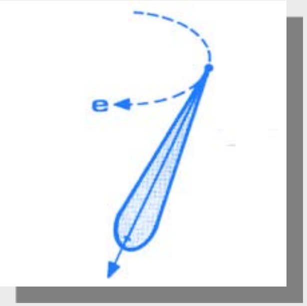


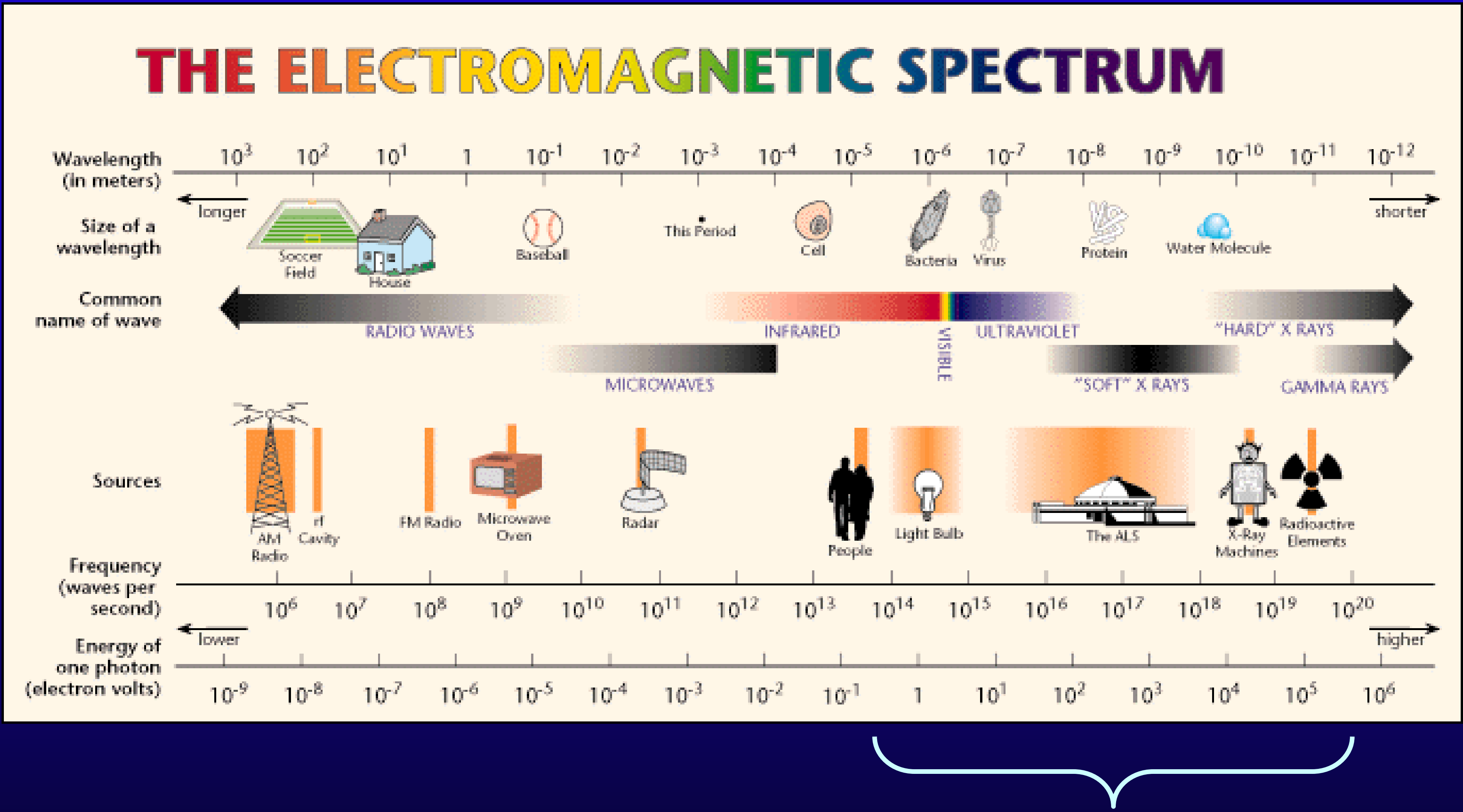
LIGHT SOURCES

Lenny Rivkin

Ecole Polythechnique Federale de Lausanne (EPFL)
and Paul Scherrer Institute (PSI), Switzerland

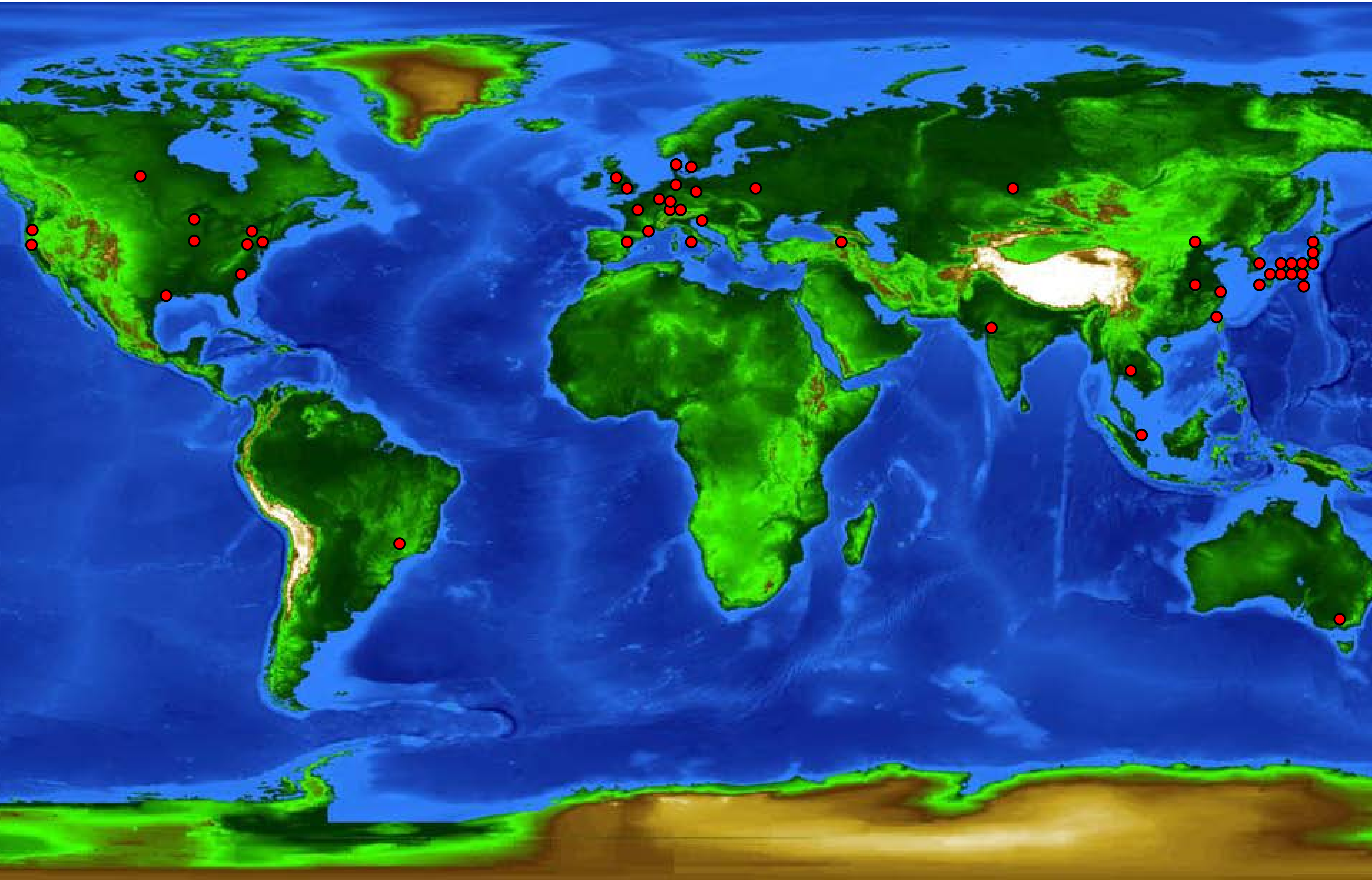
CERN Accelerator School: Introduction to Accelerator Physics

September 28, Varna, Bulgaria



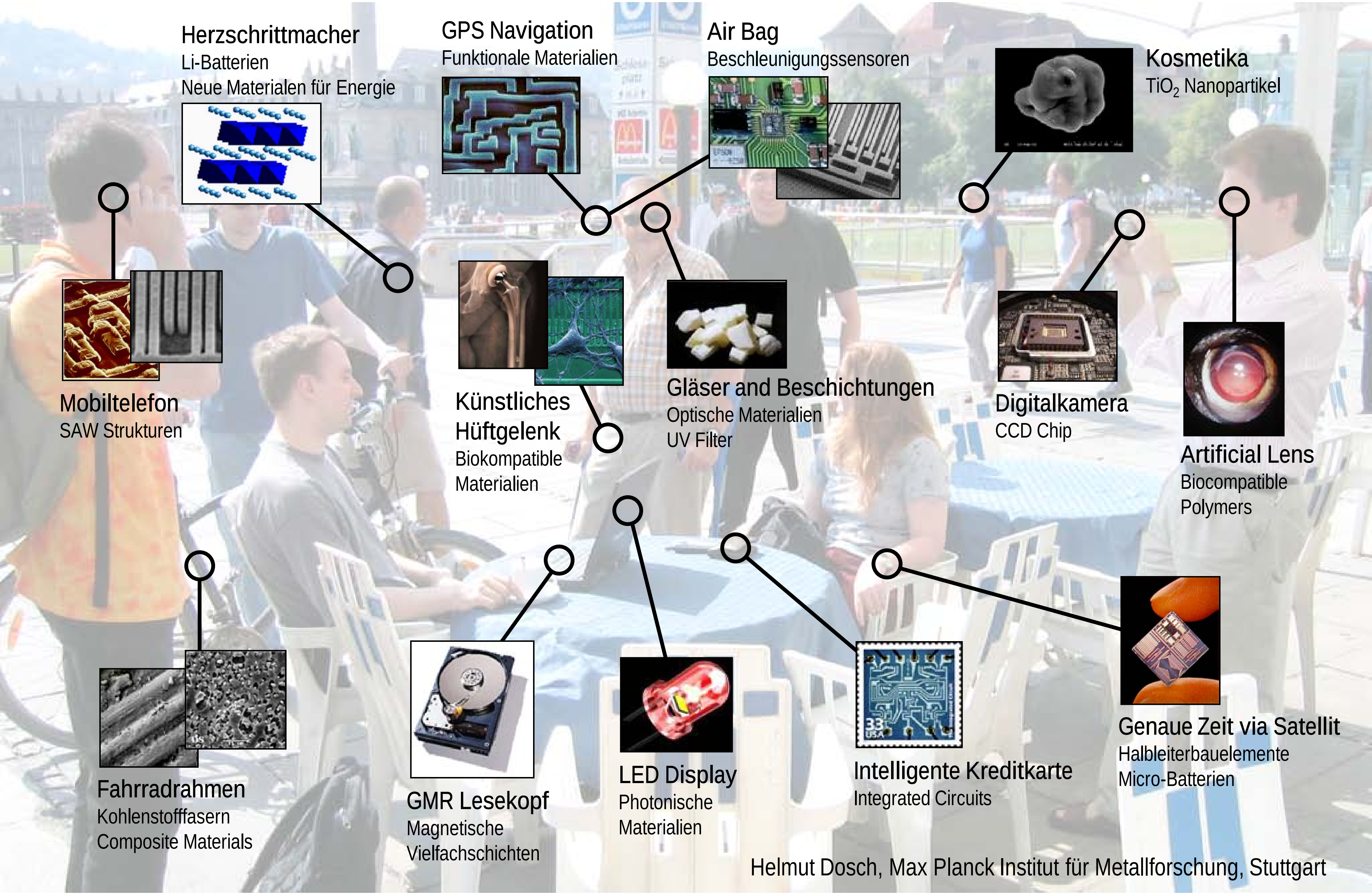
Wavelength continuously tunable !

60‘000 users world-wide



Materials – key to our technologies

Materials – key to our technologies



Herzschrittmacher
Li-Batterien
Neue Materialen für Energie

GPS Navigation
Funktionale Materialien

Air Bag
Beschleunigungssensoren

Kosmetika
TiO_2 Nanopartikel

Mobiltelefon
SAW Strukturen

Künstliches Hüftgelenk
Biokompatible Materialien

Gläser and Beschichtungen
Optische Materialien
UV Filter

Digitalkamera
CCD Chip

Artificial Lens
Biocompatible Polymers

Fahrradrahmen
Kohlenstofffasern
Composite Materials

GMR Lesekopf
Magnetische Vielfachschichten

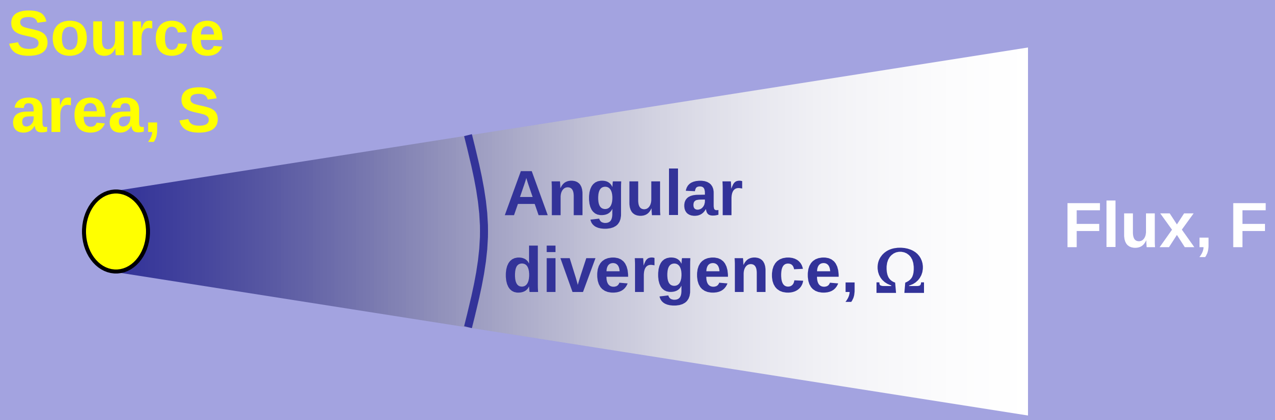
LED Display
Photonische Materialien

Intelligente Kreditkarte
Integrated Circuits

Genaue Zeit via Satellit
Halbleiterbauelemente
Micro-Batterien

Helmut Dosch, Max Planck Institut für Metallforschung, Stuttgart

The "brightness" of a light source:



Source area, S

Angular divergence, Ω

Flux, F

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

G. Margaritondo

Steep rise in brightness

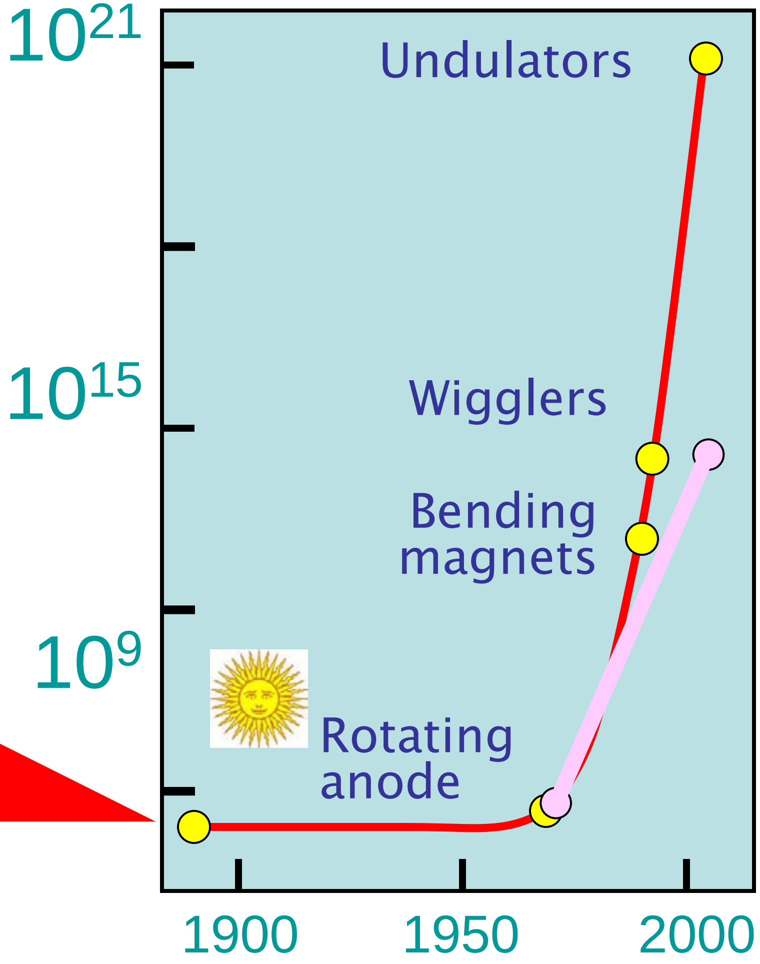
the second wave

SLS
SOLEIL (F)
DIAMOND (UK)
…

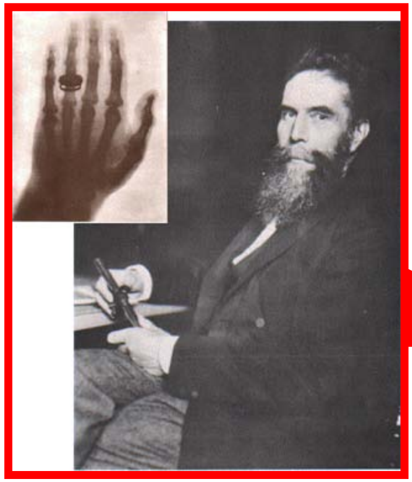
ESRF

SPring8

APS

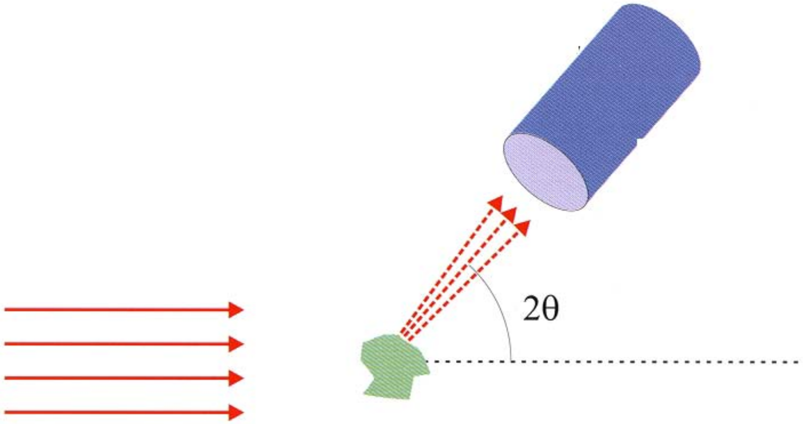


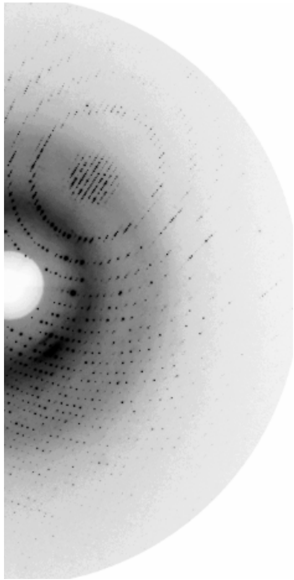
Moore's Law for semiconductors



Bertha Roentgen's hand
(exposure: 20 min)

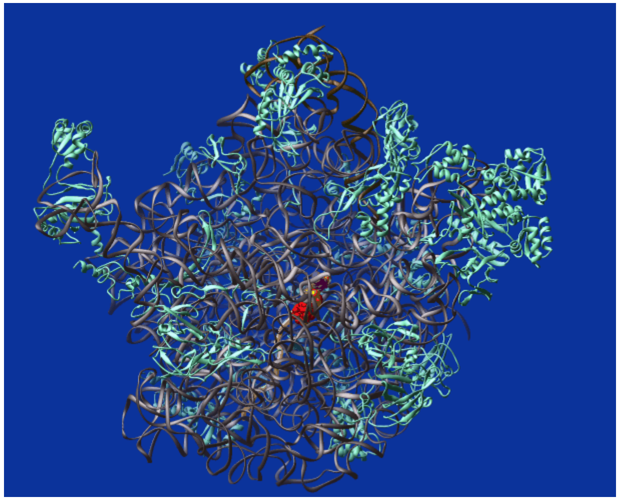
Protein structure





Diffraction pattern

Ribosome



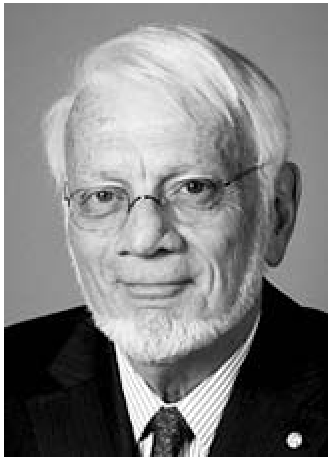
Photons in biology – insight into structures

Visualization of Alzheimer's plaques

In collaboration with M Cacquevel, J-C Bensadoun,
P. Aebischer, Brain and Mind Institute
EPFL, Lausanne, Switzerland

Structure of ribosome and proteins

V. Ramakrishnan



Th. A. Steitz

A. E. Yonath

=

2009

Higher brightness: more photons on small sample or through a pinhole of ~ λ: coherence

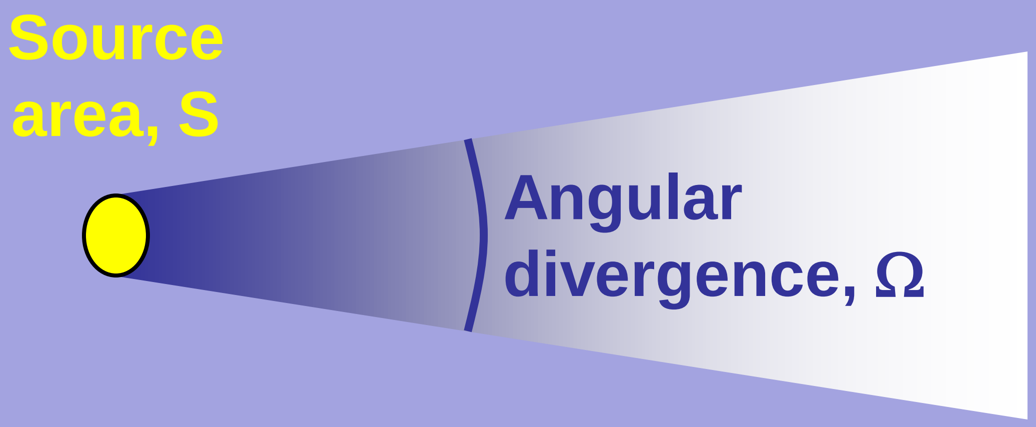
- measurements on very small probes (few μm crystals)

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

- short measurement times

- high transverse coherence
  - phase contrast imaging

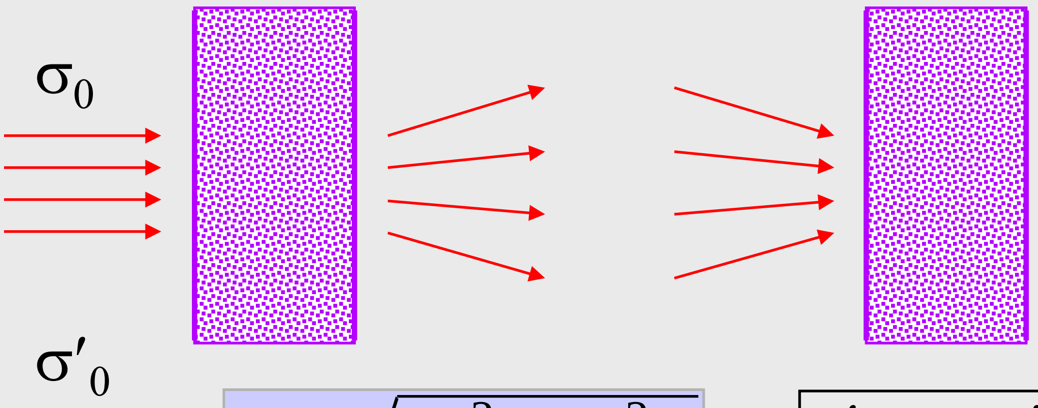
The electron beam "emittance":



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

Emittance = S x Ω

Ring equilibrium emittance



$$\sigma' = \sqrt{\sigma'^2_0 + \sigma'^2_{\mathrm{MS}}}$$

$$\sigma'_0 >> \sigma'_{\mathrm{MS}}$$

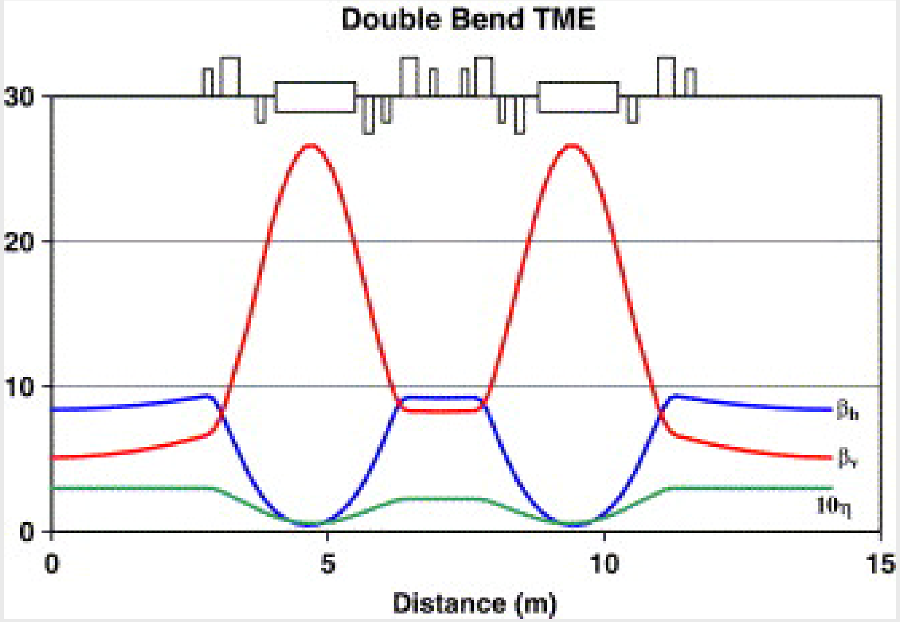
to minimize the blow up due to multiple

scattering in the absorber we can **focus** the beam

Equilibrium Emittance

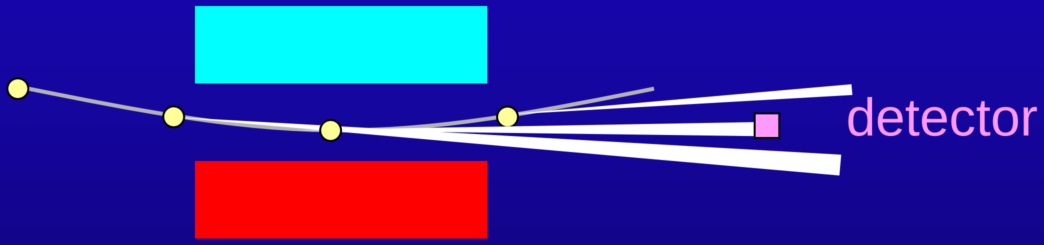
$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot \mathrm{F}_{\mathrm{latt}}$$

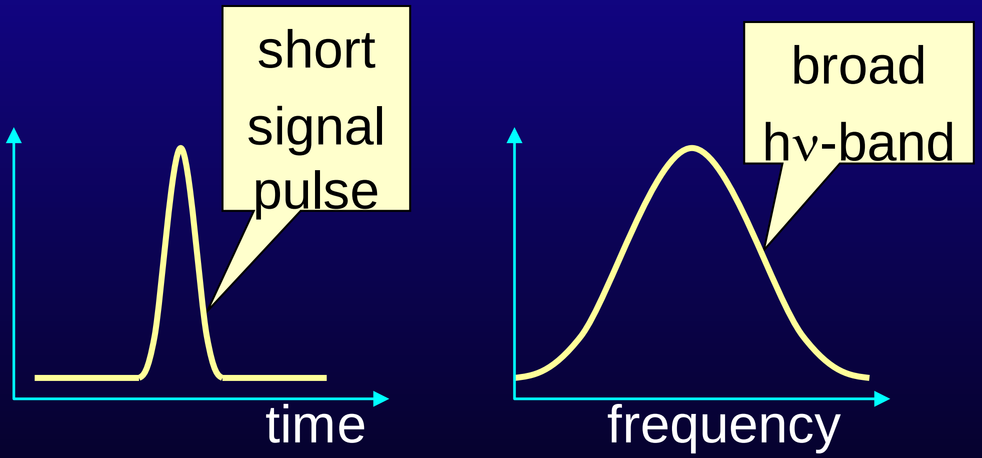
$$\mathrm{F}_{\min} = \frac{1}{12\sqrt{15}}$$



3 types of storage ring sources:

1. Bending magnets: $B \sim N_e$

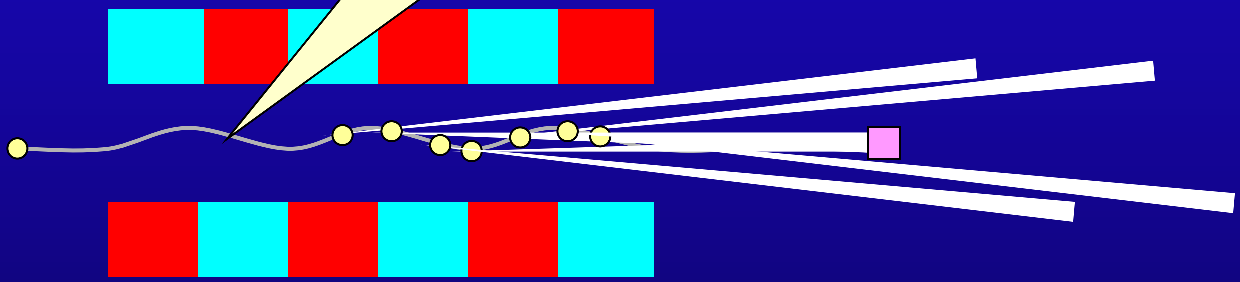




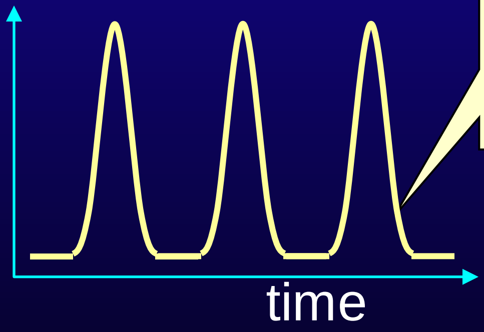
3 types of storage ring sources:

2. Wigglers:

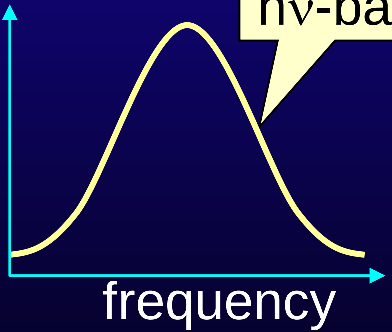
$B \sim N_e N_w$ x10



large undulations



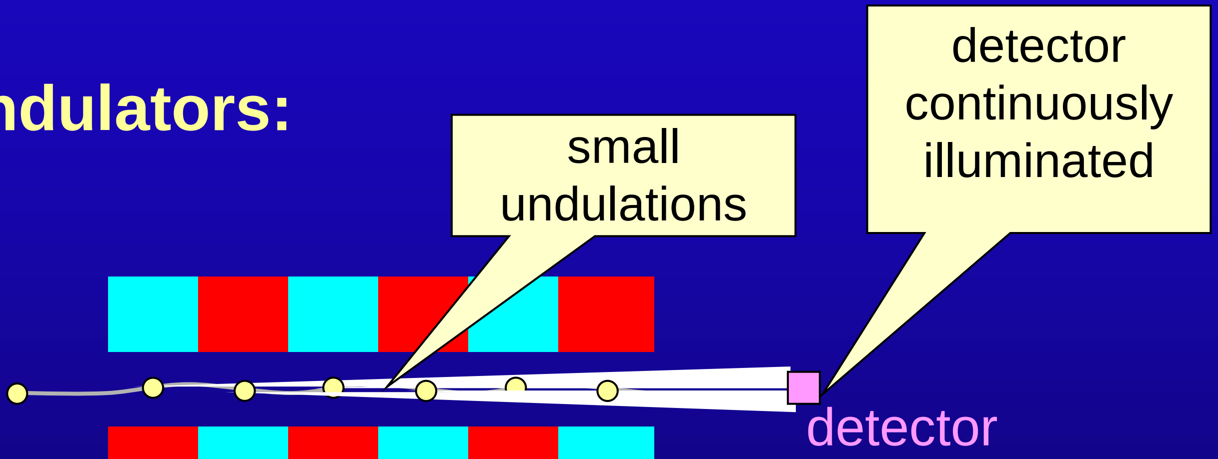
Series of short pulses



broad hν-band

3 types of storage ring sources:

3. Undulators:

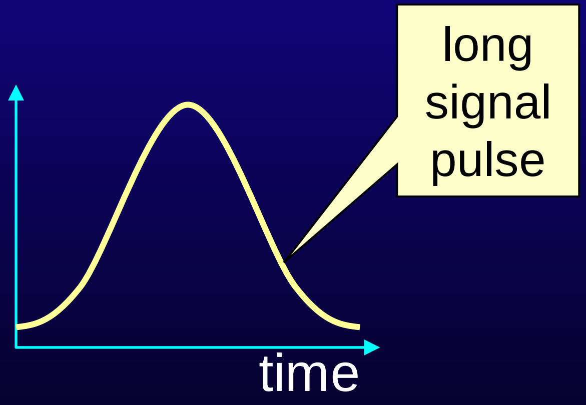


small undulations

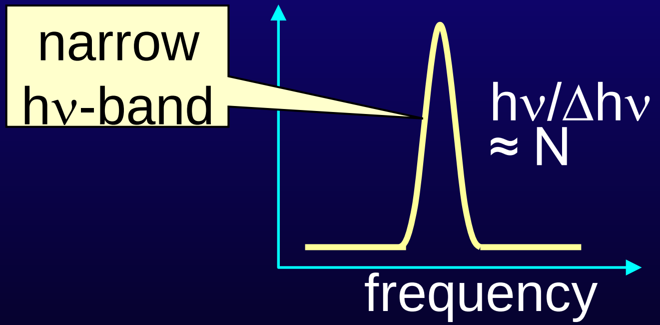
detector continuously illuminated

detector

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



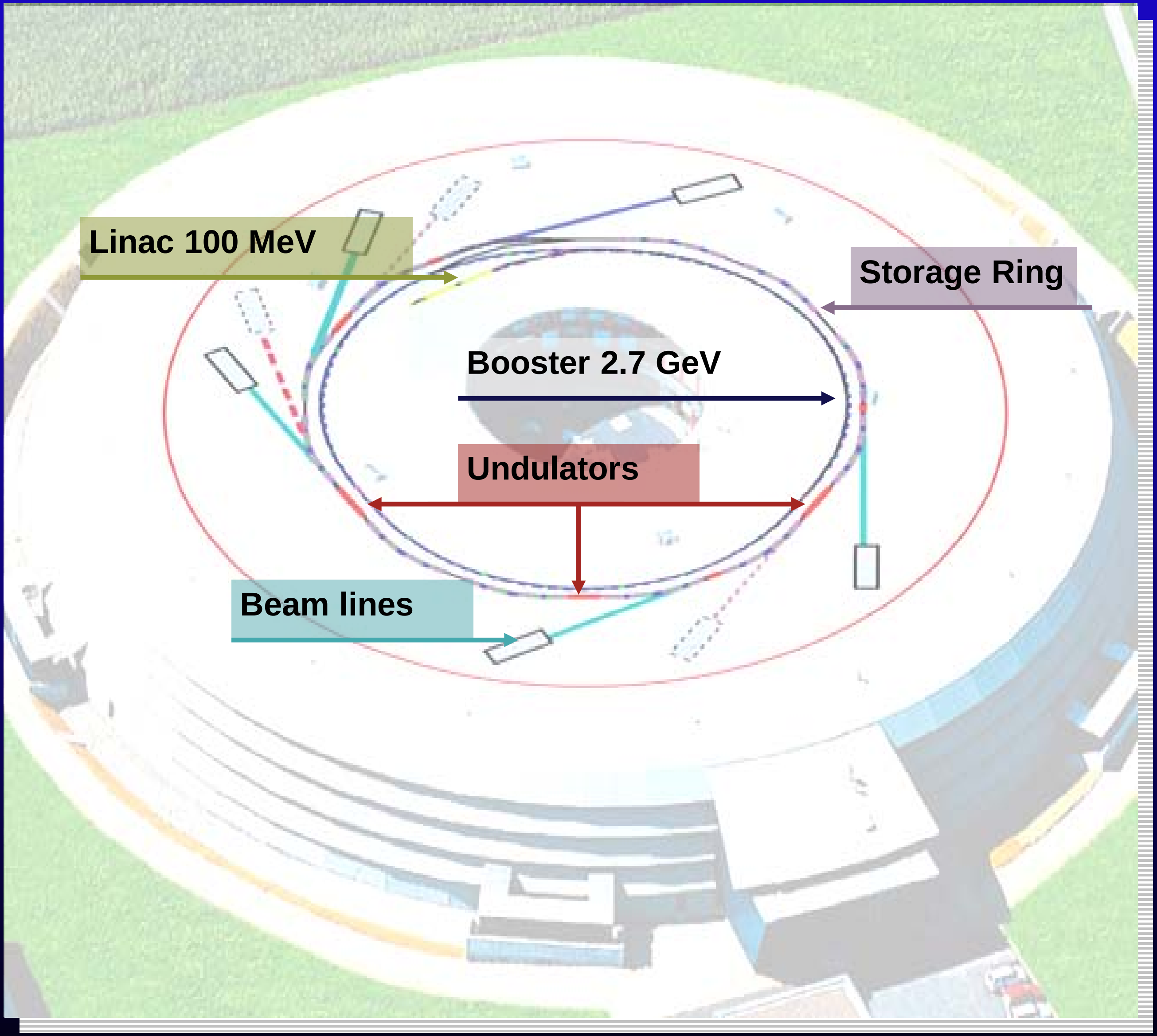
long signal pulse



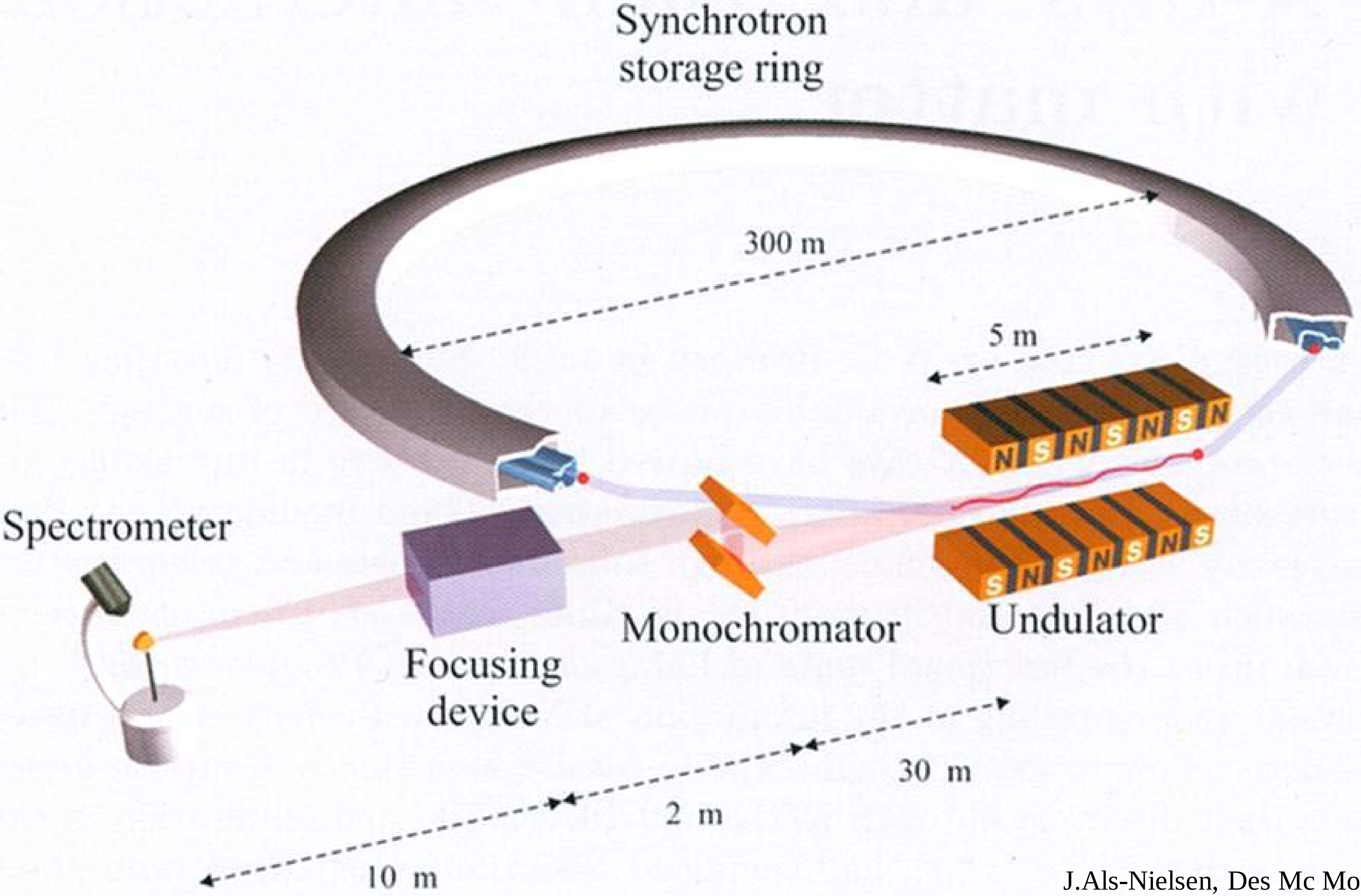
narrow hν-band

hν/Δhν ≈ N

Anatomy of a light source

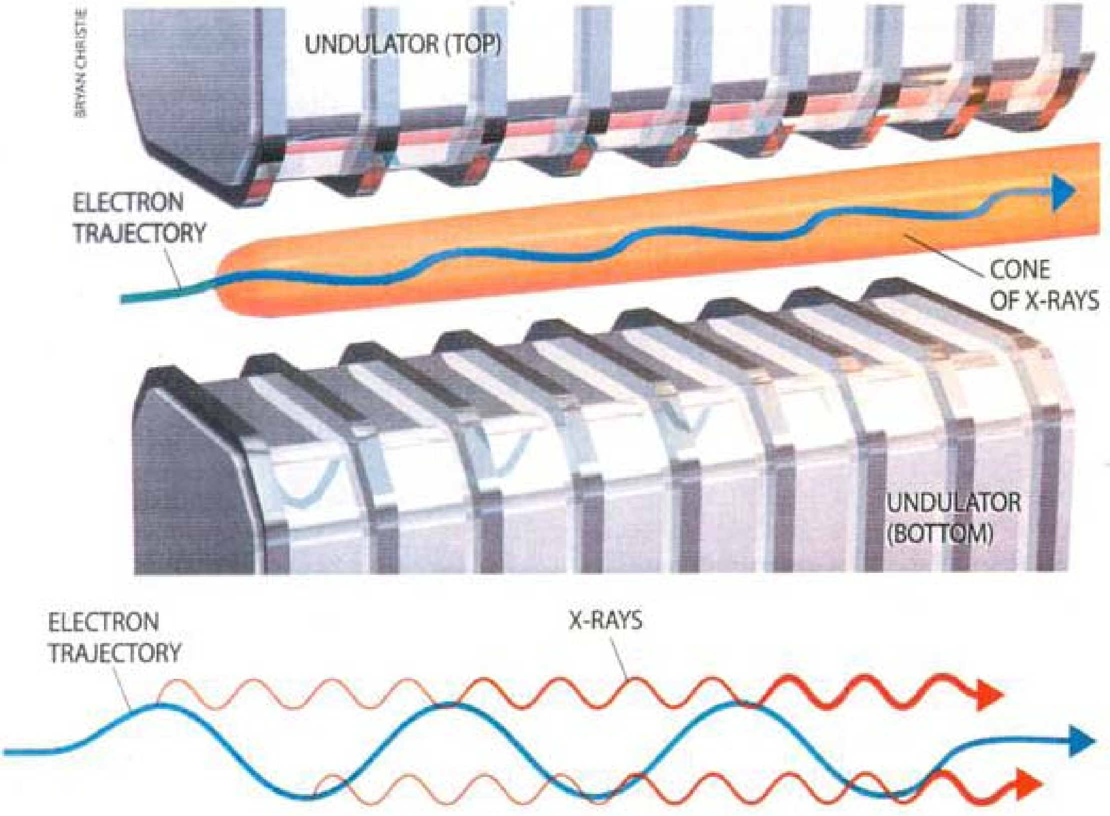


About 60 ring sources world-wide



J.Als-Nielsen, Des Mc Morrow

Undulators

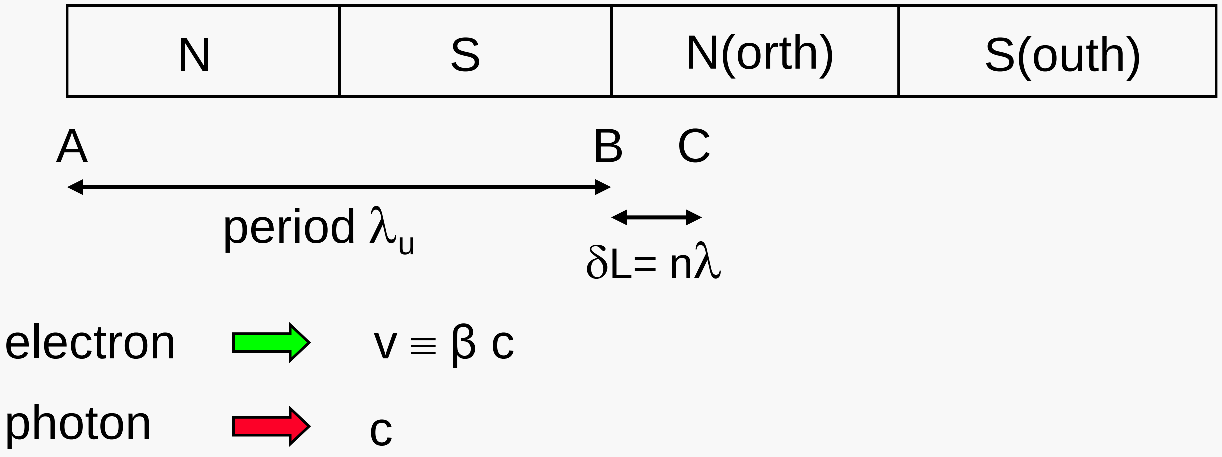


$$T_{obs} = T_{emit}(1-\beta)$$

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

Selection of wavelength in an undulator

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



N | S | N(orth) | S(outh)

A B C

period λ_u

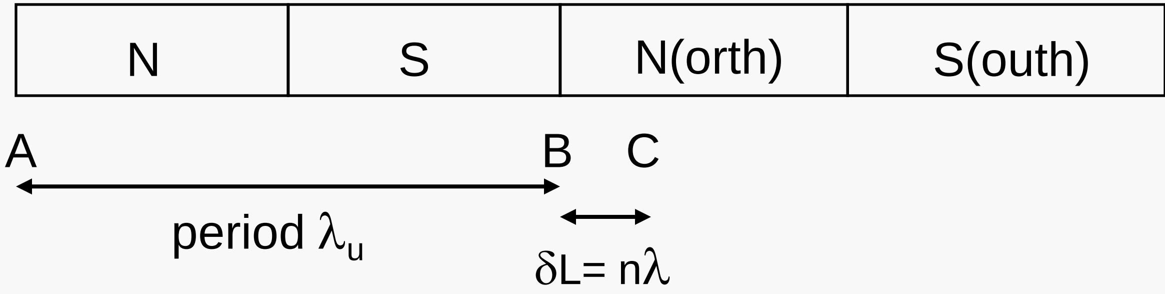
$\delta L = n\lambda$

electron $v \equiv \beta c$

photon c

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

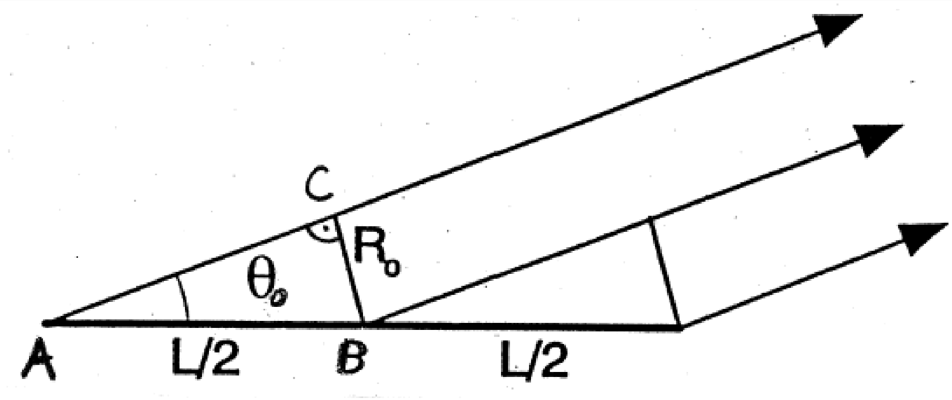
The path difference $$\delta L \equiv n\lambda \approx (1-\beta)\,\lambda_u\,, \quad 1-\beta \approx \frac{1}{2\gamma^2}$$

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

detour through slalom

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

Radiation cone of an undulator



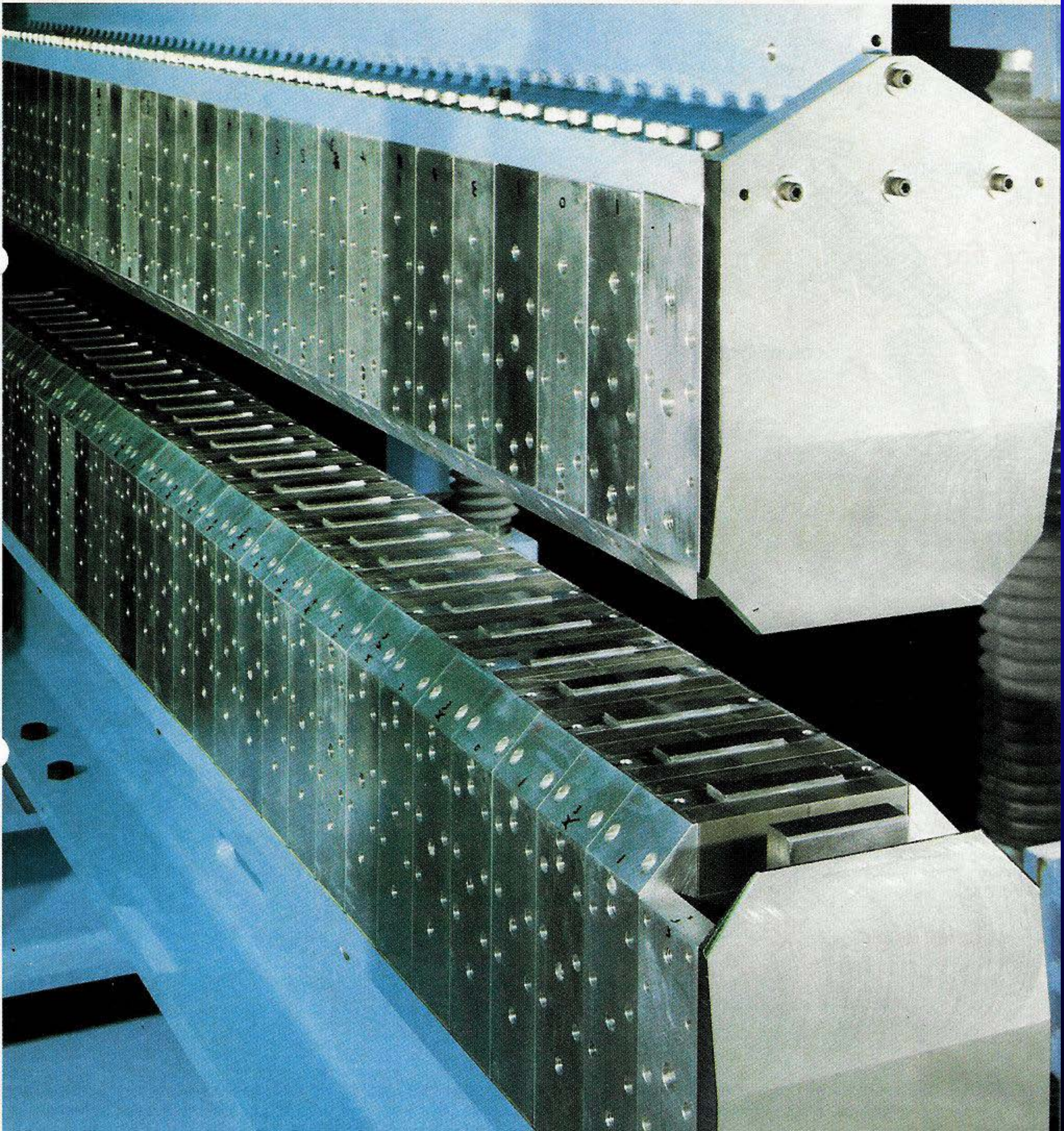
Undulator radiates from ist whole length L into a narrow cone.

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.

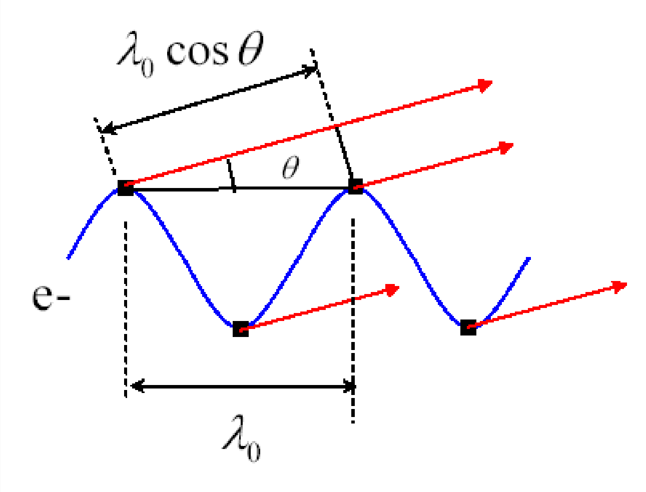
$$\Delta L = AB - AC = \frac{1}{2} L(1 - \cos\theta_0) \approx \frac{1}{4} L\theta_0^2$$

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

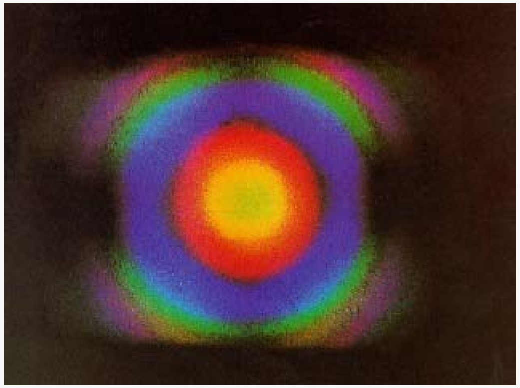
$$\boxed{\theta_0 = \sqrt{\frac{2\lambda}{L}}} \quad \boxed{R_0 = \sqrt{\frac{\lambda \cdot L}{2}}} \quad \boxed{\varepsilon_0 = \theta_0 R_0 = \lambda}$$

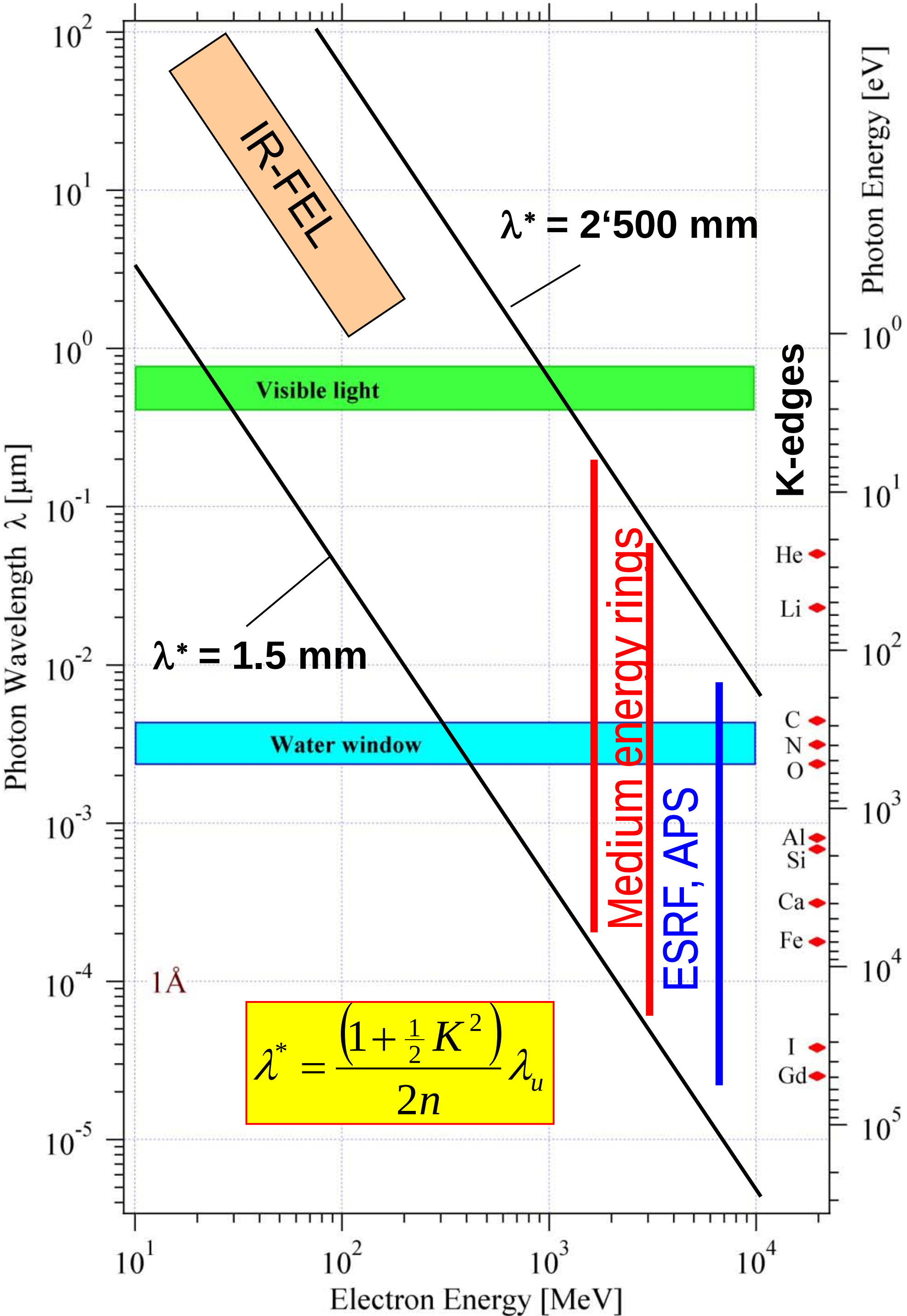


Undulator radiation



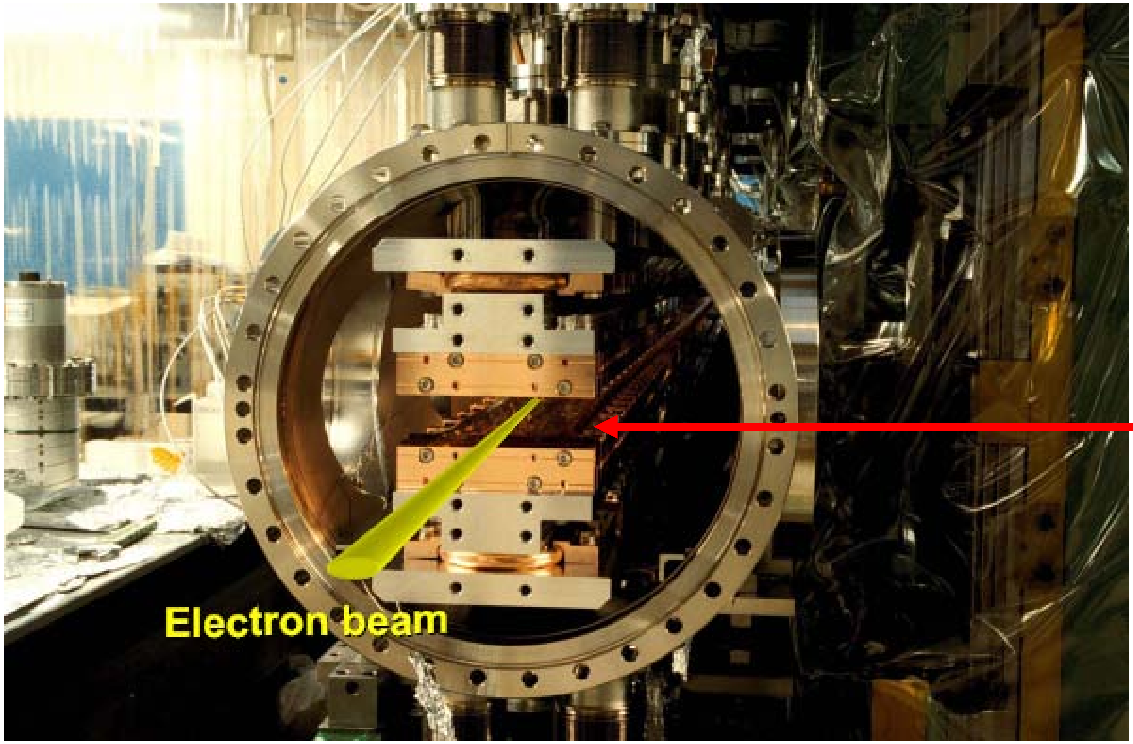
$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$





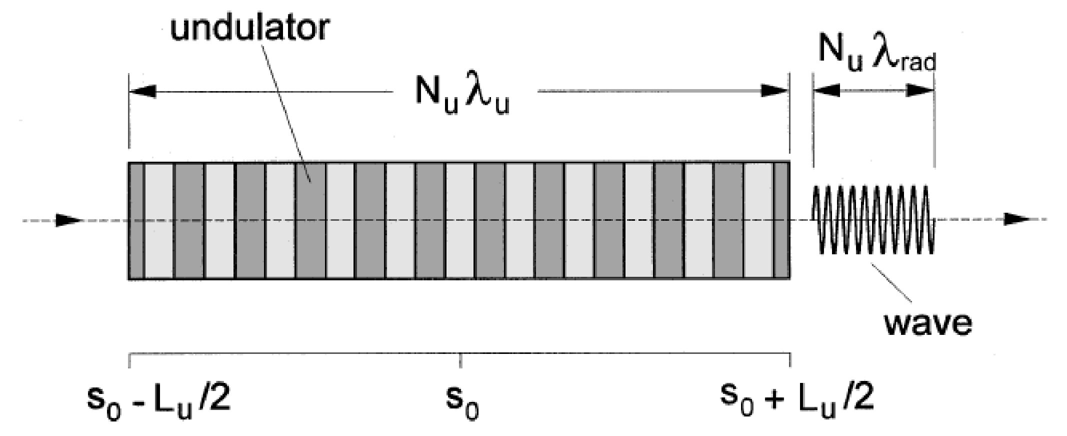
$$\lambda^* = \frac{\left(1 + \frac{1}{2}K^2\right)}{2n}\lambda_u$$

In–vacuum undulators / s.c. undulators



Gaps
down
to
3 mm

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

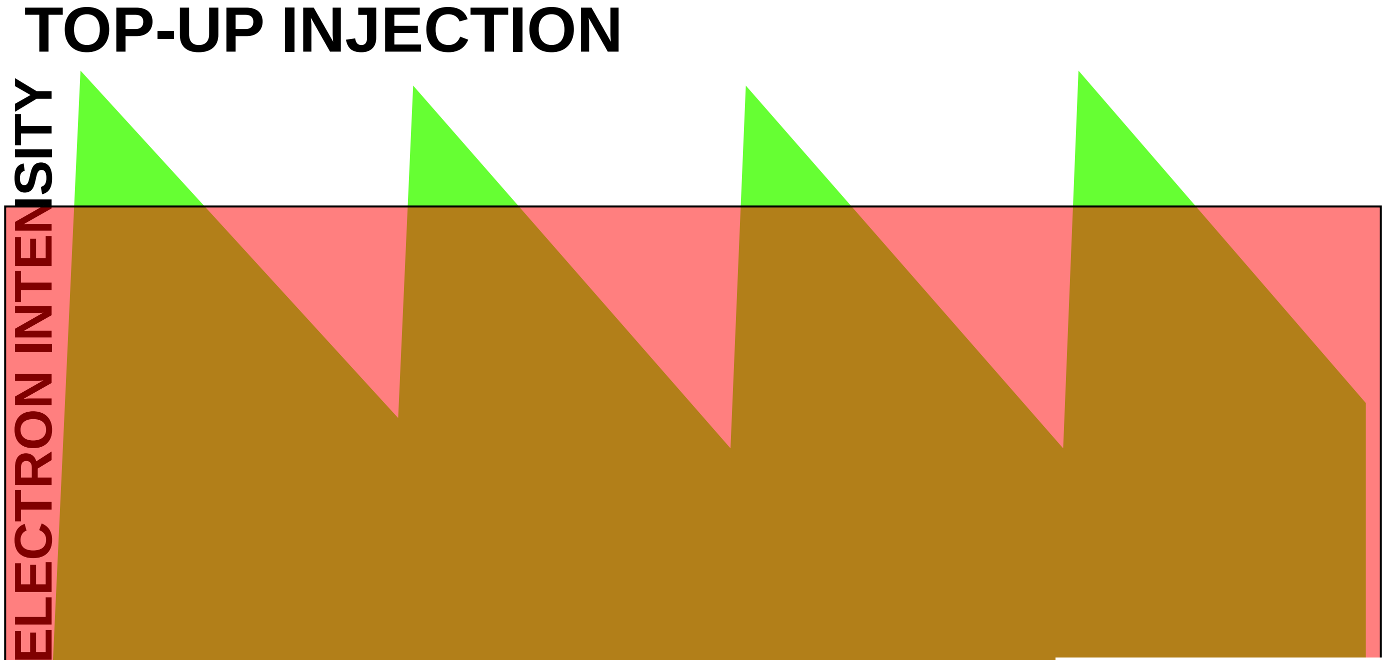
$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u}$$

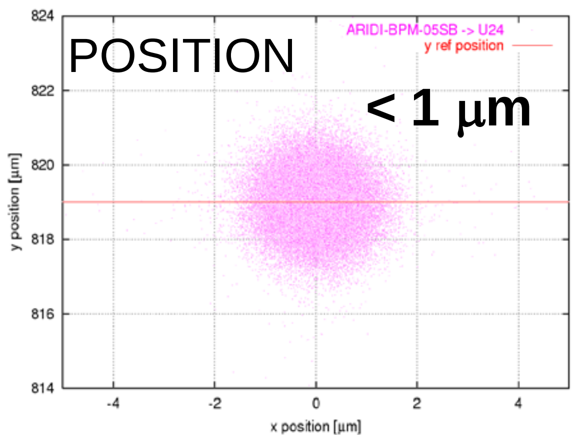
Due to the electron energy spread

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

Third Generation Light Sources in Operation

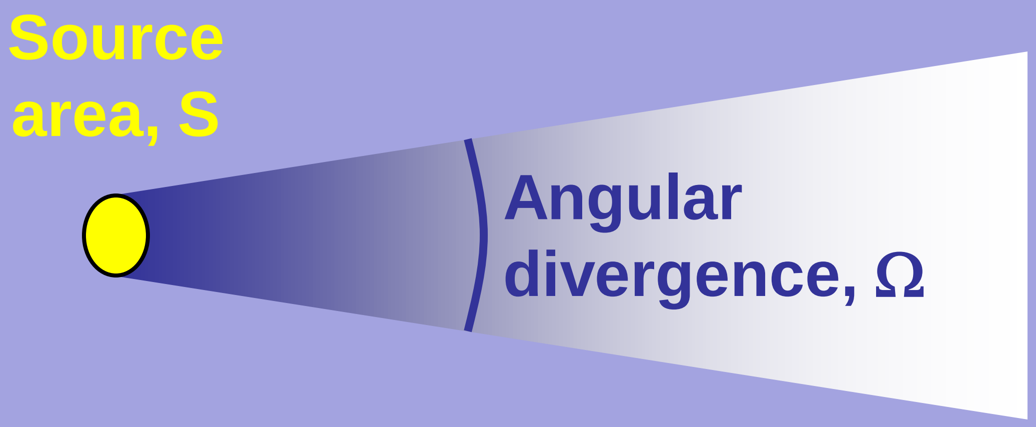
Top-up injection: key to stability





Steady state glow at the SLS

The electron beam “emittance”:



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

Emittance = S x Ω

Beam emittance

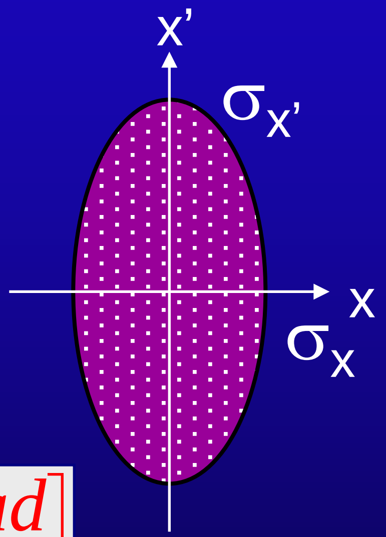
$$\text{Area} = \pi \cdot \varepsilon$$

Betatron oscillations

- Particles in the beam execute betatron oscillations with different amplitudes.

Transverse beam distribution

- Gaussian (electrons)
- “Typical” particle: 1 - σ ellipse (in a place where $\alpha = \beta' = 0$)



Units of ε $[m \cdot rad]$

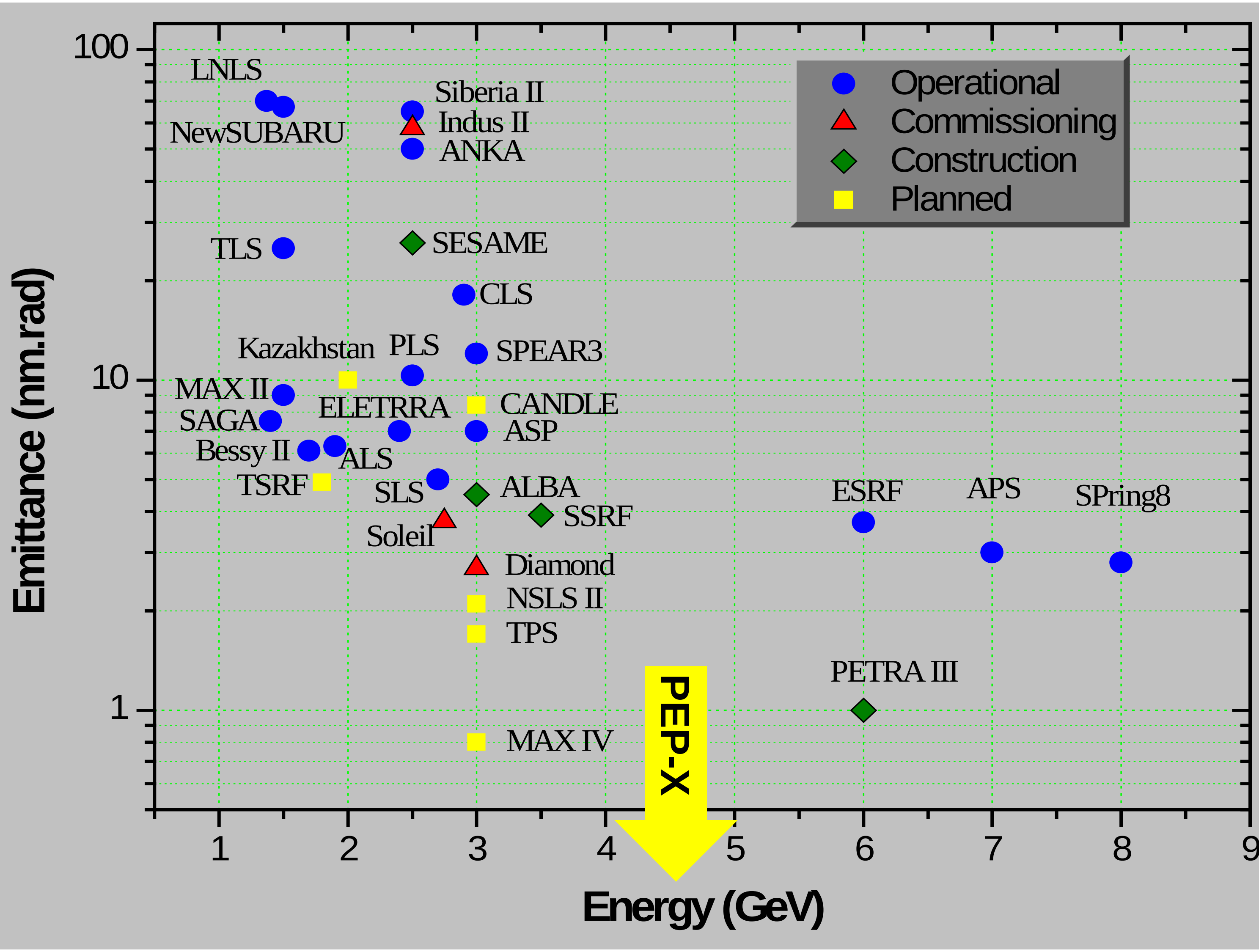
$$\text{Emittance} \equiv \frac{\sigma_x^2}{\beta}$$

$$\varepsilon = \sigma_x \cdot \sigma_{x'}$$

$$\sigma_x = \sqrt{\varepsilon\,\beta}$$
$$\sigma_{x'} = \sqrt{\varepsilon / \beta}$$

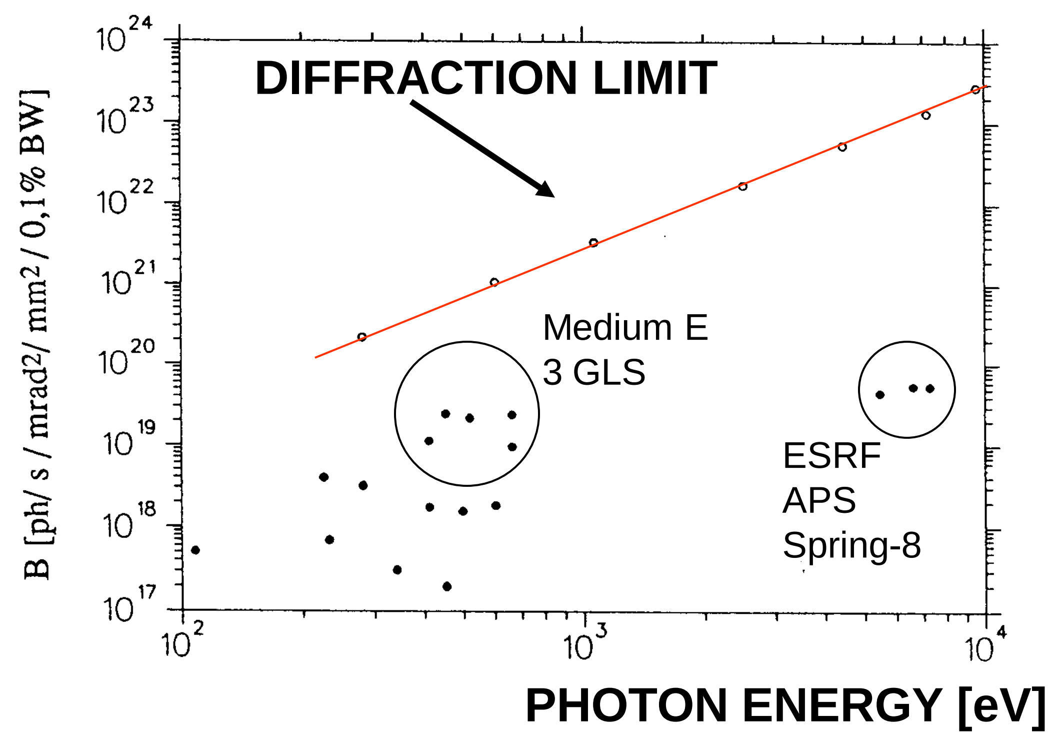
$$\beta = \frac{\sigma_x}{\sigma_{x'}}$$

Third Generation Light Sources



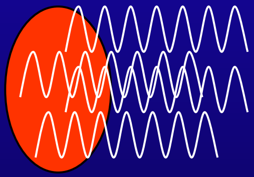
PERFORMANCE OF 3th GENERATION LIGHT SOURCES

BRIGHTNESS:



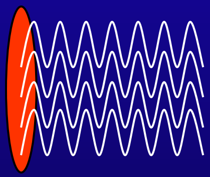
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto$ N



INCOHERENT EMISSION

Intensity $\propto$ N ^{2}



COHERENT EMISSION

FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

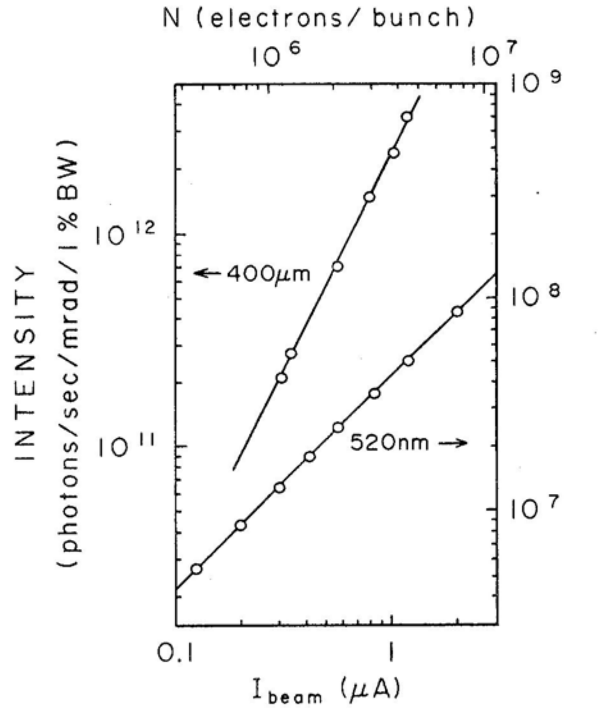


Fig. 4. Dependence of SR intensity on the beam current at $\lambda = 400$ μm and $\lambda = 520$ nm for the long pulse/short bunch beam. The ordinate is given on the left-hand side for $\lambda = 400$ μm and on the right for $\lambda = 520$ nm. The two lines show the linear and quadratic relations to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

180 MeV electrons

T. Nakazato et al., Tohoku University, Japan

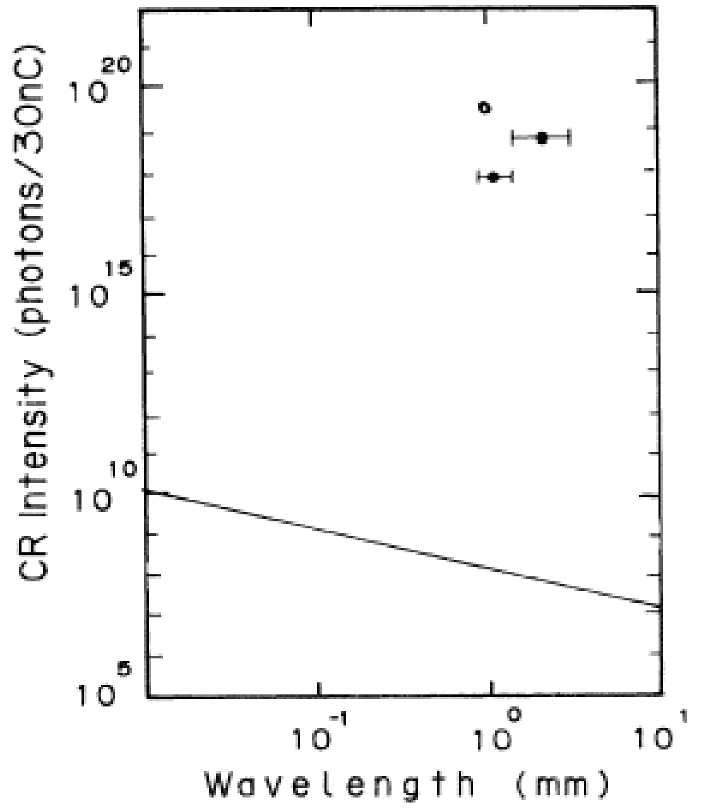
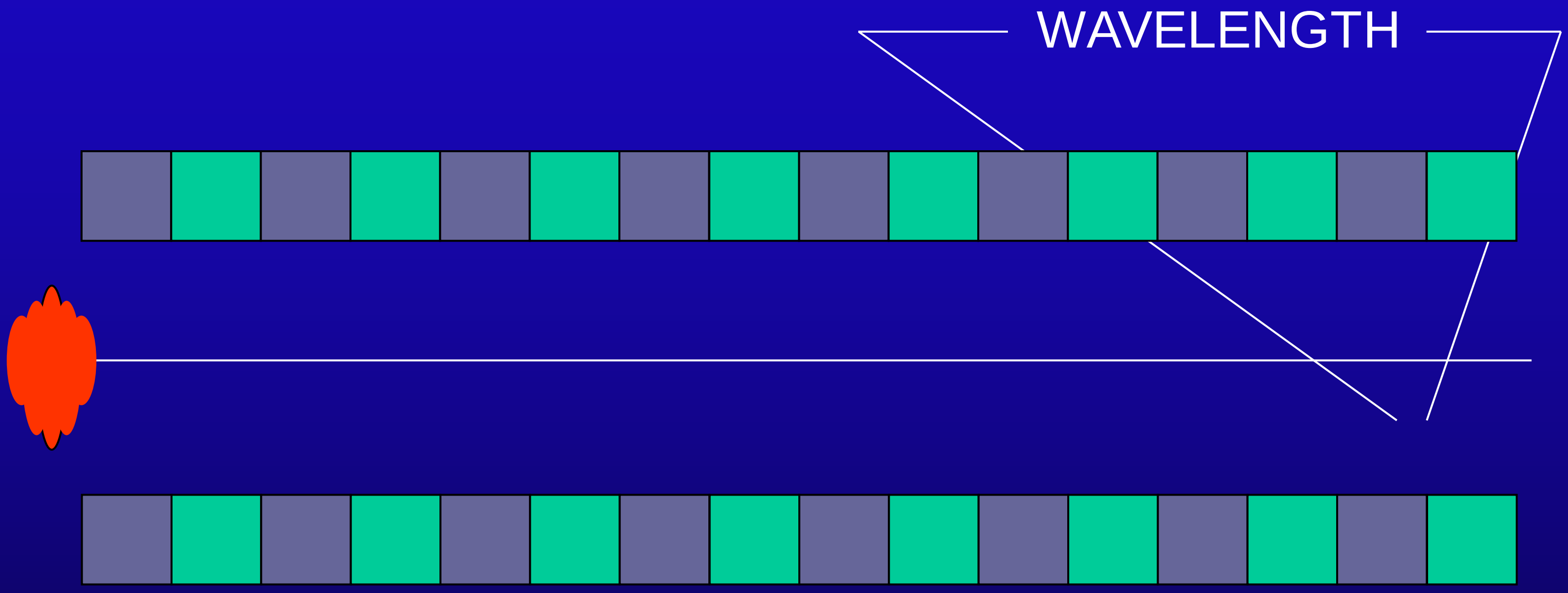


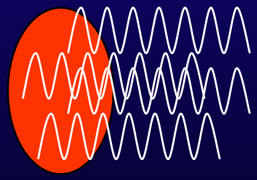
FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

30 MeV electrons

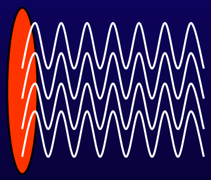
J. Ohkuma et al., Osaka University, Japan

MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE





INCOHERENT EMISSION



COHERENT EMISSION

X-Ray Laser

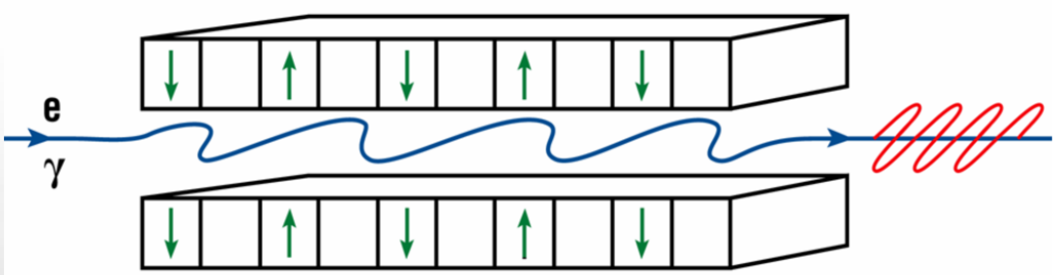
- Fully coherent source of 1 Å X-rays

  10^{12} photons pulses

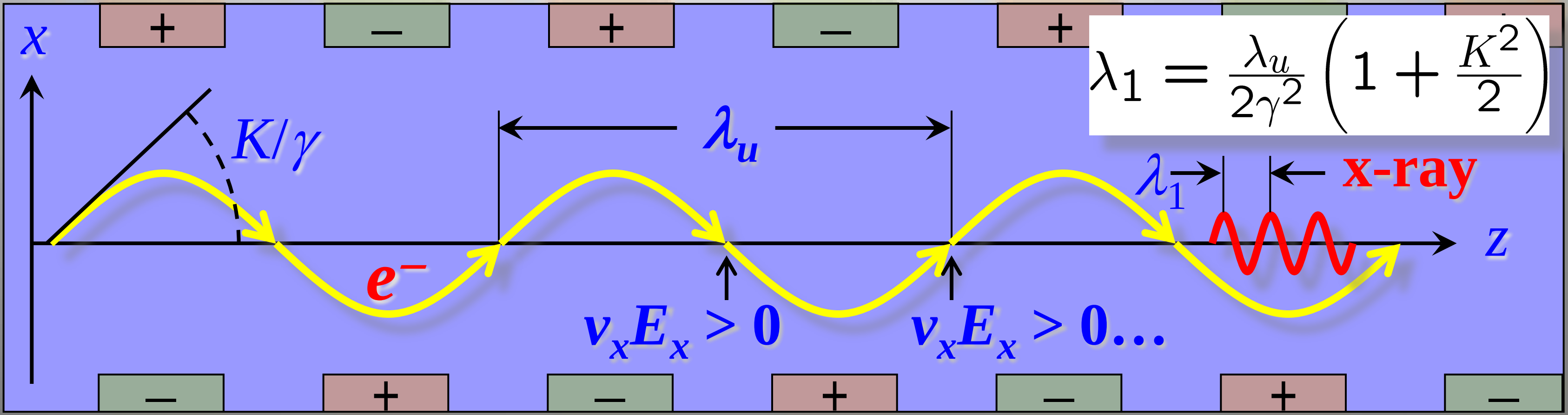
  Short pulses: femto- to atto-seconds

FEL Principles

Z. Huang

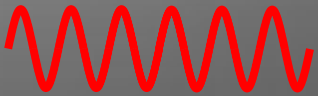


- Electrons **slip** behind EM wave by λ_1 per undulator period (λ_u)

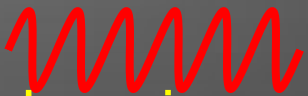


$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

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

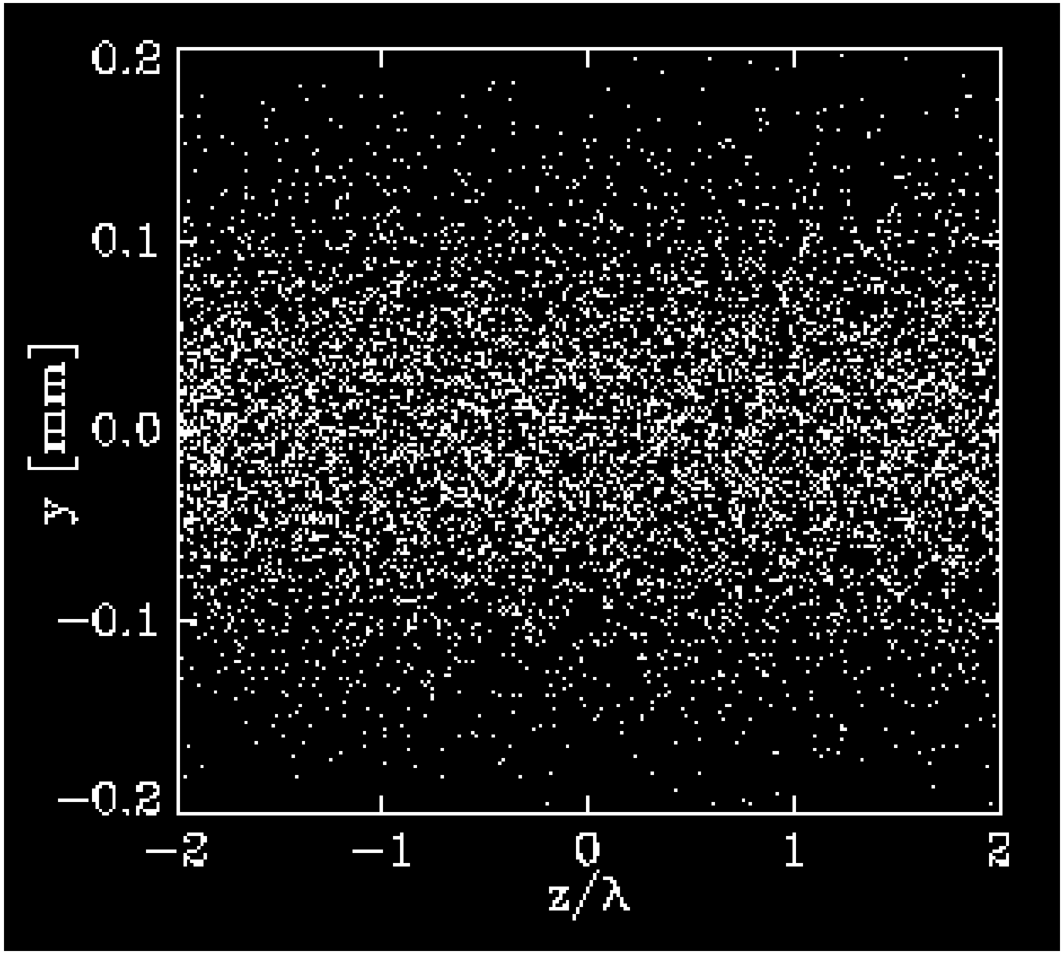


- e^- losing energy slow down, and e^- gaining energy catch up ➔ **density modulation at λ_1 (microbunching)**

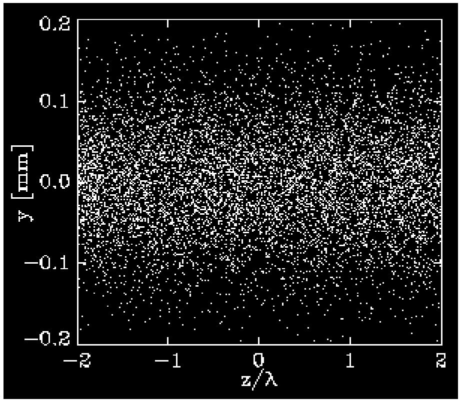


- Microbunched beam radiates coherently at λ_1, enhancing the process ➔ **exponential growth of radiation power**

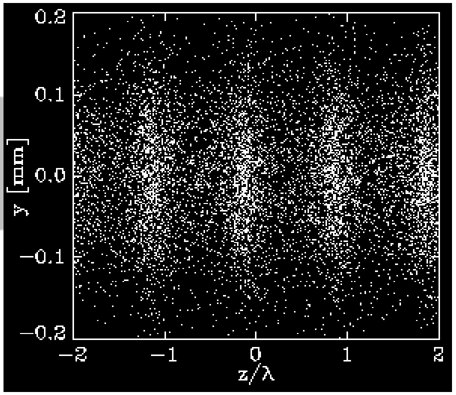
Microbunching through SASE Process



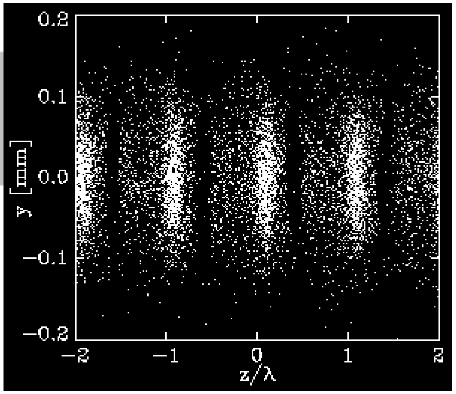
undulator entrance



half-way saturation



full saturation



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

Courtesy - Sven Reiche (PSI)

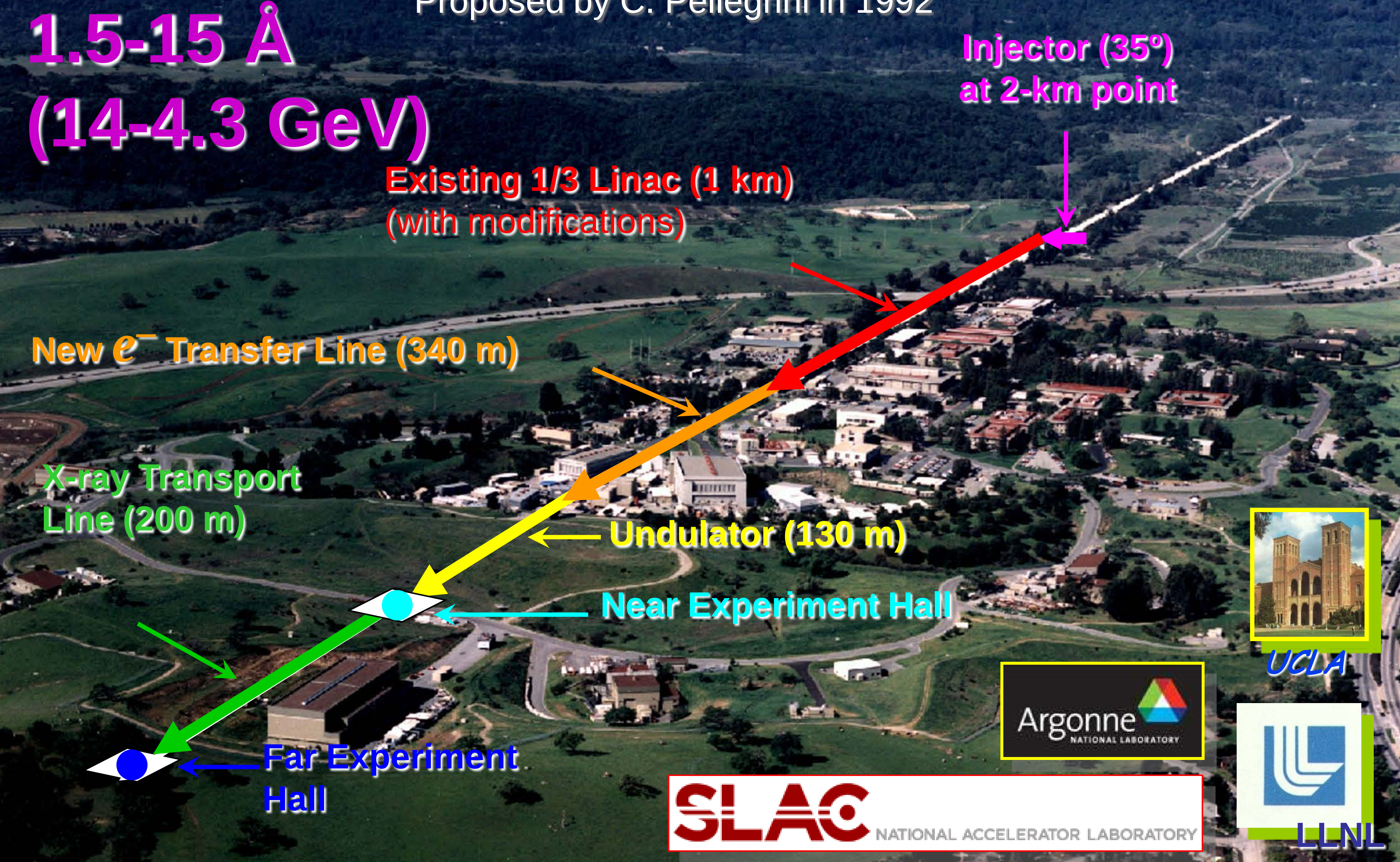
Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing 3-km linac

Proposed by C. Pellegrini in 1992

1.5-15 Å

(14-4.3 GeV)



Injector (35º)
at 2-km point

Existing 1/3 Linac (1 km)
(with modifications)

New e^- Transfer Line (340 m)

X-ray Transport
Line (200 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment
Hall

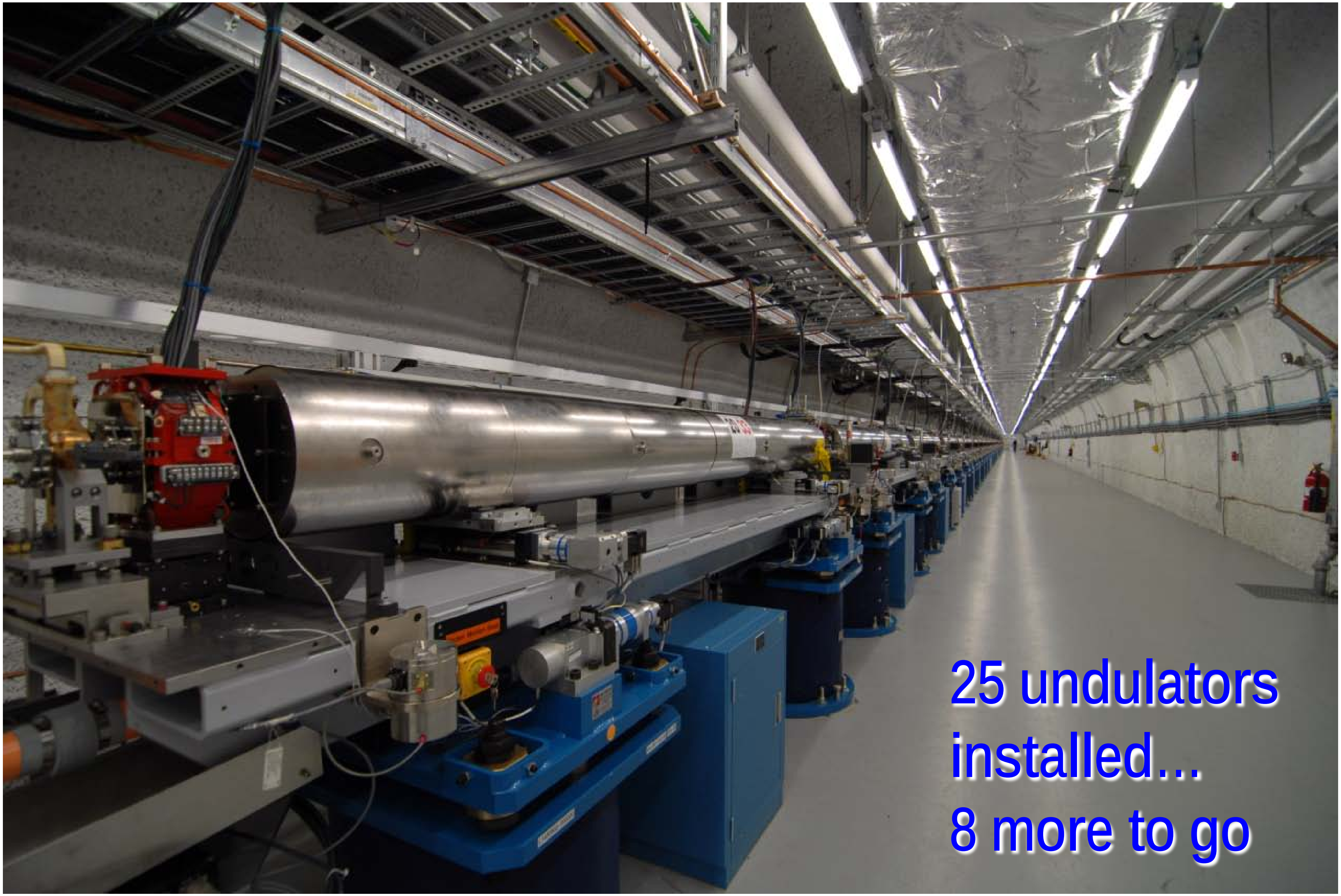
UCLA

Argonne NATIONAL LABORATORY

SLAC NATIONAL ACCELERATOR LABORATORY

LLNL

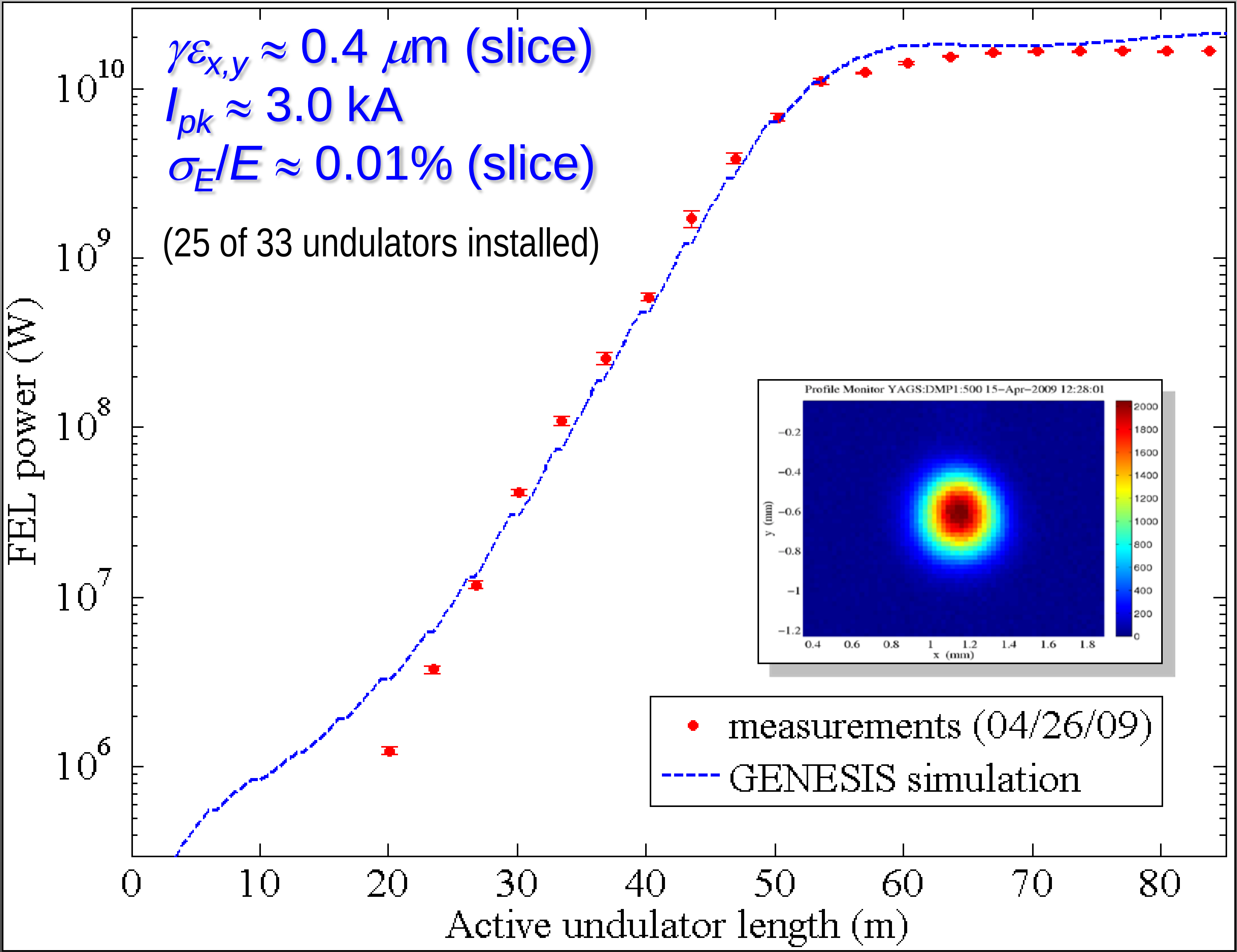
84 meters of FEL Undulator Installed



25 undulators installed…

8 more to go

Undulator Gain Length Measurement at 1.5 Å: 3.3 m



$\gamma\varepsilon_{x,y} \approx 0.4\ \mu\text{m}$ (slice)

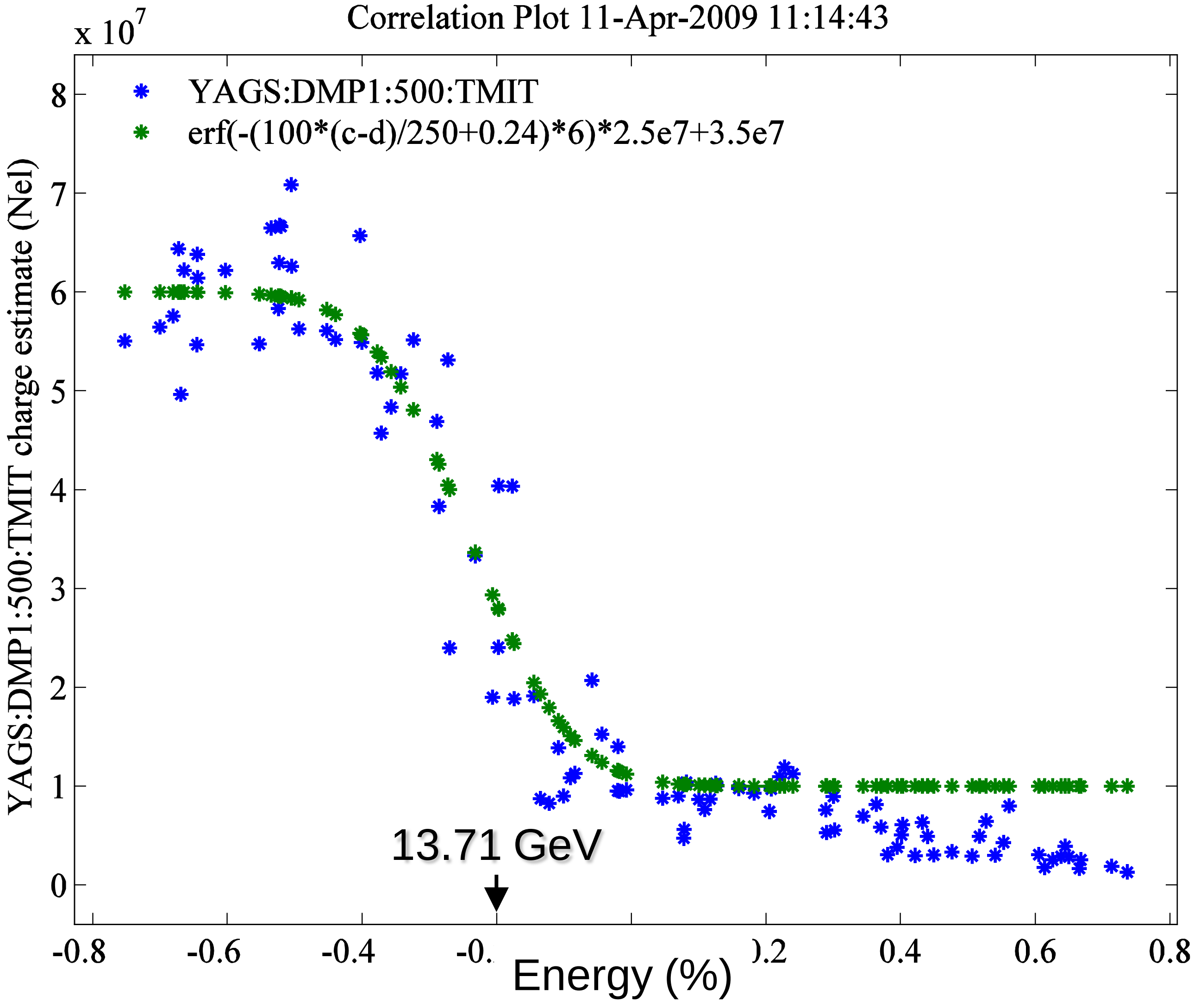
$I_{pk} \approx 3.0$ kA

$\sigma_E/E \approx 0.01\%$ (slice)

(25 of 33 undulators installed)

Second day measurements (04/11/09)

- Ni-foil in front of YAG screen has a K-edge at 1.5 Angstrom



13.71 GeV

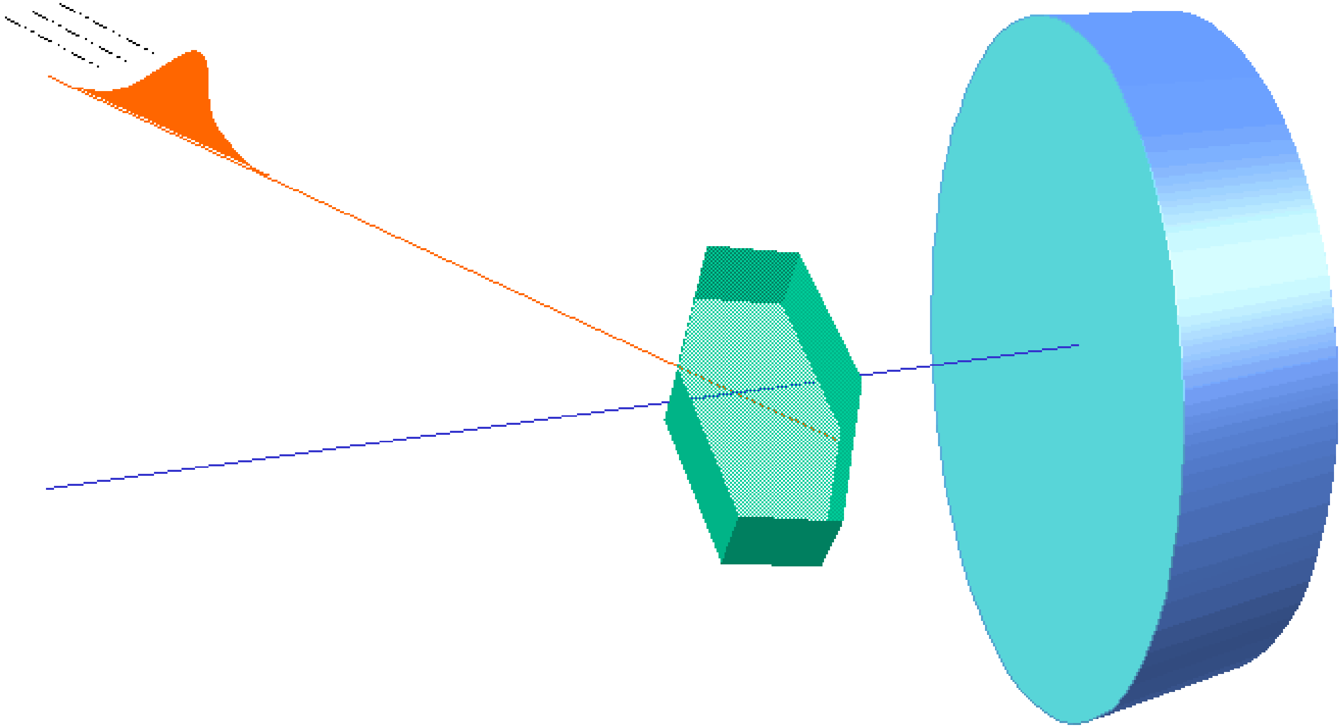
σ ≈ 0.1% (FEL BW)

Ultrafast X-ray science

> *„If you want to understand function, study structure“*
>
> *Francis Crick*

- X-ray Free Electron Lasers extend the ultrafast laser techniques to the X-ray domain
- „Seeing“ structures evolving with time as phenomena take place
- FEMTO: Slicing technique at synchrotrons
- Similar technique to reach < 1 fs with XFELs

Fast processes and short pulses

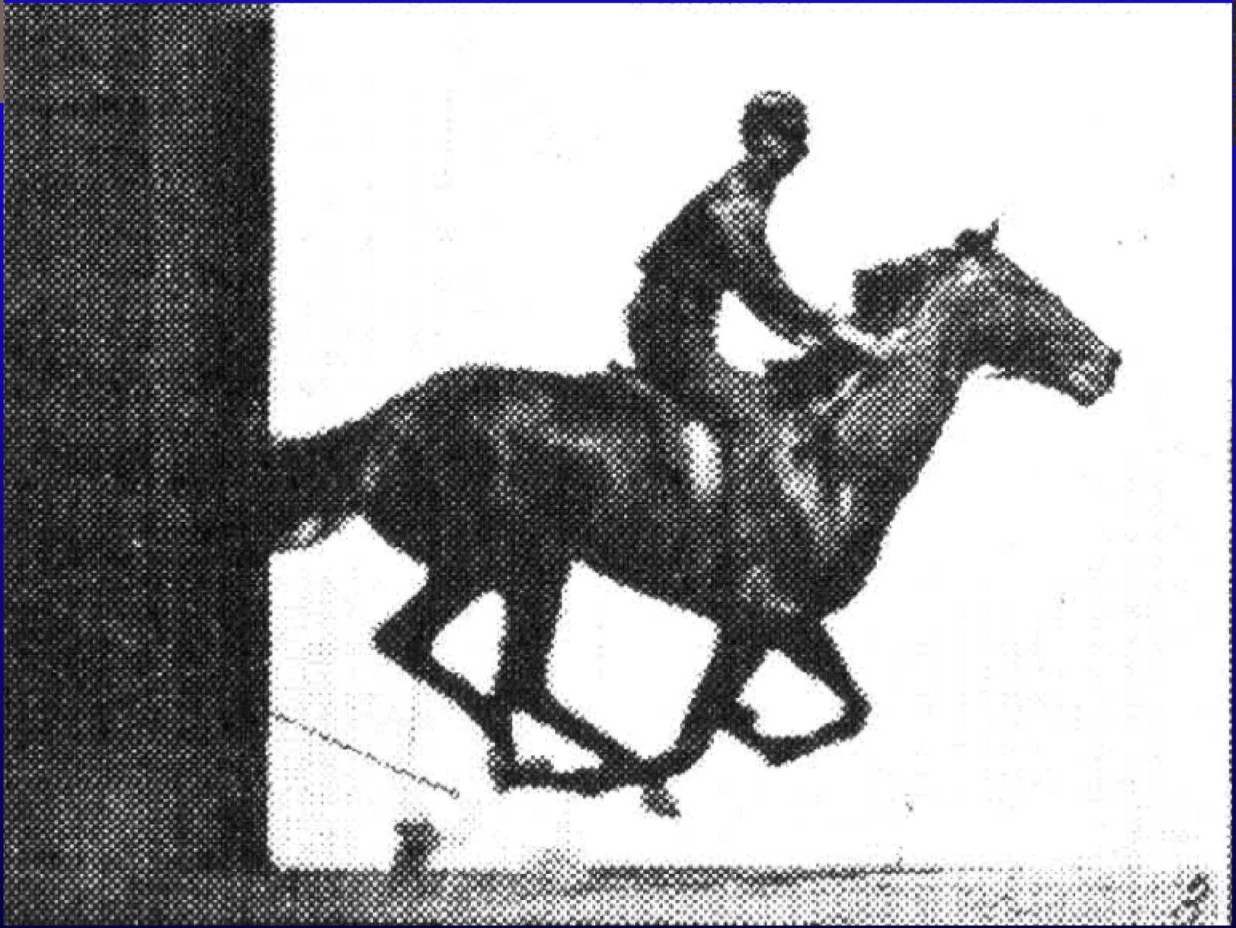


Laser pump / X-ray probe

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

E. Muybridge

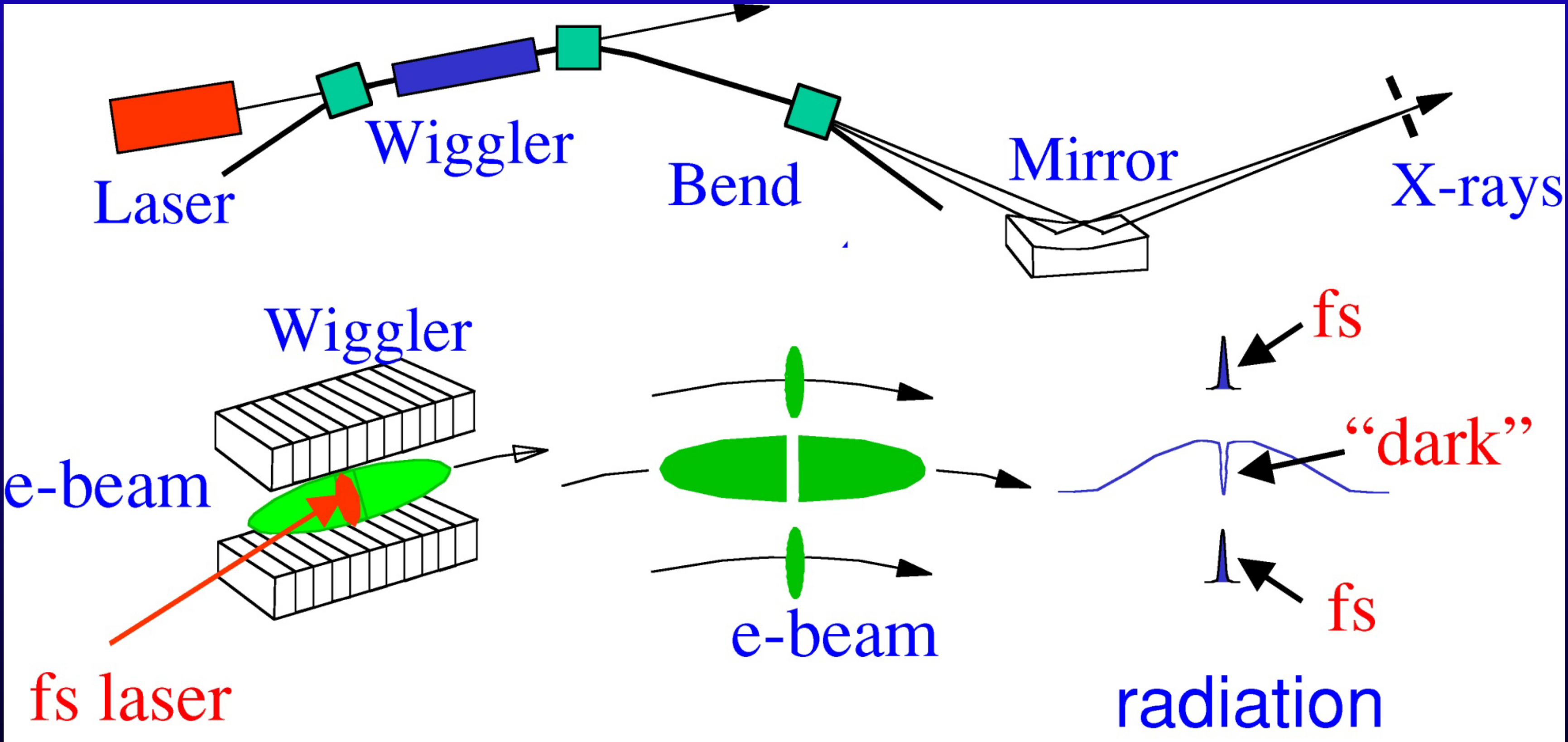


L. Stanford

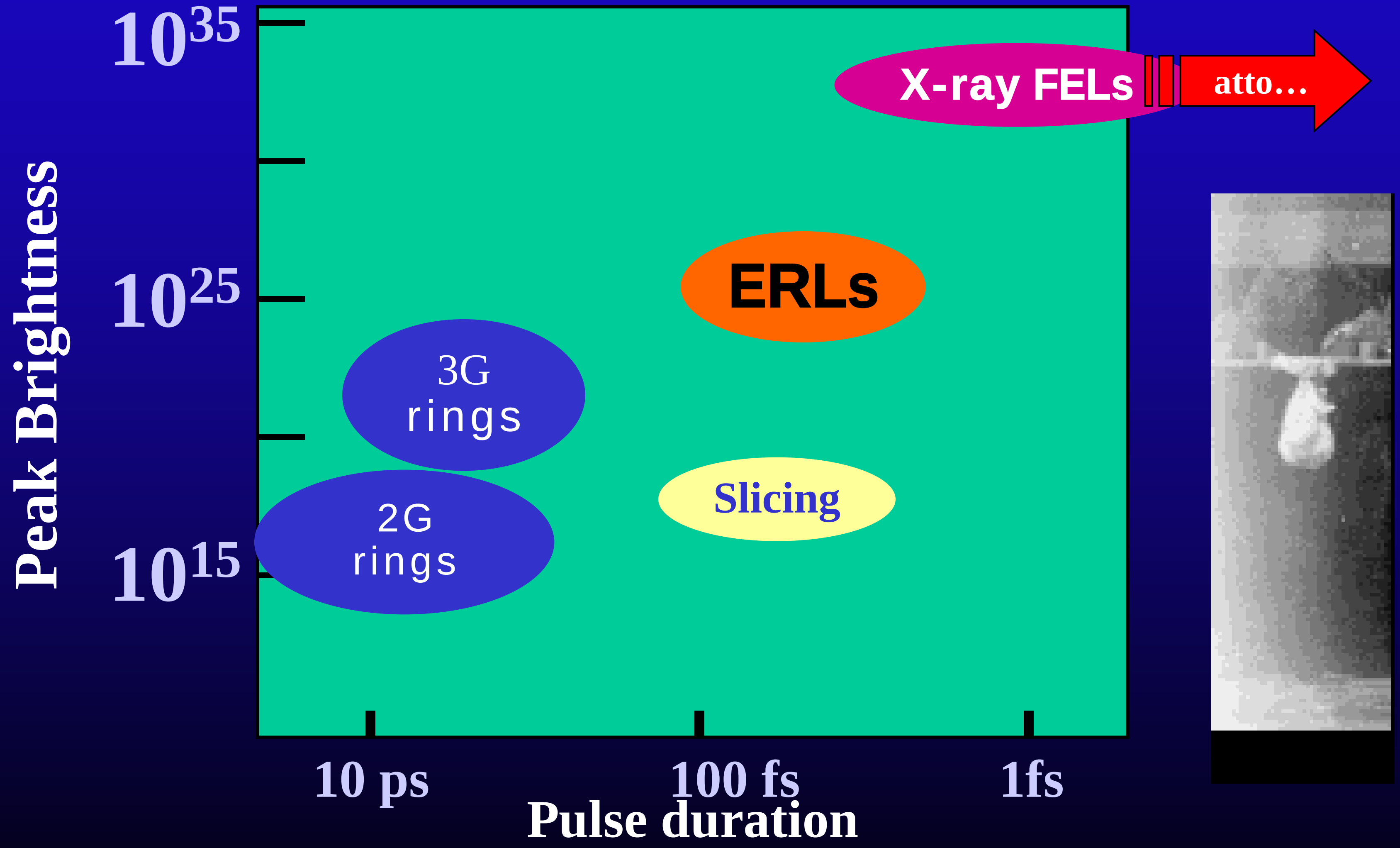
Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

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

Laser slicing
Pioneering ideas and experiments at ALS
Facilities at ALS, BESSYII, SLS



FELs and ERLs COMPLEMENT the Ring sources



H.-D. Nuhn, H. Winick

After H.-D. Nuhn, H. Winick

END

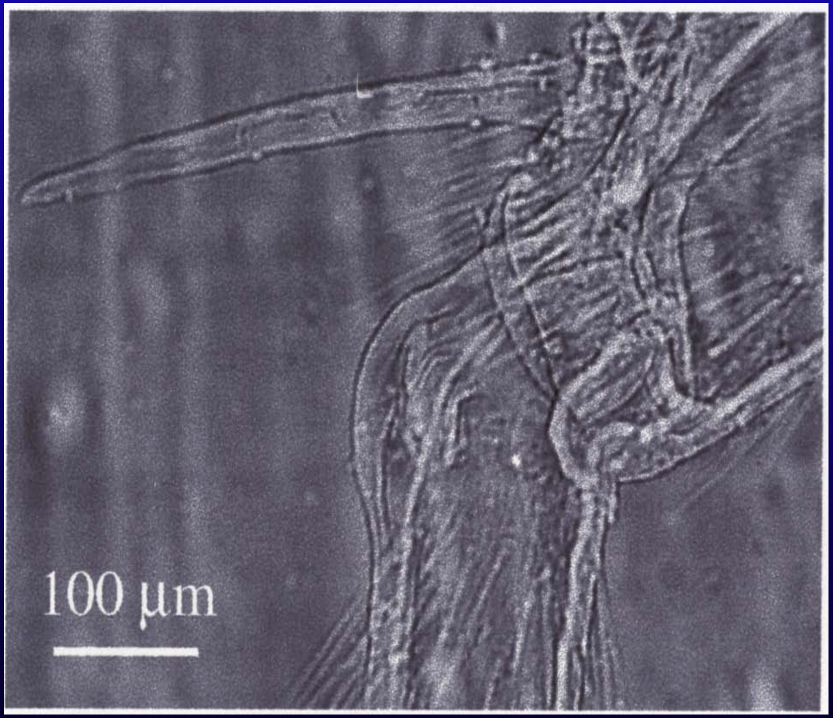
Transverse coherence

- High brightness gives coherence

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

- Holography

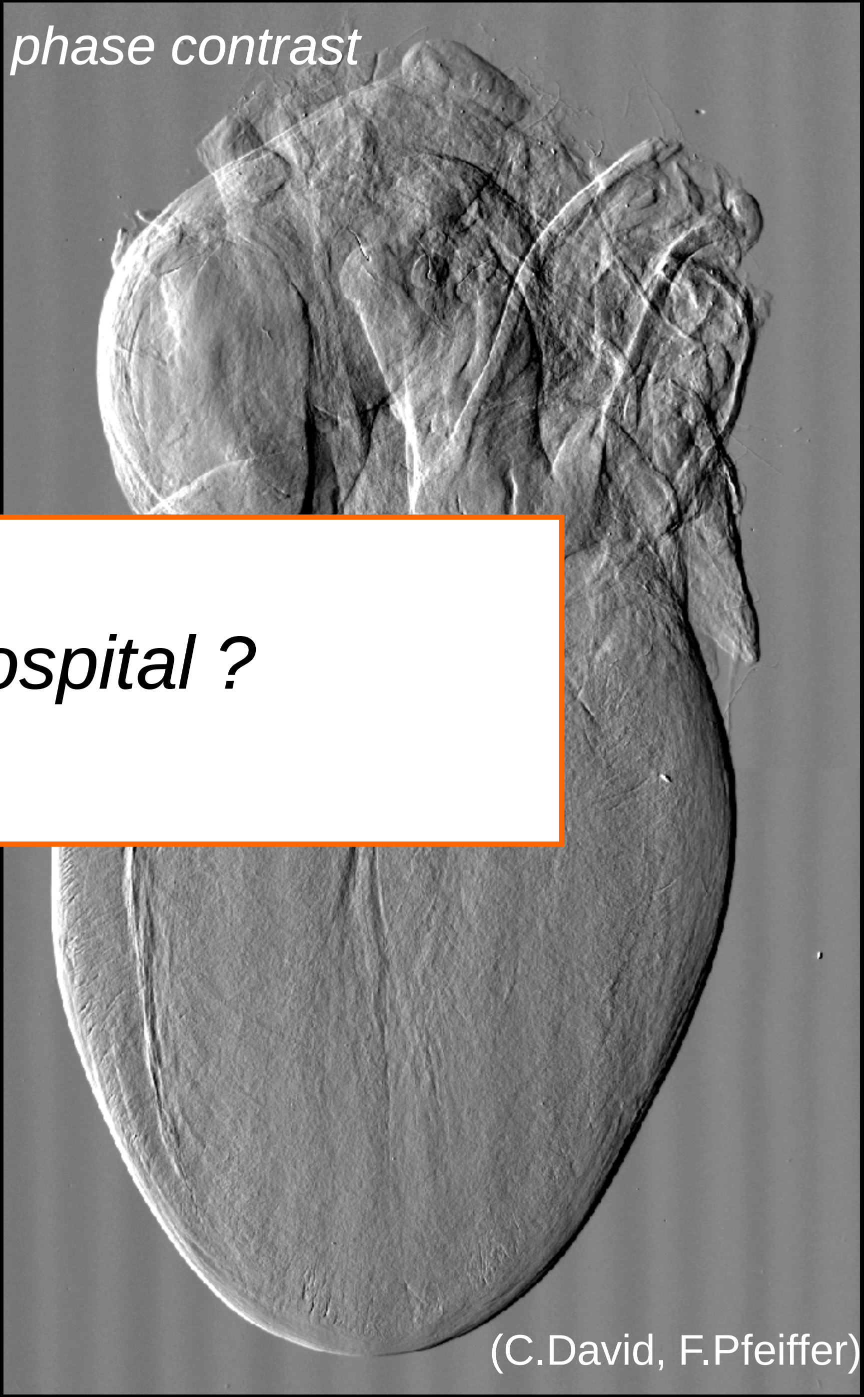
The knee of a spider



phase contrast imaging

absorption

17.5 keV,
synchrotron results



phase contrast

(C.David, F.Pfeiffer)

Into the hospital ?