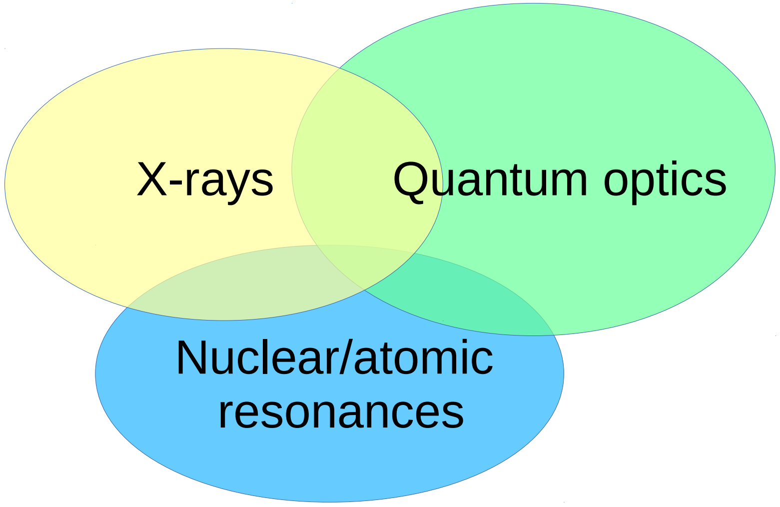
Coherence effects

Nuclear forward scattering

Storing x-ray photons

Nanocavities for x-rays

Quantum dynamics with x-rays



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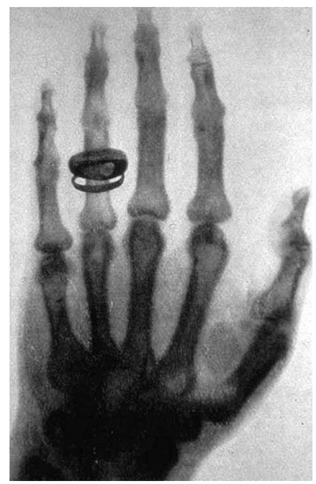
How to generate x-rays

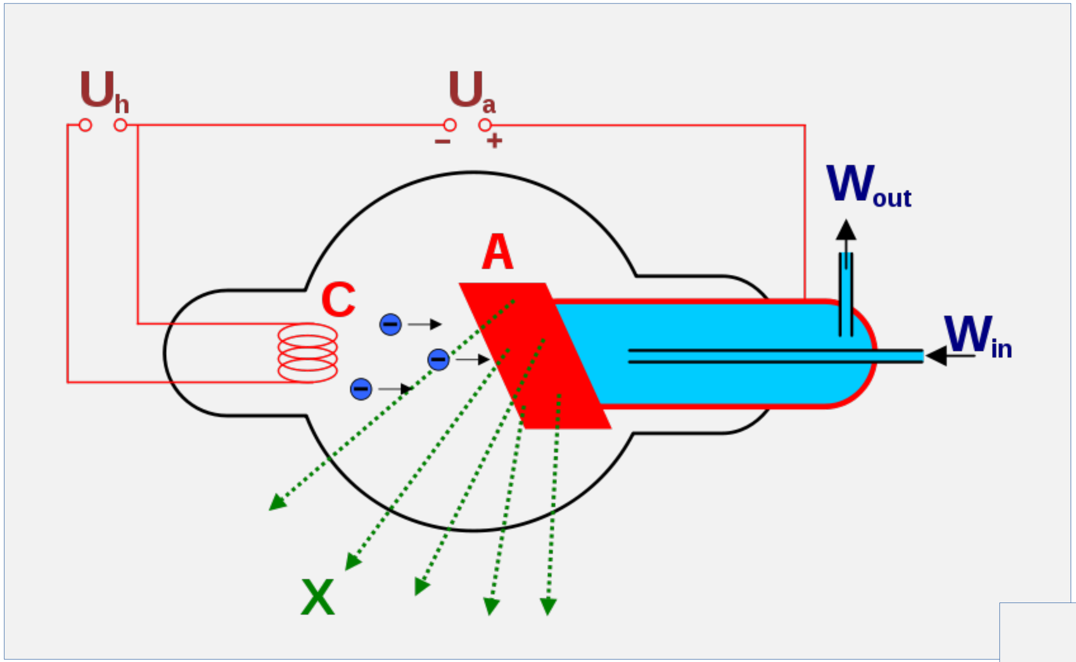
The beginnings



Wilhelm Conrad Röntgen
(1845 – 1923)
Nobel Prize 1901

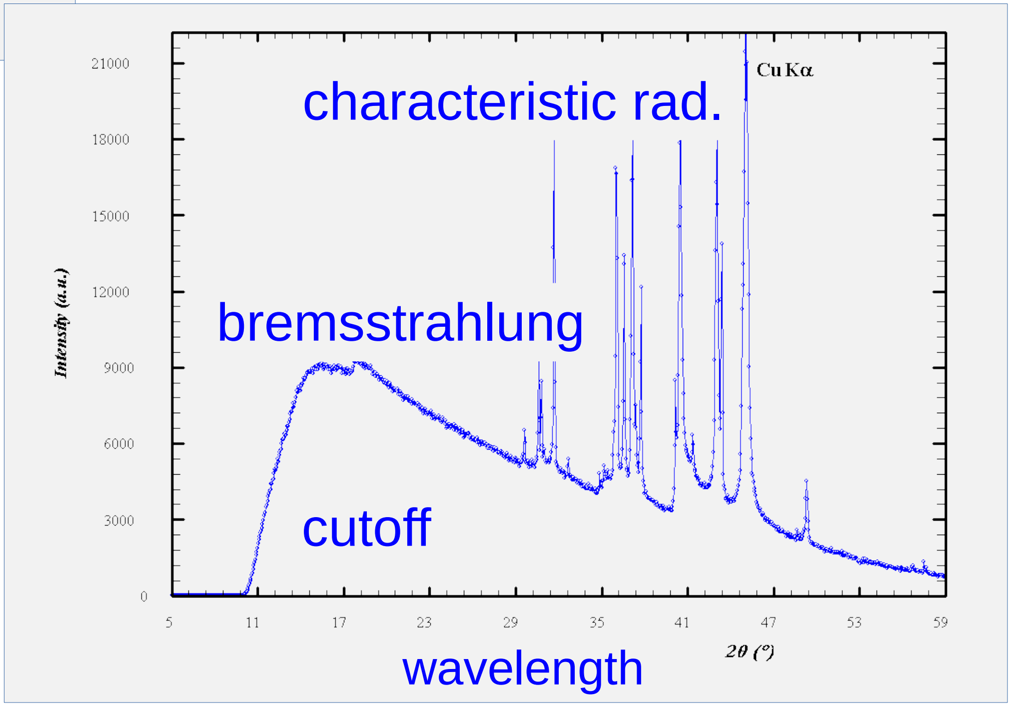
X-ray “Crookes” tube

X-ray tube

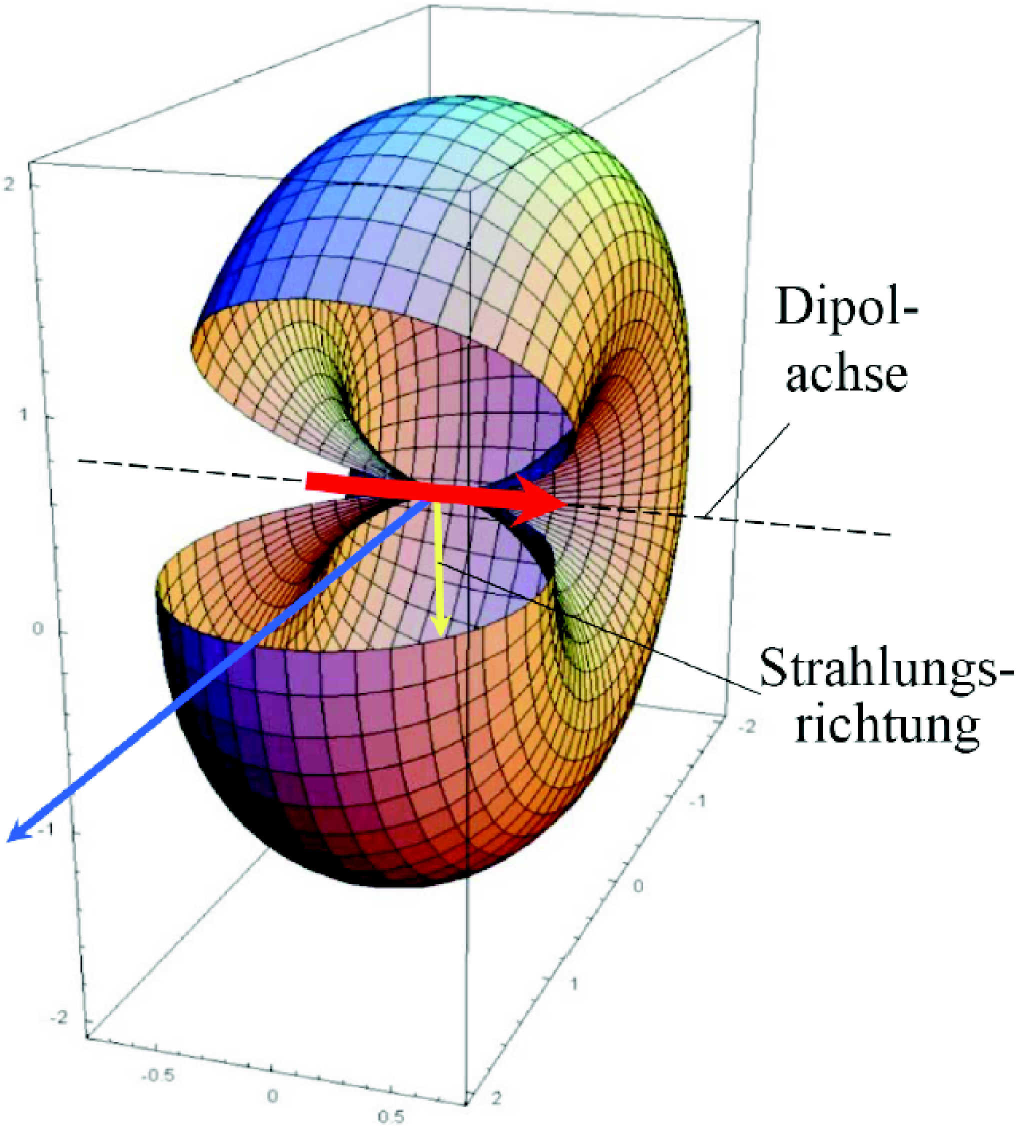


bremsstrahlung from acceleration of electrons in anode

characteristic radiation from excitation of anode atoms



Radiation pattern of Hertzian dipole



Every accelerated charge radiates electromagnetic waves

Larmor formula for the radiated power

$$P = \frac{e^2}{6\pi\varepsilon_0 m^2 c^3}\left(\frac{d\vec{p}}{dt}\right)^2$$

$\vec{p} \equiv$ momentum

Oscillatory motion:
No radiation in direction of the oscillation.

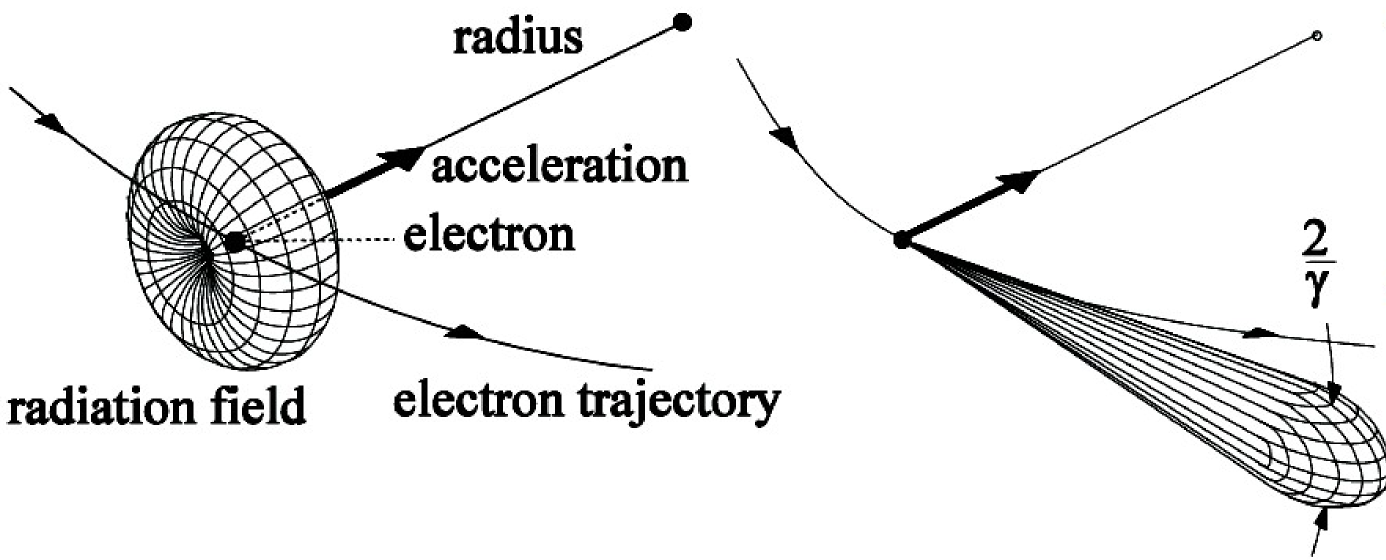
The maximum radiated power is observed perpendicular to the oscillation direction

Radiation pattern of accelerated dipole

Lorentz transformation →

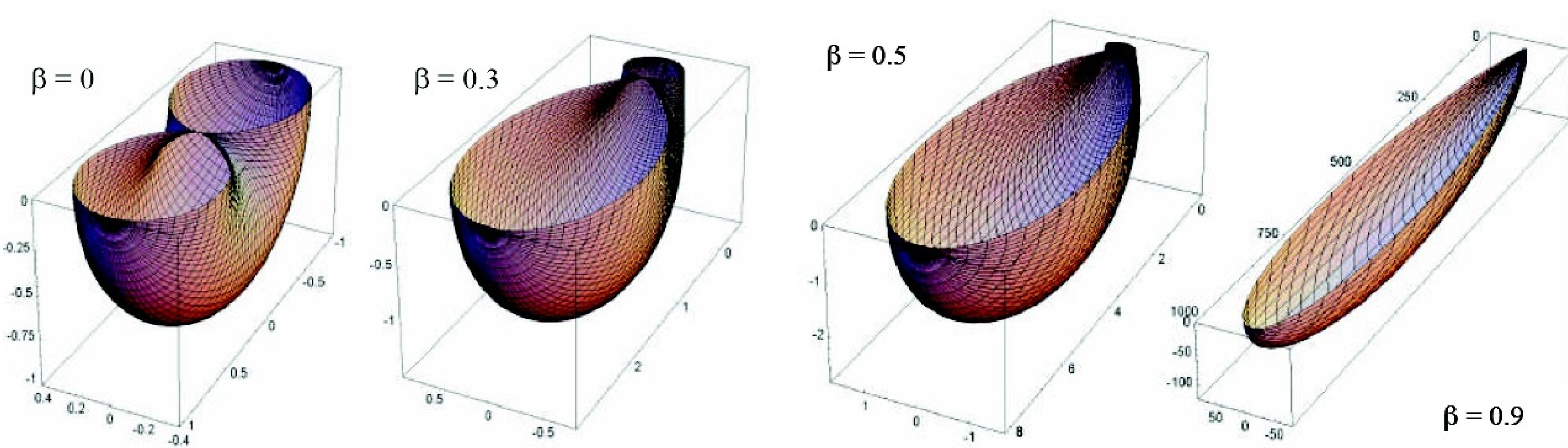
Rest frame

Laboratory frame



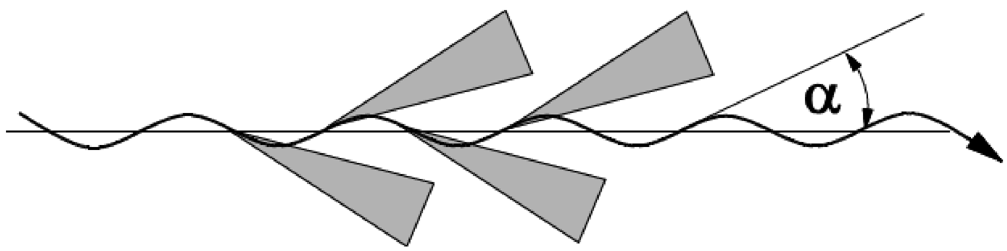
$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0c^2}$$

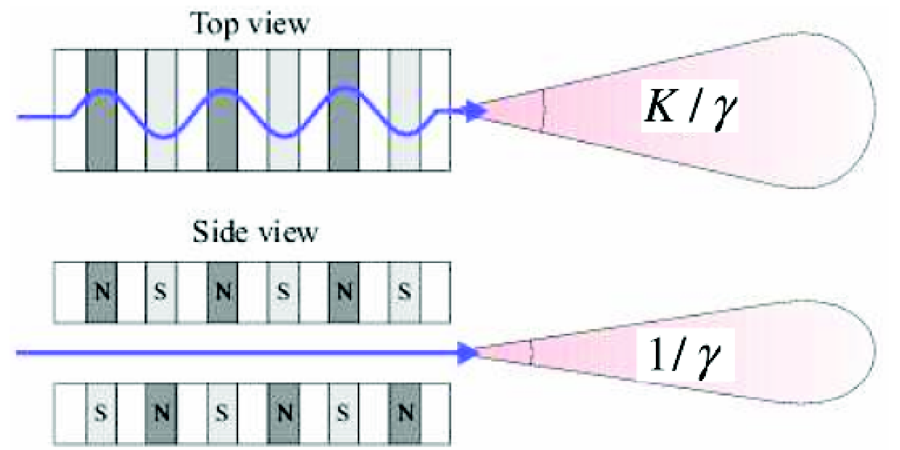
Opening angle



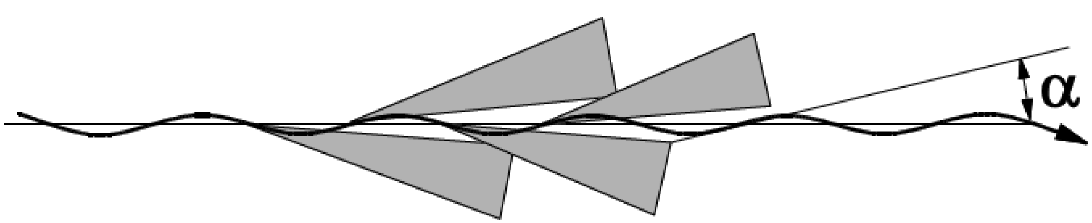
Wiggler vs undulator

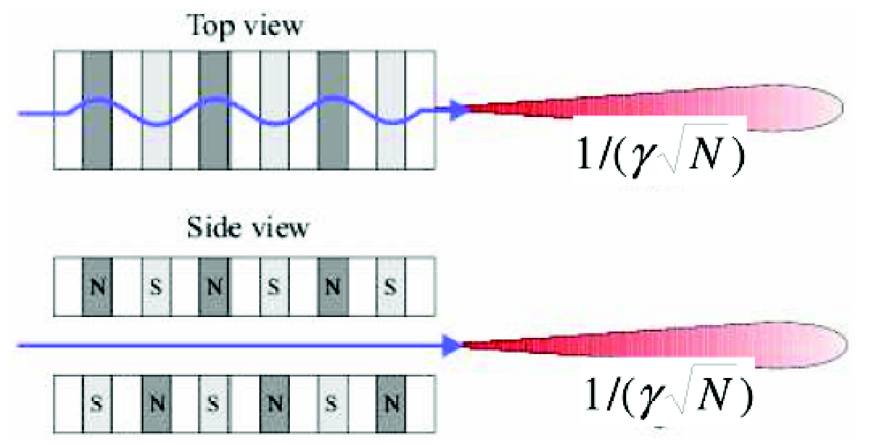
Wiggler regime: $\alpha > 1/\gamma$





Undulator regime: $\alpha < 1/\gamma$



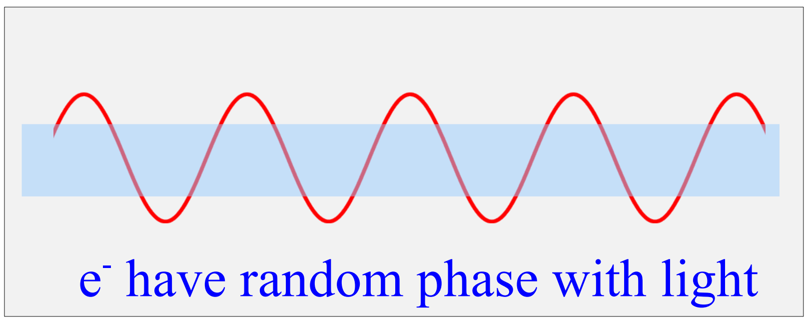


In the undulator regime the radiation cones overlap and the wave trains can interfere constructively

XFEL vs. conventional undulator

Undulator

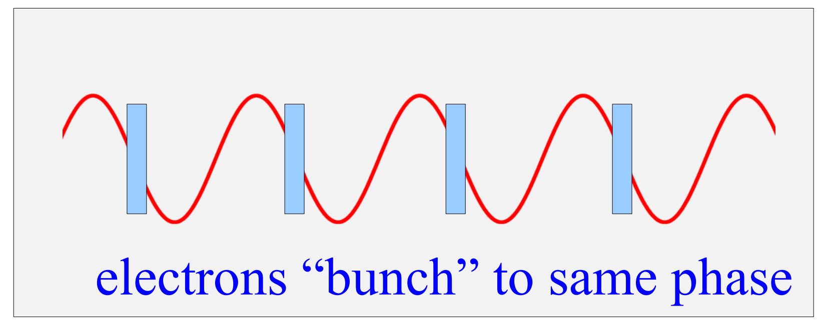
- Emissions of a single electron in different periods coherent
- Electrons uncorrelated



$$I \sim n_e$$

FEL

- Emissions of a single electron in different periods coherent
- Emission of different electrons coherent



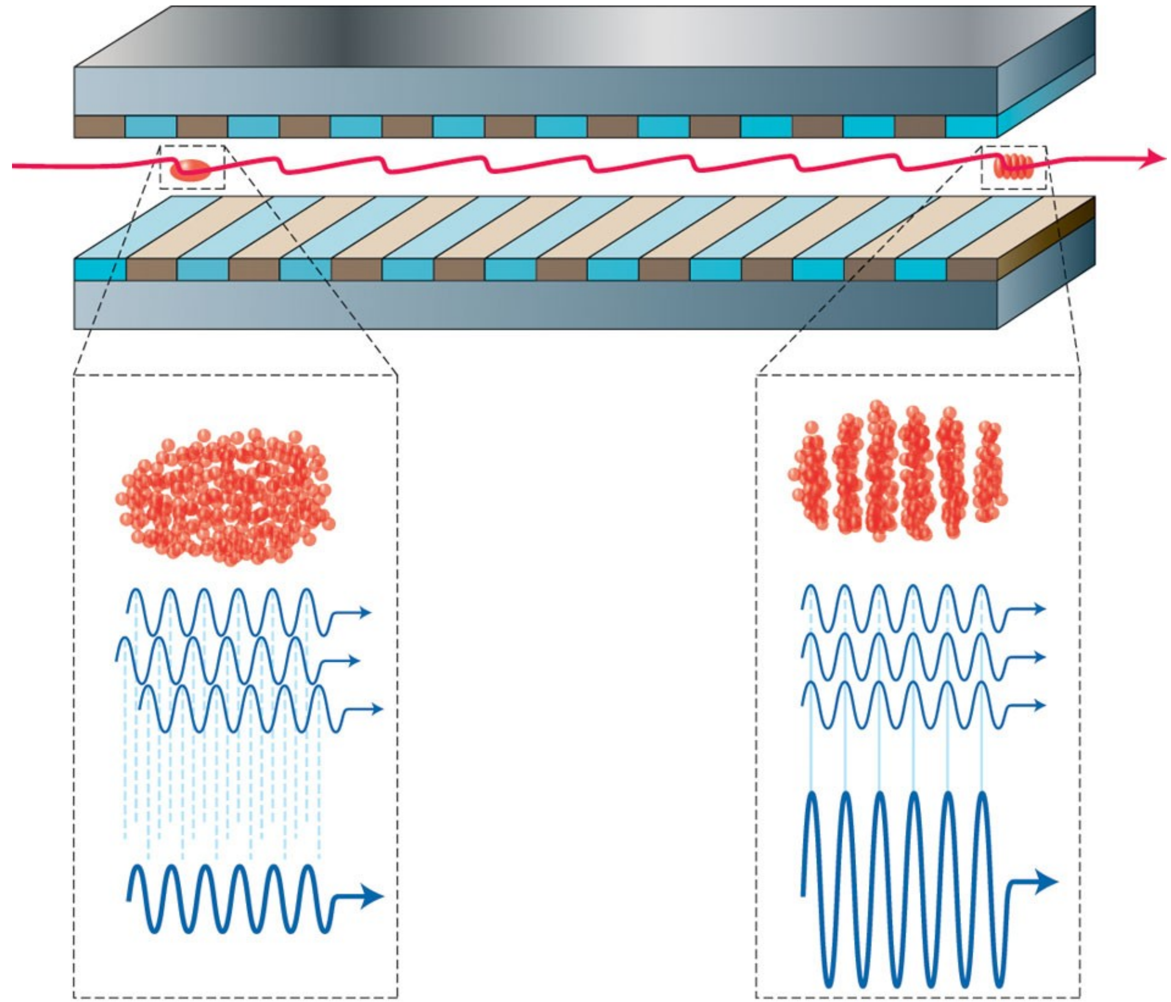
$$I \sim n_e^2$$

back-action of field on electrons
leads to bunching

courtesy Jörg Evers

Microbunching

- Energy exchange depending on relative phase of electron and field
- Oscillation amplitude depends on electron energy
- This leads to to microbunching of electrons at the light wave length
- Therefore coherent emission of all electrons



Incoherent emission: electrons randomly phased

Coherent emission: electrons bunched at radiation wavelength

Images: Nature Photonics 4, 814 (2010);

Some pictures

SLAC undulators (silver)

undulators magnets

Images: SLAC

More pictures

DESY Hamburg

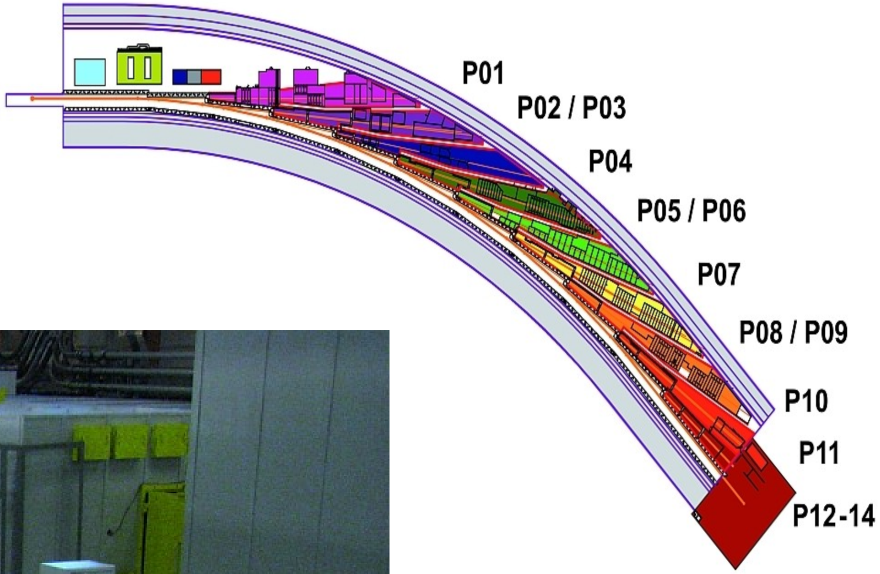
LCLS Stanford

Higher frequencies:
x-, gamma-rays

SACLA Japan

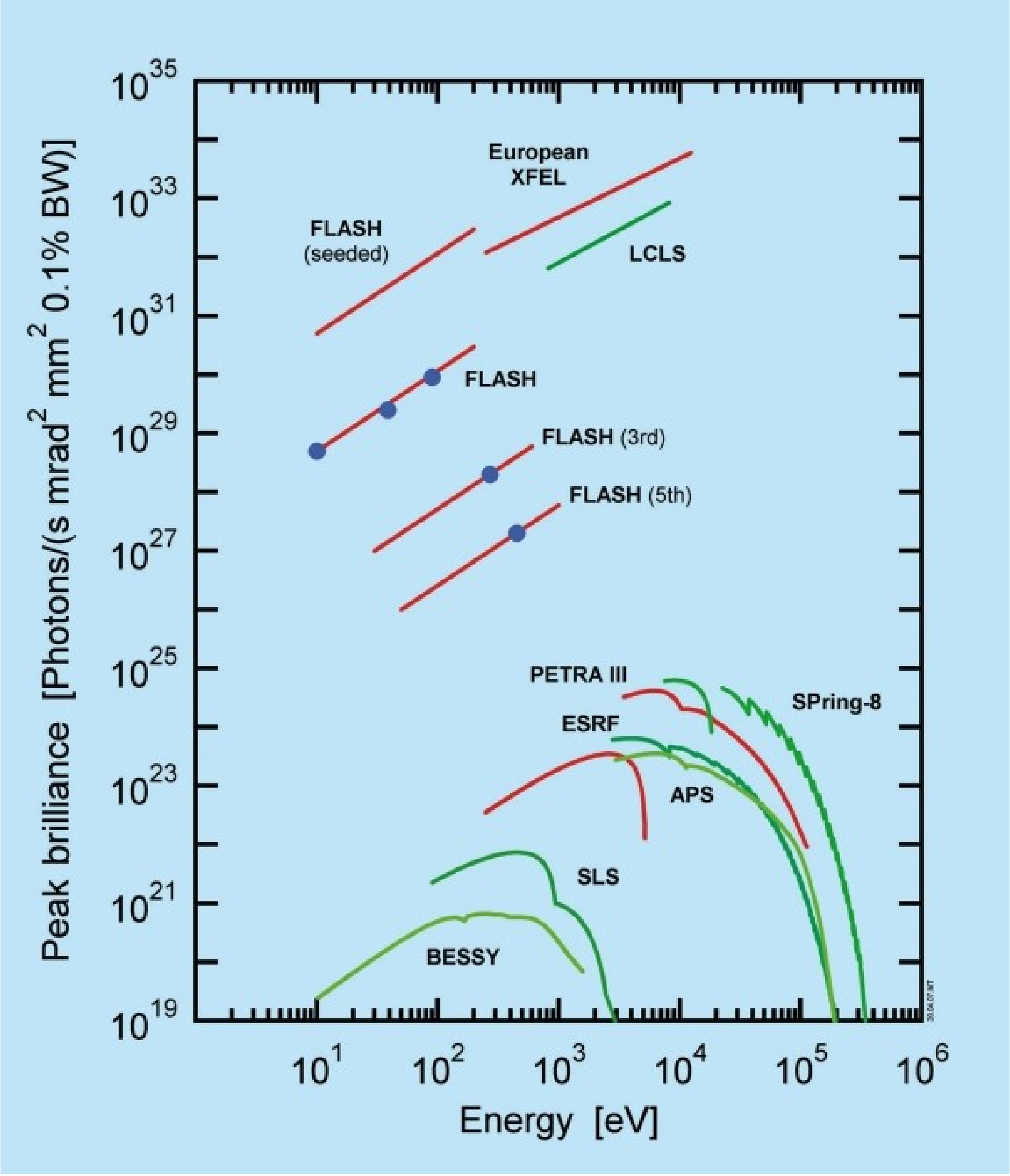
ELI NP Bucharest

Petra III

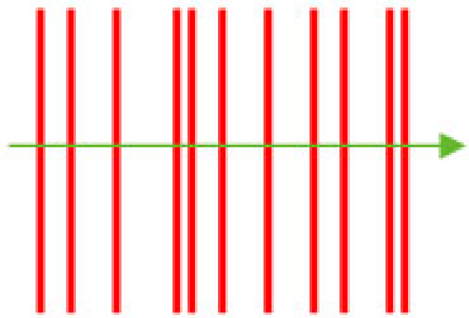


Images: DESY

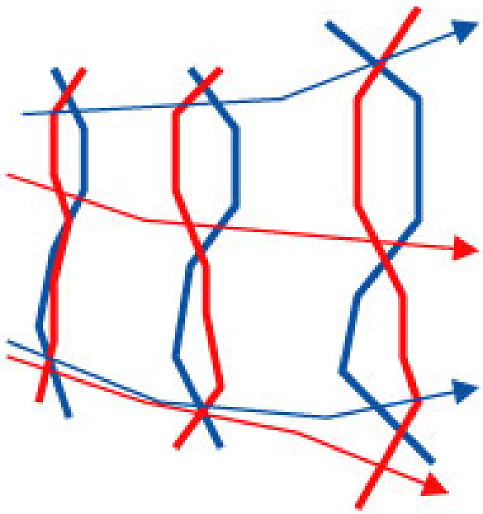
Beam quality - Brilliance



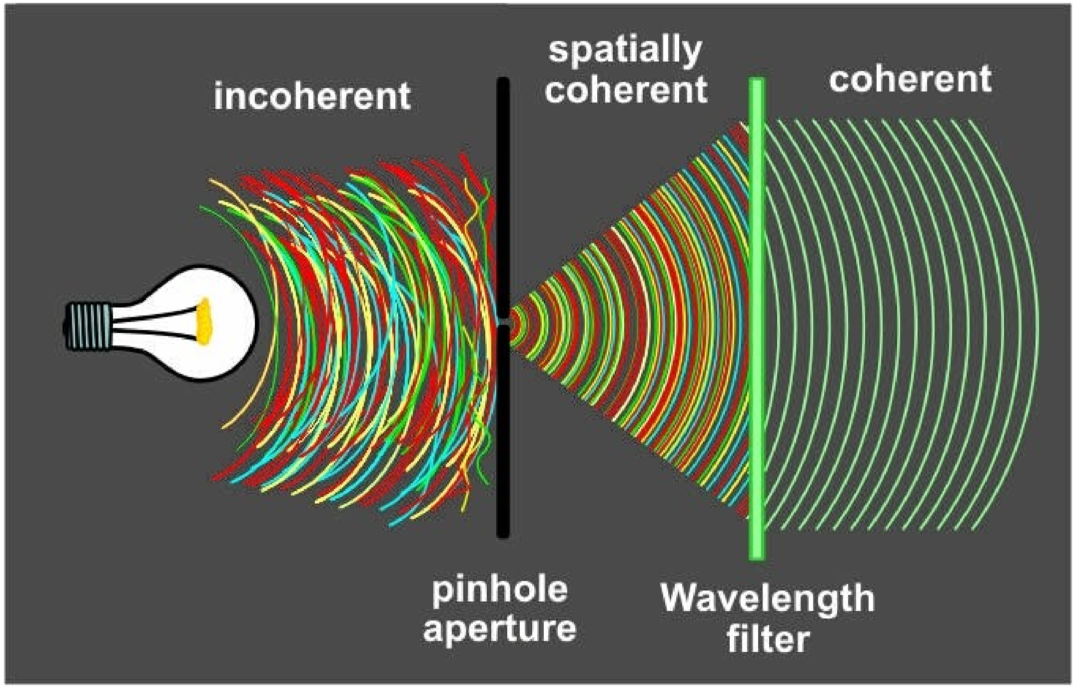
Beam quality - Coherence



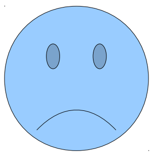
temporal coherence: random fluctuations in the *spacing* of the wavefronts

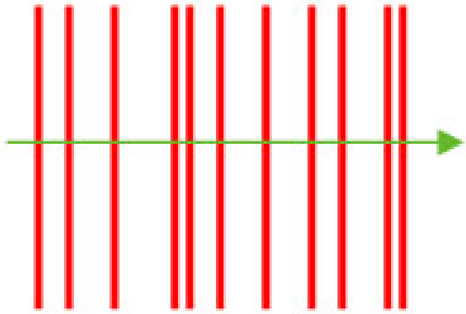


spatial coherence: random fluctuations in the *shape* of the wavefronts



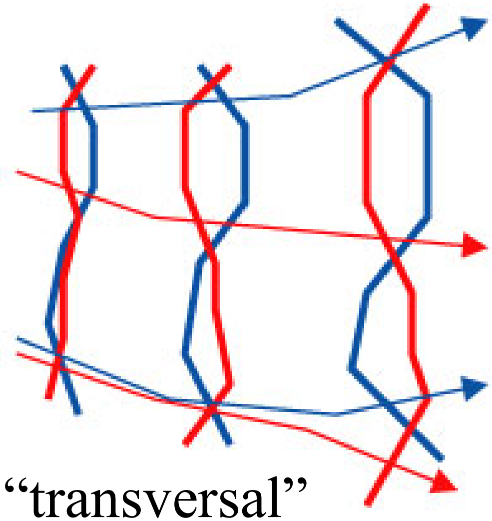
Coherence for XFEL





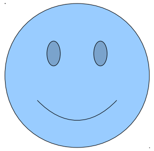
“longitudinal”

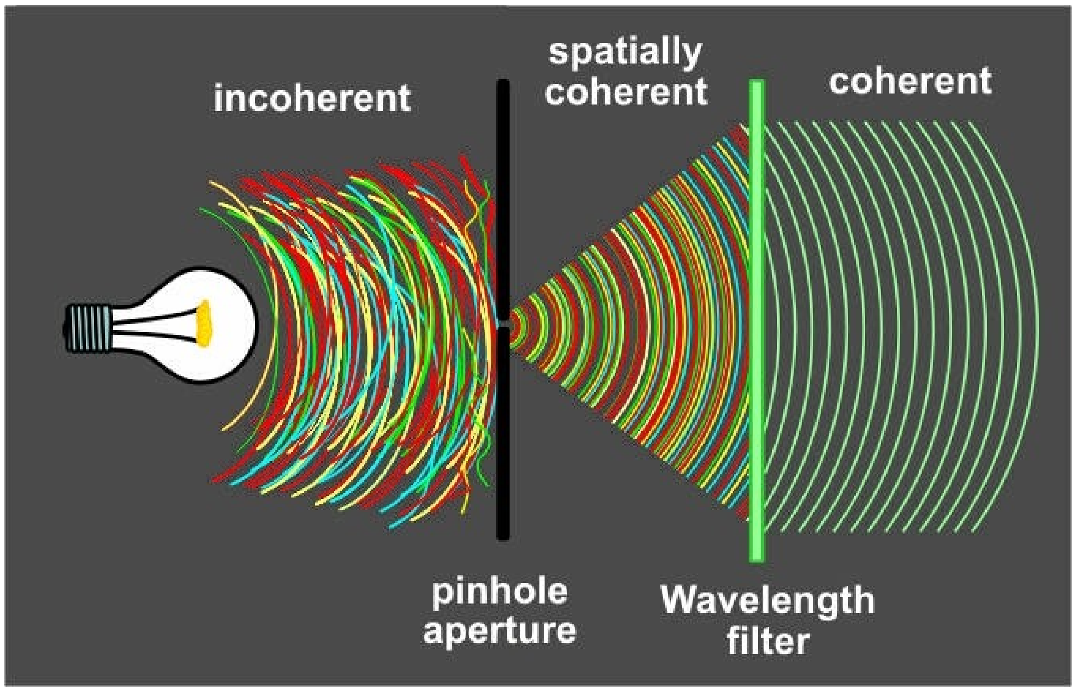
temporal coherence: random fluctuations in the *spacing* of the wavefronts



“transversal”

spatial coherence: random fluctuations in the *shape* of the wavefronts





Some photons on diffraction