Light Sources

Laboratory for Particle Accelerator Physics

EPFL

Research Instruments in Human History

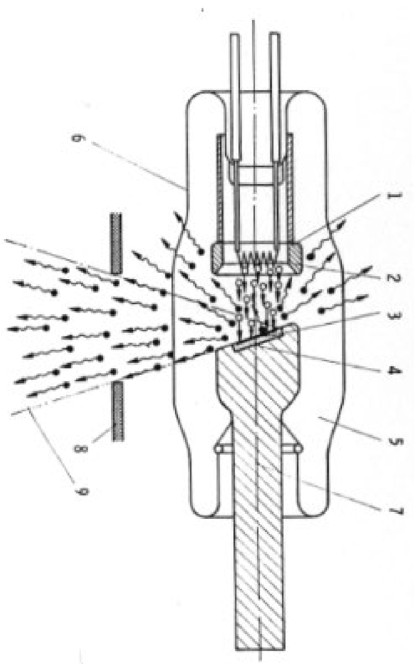
400 years of discoveries

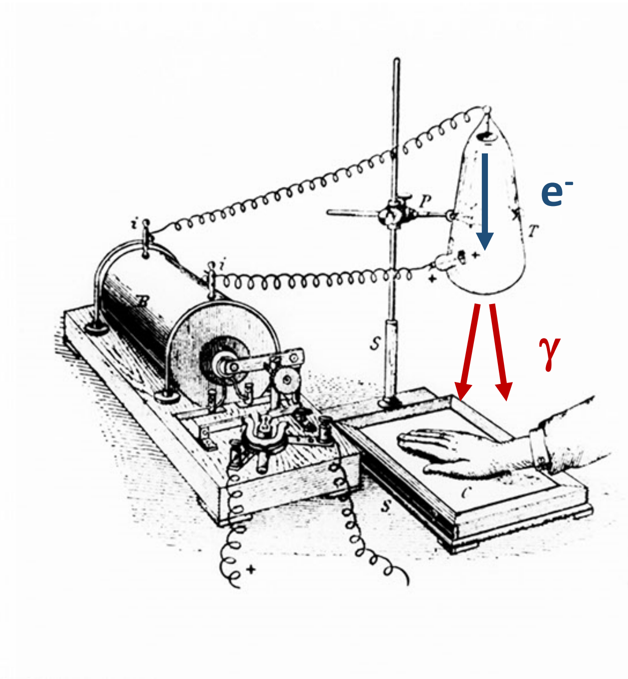
Galileo Galilei

with «telescopes» «microscopes»

Zacharias Janssen

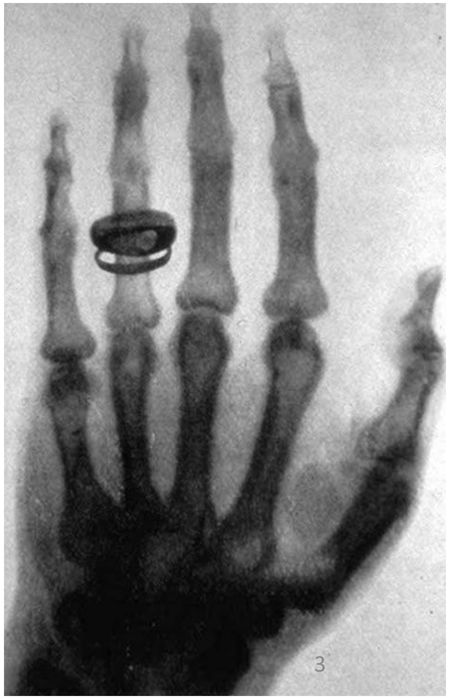
Roentgen Image (1896)





X-rays: secondary radiation generated by an „accelerator“

W.C.Röntgen



reminder: probing matter at different energies

	Energy	equivalent wavelength
alpha from rad.decay	4.9 MeV	6.4 fm
thermal neutrons	0.025 eV	1.8 Å
photons, SR	12.4 keV	1 Å
high energy electrons	100 GeV	10^{-17} m
LHC protons	7 TeV	2×10^{-19} m

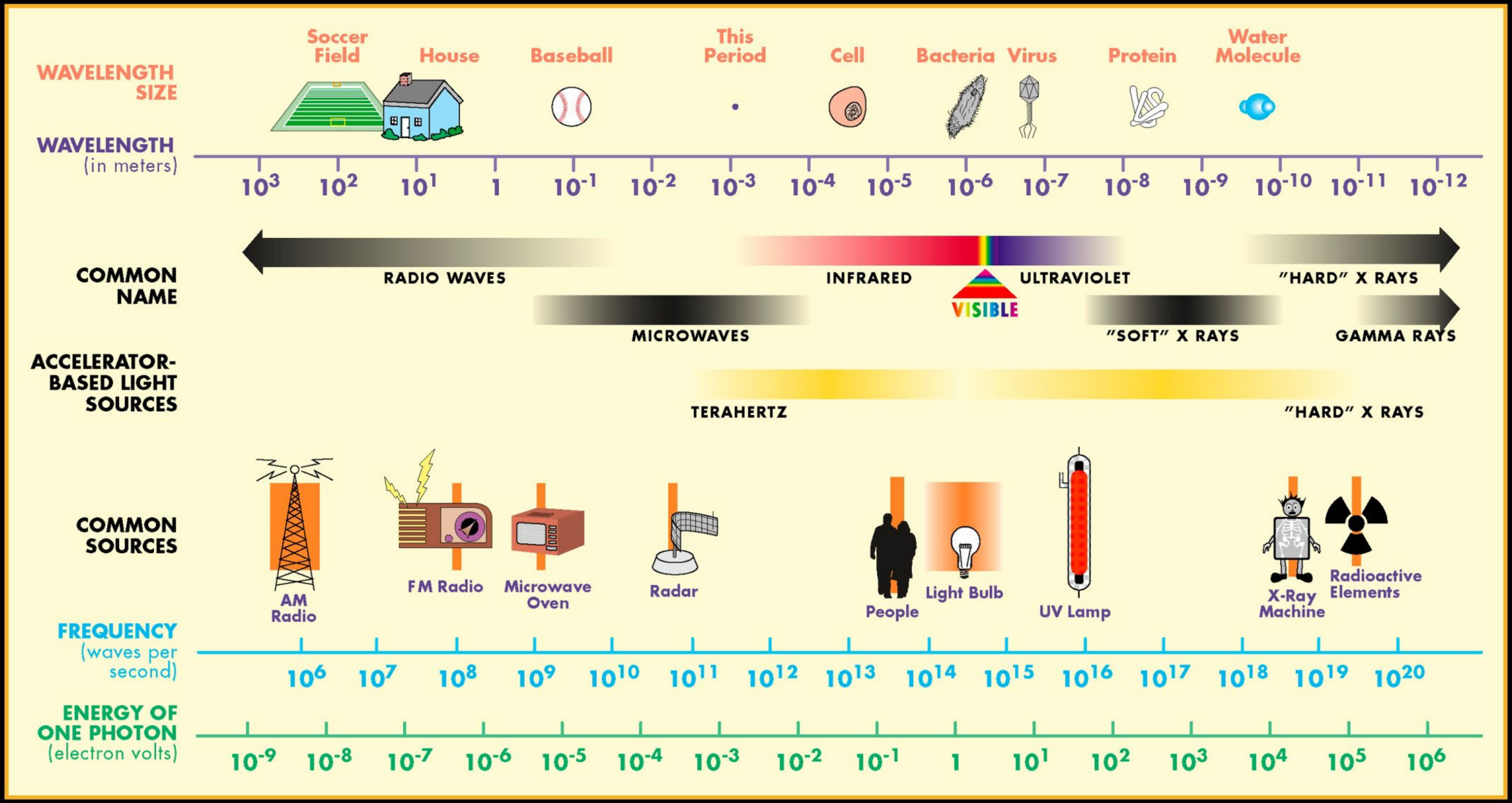
Light Sources

$1Å = 10^{-10}m$

the **de Broglie wavelength** sets the length scale for objects under study using scattering

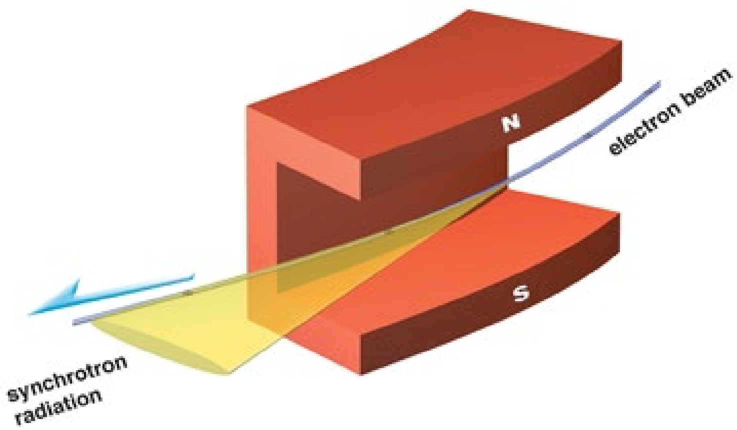
$$\lambda = \frac{h}{p} \approx \frac{hc}{E_k}, \;\; hc = 12.4 \text{ keV\AA}$$

THE ELECTROMAGNETIC SPECTRUM



synchrotron light sources

Synchrotron Radiation



radiation power:

$$P_\gamma = \frac{e^2 c}{6\pi\varepsilon_0} \times \frac{E^4}{(m_0 c^2)^4 \rho^2}$$

critical frequency:

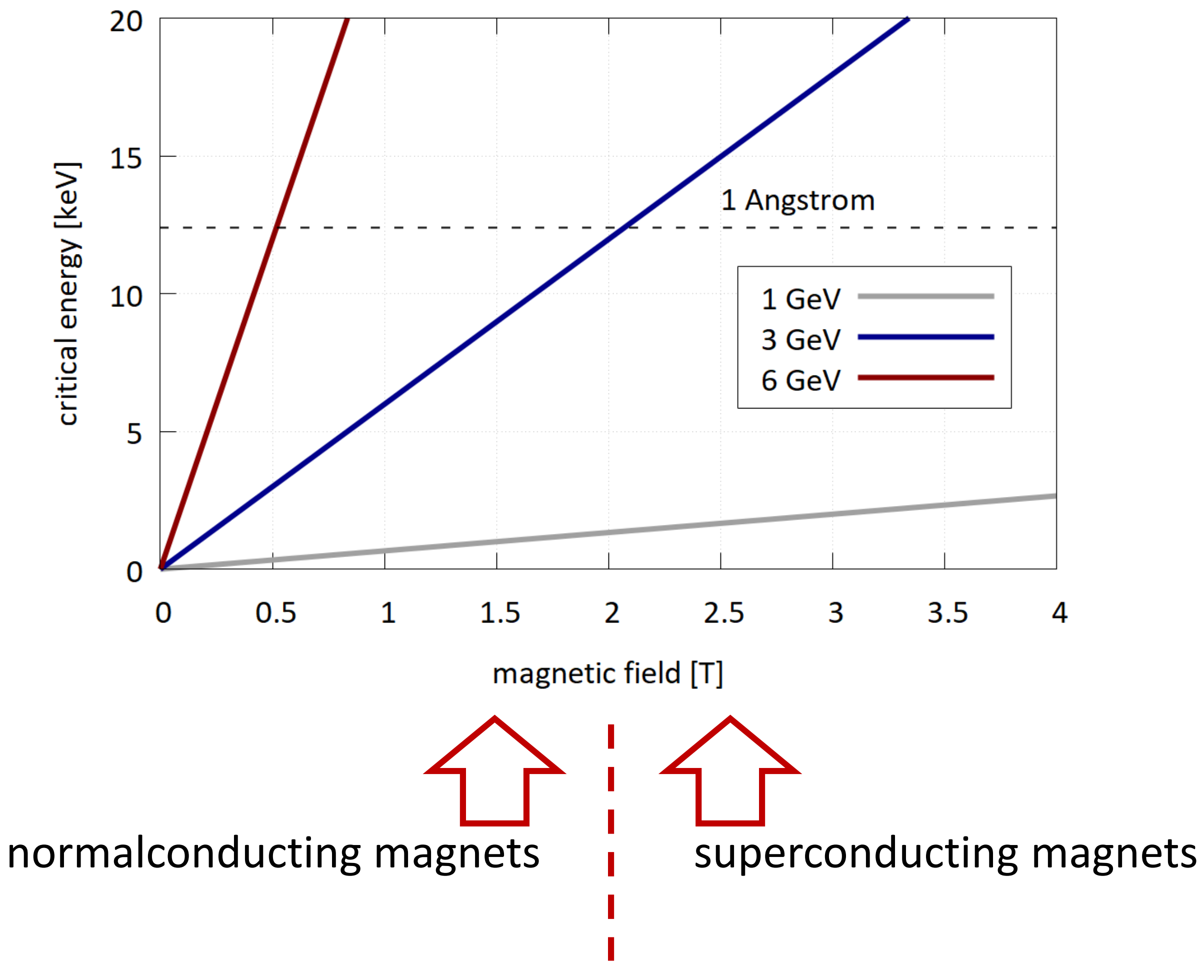
$$\omega_c = \frac{3}{2} c \times \frac{E^3}{(m_0 c^2)^3 \rho}$$

opening angle:

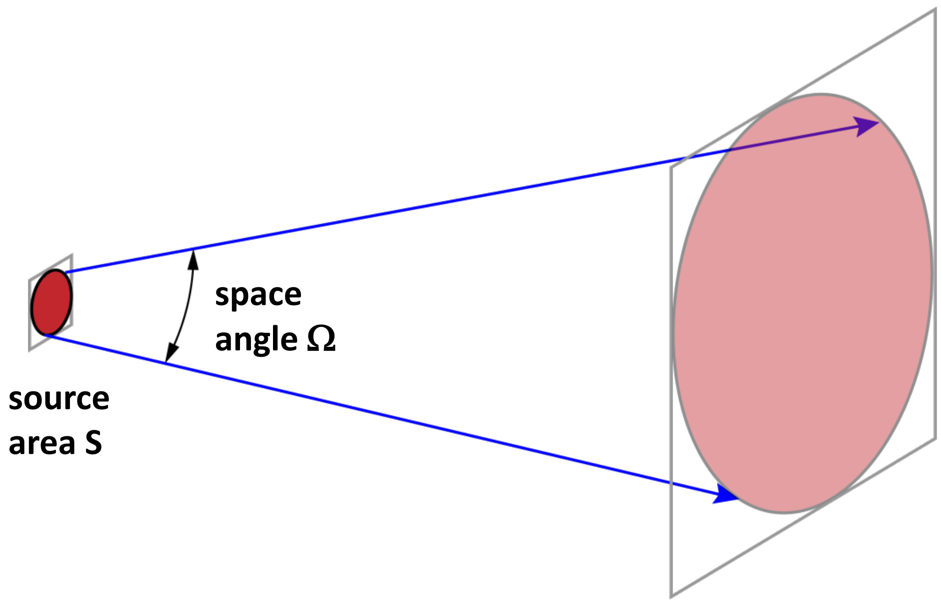
$$\theta_y \approx \frac{1}{\gamma}$$

[see Wiedemann 24.2, 24.3, 24.1]

Photon Energy



Definition of Flux and Brilliance



$$\text{Flux} = \frac{N_{\text{ph}}}{\Delta t\,(\Delta E/E)} \qquad \left[\frac{N_{\text{ph}}}{\text{s}\ (0.1\%)}\right]$$

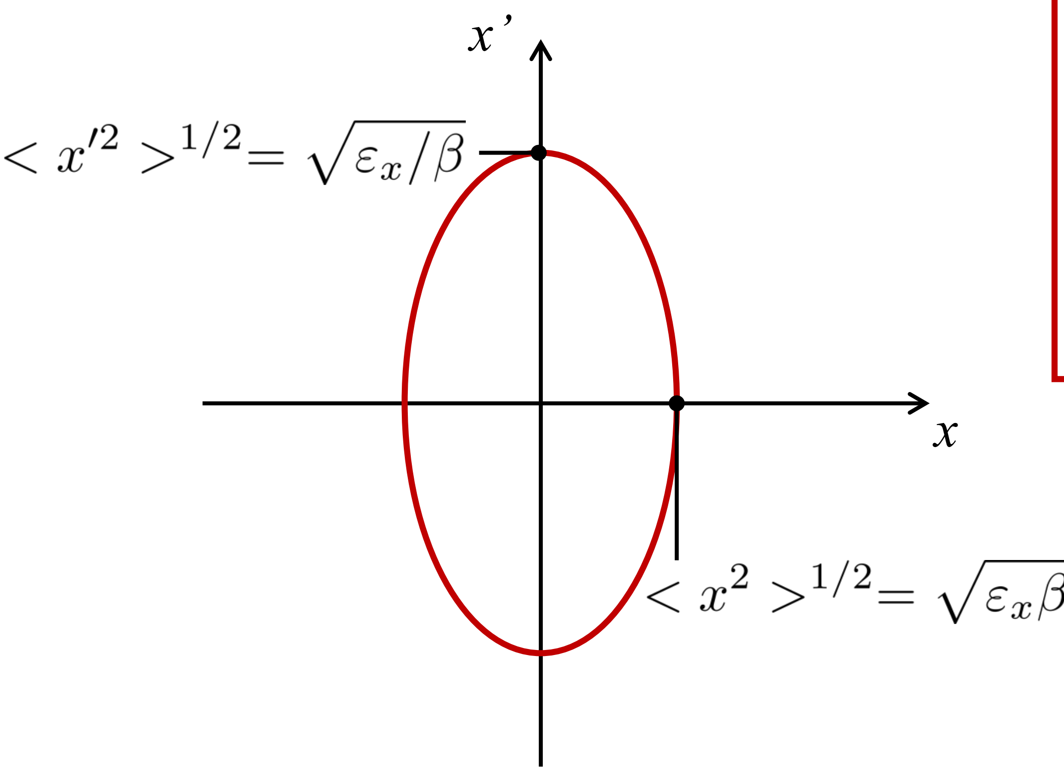
← **per time and per 0.1% energy bandwidth**

$$\text{Brilliance} = \frac{N_{\text{ph}}}{\Delta t\,(\Delta E/E)\,S\,\Omega} \qquad \left[\frac{N_{\text{ph}}}{\text{s}\ (0.1\%)\ \text{mm}^2\,\text{mrad}^2}\right]$$

← **in addition per area and per space angle**

[see Wiedemann 24.8]

reminder: phase space ellipse of a beam



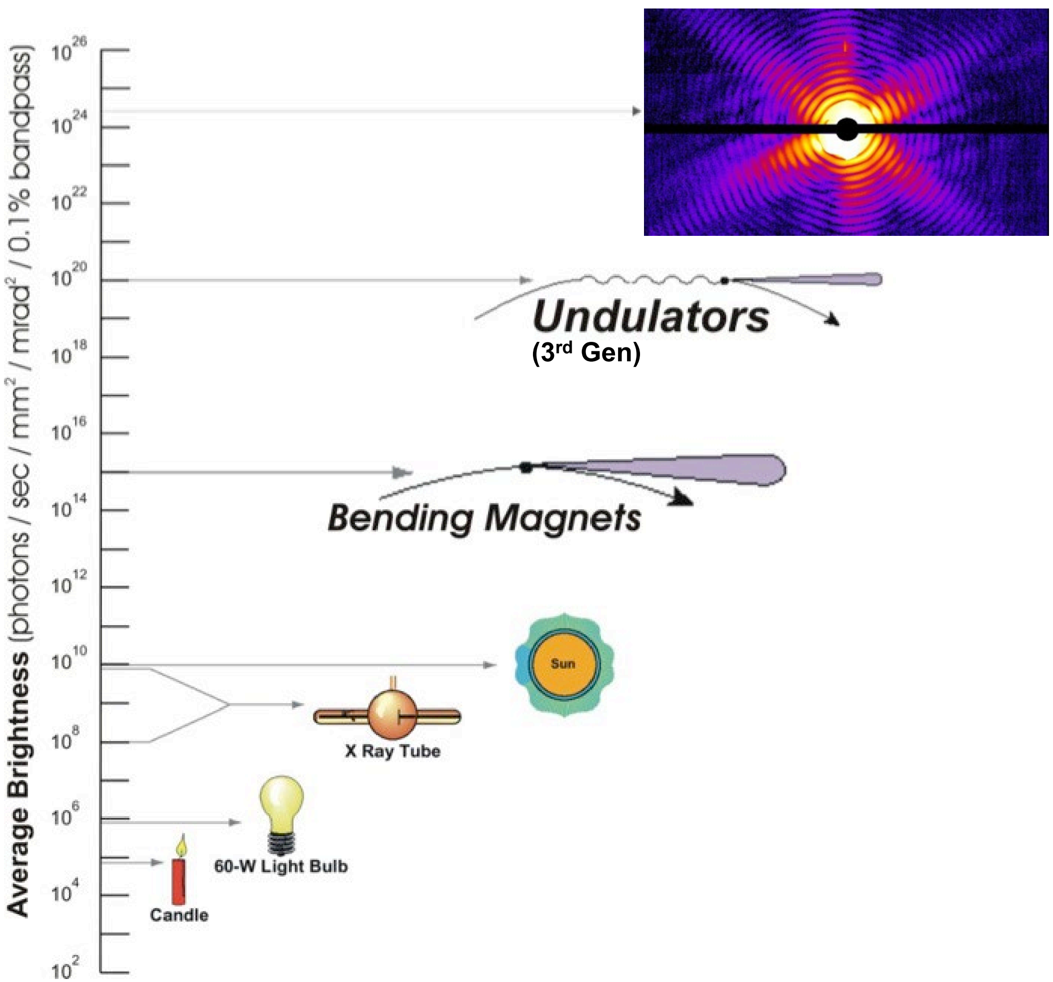
factor for photon beam brightness:

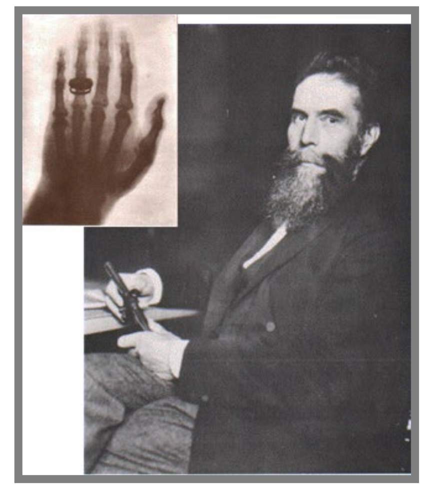
$$x_{\mathrm{rms}} \cdot y_{\mathrm{rms}} \cdot x'_{\mathrm{rms}} \cdot y'_{\mathrm{rms}}$$
$$= \varepsilon_x \cdot \varepsilon_y$$

Development of Brilliance

Average Brightness

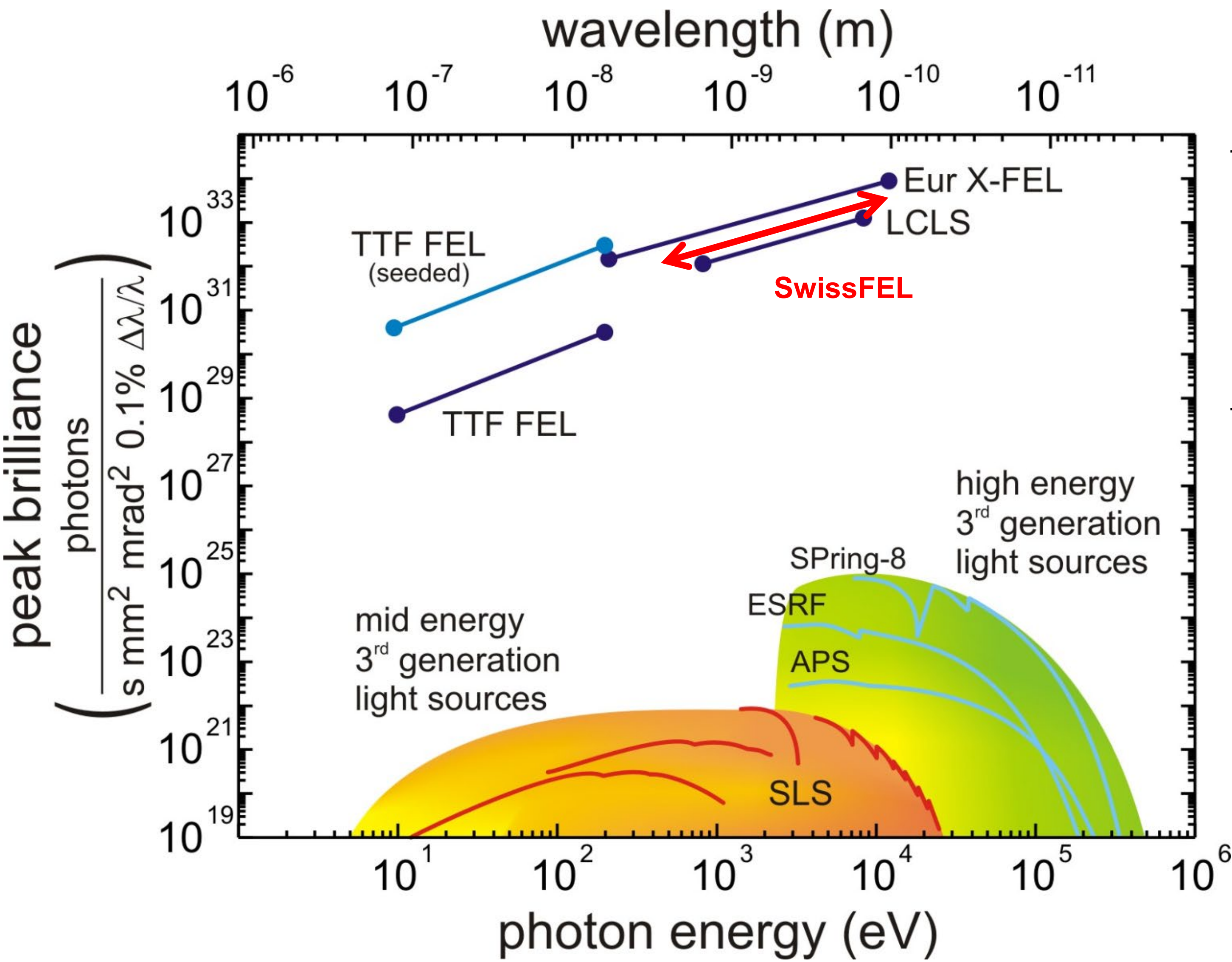
XFELs





Bertha Roentgen's hand
exposure: 20 min

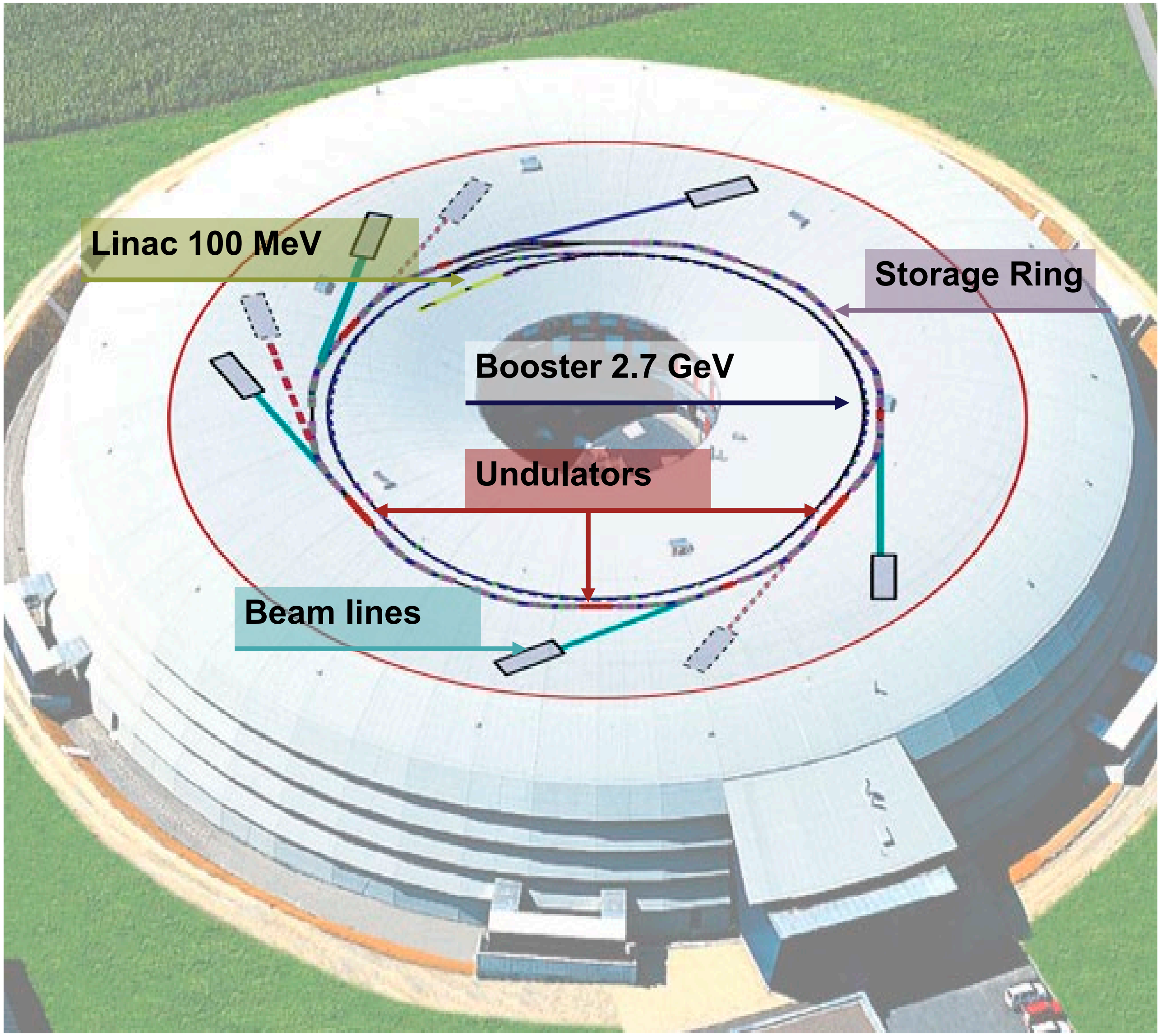
Peak brilliance vs photon energy

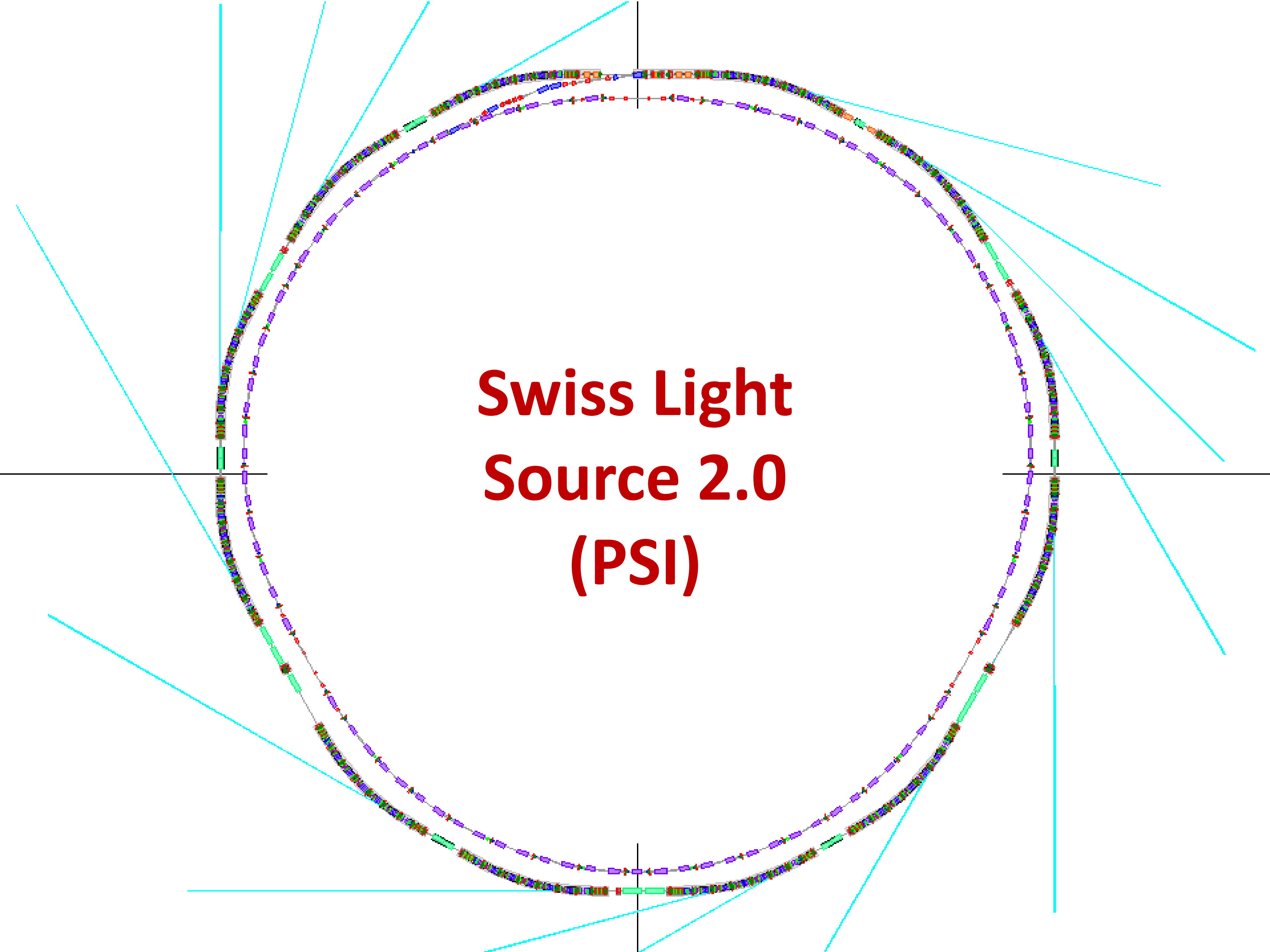


FELs

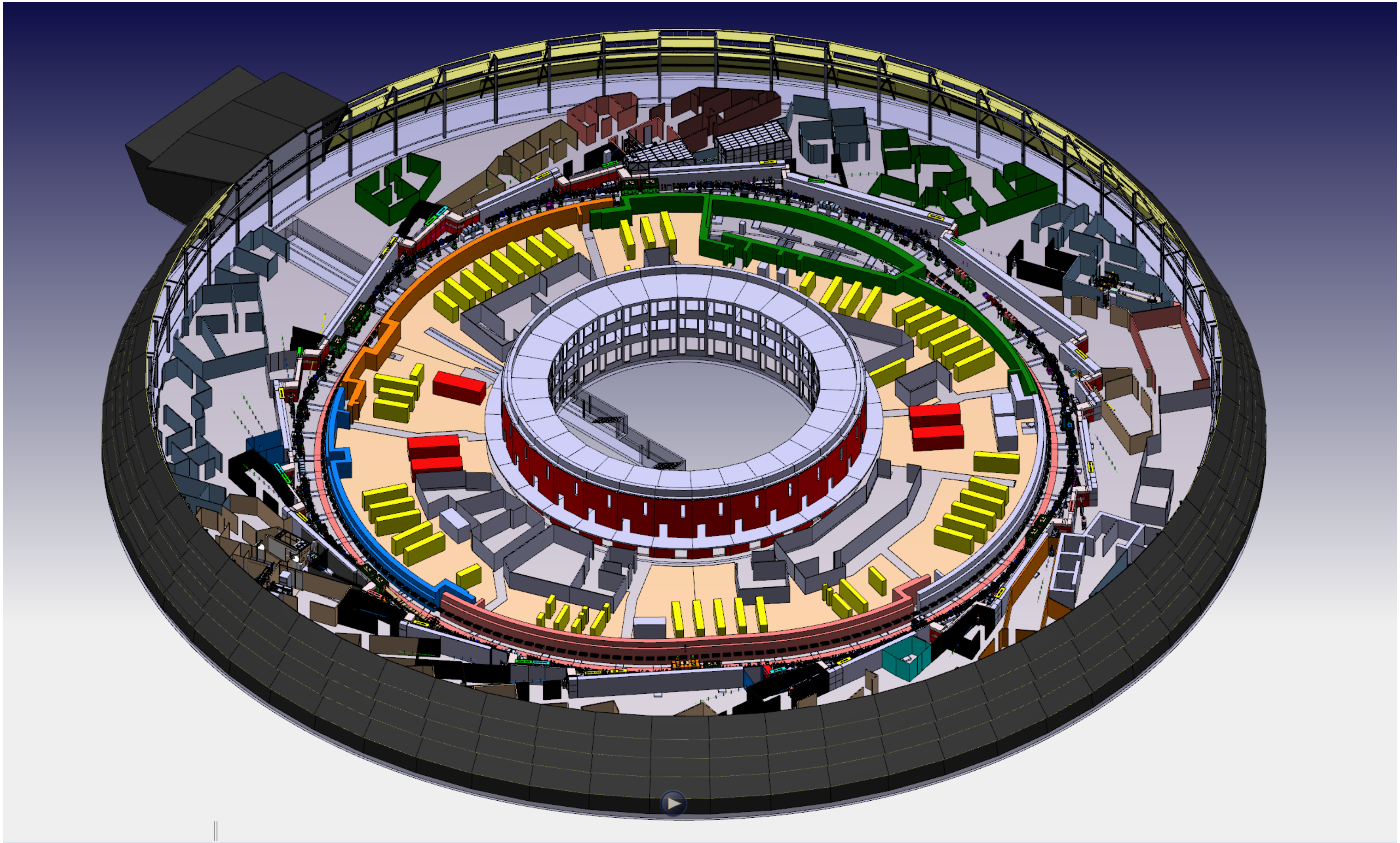
(single pass)

Example: Layout Swiss Light Source



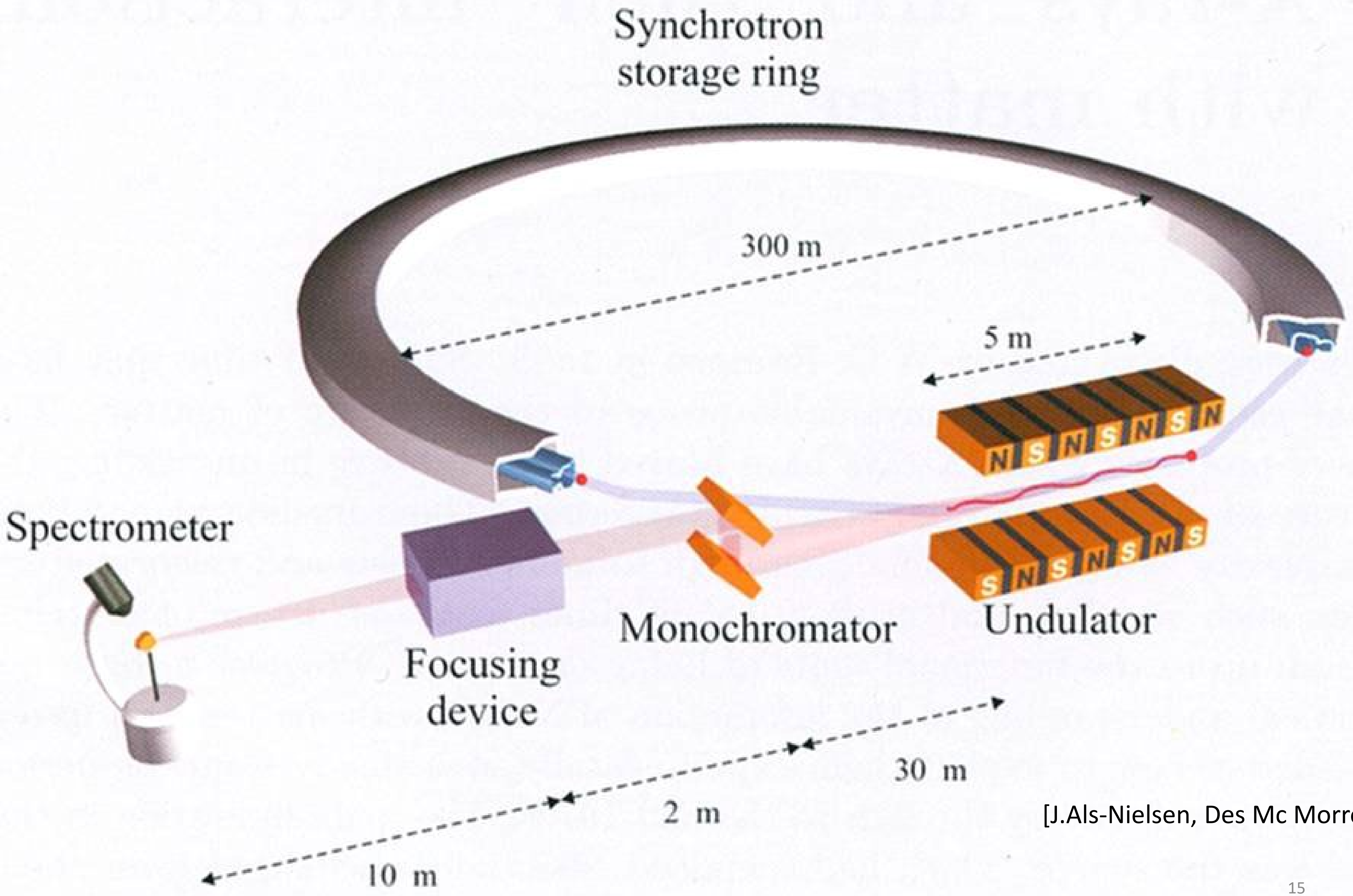

Swiss Light
Source 2.0
(PSI)

3D CAD View of SLS2.0



courtesy of U. Frommherz

Undulator based beamline

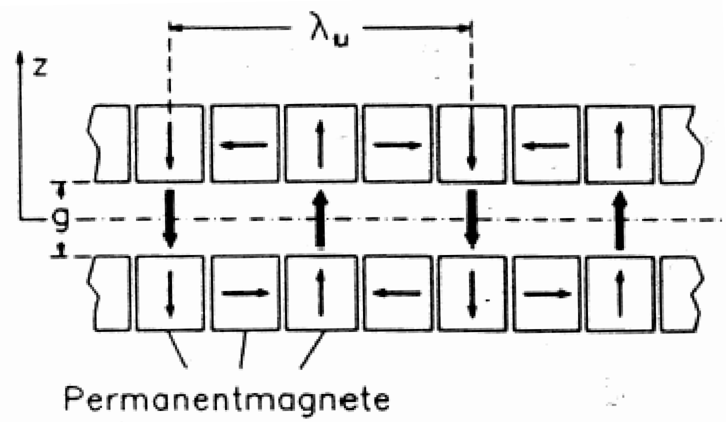


[J.Als-Nielsen, Des Mc Morrow]

Permanent magnet undulators

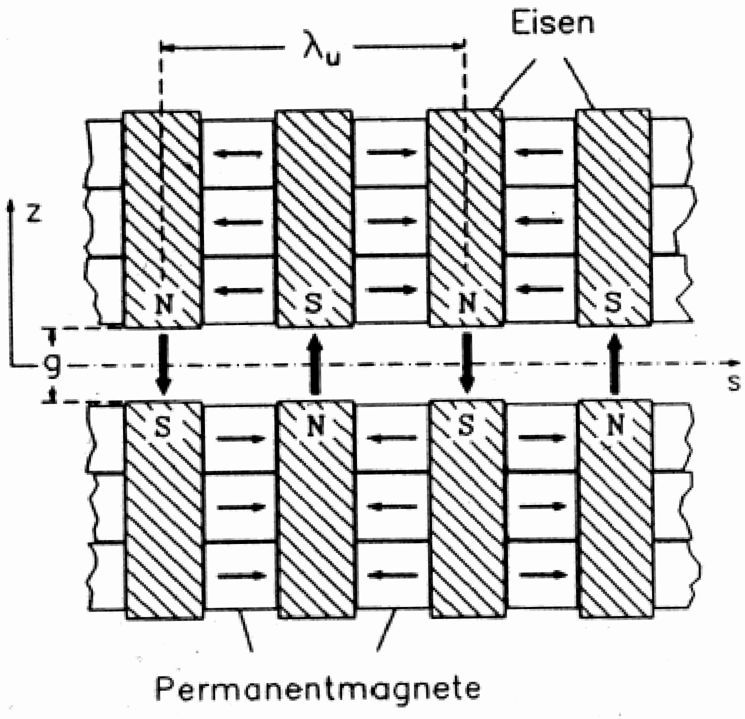
Permanent magnet materials: $SmCo_5$, NdFeB

→ e.g. a pencil made of such material corresponds to 15‘000 A-turns!

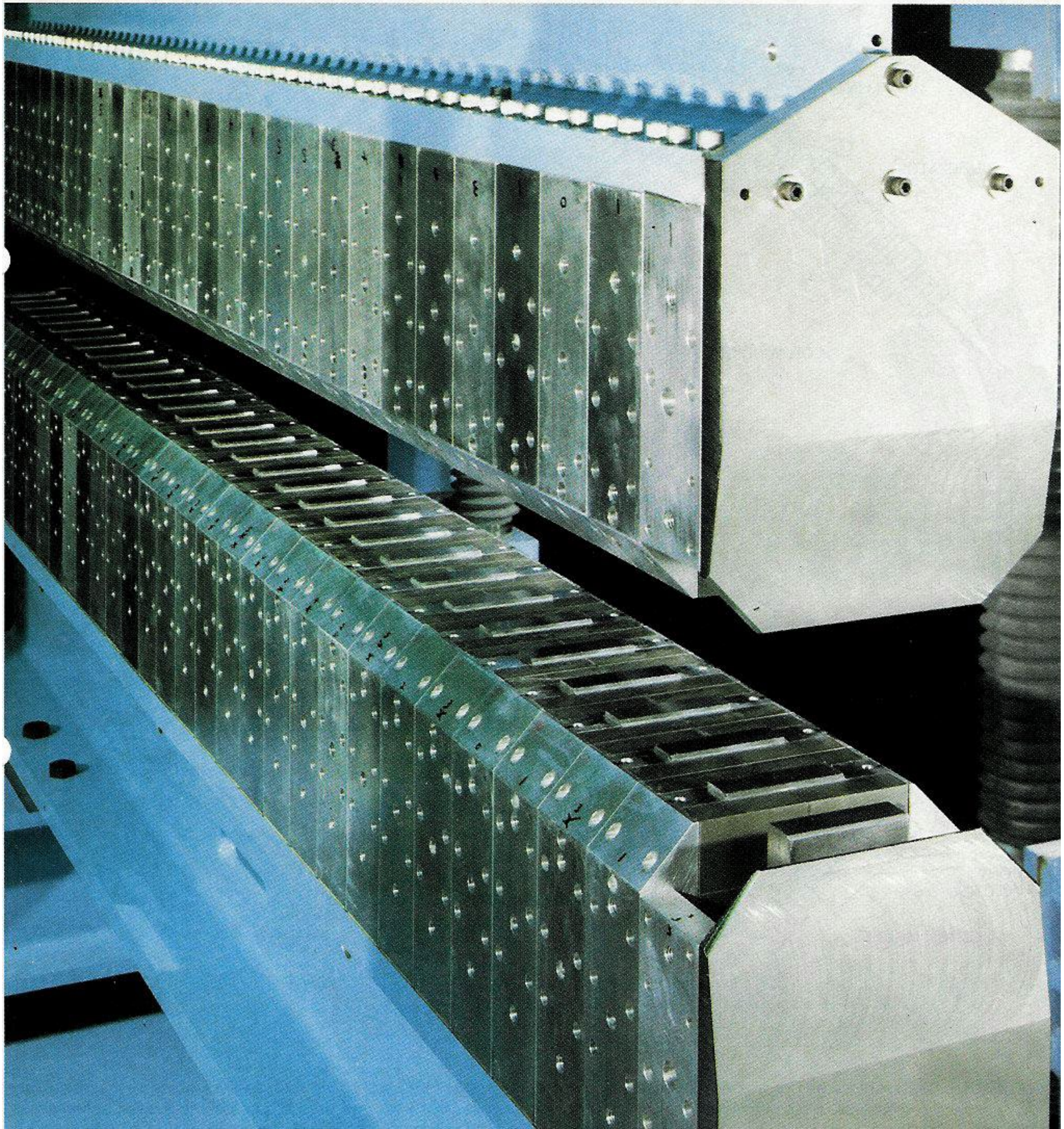


Hybrid undulator:

→ permanent magnets and iron

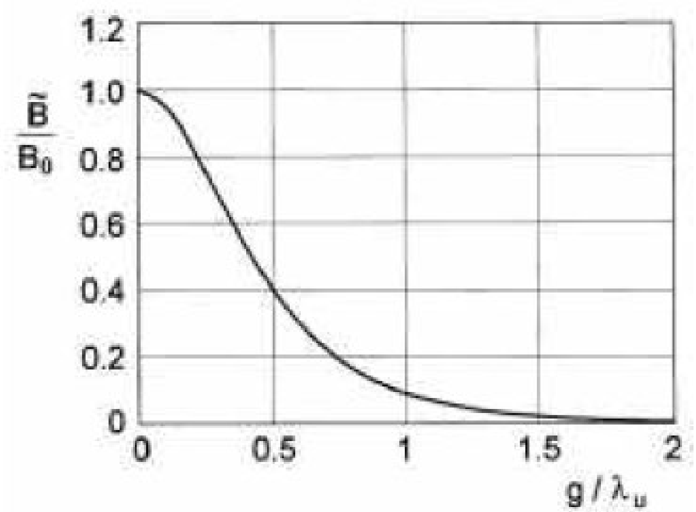


[see Wiedemann 6.7]



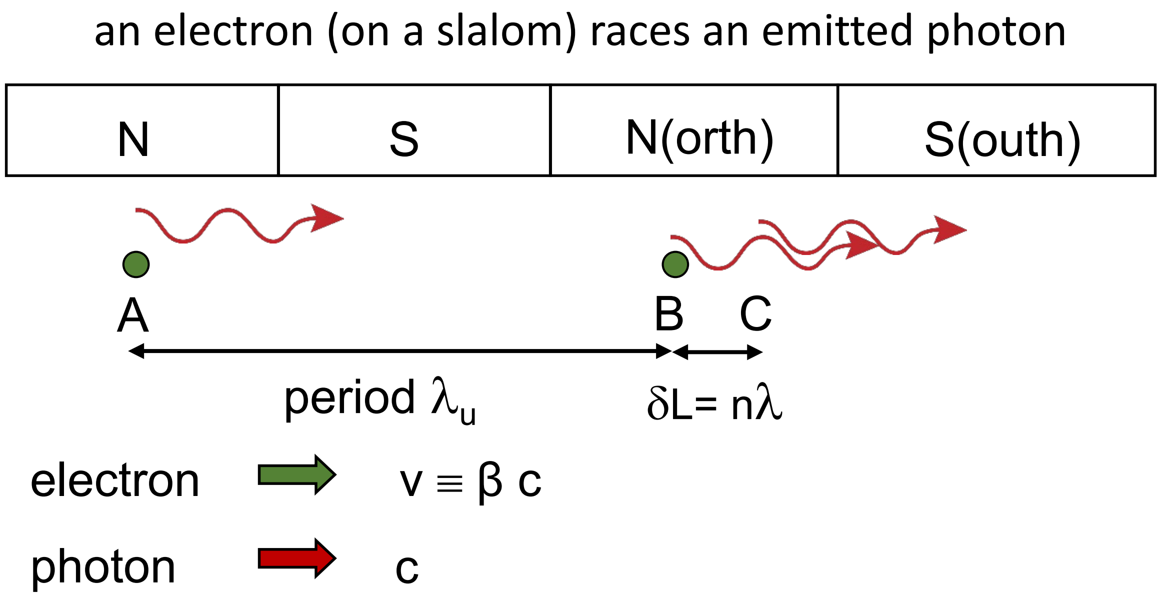
Field tuning with gap

$$B \approx 1.8 \times B_r \, e^{-\pi \frac{\Delta_{\text{gap}}}{\lambda_u}}$$



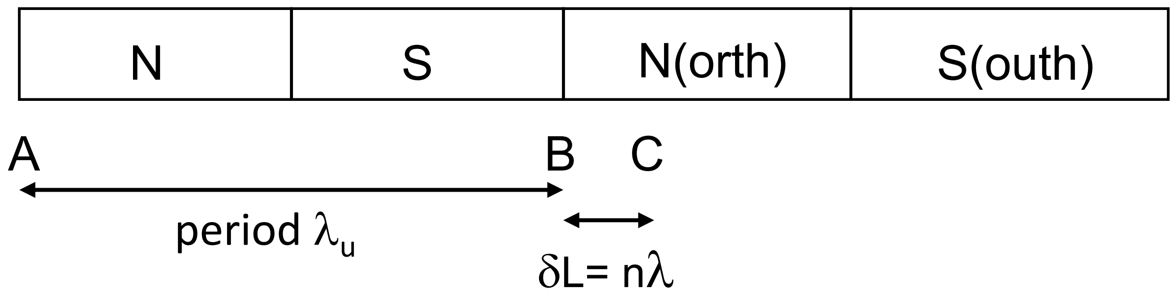
Permanent magnet material	Remanent field [T]
$SmCo_5$	0.9 – 1.0
Sm_2Co_{17}	1.0 – 1.1
NdFeB	1.0 – 1.4

Selection of wavelength in an undulator



- at A an electron emits a photon with wavelength l and flies one period λ_u ahead to B with velocity $v = \beta c$.
- there it emits another photon with the same wavelength l. At this moment the first photon is already at C.
- If δL corresponds to n wavelengths $\rightarrow$ positive interference between the two photons $\rightarrow$ intensity at this wavelength enhanced.

Selection of wavelength in an undulator II

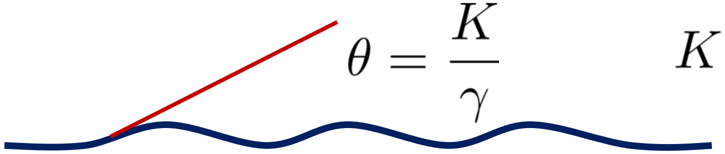


electron → $v \equiv \beta c$

photon → c

path difference: $$\delta L \equiv n\lambda \approx (1-\beta)\lambda_u, \; 1-\beta \approx \frac{1}{2\gamma^2}$$

radiation wavelength: $$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$ ← detour through slalom

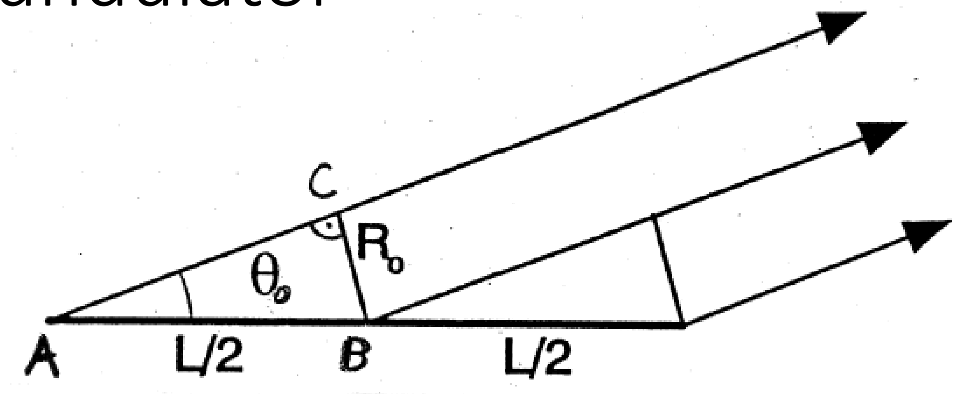


$$\theta = \frac{K}{\gamma}$$

$$K = 0.0934 \cdot \lambda_u[\mathrm{mm}] \cdot B[\mathrm{T}]$$

[see Wiedemann 6.7, 24.1]

Radiation cone of an undulator



Undulator radiates from the entire length L into a narrow cone.

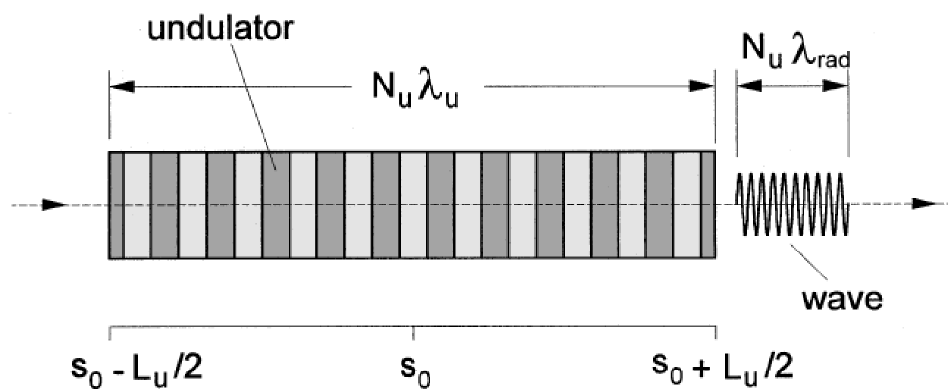
Propagation of the wave front BC is suppressed under an angle θ_0, if the path length AC is just shorter by a half wavelength compared to AB (negative interference). This defines the central cone.

Negative interference for

$$\Delta L = AB - AC = \frac{1}{2}L(1-\cos\theta_0) \approx \frac{1}{4}L\theta_0^2 \qquad \Delta L = \frac{\lambda}{2}$$

$$\theta_0 = \sqrt{\frac{2\lambda}{L}} \qquad R_0 = \sqrt{\frac{\lambda L}{2}} \quad \Rightarrow \quad \varepsilon_0 = \theta_0 R_0 = \lambda$$

Undulator line width



Undulator of infinite length

$$N_u = \infty \rightarrow \frac{\Delta\lambda}{\lambda} = 0$$

Finite length undulator

- radiation pulse has as many periods as the undulator
- the line width is:

$$\frac{\Delta\lambda}{\lambda} \propto \frac{1}{N_u}$$

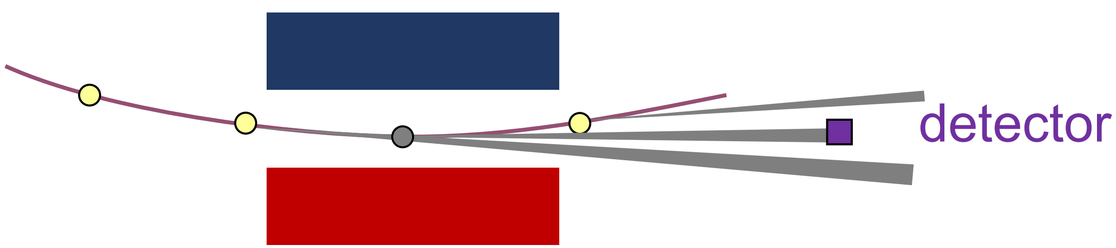
Due to the electron energy spread:

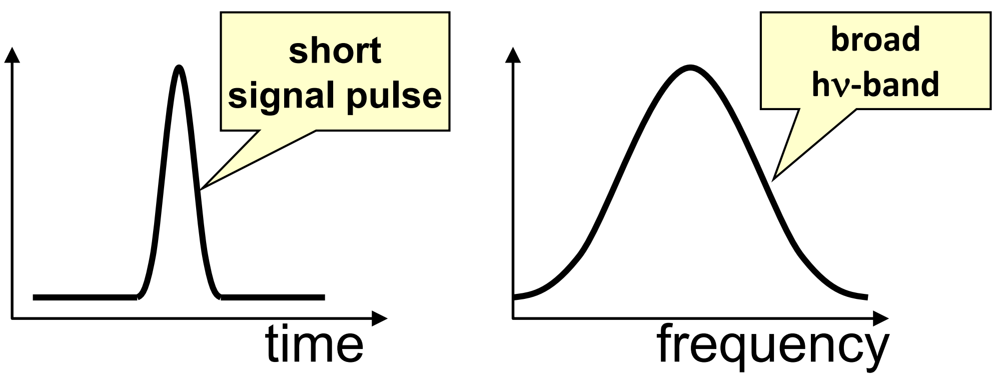
$$\frac{\Delta\lambda}{\lambda} = 2\frac{\sigma_E}{E}$$

Next: Four sources of radiation

- bending magnet
- wiggler
- undulator
- (FEL radiator)

1. Bending magnets



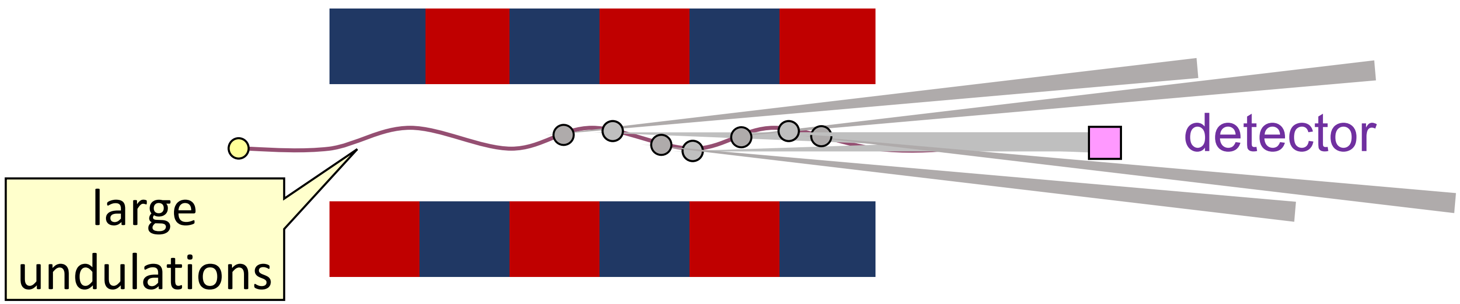


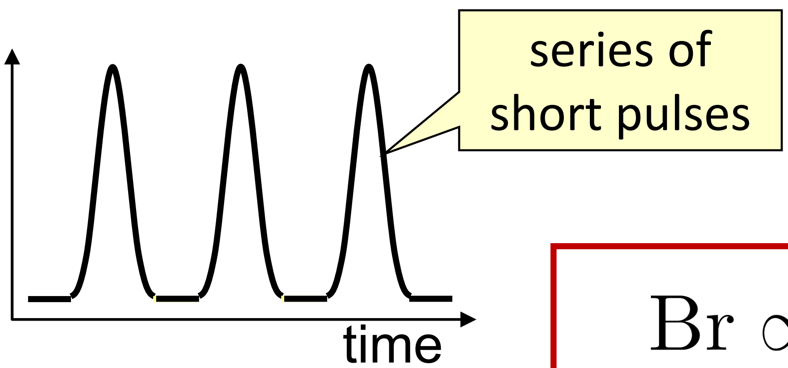
$$\mathrm{Br} \propto N_e$$

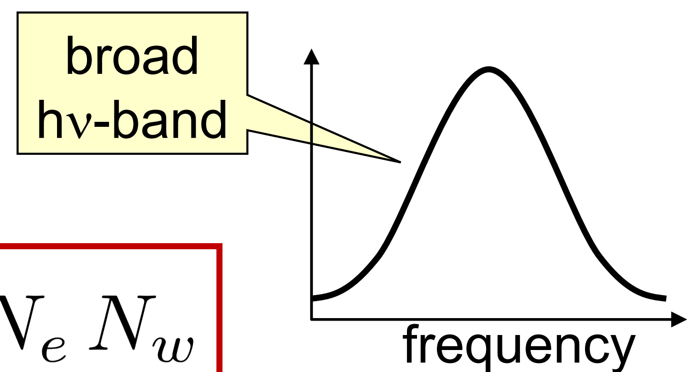
$$x'_{\mathrm{rms}} \propto 1/\gamma$$

$$y'_{\mathrm{rms}} \propto 1/\gamma$$

2. Wigglers







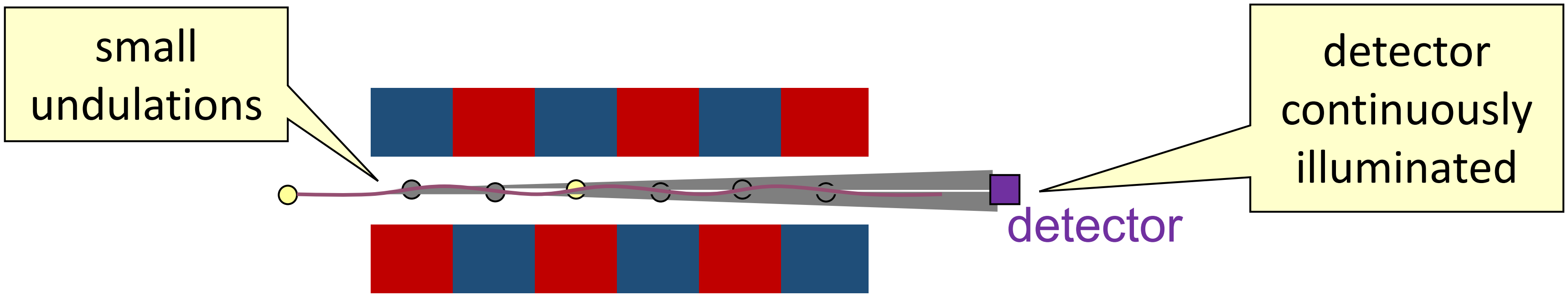
$$\mathrm{Br} \propto N_e \, N_w$$

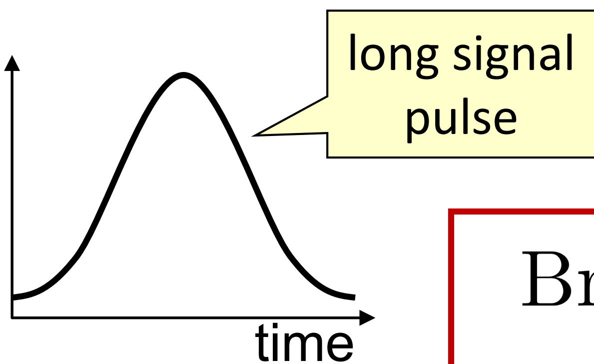
$$x'_{\mathrm{rms}} \propto K/\gamma$$

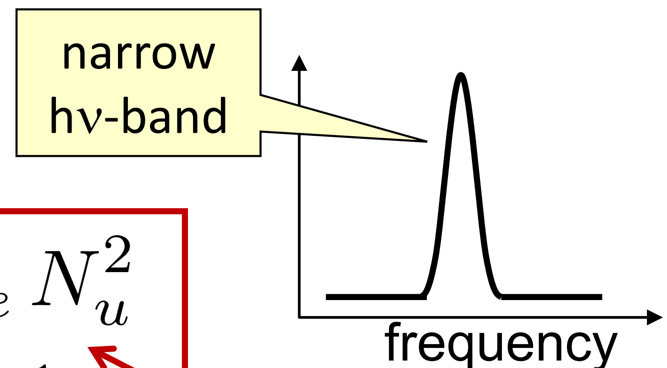
$$y'_{\mathrm{rms}} \propto 1/\gamma$$

$\times\, 10$

3. Undulators







$$\mathrm{Br} \propto N_e \, N_u^2$$

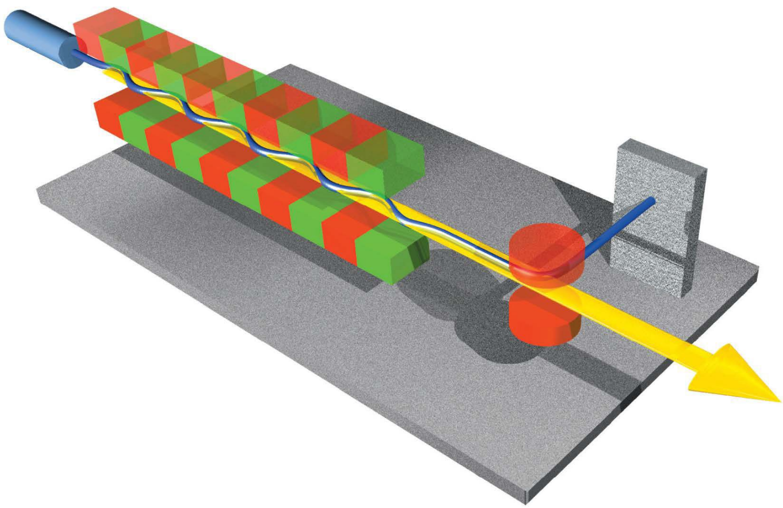
$$\theta_{x,y} \propto \frac{1}{\sqrt{N_u}\,\gamma}$$

$\times$ 1000

Btw: FEL Process – even higher brilliance

FEL-process:

- very long undulator $\rightarrow$ self bunching of electrons
- micro bunches radiate coherently like single particles with $N_e \times e$



$$\mathrm{Br} \propto N_e^2 \, N_u^2$$

$\times\, 10^8$

Performance Goals for Light Sources

1. **photon energy** in interesting range (μm to sub- Å)
2. **stability** (feedbacks, temperature stabilization, suited mechanics, top-up)
3. **Brightness**:
   - beam intensity
   - low electron beam emittance $\rightarrow$ optimized lattices
   - matching of e-beam to photon field in undulators
4. **coherence** of radiation

Small Emittance Lattices

reminder: horizontal equilibrium emittance*

$$\varepsilon_{x0} = \frac{\sigma_{x\beta}^2}{\beta_x} = C_q \frac{\gamma^2 < \mathcal{H} >_{\rm mag}}{\rho J_x}$$

$$< \mathcal{H}(s) >_{\rm mag} = \frac{1}{2\pi} \oint_{\rm mag} (\beta D'^2 + 2\alpha D D' + \gamma D^2) ds$$

* isomagnetic: dipole curvature = $1/\rho_0$ or = 0, Sands eq. 5.84

- overall scaling with γ^2, ρ^{-1}
- modification via damping partition J_x is possible
- main property: H-function optimized in lattice

Small Emittance Lattices

reminder: horizontal equilibrium emittance

$$\varepsilon_{x0} = \frac{\sigma_{x\beta}^2}{\beta_x} = C_q \frac{\gamma^2 < \mathcal{H} >_{\text{mag}}}{\rho J_x}$$

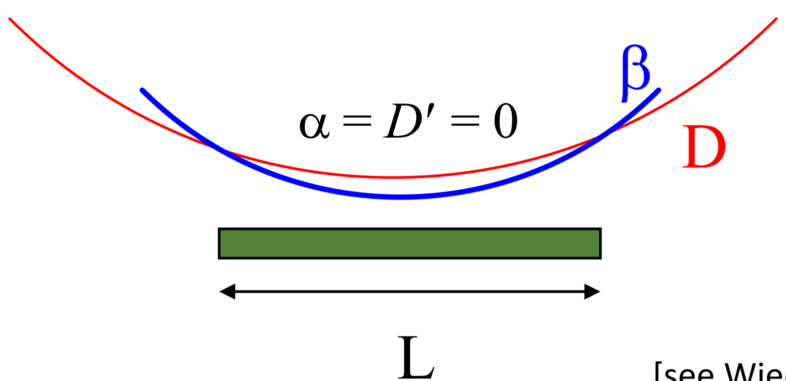
*isomagnetic only

$$< \mathcal{H}(s) >_{\text{mag}} = \frac{1}{2\pi} \oint_{\text{mag}} (\beta D'^2 + 2\alpha D D' + \gamma D^2) ds$$

one tries to minimize the H function in **bending magnets**.

$$\varepsilon_{x0} = \gamma^2 \frac{C_q}{J_x} \theta^3 F_{\text{latt}}$$

$$F_{\text{min}} = \frac{1}{12\sqrt{15}}$$

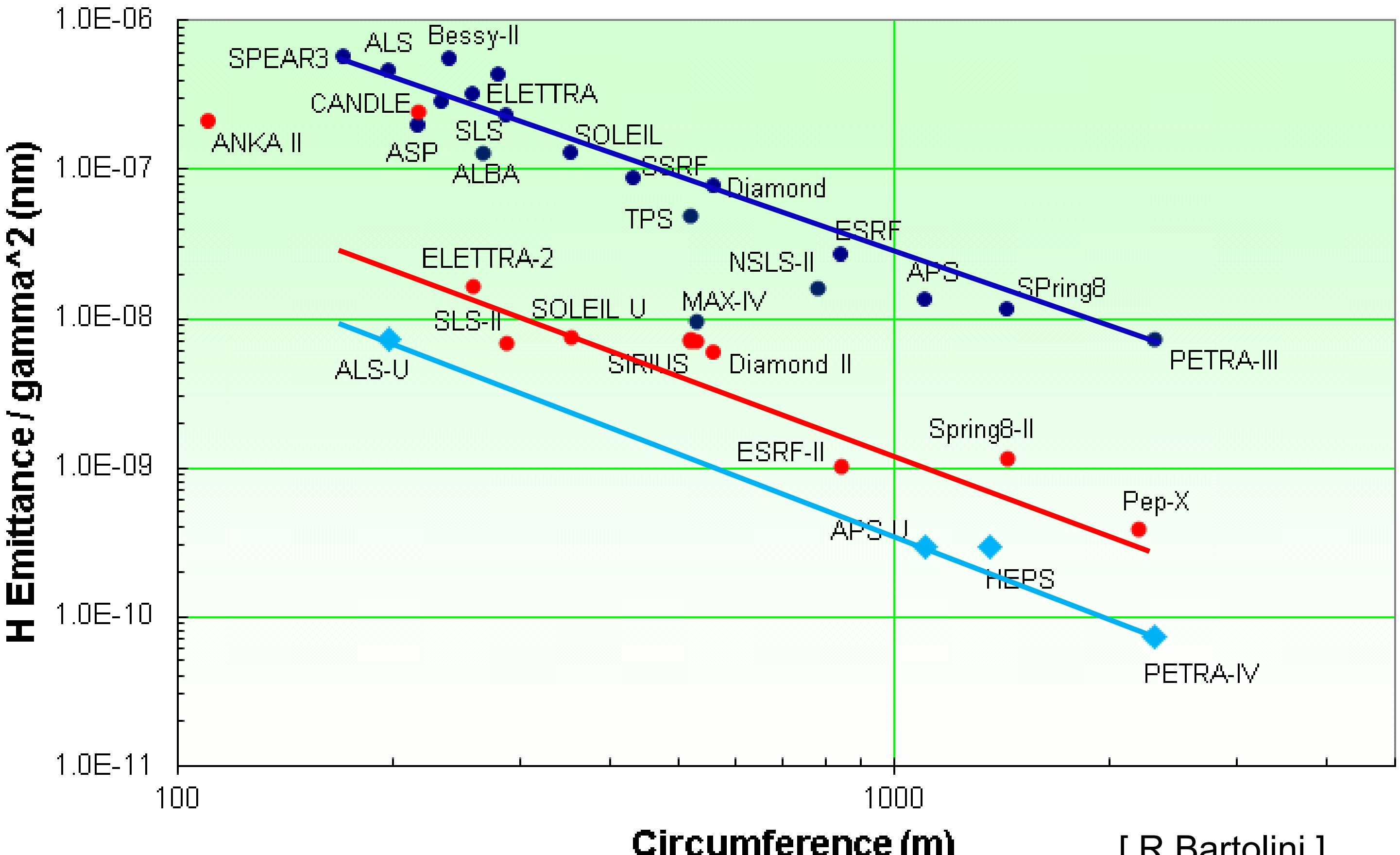


$$\beta^* = \frac{L}{2\sqrt{15}}$$

$$D^* = \frac{\theta L}{24}$$

[see Wiedemann 14.2]

Low Emittance Lattices for Light Sources



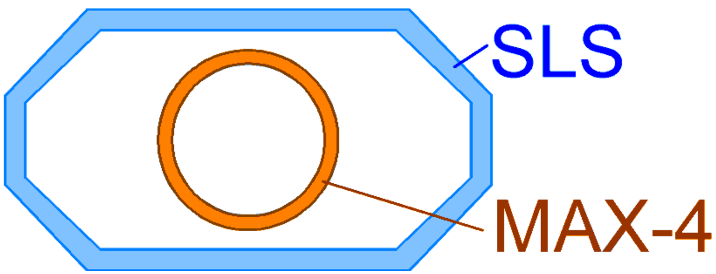
[R.Bartolini]

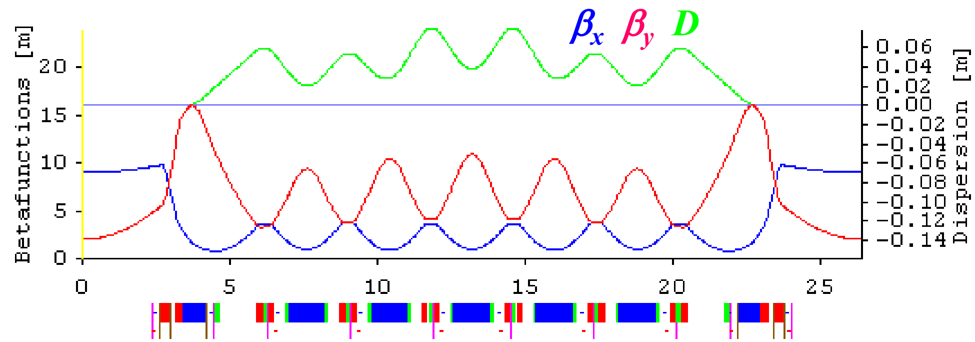
DBA/TBA → MBA + technology → On-axis inj. + technology

A revolution in storage ring technology

Pioneer work: MAX IV (Lund, Sweden)

Aperture reduction ⟷ **Multi-Bend Achromat (MBA)**





short & strong multipoles

⇨ short lattice cells

⇨ many lattice cells

⇨ low angle per bend

Technological achievement:

NEG* coating of small vacuum chambers

⇨ Small magnet bore

⇨ High magnet gradient

emittance $\varepsilon \propto (\text{energy})^{2} \times (\text{bend angle})^{3}$

⇨ Emittance reduction from nm to 10...100 pm range

*Non Evaporable Getter

The world is moving to ever brighter ring sources

2-bend achromat

BNL: **NSLS-II** (2014): 3 GeV,
<1000pm x 8 pm, 500 mA (**New**)

7- bend achromat

Sweden: **MAX-4** (2016): 3 GeV,
230 pm x 8 pm, 500 mA (**New**)

5- bend achromat

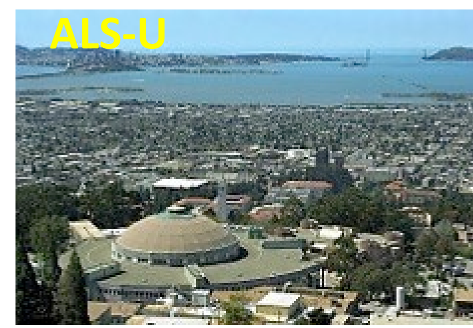
Brazil**: SIRIUS** (2016/17): 3 GeV,
280 pm x 8 pm, 500 mA (**New**)

1st multi-bend achromat ring upgrade

France: **ESRF-II** (2020): 6 GeV,
160 pm x 3 pm, 200 mA (**New**)

U.S. Proposals

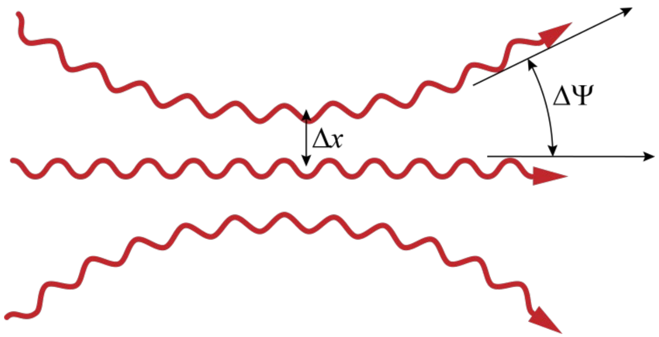
APS-U: 6 GeV, 60 pm x 8 pm,
200 mA (**Upgrade Proposal**)



ALS-U: 2 GeV, 50 pm x 50 pm,
500 mA (**Upgrade proposal**)

Other international upgrades: *Japan (Spring 8, 6 GeV), China (BAPS, 5 GeV), Germany (PETRA-IV, France (SOLEIL), Switzerland (SLS, 2.4 GeV), Italy (ELETTRA) and others are developing plans*

Diffraction limited emittance



light of wavelength λ, focused to spot size Δx will diffract with angle $\Delta\Psi \approx \lambda/\Delta x$

$$\sigma_x(\lambda)\sigma_\Psi(\lambda) = \varepsilon_\gamma(\lambda) \approx \frac{\lambda}{2\pi}$$

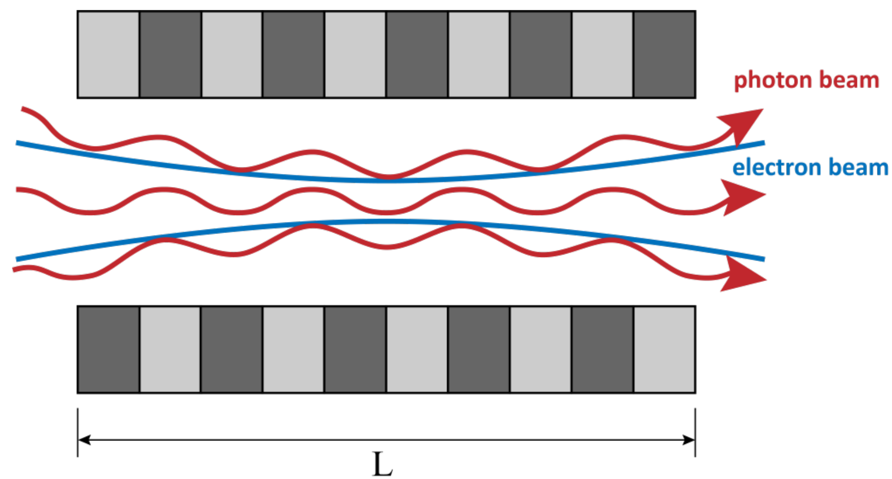
= minimum emittance of photon field

P. Elleaume, in *Wigglers, Undulators, and Their Applications*, 2003
Wiedemann, eq. 24.100 but factor 2

Undulator Matching

to obtain the best focused light beam, photon field and electron beam should match in shape

→ the distribution of the resulting radiation beam is a convolution of electron beam distribution with diffraction limited photon field



$$(f * g)(x) = \int_{-\infty}^{\infty} g(\tau) f(x - \tau) d\tau \Rightarrow \Sigma_{x,y}(\lambda) = \varepsilon_{x,y} * \varepsilon_r(\lambda) = \sqrt{\varepsilon_{x,y}^2 + \varepsilon_r^2(\lambda)}$$

Phase Space Matching of Photon- and Electron Beam

brightness resulting from convolution:

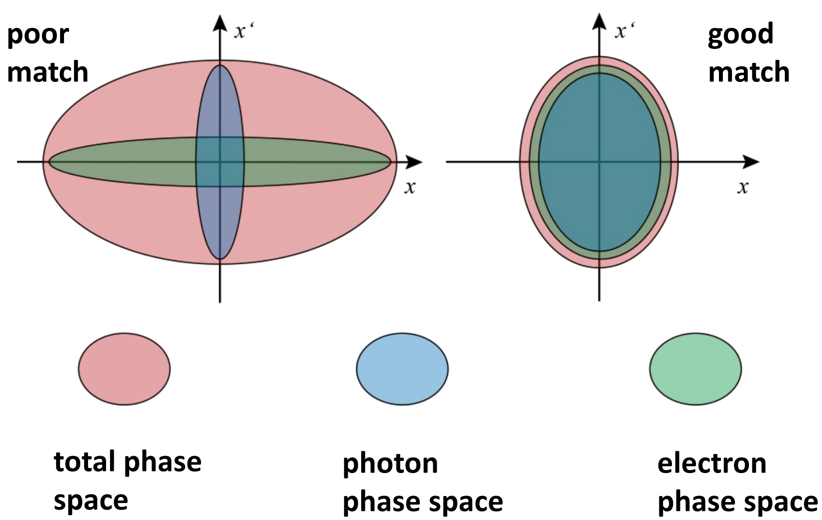
$$Br = \frac{\Phi}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

from convolution of *e* and γ phase spaces:

$$\Sigma^2 = \sigma_e^2 + \sigma_\gamma^2$$

diffraction limited photon beam dimensions:

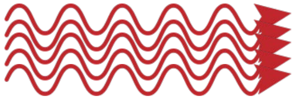
$$\sigma_x = \frac{\sqrt{\lambda L}}{4\pi}, \quad \sigma_{x'} = \sqrt{\frac{\lambda}{L}}$$

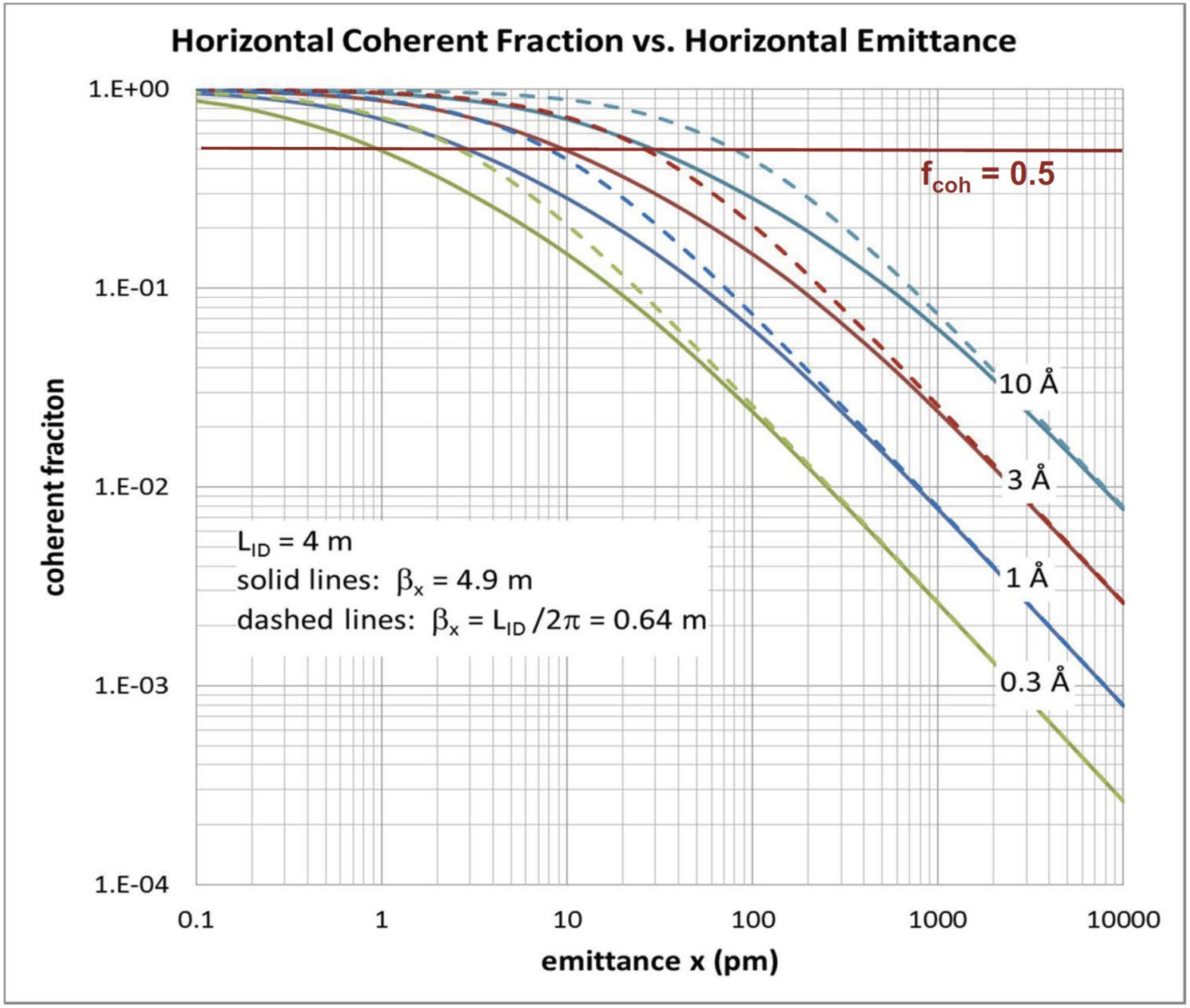


Wiedemann, 24.8.1

Coherent Fraction of Radiation

with smaller emittance and better matching also the coherent fraction of the radiation is increased

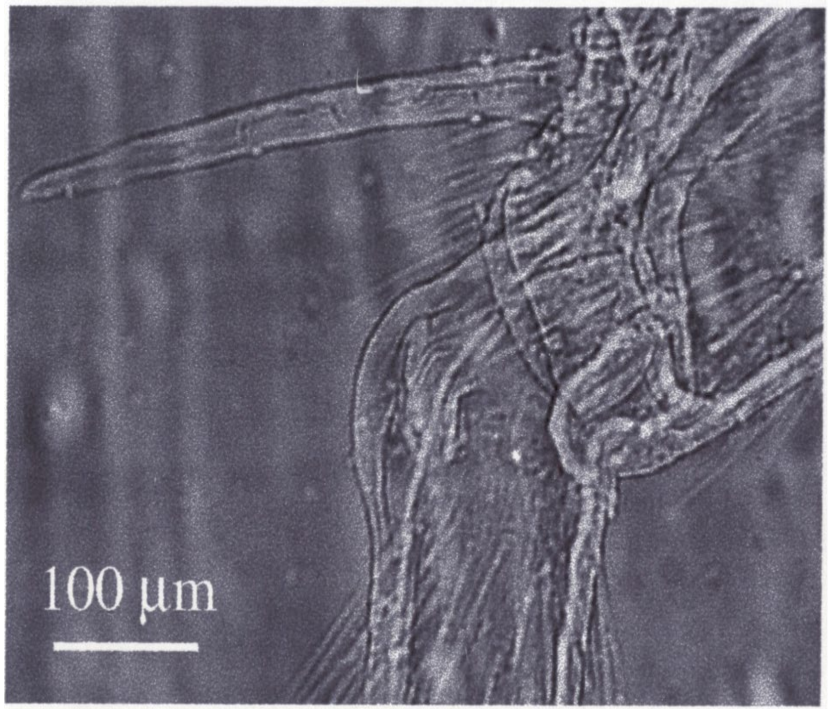




Transverse Coherence – What for?

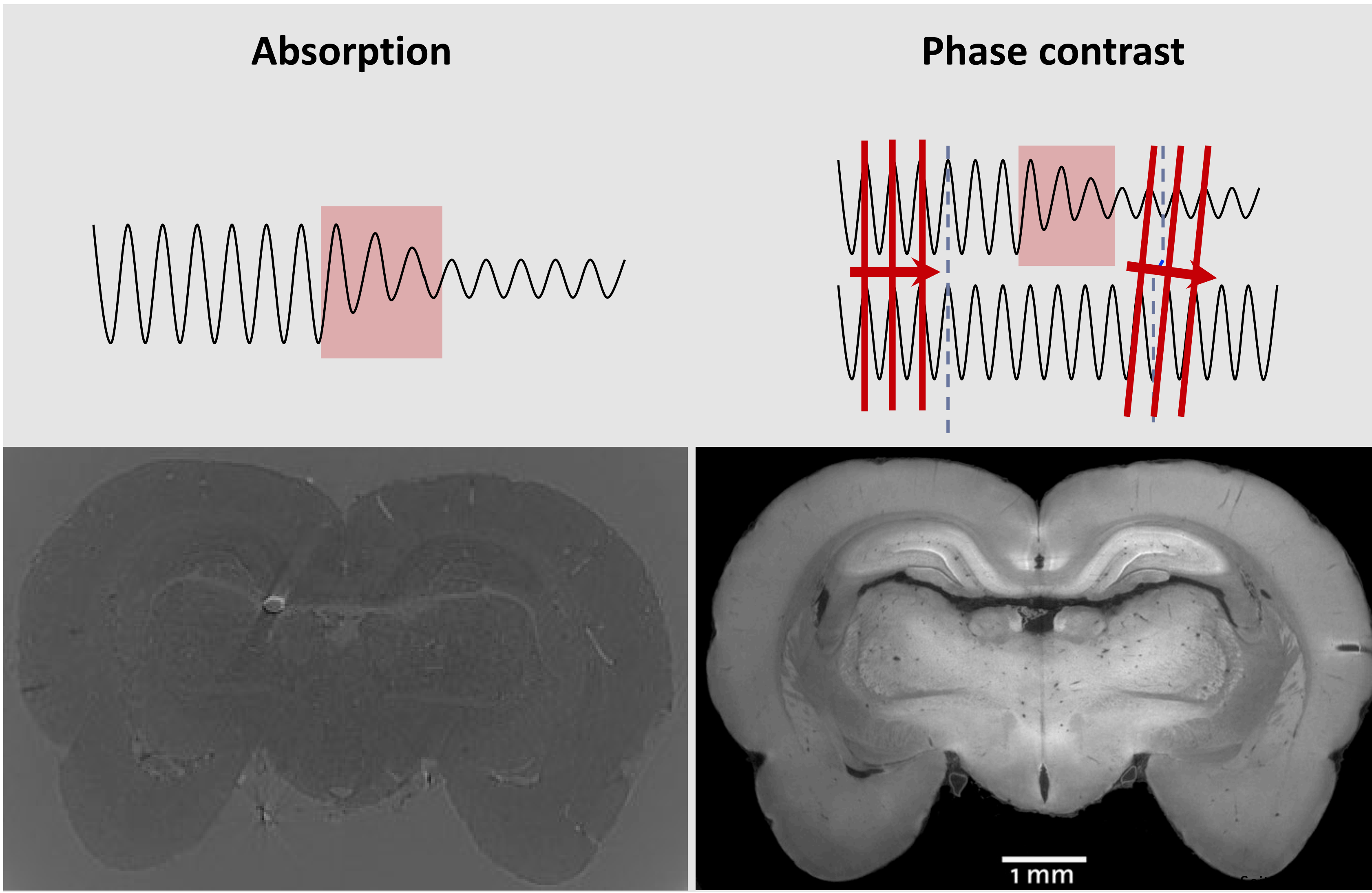
- **high brightness gives coherence**
- **wave optics methods for X-rays (see all chapters in Born & Wolf)**
- **Holography**

The knee of a spider



phase contrast imaging

Phase contrast X-Ray imaging




absorption
17.5 keV,
synchrotron results

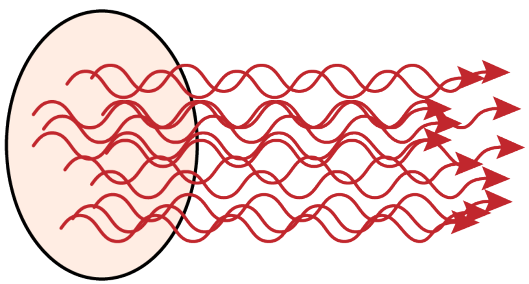
phase contrast
(C.David, F.Pfeiffer)

Next: Free Electron Laser

- layout of facilities
- exponential self bunching process
- typical parameters

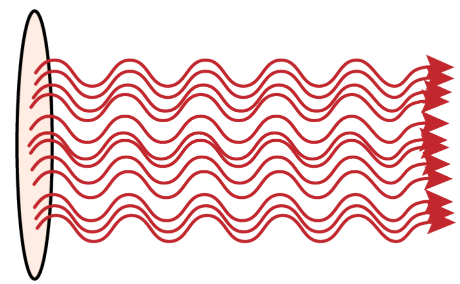
Coherent Emission by Short Electron Bunches

„long“ bunch
→ incoherent emission



Intensity $\propto N_e$

„short“ bunch (≅λ):
→ coherent emission



Intensity $\propto N_e^2$

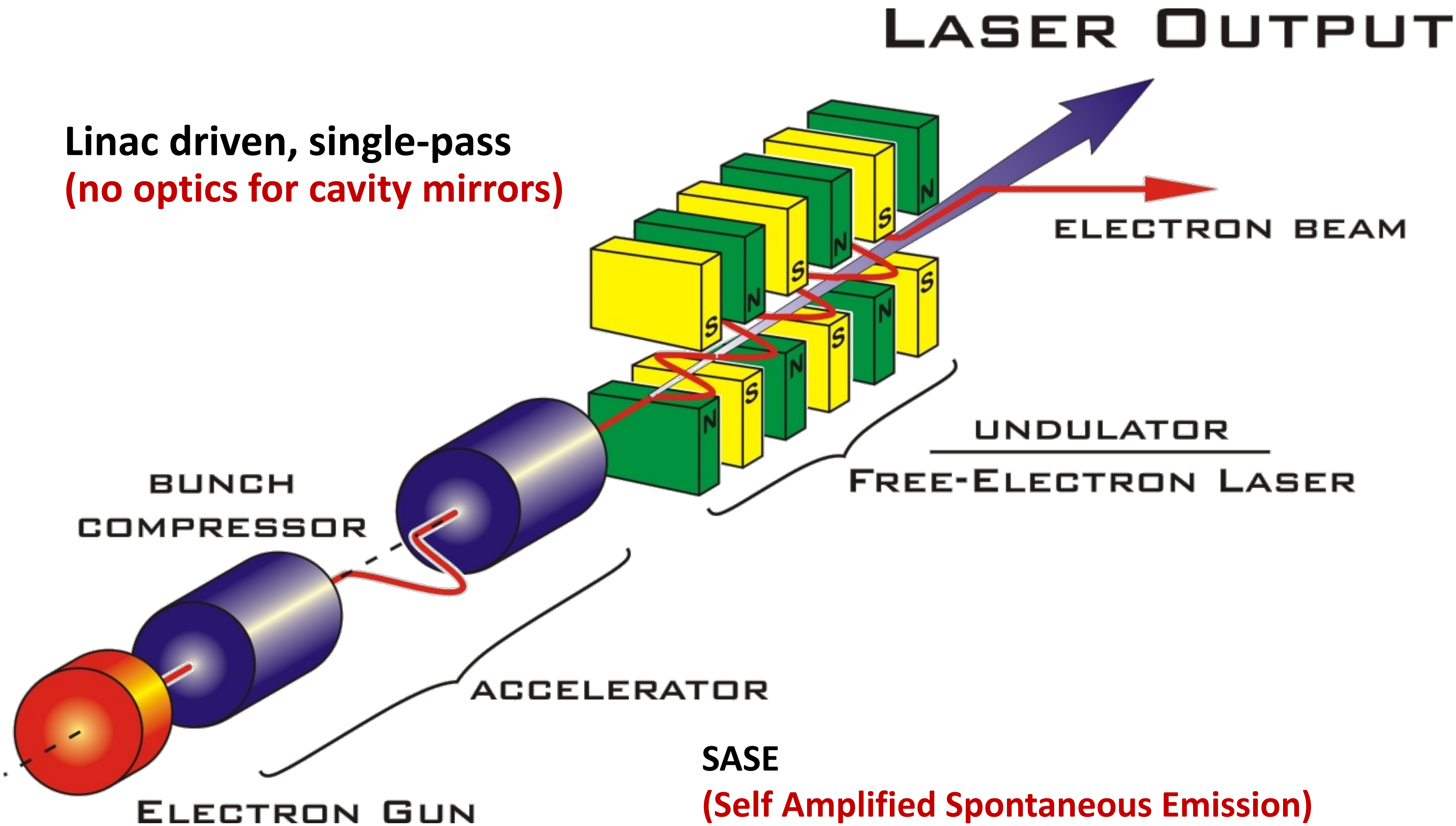
quadratic with charge:

Radiation power for single particle:

$$P_\gamma = \frac{e^2 c}{6\pi\varepsilon_0} \times \frac{E^4}{E_0^4 \rho^2}$$

Free Electron Laser Concept

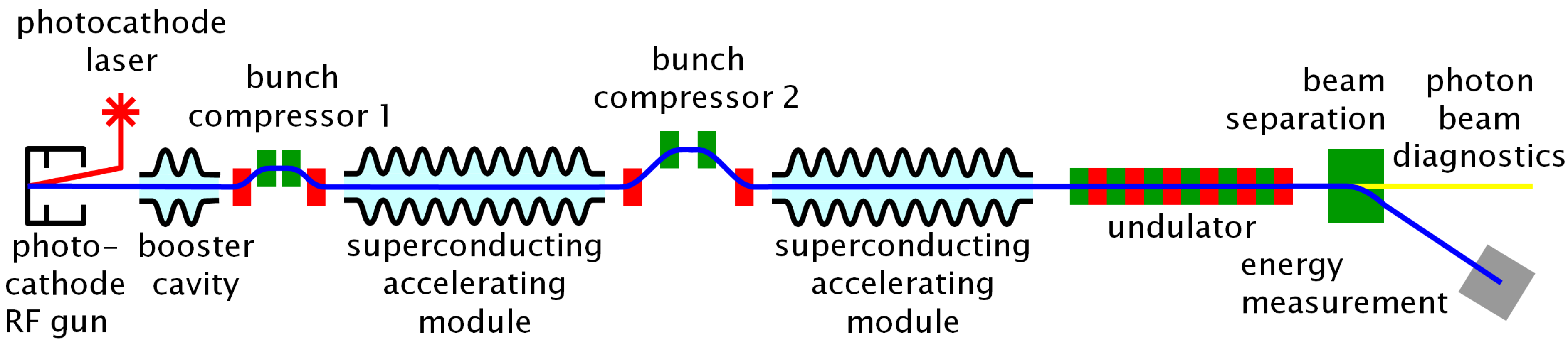
Linac driven, single-pass
(no optics for cavity mirrors)



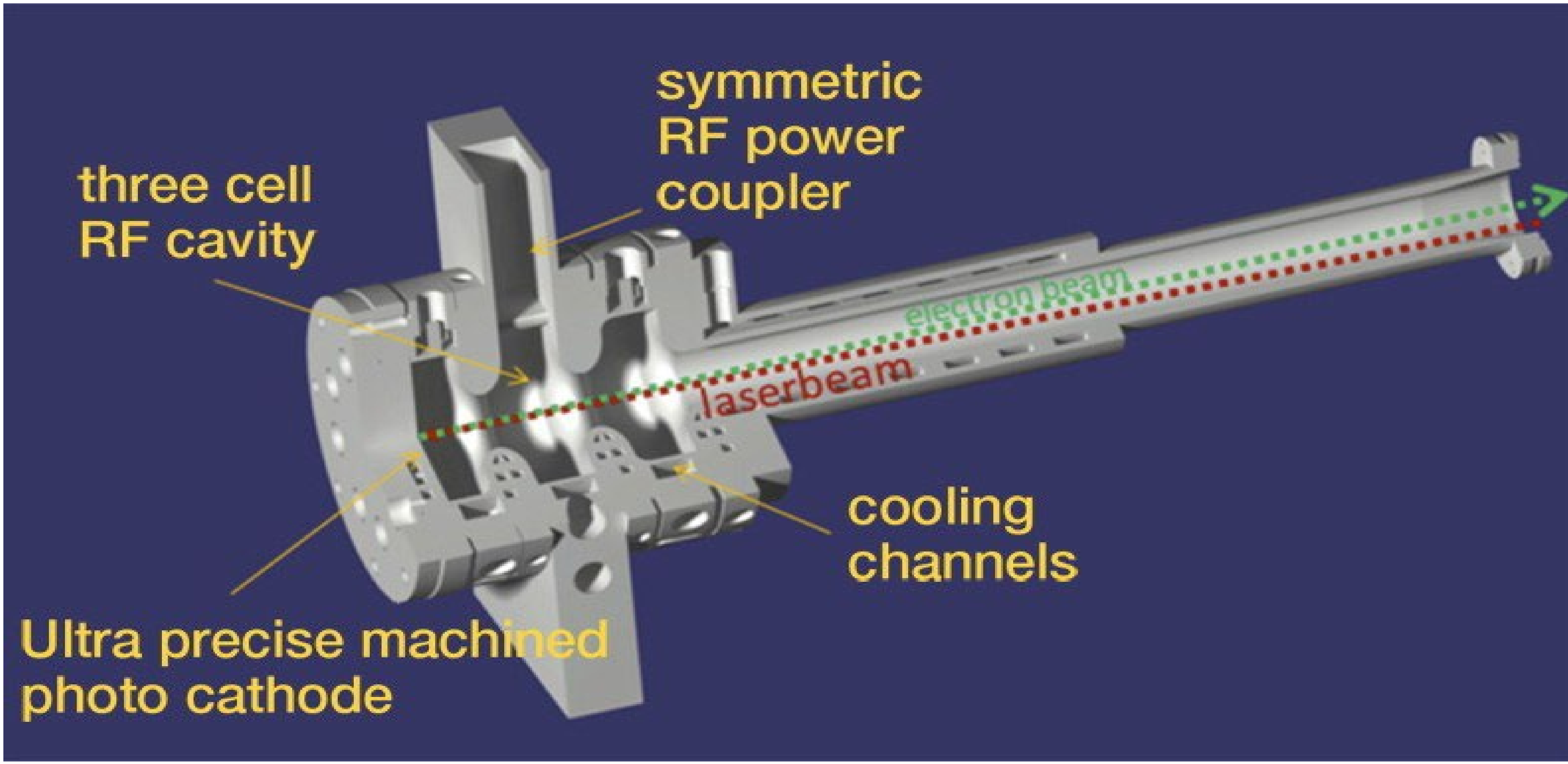
SASE
(Self Amplified Spontaneous Emission)
i.e., startup from noise

R. Bakker

Typical FEL Layout



Radio Frequency Gun (electron beam source)



fast acceleration → small emittance
LASER-pulse → short electron bunch

Bunch Compression in an FEL

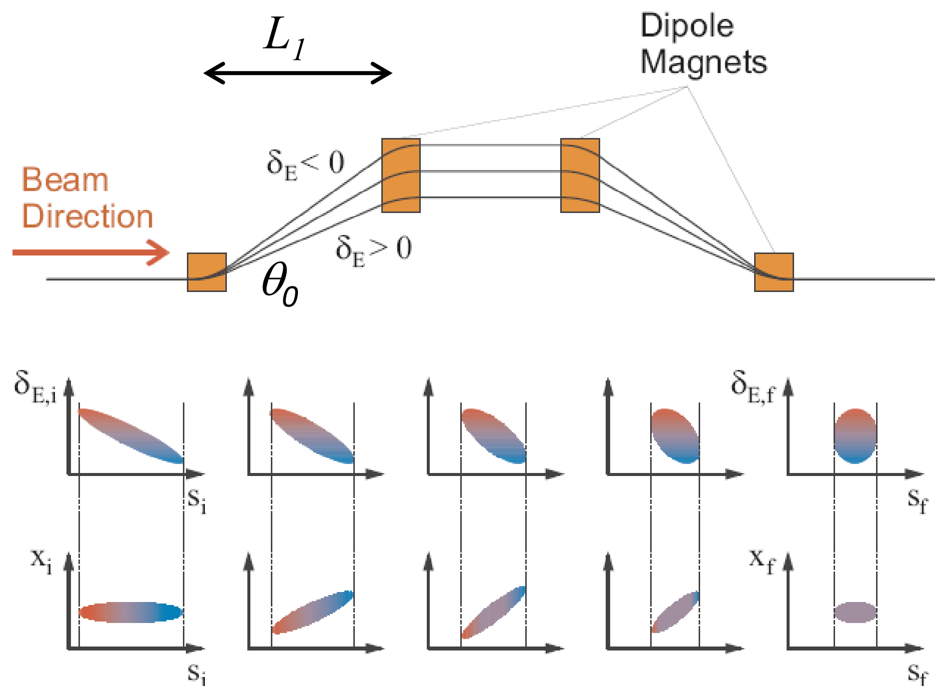
for FEL´s high charge density is essential → sophisticated compression schemes

magnetic compression:

- an energy chirp is introduced by off-crest acceleration
- the bunch is compressed by an energy dependent path length

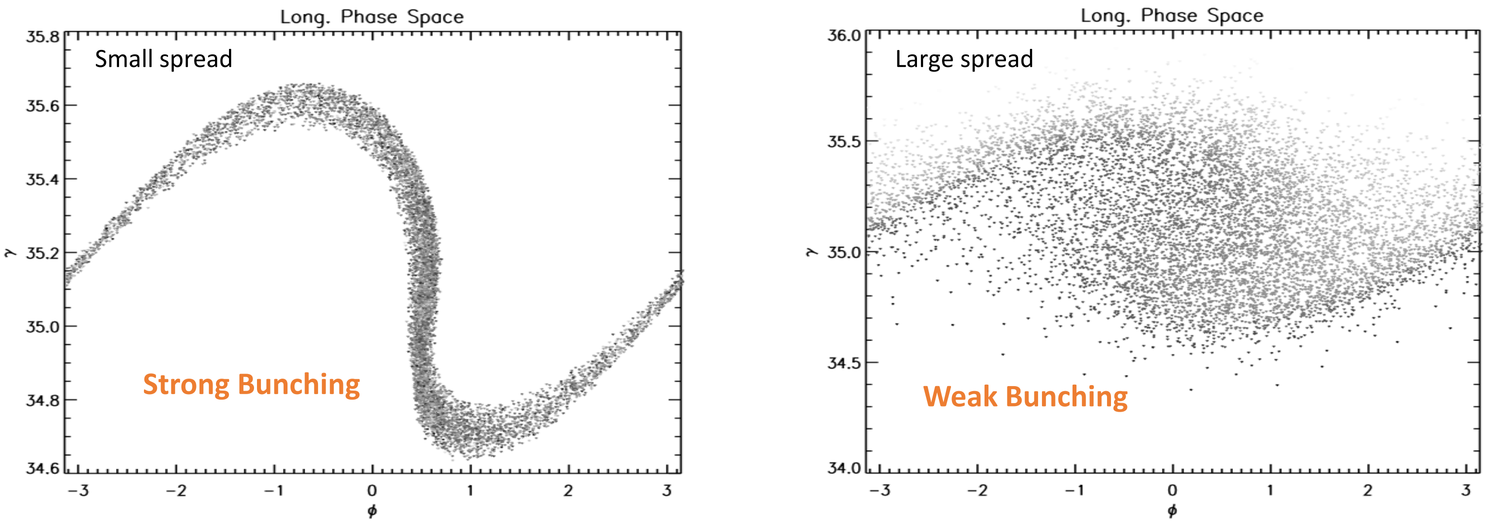
$$R_{56} = \frac{\Delta z}{\Delta p}$$

$$\approx -2L_1\theta_0^2$$



[E.Prat, PSI]

Electron Beam Requirements: Energy Spread



$\phi \propto s$

Energy Spread Constraint:

$$\frac{\sigma_\gamma}{\gamma} << \rho$$

From rings to linear accelerators - discussion

Rings:

- The number of beamlines served simultaneously
- The stability of the rings based sources
- High average brightness

Linac based:

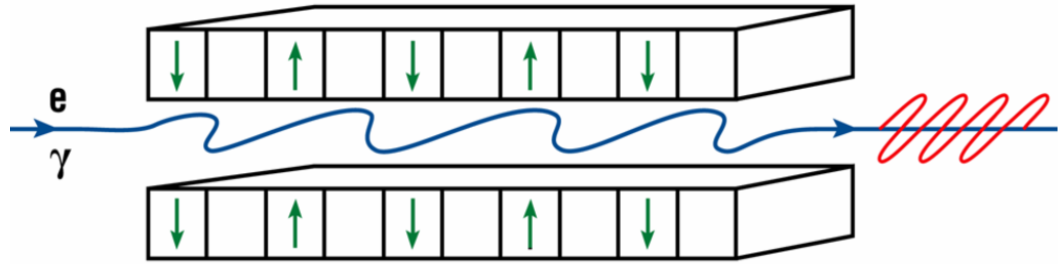
– Fewer beamlines

– Very short pulses, single shot measurements

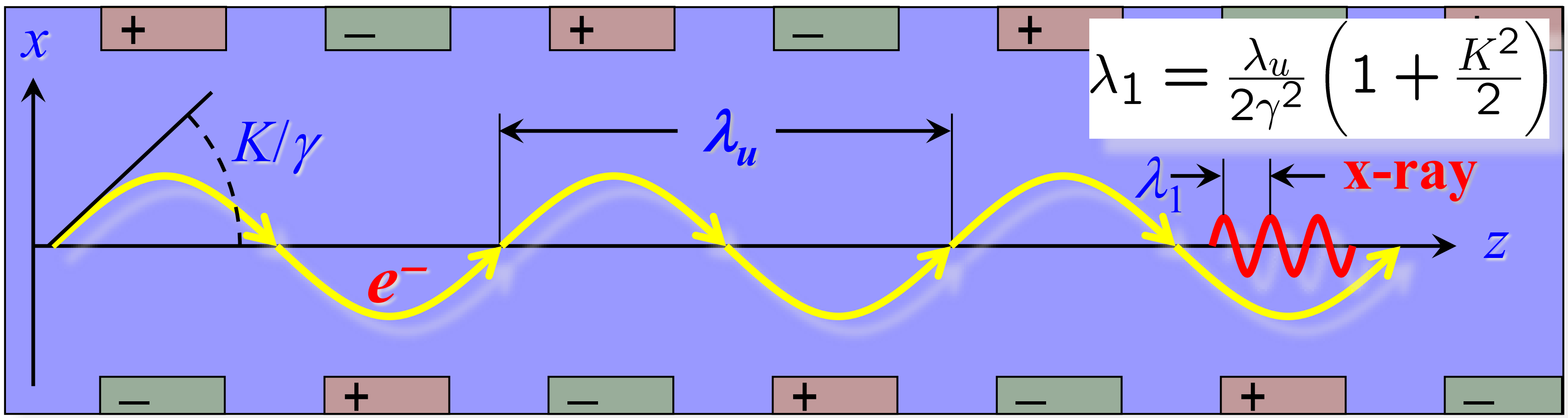
– High peak brightness

FEL Principles

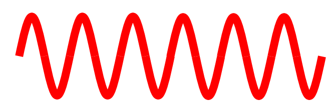
Z. Huang



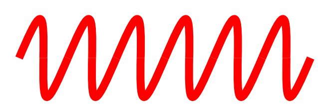
- Electrons **slip** behind EM wave by λ_1 per undulator period (λ_u)



- Due to sustained interaction, some electrons lose energy, while others gain ➔ **energy modulation at λ_1**

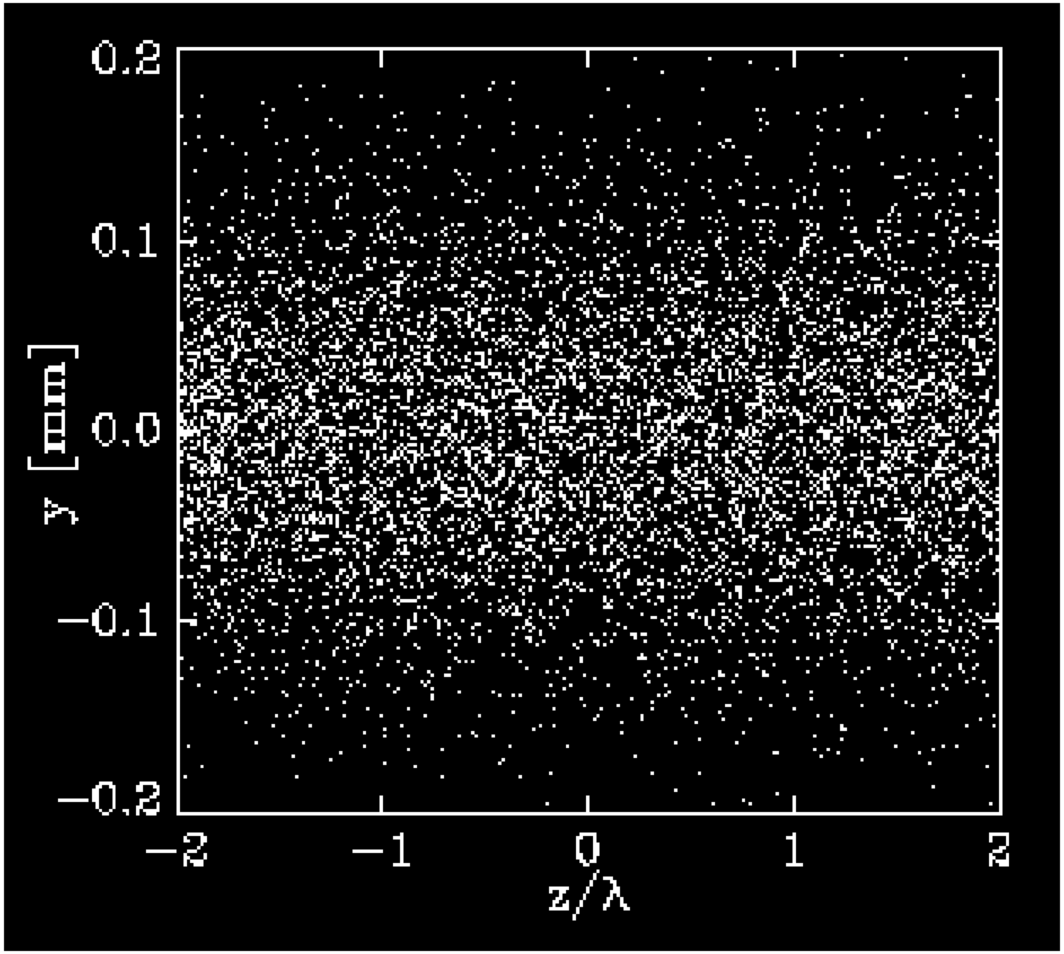


- e^- losing energy slow down, and e^- gaining energy catch up ➔ **density modulation at λ_1 (microbunching)**

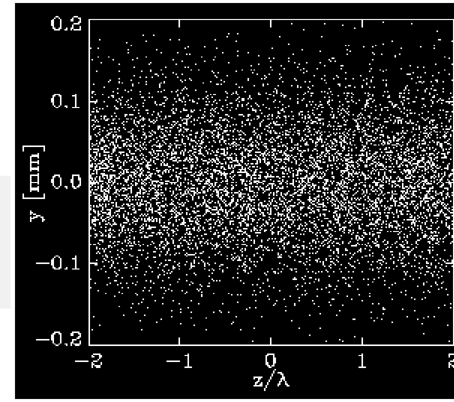


- Microbunched beam radiates coherently at λ_1, enhancing the process ➔ **exponential growth of radiation power**

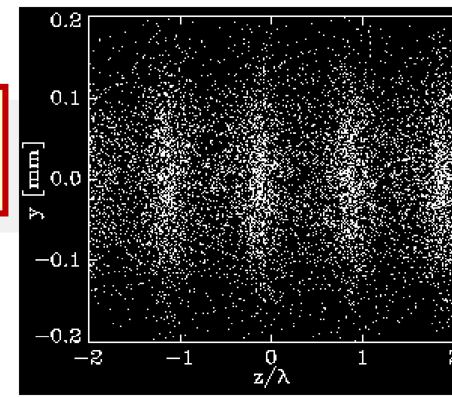
Microbunching through SASE Process



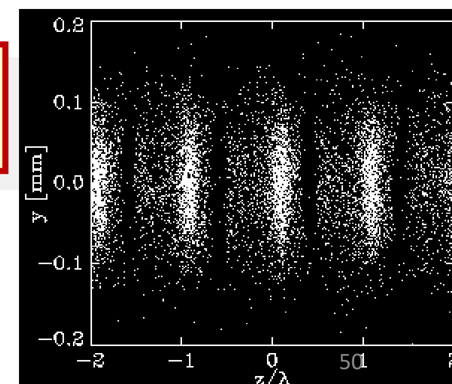
undulator entrance



half-way saturation



full saturation



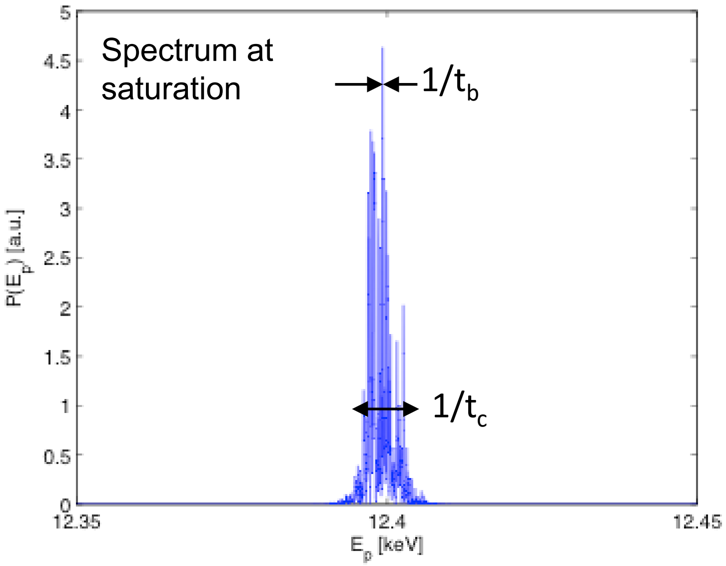
***GENESIS* - simulation for Flash (DESY) parameters**

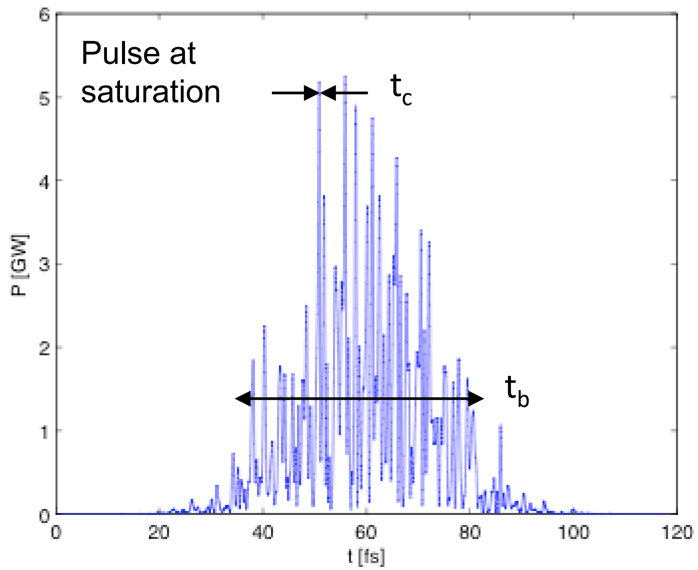
Courtesy - Sven Reiche (PSI)

SASE FELs

- FEL starts with the broadband signal of spontaneous radiation (almost a white noise signal)
- Within the FEL bandwidth $\Delta\omega$ the noise is amplified
- Spikes in spectrum and time profile.

SwissFEL: Simulation for 1 Angstrom radiation

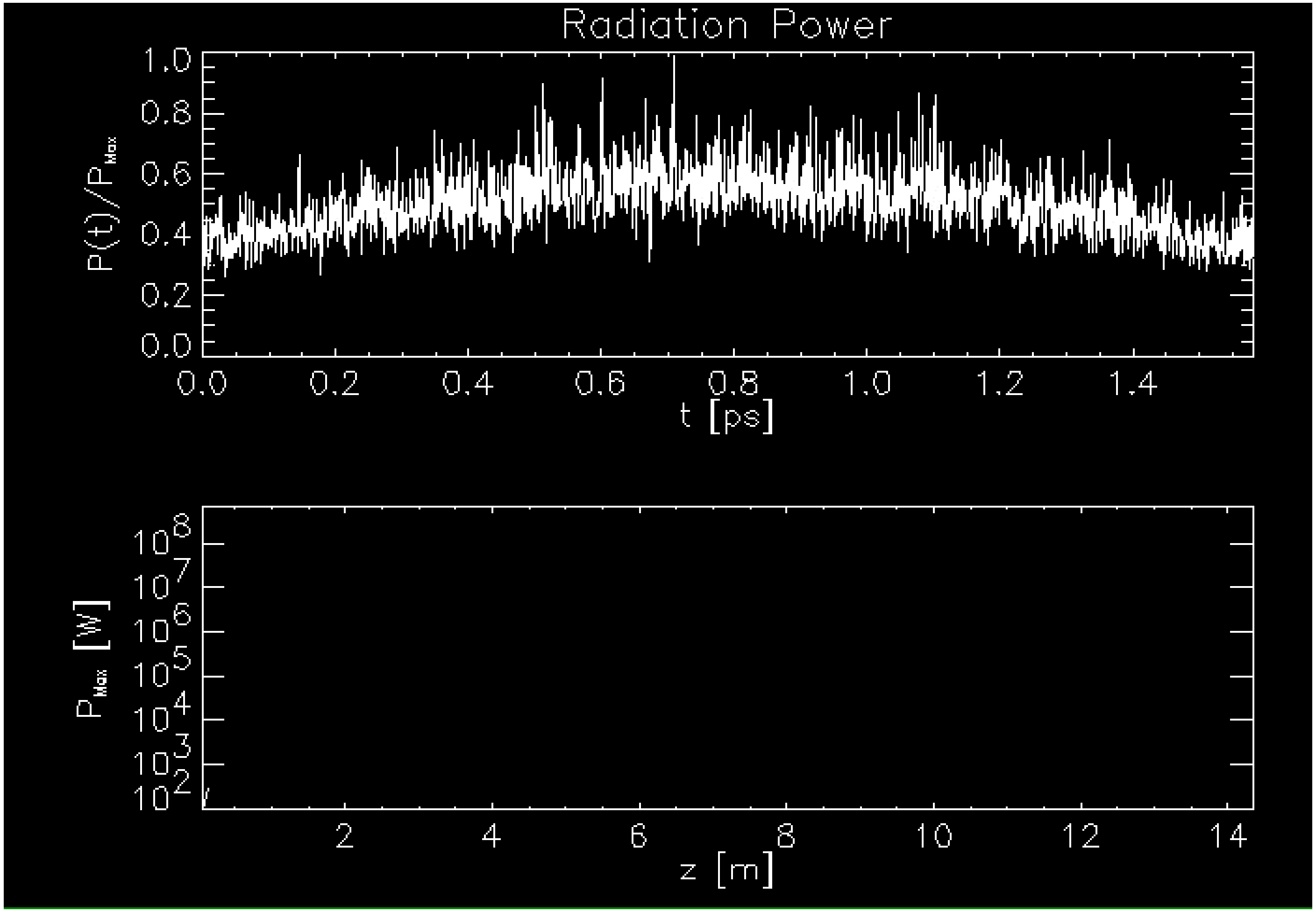




Cooperation Length: $L_c = ct_c$

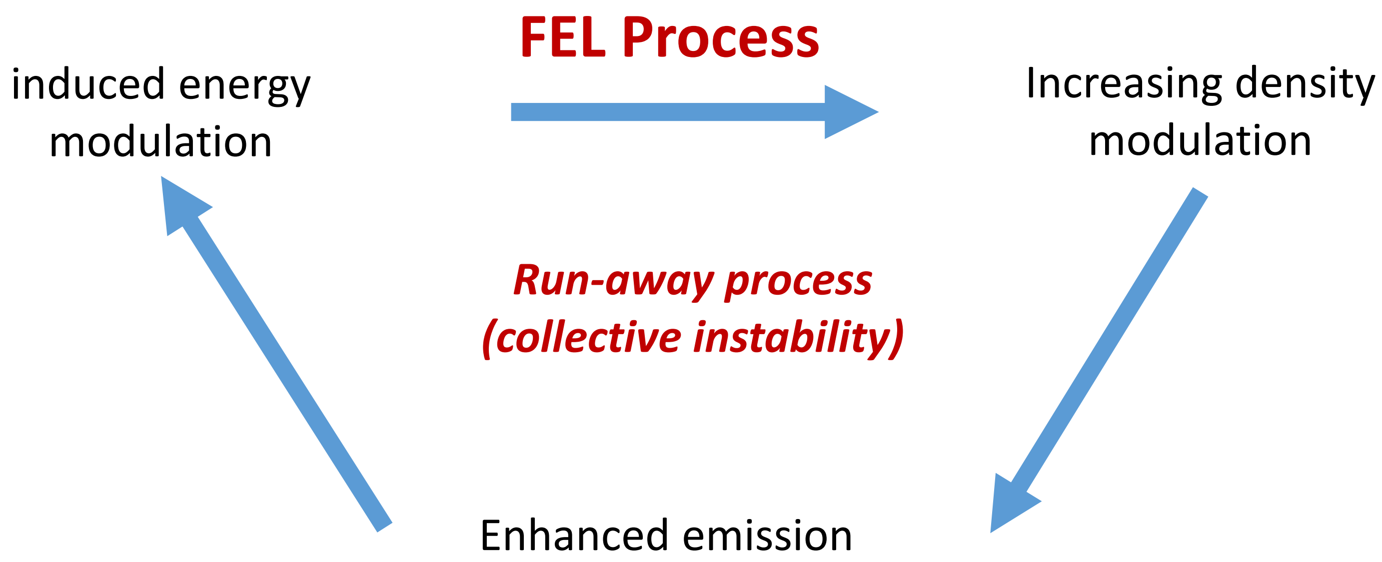
[E.Prat, PSI]

Typical Growth of SASE Pulse



Simulation for FLASH FEL

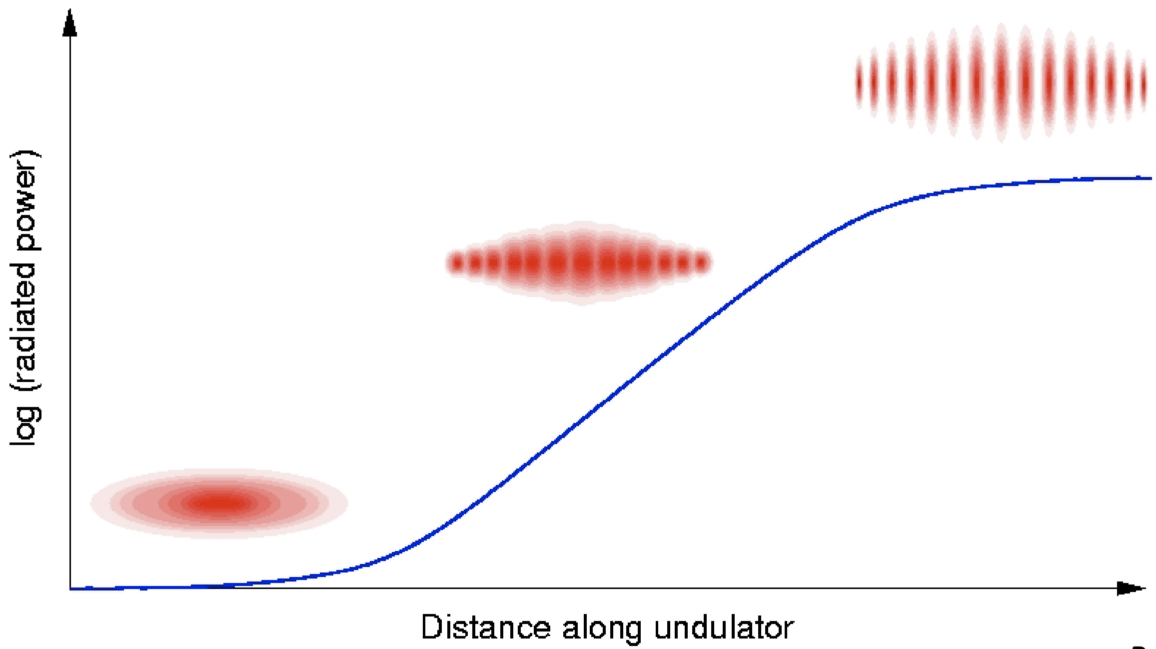
Summary of basic physics principles



FEL concept utilizes strong coherent emission in the collective instability, combined with the tuning ability of the wavelength.

$\rightarrow$ high density beam needed, low emittance, low energy spread

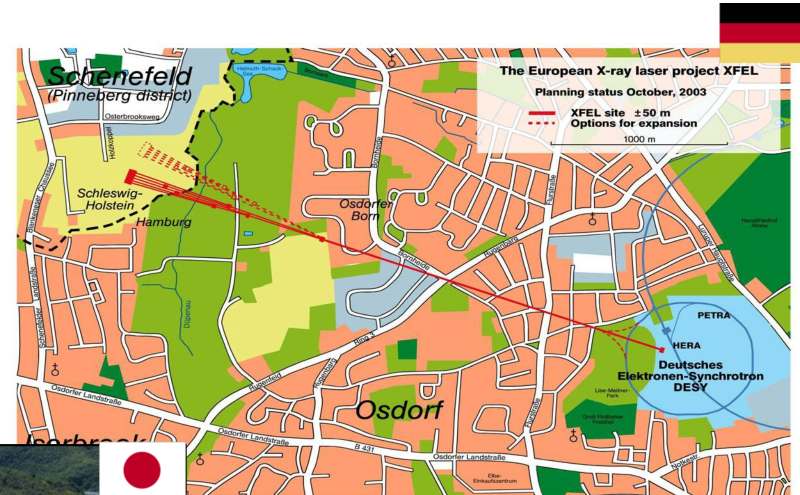
Self Amplified Spontaneous Emission (SASE)



P. Willmott
Intro to Synchr. Rad.

The World of XFELs

PAL XFEL 2016



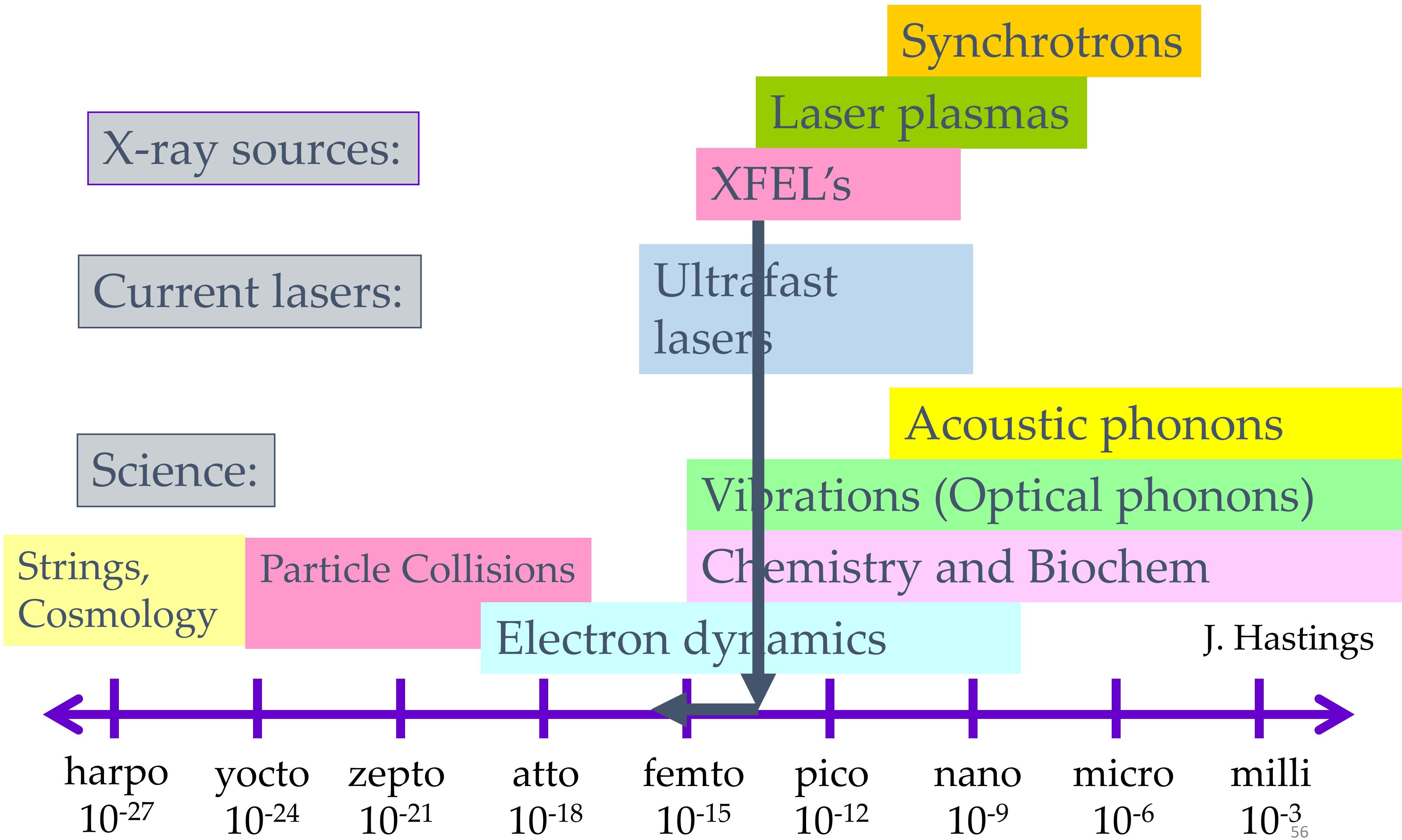
European XFEL
DESY, Hamburg 2017

SACLA 2011
8.5 GeV, 60 Hz NC

LCLS I, II 2009, 2019

SwissFEL 2017

Ultrafast Sources and Science

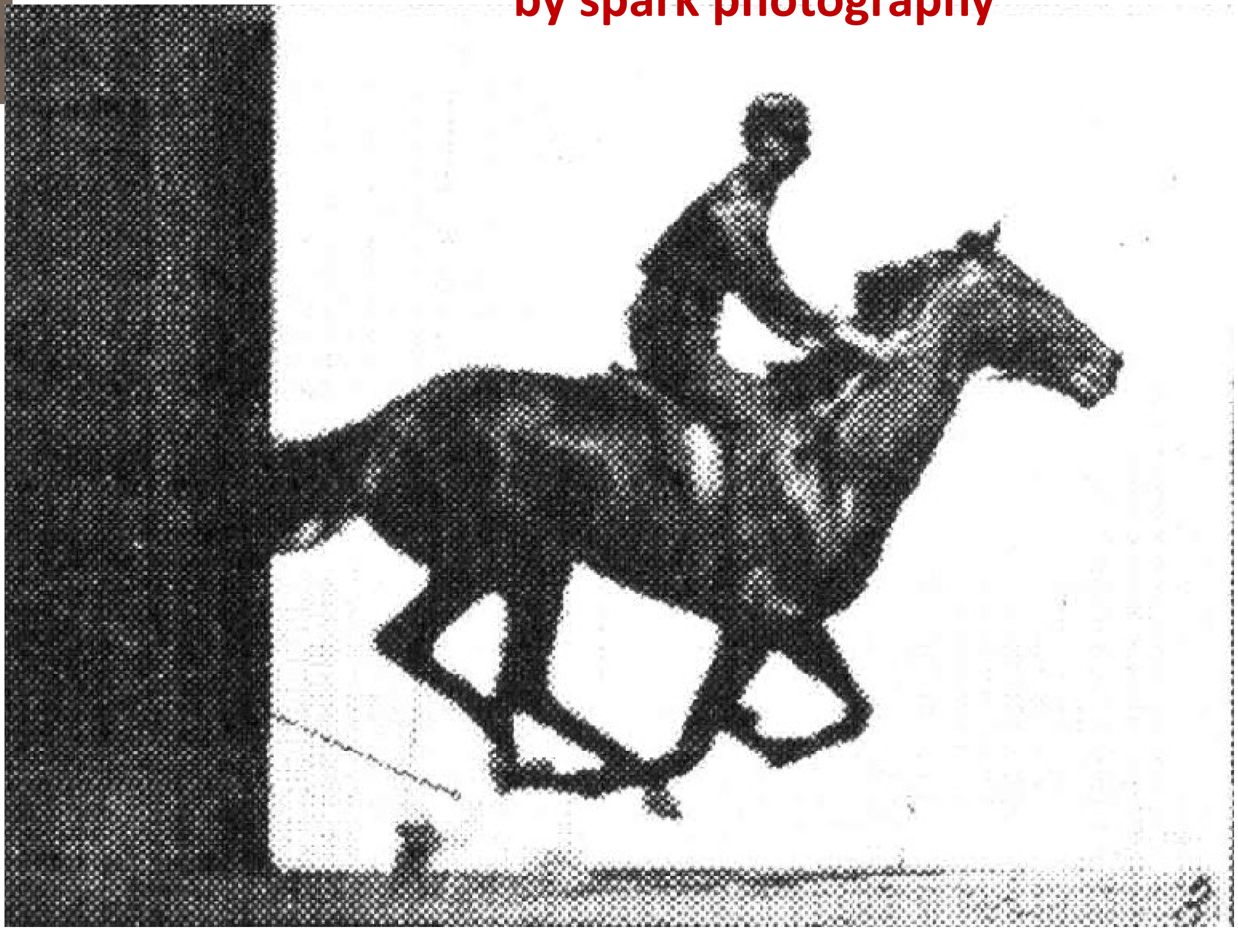


1878: E. Muybridge at Stanford

E. Muybridge

L. Stanford

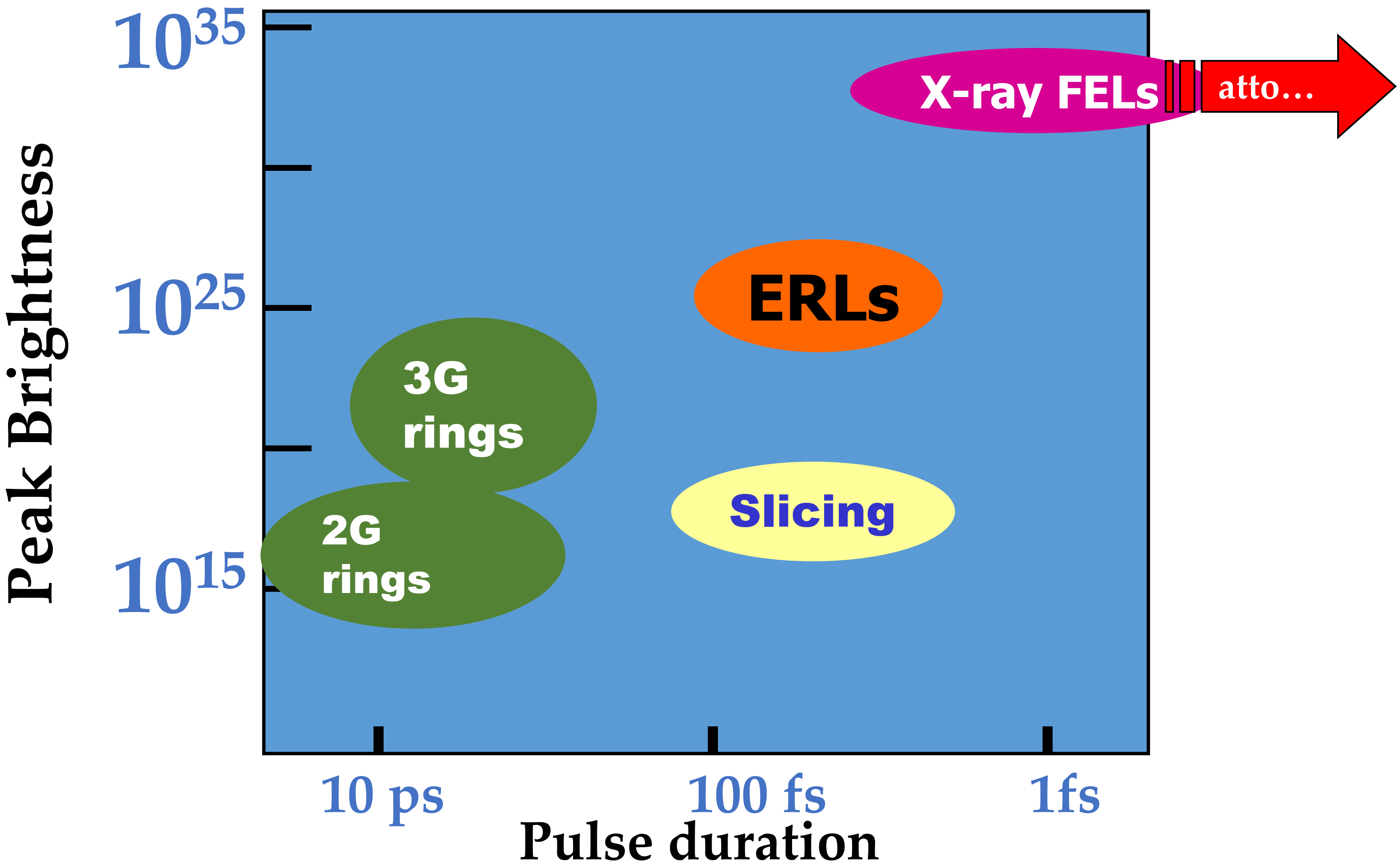
Tracing motion of animals by spark photography



Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

E. Muybridge, *Animals in Motion*, ed. by L. S. Brown (Dover Pub. Co., New York 1957).

FELs and ERLs COMPLEMENT the Ring sources



H.-D. Nuhn, H. Winick

Light Sources

- **Synchrotron Light Sources** and **Free Electron Lasers** are established tools for a broad range of basic research
- Advancements in ring dynamics have lead to a 10^8 increase in brightness since the first use of storage ring radiation; **improvement of brightness** via beam emittance, undulators, matching is a continuing research activity for rings
- Free Electron Lasers allow even brighter radiation pulses and offer in addition **extreme time resolution** down to ≈100 Attoseconds; advanced FEL dynamics is a hot topic for accelerator R&D

Appendix: The FEL Parameter ρ

- FEL parameter ρ.   Typical values= $10^{-4} - 10^{-2}$

$$\rho = \frac{1}{\gamma}\left[\left(\frac{f_c K}{4 k_u \sigma_x}\right)^2 \frac{I}{2 I_A}\right]^{1/3}$$

K: undulator strength parameter
f_c: coupling factor (~0.9 for planar undulator)
I: electron peak current
σ_x: transverse beam size
I_A: Alfven current (≈17 kA)
$k_u = 2\pi/\lambda_u$: k of undulator period

- Scaling of 1D theory

Gain length

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\,\rho}$$

Efficiency

$$P_{\mathrm{FEL}} \approx \rho P_{\mathrm{beam}}$$

SASE Spike Length

$$L_c = \frac{\lambda}{4\pi\rho}$$

Bandwidth

$$\frac{\Delta\omega}{\omega} = 2\rho$$

Wiedemann, 27.2.1