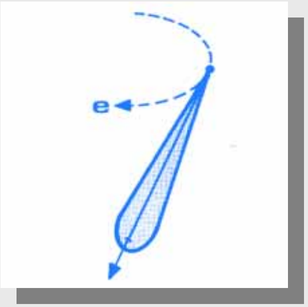
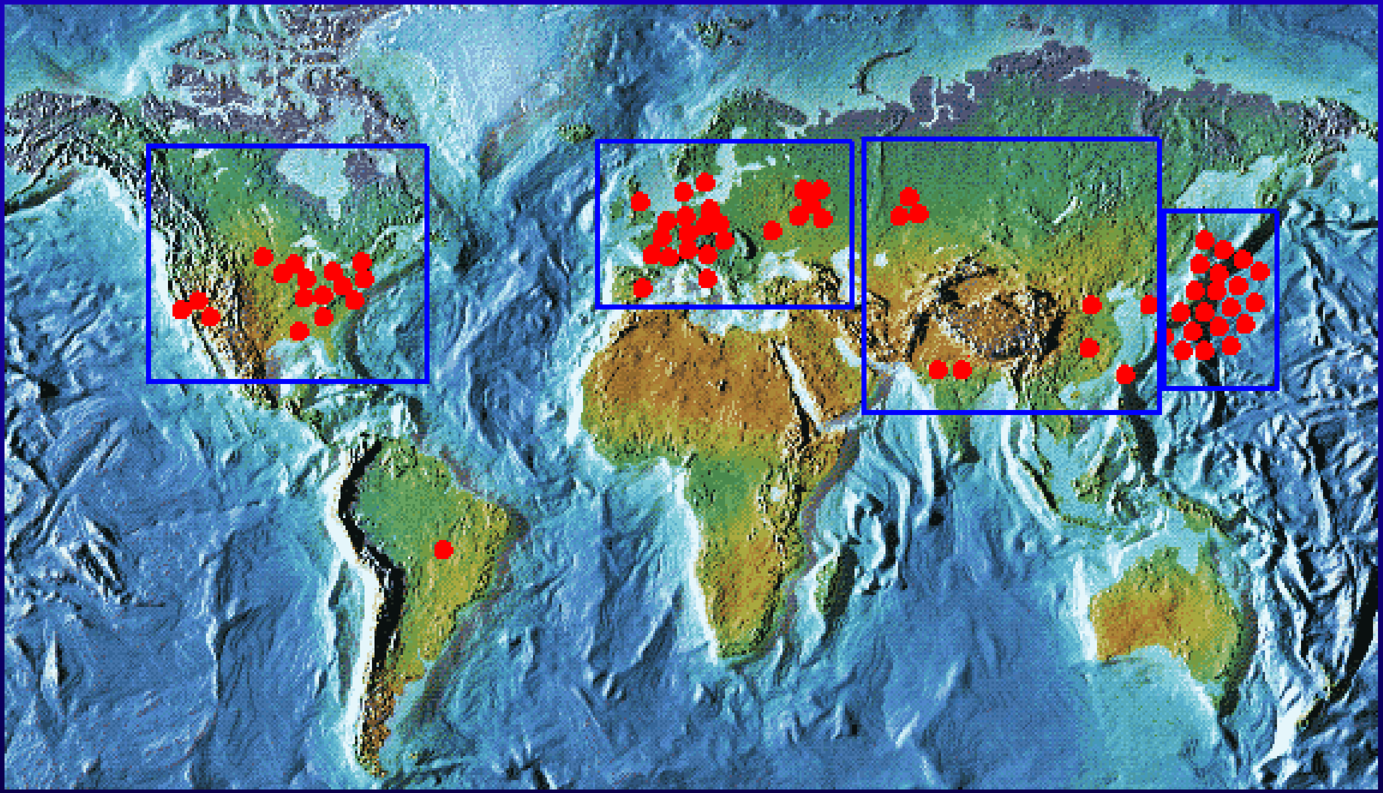


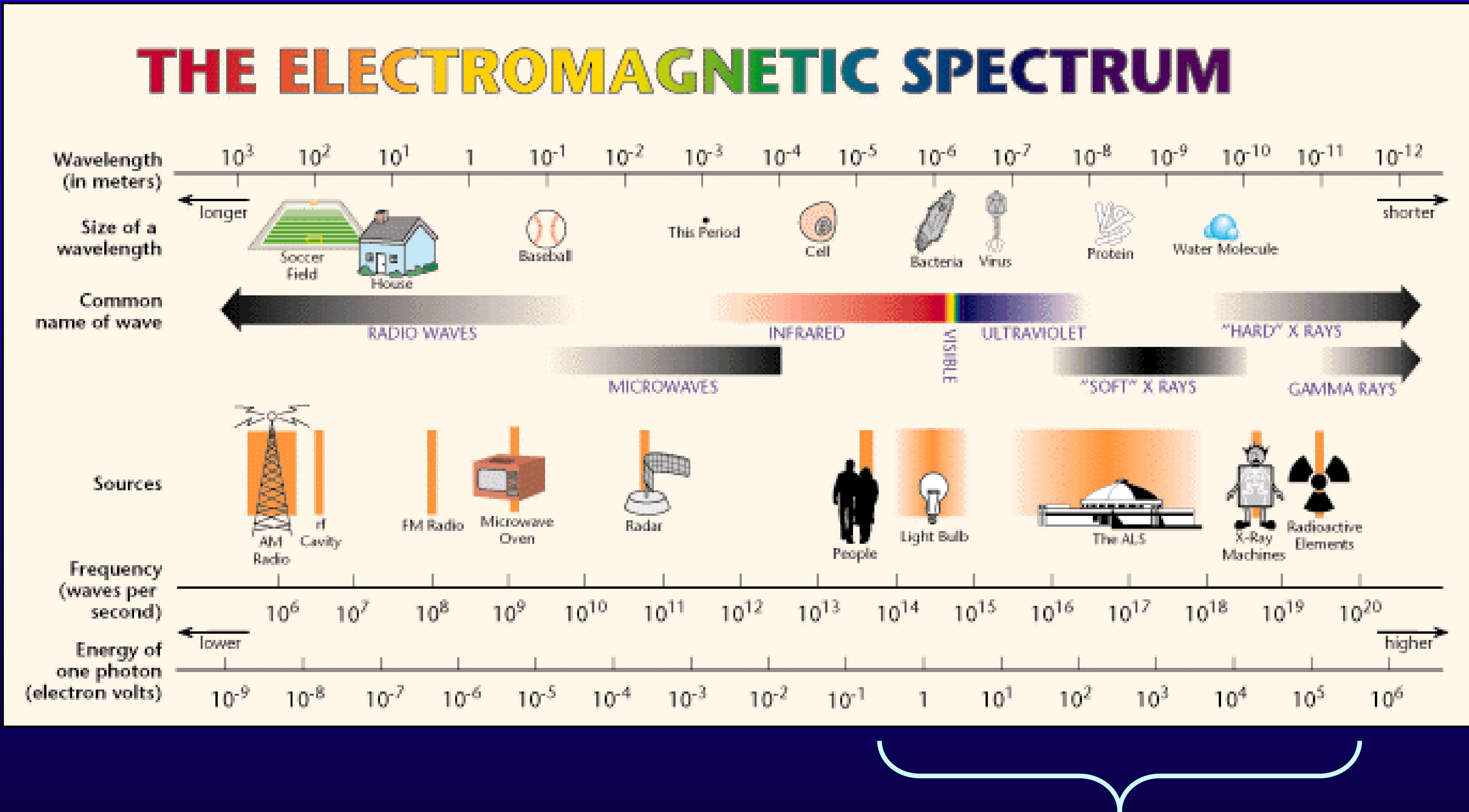
SYNCHROTRON RADIATION SOURCES AND PROPERTIES

Lenny Rivkin
Paul Scherrer Institute, Switzerland

ICTP SCHOOL ON SYNCHROTRON RADIATION AND APPLICATIONS
Trieste, Italy, May 2006

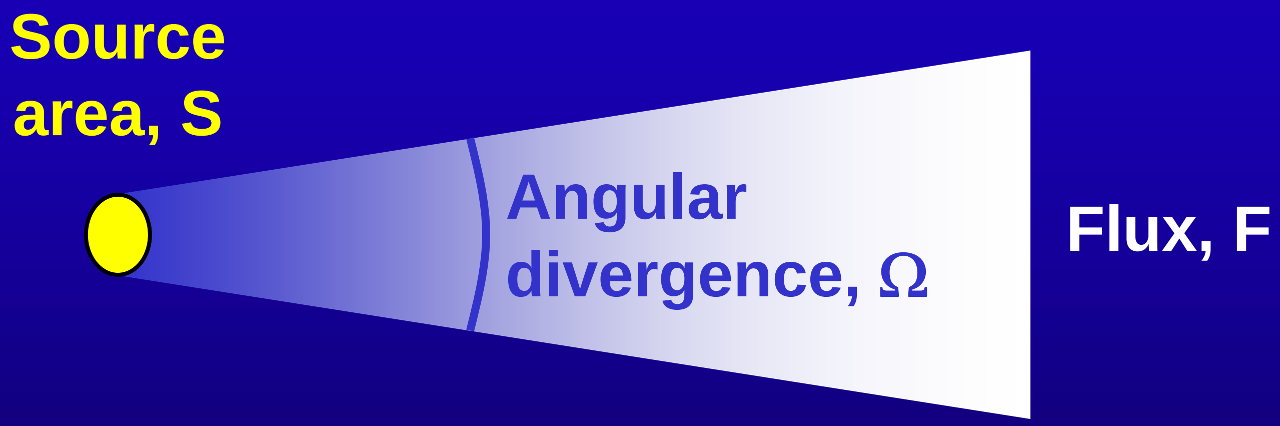
60 000 users world-wide





Wavelength continuously tunable !

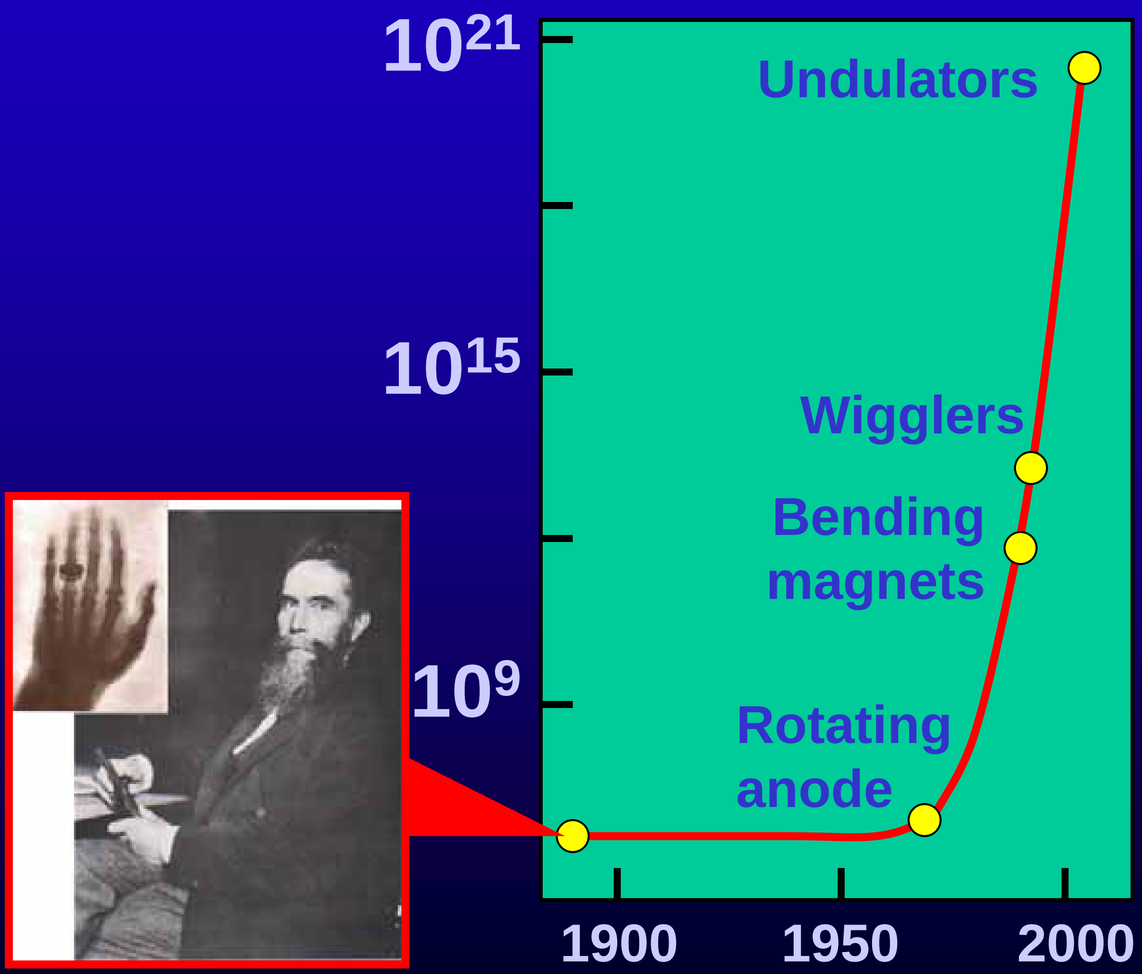
The “brightness” of a light source:



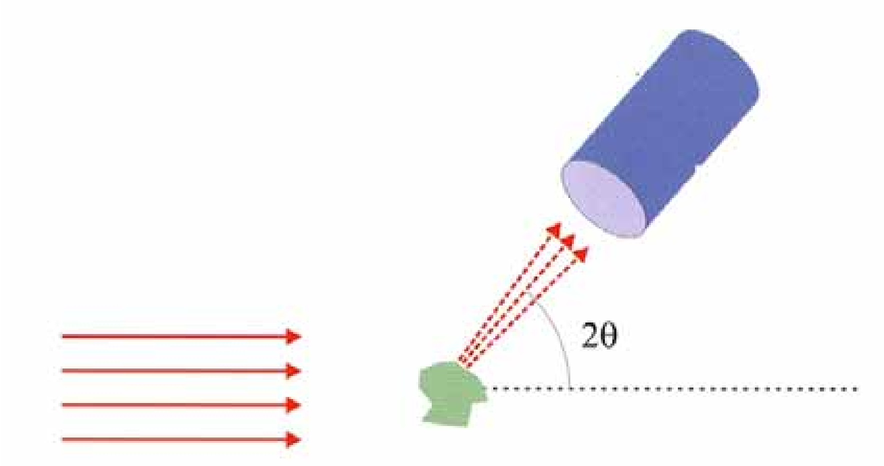
$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

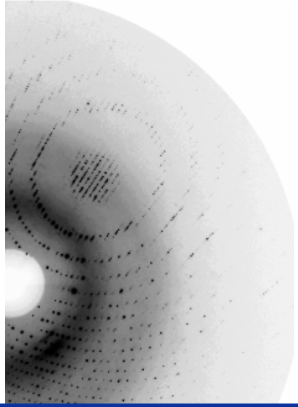
Steep rise in brightness/brilliance

(units: photons/mm^2/s/mrad^2, 0.1% bandwidth)

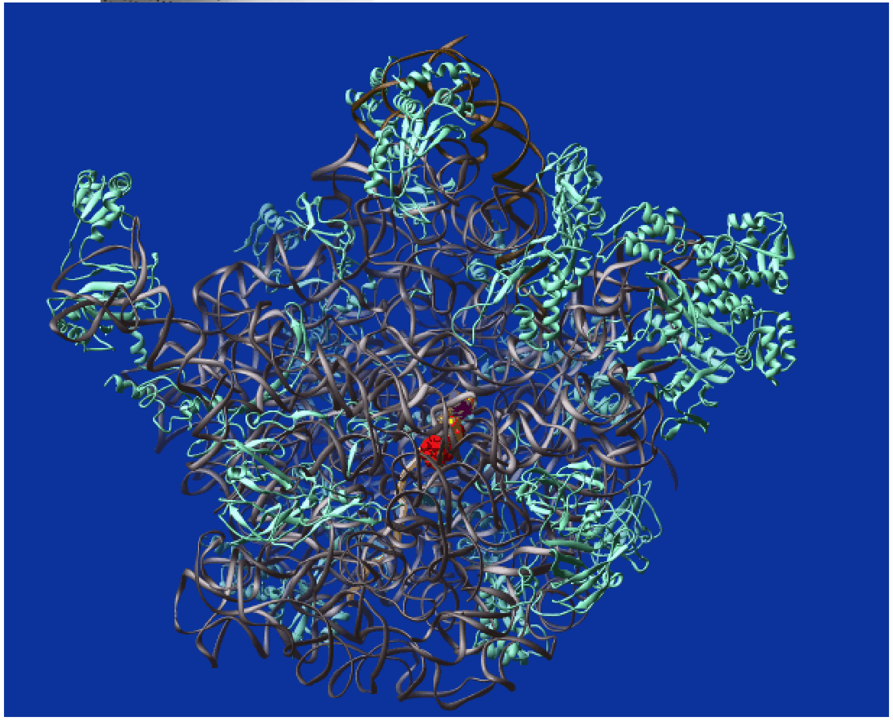


Protein structure

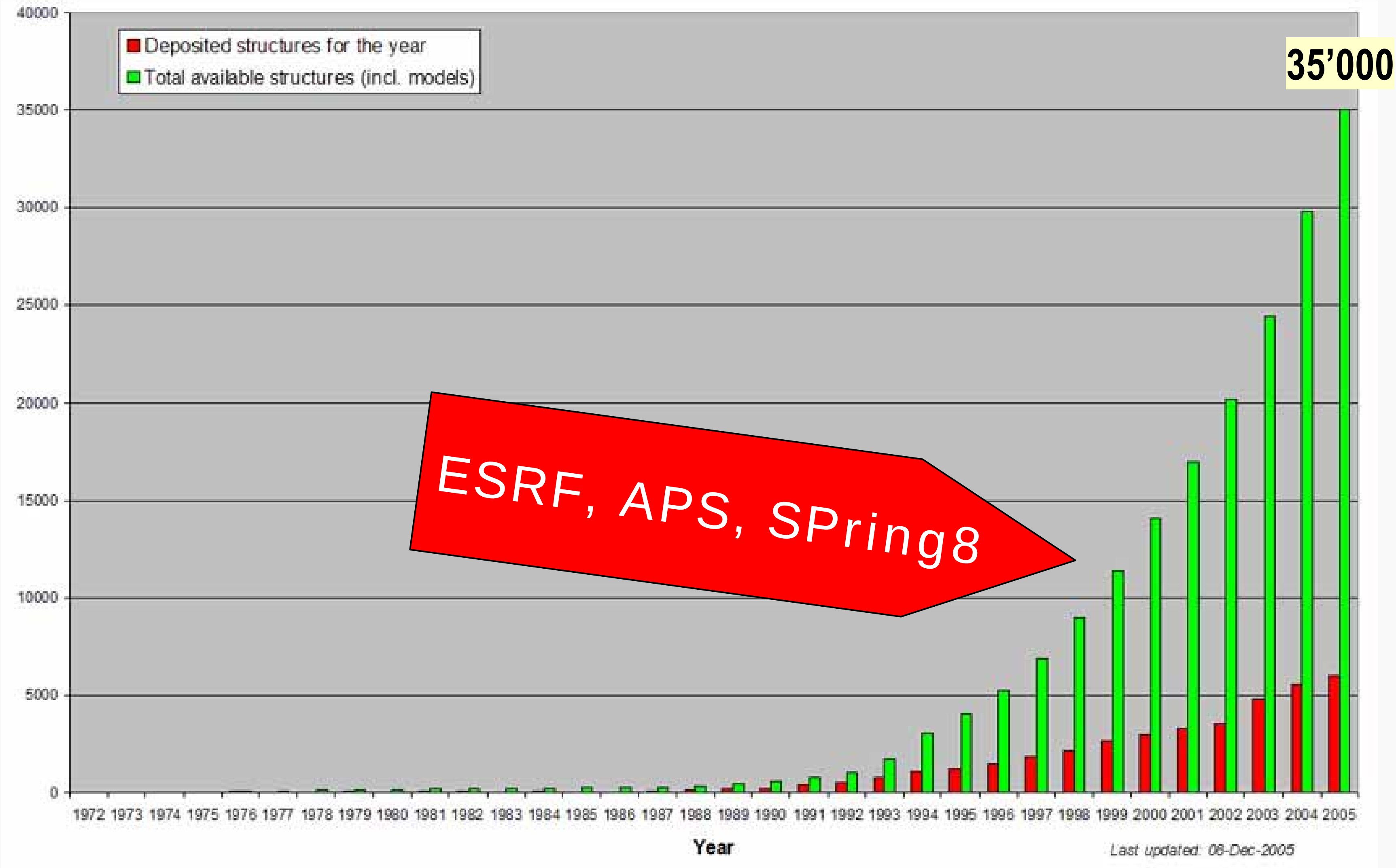




Diffraction pattern



Spectacular growth of structural biology



Higher brightness:

more photons on small sample

- measuremens on very small probes
  (few μm crystals)

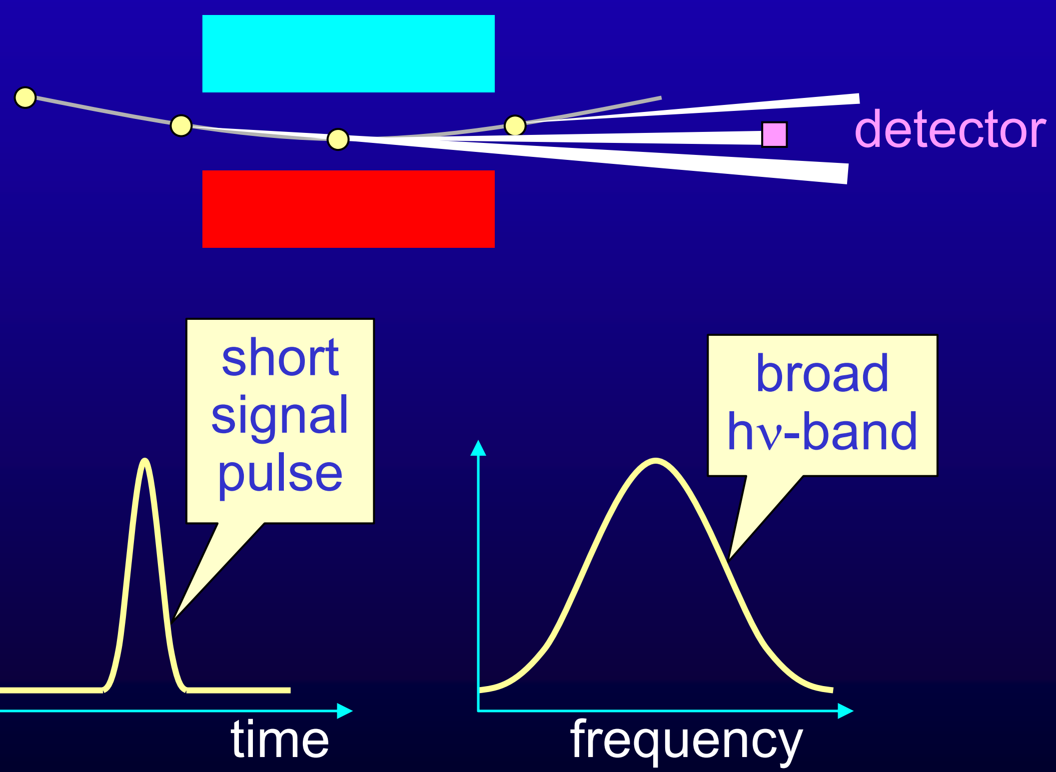
- small divergence:
  - compact mirrors, optics elements
  - minimized aberrations

- short measurment times

- high transverse coherence
  - phase contrast imaging

3 types of storage ring sources:

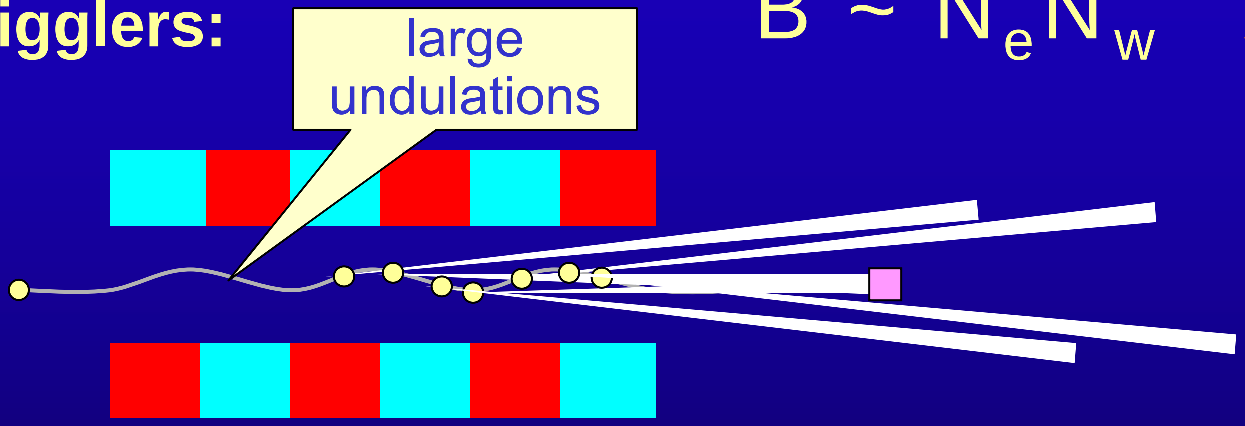
1. Bending magnets: $B \sim N_e$

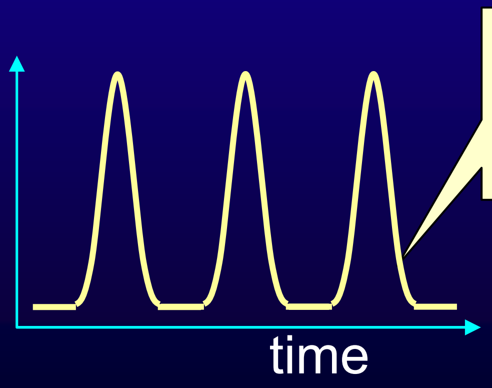


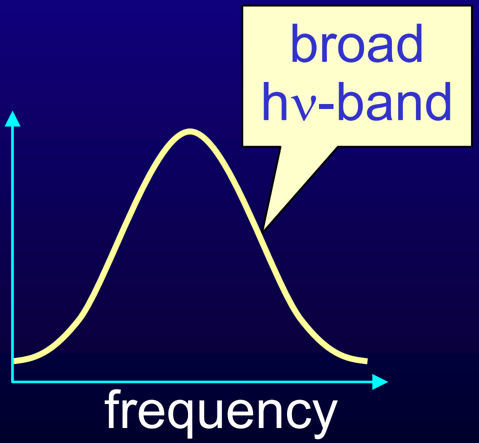
3 types of storage ring sources:

2. Wigglers:

$B \sim N_e N_w$ x10

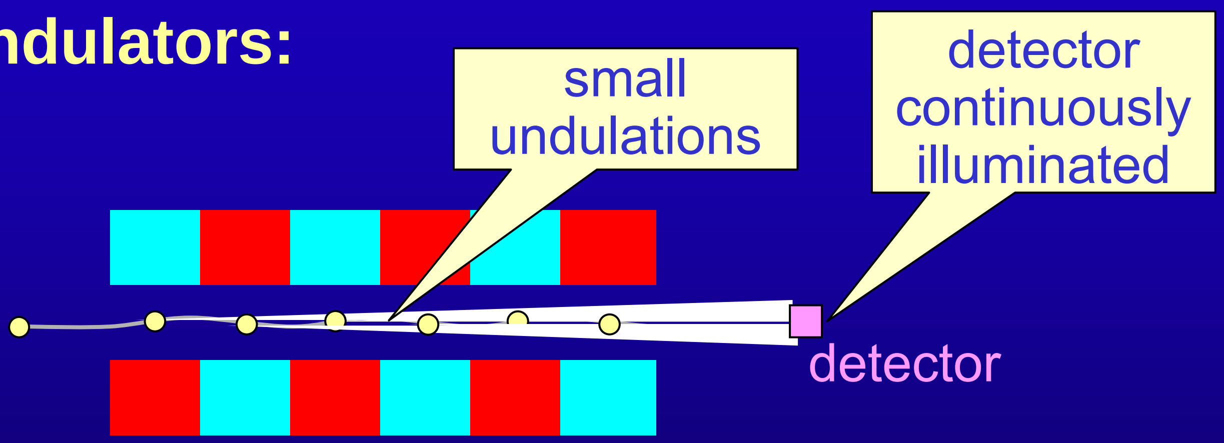




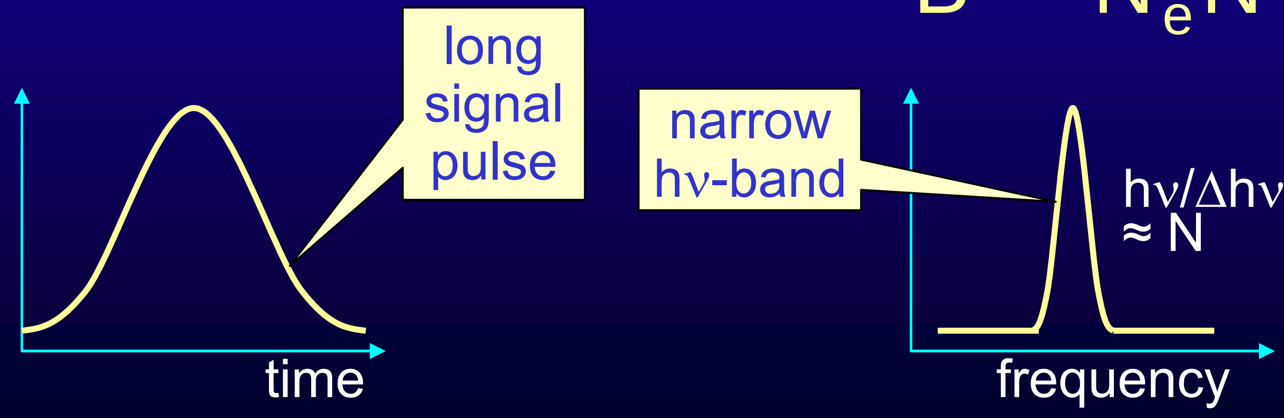


3 types of storage ring sources:

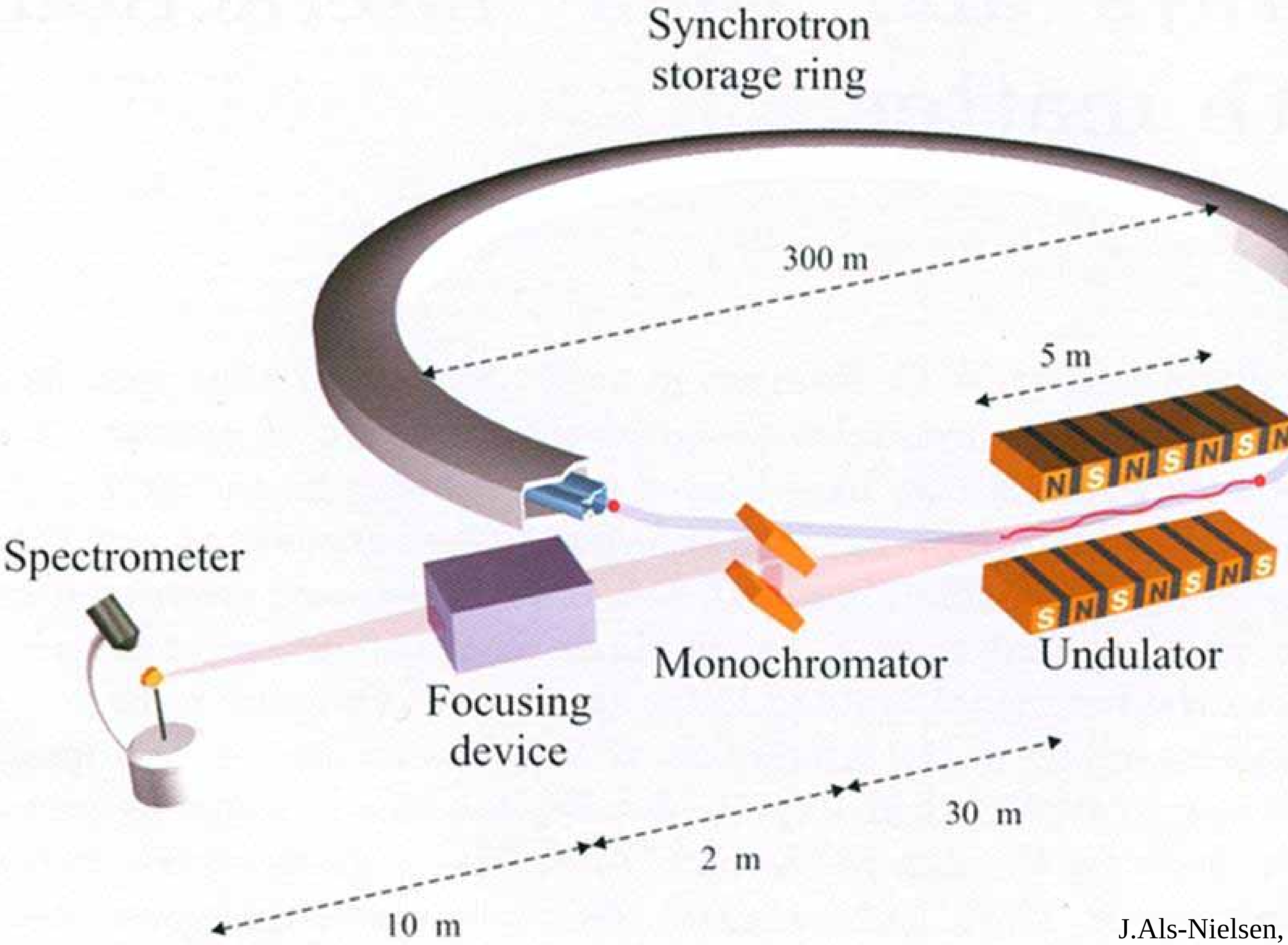
3. Undulators:



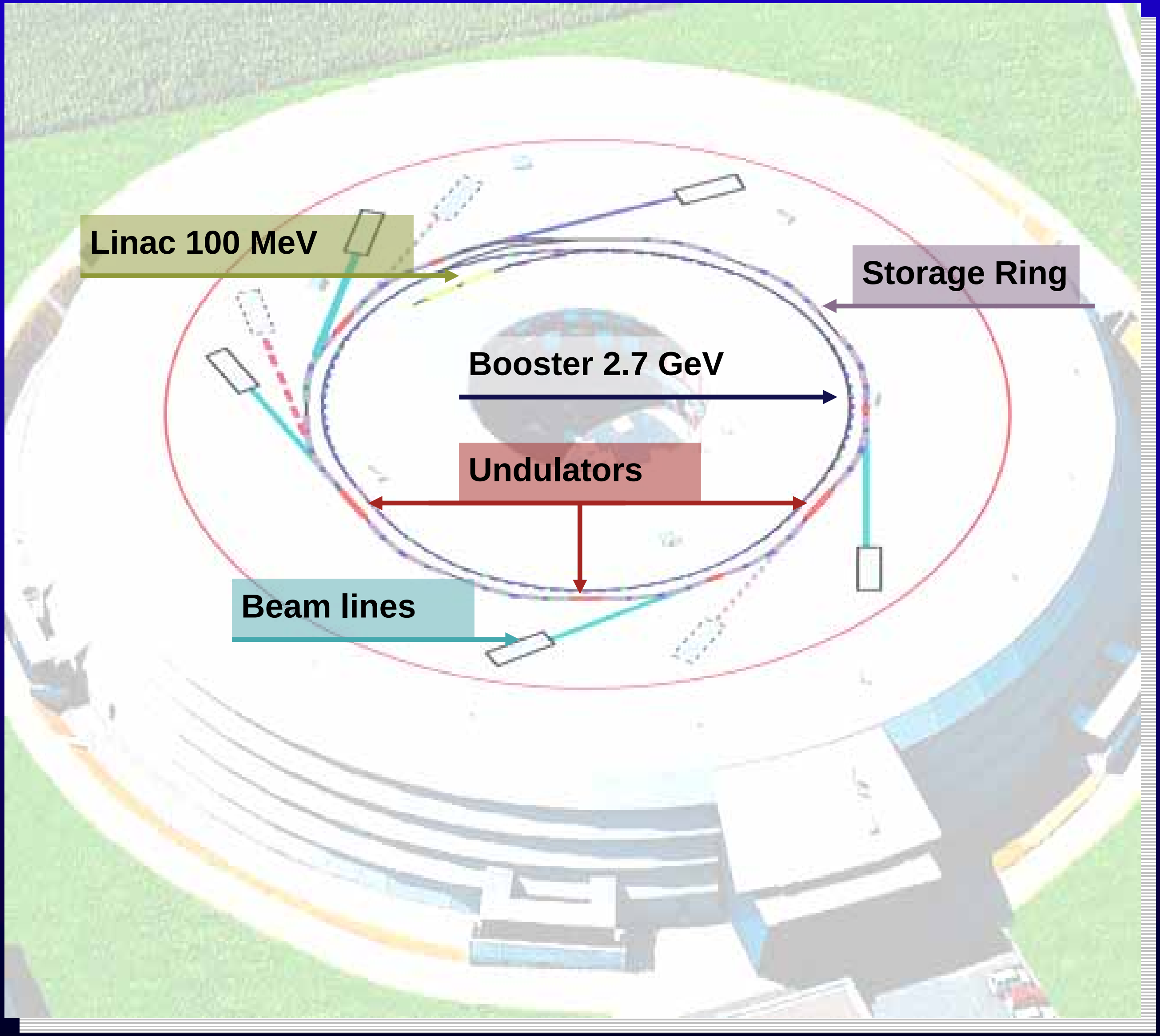
$$B \sim N_e N_u^2 \quad x10^3$$



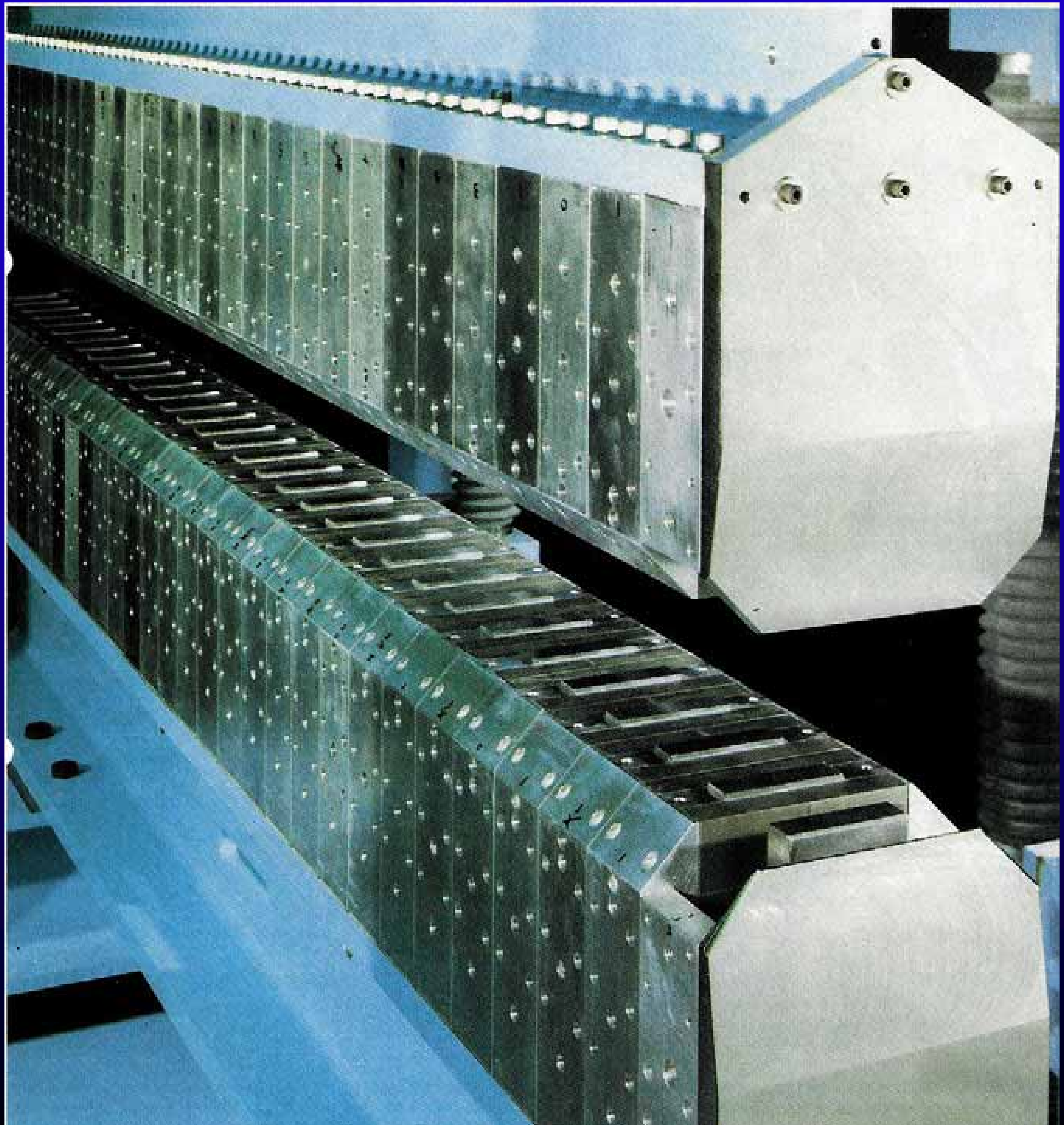
About 60 ring sources world-wide



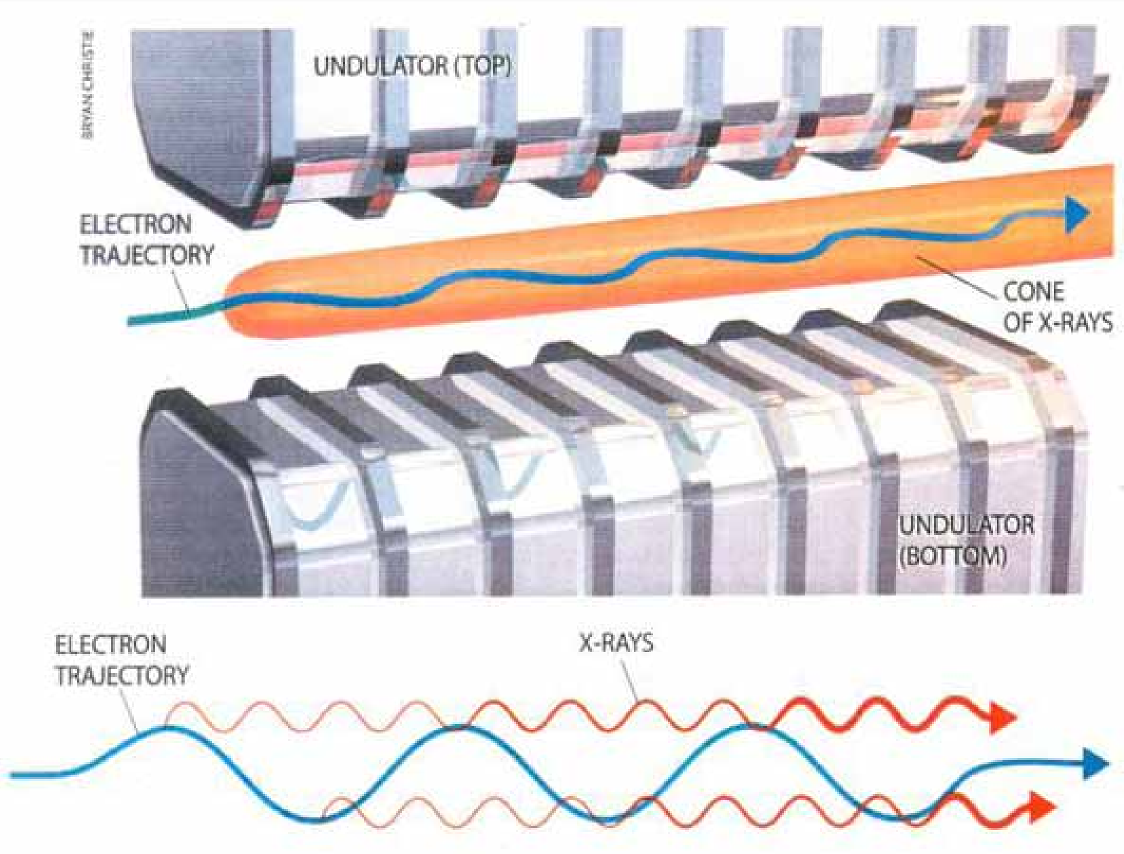
J.Als-Nielsen, Des Mc Morrow


Linac 100 MeV
Storage Ring
Booster 2.7 GeV
Undulators
Beam lines

Electromagnetic undulator, long periods (212 mm)



Undulators

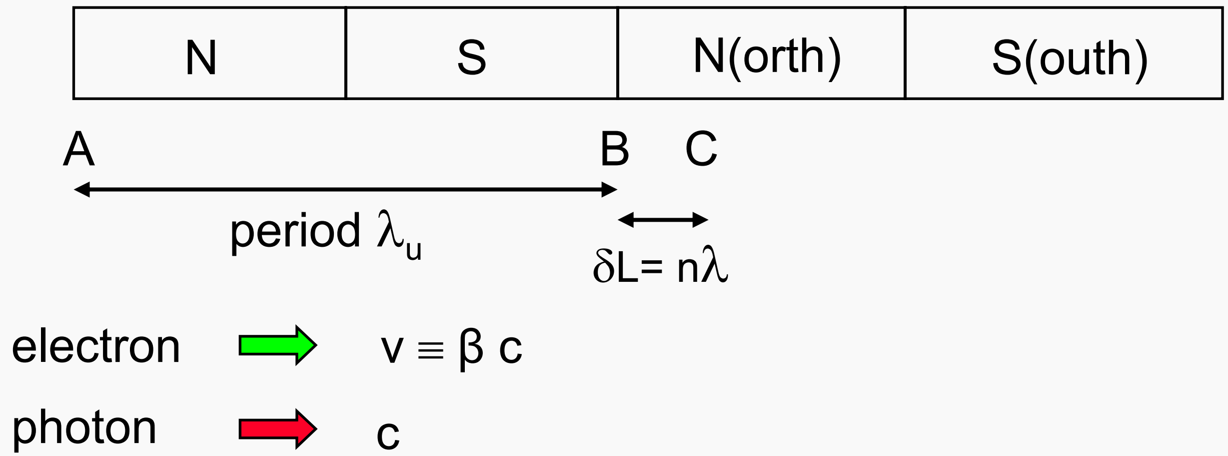


$$T_{obs} = T_{emit}(1 - \beta)$$

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

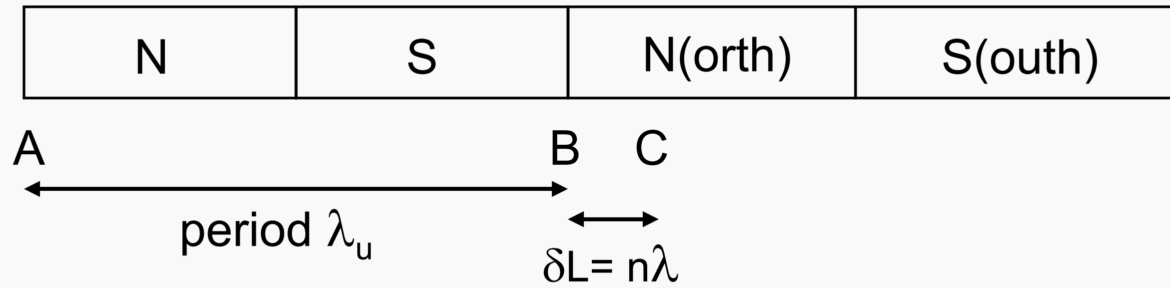
Selection of wavelength in an undulator

In an undulator
an electron
(on a slalom)
races an emitted
photon



at A an electron emits a photon with wavelength λ and flies one period λ_u ahead to B with velocity $v = \beta c$. There it emits another photon with the same wavelength λ. At this moment the first photon is already at C. If the path difference δL corresponds to n wavelengths, then we have a positive interference between the two photons. This enhances the intensity at this wavelength.

Selection of wavelength in an undulator II



electron → $v \equiv \beta c$

photon → c

The path difference $\delta L \equiv n\lambda \approx (1-\beta)\lambda_u \,, \quad 1-\beta \approx \dfrac{1}{2\gamma^2}$

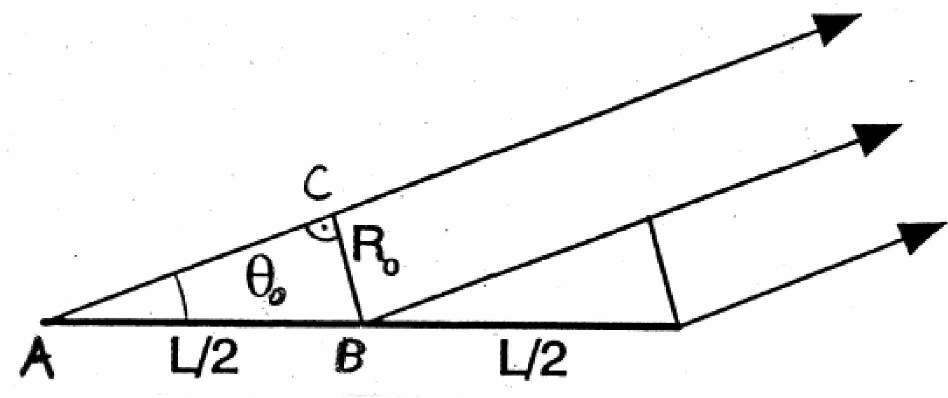
$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

detour through slalom

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

Radiation cone of an undulator

Undulator radiates from ist whole 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.

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

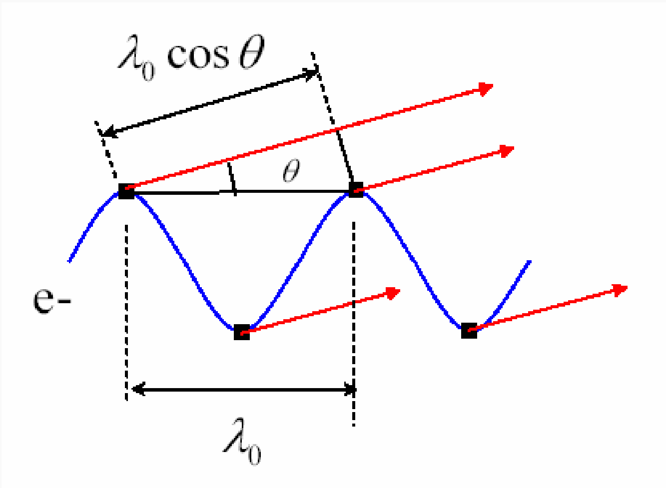
Negative interference for $\Delta L = \frac{\lambda}{2}$

$$\theta_0 = \sqrt{\frac{2\lambda}{L}}$$

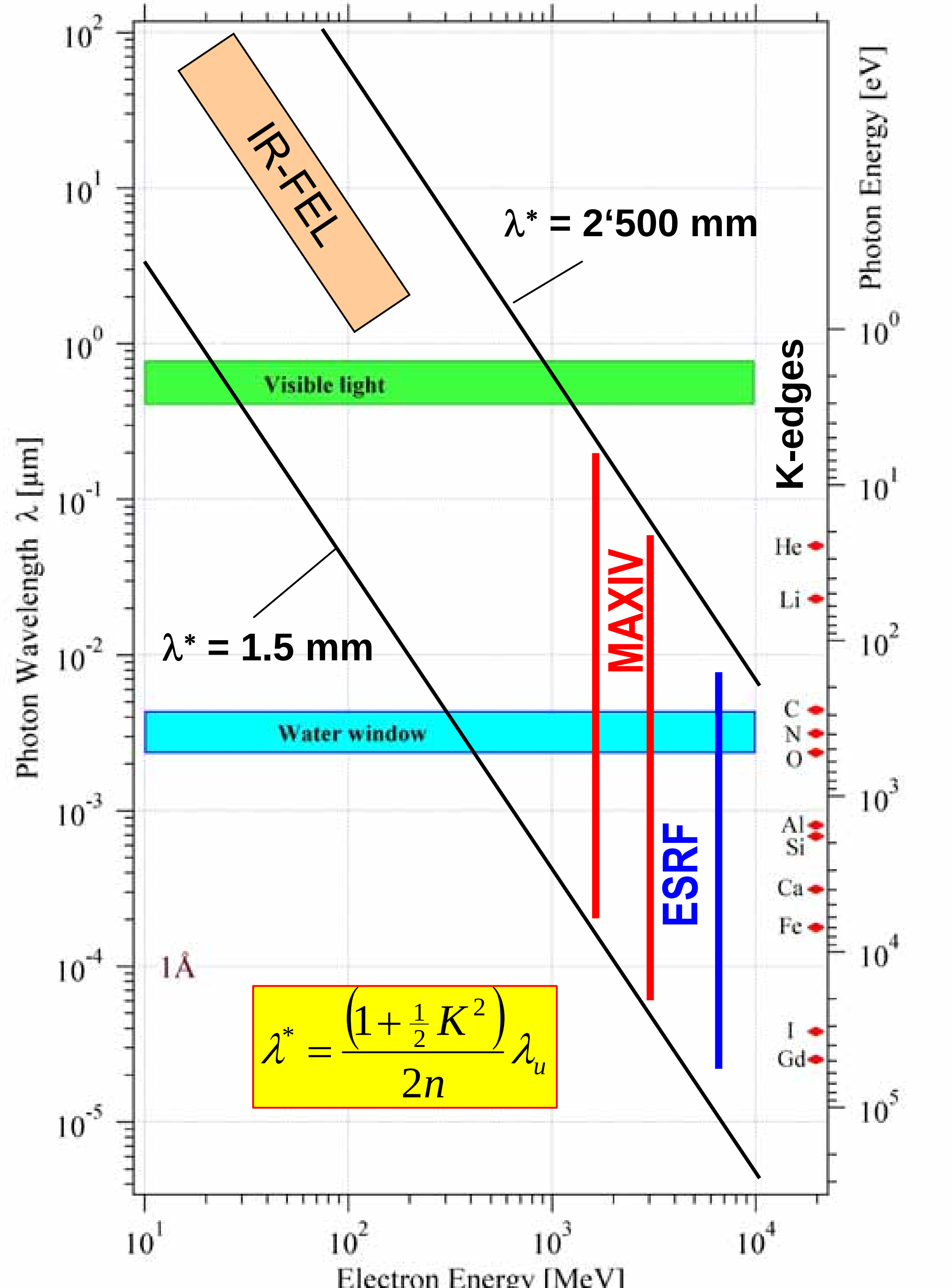
$$R_0 = \sqrt{\frac{\lambda \cdot L}{2}}$$

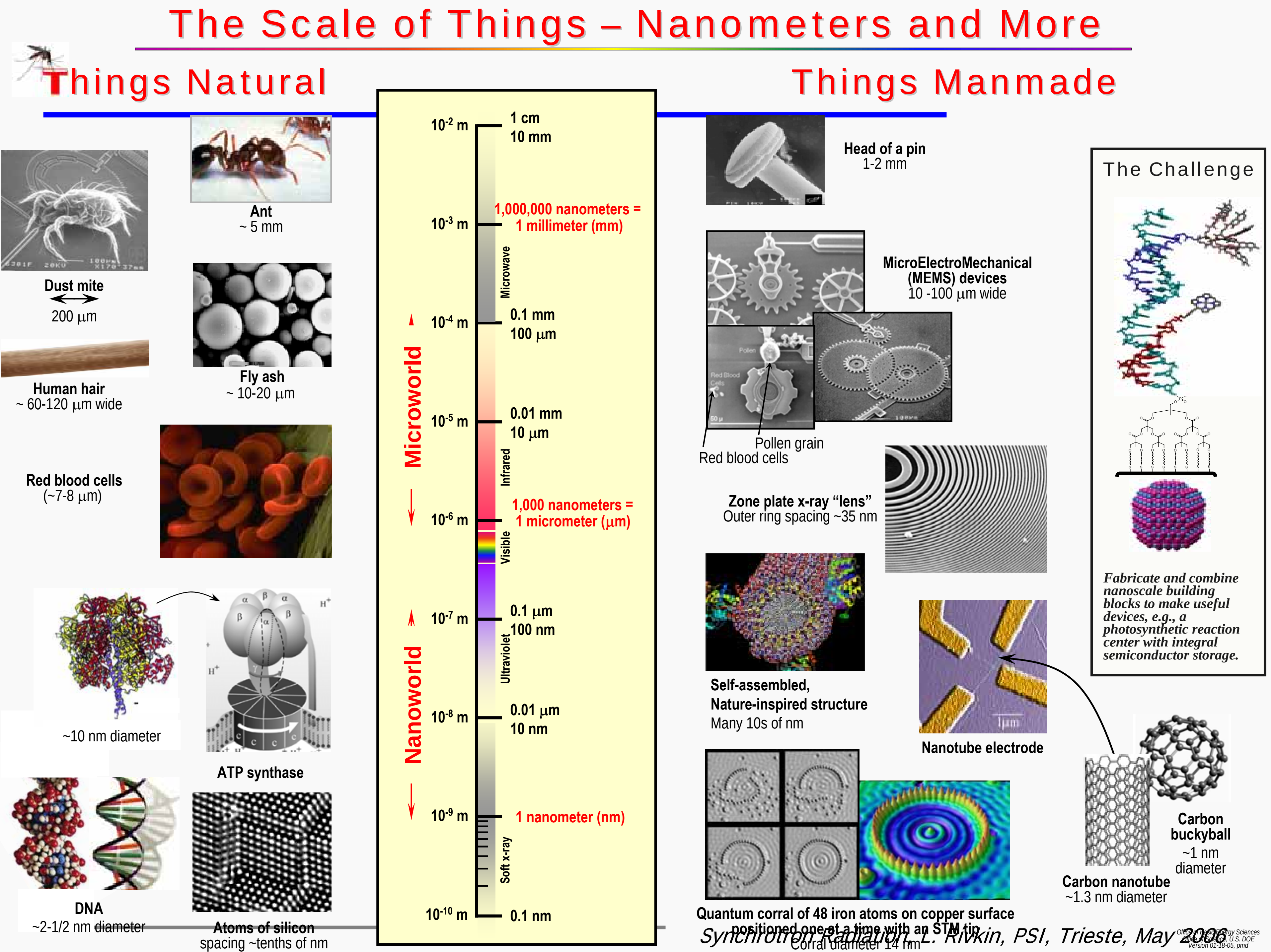
$$\varepsilon_0 = \theta_0 R_0 = \lambda$$

Undulator radiation

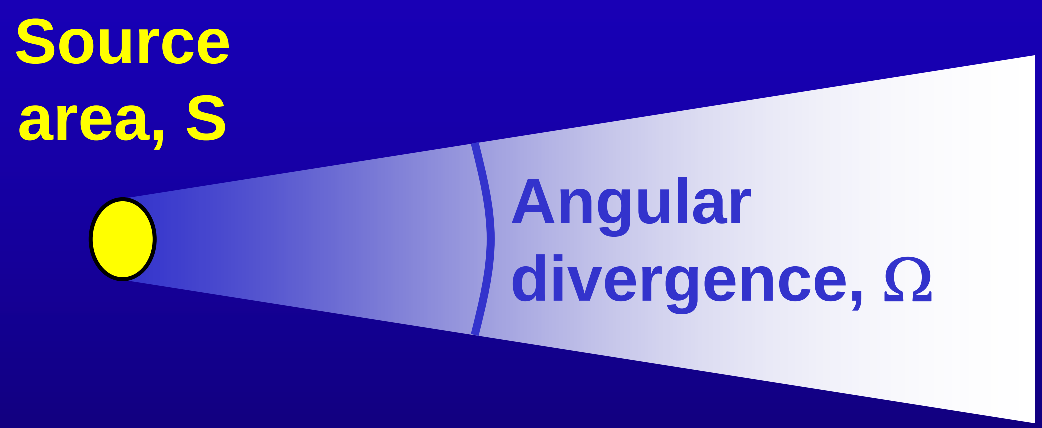


$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$




The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Dust mite
200 µm
Ant
~ 5 mm
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
Microworld
10-5 m
0.01 mm
10 µm
Infrared
10-6 m
1,000 nanometers =
1 micrometer (µm)
Visible
10-7 m
0.1 µm
100 nm
Ultraviolet
Nanoworld
10-8 m
0.01 µm
10 nm
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
Carbon nanotube
~1.3 nm diameter
Carbon
buckyball
~1 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.
Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 01-18-05, pmd

The electron beam “emittance”:



The brightness depends on the geometry of the source, i.e., on the electron beam emittance

Emittance = S x Ω

WHAT DO USERS EXPECT FROM A HIGH PERFORMANCE LIGHT SOURCE ?

- PROPER PHOTON ENERGY FOR THEIR EXPERIMENTS
- BRILLIANCE →
- STABILITY

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

FIGURE OF MERIT

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

$$\Sigma_x \Sigma_{x'} \approx \sigma_x \sigma_x' \sim \varepsilon_x$$

Photon beam size (U):

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

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

Undulator based sources

Brightness

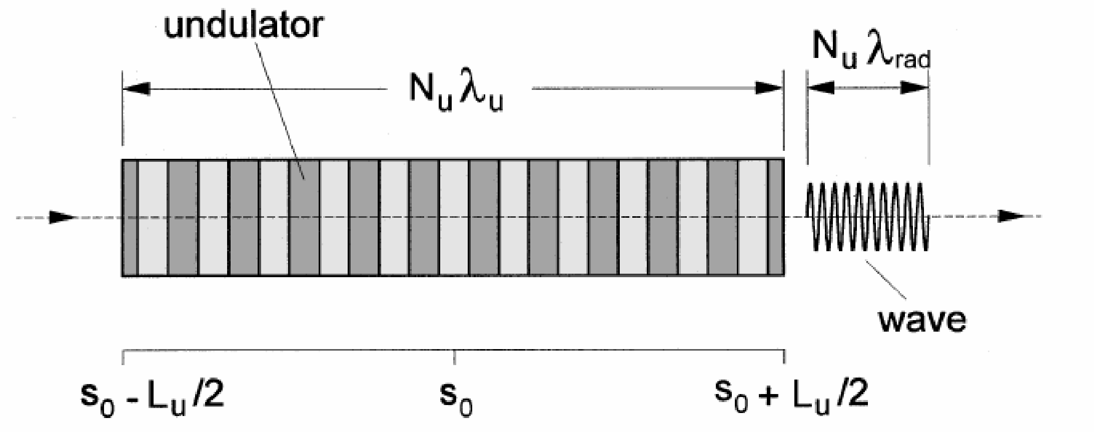
$$B = \frac{N_{ph}}{\Delta t} \cdot \frac{1}{\Delta S \cdot \Delta \Omega} \cdot \frac{1}{\Delta\lambda/\lambda}$$

Flux $N_{ph} \propto N_u$ **(periods)**

The line width $\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u}$ **if** $\frac{1}{N_u} > 2\pi \cdot \frac{\sigma_E}{E}$

If energy spread is small enough $B \sim N_u^2$

Undulator line width



Undulator of infinite length

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

Finite length undulator

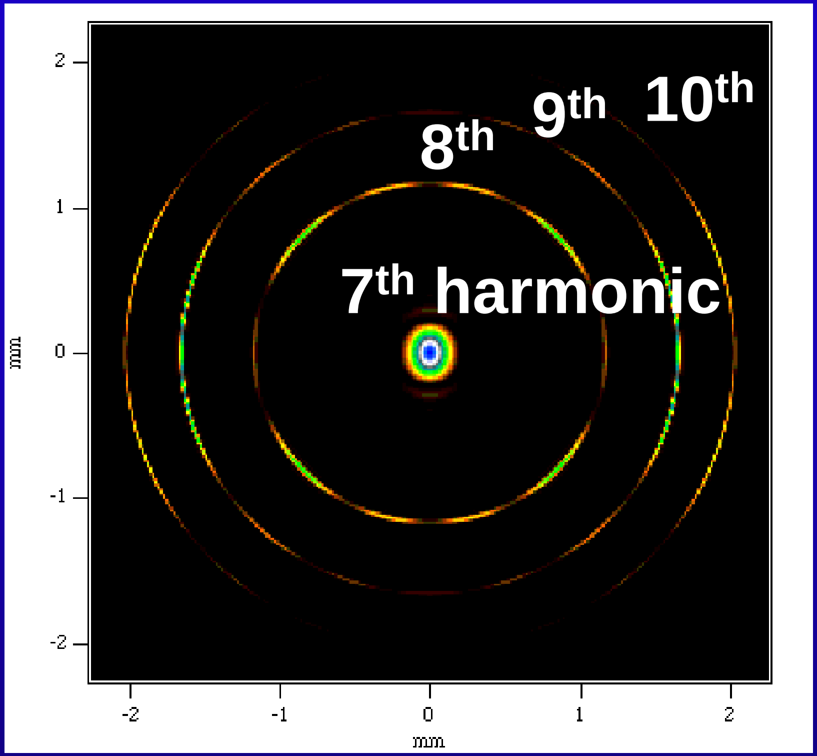
- radiation pulse has as many periods as the undulator
- the line width is

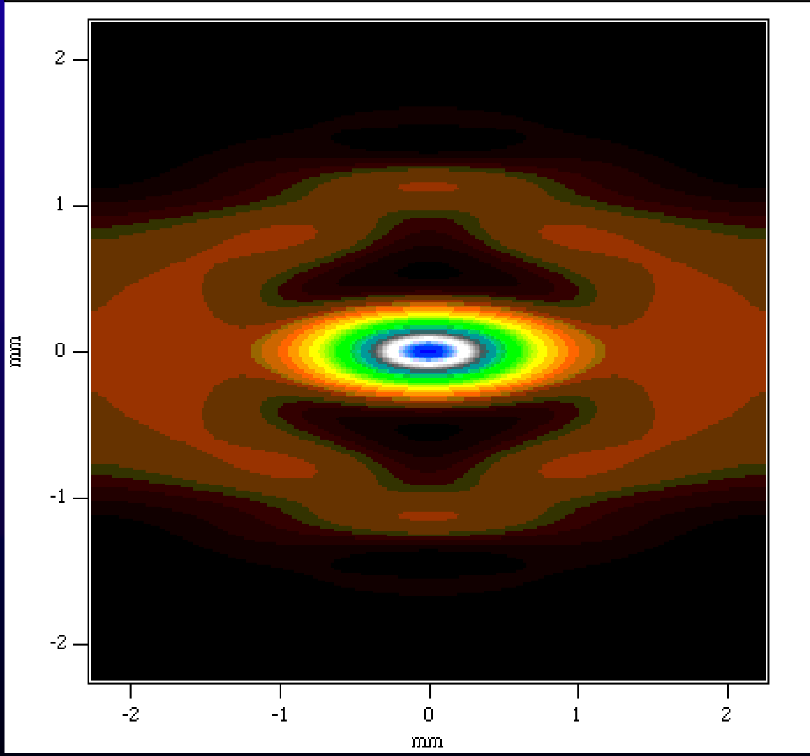
$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u}$$

Due to the electron energy spread

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

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





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

Storage ring based sources

The flagships: ESRF, APS, SPring8

- Proof-of-principle, development of new techniques

Medium energy machines: to serve large user community

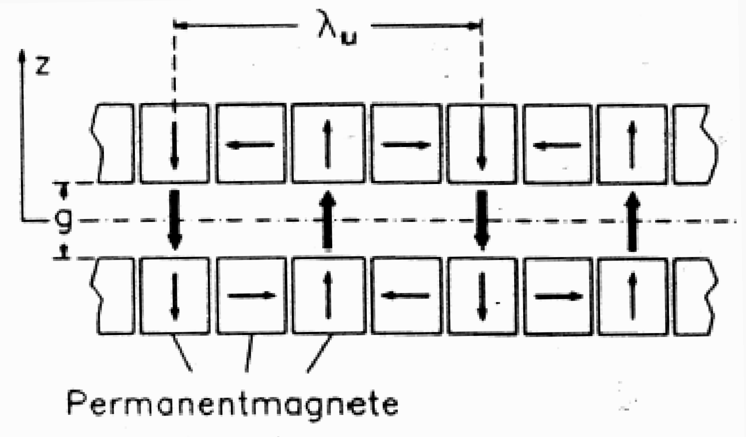
- Short period, small gap undulators
- Use of higher harmonics
- Stability with top-up

Permanent magnet undulators

Permanent magnet materials: $SmCo_5$, NdFeB

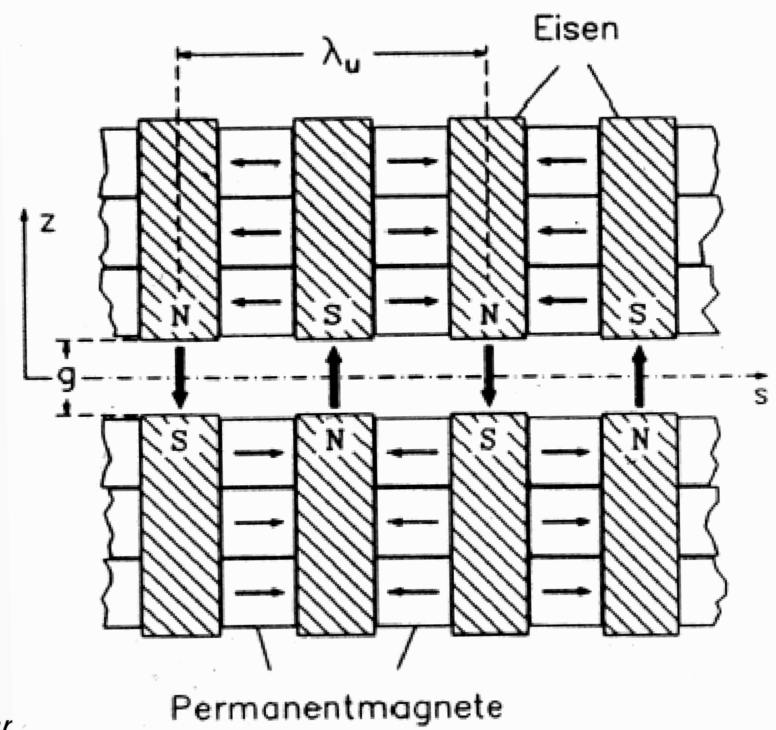
e.g. a pencil made of such material

corresponds to 15‘000 A-turns!



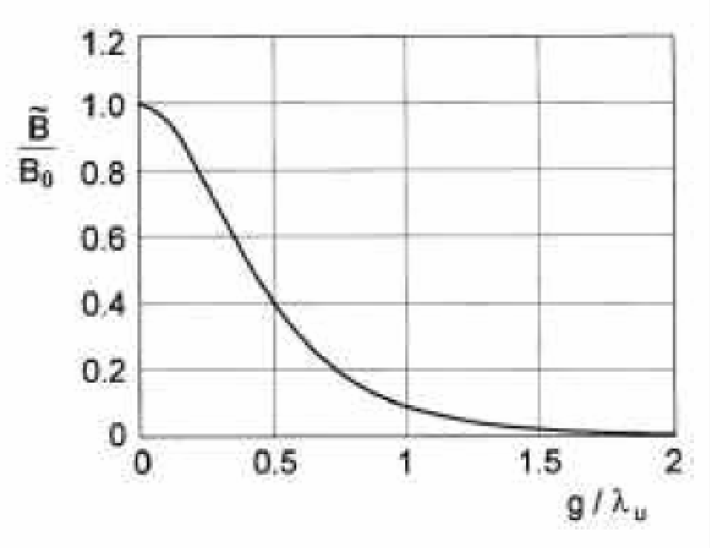
Hybrid undulator:

permanent magnets and iron



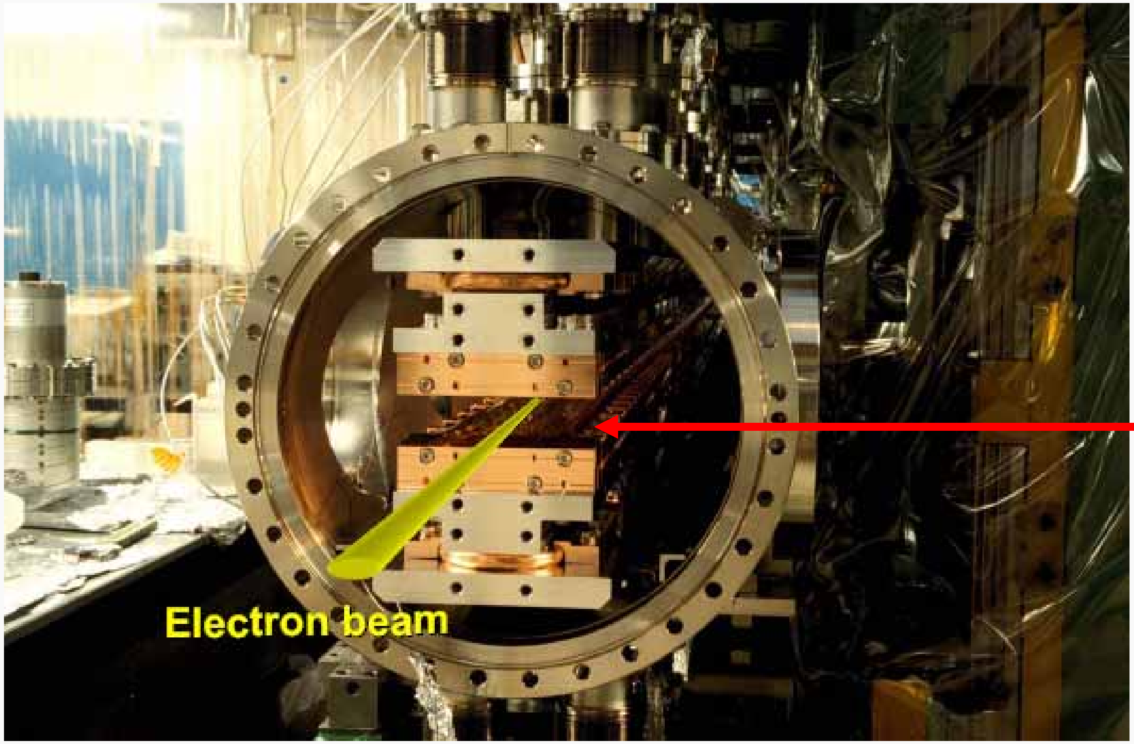
Field tuning with gap

$$B \approx 1.8 \cdot B_r \cdot e^{-\pi \cdot \frac{gap}{\lambda_u}}$$



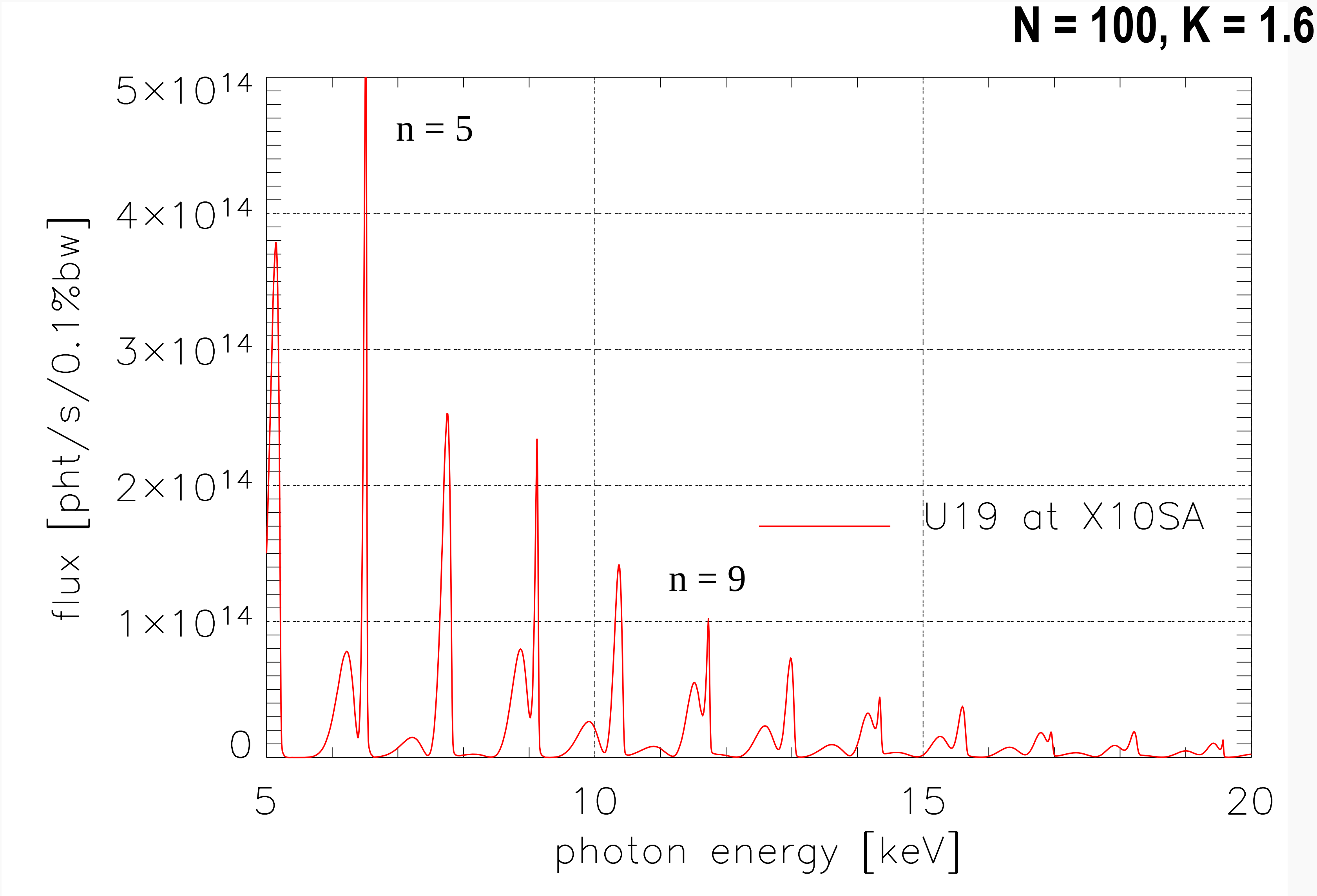
Permanent magnet material	Remanent field [T]
$SmCo_5$	0.9 – 1.0
Sm_2Co_{17}	1.0 – 1.1
NdFeB	1.0 – 1.4

In-vacuum undulators / s.c. undulators

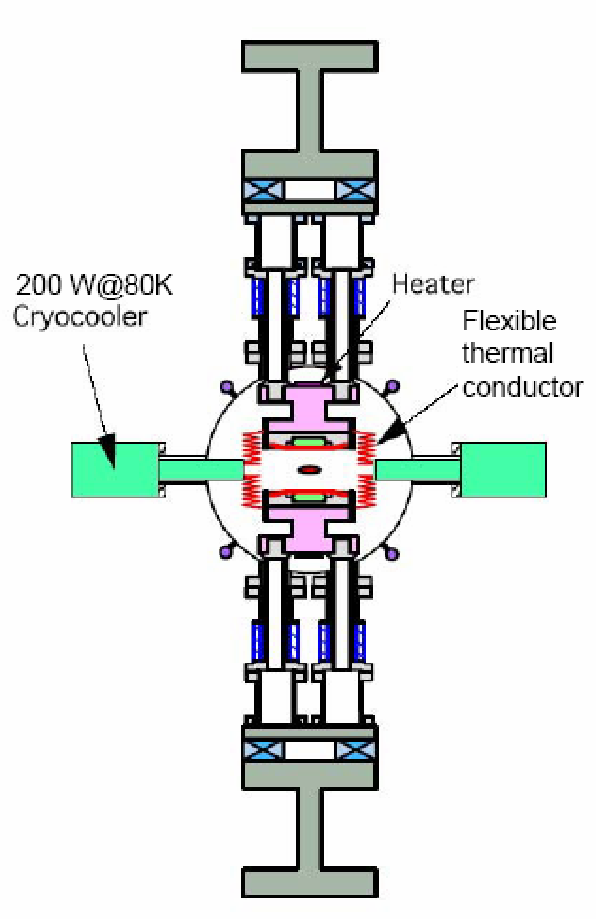


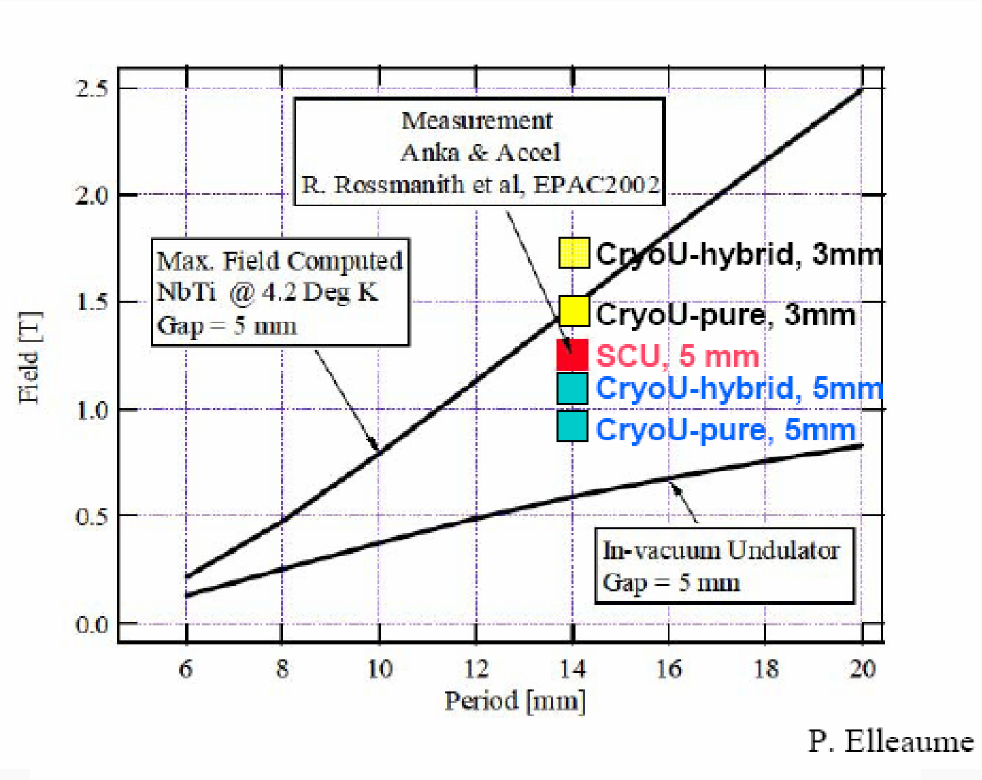
Gaps down to 3 mm

High harmonics with small gap (5 mm)



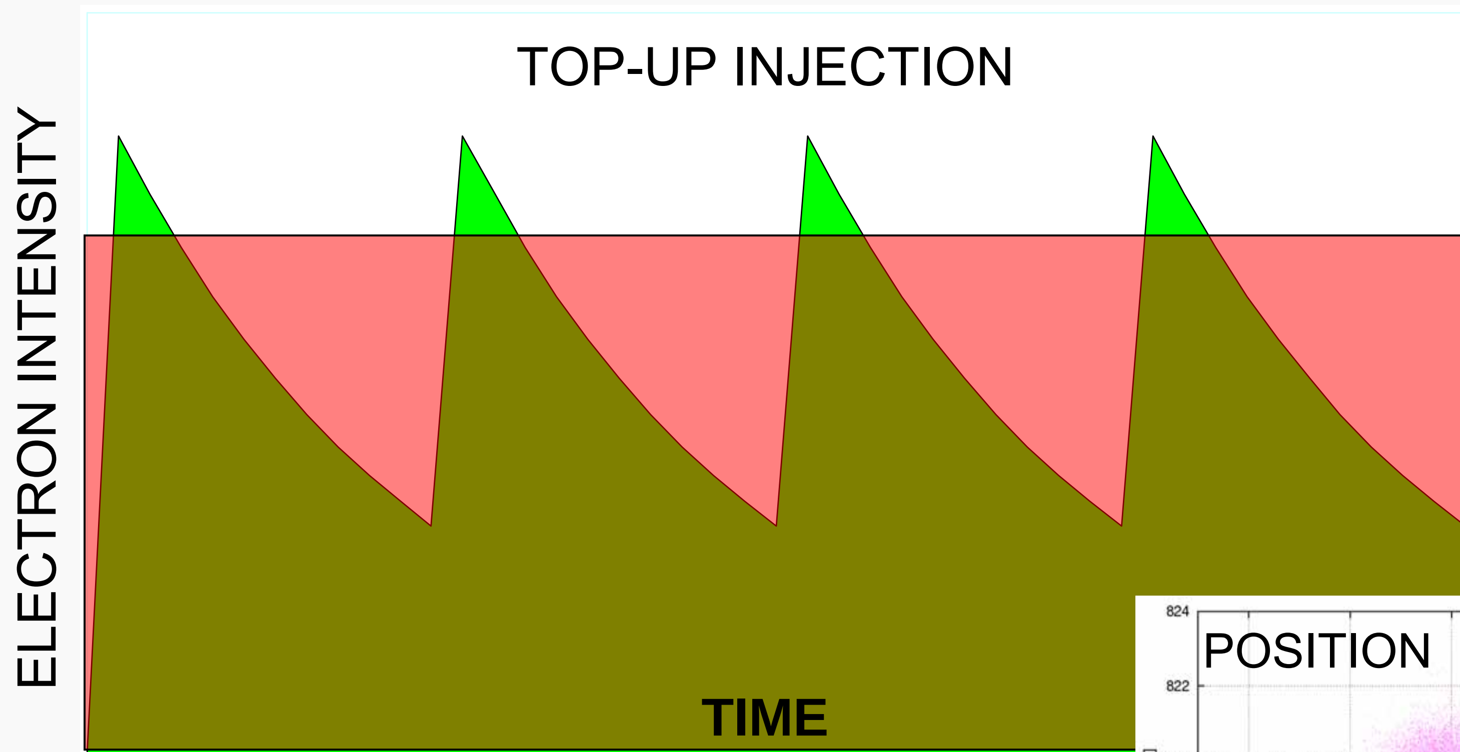
Cryo-cooled undulators

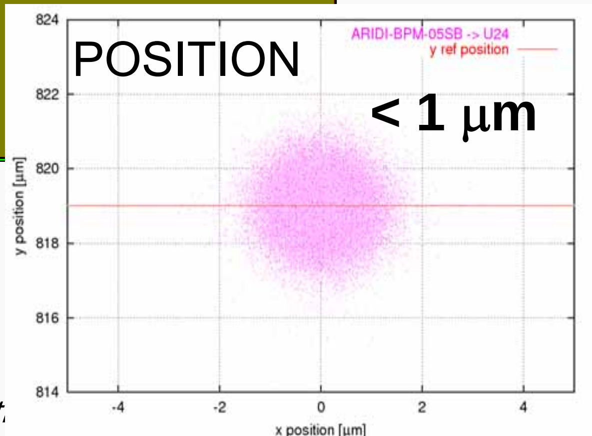




H. Kitamura, SPring-8

INTENSITY STABILITY





Steady state glow at the SLS

Transverse coherence

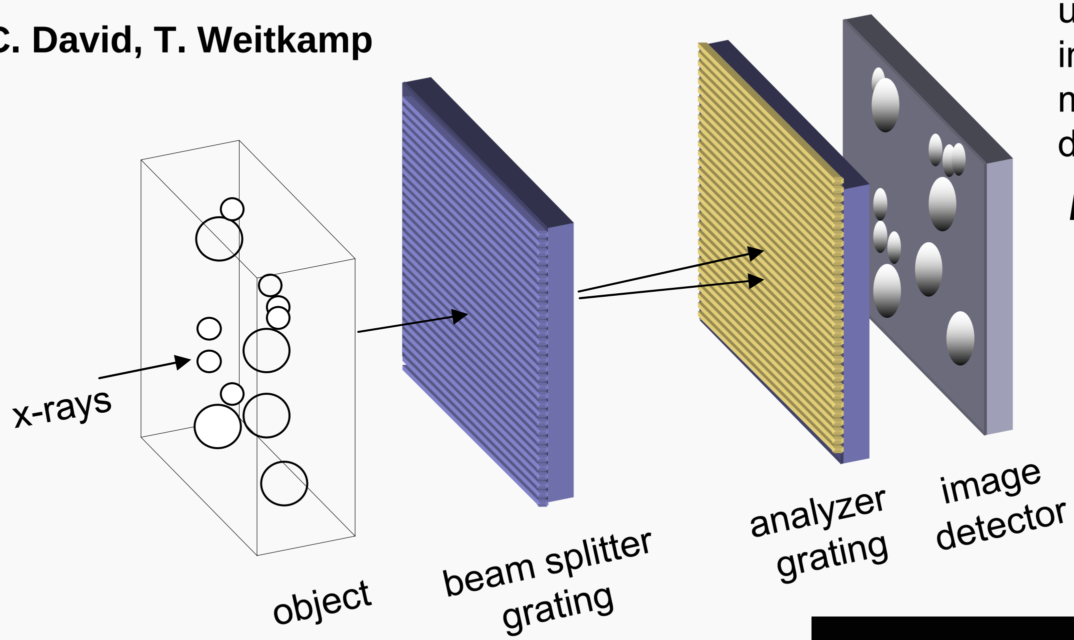
- High brightness gives coherence

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

- Holography

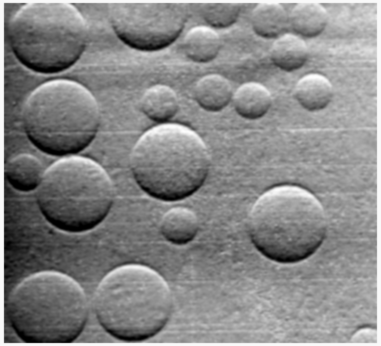
X-ray phase contrast imaging

C. David, T. Weitkamp



using a shearing interferometer based on microfabricated silicon diffraction gratings

F. Pfeiffer et al., PRL 94, April 2005



Phase-object example:
100μm and 200μm styrene beads

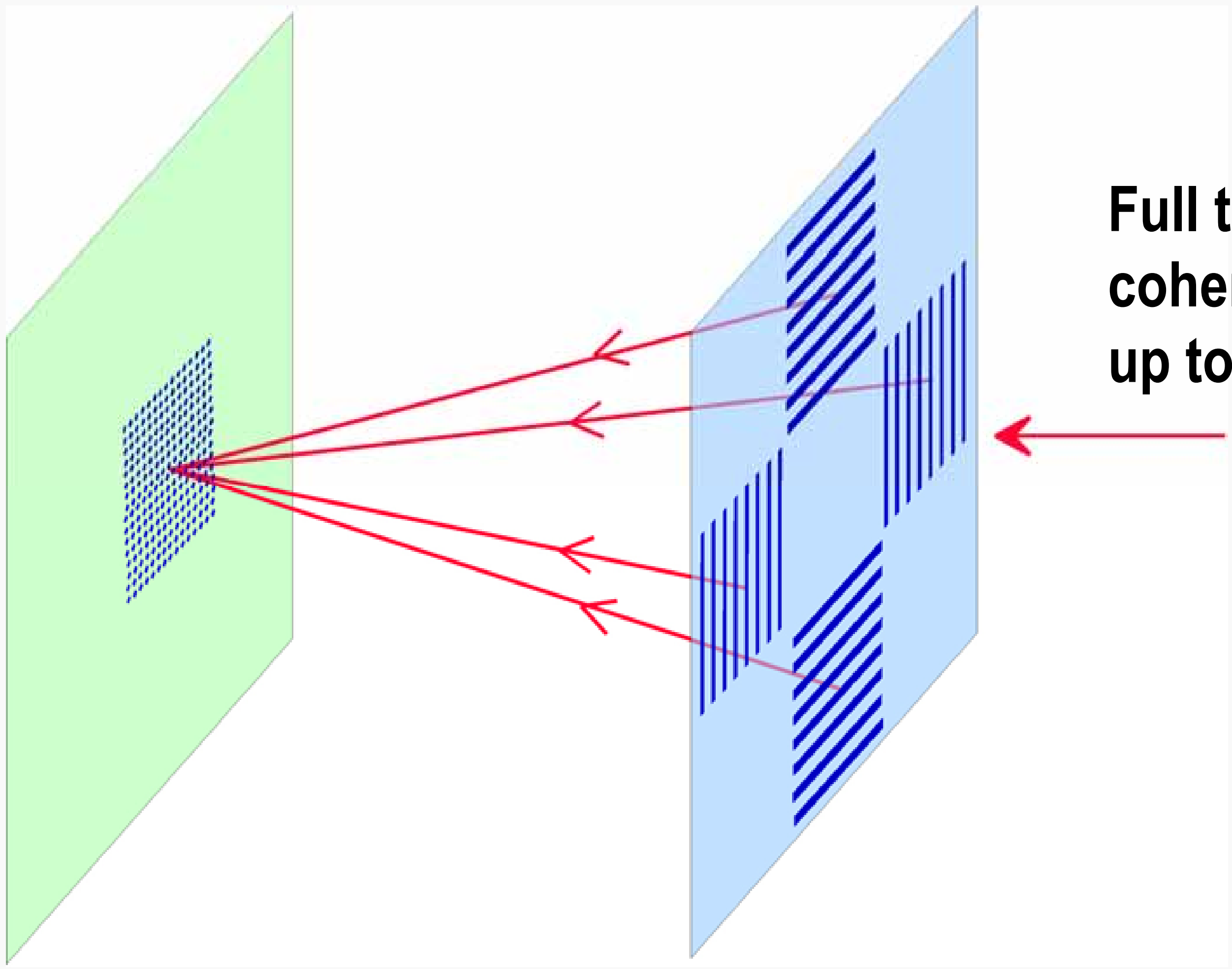
Advantages:

- significantly enhanced contrast compared to conventional "absorption-mode" for light materials
- High potential in medical diagnosis and research

Tomographic phase reconstruction of a spider

Writing ultra-small structures…

H. Solak, PSI

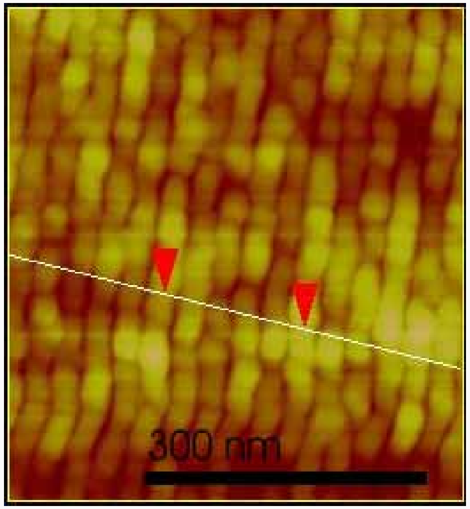


Full transverse coherence up to 90 eV

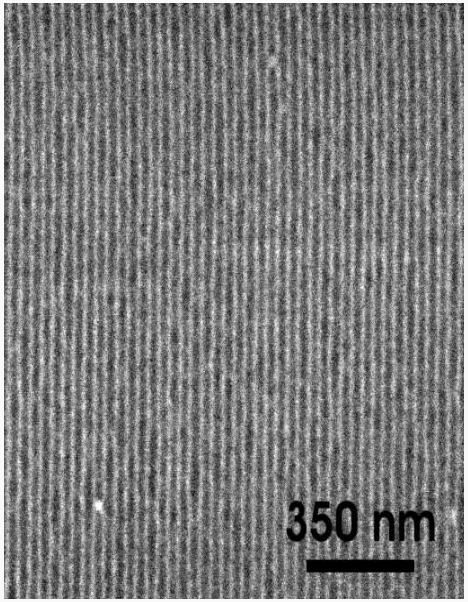
H. Solak, PSI

Record resolution in lithography with photon beams

- Large area **15 nm** resolution (30 nm period)*
- 10nm seems feasible
- Directed self-assembly



AFM of 30 nm period grating (PMMA)



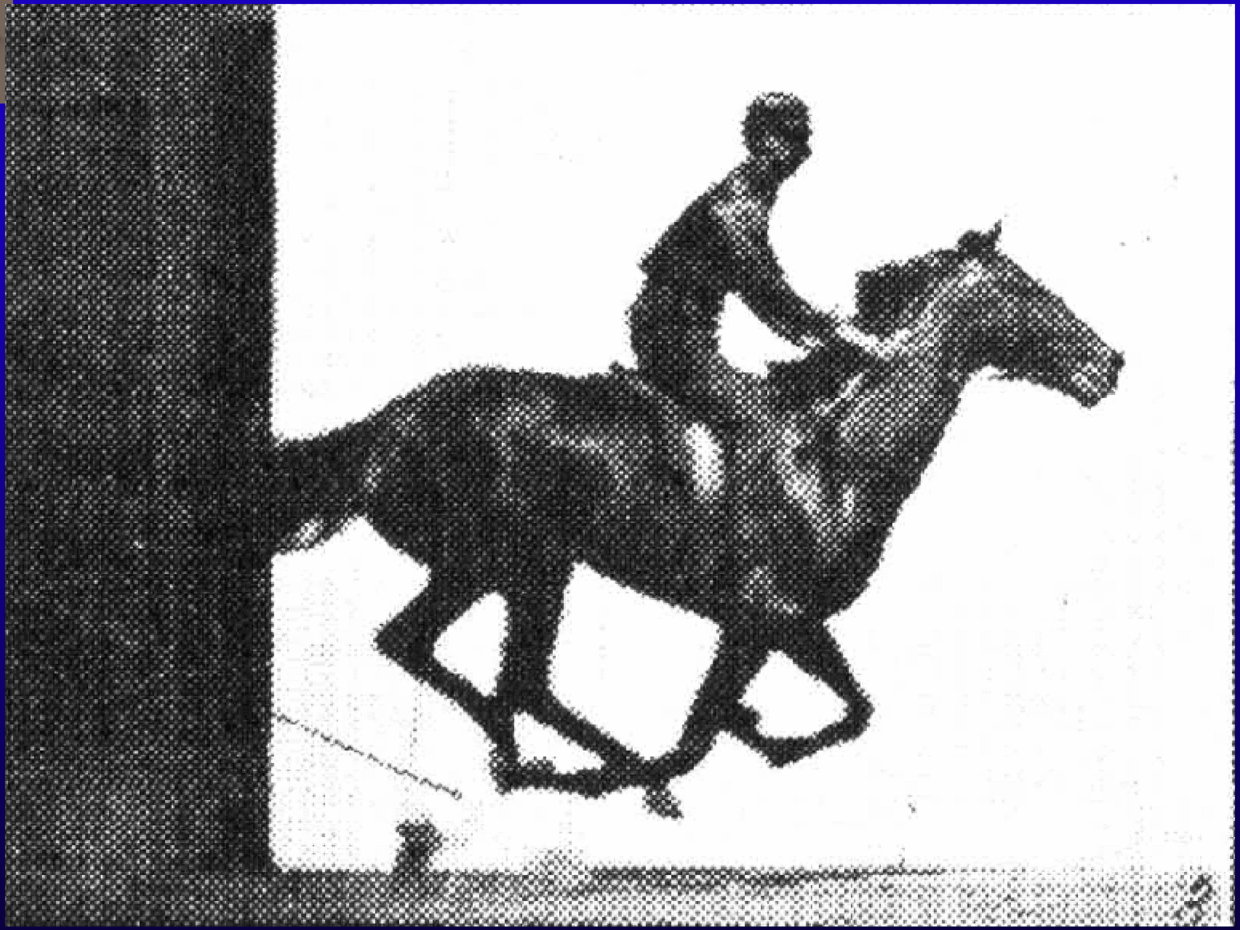
SEM of 35 nm period grating (PMMA)

* Previous record stood at 17.5 nm (D. C. Flanders Appl. Phys. Lett. 36, 93 (1980))

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

E. Muybridge

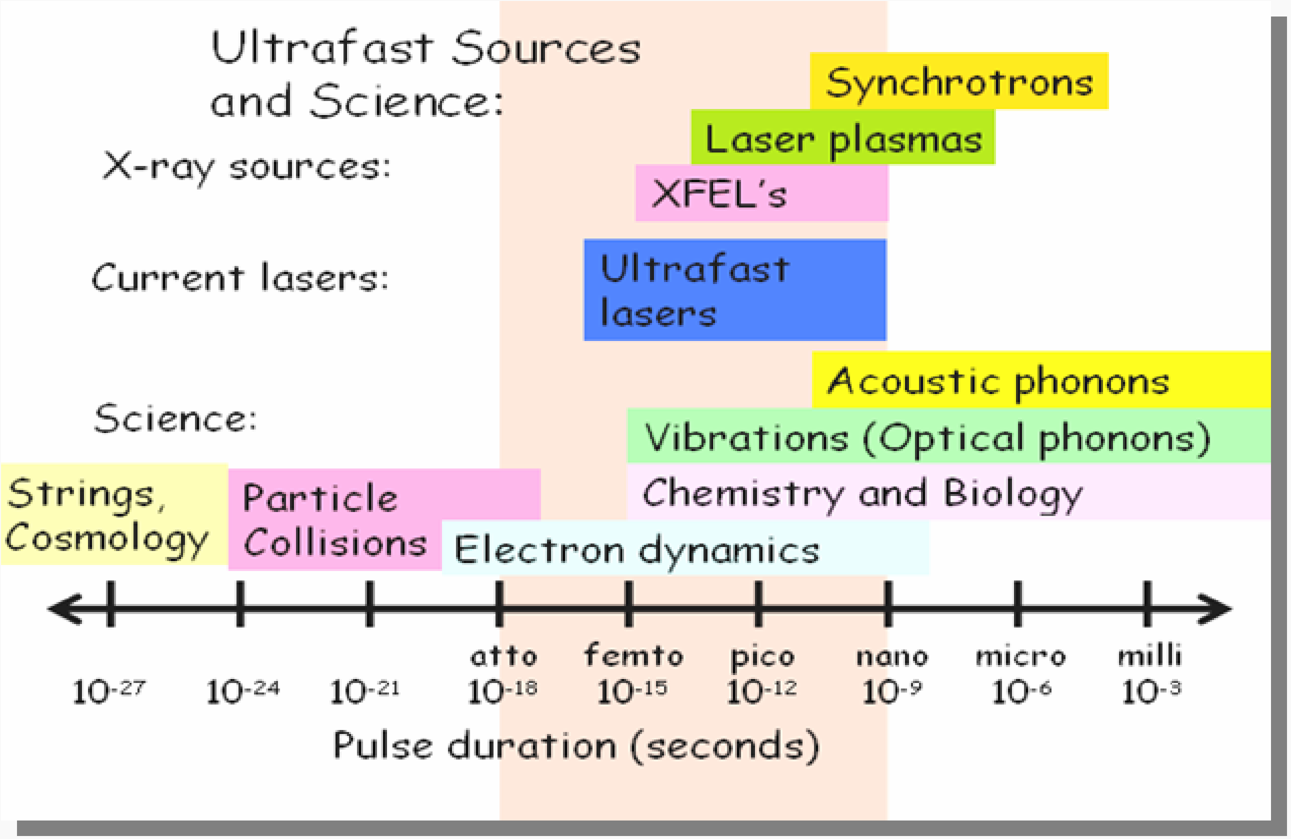


L. Stanford

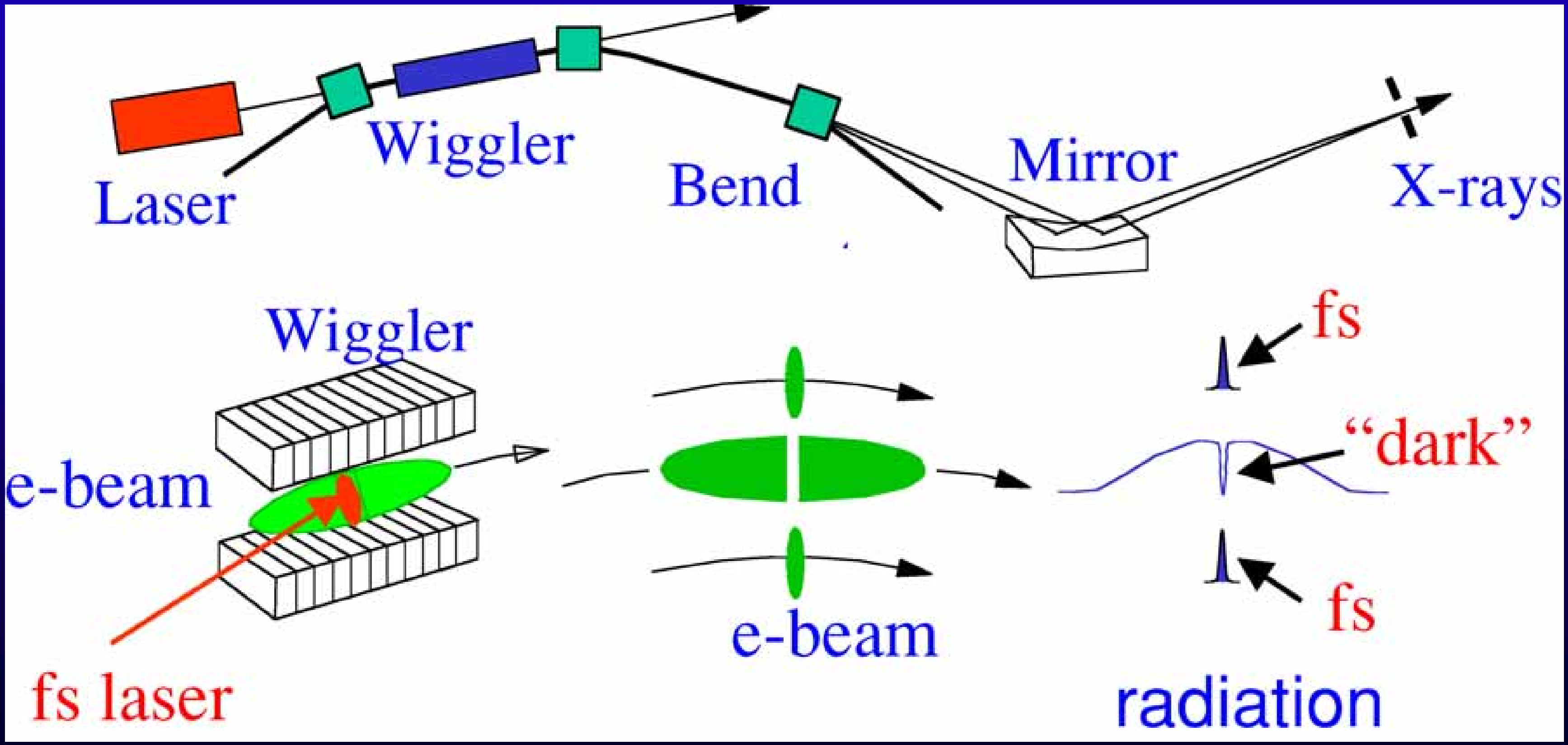
Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

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

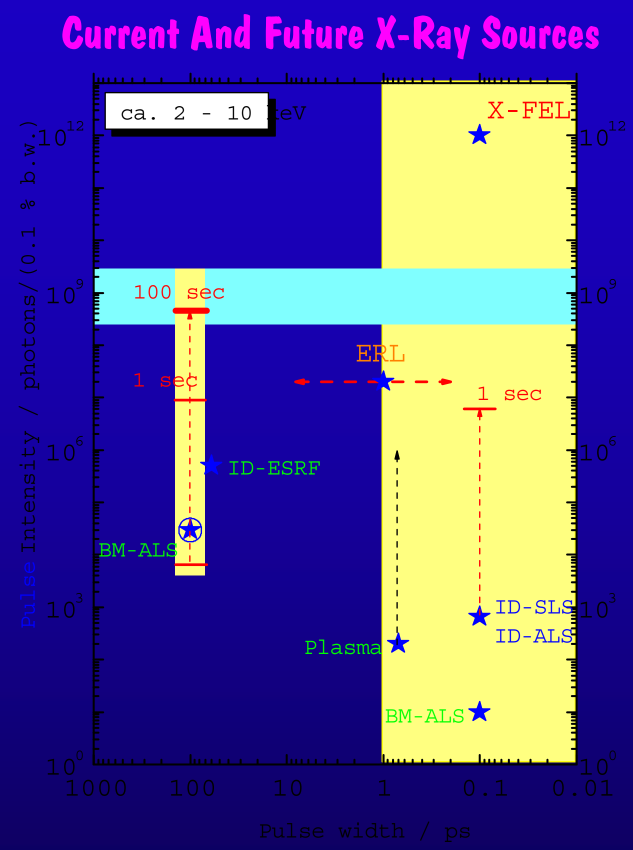
Time resolved studies: the relevant time scales



Laser slicing: fs pulses



Low intensity...



With pump-probe techniques one can accumulate signal. That helps.