HZB BESSY II Light Source

Old & New Lightsources - Motivation

Towards a 4th generation Synchrotron Radiation Source

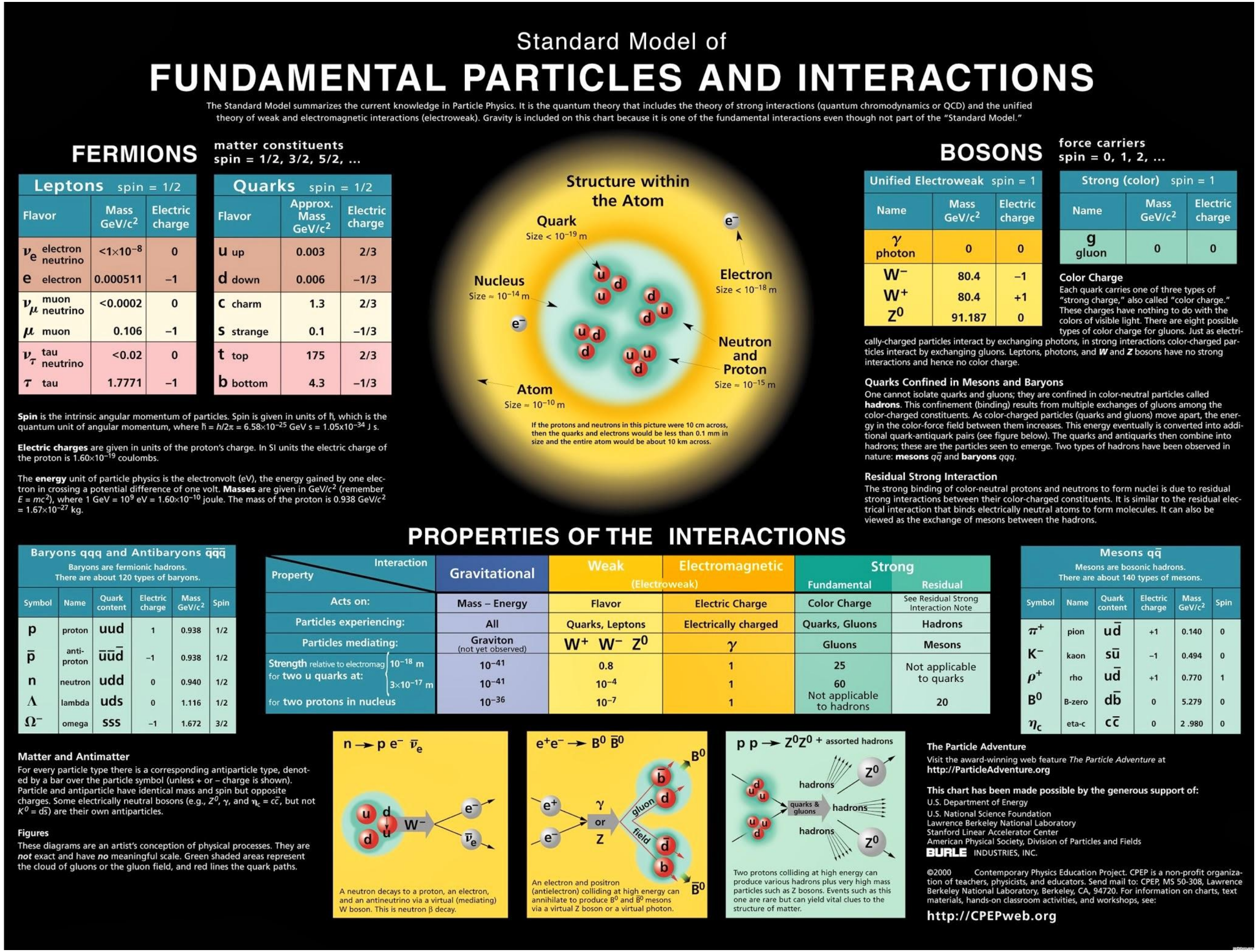
EPICS Summer School
Paul Goslawski

New Lightsource

Outlook

- What is a Synchrotron Radiation Source or Lightsource?
  - **And why are synchrotron lightsources cool?**
- History & Developments of Synchrotron Lightsources
  - **Brilliance - 1st, 2nd, 3rd and 4th generation**
- “Old” machines need new infrastructure/software
  - **Digitalization by Digital Natives**

What is a synchrotron radiation lightsource?


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin = 1/2
Flavor | Mass GeV/c² | Electric charge
νe electron neutrino | <1×10⁻⁸ | 0
e electron | 0.000511 | –1
νμ muon neutrino | <0.0002 | 0
μ muon | 0.106 | –1
ντ tau neutrino | <0.02 | 0
τ tau | 1.7771 | –1
Quarks spin = 1/2
Flavor | Approx. Mass GeV/c² | Electric charge
u up | 0.003 | 2/3
d down | 0.006 | –1/3
c charm | 1.3 | 2/3
s strange | 0.1 | –1/3
t top | 175 | 2/3
b bottom | 4.3 | –1/3
Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where ħ = h/2π = 6.58×10⁻²⁵ GeV s = 1.05×10⁻³⁴ J s.
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10⁻¹⁹ coulombs.
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember E = mc²), where 1 GeV = 10⁹ eV = 1.60×10⁻¹⁰ joule. The mass of the proton is 0.938 GeV/c² = 1.67×10⁻²⁷ kg.
Structure within the Atom
Quark Size < 10⁻¹⁹ m
Nucleus Size ≈ 10⁻¹⁴ m
Electron Size < 10⁻¹⁸ m
Neutron and Proton Size ≈ 10⁻¹⁵ m
Atom Size ≈ 10⁻¹⁰ m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
BOSONS force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name | Mass GeV/c² | Electric charge
γ photon | 0 | 0
W⁻ | 80.4 | –1
W⁺ | 80.4 | +1
Z⁰ | 91.187 | 0
Strong (color) spin = 1
Name | Mass GeV/c² | Electric charge
g gluon | 0 | 0
Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.
Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons qq̄ and baryons qqq.
Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.
PROPERTIES OF THE INTERACTIONS
Property / Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong Fundamental | Strong Residual
Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note
Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons
Particles mediating: | Graviton (not yet observed) | W⁺ W⁻ Z⁰ | γ | Gluons | Mesons
Strength relative to electromag for two u quarks at: 10⁻¹⁸ m | 10⁻⁴¹ | 0.8 | 1 | 25 | Not applicable to quarks
3×10⁻¹⁷ m | 10⁻⁴¹ | 10⁻⁴ | 1 | 60 |
for two protons in nucleus | 10⁻³⁶ | 10⁻⁷ | 1 | Not applicable to hadrons | 20
Baryons qqq and Antibaryons q̄q̄q̄
Baryons are fermionic hadrons. There are about 120 types of baryons.
Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin
p | proton | uud | 1 | 0.938 | 1/2
p̄ | anti-proton | ūūd̄ | –1 | 0.938 | 1/2
n | neutron | udd | 0 | 0.940 | 1/2
Λ | lambda | uds | 0 | 1.116 | 1/2
Ω⁻ | omega | sss | –1 | 1.672 | 3/2
Mesons qq̄
Mesons are bosonic hadrons. There are about 140 types of mesons.
Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin
π⁺ | pion | ud̄ | +1 | 0.140 | 0
K⁻ | kaon | sū | –1 | 0.494 | 0
ρ⁺ | rho | ud̄ | +1 | 0.770 | 1
B⁰ | B-zero | db̄ | 0 | 5.279 | 0
ηc | eta-c | cc̄ | 0 | 2 .980 | 0
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z⁰, γ, and ηc = cc̄, but not K⁰ = ds̄) are their own antiparticles.
Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.
n → p e⁻ ν̄e
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.
e⁺e⁻ → B⁰ B̄⁰
gluon field
An electron and positron (antielectron) colliding at high energy can annihilate to produce B⁰ and B̄⁰ mesons via a virtual Z boson or a virtual photon.
p p → Z⁰Z⁰ + assorted hadrons
hadrons
quarks & gluons
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.
The Particle Adventure
Visit the award-winning web feature The Particle Adventure at http://ParticleAdventure.org
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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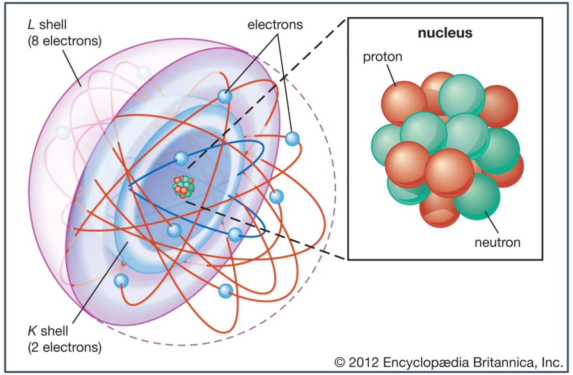
L shell
(8 electrons)
electrons
nucleus
proton
neutron
K shell
(2 electrons)
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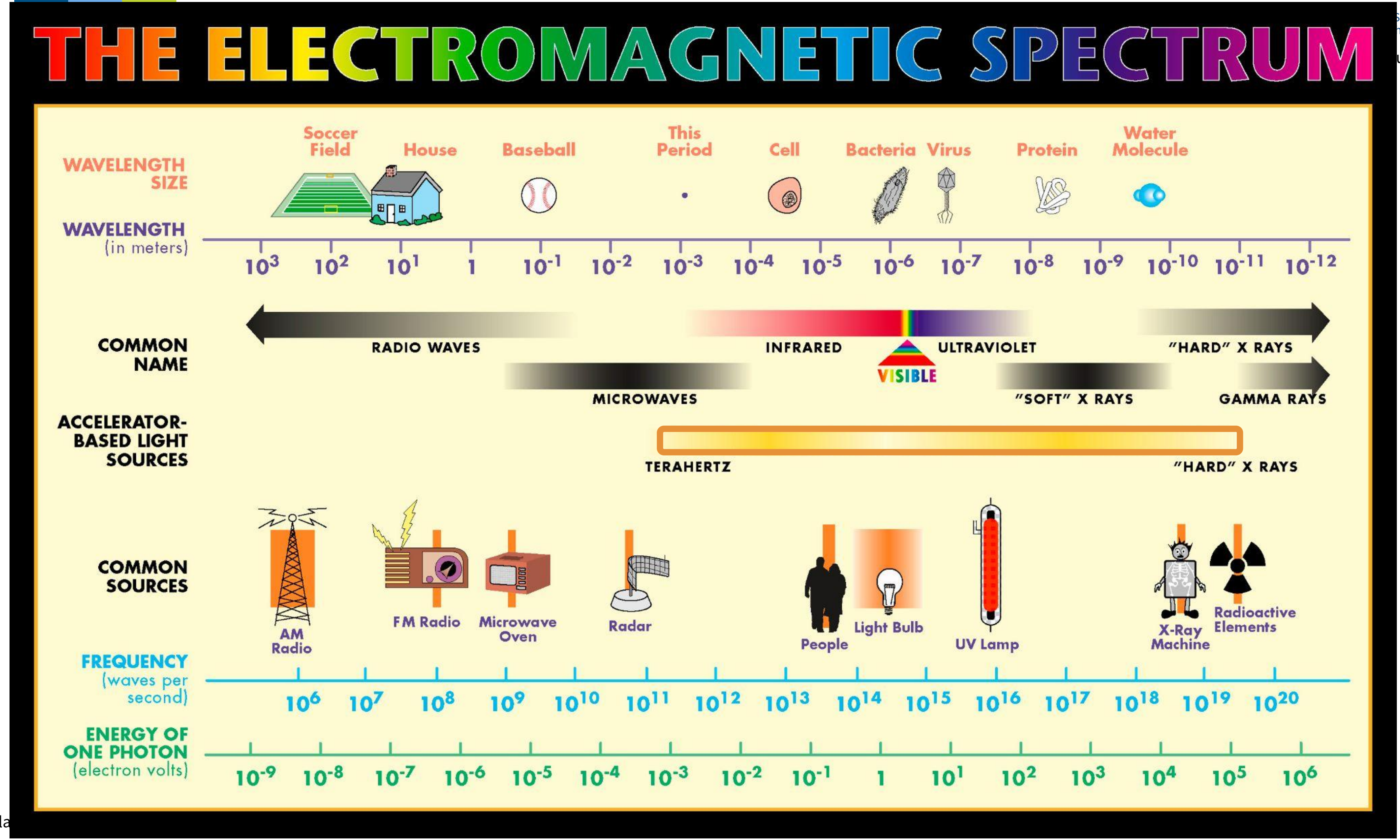
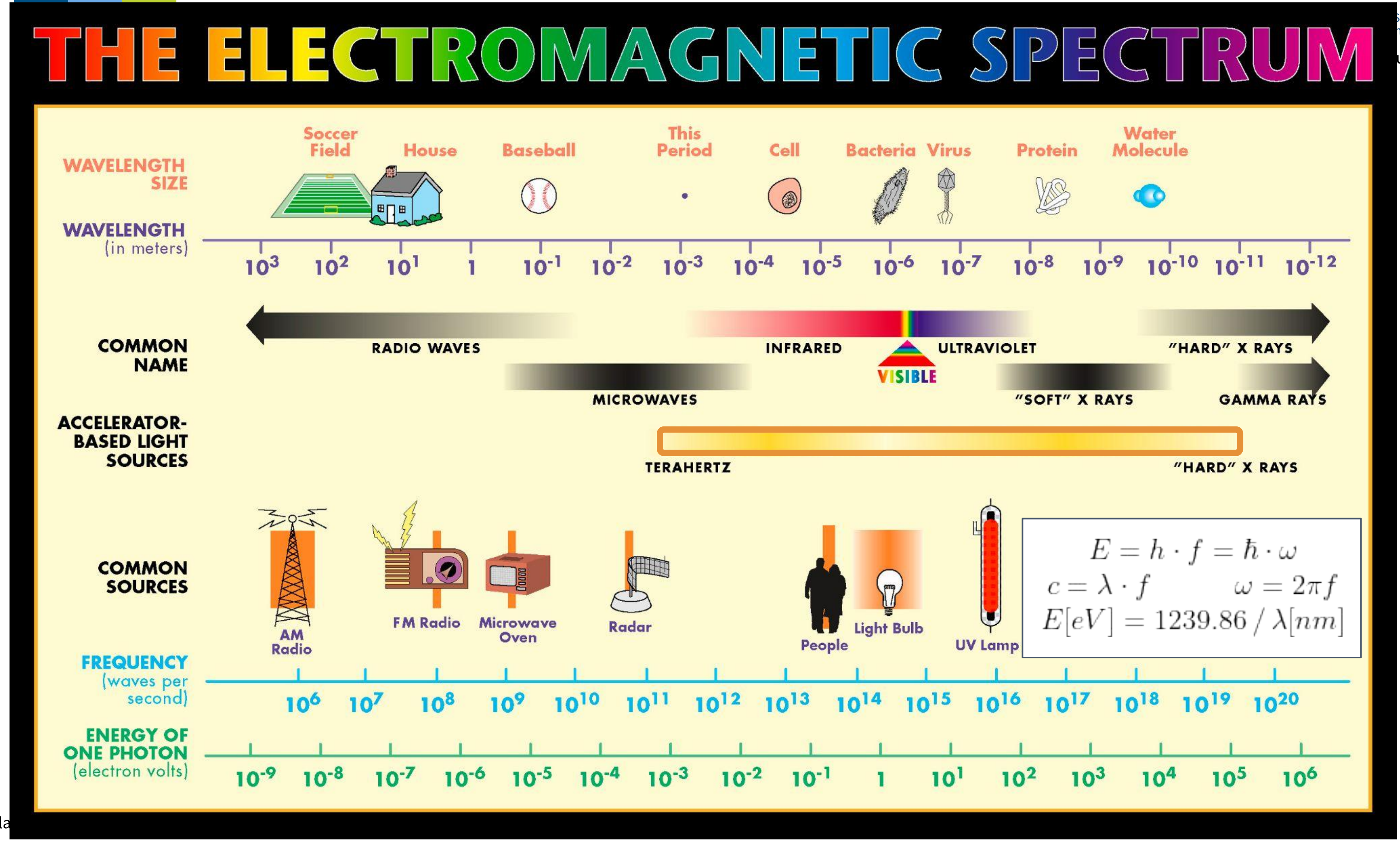
use only


THE ELECTROMAGNETIC SPECTRUM
WAVELENGTH SIZE
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
WAVELENGTH (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
COMMON NAME
RADIO WAVES
INFRARED
ULTRAVIOLET
"HARD" X RAYS
VISIBLE
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
ACCELERATOR-BASED LIGHT SOURCES
TERAHERTZ
"HARD" X RAYS
COMMON SOURCES
AM Radio
FM Radio
Microwave Oven
Radar
People
Light Bulb
UV Lamp
X-Ray Machine
Radioactive Elements
FREQUENCY (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
ENERGY OF ONE PHOTON (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6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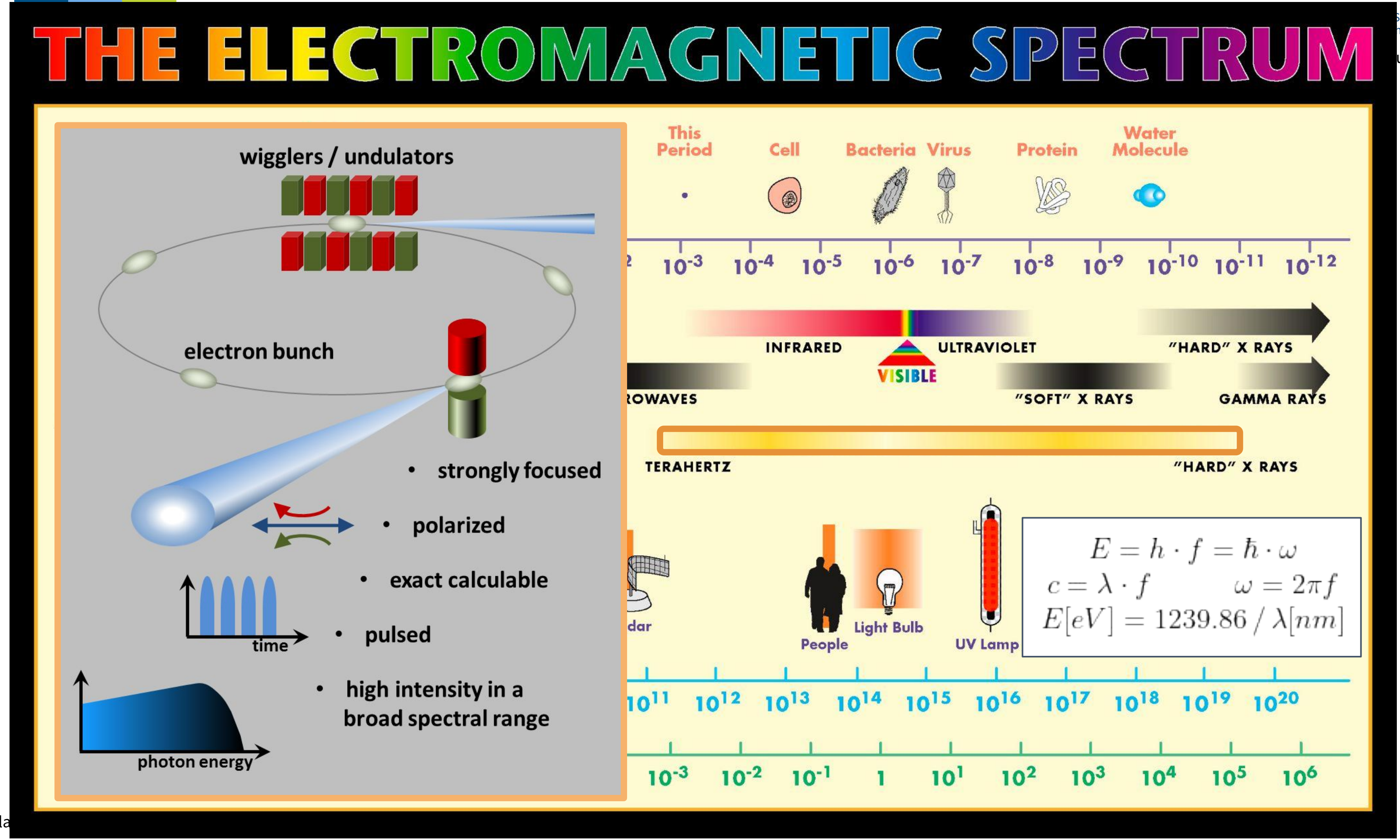
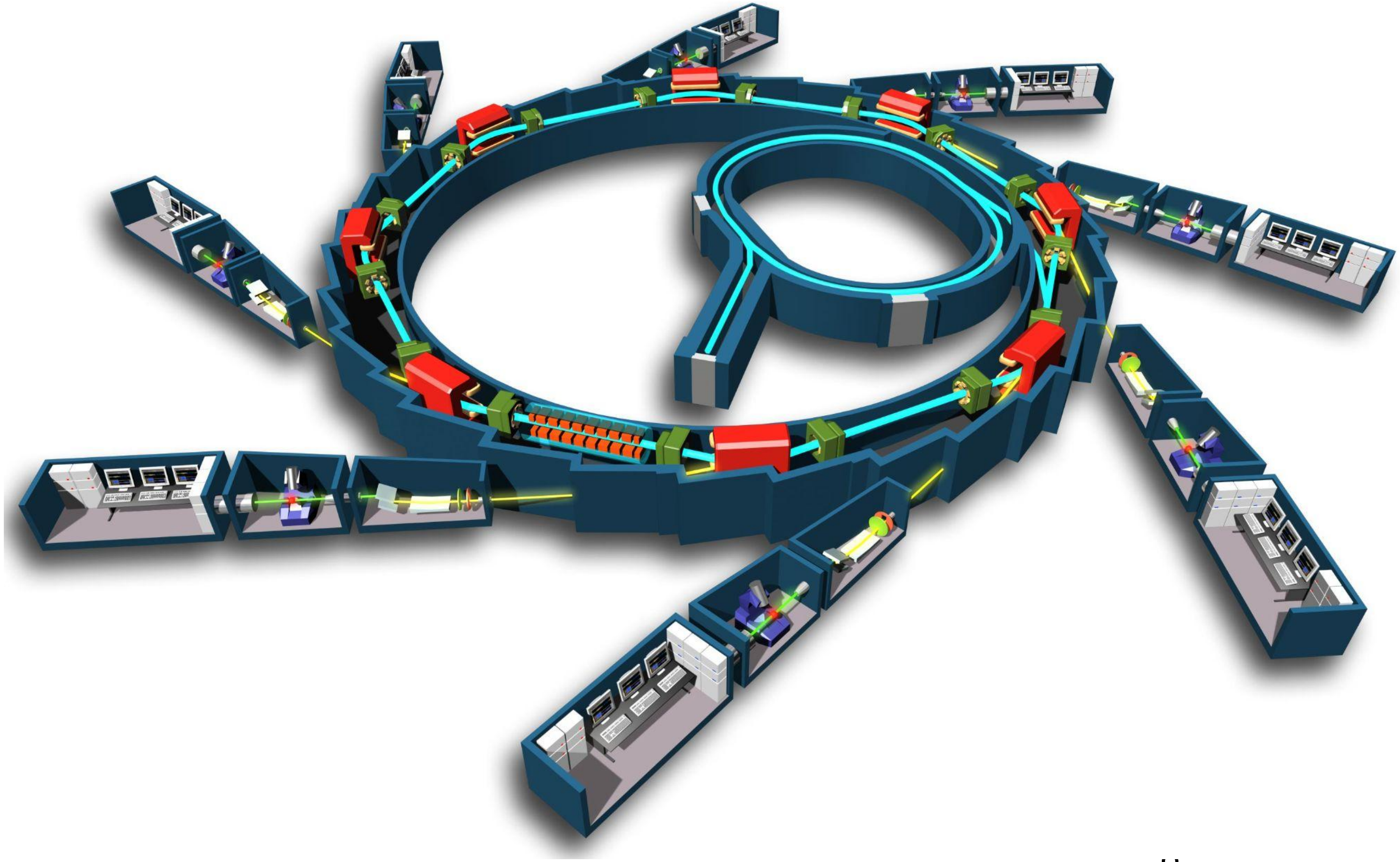
COMMON SOURCES
AM Radio
FM Radio
Microwave Oven
Radar
People
Light Bulb
UV Lamp
$E = h \cdot f = \hbar \cdot \omega$
$c = \lambda \cdot f \qquad \omega = 2\pi f$
$E[eV] = 1239.86 / \lambda[nm]$
FREQUENCY (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
ENERGY OF ONE PHOTON (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6



THE ELECTROMAGNETIC SPECTRUM
wigglers / undulators
electron bunch
strongly focused
polarized
exact calculable
pulsed
time
high intensity in a broad spectral range
photon energy
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
10-3 10-4 10-5 10-6 10-7 10-8 10-9 10-10 10-11 10-12
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
ROWAVES
"SOFT" X RAYS
GAMMA RAYS
TERAHERTZ
"HARD" X RAYS
dar
People
Light Bulb
UV Lamp
$E = h \cdot f = \hbar \cdot \omega$
$c = \lambda \cdot f \qquad \omega = 2\pi f$
$E[eV] = 1239.86 / \lambda[nm]$
1011 1012 1013 1014 1015 1016 1017 1018 1019 1020
10-3 10-2 10-1 1 101 102 103 104 105 106

A synchrotron radiation (light source) facility - A large-scale research facility



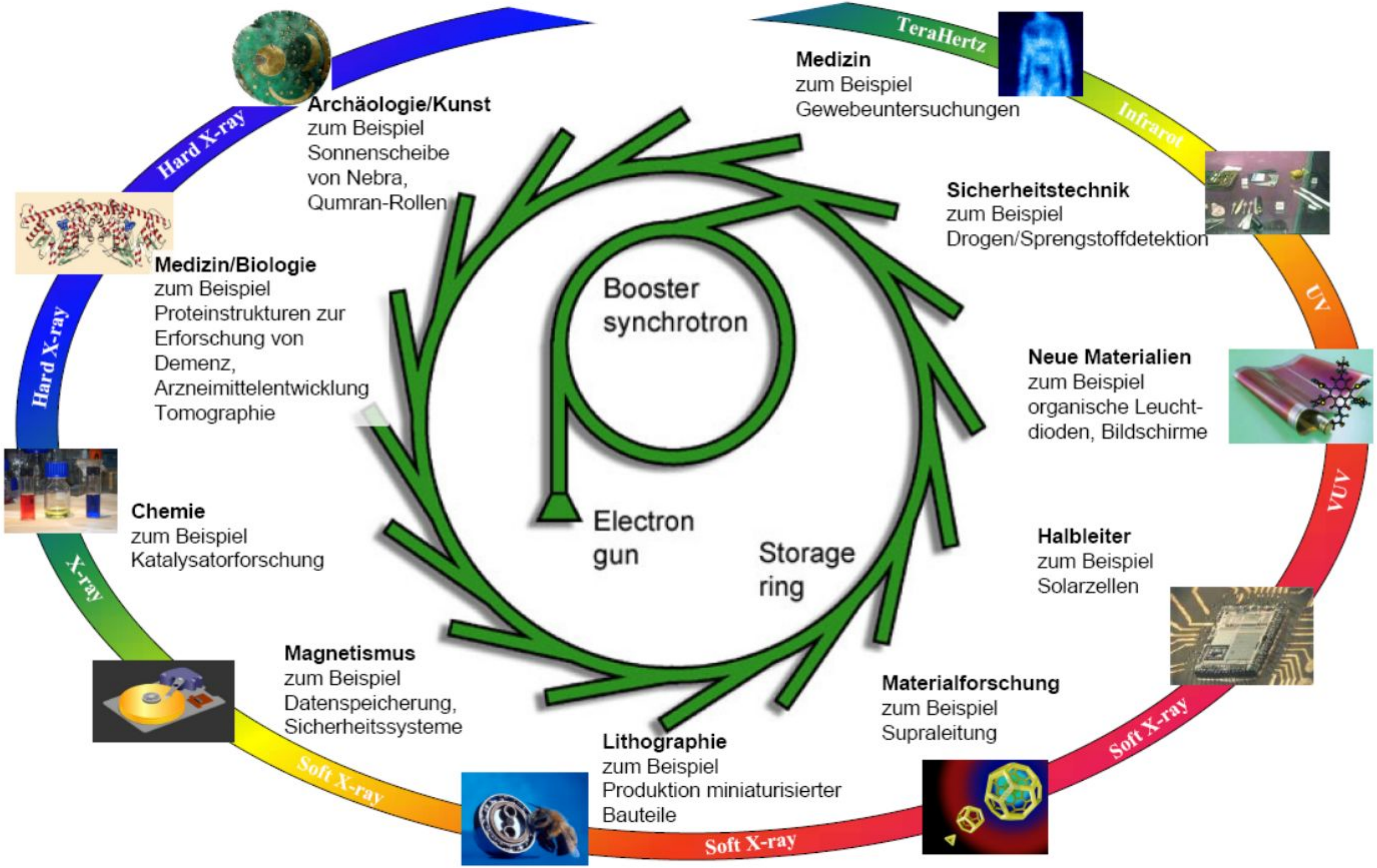
PETRA III
MAXIV
DELTA
ELSA
ASTRIDII
SSRC
SOLARIS
BESSYII
ANKA
DELSY
CLS
DIAMOND
SLS
KSRS
SPRING8
CHESS
SOLEIL
BSRF
PLS
PFKEK
NSSR
CANDLE
APS
NSRL
UVSOR
NSLS II
ILSF
TSRF
ALS
ALBA
SSRF
SUBARU
HISOR
RITSSR
CAMD
SURF
DAFNE
INDUS
SRLI
TPS
SAGA
SSRL
ESRF
ELETTRA
NSRRC
SESAME
HELIOS2
SIRIUS
LNLS
AS

Why are Synchrotron Lightsources cool ? Usage & Applications

Why are Synchrotron Lightsources cool ? Usage & Applications

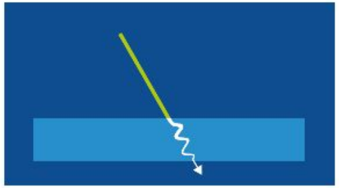
Swiss Army Knifes for Science and High-Tech

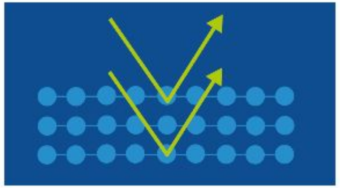
Why are Synchrotron Lightsources cool ? Usage & Applications

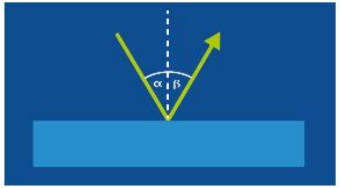


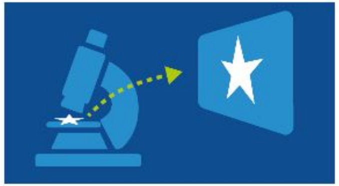
Usage & Applications of Synchrotron Radiation

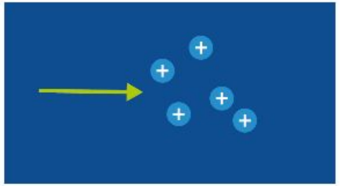
Experimental Techniques at Lightsource Beamlines

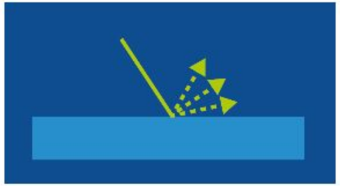

Absorption

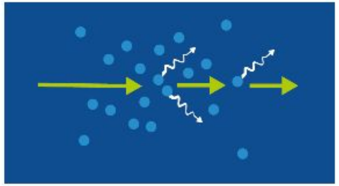

Diffraction


Reflection


Imaging

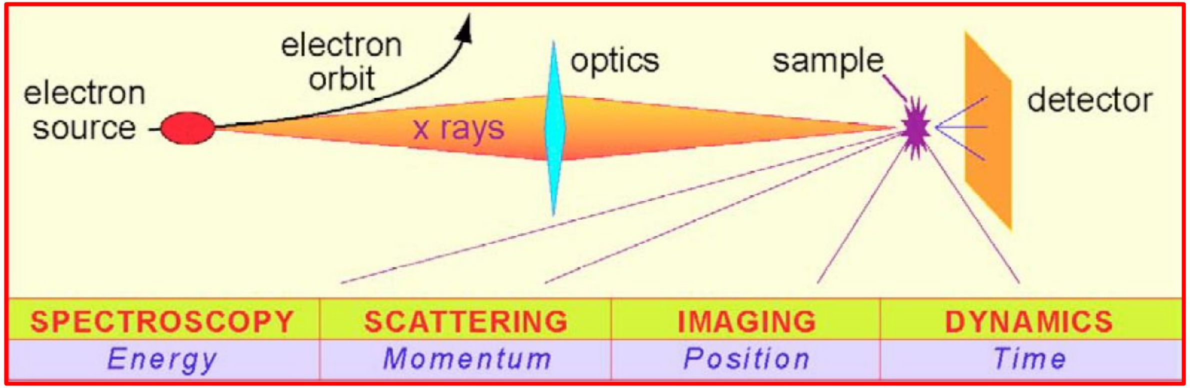

Ion Spectroscopy


Photoelectron Emission


Scattering

Usage & Applications of Synchrotron Radiation

Experimental Techniques at Lightsource Beamlines



SPECTROSCOPY

01 Low-Energy Spectroscopy
02 Soft X-Ray Spectroscopy
03 Hard X-Ray Spectroscopy
04 Optics/Calibration/Metrology

SCATTERING

05 Hard X-Ray Diffraction
06 Macromolecular Crystallography
07 Hard X-Ray Scattering
08 Soft X-Ray Scattering

IMAGING

09 Hard X-Ray Imaging
10 Soft X-Ray Imaging
11 Infrared Imaging
12 Lithography

Usage & Applications of Synchrotron Radiation

For internal use only
Courtesy to PTB, M. Kumrey

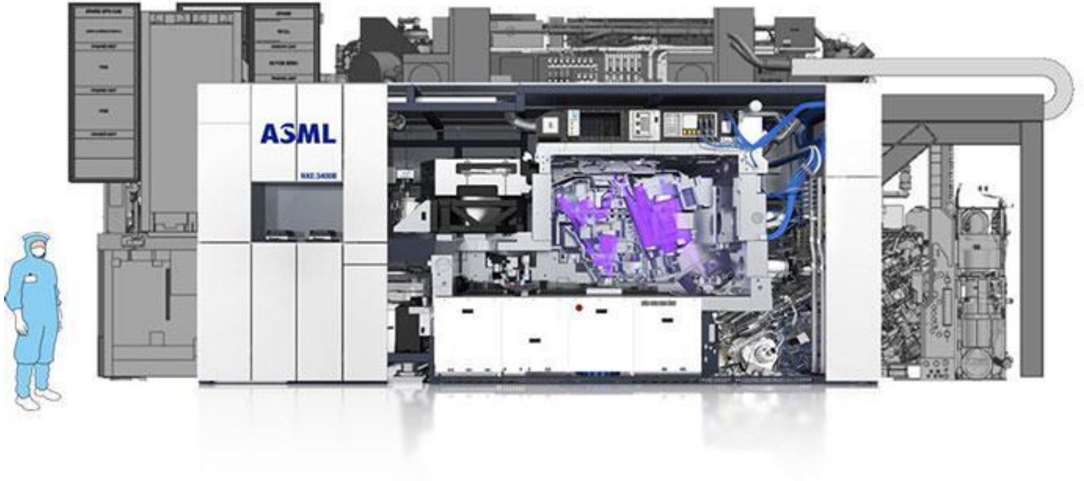
EUV-lithography targeting 5 nm process nodes

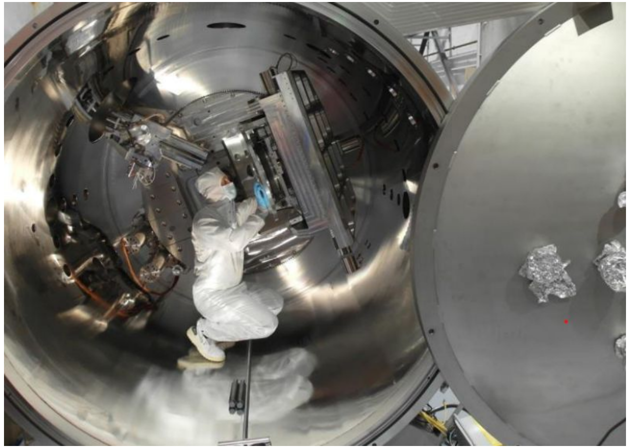
- Changing lithography radiation source from 193 nm to 13.5 nm

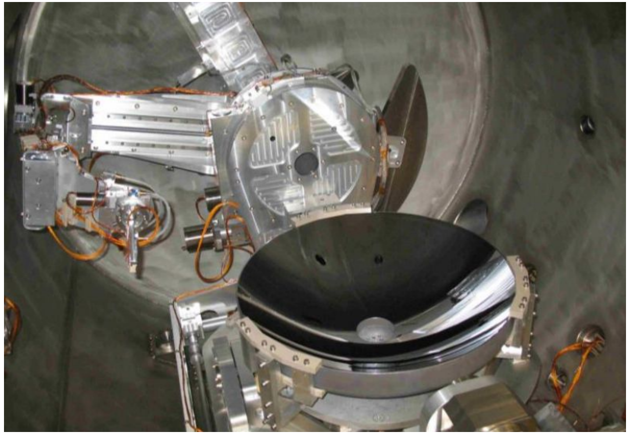
PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

ASML

ZEISS



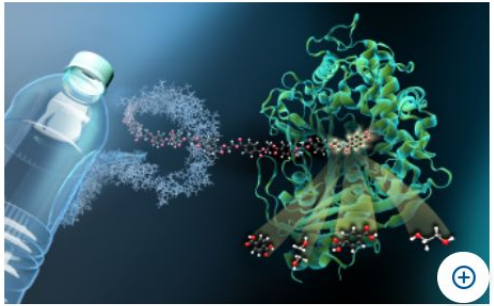




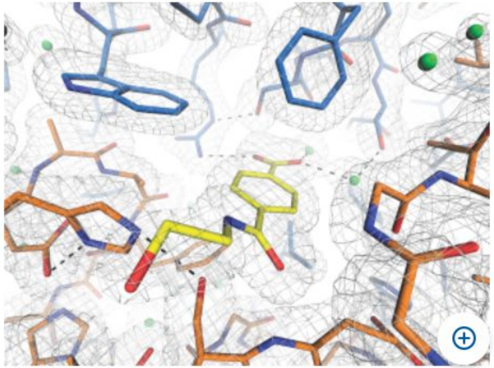
Usage & Applications of Synchrotron Radiation

“Molecular scissors” for plastic waste

- 2016 bacterium discovered that grows on PET, produces two enzymes
  - PETase, which breaks down plastic into smaller building blocks
  - MHETase splits it into the basic buildings blocks of PET
    (terephtahlic acid and ethylene glycol)
- Synthesis of new PET without oil.



The enzyme MHETase is a huge and complex molecule. MHET-molecules from PET plastic dock at the active site inside the MHETase and are broken down into their basic building blocks. © M. Künsting/HZB



MHETase at work: a MHET-molecule (which is a building block of PET) is broken down into the basic building blocks terephthalic acid and ethylene glycol. © Gert Weber/HZB

A research team from the University of Greifswald and Helmholtz-Zentrum-Berlin (HZB) has solved the molecular structure of the important enzyme MHETase at BESSY II. MHETase was discovered in bacteria and together with a second enzyme - PETase - is able to break down the widely used plastic PET into its basic building blocks. This 3D structure already allowed the researchers to produce a MHETase variant with optimized activity in order to use it, together with PETase, for a sustainable recycling of PET. The results have been published in the research journal Nature Communications.

Plastics are excellent materials: extremely versatile and almost eternally durable. But this is also exactly the problem, because after only about 100 years of producing plastics, plastic particles are now found everywhere – in groundwater, in the oceans, in the air, and in the food chain. Around 50 million tonnes of the industrially important polymer PET are produced every year. Just a tiny fraction of plastics is currently recycled at all by expensive and energy-consuming processes which yield either downgraded products or depend in turn on adding 'fresh' crude oil.

Bacteria on PET discovered in 2016

In 2016, a group of Japanese researchers has discovered a bacterium that grows on PET and partially feeds on it. They found out that his bacterium possesses two special enzymes, PETase and MHETase, which are able to digest PET plastic polymers. PETase breaks down the plastic

Usage & Applications of Synchrotron Radiation

ADVANTAGES OF BIOCATALYSTS

- Bio-based catalysts
- Bio-degradable catalysts
- Low reaction temperatures
- Mild reaction conditions
- Specificity
- Non-toxic
- Efficiency

Courtesy to G. Weber

Biocatalysis is a sustainable technology for the 21st century

Collaborators of HZB taking advantage of biocatalysts in PET recycling:
The French company Carbios has taken a fungal PET hydrolase to TRL9, unlocking a sustainable PET recycling at low reaction temperatures.

Arnal *et al.* ACS Catalysis *(2023)*

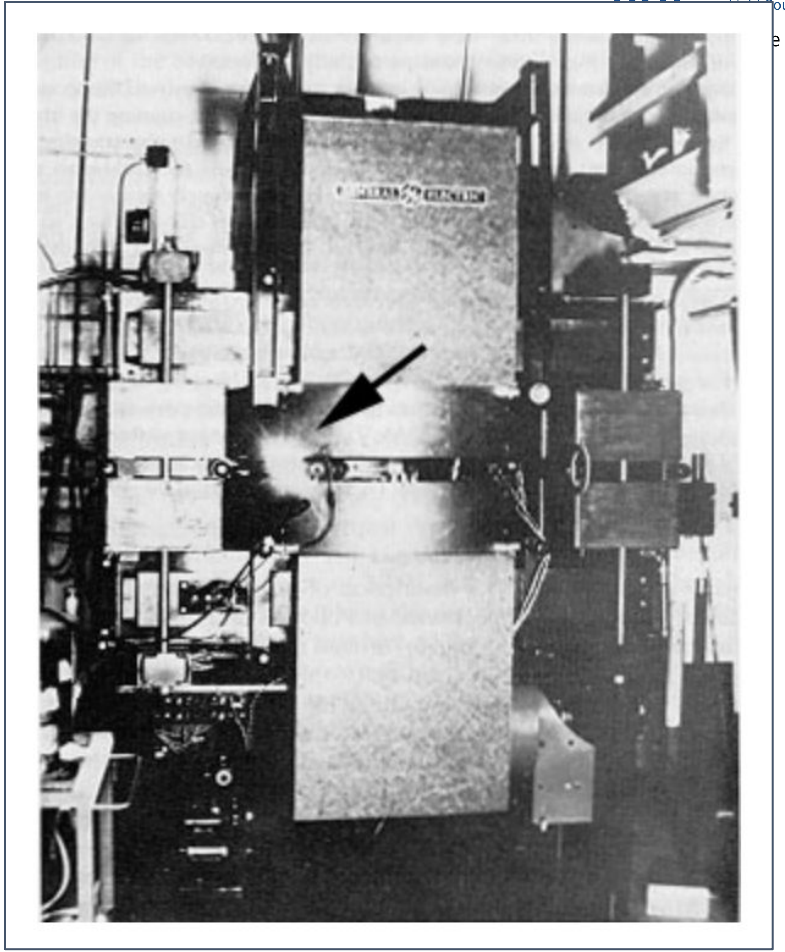
History & Development of Synchrotron Lightsources

History & Development of Lightsources

e only

& Physics … & Particle Accelerators

- Wilhelm Conrad Röntgen: Nov 1895
- Quantum world…
- First particle accelerators ~ 1940
- Do particles in accelerators radiate or not?
  - Protons, Neutrons, Electrons, Particle Zoo
  - Ivanenko, Pomeranchuk, Swinger
- **First synchrotron radiation** 1946 at a Synchrotron from GE
  - Parasitic use
- Tantalus, ~ 1970 first particle accelerator for synchrotron rad.



History & Development of Lightsources

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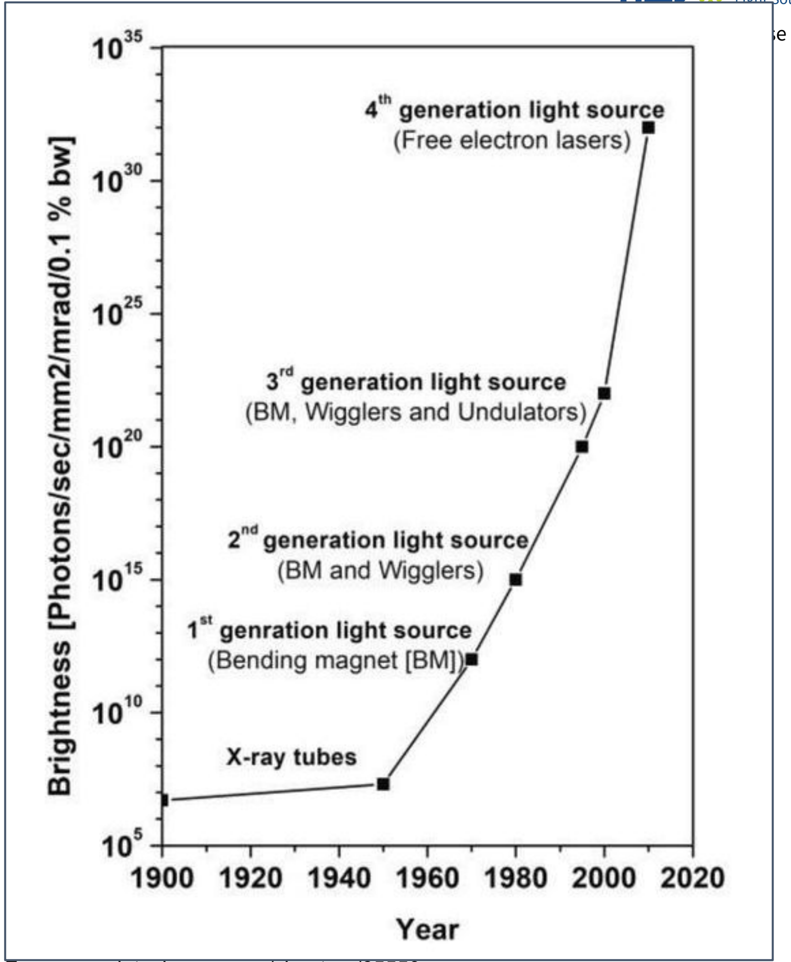

From: www.intechopen.com/chapters/65550

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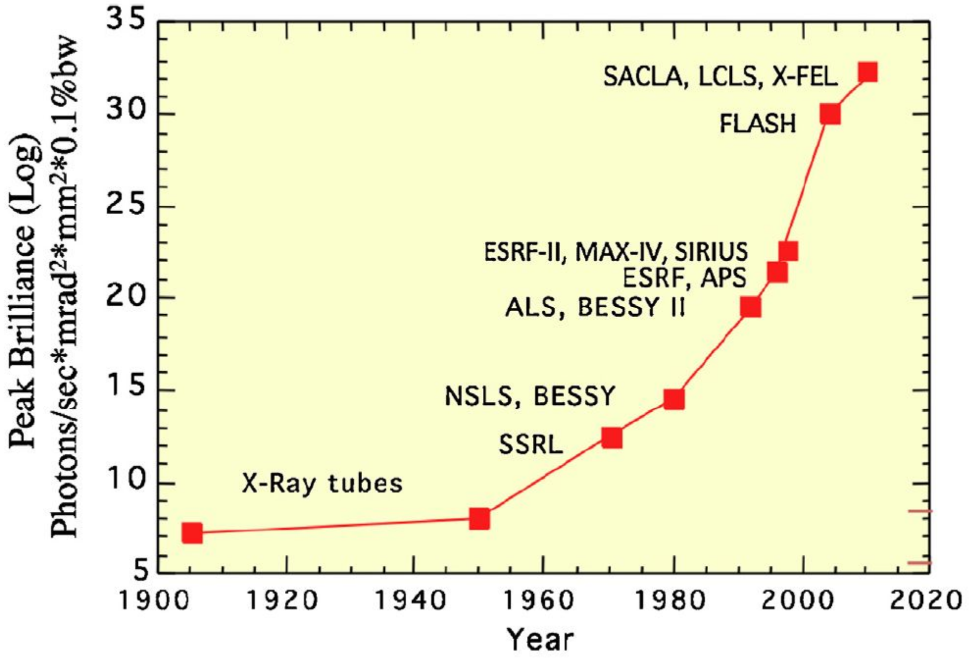


Fig. 1. Peak brilliance of laboratory X-ray sources, 1st (SSRL), 2nd (NSLS, BESSY), and 3rd generation (ALS, BESSY II, APS, ESRF) synchrotron radiation sources, diffraction limited storage rings (ESRF-II, MAX-IV, SIRIUS) and Free Electron Lasers (FLASH, SACLA, LCLS, X-FEL).

From: dx.doi.org/10.1016/j.elspec.2015.06.009

Brilliance (or Brightness) of the Radiation Source

is defined by

$$B(\lambda) = \frac{F(\lambda)}{4\pi^2 \Sigma_x \Sigma_y \Sigma'_x \Sigma'_y} \quad \left[\frac{\text{photons}}{\text{mm}^2 \cdot \text{mrad}^2 \cdot \text{s} \cdot (0.1\%\text{BW})}\right]$$

$$F(\lambda) = \frac{N \cdot E}{t \cdot \Delta E} \cdot X$$

and the effective source sizes and divergences are **convolutions** between electron and intrinsic photon source sizes and divergences… assuming Gaussian distributions:

$$\Sigma_{x,y} = \sqrt{(\sigma^2_{x,y} + \sigma^2_R)} \qquad \Sigma'_{x,y} = \sqrt{(\sigma'^2_{x,y} + \sigma'^2_R)}$$

For electrons, electron bunches:

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y} \beta_{x,y}}$$

$$\sigma'_{x,y} = \sqrt{\epsilon_{x,y} / \beta_{x,y}}$$

For photons:

$$\sigma_R = \sqrt{\epsilon_R \beta_R}$$

$$\sigma'_R = \sqrt{\epsilon_R / \beta_R}$$

and some more assumptions, beta functions adjusted $(\beta_x = \beta_y = \beta_R)$:

$$B(\lambda) = \frac{F(\lambda)}{4\pi^2 (\epsilon_x + \epsilon_R)(\epsilon_y + \epsilon_R)}$$

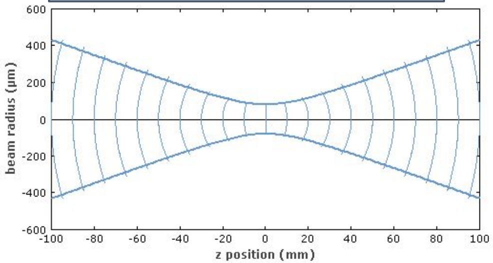
The Diffraction Limit

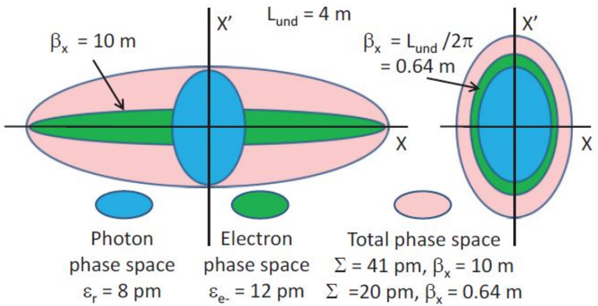
- Brilliance of radiation source: $$B(\lambda) = \frac{F(\lambda)}{4\pi^2(\epsilon_x + \epsilon_R)(\epsilon_y + \epsilon_R)}$$

electron beam : $\epsilon_{x,e^-} \sim E^2/N_d^3$
photon beam : $\epsilon_\gamma = \sigma_\gamma \sigma_\gamma'$

- Photon diffraction limited emittance:

$$\epsilon_\gamma = \sigma_\gamma \, \sigma_\gamma' = \frac{\lambda}{4\pi}$$





Storage ring based (transverse) diffraction limited radiation source

$$\epsilon_{x,y,e^-} \ll \epsilon_\gamma = \frac{\lambda}{4\pi}$$

- Diffraction Limited for

0.1 keV	~ 12.4 nm	→	1000 pm rad
1.0 keV	**~ 1.24 nm**	**→**	**100 pm rad**
10.0 keV	~ 0.124 nm	→	10 pm rad

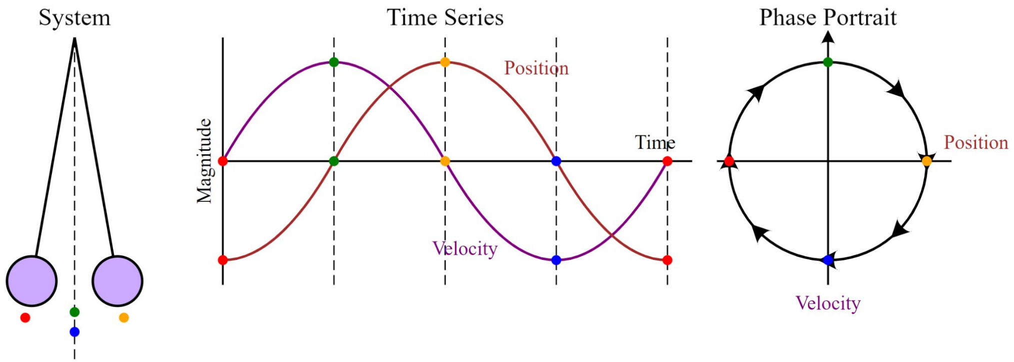
1 keV diffraction limited radiation
→ 100 pm rad e^- beam emittance

HZB BESSY II Light Source

For internal use only

Source Size, Emittance, Beta-Fct., Dynamical System, Phase Space

The **phase space**, defined by the right variables (often position & momentum) represents all possible states of a dynamical system.



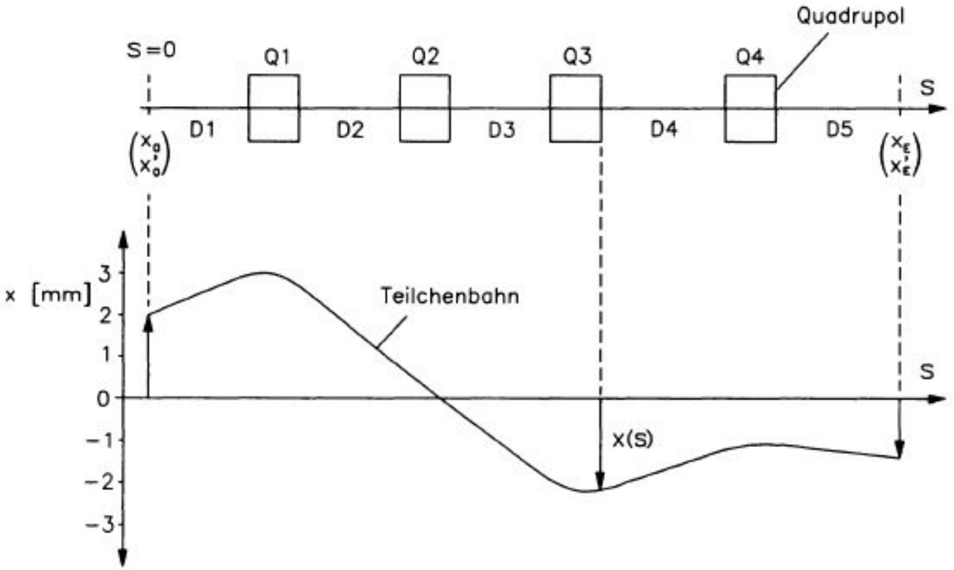
HZB BESSY II Light Source

For internal use only

Source Size, Emittance, Beta-Fct., Dynamical System, Phase Space

The **phase space**, defined by the right variables (often position & momentum) represents all possible states of a dynamical system.

The phase space for electrons in an accelerator (or a magnetic transport system - beam line)



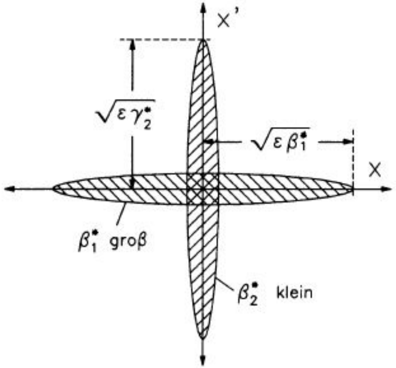
Source Size, Emittance, Beta-Fct., Dynamical System, Phase Space

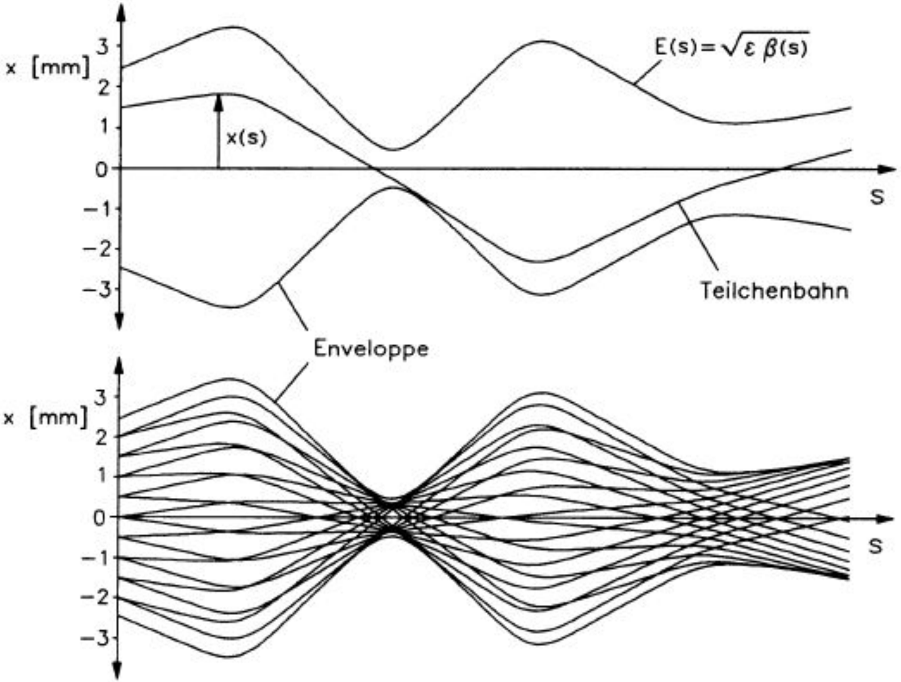
The **phase space**, defined by the right variables (often position & momentum) represents all possible states of a dynamical system.

The phase space for electrons in an accelerator (or a magnetic transport system - beam line)

Emittance:
Area phase space

Beta-Fct:
Amplitude (s)





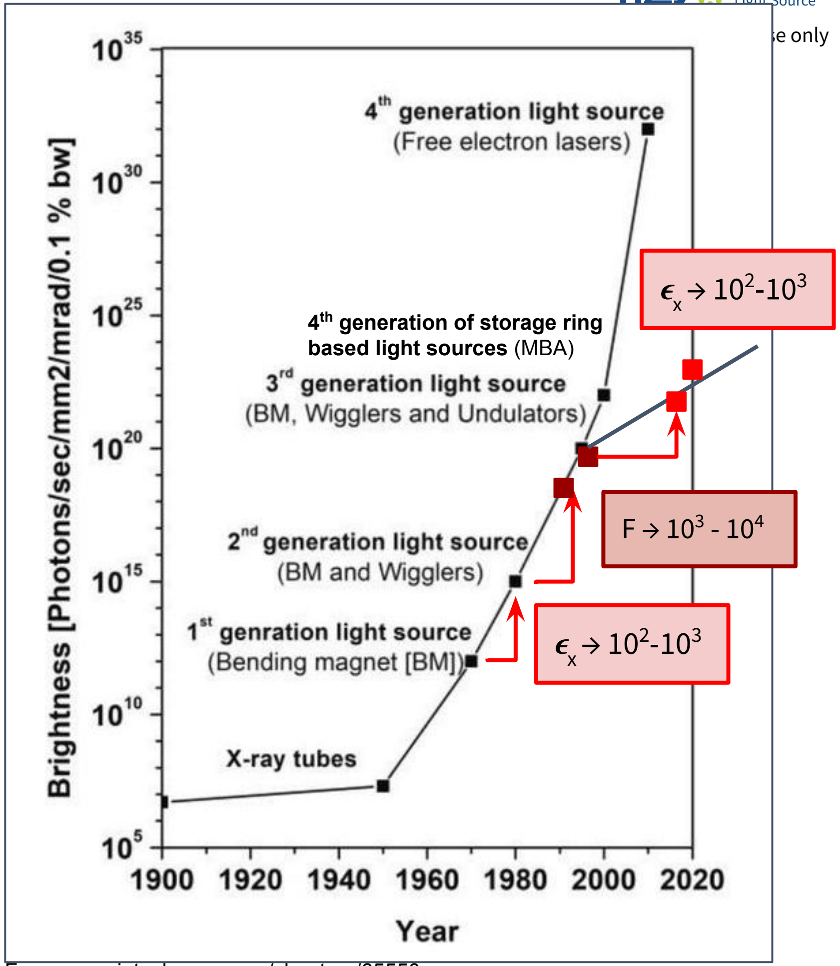
History & Development of Lightsources

Brilliance increase - orders of magnitudes

- Two possibilities of improvement
  - The generation of photons: F, X
  - or the source emittance: ϵ_{xy}

$$B(\lambda) = \frac{\boxed{F(\lambda)}}{4\pi^2(\underline{\epsilon_x} + \epsilon_R)(\underline{\epsilon_y} + \epsilon_R)}$$

$$F(\lambda) = \frac{N \cdot E}{t \cdot \Delta E} \cdot \boxed{X}$$

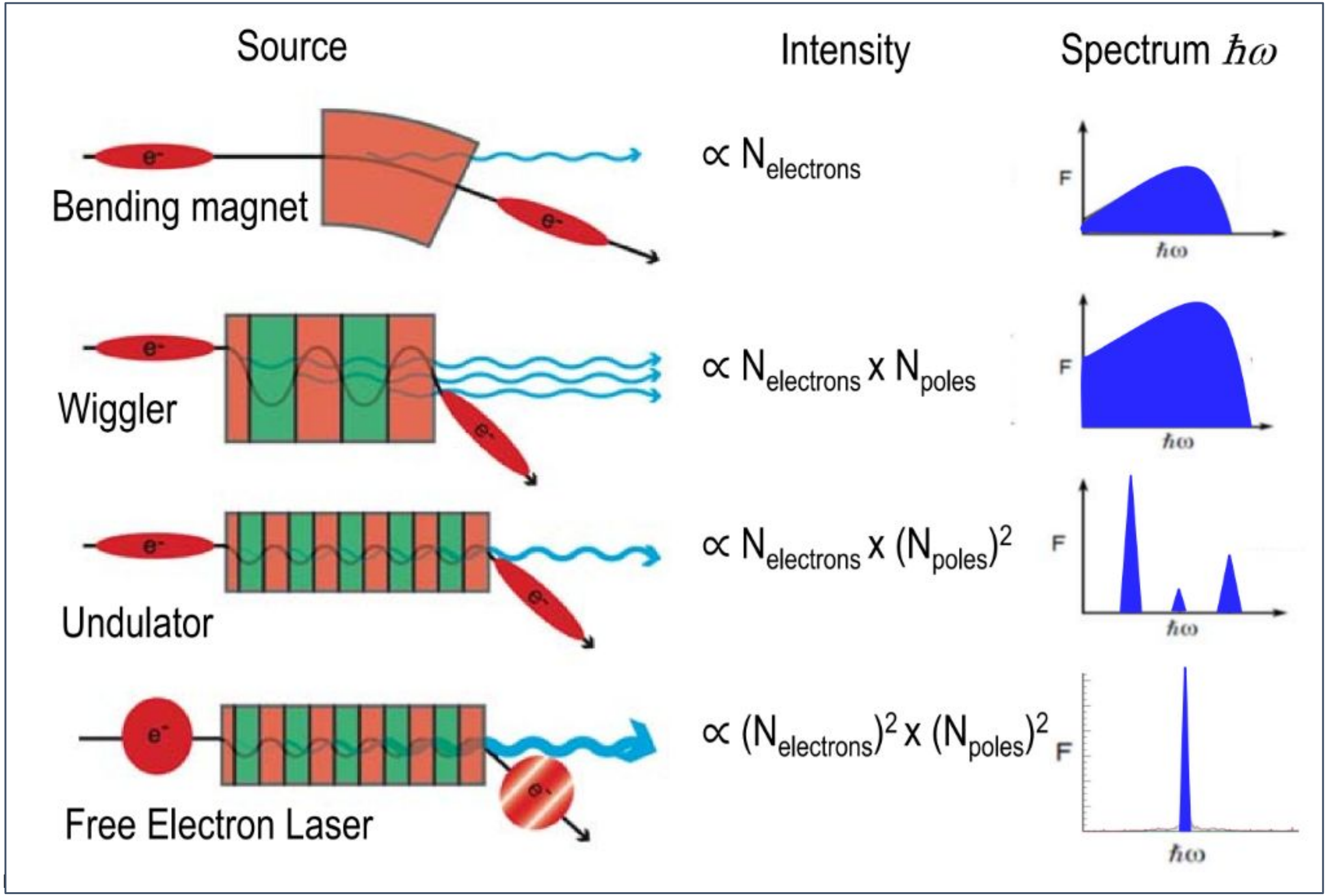


From: www.intechopen.com/chapters/65550

History & Development of Lightsources

For internal use only

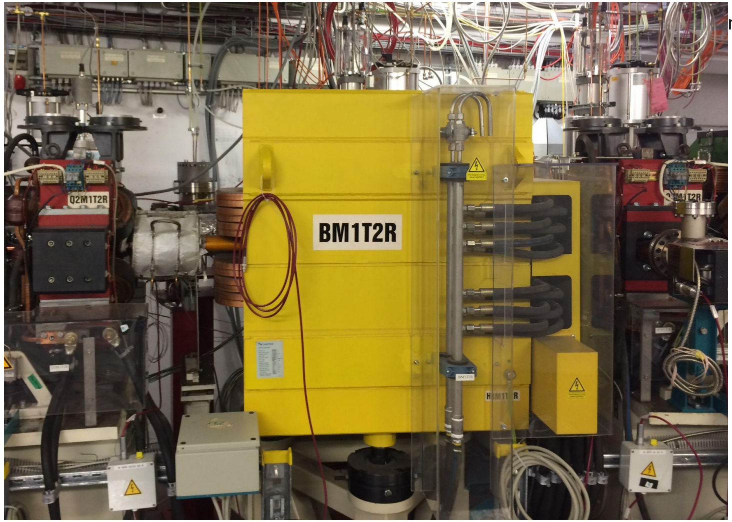
From: httpsi.stack.imgur.comjRAPD.png



History & Development of Lightsources

Bending magnets & Undulators

nal use only

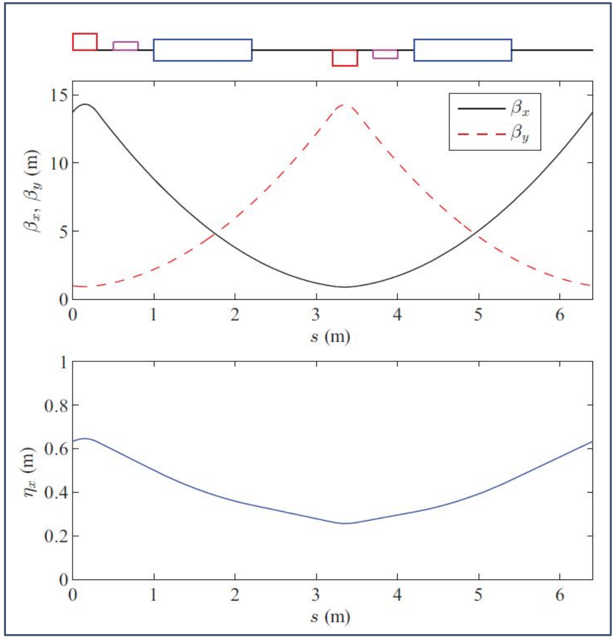


History & Development of Lightsources

Electrons, Emittance & Magnetic Lattices

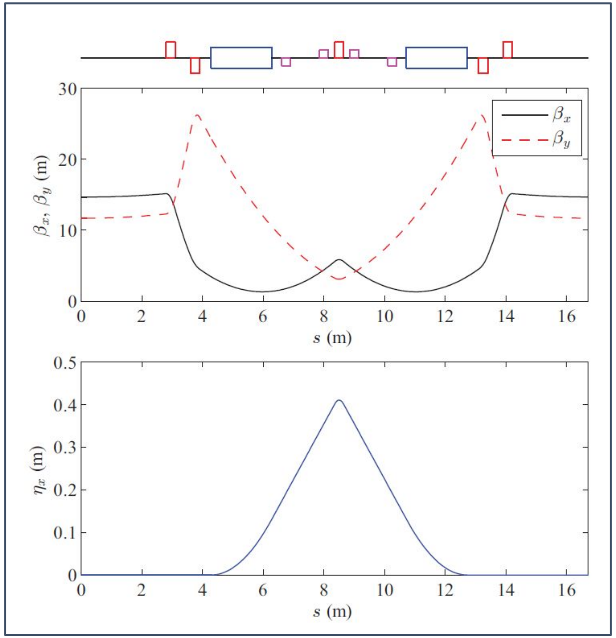
FODO

ϵ_x ~ 100 - 900 nm rad @ 2 GeV



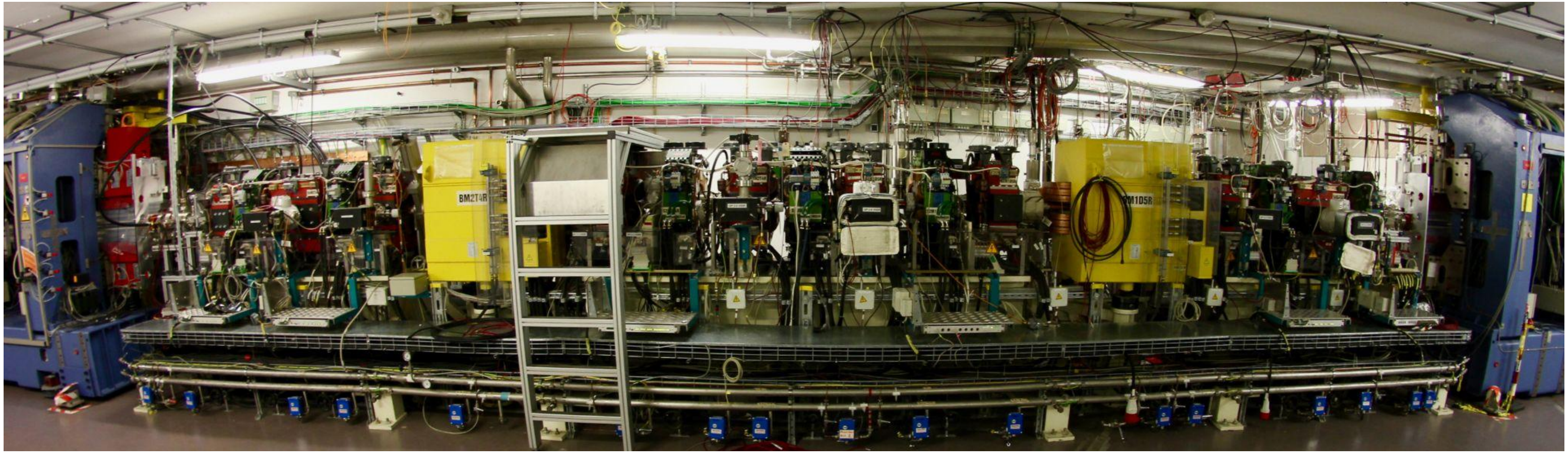
DBA / TBA

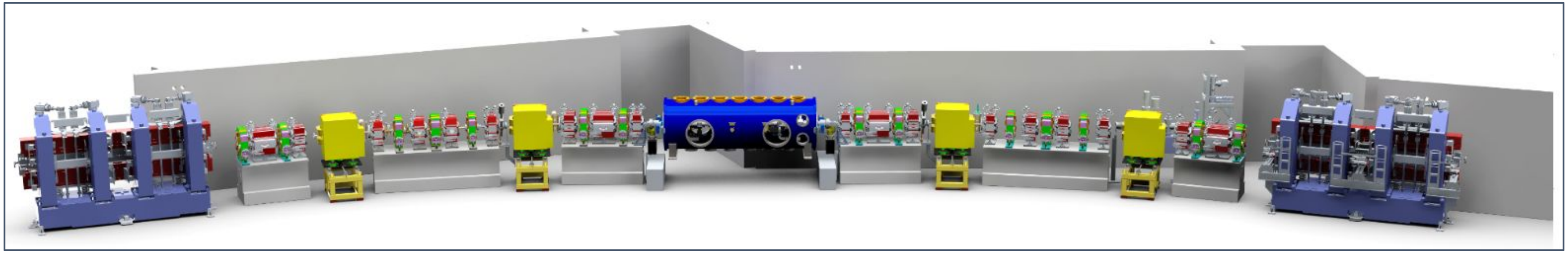
ϵ_x ~ 1 - 20 nm rad @ 2 GeV



History & Development of Lightsources

Electrons, Emittance & Magnetic Lattices

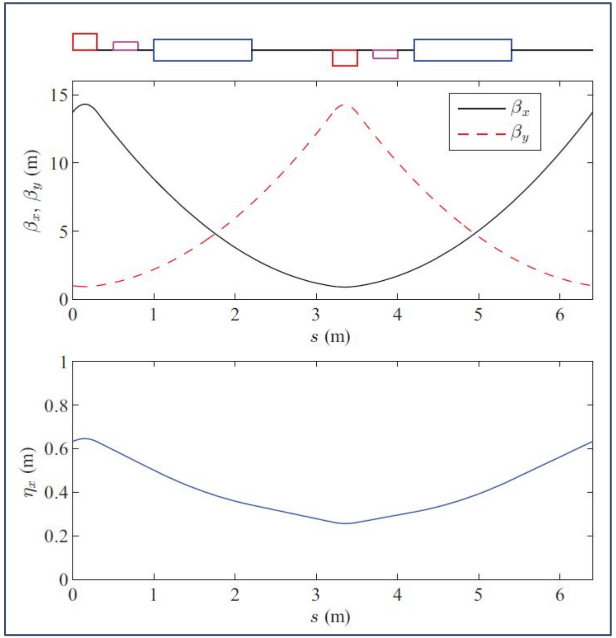




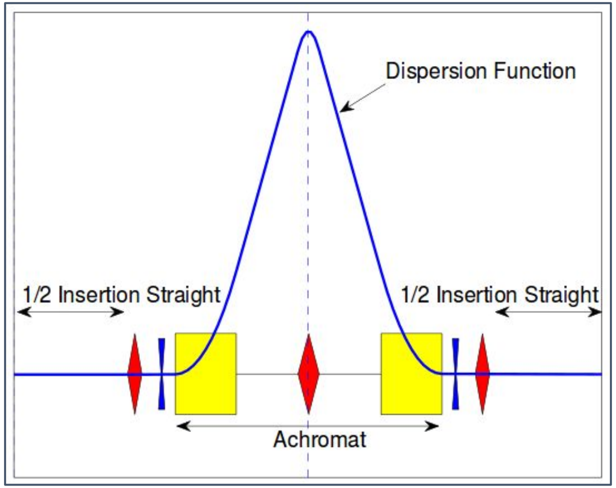
History & Development of Lightsources

Electrons, Emittance & Magnetic Lattices

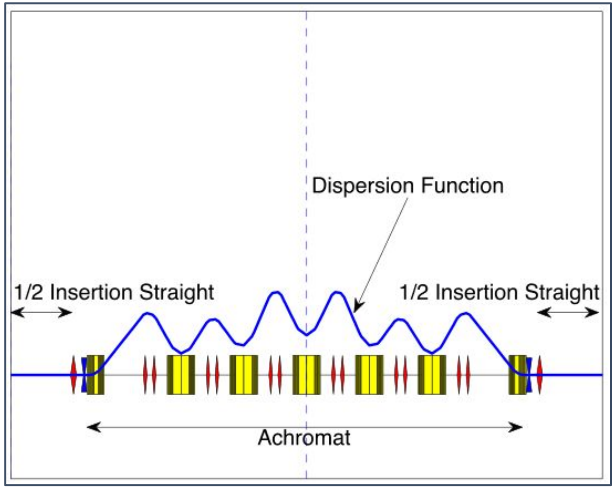
FODO
ϵ_x ~ 100 - 900 nm rad @ 2 GeV



DBA / TBA
ϵ_x ~ 1 - 20 nm rad @ 2 GeV



MBA
ϵ_x ~ 0.1 - 0.3 nm rad @ 2 GeV



History & Development of Lightsources

The first 4th generation storage ring based lightsources


photo credit to Felix Gerlach

MAX IV Laboratory is a Swedish national laboratory providing scientists with the most brilliant X-rays for research. With more than 30 years of experience operating the MAX I-III facilities, it is now operating MAX IV, which was inaugurated 2016. Fully developed it will house more than 20 beamlines and welcome up to 2000 researchers per year.

- MAX IV welcomed first expert users in December 2015, the regular call for proposals started in August 2017.
- Ongoing construction and commissioning will bring the number of beamlines at MAX IV up to 16 by 2021.

MAX IV

Website
https://www.maxiv.lu.se/

Location
Sweden, Lund

Specifications

Energy: 3 GeV
Current: 500 mA
Operational Beamlines: 6
Horizontal emittance: 330 pm rad


Aerial photograph of Sirius

LNLS sirius Brazilian Synchrotron Light Laboratory

Website
http://www.lnls.cnpem.br/en/

Location
Brazil, Campinas (SP)

Specifications
Energy: 3 GeVCurrent: Current: 350 mA (in top-up mode). Presently operating with 100 mA (in top-up mode).
Operational Beamlines: 10
Horizontal emittance: 250 pm

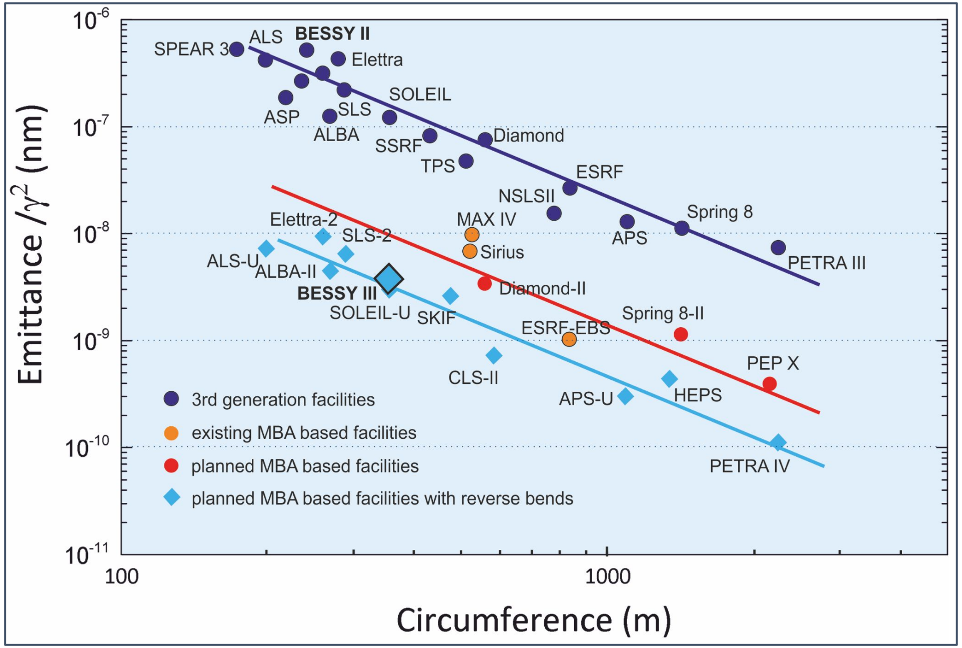
See
Accelerators: https://lightsources.org/
Beamlines/Exp: https://www.wayforlight.eu/

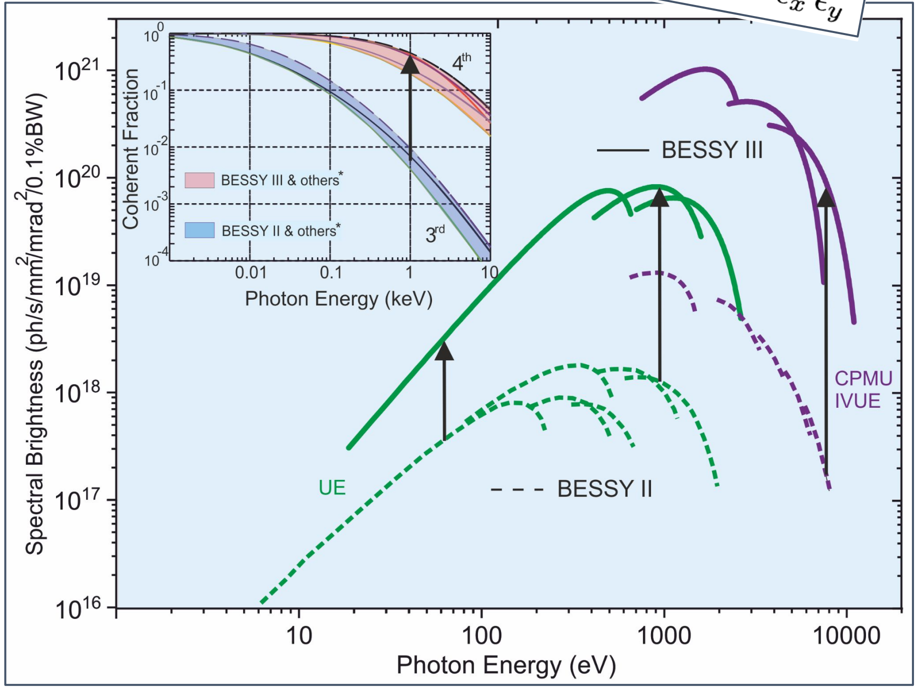

ESRF-EBS: 6 GeV, 133 pmrad

BESSY III

100x times more brightness than BESSY II & 1000x times smaller focus at sample (10µm down to 10nm)

$$B(\lambda) = \frac{F(\lambda)}{4\pi^2 \epsilon_x \epsilon_y}$$

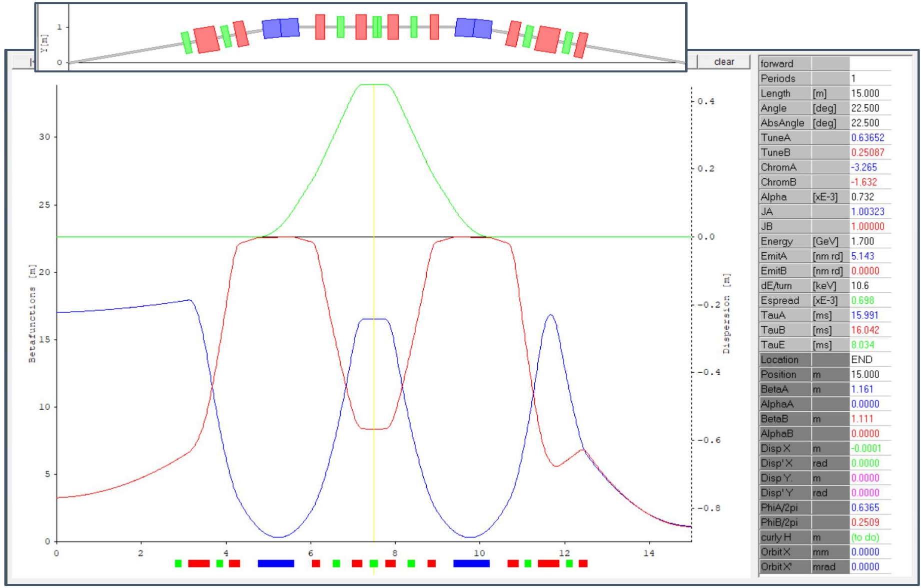




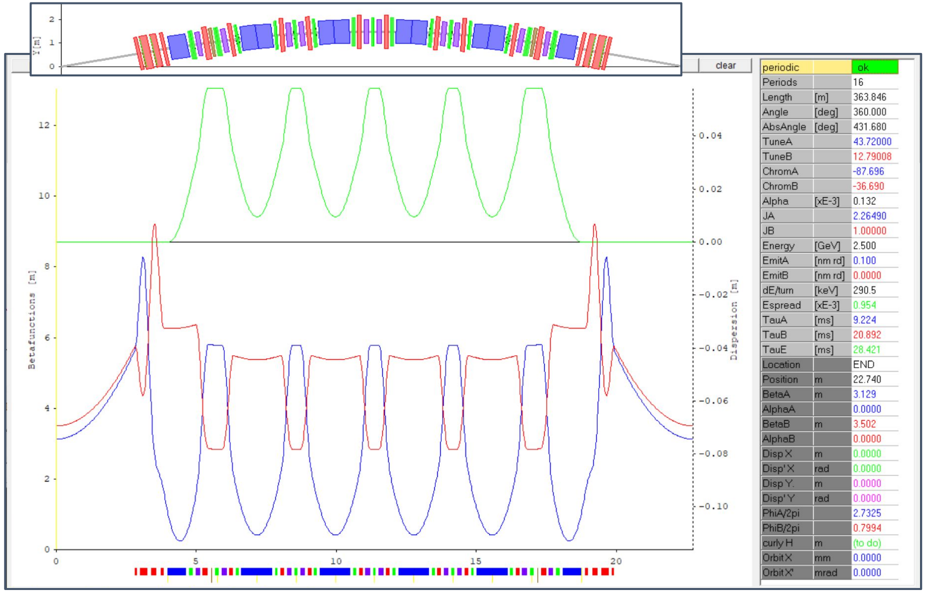
In situ & operando, sample environment, material & metrology labs → Integrated Research Campus

BESSY II/III magnetic structure/lattice

BESSY II (1.7 GeV, 5 nmrad)



BESSY III (2.5 GeV, 100 pm rad)



- BESSY II: 2x bends, 9x quadrupoles, 7x sextupoles x16 sectors ~ 288 devices
- BESSY III: 6x bends, 28x quadrupoles, 15x sextupoles, 2 oct… x16 sectors ~ 816 devices

“Old” machines need new infrastructure/software

Digitalization by Digital Natives

Control System: Accelerator – Beamline

EPICS, TANGO, SCADA

Accelerator Systems:

- More than **1000s** devices & signals:

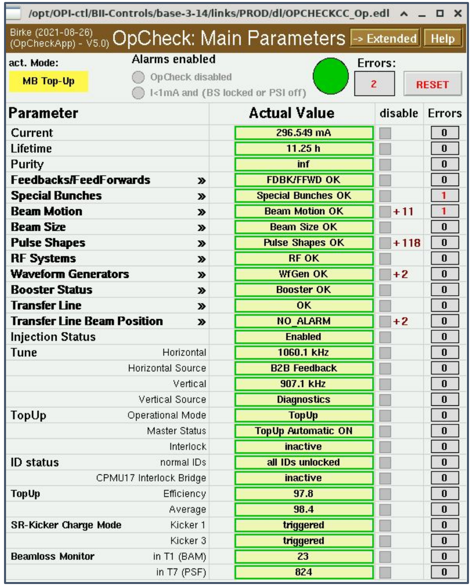
  Subsystems: e-Gun, Injection Line, Booster, Transfer Line, Storage Ring with
  Subgroups: Magnets + PowerSupplies, Diagnostics (electrical, optical, temperatures, pressure, waterflow,…),
  RF + Cavities, Vacuum & Construction + pumps, Radiation Protection + detectors,
  Electronics+Automation+Interlock

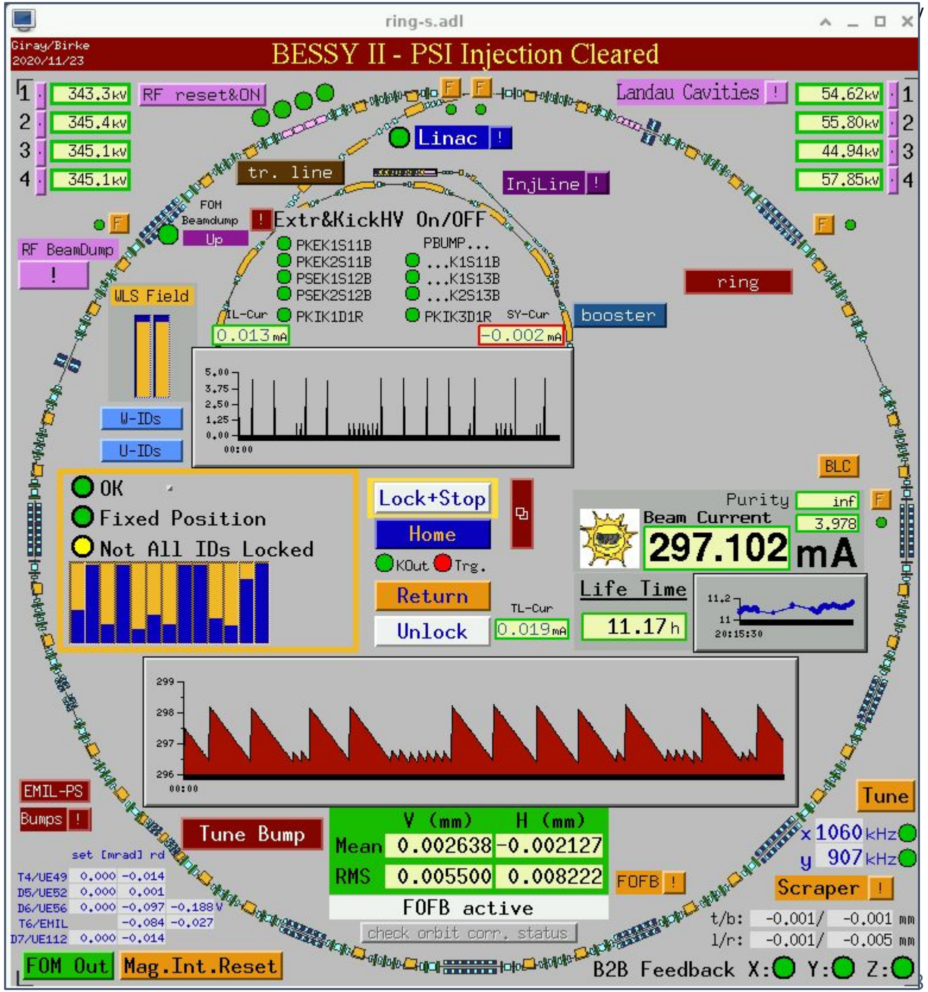
Beamlines and Experiments:

- About **100** devices & signals: (see Talk of J. Viefhaus)

  Subsystems: Undulator, Front-End, Mirrors, Monochromators, Apertures, Experiments
  Subgroups: Optics+Beamline group, Vacuum & Construction, …

Control System: Accelerator





Control System: Accelerator - EPCIS-IOC

/opt/OPI-ctl/BII-Controls/base-3-14/links/PROD/dl/IOCWatch.edl

IOC Stats

Name	CPU	Mem	FD	Boot Time	Dist Version
IOCS1G				2024-07-22T08:56:44	2024-07-09T08:25:55
IOC1S1G				2024-07-22T09:32:15	2023-03-13T07:46:21
IOC2S1G				2024-07-29T09:38:08	2024-07-29T09:36:42
IOC3S1G				2024-07-22T08:57:31	2023-03-13T07:46:21
IOC4S1G				2024-07-22T09:32:26	2023-09-11T13:35:08
IOC5S1G				2024-07-22T08:56:37	2023-03-13T07:46:21
IOC6S1G				2024-07-22T09:32:55	2023-03-13T07:46:21
IOCS2G				2024-07-22T08:58:29	2023-08-30T08:20:32
IOCS3G				2024-07-22T08:59:37	2024-05-30T11:08:21
IOCS4G				2024-07-22T09:00:45	2024-07-09T08:25:55
IOC1S4G				2024-07-22T09:00:05	2024-07-09T08:25:55
IOCS5G				2024-07-22T09:01:53	2024-04-22T09:04:17
IOCS6G				2024-07-22T09:04:28	2024-04-22T12:59:41
IOCS7G				2024-07-22T09:05:12	2023-08-30T08:20:32
IOCS8G				2024-07-22T11:36:34	2024-04-22T12:59:41
IOCS9G				2024-07-22T09:07:14	2023-08-30T08:20:32
IOCS10G				2024-07-22T09:07:45	2023-08-30T08:20:32
IOCS11G				2024-07-22T09:08:33	2023-08-30T08:20:32
IOC1S11G				2024-07-22T09:08:33	2023-03-13T07:46:21
IOCS12G				2024-07-22T09:09:13	2023-05-22T13:54:10
IOCS13G				2024-07-22T09:09:32	2024-07-09T08:25:55
IOC1S13G				2024-07-22T09:09:38	2023-03-13T07:46:21
IOCS14G				2024-07-22T09:13:11	2023-05-22T13:54:10
IOCS15G				2024-07-22T09:13:44	2024-07-09T08:25:55
IOCS16G				2024-07-22T09:14:58	2024-07-09T08:25:55
IOC1S16G				2024-07-25T02:16:43	2023-03-13T07:46:21
IOC2S16G				2024-07-25T02:13:22	2023-03-13T07:46:21
IOC3S16G				2024-07-22T09:14:50	2023-03-13T07:46:21
IOCX115B				2024-07-22T09:33:10	2023-09-01T13:41:58
IOC1X115B				2024-07-22T09:32:58	2023-03-13T07:46:21
IOC1S6G					

Name	CPU	Mem	FD	Boot Time	Dist Version
SIOC1C				2023-09-12T15:13:05	2023-09-12T15:12:54
SIOC2C				2023-08-23T16:04:27	2023-03-13T07:46:21
SIOC3C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC4C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC5C				2023-09-01T11:36:41	2023-03-13T07:46:21
SIOC6C				2024-03-11T08:53:07	2024-03-11T08:52:45
SIOC7C				2023-12-13T07:01:24	2023-03-16T11:04:48
SIOC8C				2023-08-23T16:04:37	2023-03-13T07:46:21
SIOC9C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC10C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC11C				2023-08-23T16:04:24	2023-03-13T07:46:21
SIOC12C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC13C				2024-07-19T16:33:21	2023-03-13T07:46:21
SIOC14C				2023-10-30T07:48:55	2023-10-30T07:48:45
SIOC15C				2023-08-23T16:04:24	2023-03-13T07:46:21
SIOC16C				2024-05-28T16:22:15	2024-05-28T16:21:08
SIOC17C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC18C				2023-08-23T16:04:25	2023-05-08T10:33:53
SIOC19C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC20C				2024-02-12T09:43:52	2024-02-12T09:42:07
SIOC21C				2024-07-30T15:58:23	2024-07-30T15:54:08
SIOC22C				2023-08-23T16:08:51	2023-03-13T07:46:21
SIOC23C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC24C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC25C				2024-04-15T10:06:17	2024-04-15T10:04:01
SIOC26C				2023-08-23T16:04:24	2023-03-13T07:46:21
SIOC27C				2023-08-23T16:04:24	2023-06-12T11:16:52
SIOC28C				2024-07-22T10:54:46	2023-03-13T07:46:21
SIOC29C				2023-08-23T16:04:24	2023-03-13T10:07:30
SIOC30C				2024-03-04T18:31:59	2024-03-04T18:25:09
SIOC31C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC32C				2024-07-22T11:12:17	2023-10-17T12:59:49
SIOC33C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC34C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC35C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC36C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC37C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC38C				2024-05-07T11:08:26	2024-05-07T11:03:34
SIOC39C				2024-02-20T11:50:00	2024-02-20T11:47:58
SIOC40C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC41C				2023-08-23T16:04:25	2023-03-28T12:17:21
SIOC42C				2023-08-23T16:04:24	2023-03-13T07:46:21
SIOC43C				2024-04-15T09:50:19	2024-04-15T09:49:41
SIOC45C				2023-08-23T16:04:25	2023-06-05T13:24:08
SIOC46C				2024-06-24T11:03:19	2023-05-15T09:39:36
SIOC47C				2024-06-24T11:03:21	2023-05-15T09:39:36

Name	CPU	Mem	FD	Boot Time	Dist Version
SIOC48C				2024-06-24T11:03:25	2023-05-15T09:39:36
SIOC49C				2024-02-26T09:55:25	2023-03-13T07:46:21
SIOC50C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC51C				2023-08-23T16:04:26	2023-03-13T07:46:21
SIOC52C				2023-08-23T16:04:24	2023-03-13T07:46:21
SIOC53C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC54C				2024-03-11T17:13:28	2023-03-24T16:24:24
SIOC55C				2024-04-22T19:34:18	2023-03-13T07:46:21
SIOC56C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC57C				2024-07-22T09:16:26	2024-06-17T11:58:27
SIOC58C				2024-07-22T09:16:48	2024-06-17T11:58:27
SIOC59C				2024-07-22T09:17:23	2024-06-17T11:58:27
SIOC60C				2024-07-22T09:17:44	2024-06-17T11:58:27
SIOC61C				2024-07-22T09:18:13	2024-06-17T11:58:27
SIOC62C				2024-06-17T12:06:44	2024-06-17T11:58:27
SIOC63C				2024-07-22T20:51:00	2024-03-11T09:52:07
SIOC64C				2024-06-17T12:07:56	2024-06-17T11:58:27
SIOC65C				2023-08-23T16:04:25	2023-05-22T09:49:08
SIOC66C				2023-08-23T16:04:25	2023-03-17T15:41:40
SIOC67C				2024-07-30T15:14:10	2024-07-30T15:12:25
SIOC68C				2024-07-22T11:24:02	2024-06-17T11:58:27
SIOC69C				2024-06-27T12:58:52	2024-06-27T12:58:25
SIOC70C				2024-07-22T11:25:13	2024-06-17T11:58:27
SIOC71C				2024-07-22T11:26:41	2024-06-17T11:58:27
SIOC72C				2024-01-02T15:41:36	2023-03-13T10:07:30
SIOC73C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC74C				2024-06-17T09:56:59	2024-06-17T09:56:40
SIOC75C				2023-08-23T16:04:27	2023-03-13T07:46:21
SIOC76C				2024-03-18T13:08:16	2024-03-18T13:05:38
SIOC78C				2024-06-17T12:10:25	2024-06-17T11:58:27
SIOC79C				2024-06-17T12:10:55	2024-06-17T11:58:27
SIOC80C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC81C				2023-08-23T16:04:24	2023-08-08T11:00:05
SIOC82C				2023-08-23T16:04:24	2023-03-13T10:07:30
SIOC84C				2024-07-15T11:10:20	2024-07-02T20:20:53
SIOC85C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC86C				2023-08-23T16:04:25	2023-06-12T07:05:40
SIOC87C				2024-01-16T15:01:03	2024-01-16T14:47:05
SIOC88C				2023-08-23T16:04:24	2023-06-08T11:37:37
SIOC89C				2023-08-23T16:04:25	2023-03-13T07:46:21
SIOC90C				2024-07-01T08:16:04	2024-07-01T08:14:22
SIOC91C				2024-07-02T18:31:13	2024-06-17T11:58:27
SIOC93C					
SIOC95C				2024-02-12T10:26:38	2024-02-12T10:26:12
SIOC96C					
MIOC1S15G				2024-05-31T13:55:07	2024-05-30T15:42:30

~ 30 IOC

~ 100 SIOC

“Old” machines need new infrastructure/software

3rd generation Lightsources are from the beginning of this century ~ 2000

- “Old” digital structures, old software, not so old hardware
  → Generation exchange!

- **Modernize!**

  This opportunity is especially given by a greenfield facility,
  going into operation in 2035 → **BESSY III**

- Better workflow between simulations and real machine in order to describe and understand the machine and close the gap of non-understanding!

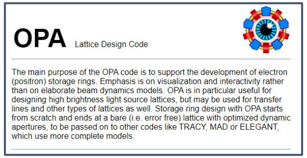
  → Digital Twin
  → AI tools to optimise beamlines and/or storage ring

“Old” machines need new infrastructure/software

Simulation ⟷ **Middle-Layer** ⟷ **Real Machine**

Simulation

- Design:



- Advanced Codes:
  - AT - Accelerator Toolbox for matlab or **pyAT** (ESRF, Diamond, SLAC, ALS)
  - elegant, (APS, ALS)
  - Xsuite, madX, pymadx (CERN)

Middle-Layer

MML, Matlab Middle Layer

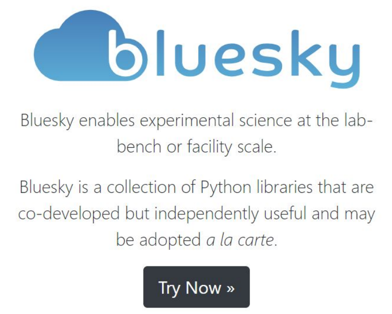
pyMML

Real Machine

Control System

BPMs
BeamPositionMonitors
Orbit

PowerSupplies
magnets



Thank you for your attention

Material

https://xdb.lbl.gov/

https://xdb.lbl.gov/Section2/Sec_2-2.html

https://www.isa.au.dk/accfys/Download/SLDB.pdf

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

https://de.wikipedia.org/wiki/Tantalos

https://www.helmholtz-berlin.de/pubbin/igama_output?modus=einzel&sprache=en&gid=1652&typoid=

https://en.wikipedia.org/wiki/X-ray_crystallography

Vortrage, Folien aus dem Netz:

https://www.slac.stanford.edu/pubs/slacpubs/16250/slac-pub-16451.pdf

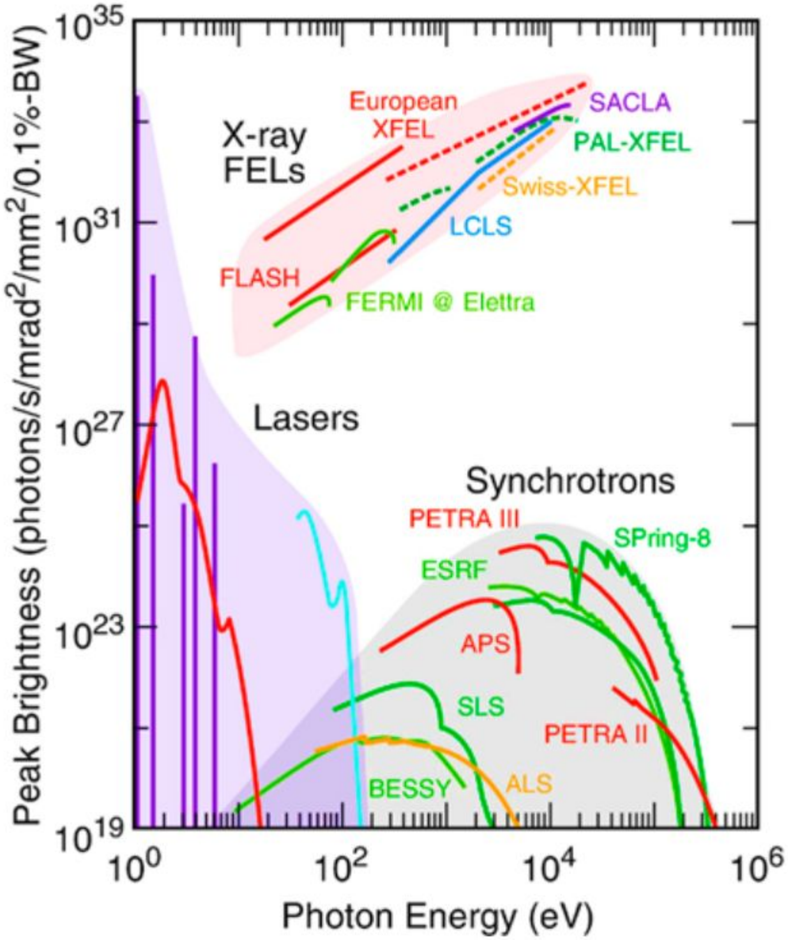
https://www.intechopen.com/chapters/51599

Backup Slides

History and Overview of Lightsources

Other Lightsources

- X-Ray Tubes
  - Bremsstrahlung,
    “braking radiation, deceleration radiation”
  - electrons interact with atomic nucleus
- LASERs
  - Fully coherent
  - But only up to 100 (10) nm, i.e., 10 (100) eV
- X-Free Electron Lasers
- Storage Ring based Synchrotrons

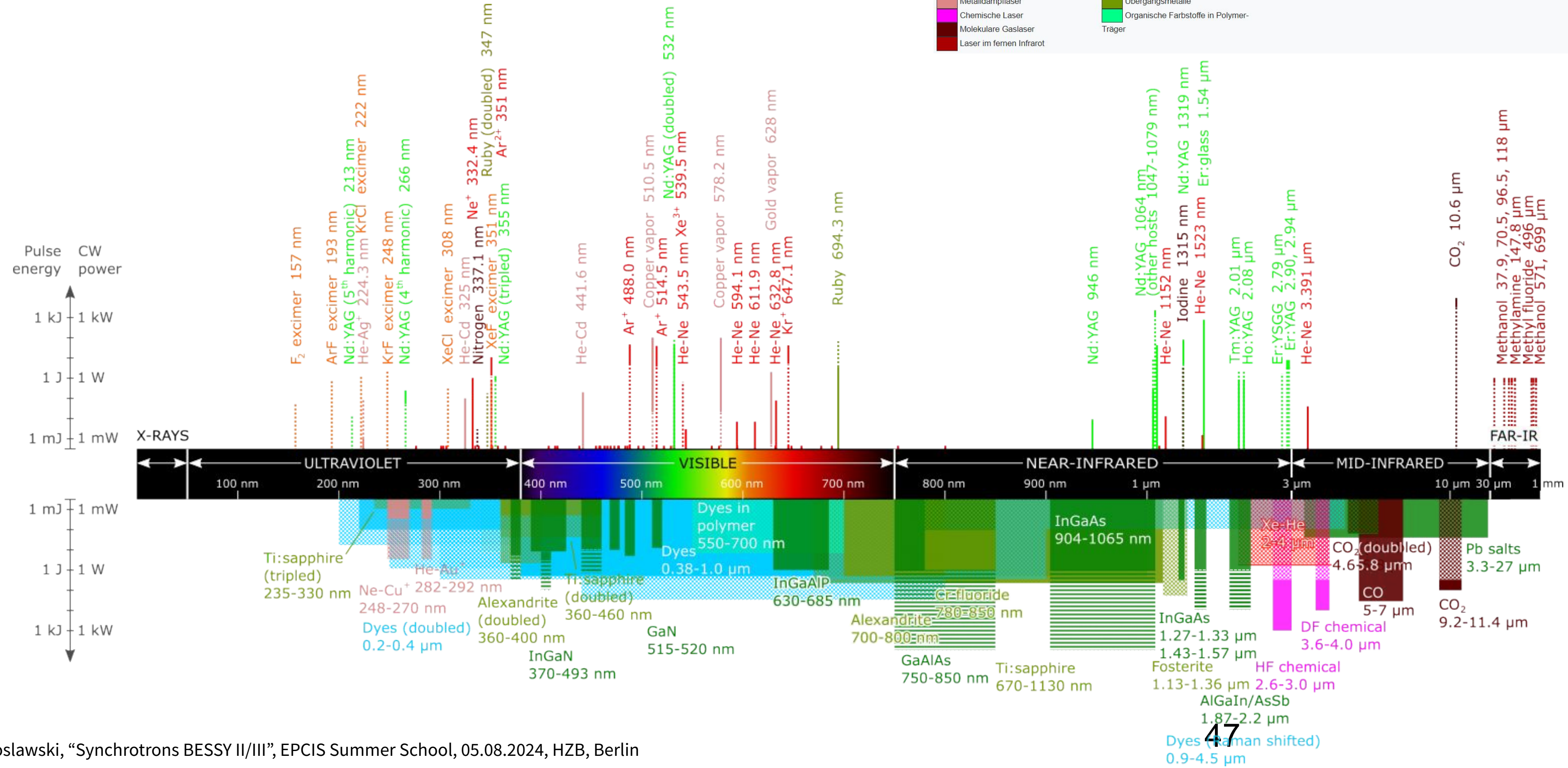


History and Overview of Lightsources

Commercial available LASERs

Deutsch: Übersicht der im Handel erhältlichen Laserwellenlängen. Lasertypen mit diskreten Laserlinien sind über der Leiste der Wellenlängen angezeigt, während unterhalb Laser angezeigt werden, die in einem Wellenlängenbereich emittieren können. Volle Linien oder Flächen bedeuten Dauerstrichlicht (CW), gepunktete bedeuten gepulste Emission. Die Höhe der Linien gibt einen Hinweis auf die maximale Leistung / Pulsenergie, die im Handel erhältlich ist. Für die Ar^{+}-Kr^{+}-Laser sind nur die wichtigsten Linien gekennzeichnet, die vielen anderen sind nur durch einen kurzen Strich angedeutet, unabhängig von ihrer Leistung. Beachten Sie, dass die Wellenlängen-Achse stark verzerrt ist: bis zu 1000 nm ist sie linear, dann logarithmisch (mit 300 px pro Zehnerstelle bis zu 10 µm, dann 30 px pro Zehnerstelle). Dies ist für eine bessere Präsentation des sichtbaren Bereichs erforderlich. Für Halbleiterlaser sind Leistungen, die mit einer einzigen Diode erreicht werden, mit einer soliden Füllung gekennzeichnet, während die Bereiche mit horizontalen Linien nur mit Barren oder Stapel von Barren erreicht werden.

Gaslaser	Festkörperlaser	Flüssige Laserstoffe	
Excimerlaser	Lanthanide	Farbstofflaser	Dauerstrichlicht (CW)
Edelgas-Laser	Halbleiterlaser		Puls-Emission
Metalldampflaser	Übergangsmetalle		Halbleiter-Barren oder -Stapel
Chemische Laser	Organische Farbstoffe in Polymer-Träger		
Molekulare Gaslaser			
Laser im fernen Infrarot			



Two partners & two synchrotron radiation sources

HZB Helmholtz Zentrum Berlin

Fernsehturm am Alexanderplatz

From Wikipedia: WISTA
By Fotograf: Dirk Laubner - WISTA.Plan, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=94360137

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

BESSY II

1.7 GeV
240 m
16 Straights, 5m
DBA
5 nm rad
300 mA

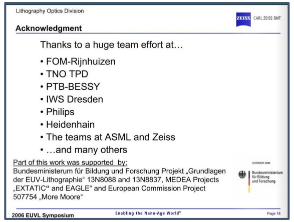
Soft and tender X-rays
Spectro-Microscopy
Timing: low α, femto-slicing
TRIBs/Two orbit mode

MLS Metrology Light Source

630 MeV
48 m
4 Straights (2x2.5m, 2x6m)
DBA
100 nm rad (std mode)
200 mA

THz / IR to VUV, EUV
Optimised for low α,
SSMB studies

Solar Energy	Chemical Energy	Quantum & Functional Materials
Photon Science	Accelerators	Scientific Instrumentation & Support


Lithography Optics Division

CARL ZEISS SMT

Acknowledgment

Thanks to a huge team effort at…

- FOM-Rijnhuizen
- TNO TPD
- PTB-BESSY
- IWS Dresden
- Philips
- Heidenhain
- The teams at ASML and Zeiss
- …and many others

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Bundesministerum für Bildung und Forschung Projekt „Grundlagen der EUV-Lithographie“ 13N8088 and 13N8837, MEDEA Projects „EXTATIC“ and EAGLE“ and European Commission Project 507754 „More Moore“

Bundesministerium für Bildung und Forschung

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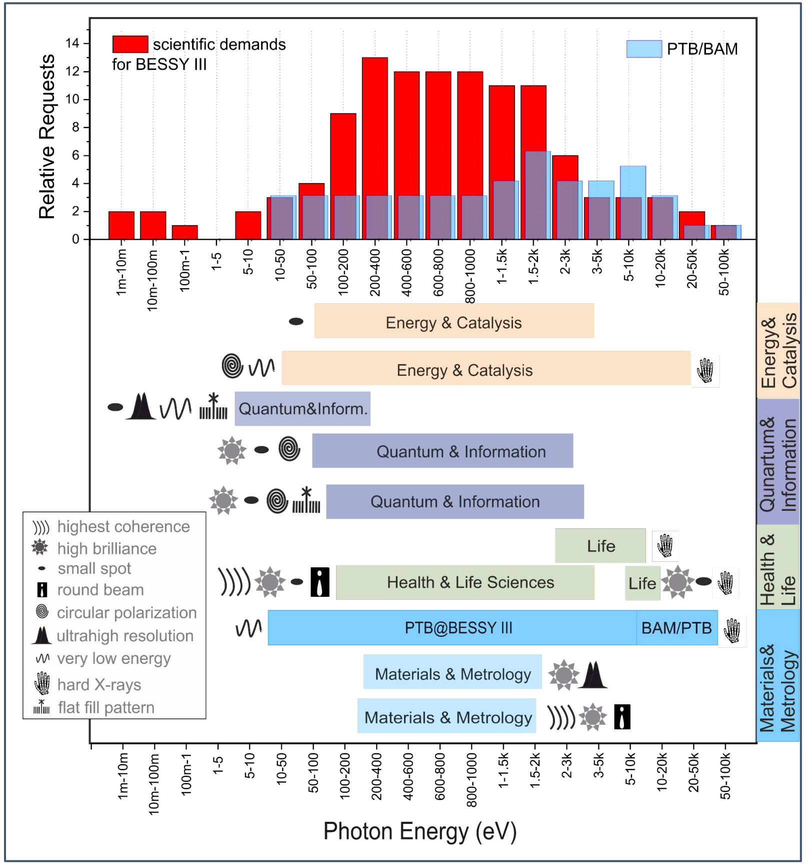
ZEISS ASML

BESSY III Requirements & Objectives



Facility parameters

1. 1st undulator harmonics polarized up to 1 keV from conventional APPLE-II
2. Diffraction limited till 1 keV
3. Stay in Berlin-Adlershof
4. Nanometer spatial res. & phase space matching
5. **PTB/BAM** metrology applications

Ring parameters

1. Ring Energy **2.5 GeV** (1.7 GeV)
2. Emittance **100 pm rad** (5 nm rad)
3. Circumference **350 m**
   16 straights @ 5.6 m
   (240 m @ 4.5 m)
4. Low beta straights & maybe round beams
5. **Metrology source**
   Homogenous bends
   Measuring the field at the source point with a NMR probe in a volume of 10x10x10 mm
6. **Momentum compaction factor** **> 1.0e-4**

1-2 bends per arc

Already at BESSY II, a 3rd generation **without** combined function bends

4th Generation Lightsource Lattices

The Higher Order Achromat, HOA-MBA

- MAX IV, SLS 2.0 … up to 3 GeV
  - A. Streun, J. Bengtsson, S. Leeman, et al.

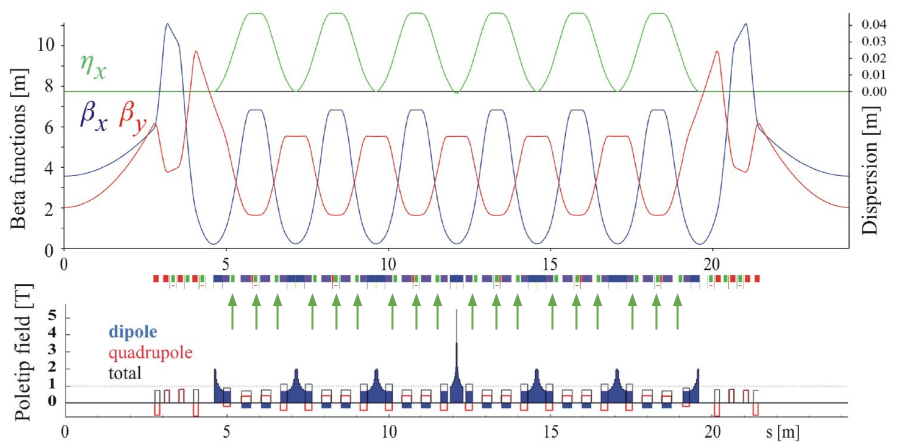
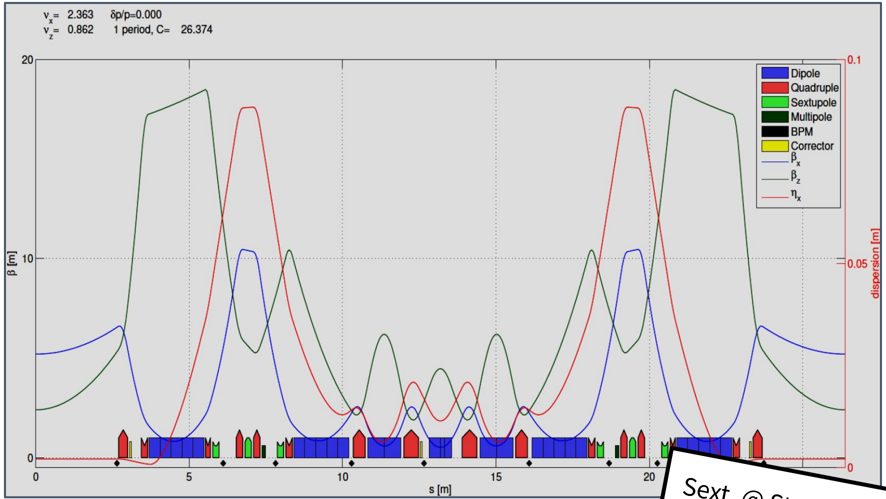


Figure 2.3: Optical functions and field components for one 7BA-arc where the center LGB has bee interchanged by a super-LGB of 5.5 T peak field. Bending magnets are in dark blue, quadrupoles red and se

Sext. distributed
LGB - yes
RB - yes

The Hybrid, HMBA

- ESRF-EBS, PETRA IV … above 3 GeV
  - P. Raimondi



Sext. @ Start/End
LGB - yes
RB - no

$$\epsilon_{x,e^-} \sim E^2/N_d^3$$

$$x_D = D \cdot \Delta p/p$$

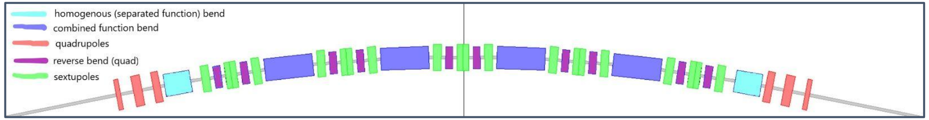
The process towards a BESSY III lattice - metrology challenge

A deterministic lattice approach

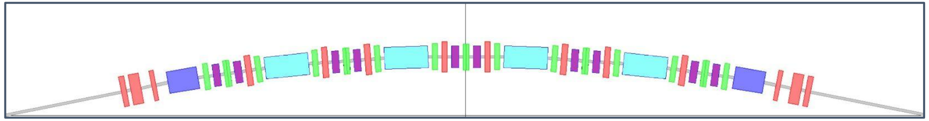
- Stepwise: Power and Function of each Component &“Knob” → **LEGO approach**
- After first “wild” lattices we concluded on:
- **Limiting the hardware** (conservative ansatz)
  - Bore radius of 12.5 mm
    Radius of inner/outer vac. pipe of 9/11mm
  - Bends up to 1.4 T
  - Quads up to 60 - 80 T/m (depends on RB)
  - Sextupoles up to 4000 T/m^2
  - Spacing between magnets 100 mm
- Higher**O**rder**A**chromat Appraoch:
  - 6MBA + **homogenous metrology bend**
  - With Reverse Bends, so far no LGBs

A homogenous metrology bend

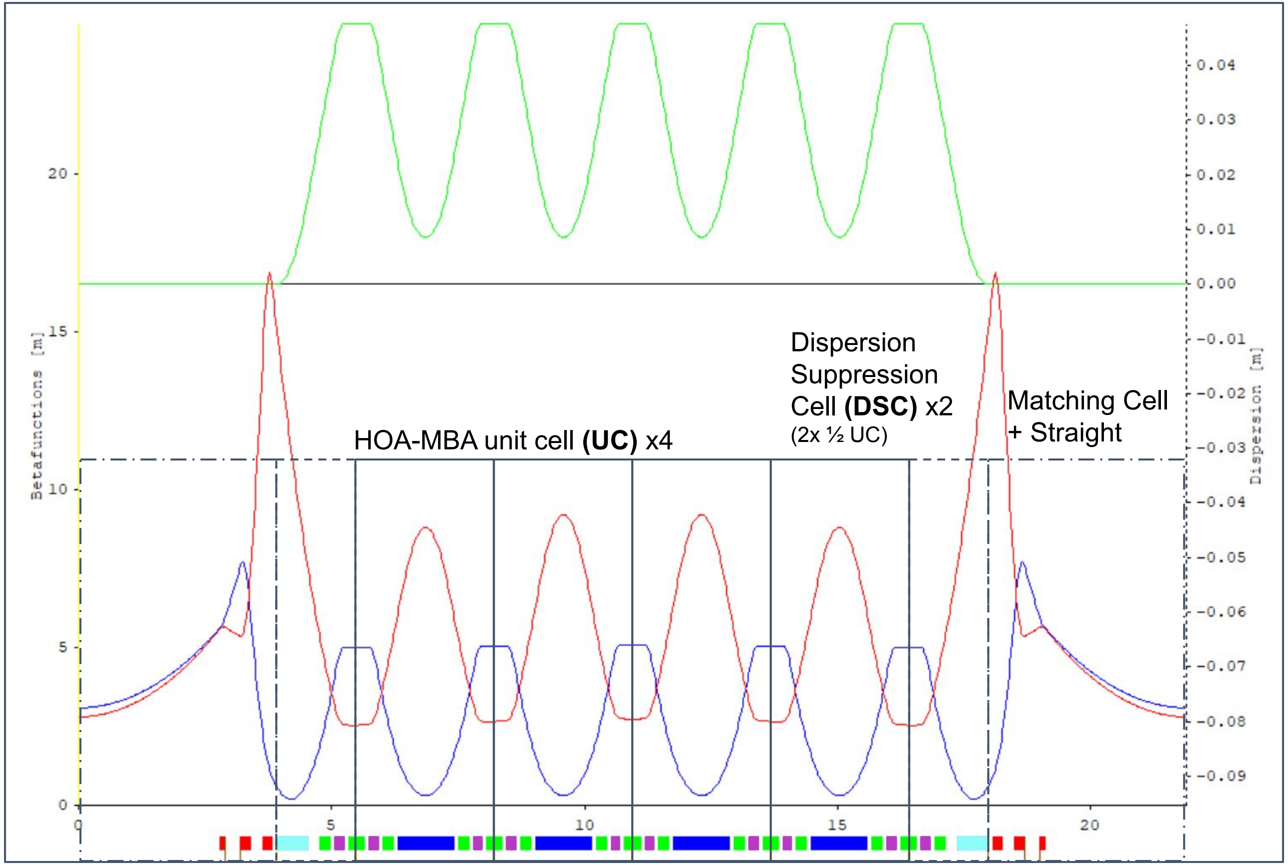
- Include it right from the beginning
  → Symmetric sector cell ansatz
- Two lattice candidates:
  - **cf**-lattice: combined function bend
    In center of 6MBA (community standard)
    sf - **cf - cf - cf - cf** - sf



  - **sf**-lattice: separated (homogenous)
    Bend in the center of 6MBA (metrology):
    cf - **sf - sf - sf - sf** - cf



LEGO Approach - Basic building blocks of one sector



16 straights & sectors:

360° / 16 = 22.5° per sector

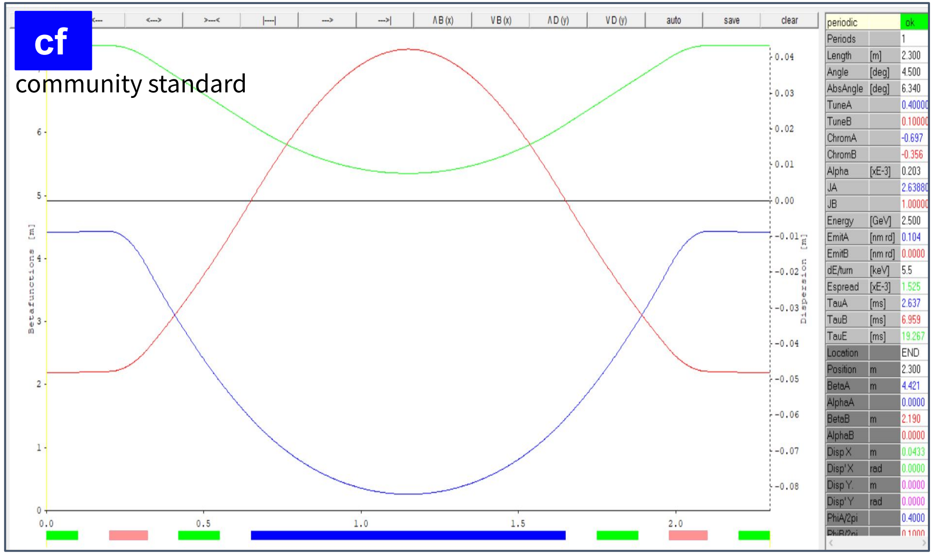
4*4.5°   main UC bend &
2*2.25° DSC bend

The process towards a BESSY III lattice - Linear Beam Dynamics

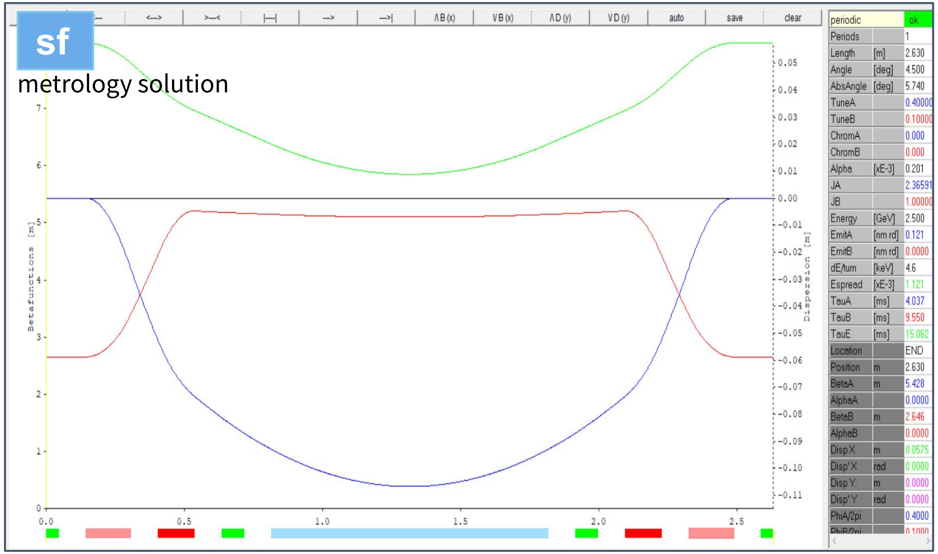
LEGO approach - the “one and only” (deterministic) MBA-Unit Cell (UC) for and for the hardware specifications of our project

- The two different MBA-UCs: **cf & sf**
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0)

Impact of reverse bend on alpha & emittance
Magnet arrangement



SX, RB, SY, B, …



SX, RB, QD, SY, B, …

The process towards a BESSY III lattice - Linear Beam Dynamics

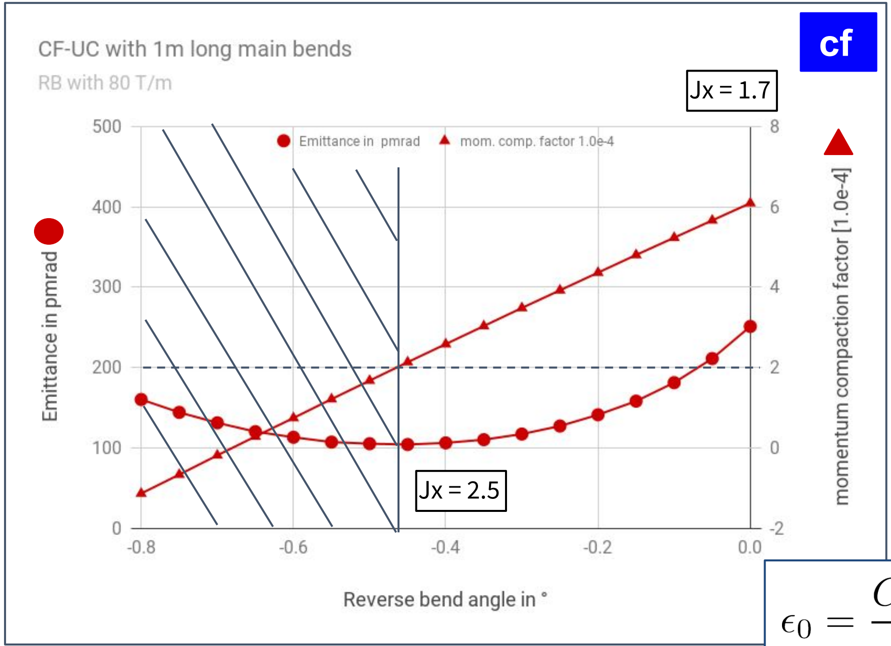
LEGO approach - Unit Cell - Impact of Reverse Bend

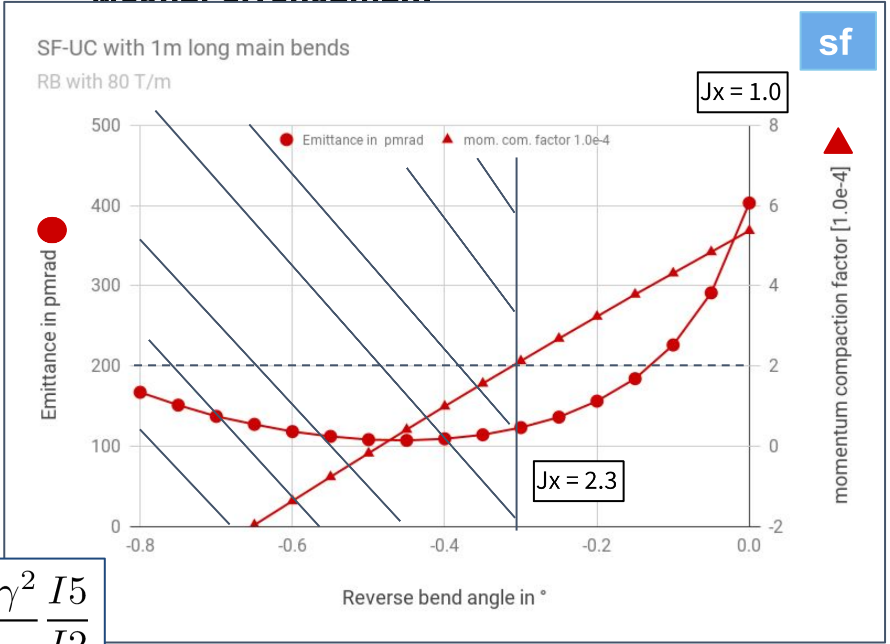
- The two different MBA-UCs: **cf & sf**
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0)

and for the hardware specifications of our project

Impact of reverse bend on alpha & emittance

Magnet arrangement

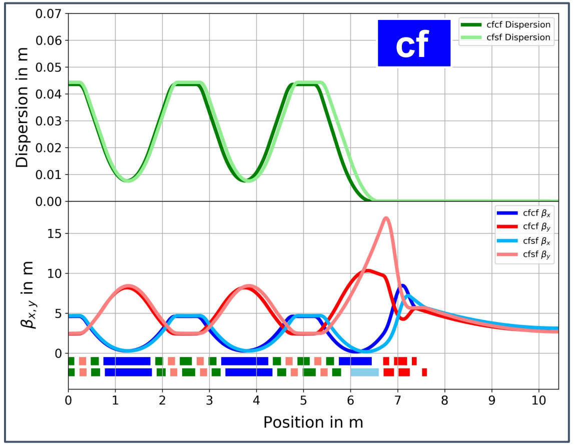


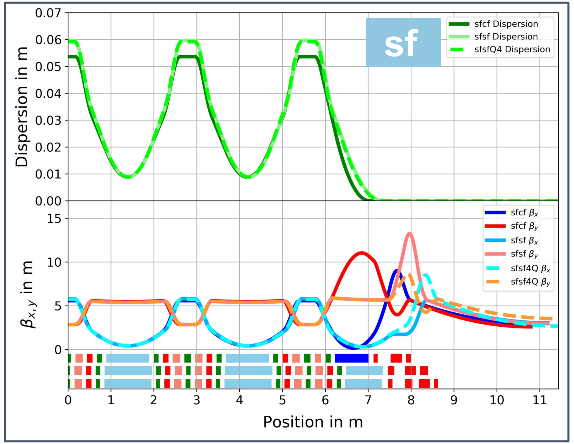


$$\epsilon_0 = \frac{C_q \gamma^2}{j_X} \frac{I5}{I2}$$

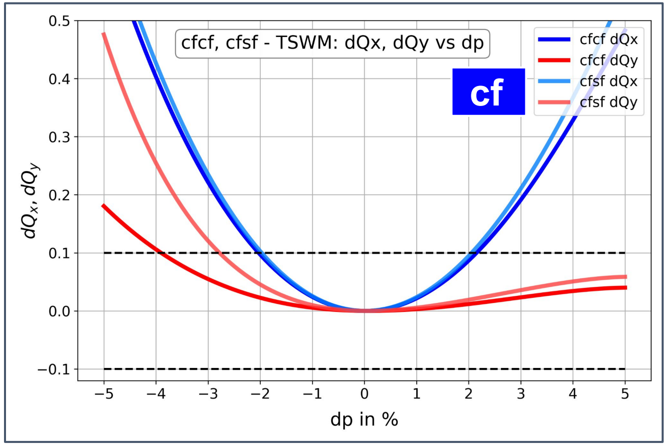
The process towards a BESSY III lattice - Non-Linear Beam Dynamics

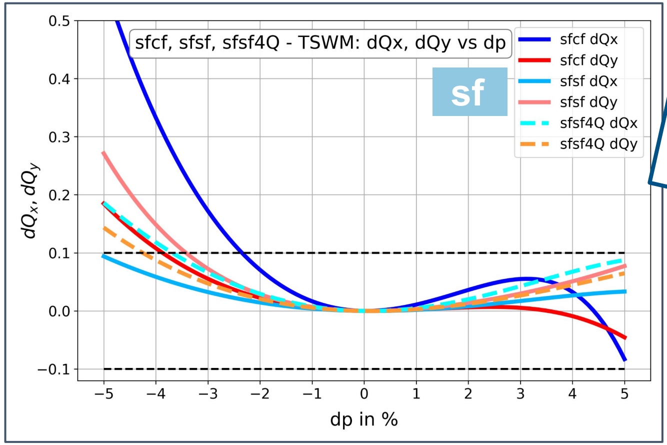
TSWM
Chromatic Tune Shift





With two sextupole families only: Sx, Sy

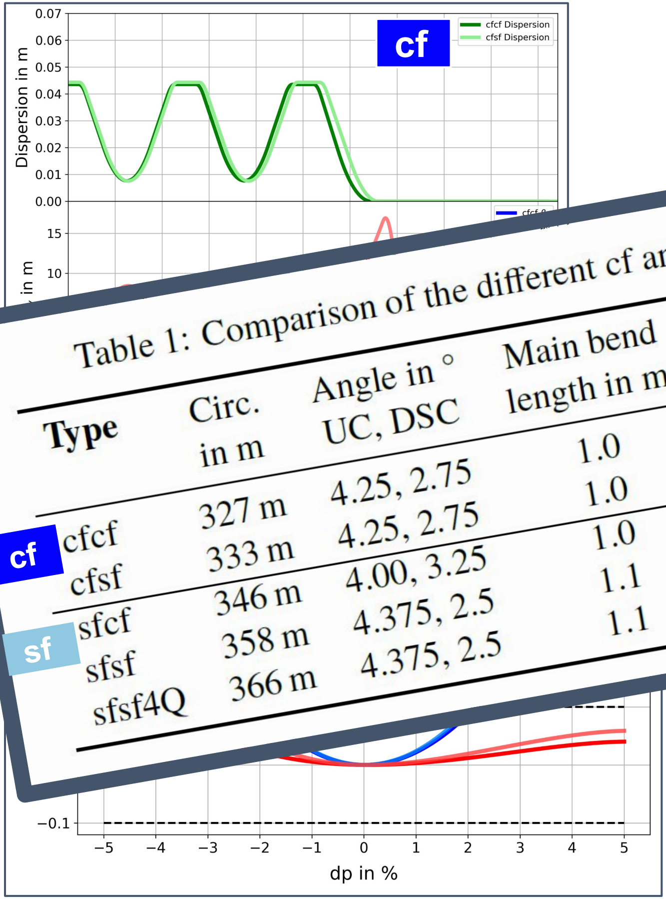


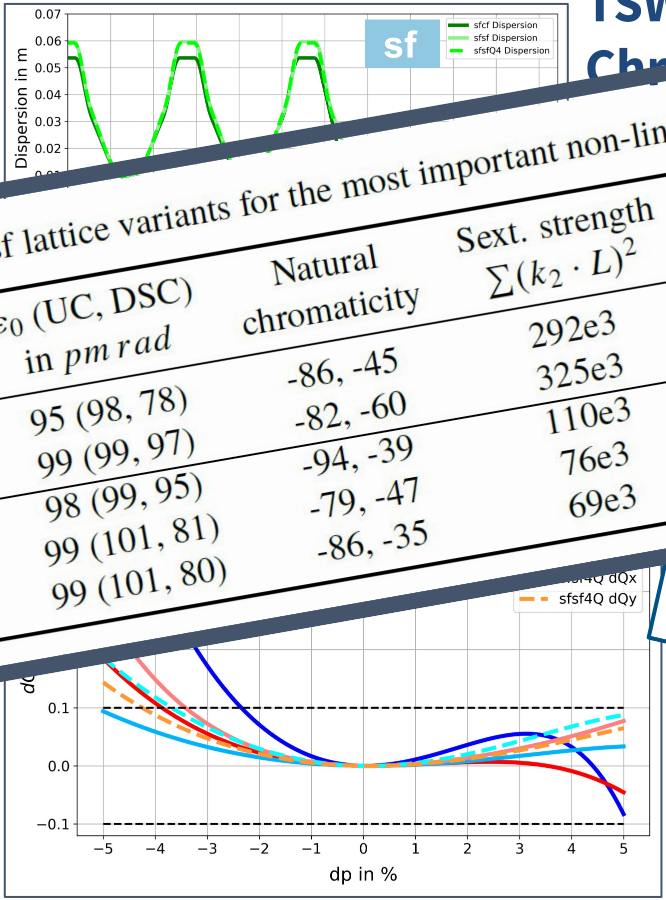


The flatter the curve the better
→ Robustness, Lifetime

$$\frac{1}{\tau_t} = \frac{N r_e^2 c}{8\pi} \frac{1}{\sigma_x \sigma_y \sigma_s} \frac{1}{\gamma^2 \delta_{acc}^3} D(\zeta)$$

The process towards a BESSY III lattice - Non-Linear Beam Dynamics





TSWM

Chro ... ift

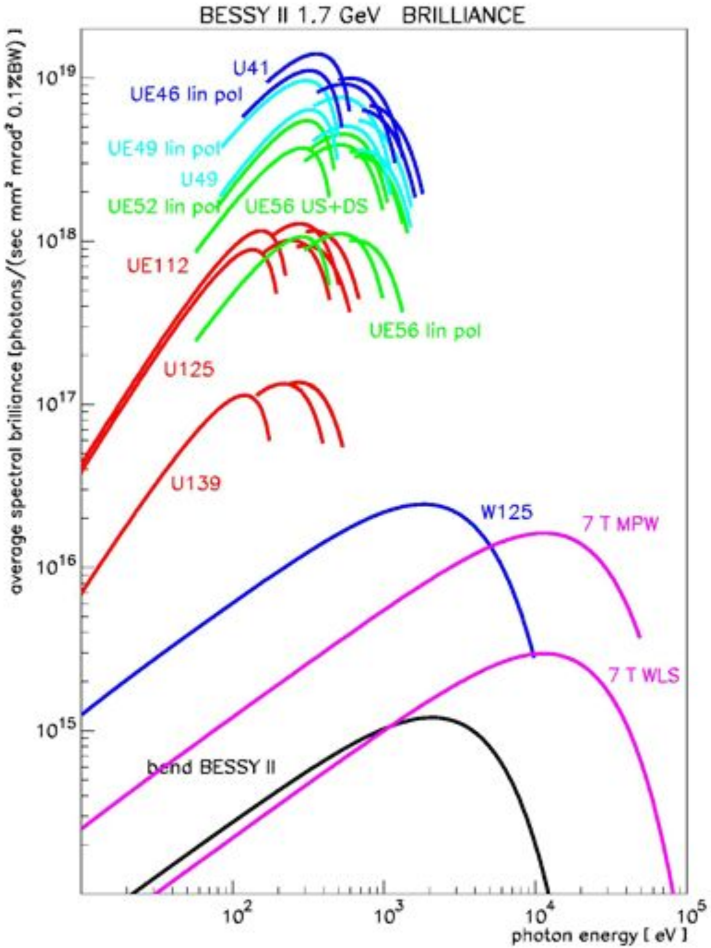
Table 1: Comparison of the different cf and sf lattice variants for the most important non-linear parameters.

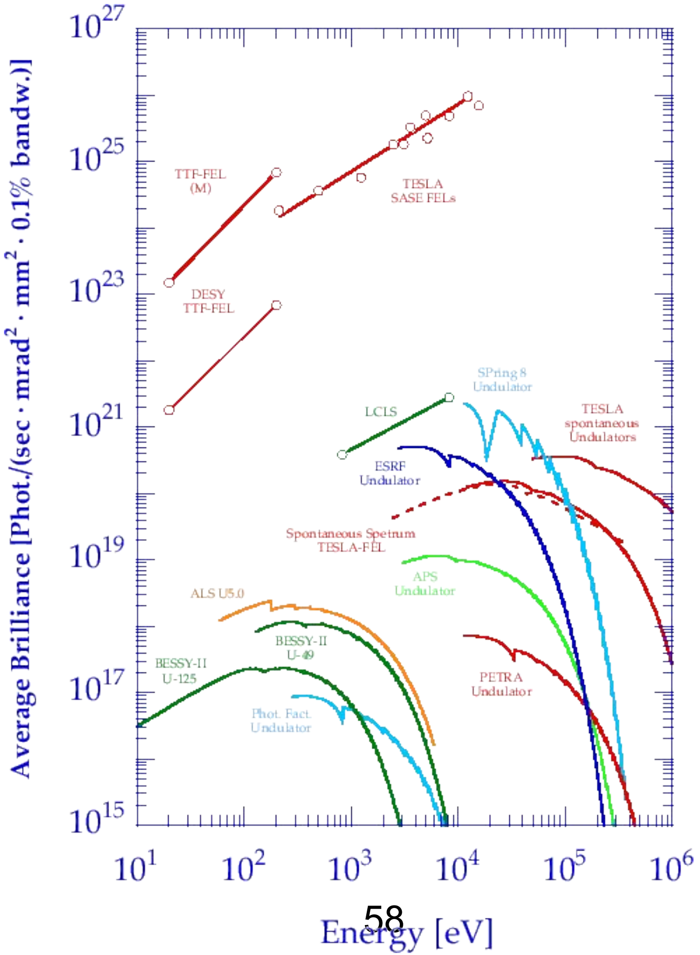
	Type	Circ. in m	Angle in ° UC, DSC	Main bend length in m	ε_0 (UC, DSC) in $pm\,rad$	Natural chromaticity	Sext. strength $\sum(k_2 \cdot L)^2$	TSWM, dp in % for $dQ_{x,y} = 0.1$
cf	cfcf	327 m	4.25, 2.75	1.0	95 (98, 78)	-86, -45	292e3	2.0, 3.9
	cfsf	333 m	4.25, 2.75	1.0	99 (99, 97)	-82, -60	325e3	2.1, 2.8
sf	sfcf	346 m	4.00, 3.25	1.0	98 (99, 95)	-94, -39	110e3	2.3, 3.9
	sfsf	358 m	4.375, 2.5	1.1	99 (101, 81)	-79, -47	76e3	5.0, 3.4
	sfsf4Q	366 m	4.375, 2.5	1.1	99 (101, 80)	-86, -35	69e3	3.8, 4.3

...tter the curve the better
→ Robustness, Lifetime

$$\frac{1}{\tau_t} = \frac{N r_e^2 c}{8\pi} \frac{1}{\sigma_x \sigma_y \sigma_s} \frac{1}{\gamma^2 \delta_{acc}^3} D(\zeta)$$

History & Development of Lightsources





Usage & Applications

Photon Interaction with Matter

Usage & Applications of Synchrotron Radiation

Photons with Matter

- Coherent - Rayleigh
- Incoherent - Compton
  $\gamma + A \rightarrow A + e^- + \gamma'$
  (photon scattering at quasi-free electrons)
- Atomic photo-effect
  $\gamma + A \rightarrow A^+ + e^-$
- Holes in atomic shell
  - Characteristic X-ray
  - Auger-Process

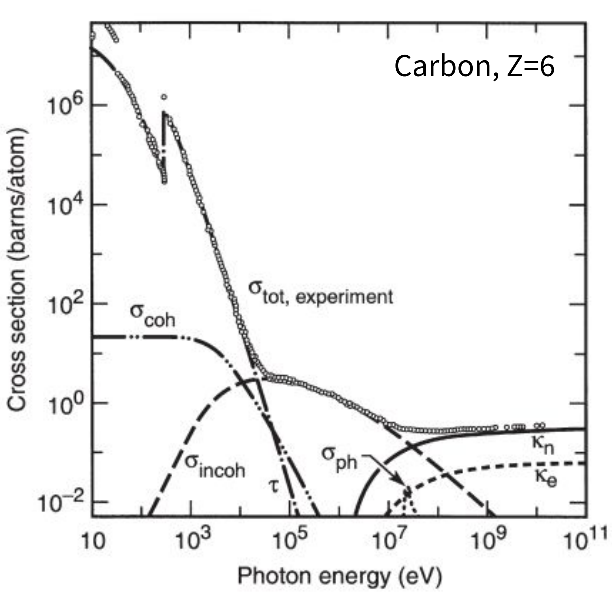


Fig. 3-1. *Total photon cross section σ_{tot} in carbon, as a function of energy, showing the contributions of different processes: τ, atomic photo-effect (electron ejection, photon absorption); σ_{coh}, coherent scattering (Rayleigh scattering—atom neither ionized nor excited); σ_{incoh}, incoherent scattering (Compton scattering off an electron); κ_n, pair production, nuclear field; κ_e, pair production, electron field; σ_{ph}, photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle). (From Ref. 3; figure courtesy of J. H. Hubbell.)*

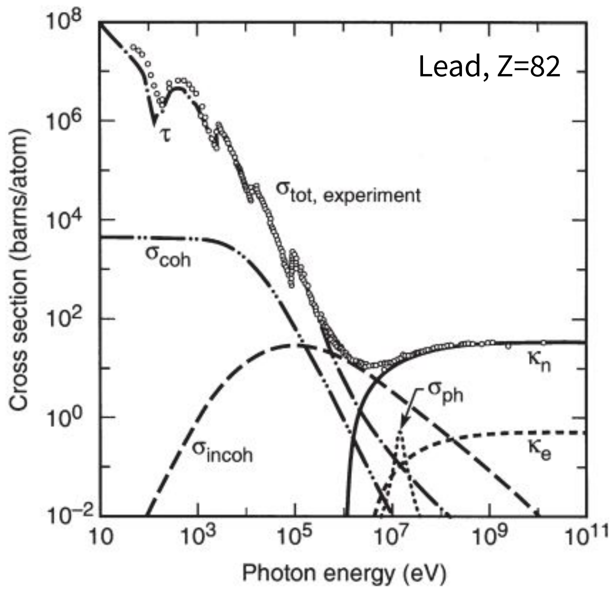


Fig. 3-2. *Total photon cross section σ_{tot} in lead, as a function of energy. See Fig. 3-1. (From Ref. 3; figure courtesy of J. H. Hubbell.)*

$$\sigma_{\mathrm{PH}} \sim Z^5/(\hbar\omega)$$

60

HZB BESSY II Light Source

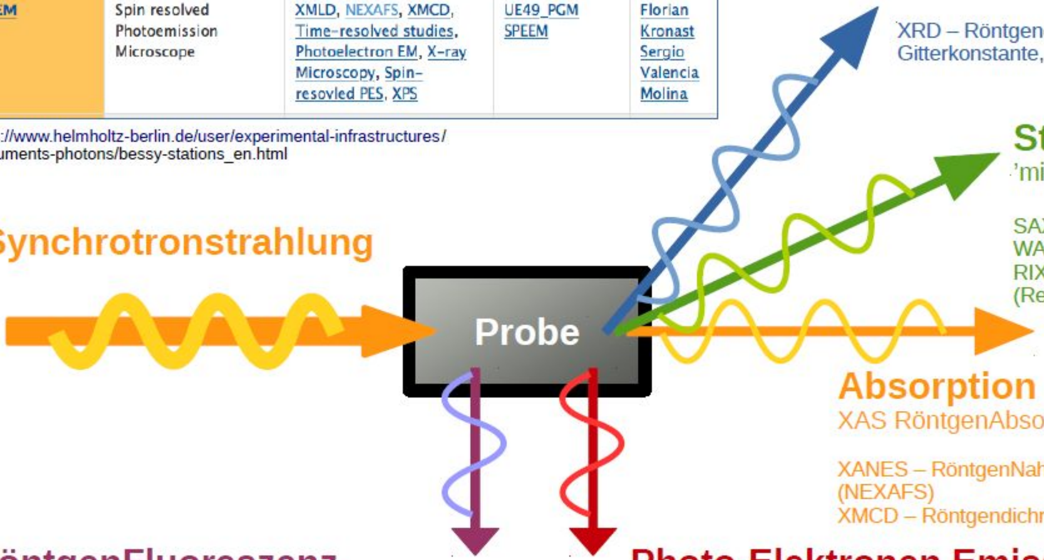
For internal use only

Usage & Applications of Synchrotron Radiation

Experimental Techniques at Lightsource Beamlines

SMART	Spectro-Microscopy with aberration correction for relevant techniques	NEXAFS, XMCD, Surface Diffraction, Photoelectron EM, X-ray Microscopy, XPS, UPS	UE49_PGM SMART	Thomas Schmidt
SPEEM	Spin resolved Photoemission Microscope	XMLD, NEXAFS, XMCD, Time-resolved studies, Photoelectron EM, X-ray Microscopy, Spin-resovled PES, XPS	UE49_PGM SPEEM	Florian Kronast Sergio Valencia Molina

https://www.helmholtz-berlin.de/user/experimental-infrastructures/instruments-photons/bessy-stations_en.html



Beugung
'makroskopisch Wellencharakter'

XRD – Röntgendiffraktion
Gitterkonstante, Kristallstrukturanalyse

Streuung
'mikroskopisch Teilchencharakter'

SAXS – SmallAngleX-rayScattering
WAXS – WideAngleX-rayScattering
RIXS – ResonantInelasticX-rayScattering
(Resoanant X-ray Raman)

Absorption
XAS RöntgenAbsorptionsSepctroskopie

XANES – RöntgenNahkantenAbsorptionsSpektroskopie
(NEXAFS)
XMCD – Röntgendichroismus mit zirkular polarisierten X-rays

RöntgenFluoreszenz
Elementare Zusammensetzung der Probe

RFA, RFS, XRF – X-rayFluorescenceSpectroscopy
Kernnahe Elektronen herausgelöst, Niveaus werden
von Elektronen aus höheren Niveaus besetzt > Fluoresenz

Photo-Elektronen Emission
Photoeffekt – herausgelöste Elektronen

PES – PhotoElektronen(Emissions)Spektroskopie,
(UPS, XPS, ARPES,
PEEM - Keine Energie, Intensitätsverteilung, 2D Mikroskopie)