High brightness photon and electron beams, Applications

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Instruments needed for human exploration

Galileo Galilei

400 years of discoveries

with «telescopes»
«microscopes»

Zacharias Janssen

20 Nobels with X-rays

Chemistry

1936: Peter Debye

1962: Max Purutz and Sir John Kendrew

1976 William Lipscomb

1985 Herbert Hauptman and Jerome Karle

1988 Johann Deisenhofer, Robert Huber and Hartmut Michel

1997 Paul D. Boyer and John E. Walker

2003 Peter Agre and Roderick Mackinnon

2009 V. Ramakrishnan, Th. A. Steitz, A. E. Yonath

2012 Robert J. Lefkowitz and Brian K. Kobilka

Physics

1901 Wilhem Rontgen

1914 Max von Laue

1915 Sir William Bragg and son

1917 Charles Barkla

1924 Karl Siegbahn

1927 Arthur Compton

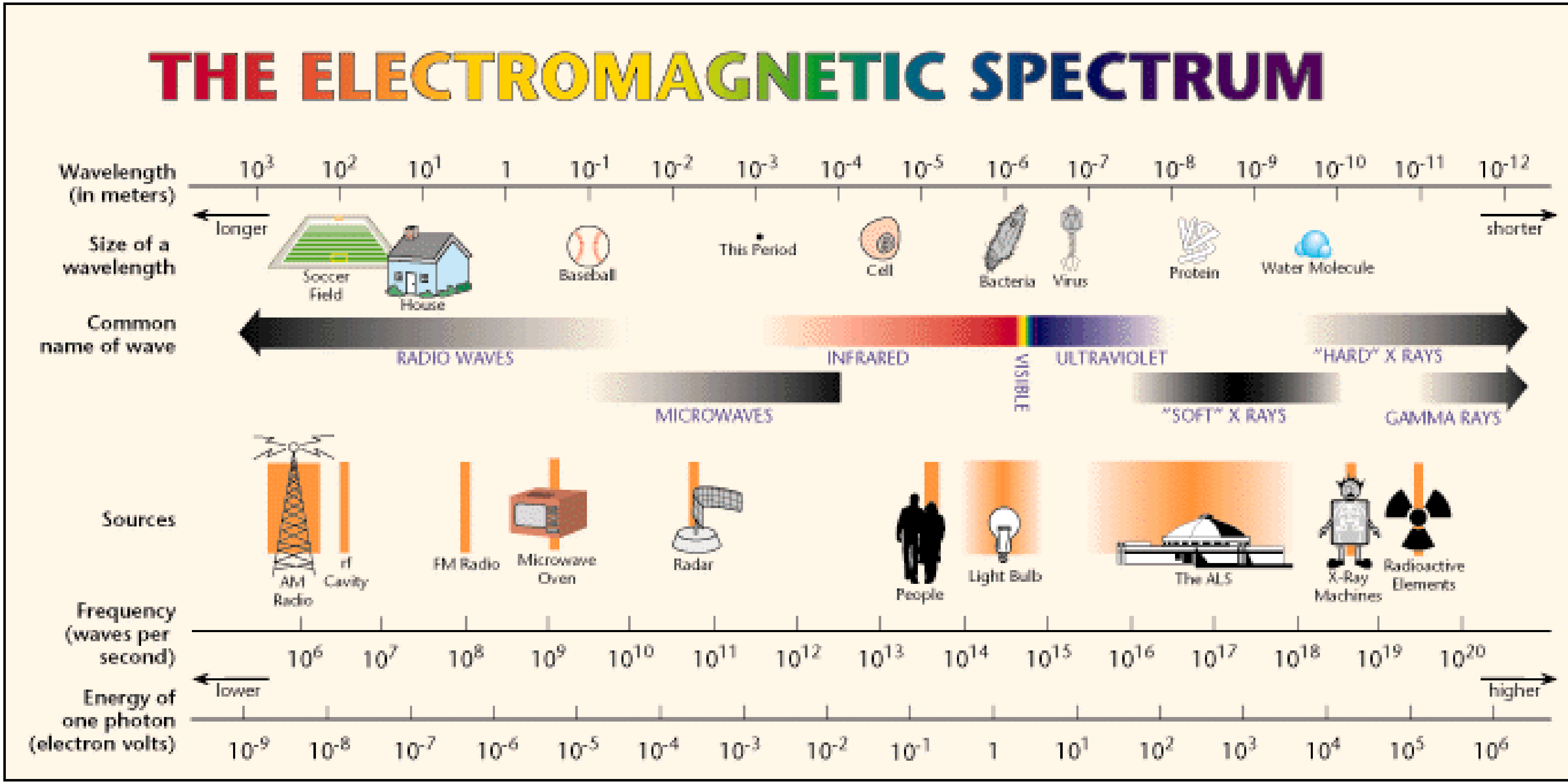
1981 Kai Siegbahn

Medicine

1946 Hermann Muller

1962 Frances Crick, James Watson and Maurice Wilkins

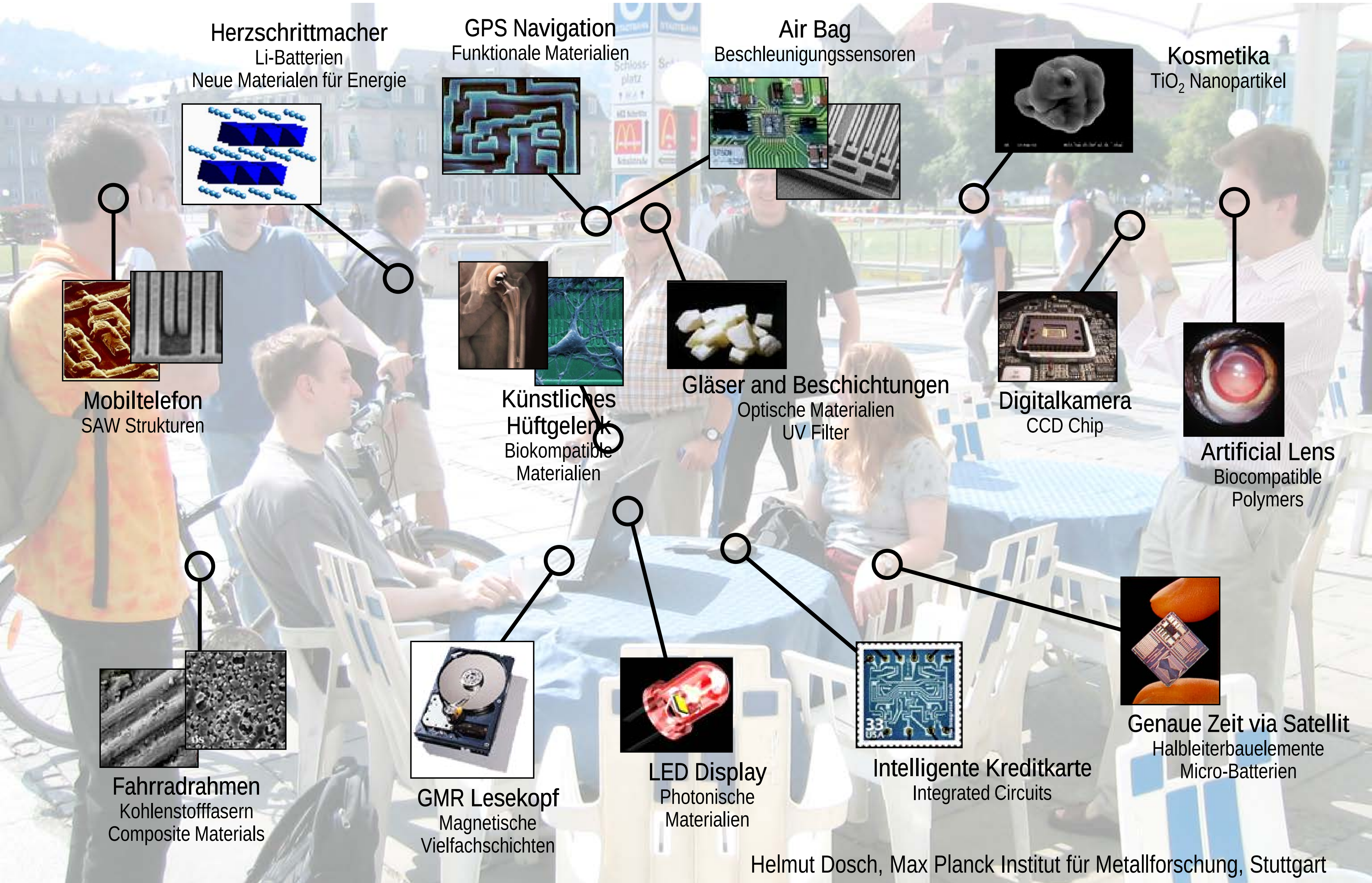
1979 Alan Cormack and Godfrey Hounsfield

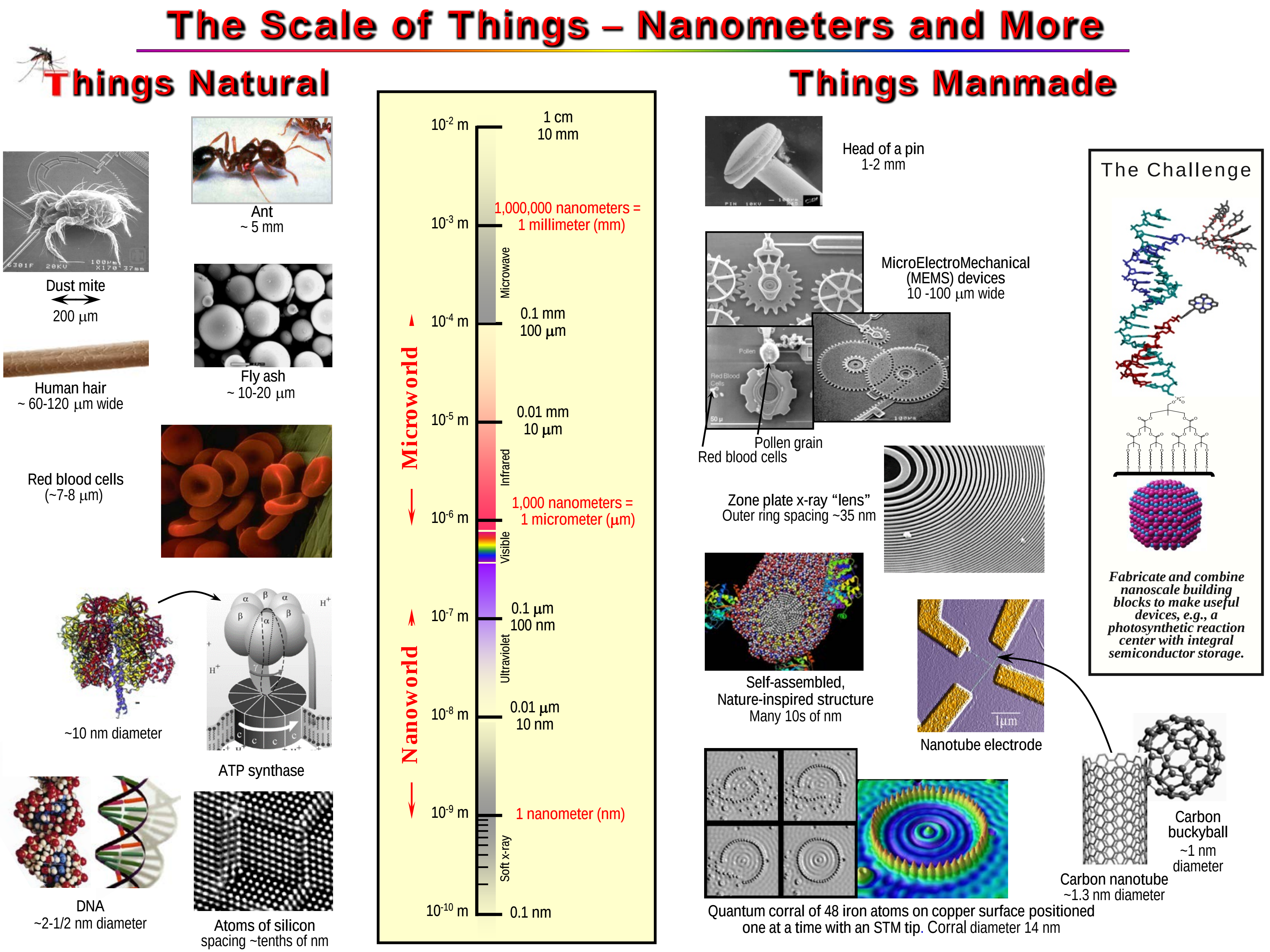


Wavelength continuously tunable !

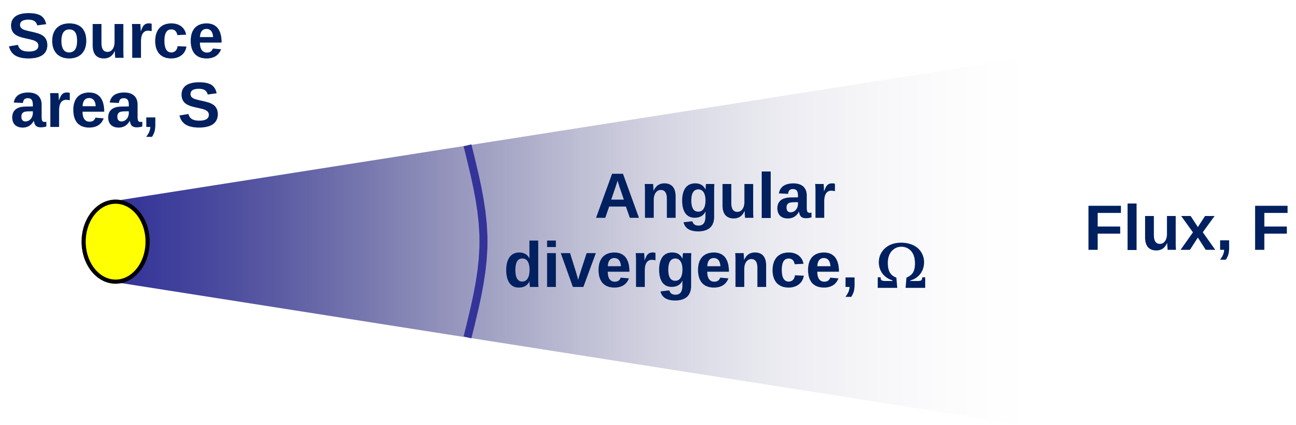
Materials – key to our technologies

Materials – key to our technologies




The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Ant
~ 5 mm
Dust mite
200 µm
Human hair
~ 60-120 µm wide
Fly ash
~ 10-20 µm
Red blood cells
(~7-8 µm)
~10 nm diameter
ATP synthase
DNA
~2-1/2 nm diameter
Atoms of silicon
spacing ~tenths of nm
10-2 m
1 cm
10 mm
10-3 m
1,000,000 nanometers =
1 millimeter (mm)
Microwave
10-4 m
0.1 mm
100 µm
10-5 m
0.01 mm
10 µm
Infrared
Microworld
10-6 m
1,000 nanometers =
1 micrometer (µm)
Visible
10-7 m
0.1 µm
100 nm
Ultraviolet
10-8 m
0.01 µm
10 nm
Nanoworld
10-9 m
1 nanometer (nm)
Soft x-ray
10-10 m
0.1 nm
Head of a pin
1-2 mm
MicroElectroMechanical
(MEMS) devices
10 -100 µm wide
Pollen grain
Red blood cells
Zone plate x-ray "lens"
Outer ring spacing ~35 nm
Self-assembled,
Nature-inspired structure
Many 10s of nm
Nanotube electrode
1µm
Carbon buckyball
~1 nm diameter
Carbon nanotube
~1.3 nm diameter
Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip. Corral diameter 14 nm
The Challenge
Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.

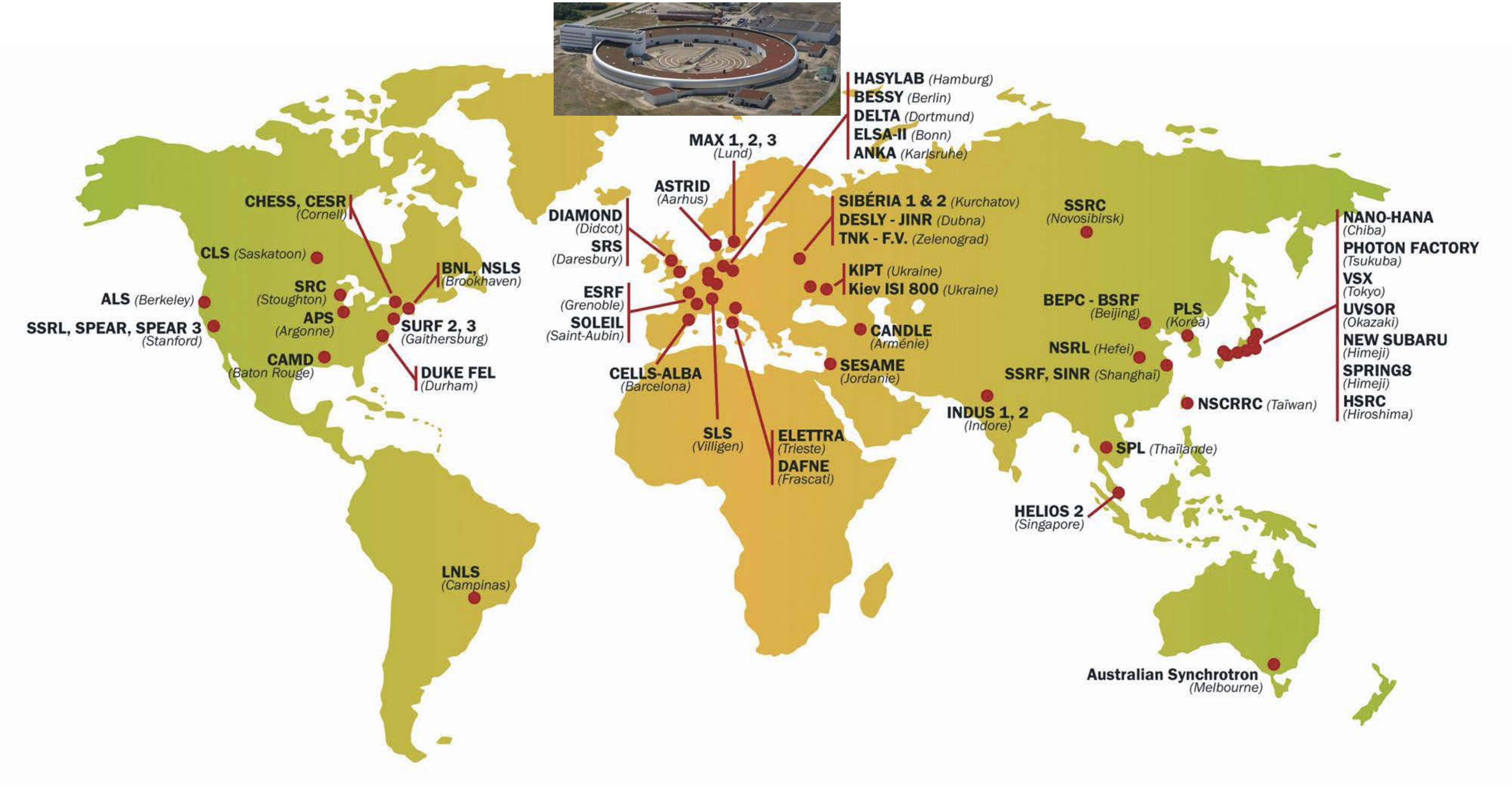
The "brightness" of a light source:



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

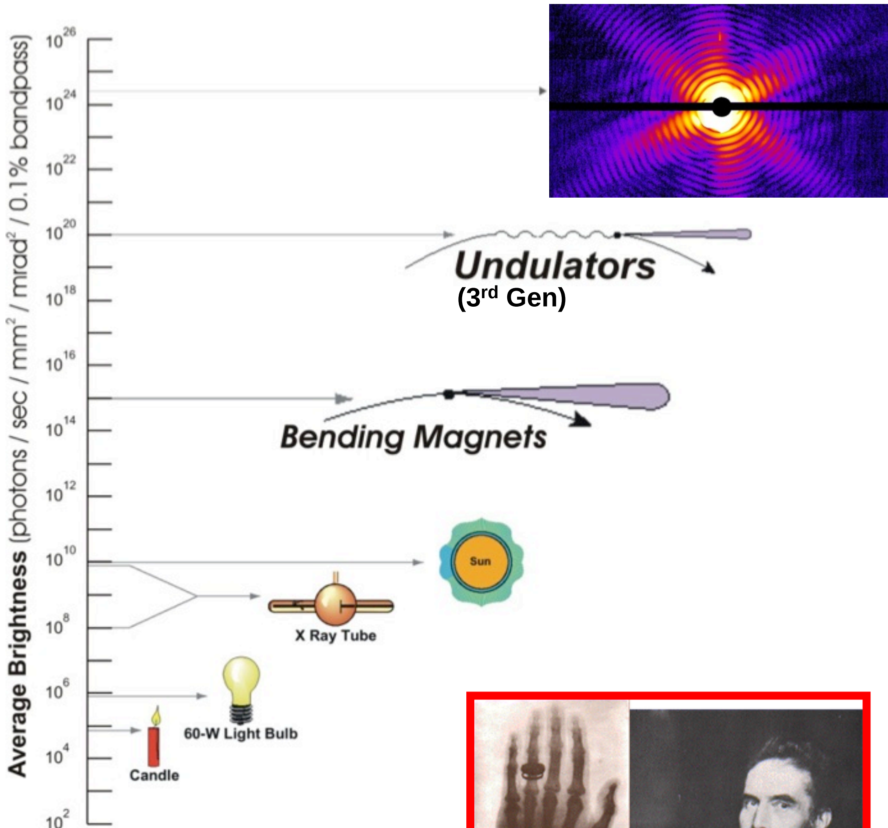
Light sources: > 50 producing synchrotron light

60‘000 users world–wide



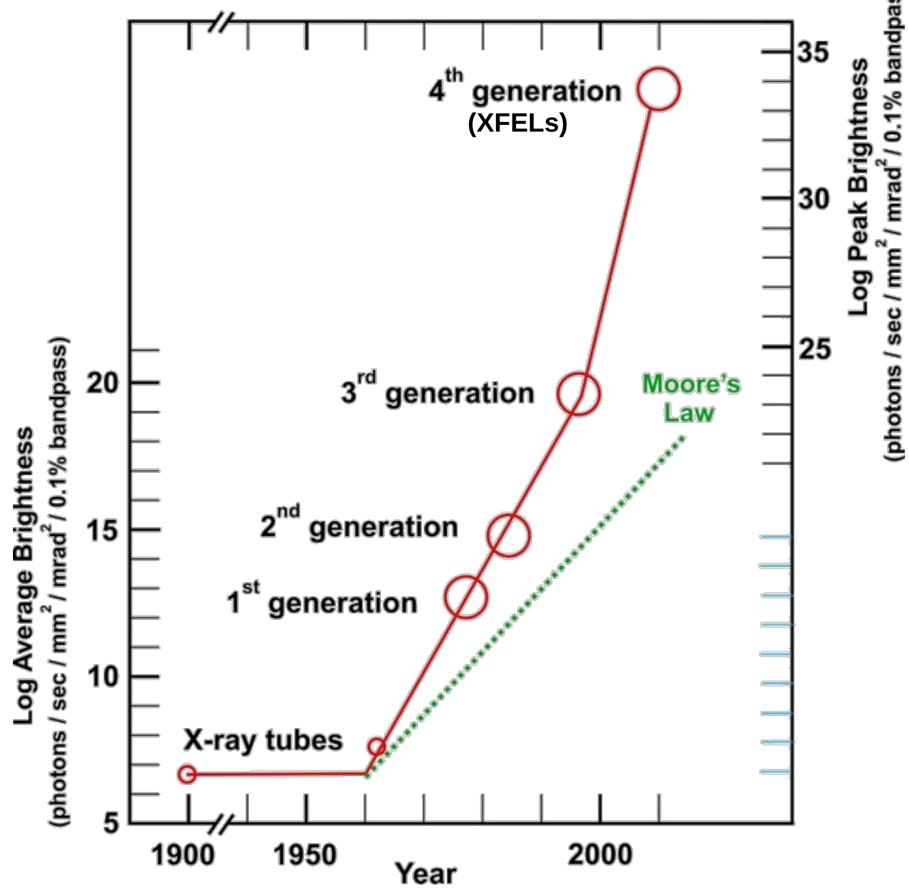
X-rays Brightness

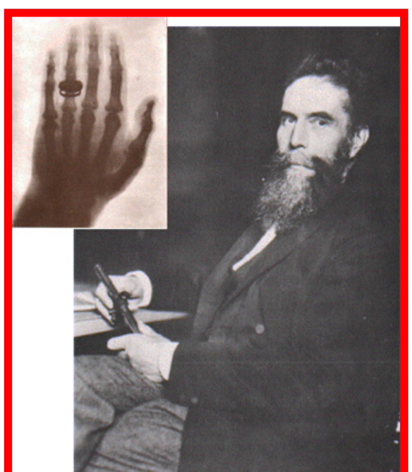
Average Brightness



XFELs

Peak Brightness



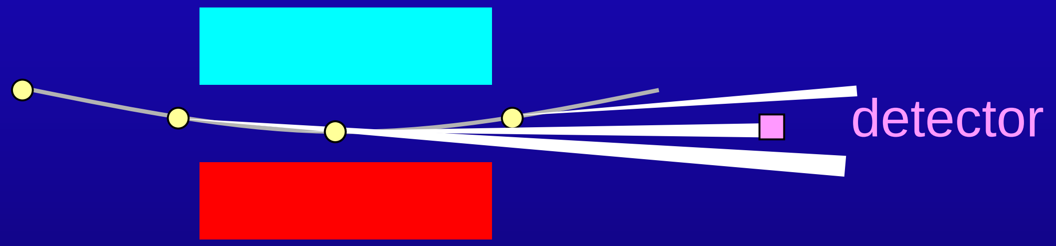


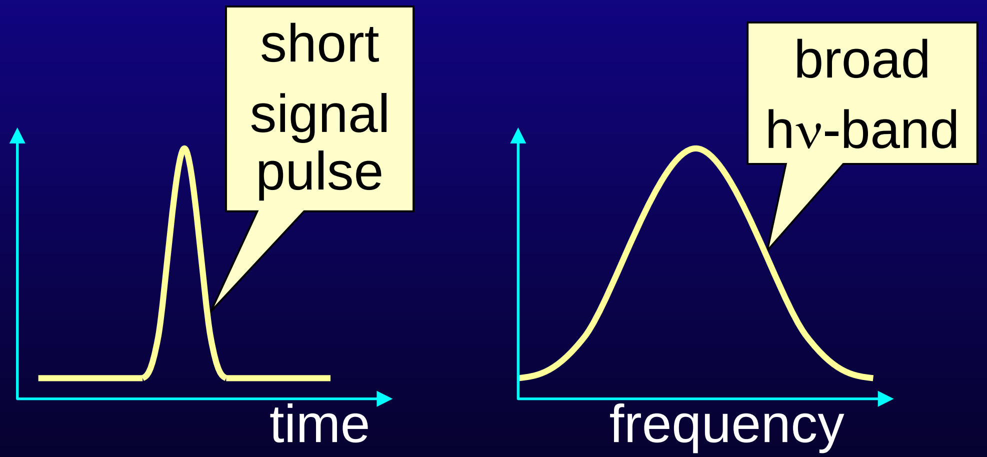
Bertha Roentgen's hand
(exposure: 20 min)

Sources of Synchrotron Radiation

3 types of storage ring sources:

1. Bending magnets: $B \sim N_e$

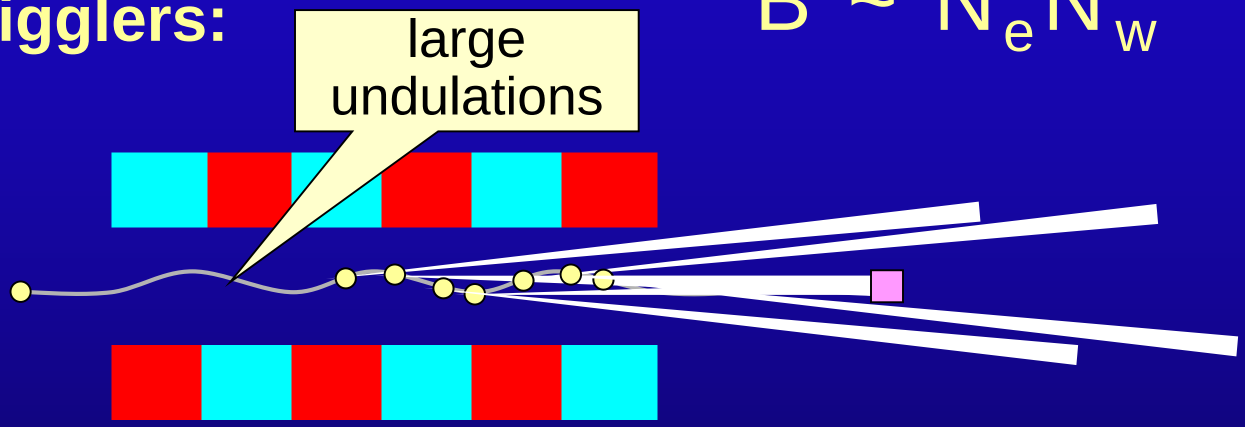


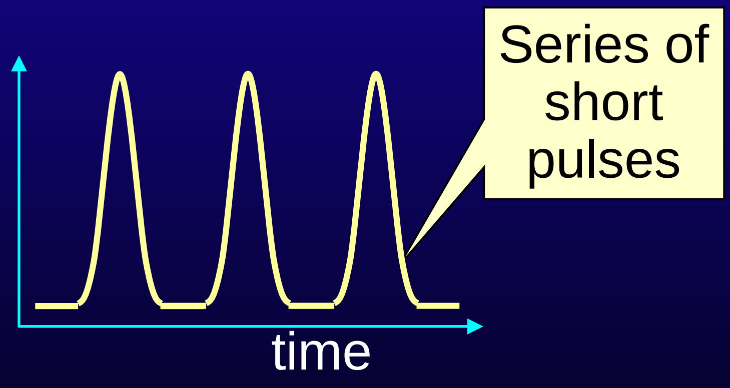


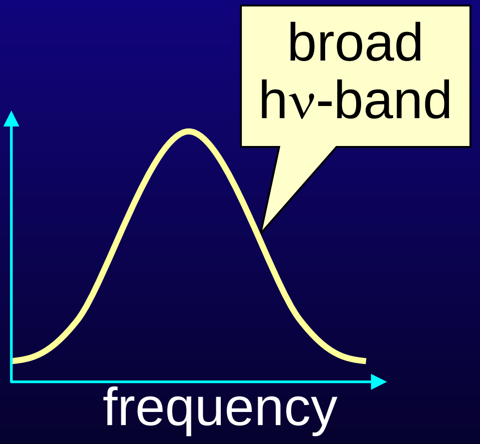
3 types of storage ring sources:

2. Wigglers:

$B \sim N_e N_w$ x10

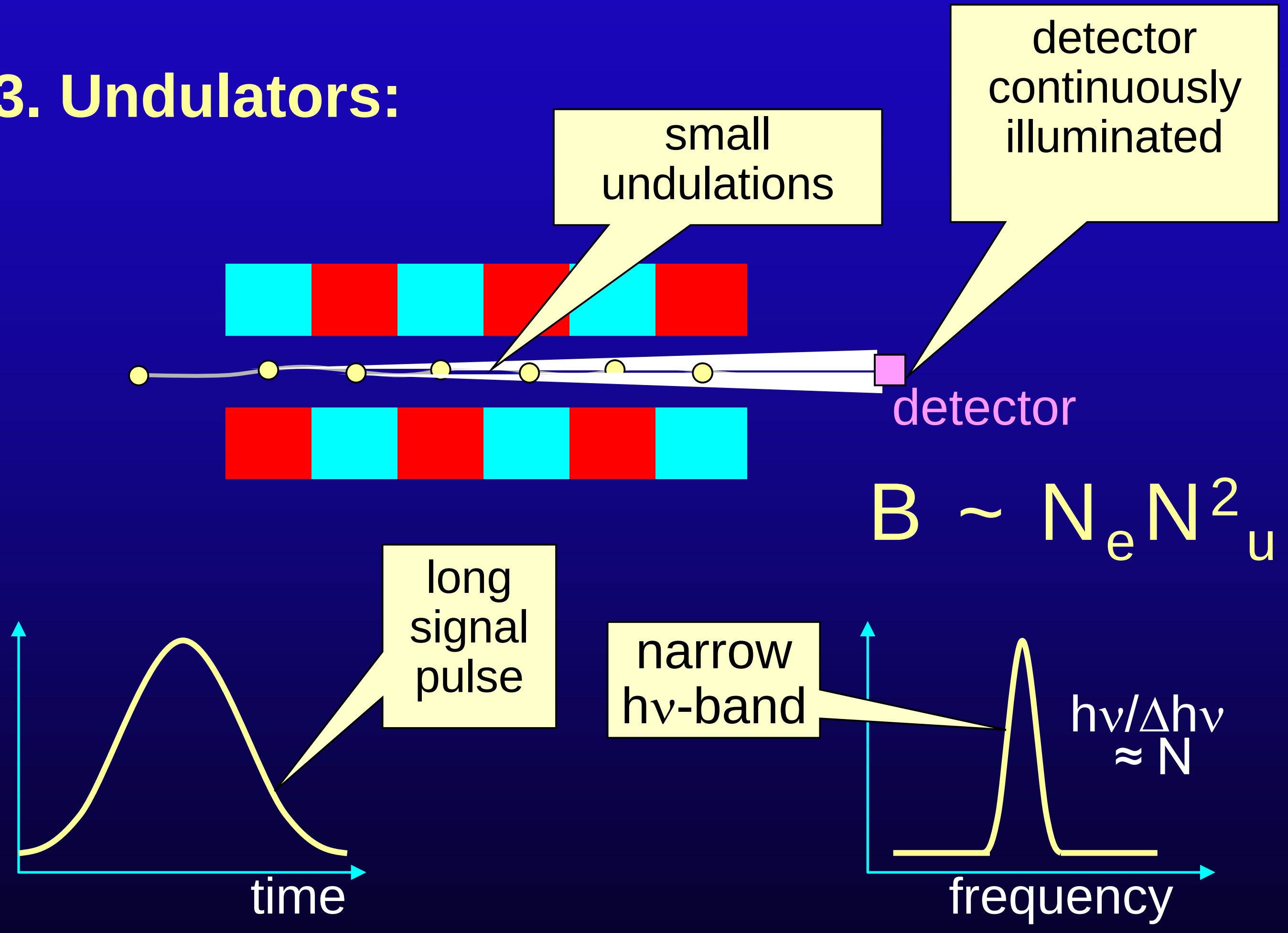






3 types of storage ring sources:

3. Undulators:



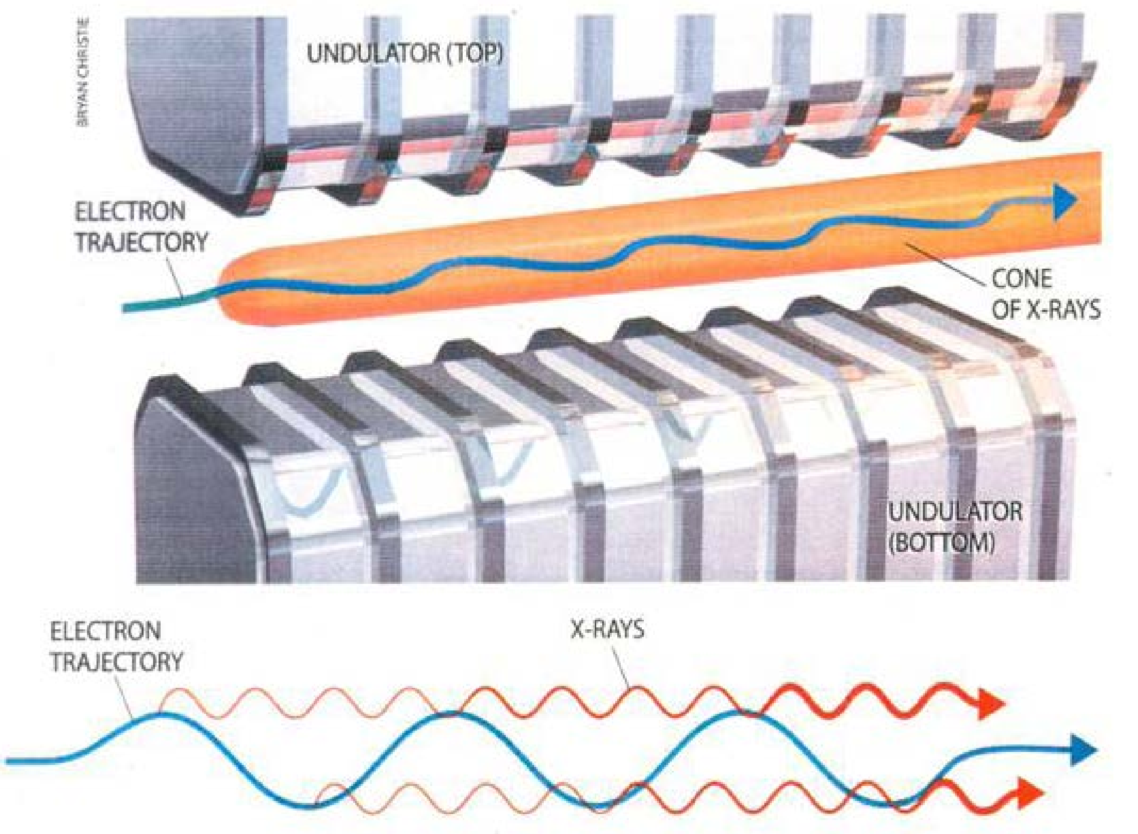
$$B \sim N_e N^2_u \quad \times 10^3$$

Bright beams of particles: phase space density

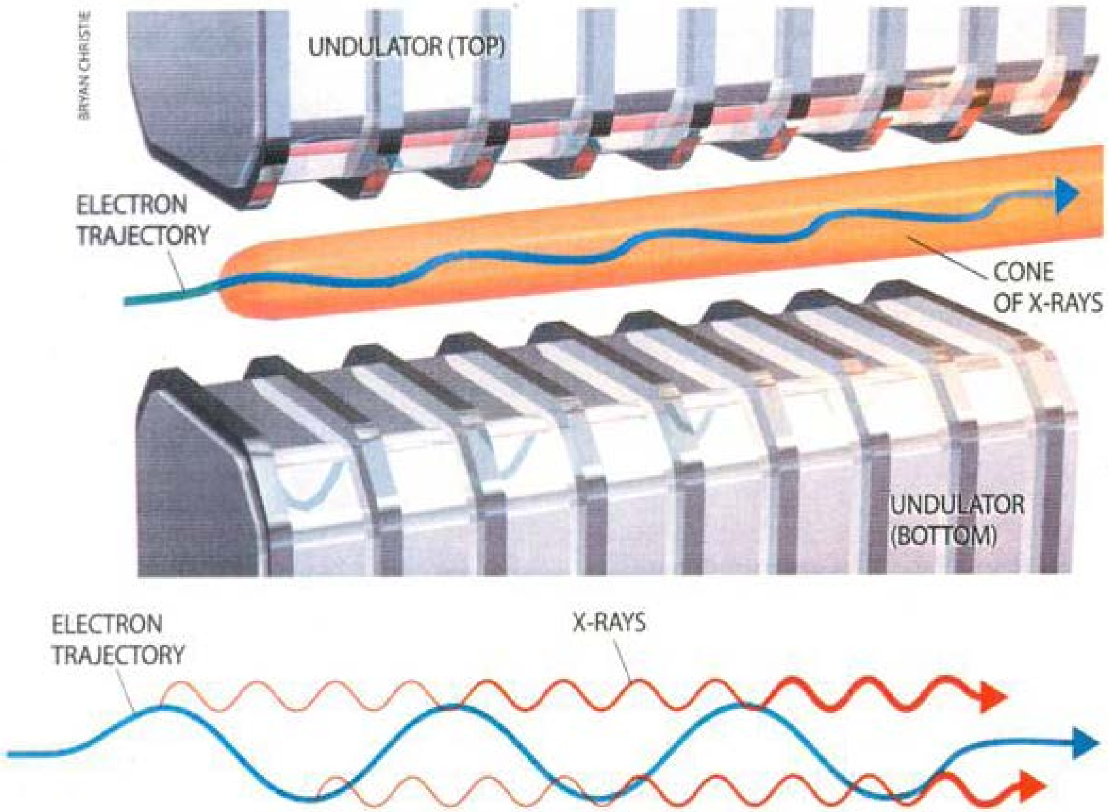
Incoherent, spontaneous emission of light:

Large phase space

Coherent, stimulated emission of light



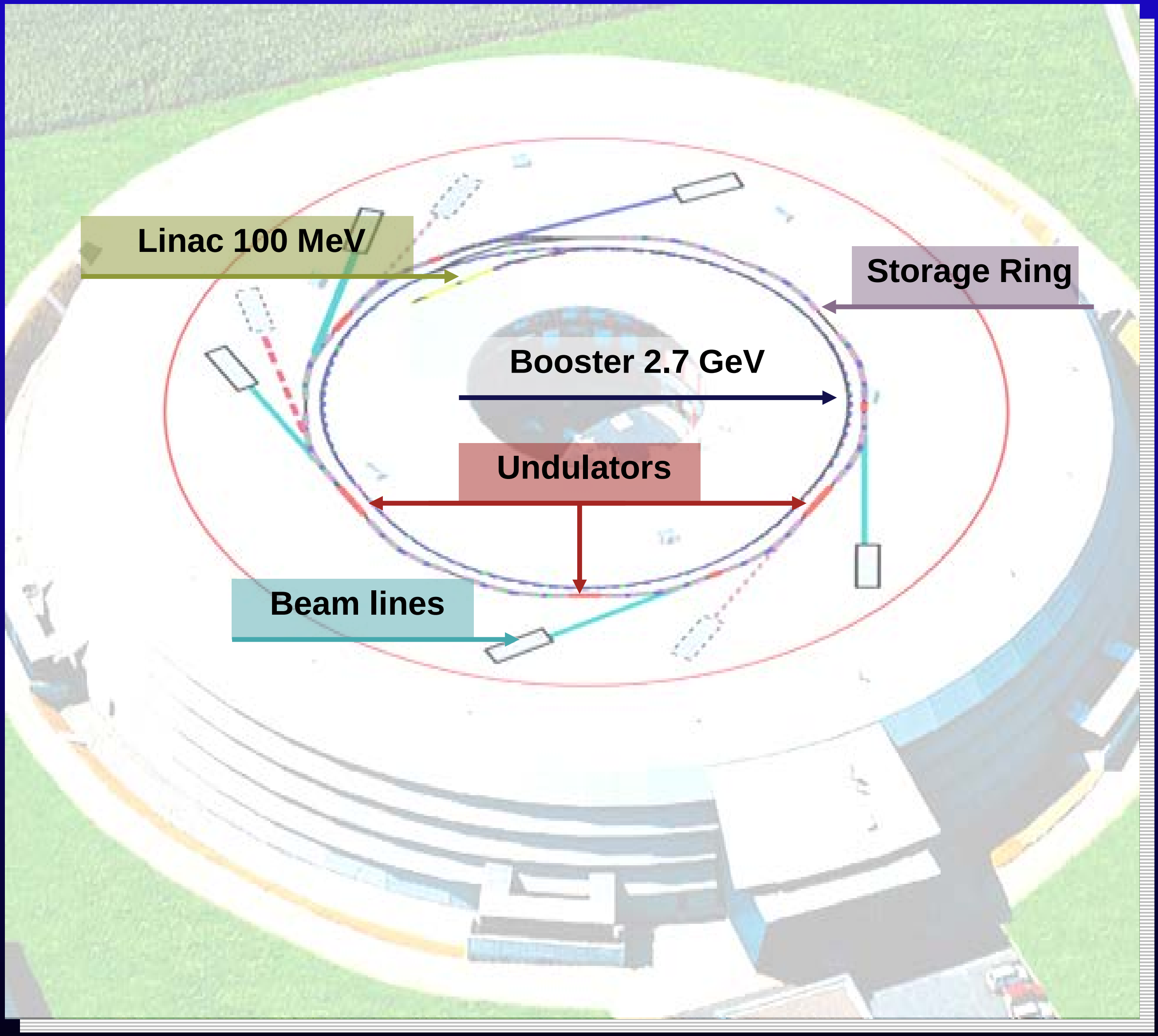
Undulators



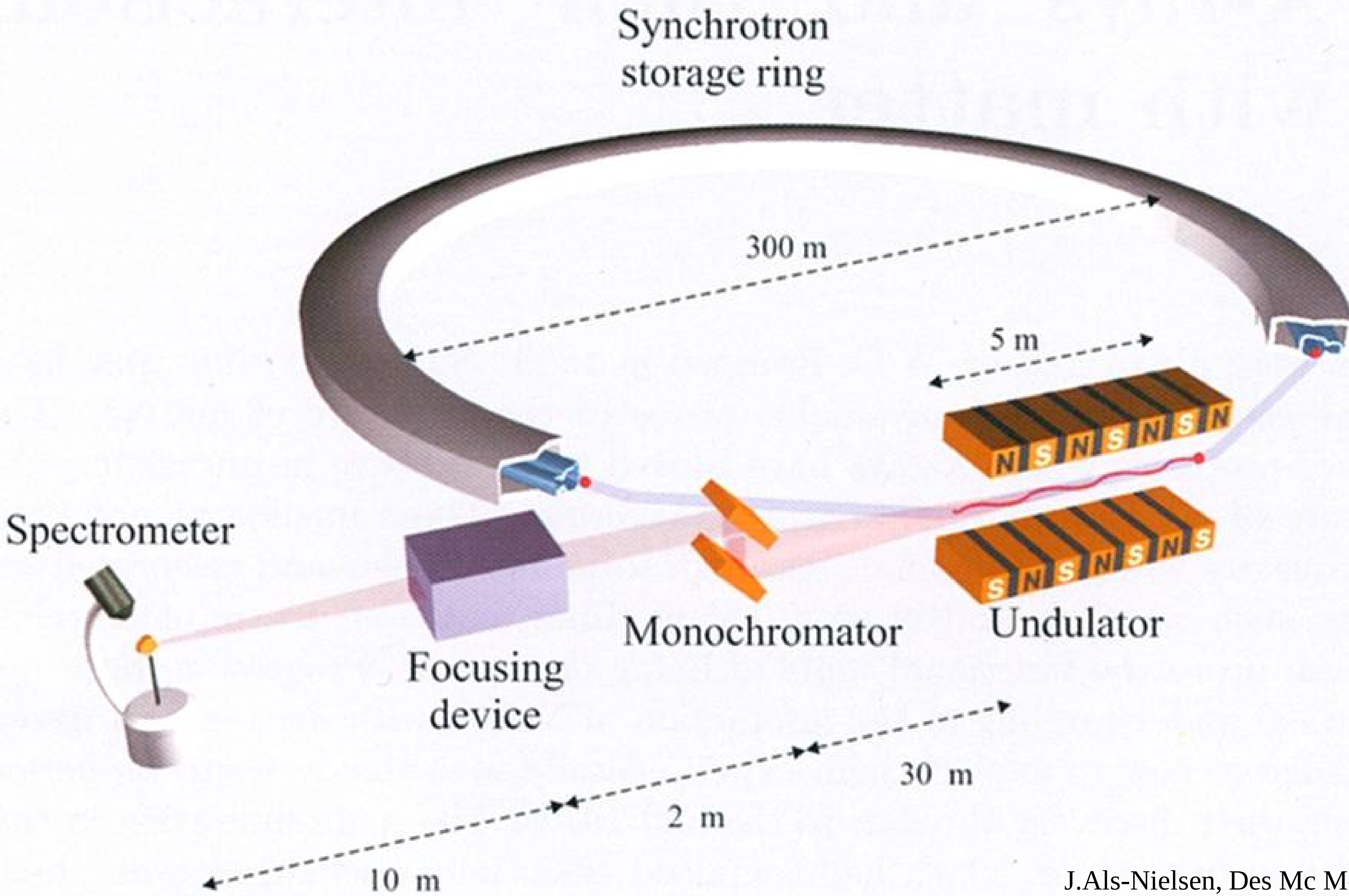
$$T_{obs} = T_{emit}(1 - \beta)$$

$$\lambda_{light} \approx \frac{\lambda_u}{2\gamma^2}$$

Anatomy of a light source

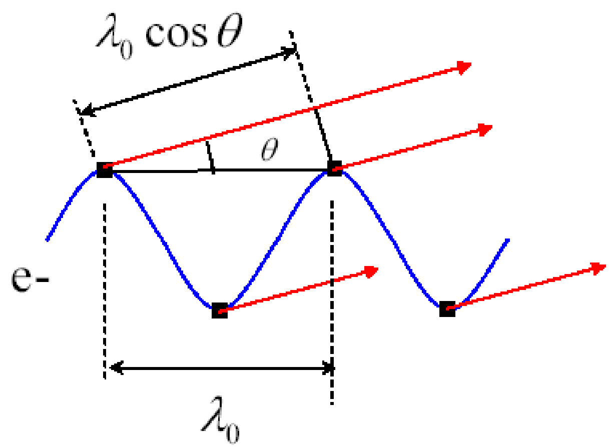


Undulator based beamline

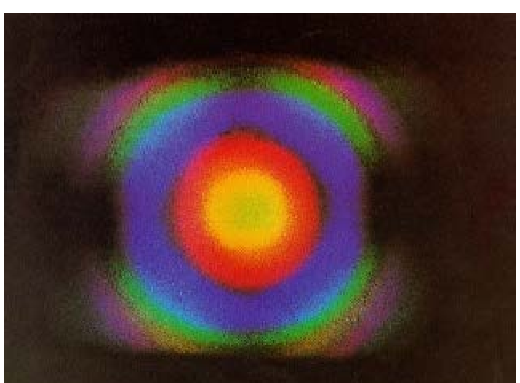


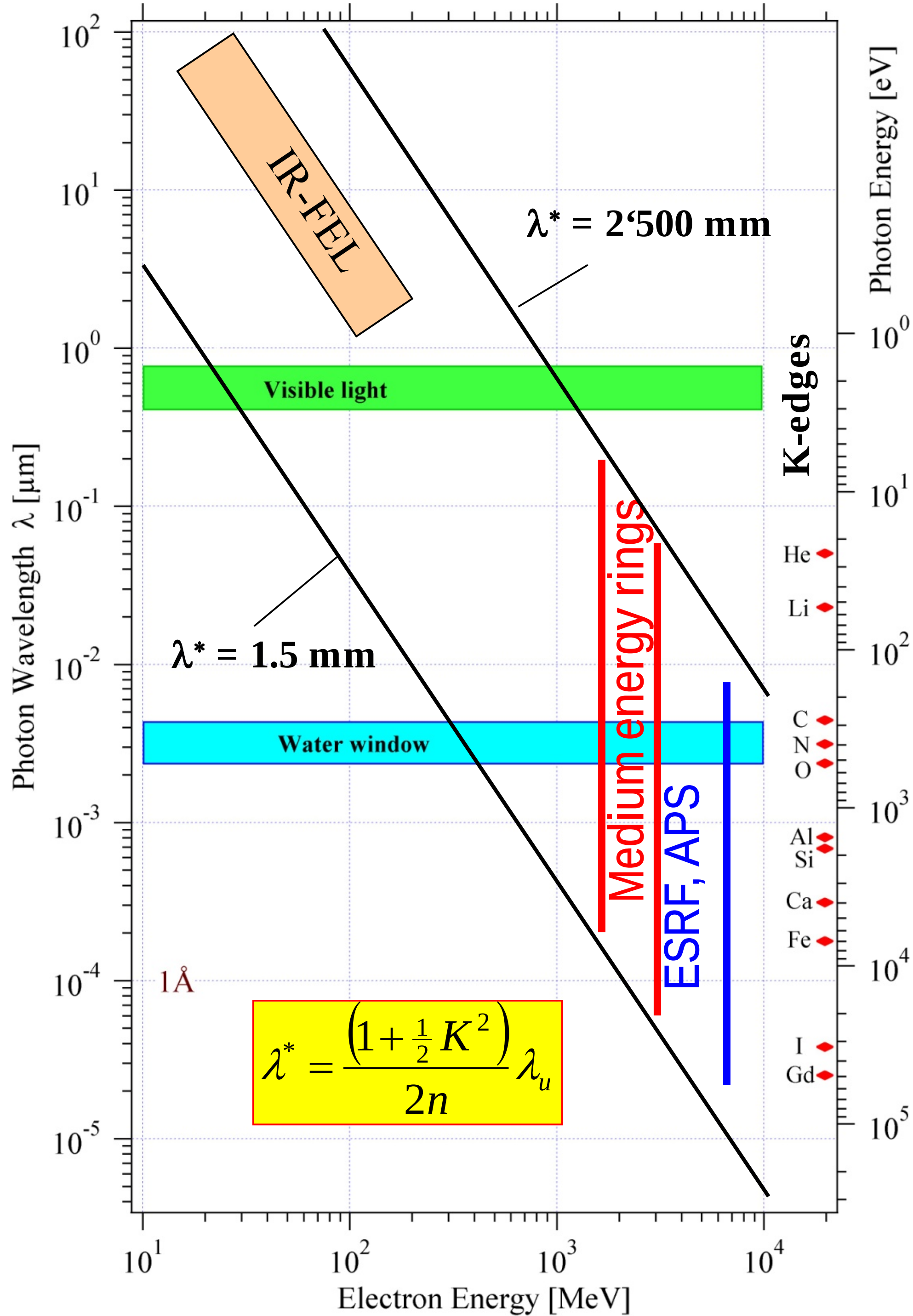
J.Als-Nielsen, Des Mc Morrow

Undulator radiation

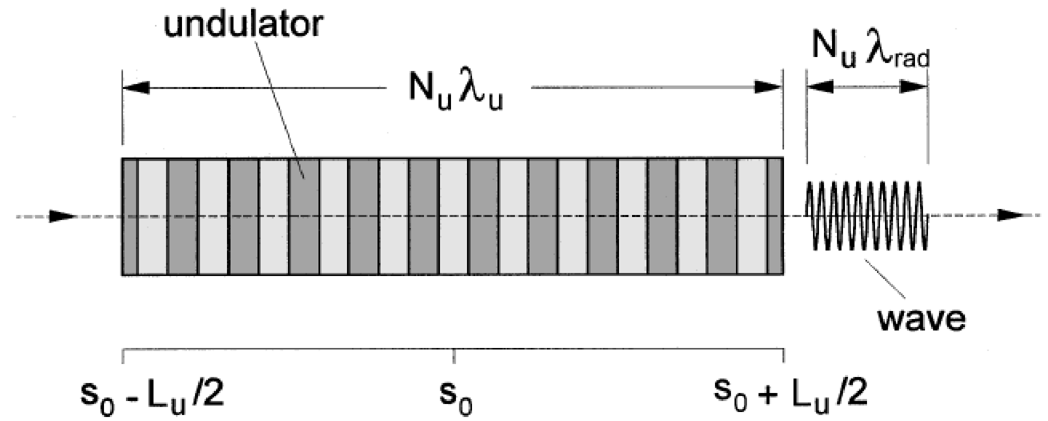


$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$





Undulator line width



Undulator of infinite length

$$N_u = \infty \quad \Rightarrow \quad \frac{\Delta\lambda}{\lambda} = 0$$

Finite length undulator

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

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

Due to the electron energy spread

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

Particle beam emittance:

Emittance = S x Ω

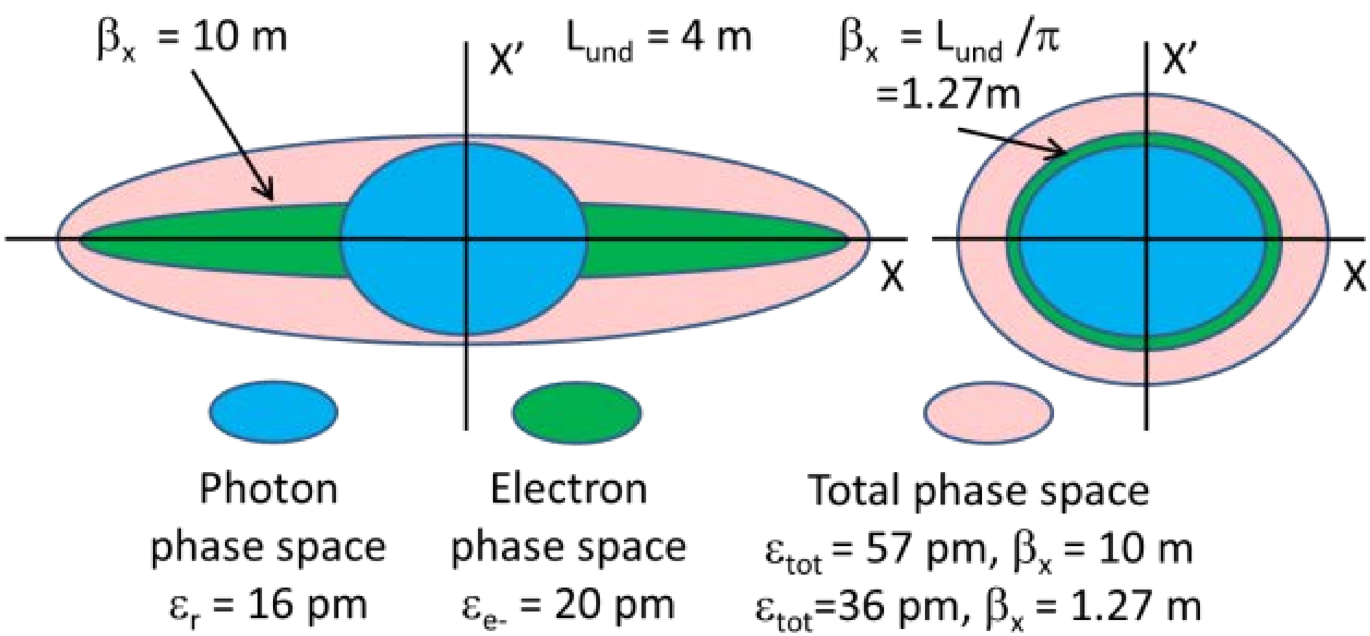
X-ray emittance from electron source: a convolution of electron and photon phase space

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

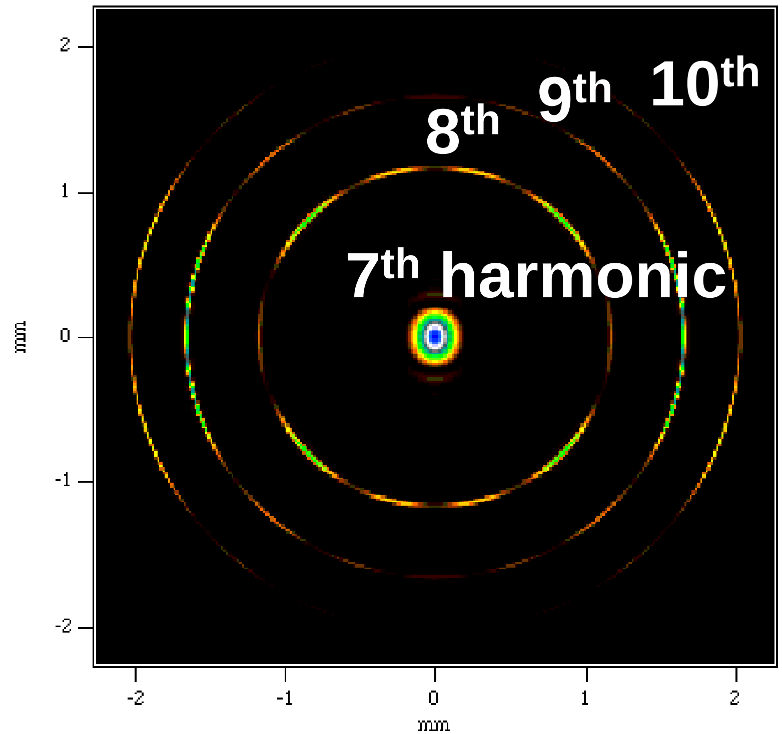
$$\text{Brightness} = \frac{\Phi}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

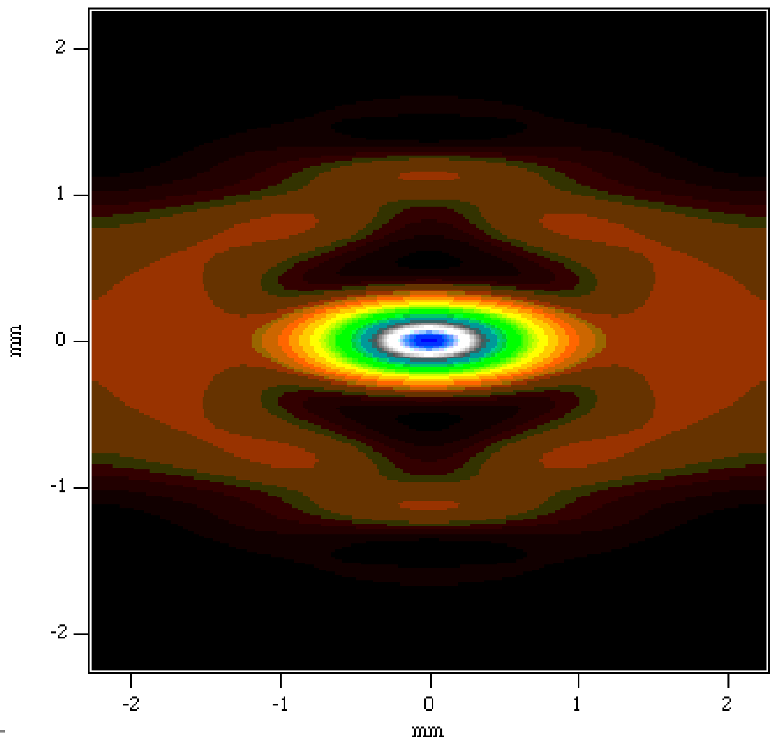
$$\sigma_\gamma' = \sqrt{\frac{\lambda}{L}}$$

$$\sigma_\gamma = \frac{\sqrt{\lambda L}}{4\pi}$$



Undulator radiation from 6 GeV beam with zero emittance, energy spread (example ESRF)





Emittance 4 nm·rad, 1% coupling, finite energy spread

Small emittance lattices

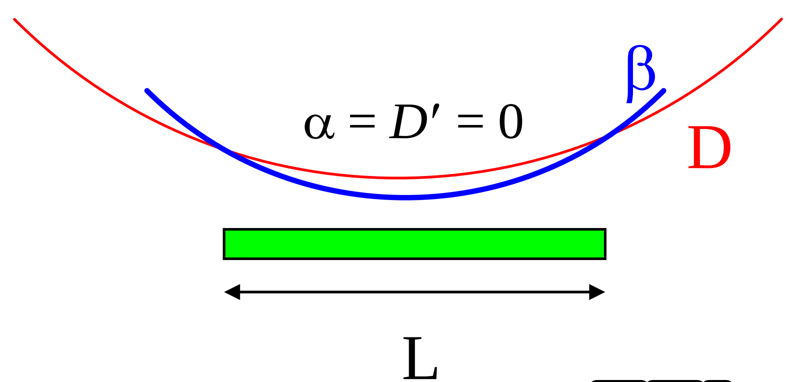
Equilibrium horizontal emittance

$$\varepsilon_{x0} \equiv \frac{\sigma_{x\beta}^2}{\beta} = \frac{C_q E^2}{J_x} \cdot \frac{\langle \mathcal{H} \rangle_{mag}}{\rho}$$

- one tries to optimize the $\mathcal{H}$ function in **bending magnets**
- the equilibriun $\mathcal{H} = \gamma D^2 + 2\alpha D D' + \beta D'^2$ ritten as:

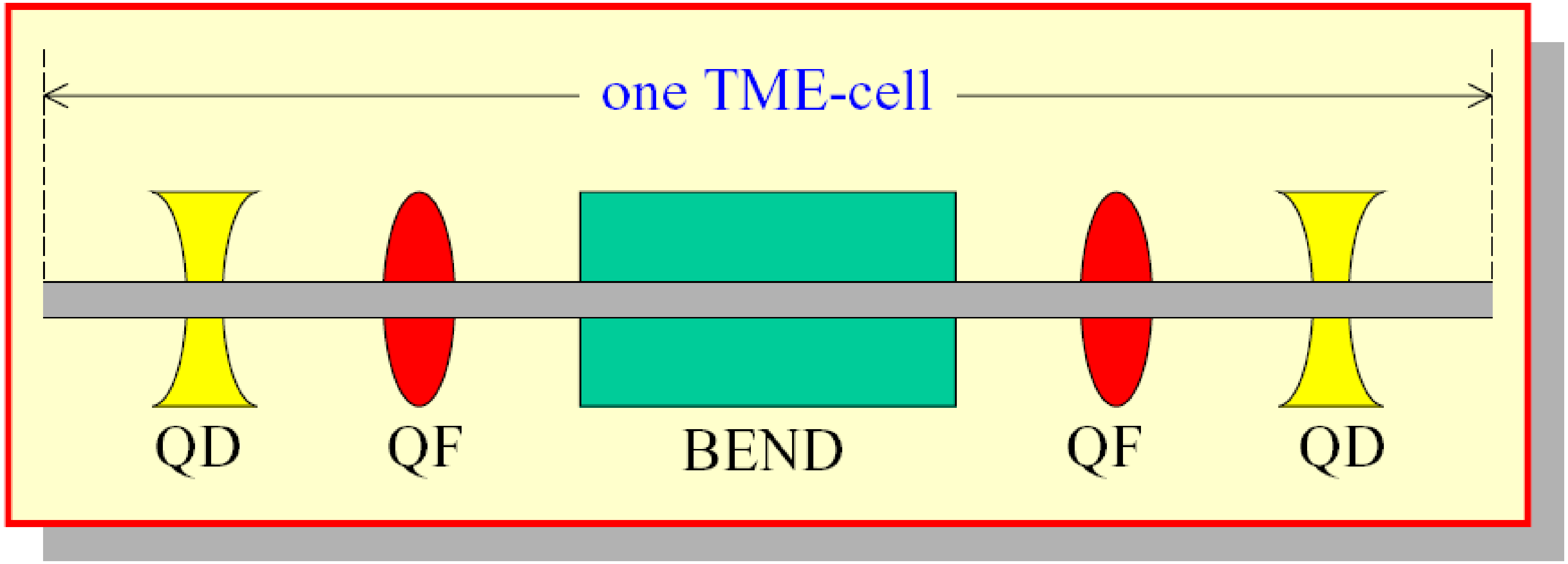
th $$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot \mathbf{F_{latt}}$$

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

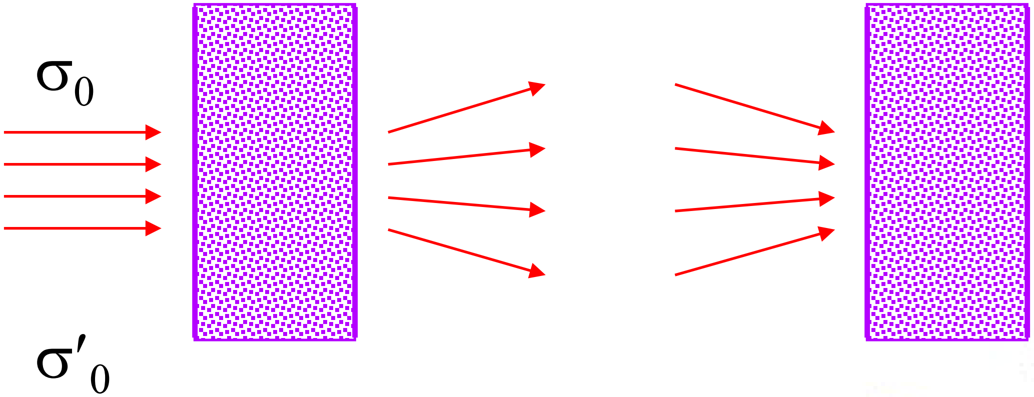


$$\beta^* = \frac{L}{2\sqrt{15}}, \quad D^* = \frac{L\theta}{24}$$

Theoretical minimum emittance

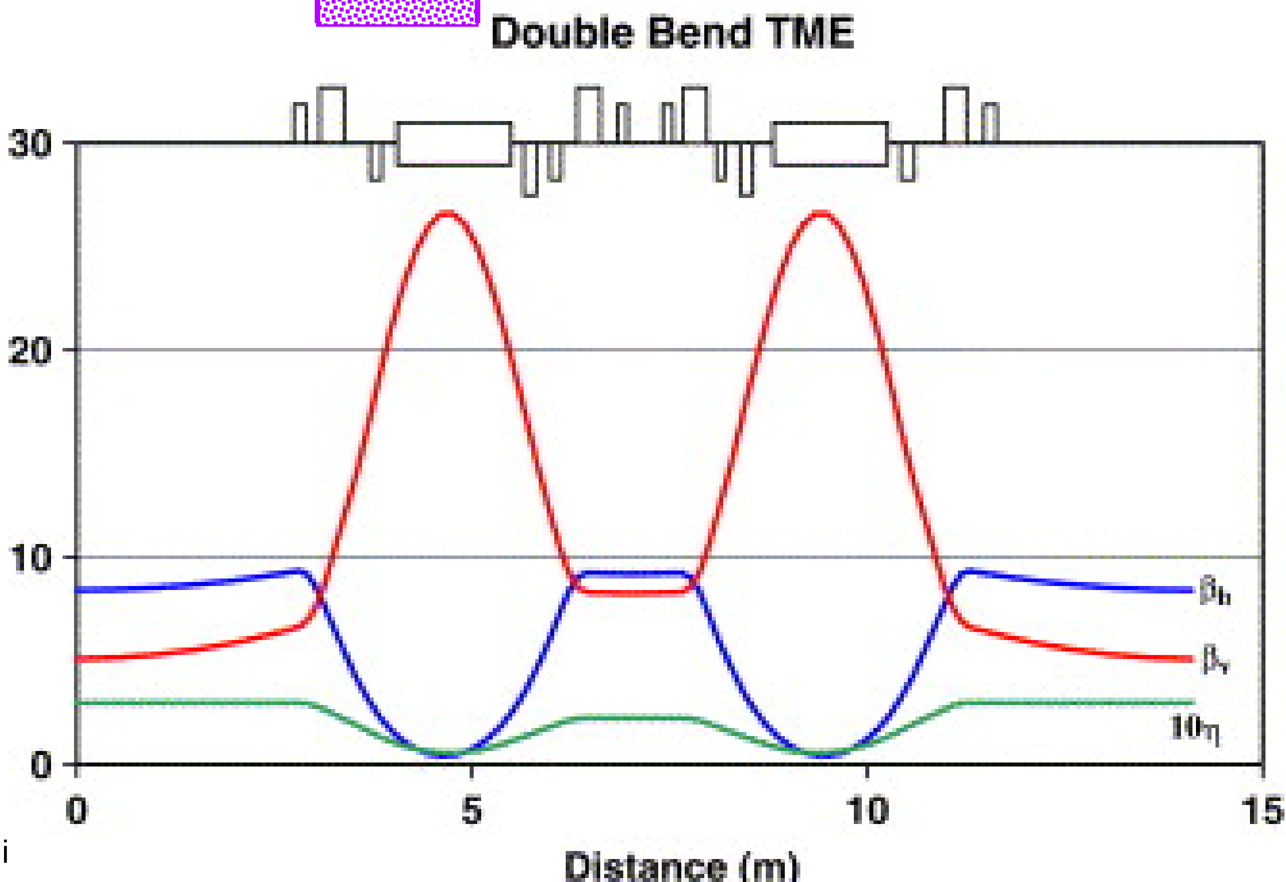


Minimum emittance lattices



$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot \mathrm{F}_{\mathrm{latt}}$$

$$\mathrm{F}_{\mathrm{min}} = \frac{1}{12\sqrt{15}}$$

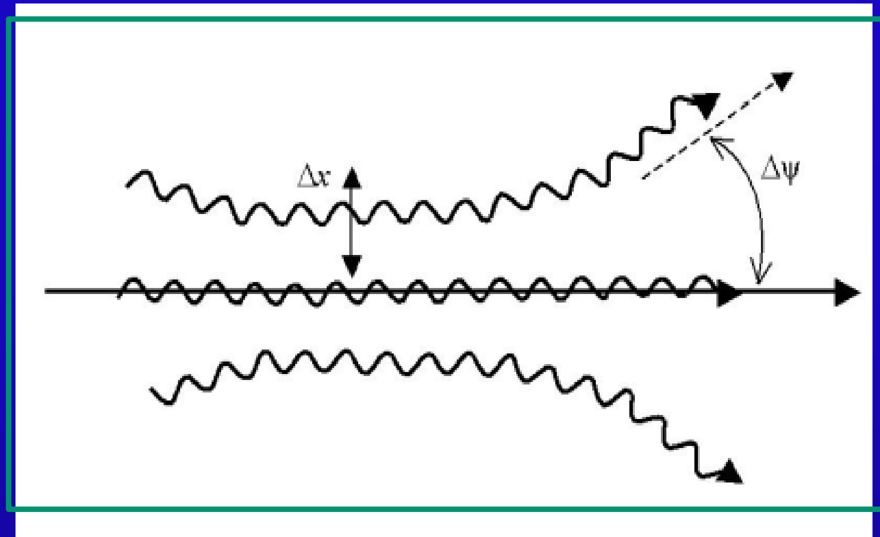


Tight focus in the middle of the bending magnets – need space!

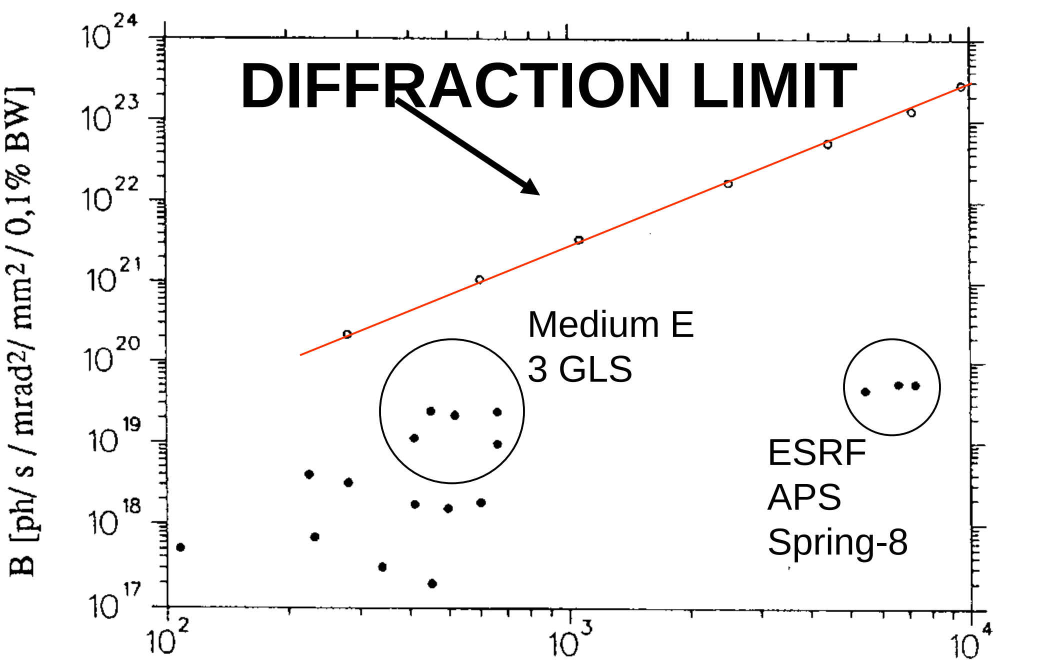
Many bending magnets – need space!

Diffraction limited storage rings

HITTING THE DIFFRACTION LIMIT



BRIGHTNESS:



Light of wavelength

λ

focused to spot size

Δx

will diffract with angle

$\Delta\psi = \sim \lambda/\Delta x$

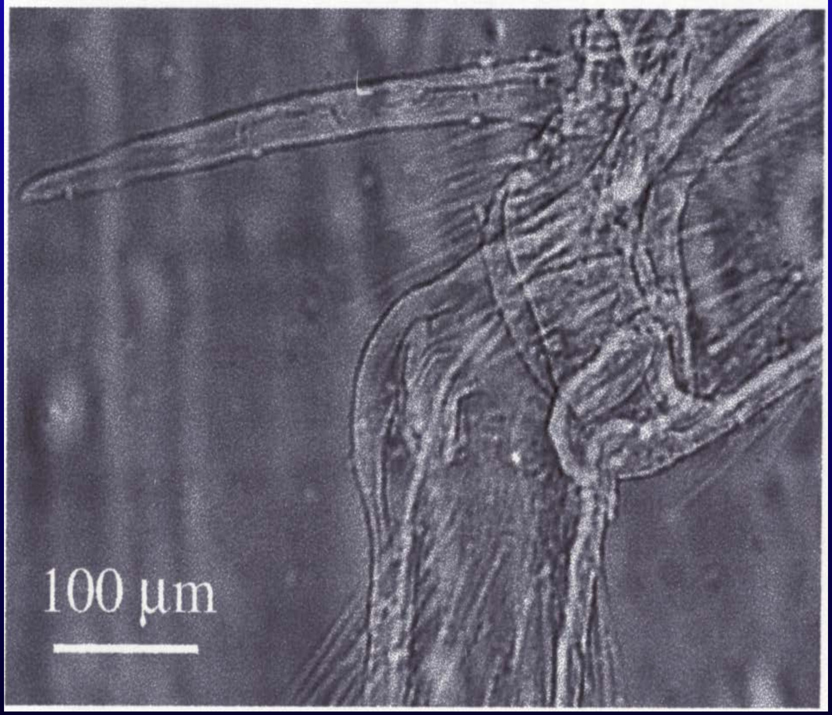
Transverse coherence

- **High brightness gives coherence**

- **Wave optics methods for X-rays (all chapters in Born & Wolf)**

- **Holography**

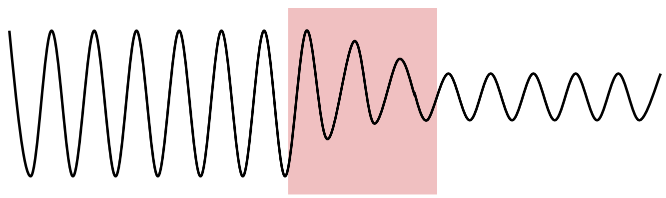
The knee of a spider

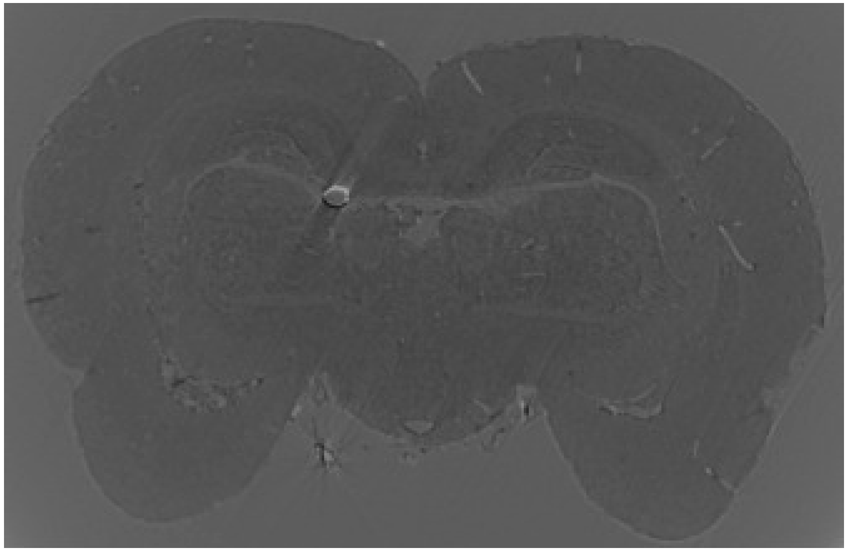


phase contrast imaging

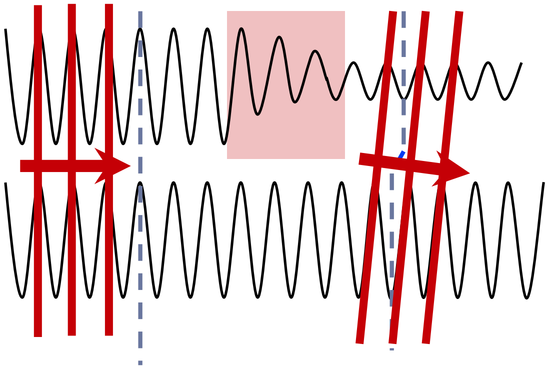
Phase contrast X-Ray imaging

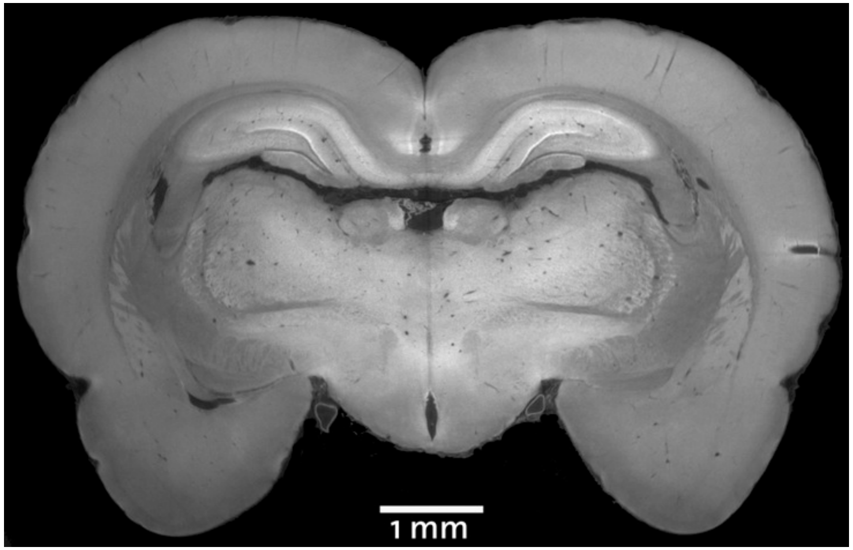
Absorption





Phase contrast

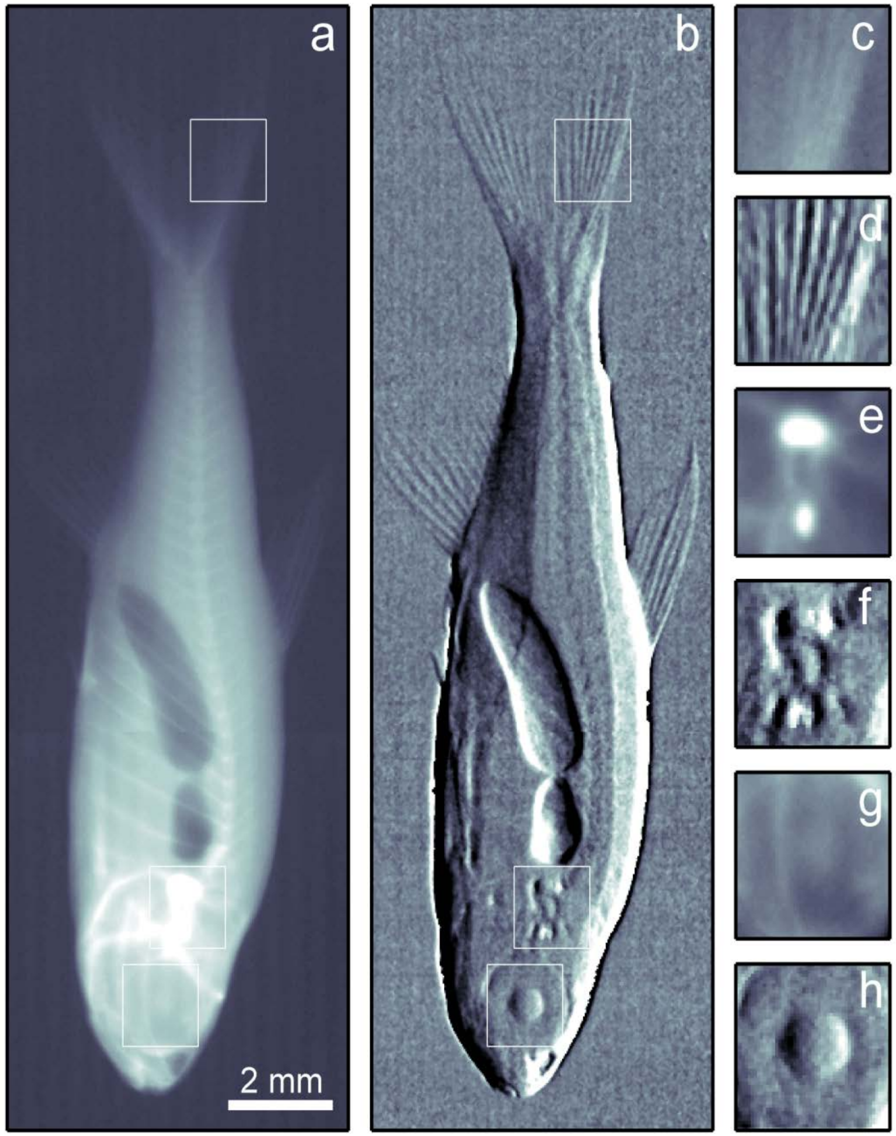




X–ray Radiography of a fish

conventional
Absorption a

(+ details c , e, g)

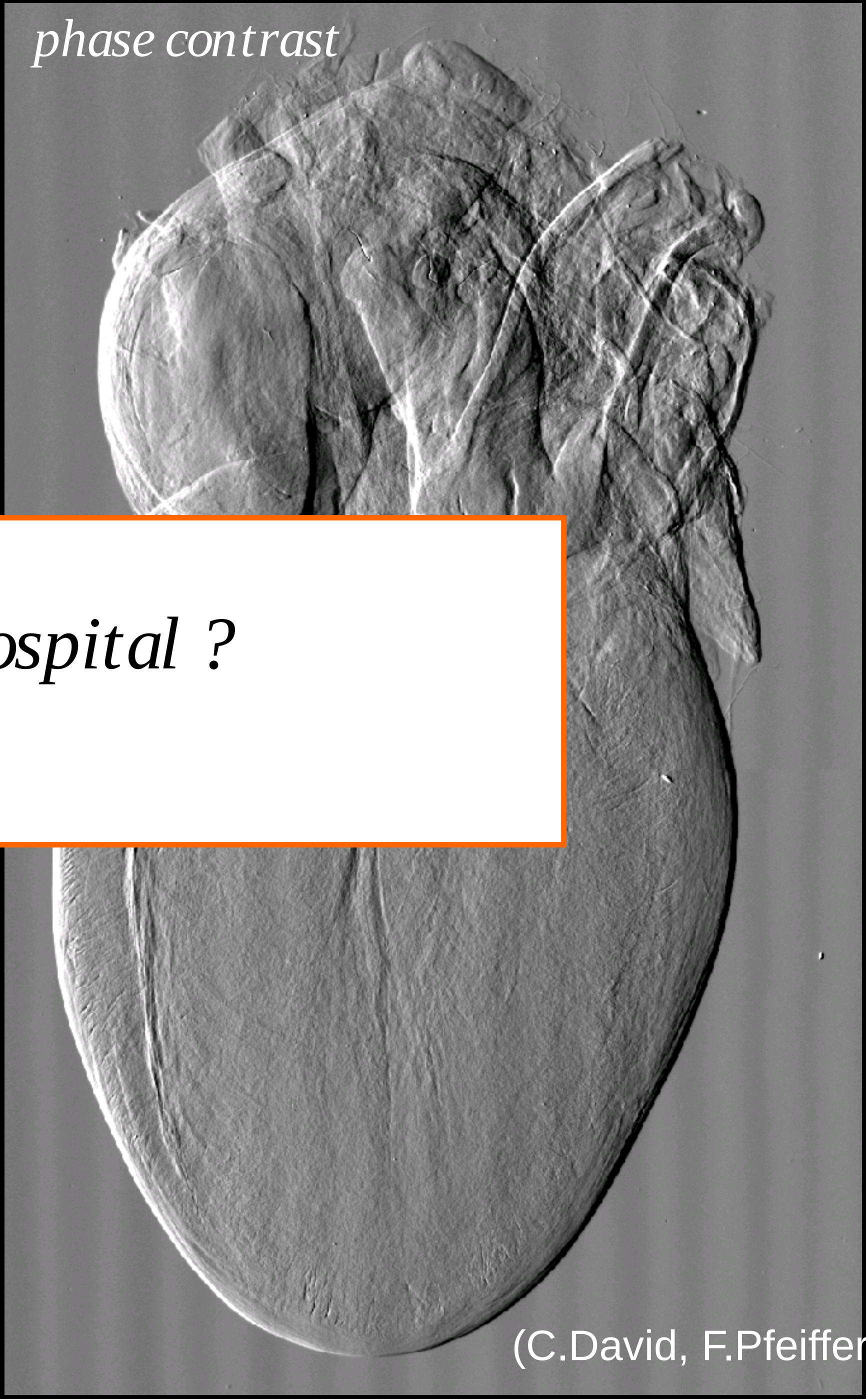


Phase contrast
Microscopy b

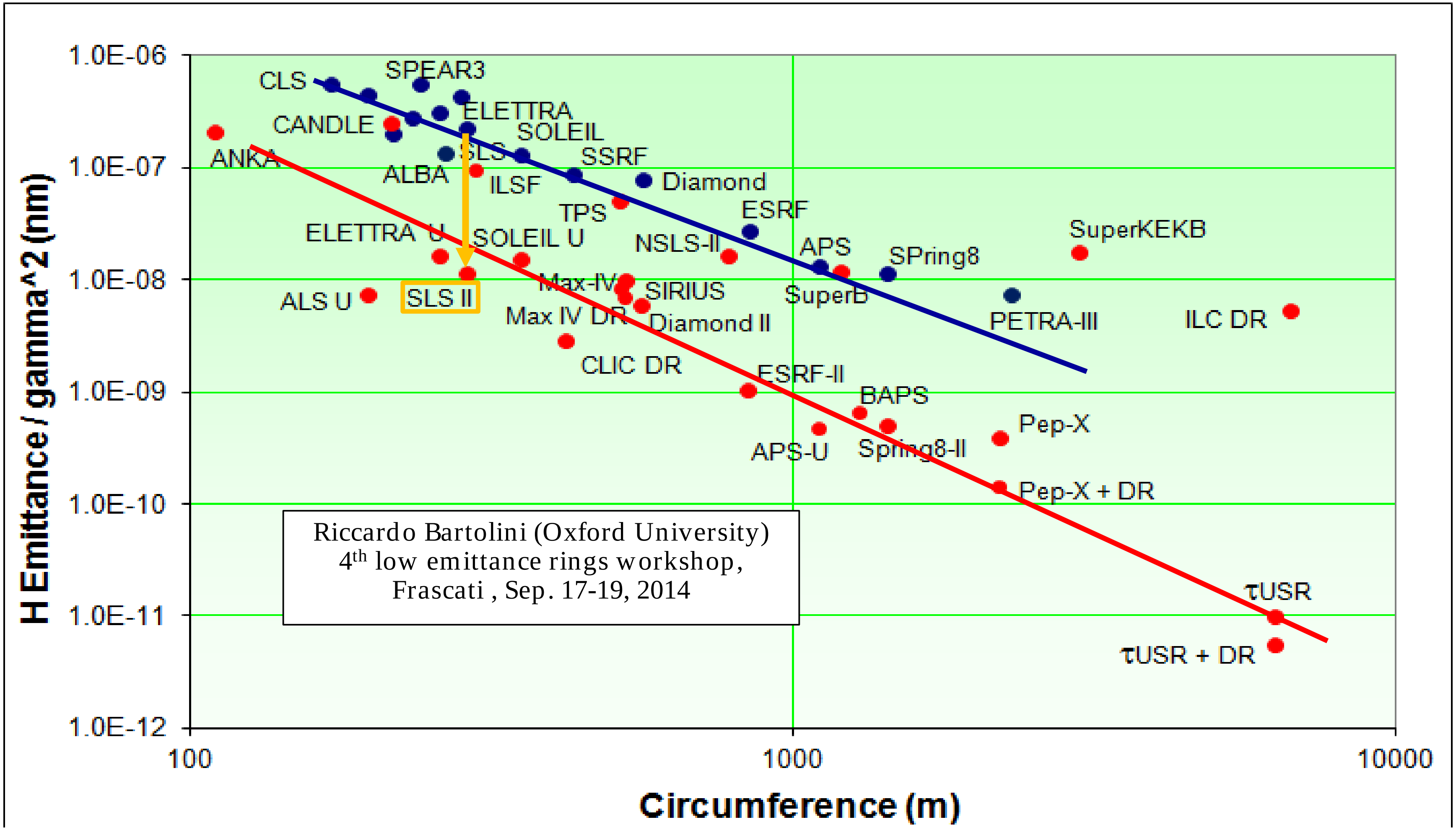
(+ details d, f, h)

(F.Pfeiffer)

Into the hospital ?



The storage ring generational change

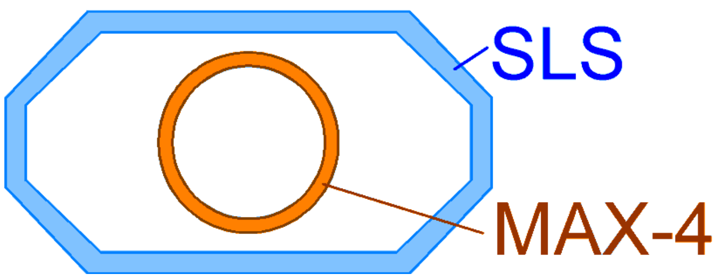


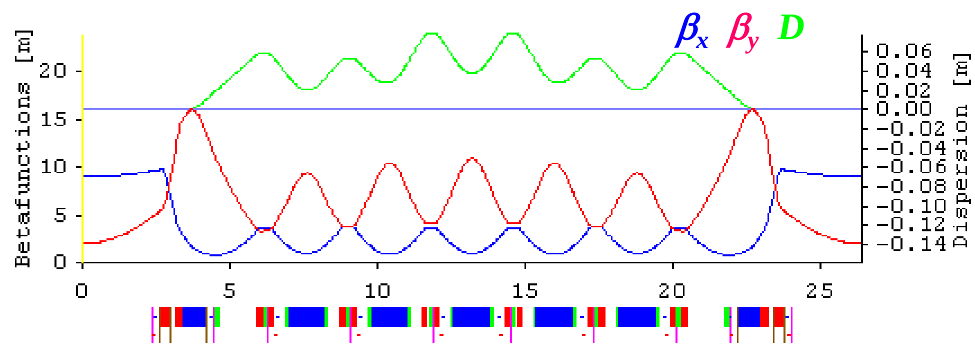
Storage rings in operation (•) and planned (•).
The old (—) and the new (—) generation.

A revolution in storage ring technology

Pioneer work: MAX IV (Lund, Sweden)

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





Technological achievement:
NEG* coating of small vacuum chambers

- ⇨ short lattice cells
- ⇨ many lattice cells
- ⇨ low angle per bend

- ⇨ Small magnet bore
- ⇨ High magnet gradient

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

*Non Evaporable Getter

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

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

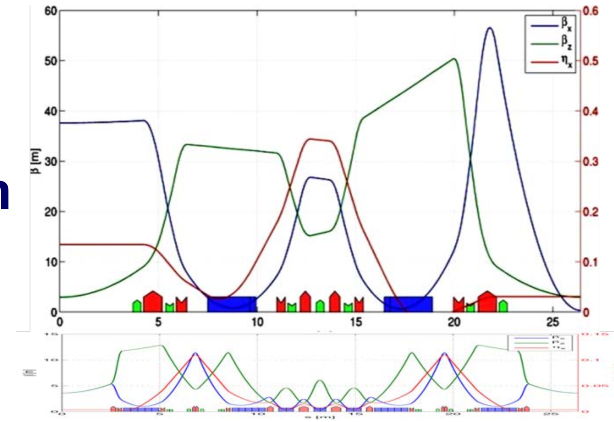
APS-U: 6 GeV, 60 pm x 8 pm,
200 mA (**Upgrade Proposal**)

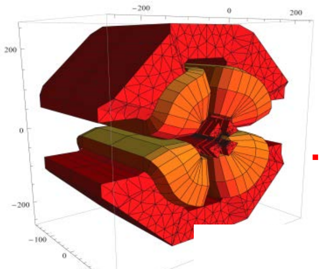
ALS-U: 2 GeV, 50 pm x 50 pm,
500 mA (**Upgrade proposal**)

***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**

ESRF-II – hybrid 7BA

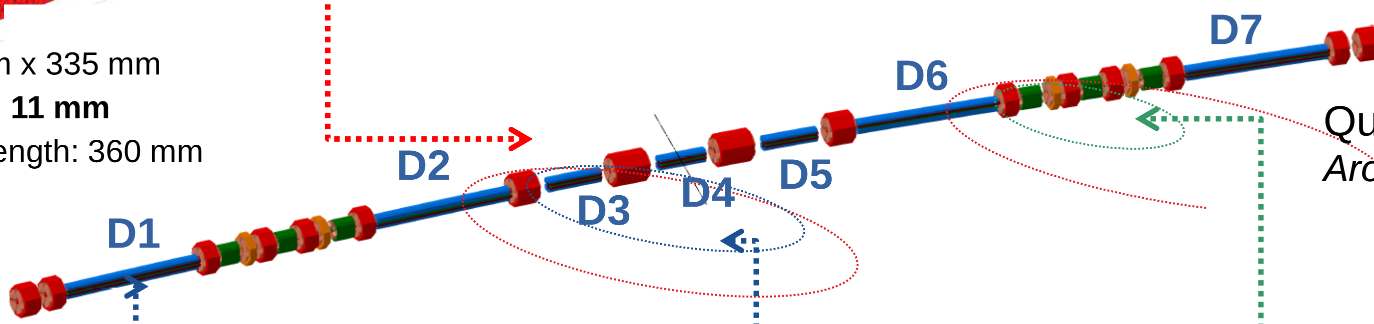
6 GeV, 844 m, 4 nm → 0.15 nm





High gradient quadrupoles
85 T/m

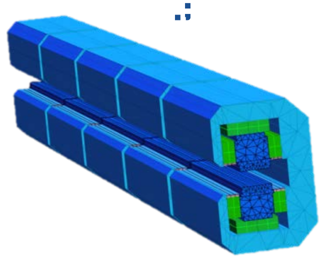
- Spec: 100 T/m x 335 mm
- **Bore radius: 11 mm**
- Mechanical length: 360 mm
- 1 kW



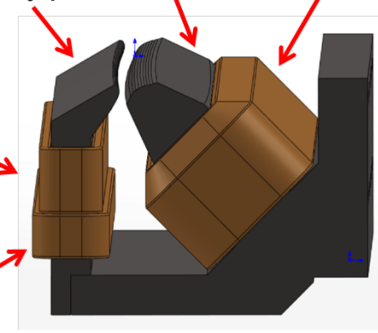
Quadrupole
Around 50 T/m

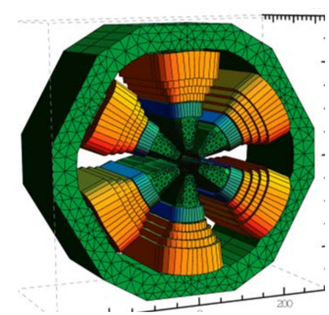
Combined dipole quadrupoles
0.85 T / 45 T/m & 0.34 T / 50 T/m

Sextupoles
1700 T/m^{-2}



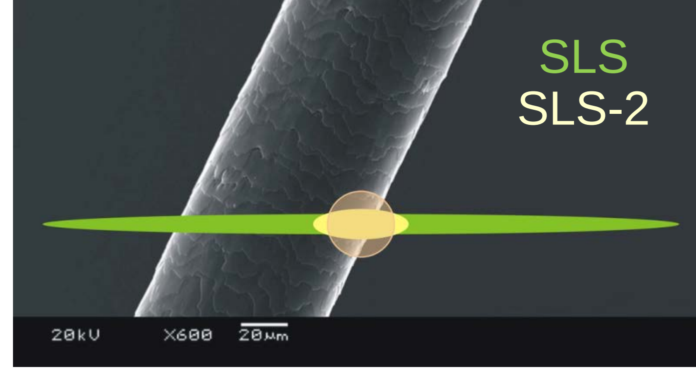
Permanent magnet dipoles
longitudinal gradient 0.16 – 0.6 T,
magnetic gap 22 mm
2 metre long, 5 modules
With a small tuning coil 1%

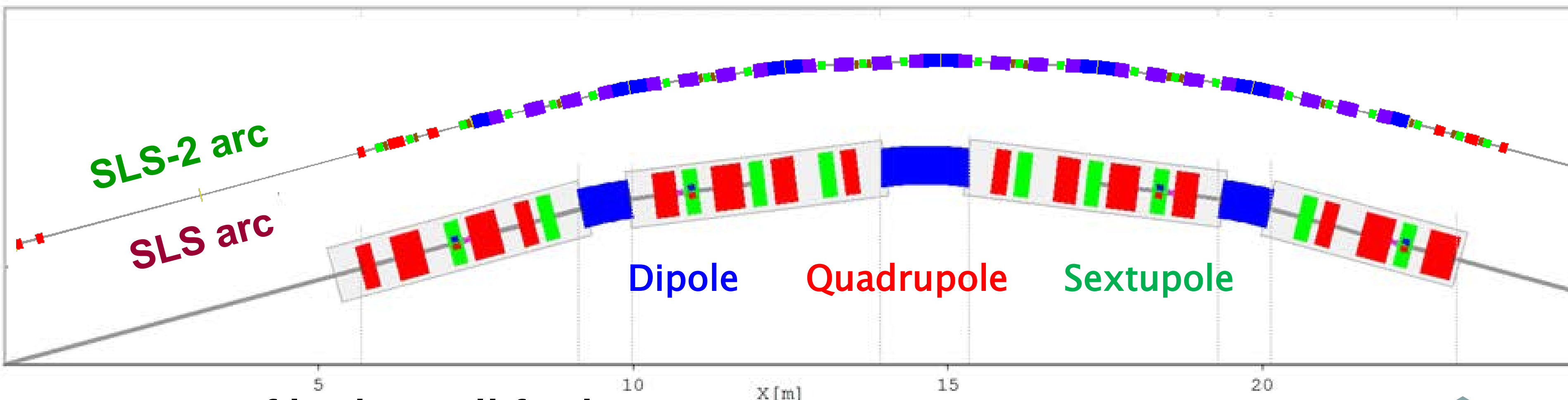




SLS 2.0 upgrade plans

ε_x = **140 pm.rad @ 2.4 GeV**

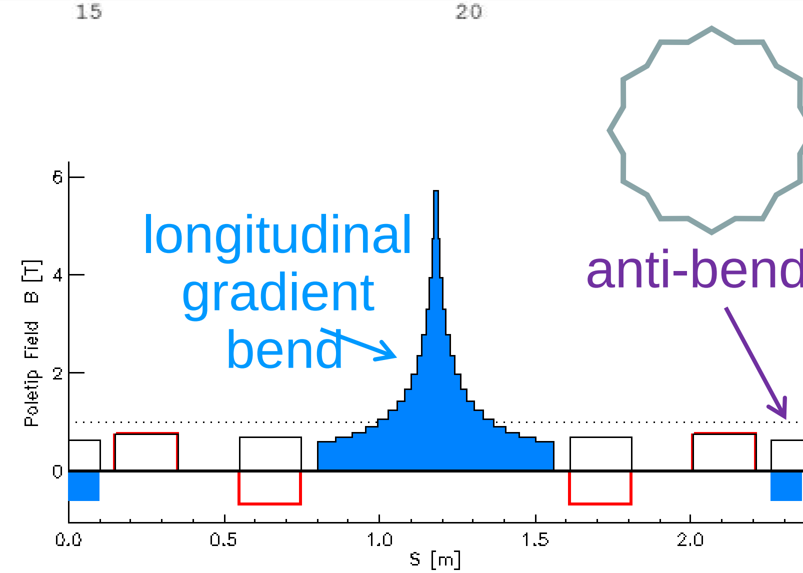




New type of lattice cell for low emittance

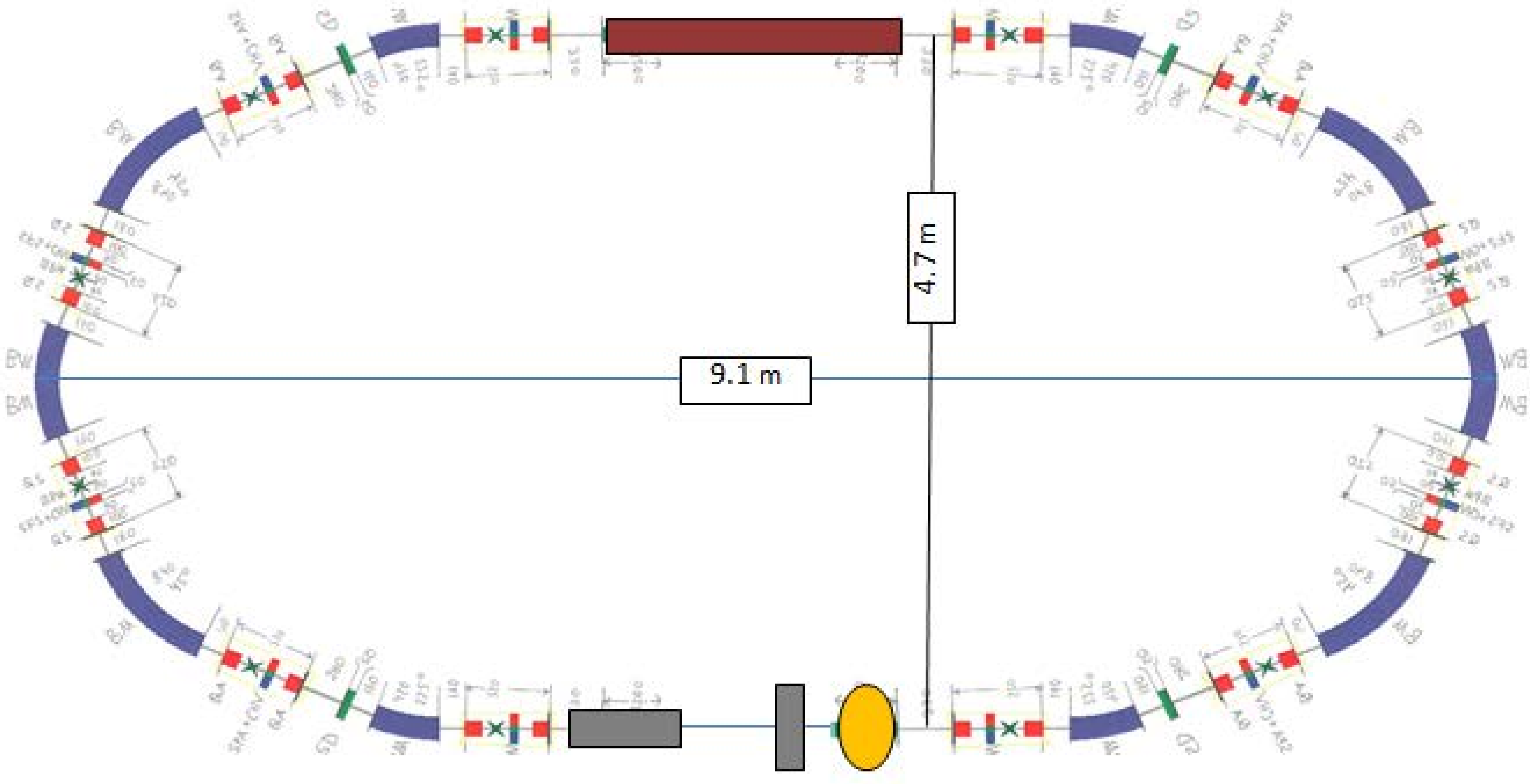
- bending magnets with longitudinal field variation (2 T peak)
- options for 5-6 T peak field superbends
- anti-bends for beam dynamics

⇒ (star-shaped lattice)

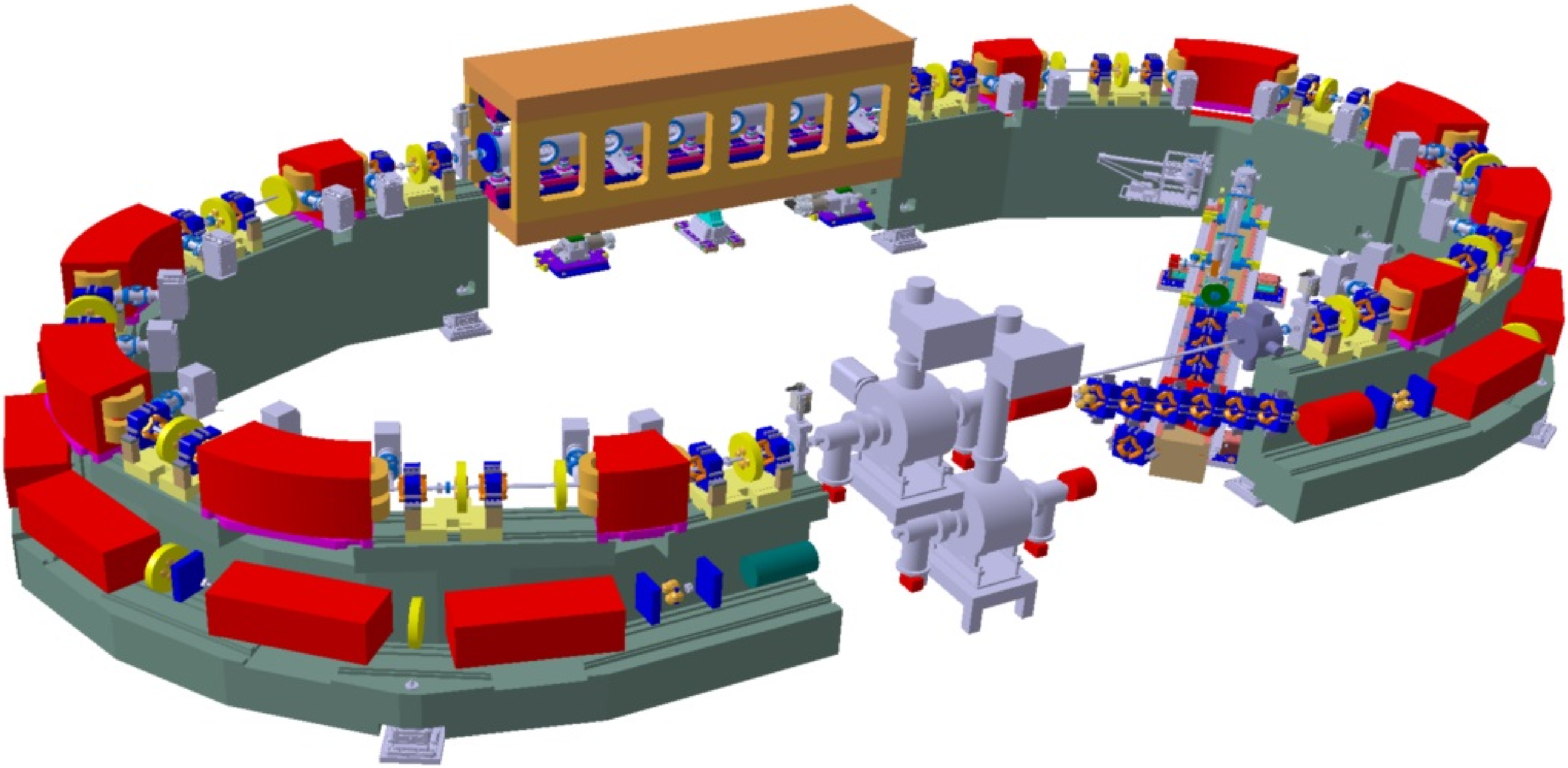


Compact light source COSAMI

Conventional, normal conducting magnetic structure

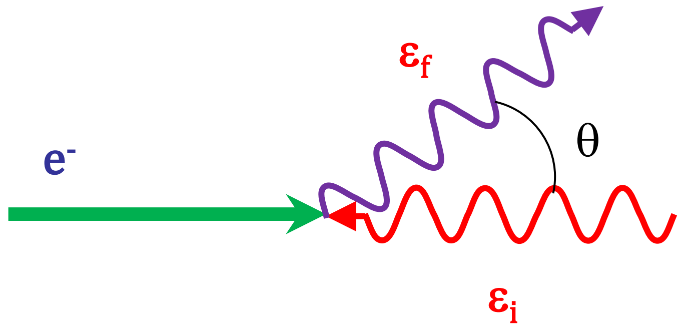


Injector and storage ring integration



When an electron collides with a photon…

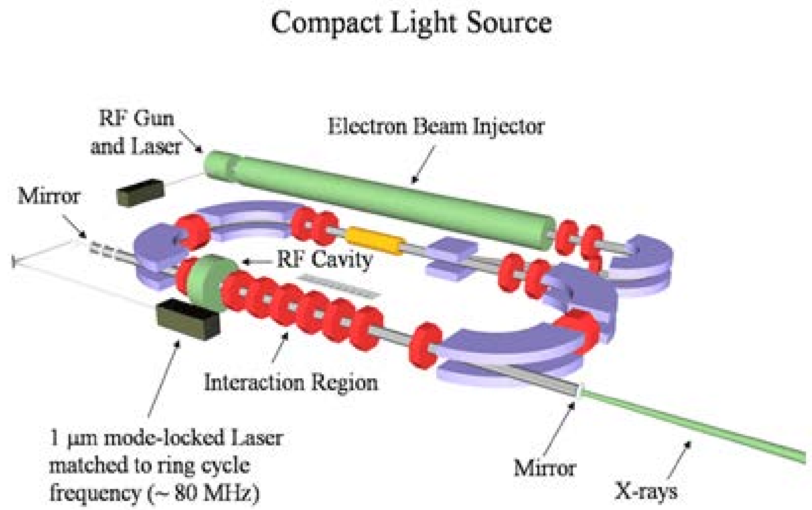
Also known as **Compton** or Thomson scattering

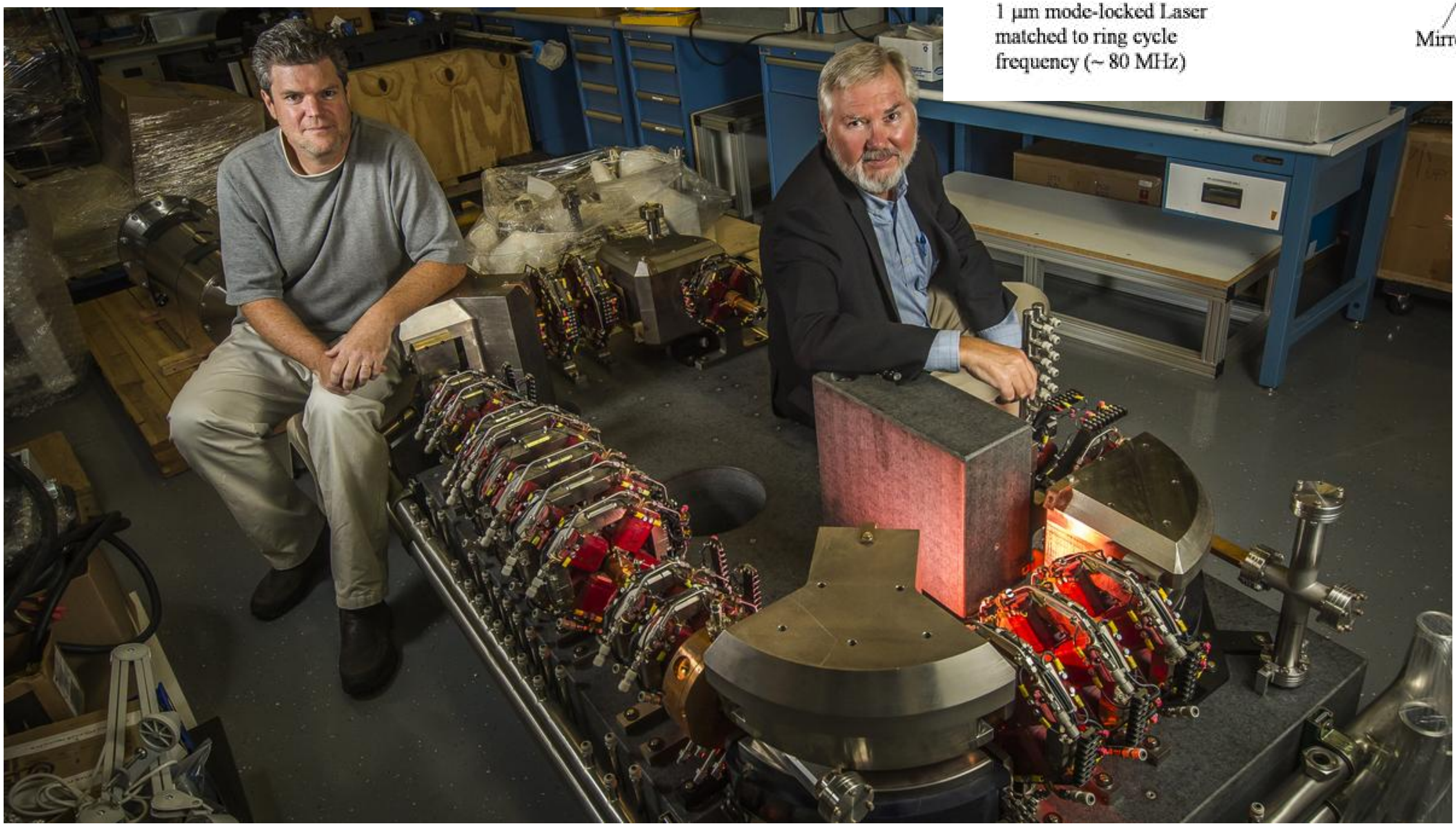


$$\varepsilon_f = \frac{4\gamma^2 \varepsilon_i}{1 + \gamma^2 \theta^2}$$

- backscattered photon has the maximum energy
- at an angle of $1/\gamma$ the energy drops by a factor of 2
- undulator's periodic magnetic field could be viewed as a «photon», with useful parallels between the two cases

Compact light source based on Compton scattering



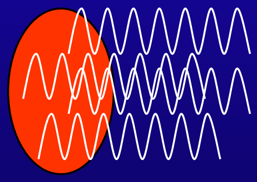


www.lynceantech.com

Free Electron Lasers

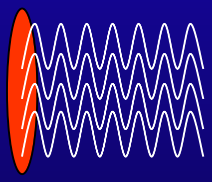
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$



INCOHERENT EMISSION

Intensity $\propto N^2$



COHERENT EMISSION

FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

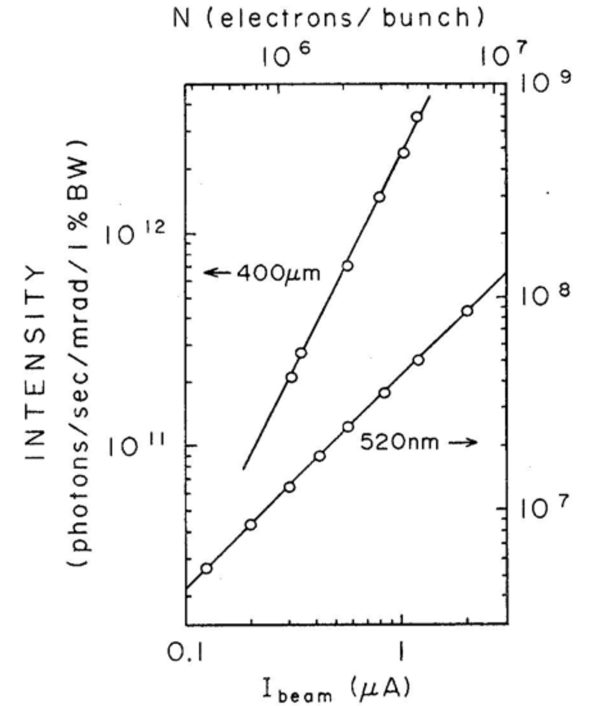


Fig. 4. Dependence of SR intensity on the beam current at $\lambda = 400$ μm and $\lambda = 520$ nm for the long pulse/short bunch beam. The ordinate is given on the left-hand side for $\lambda = 400$ μm and on the right for $\lambda = 520$ nm. The two lines show the linear and quadratic relations to the beam current. The beam current is converted to the average number of electrons in a bunch on the upper side.

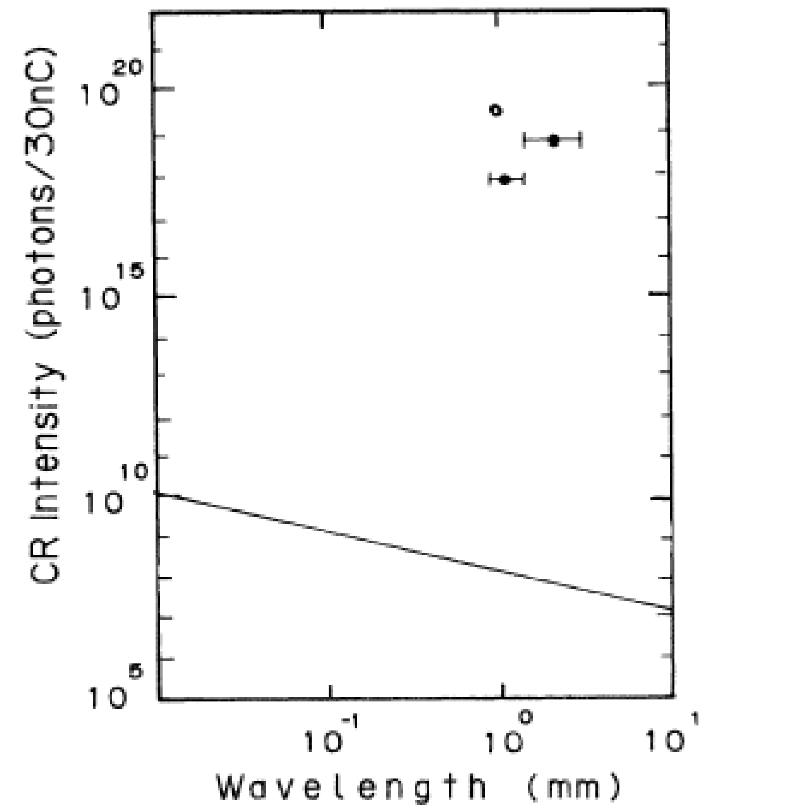


FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

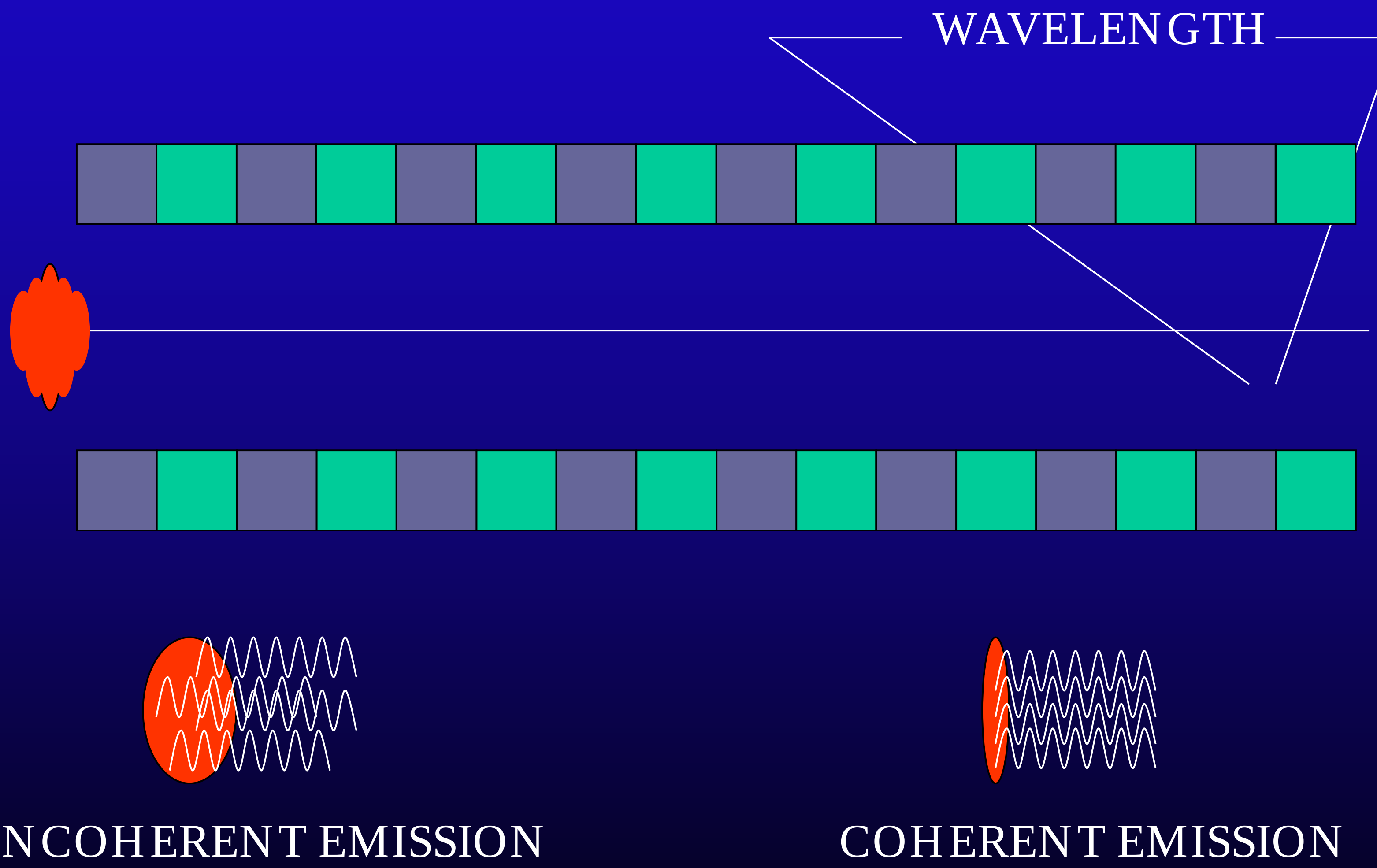
180 MeV electrons

T. Nakazato et al., Tohoku University, Japan

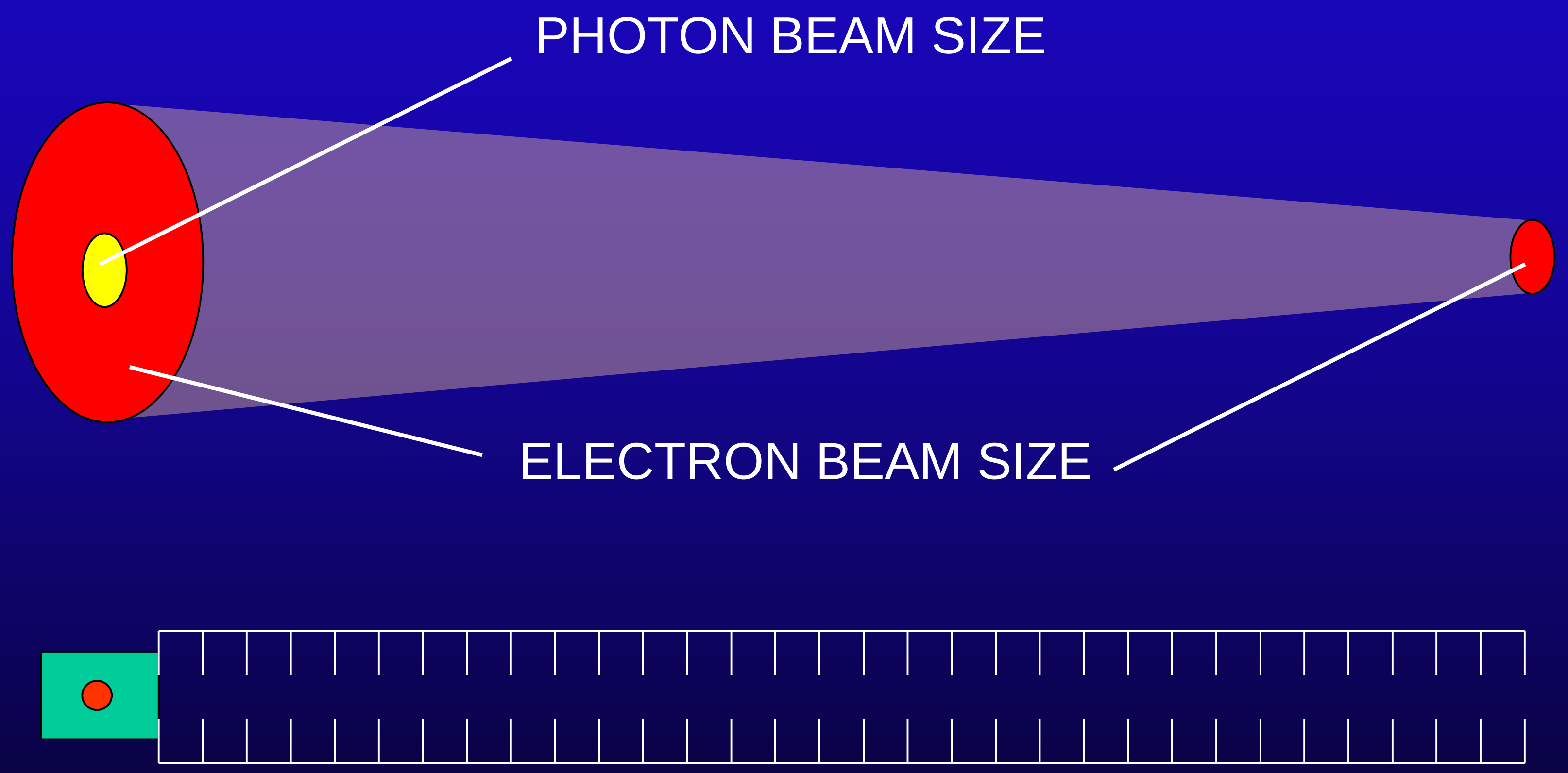
30 MeV electrons

J. Ohkuma et al., Osaka University, Japan

MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE

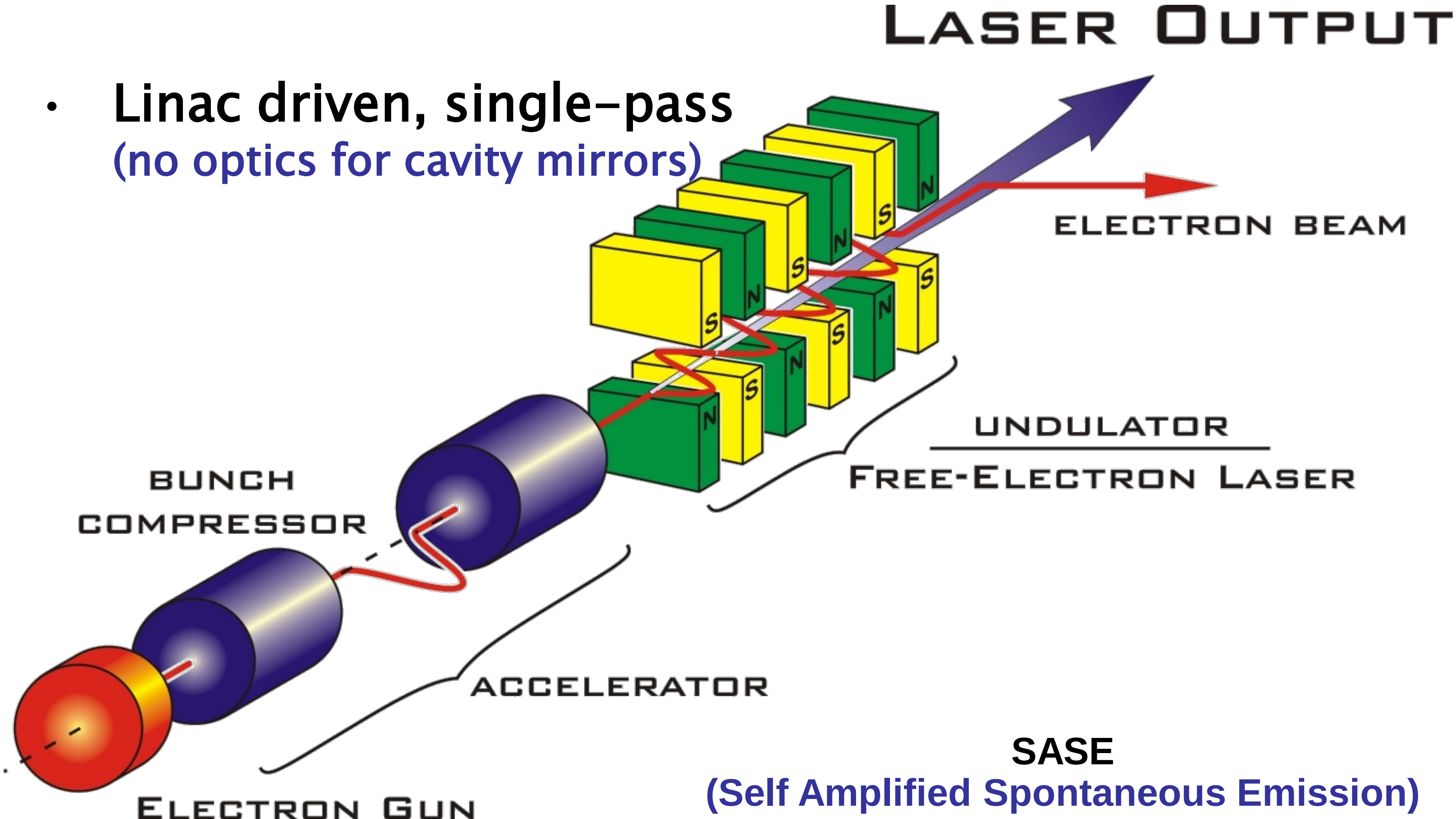


THE ELECTRON BEAM SHOULD BE ~ 1 Å
AS SMALL AS THE X-RAY WAVELENGTH!



Free Electron Laser Keywords:

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



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

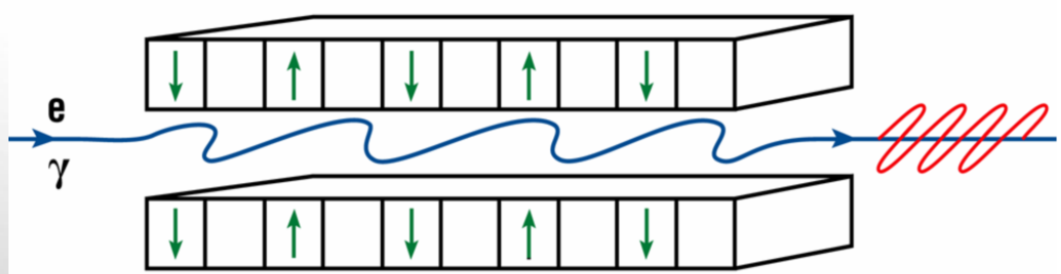
R. Bakker

From rings to linear accelerators

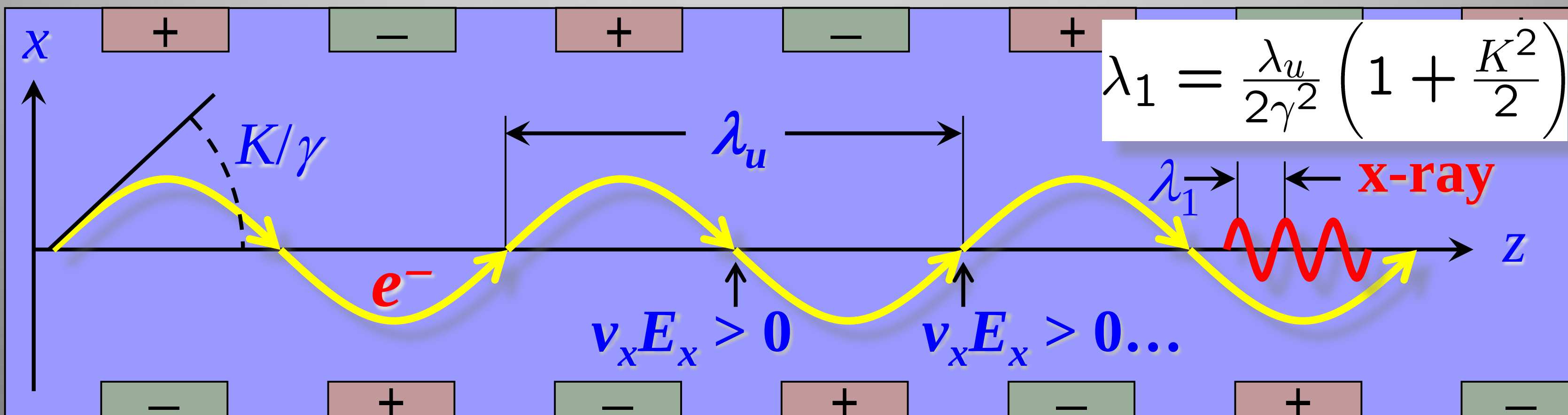
- o The number of beamlines served simultaneously
- o The stability of the rings based sources
- o High average brightness
- – Fewer beamlines
- – Very short pulses, single shot measurements
- – High peak brightness

FEL Principles

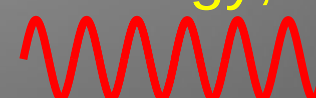
Z. Huang



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



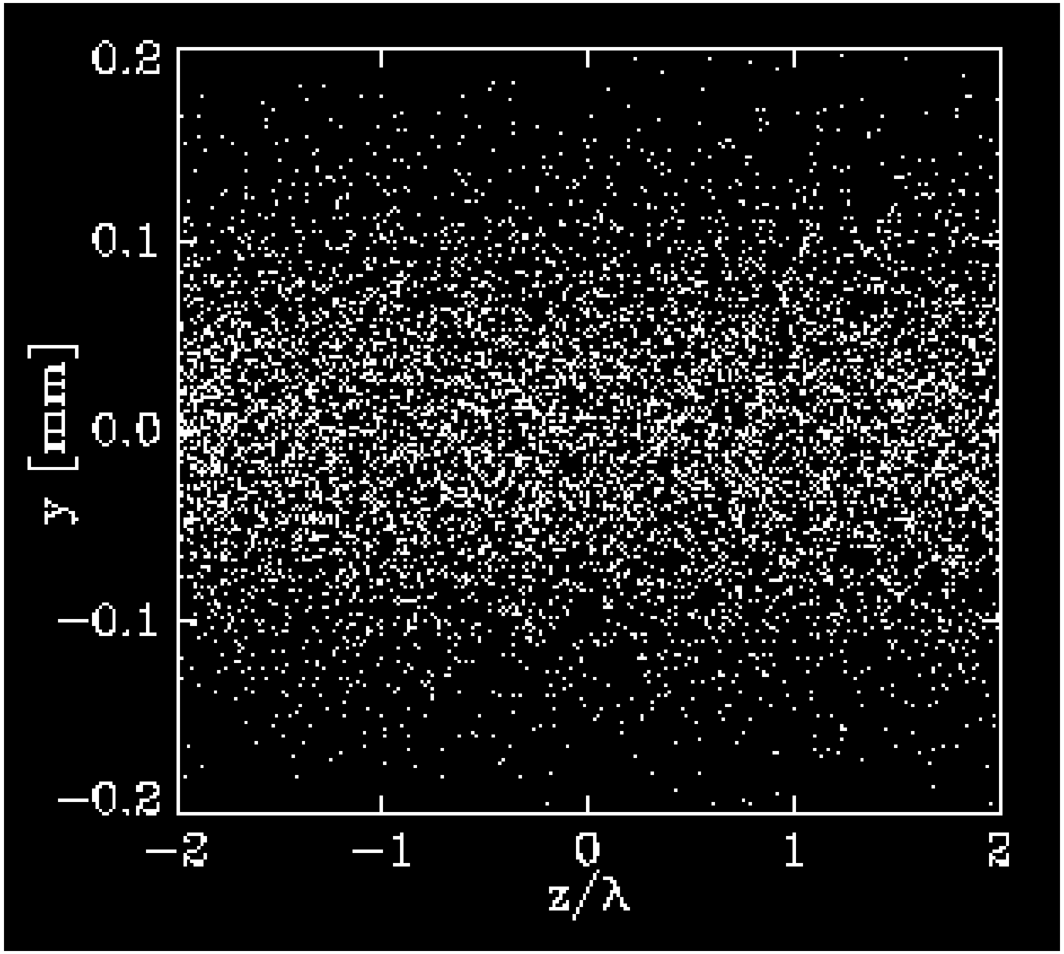
- Due to sustained interaction, some electrons lose energy, while others gain ➔ **energy modulation at λ_1**



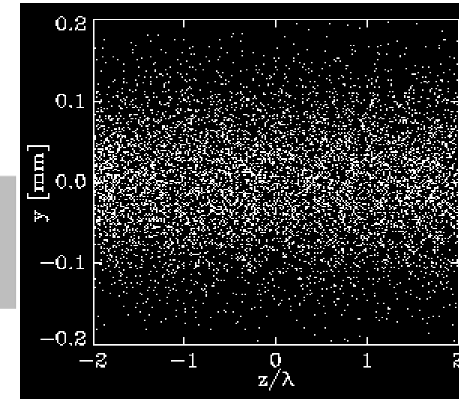
- e^- losing energy slow down, and e^- gaining energy catch up ➔ **density modulation at λ_1 (microbunching)**

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

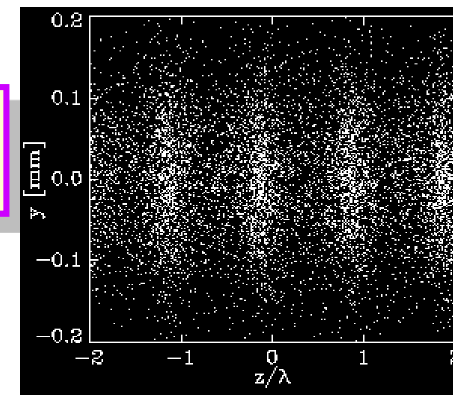
Microbunching through SASE Process



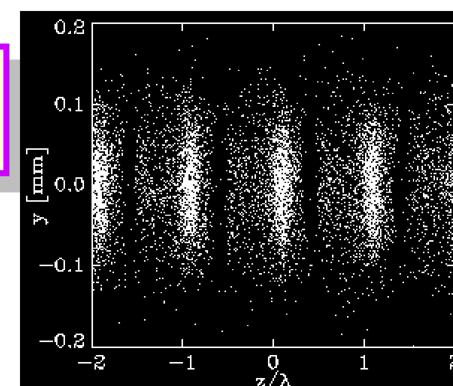
undulator entrance



half-way saturation



full saturation

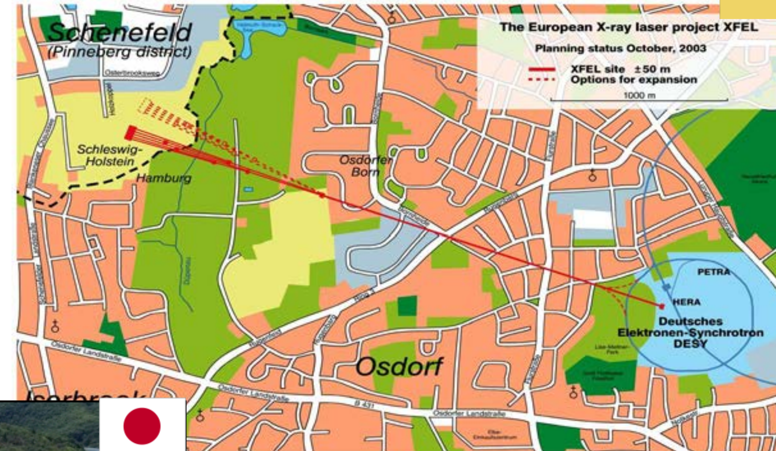


***GENESIS* - simulation for TTF parameters**

Courtesy - Sven Reiche (PSI)

The World of XFELs

PAL XFEL 2016



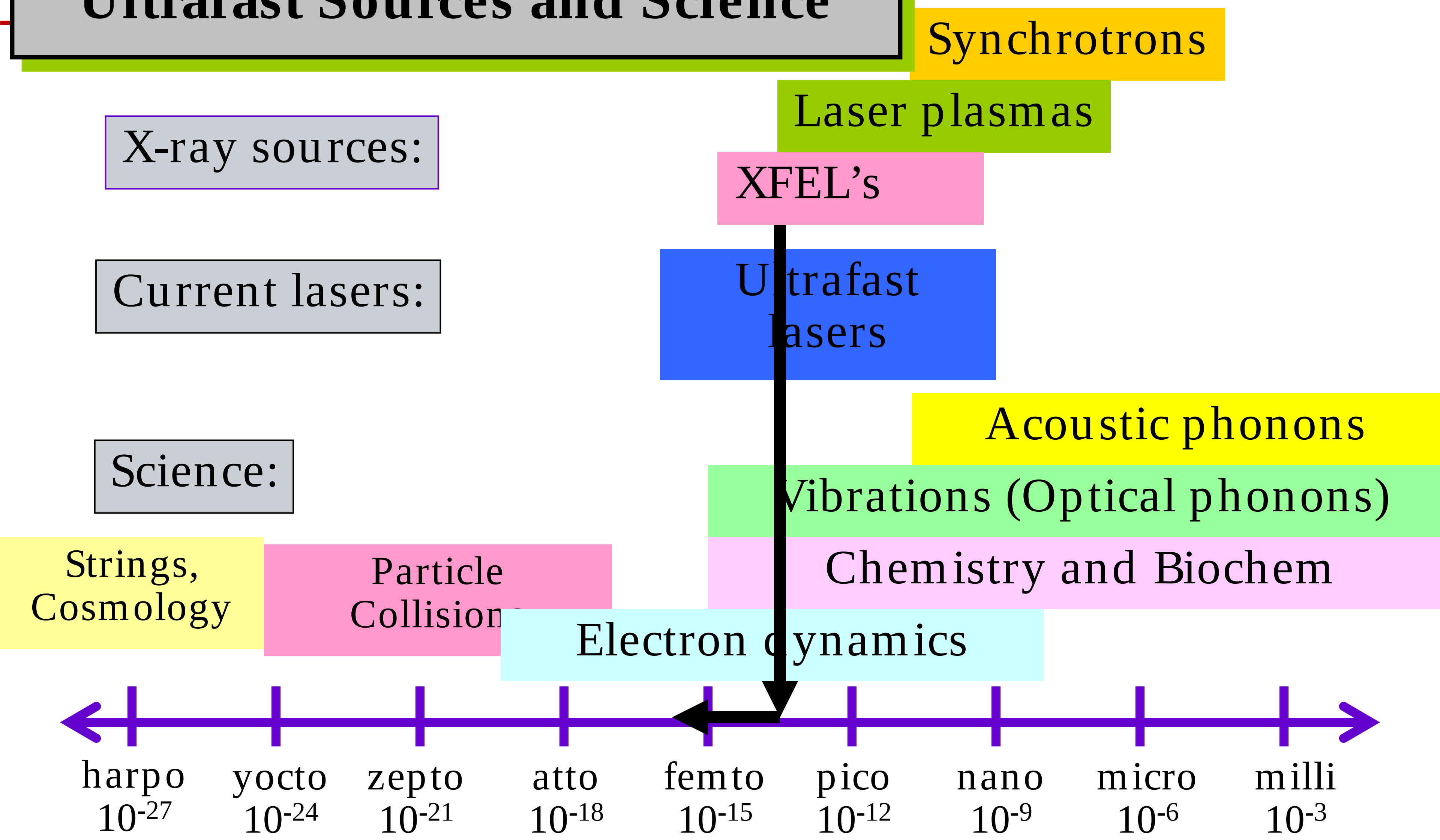
European XFEL
DESY, Hamburg 2017

SACLA 2011
8.5 GeV, 60 Hz NC

LCLS I, II 2009, 2019

SwissFEL 2017

Ultrafast Sources and Science



J. Hastings

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

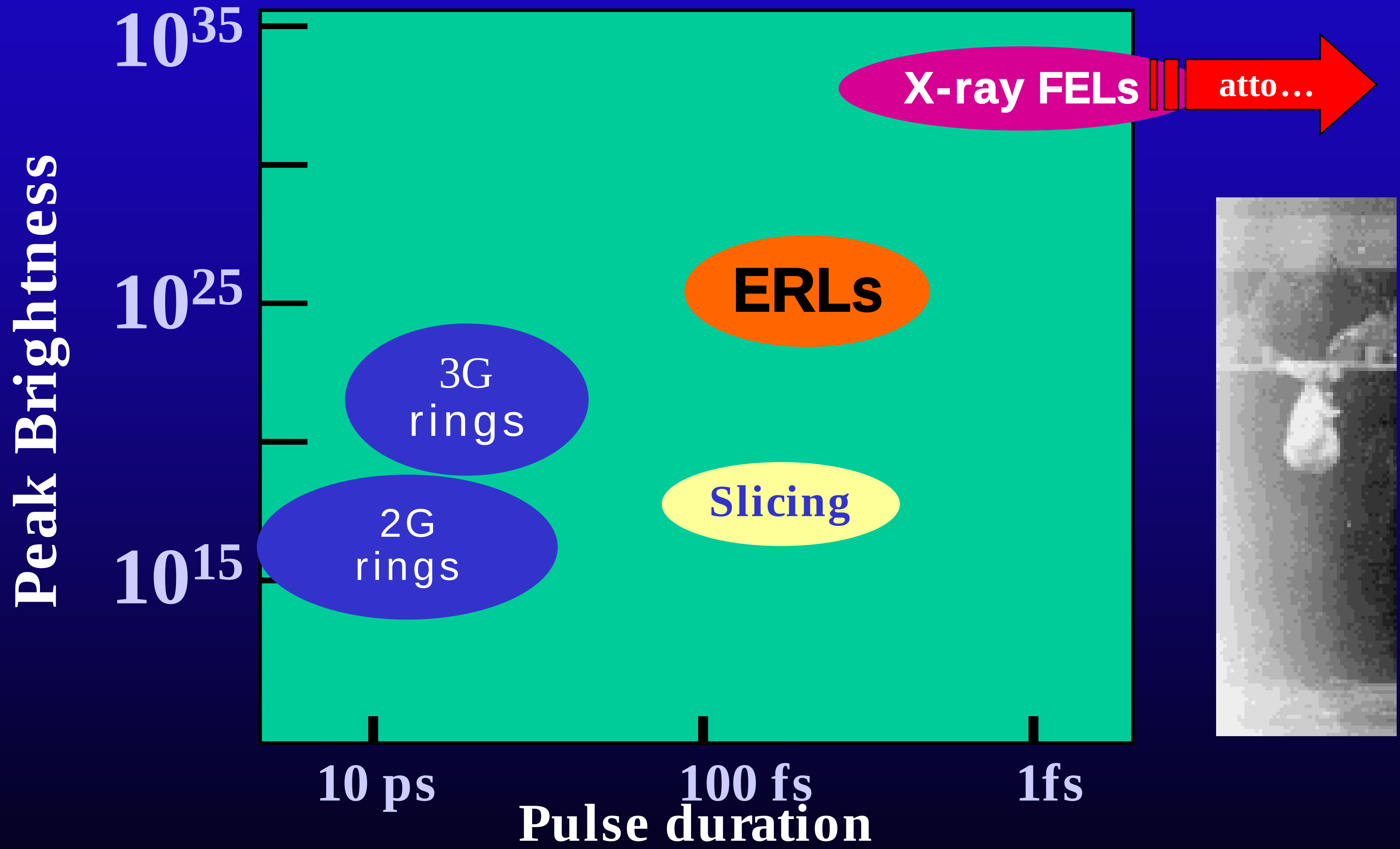
E. Muybridge

L. Stanford

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

After H.-D. Nuhn, H. Winick

END