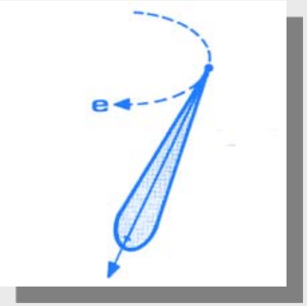
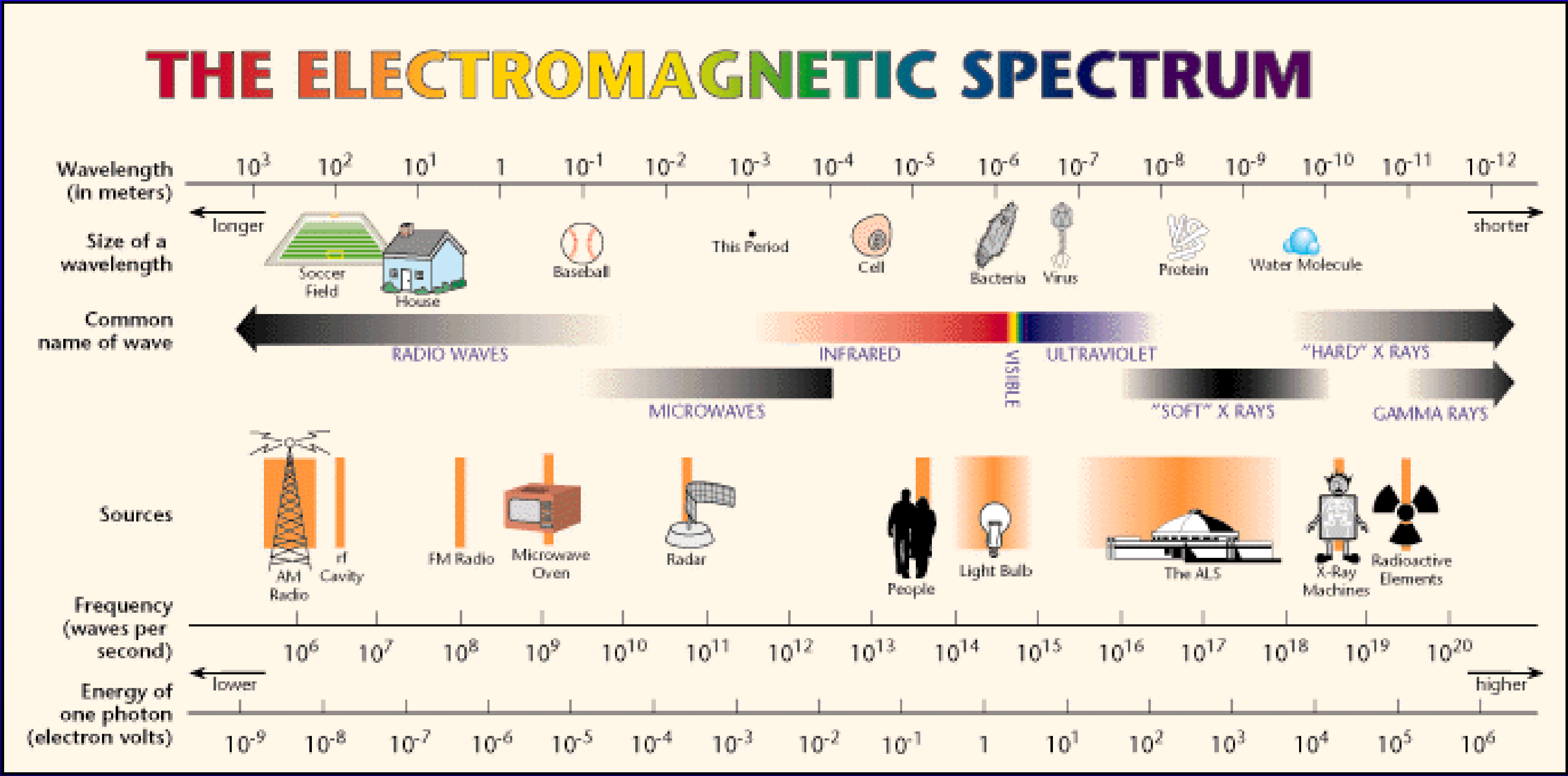


LIGHT SOURCES

Lenny Rivkin

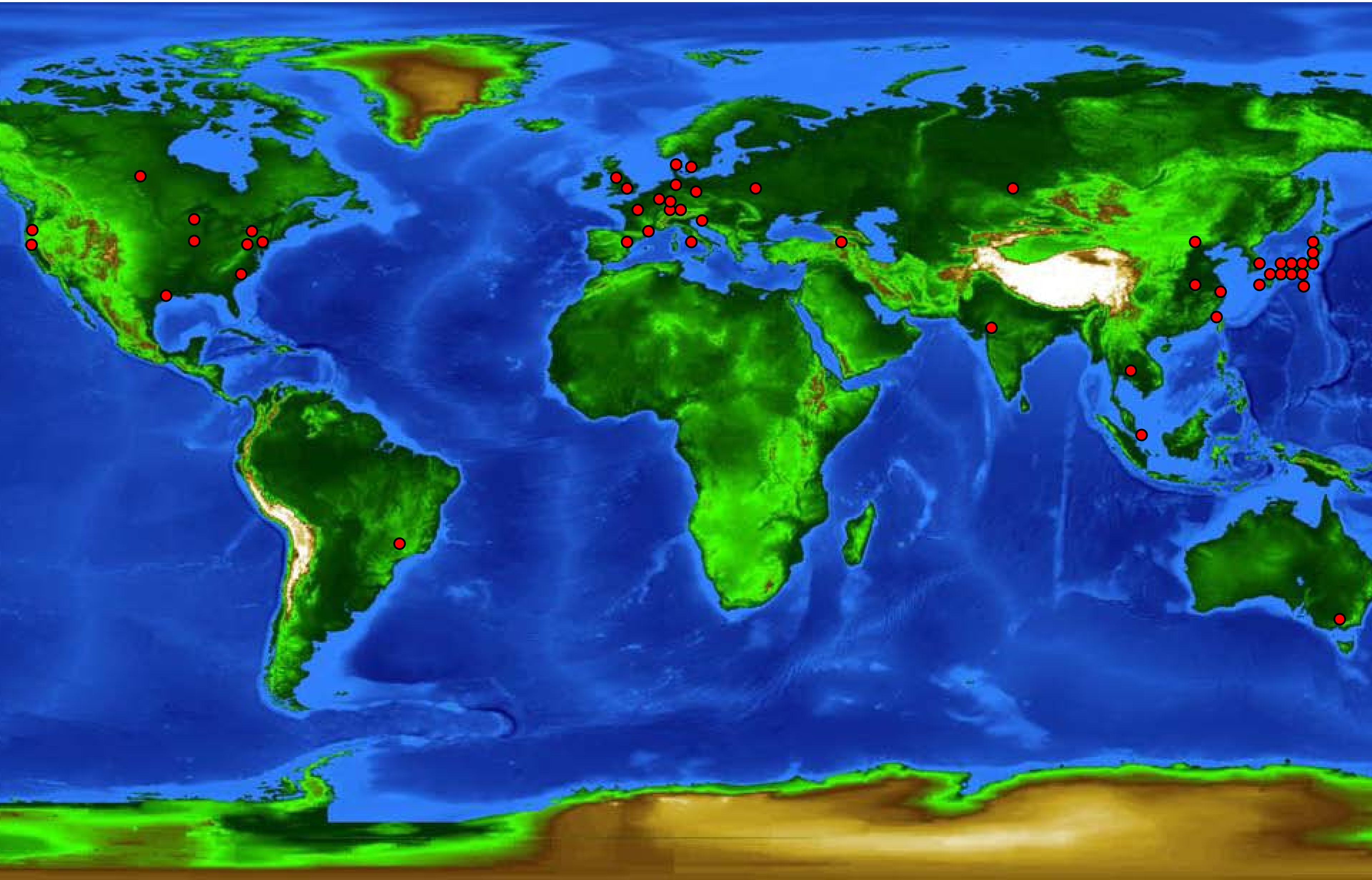
Ecole Polythechnique Federale de Lausanne (EPFL)
and Paul Scherrer Institute (PSI), Switzerland

African School on Fundamental Physics and its Applications
August 2010, NITheP at Stellenbosch, South Africa

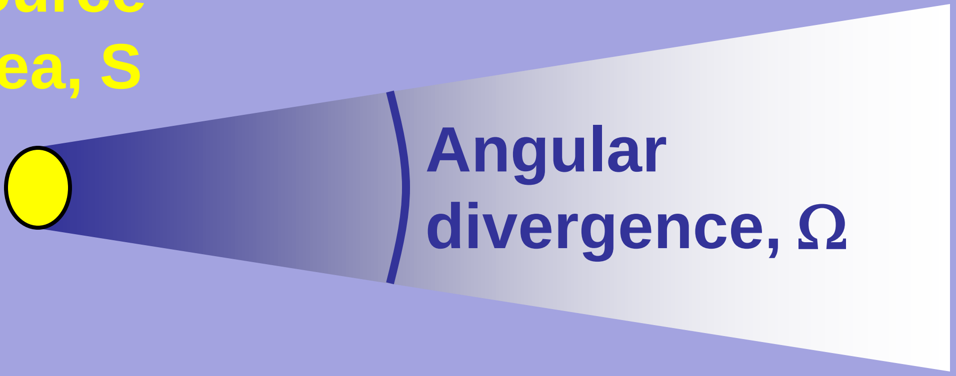


Wavelength continuously tunable !

60‘000 users world–wide



The "brightness" of a light source:



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

G. Margaritondo

Steep rise in brightness

the second wave

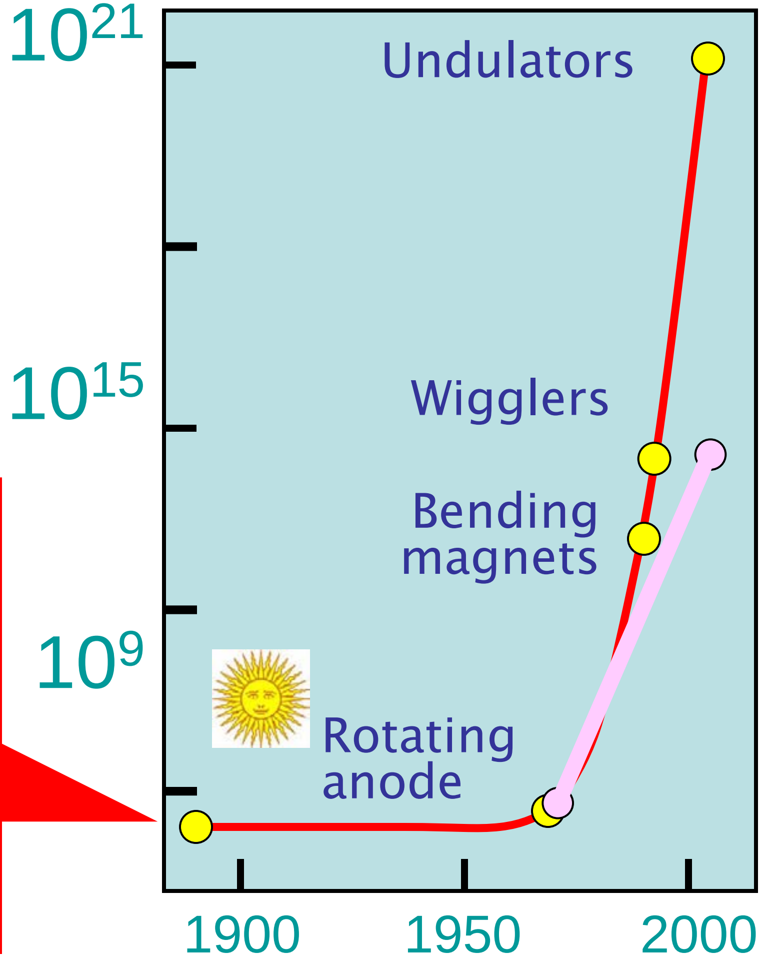
XFEL

SLS
SOLEIL (F)
DIAMOND (UK)
…

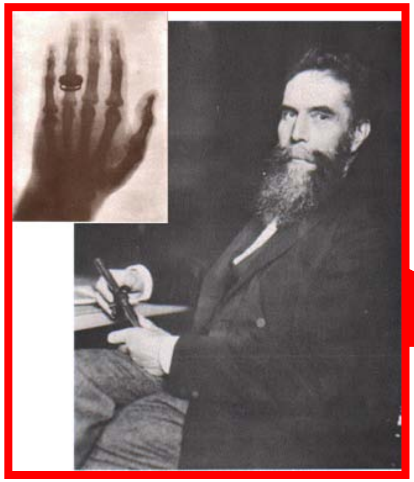
ESRF

SPring8

APS



Moore's Law for semiconductors



Bertha Roentgen's hand
(exposure: 20 min)

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

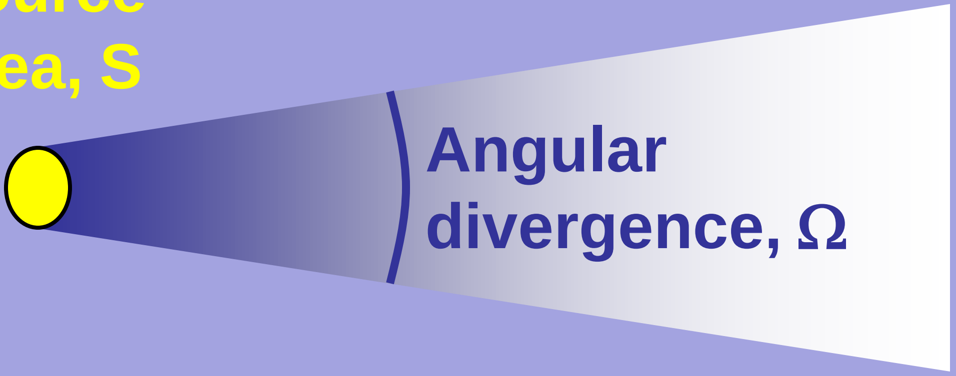
- measurements on very small probes (few μm crystals)

- 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

Radiation effects in electron storage rings

Average radiated power restored by RF

$$\boxed{U_0 \cong 10^{-3} \text{ of } E_0}$$

- Electron loses energy each turn
- RF cavities provide voltage to accelerate electrons back to the nominal energy

$$\boxed{V_{RF} > U_0}$$

Radiation damping

- Average rate of energy loss produces **DAMPING** of electron oscillations in all three degrees of freedom (if properly arranged!)

Quantum fluctuations

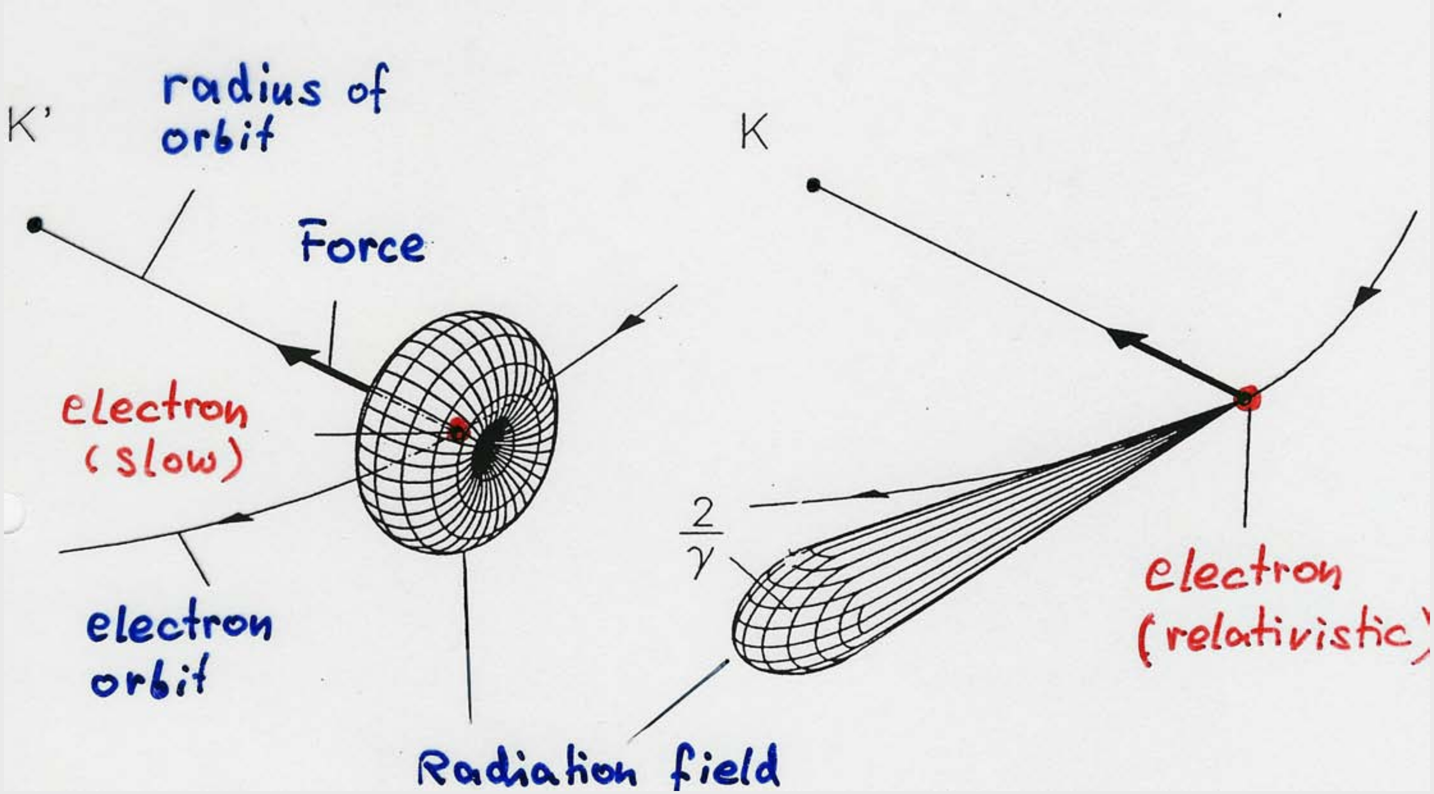
- Statistical fluctuations in energy loss (from quantised emission of radiation) produce **RANDOM EXCITATION** of these oscillations

Equilibrium distributions

- The balance between the damping and the excitation of the electron oscillations determines the equilibrium distribution of particles in the beam

Radiation is emitted into a narrow cone

$$\theta = \frac{1}{\gamma} \cdot \theta_e$$



v << c

v ≈ c

RADIATION DAMPING

TRANSVERSE OSCILLATIONS

Average energy loss and gain per turn

- Every turn electron radiates small amount of energy

$$E_1 = E_0 - U_0 = E_0\left(1 - \frac{U_0}{E_0}\right)$$

- only the amplitude of the momentum changes

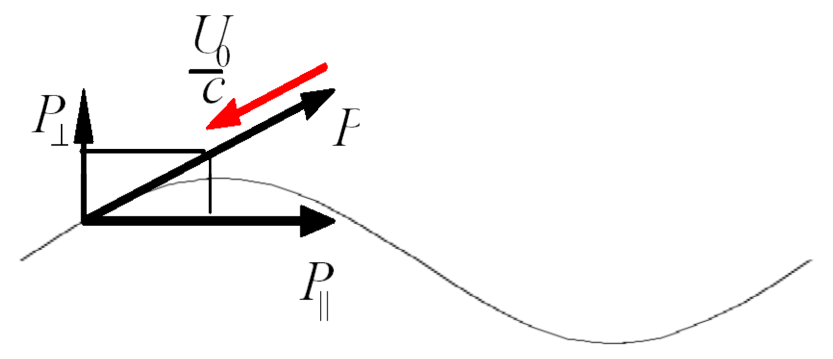
$$P_1 = P_0 - \frac{U_0}{c} = P_0\left(1 - \frac{U_0}{E_0}\right)$$

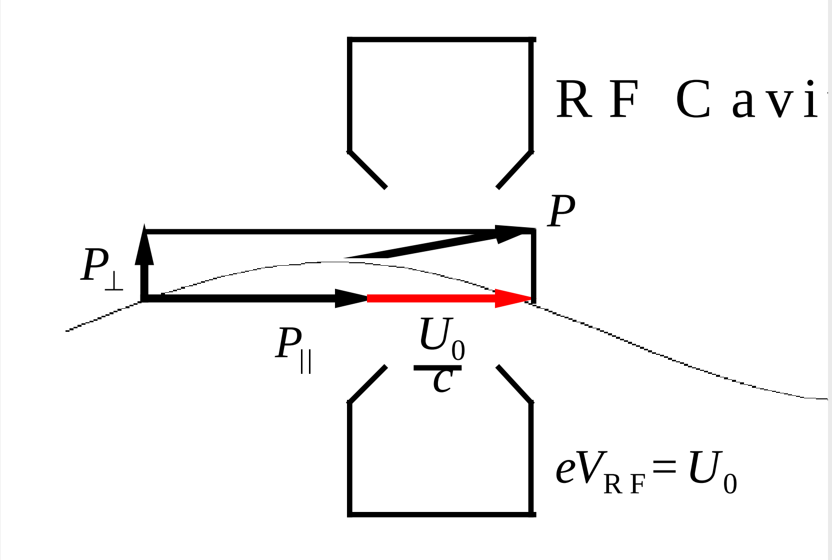
- Only the longitudinal component of the momentum is increased in the RF cavity

- Energy of betatron oscillation

$$\boxed{E_\beta \propto A^2}$$

$$\boxed{A_1^2 = A_0^2\left(1 - \frac{U_0}{E_0}\right) \quad \text{or} \quad A_1 \cong A_0\left(1 - \frac{U_0}{2E_0}\right)}$$





Damping of vertical oscillations

- But this is just the exponential decay law!

$$\boxed{\frac{\Delta A}{A} = -\frac{U_0}{2E}}$$

$$\boxed{A = A_0 \cdot e^{-t/\tau}}$$

- The oscillations are exponentially **damped** with the **damping time** **(milliseconds!)**

$$\boxed{\tau = \frac{2E\,T_0}{U_0}}$$

the time it would take particle to ‘lose all of its energy’

- In terms of radiation power

$$\boxed{\tau = \frac{2E}{P_\gamma}}$$

and since $\boxed{P_\gamma \propto E^4}$

$$\boxed{\tau \propto \frac{1}{E^3}}$$

Quantum nature of synchrotron radiation

Damping only

- If damping was the whole story, the beam emittance (size) would shrink to microscopic dimensions!
- Lots of problems! (e.g. coherent radiation)

Quantum fluctuations

- Because the radiation is emitted in quanta, radiation itself takes care of the problem!
- It is sufficient to use quasi-classical picture:
  - » *Emission time is very short*
  - » *Emission times are statistically independent (each emission - only a small change in electron energy)*

Purely stochastic (Poisson) process

Visible quantum effects

I have always been somewhat amazed that a purely quantum effect can have gross macroscopic effects in large machines;

and, even more,

that Planck's constant has just the right magnitude needed to make practical the construction of large electron storage rings.

A significantly larger or smaller value of $\hbar$

would have posed serious -- perhaps insurmountable -- problems for the realization of large rings.

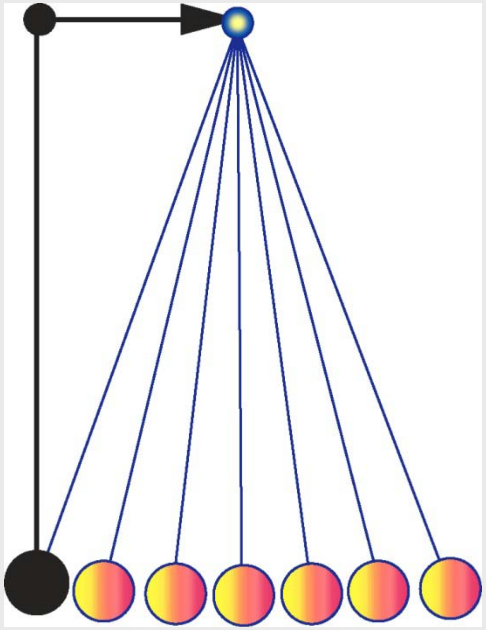
Mathew Sands

Excitation of betatron oscillations

Electron emitting a photon

- at a place with non-zero dispersion
- starts a betatron oscillation around a new reference orbit

$$\boxed{x_\beta \approx D \cdot \frac{\varepsilon_\gamma}{E}}$$



Horizontal oscillations: equilibrium

Emission of photons is a random process

- How far particle will wander away in this random walk is limited by the radiation damping
- The balance is achieved on the time scale of the damping time τ_x

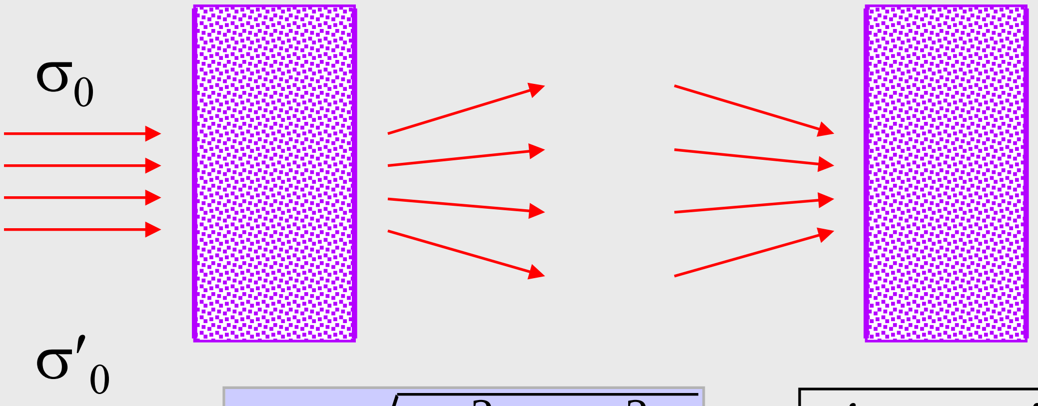
$$\sigma_{x\beta} \approx \sqrt{\mathcal{N} \cdot \tau_x} \cdot D \cdot \frac{\varepsilon_\gamma}{E} = \sqrt{2} \cdot D \cdot \frac{\sigma_\varepsilon}{E}$$

- Typical horizontal beam size ~ 1 mm

Quantum effect visible to the naked eye!

- Vertical size - determined by coupling

Ring equilibrium emittance



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

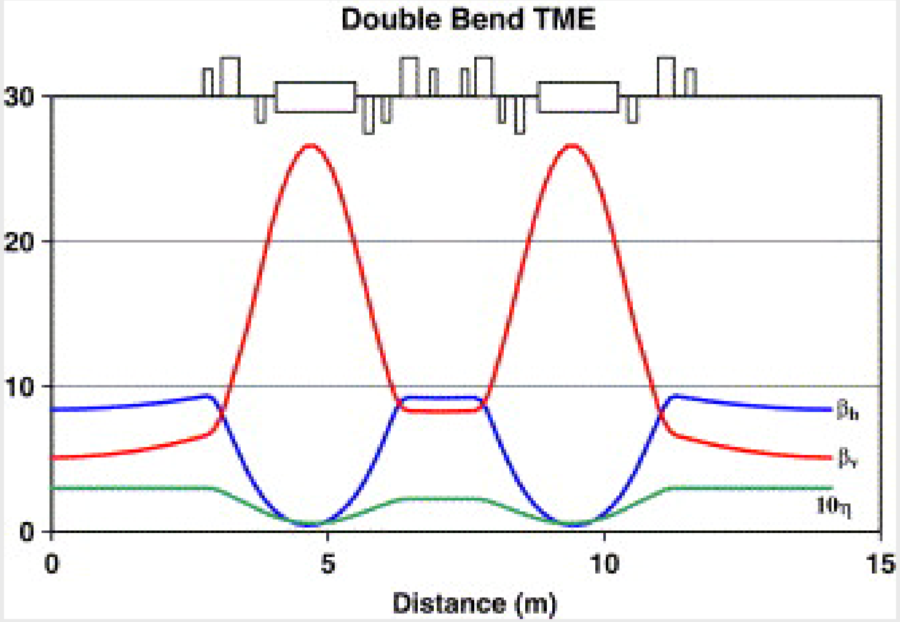
$$\sigma'_0 >> \sigma'_{MS}$$

to minimize the blow up due to multiple scattering in the absorber we can **focus** the beam

Equilibrium Emittance

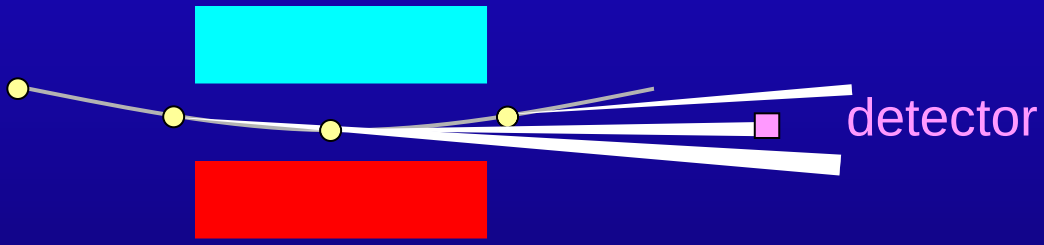
$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot \mathrm{F}_{\mathrm{latt}}$$

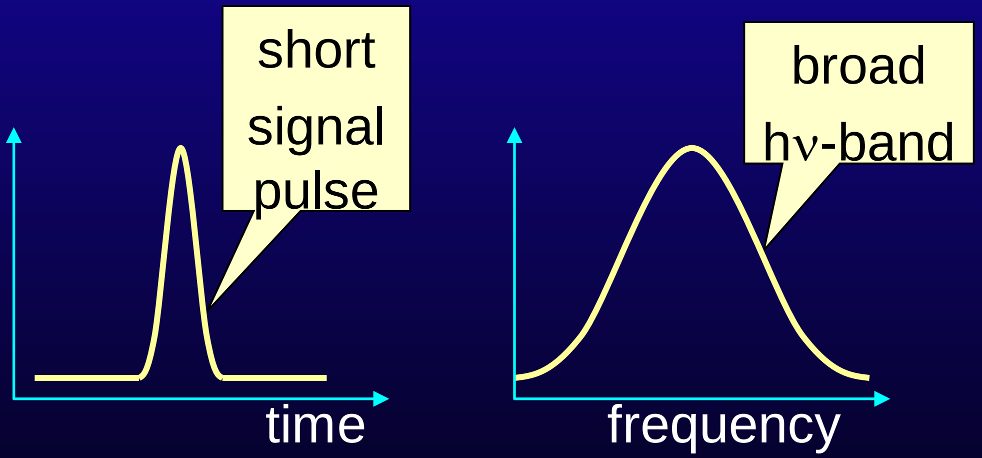
$$\mathrm{F}_{\min} = \frac{1}{12\sqrt{15}}$$



3 types of storage ring sources:

1. Bending magnets: $B \sim N_e$



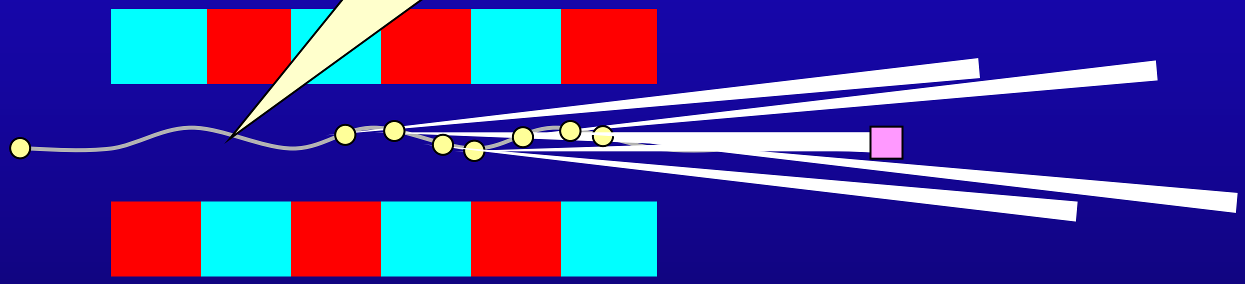

short signal pulse

broad hν-band

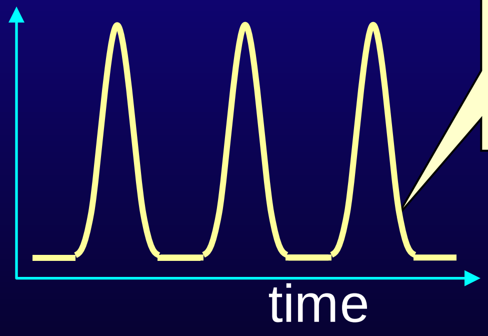
3 types of storage ring sources:

2. Wigglers:

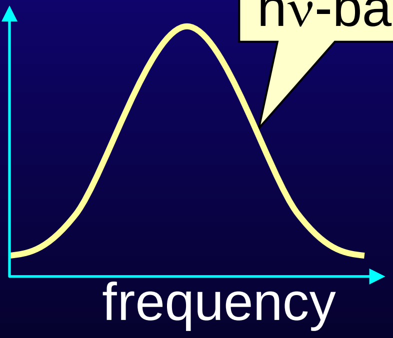
$B \sim N_e N_w$ x10



large undulations



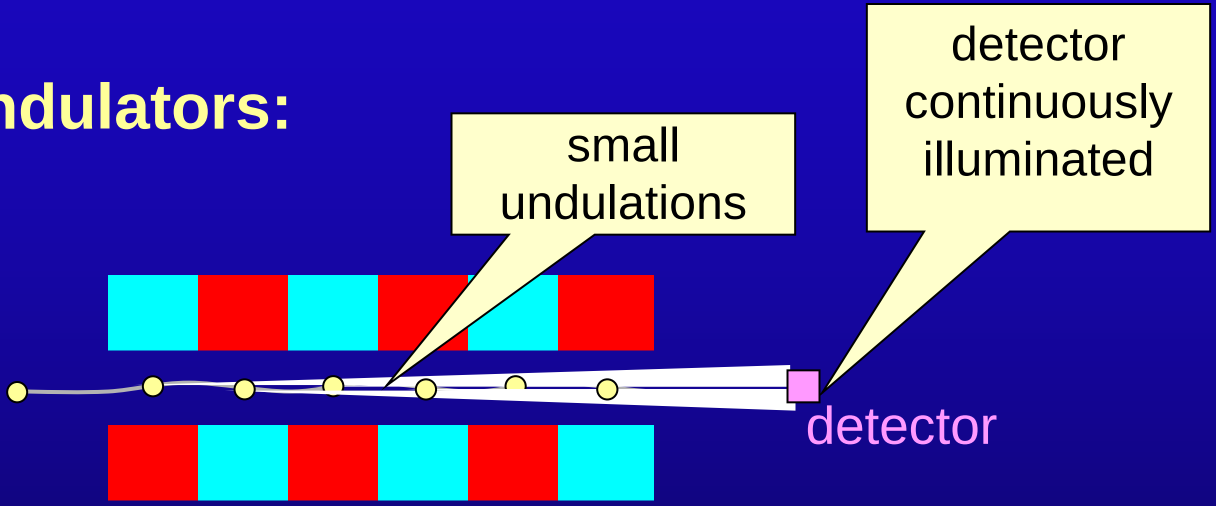
Series of short pulses



broad hν-band

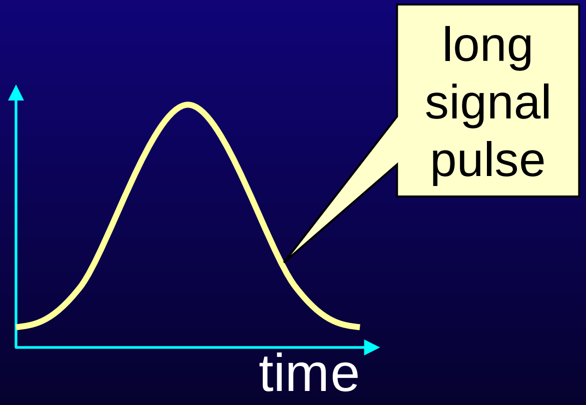
3 types of storage ring sources:

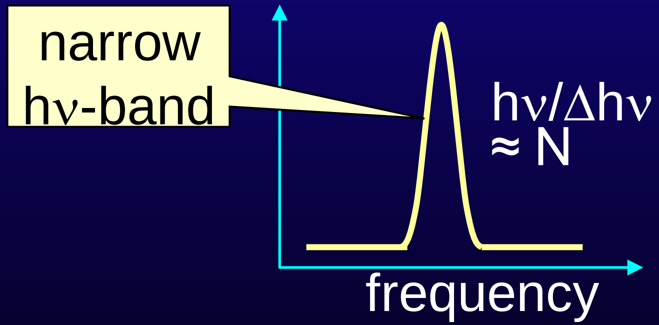
3. Undulators:


small undulations

detector continuously illuminated

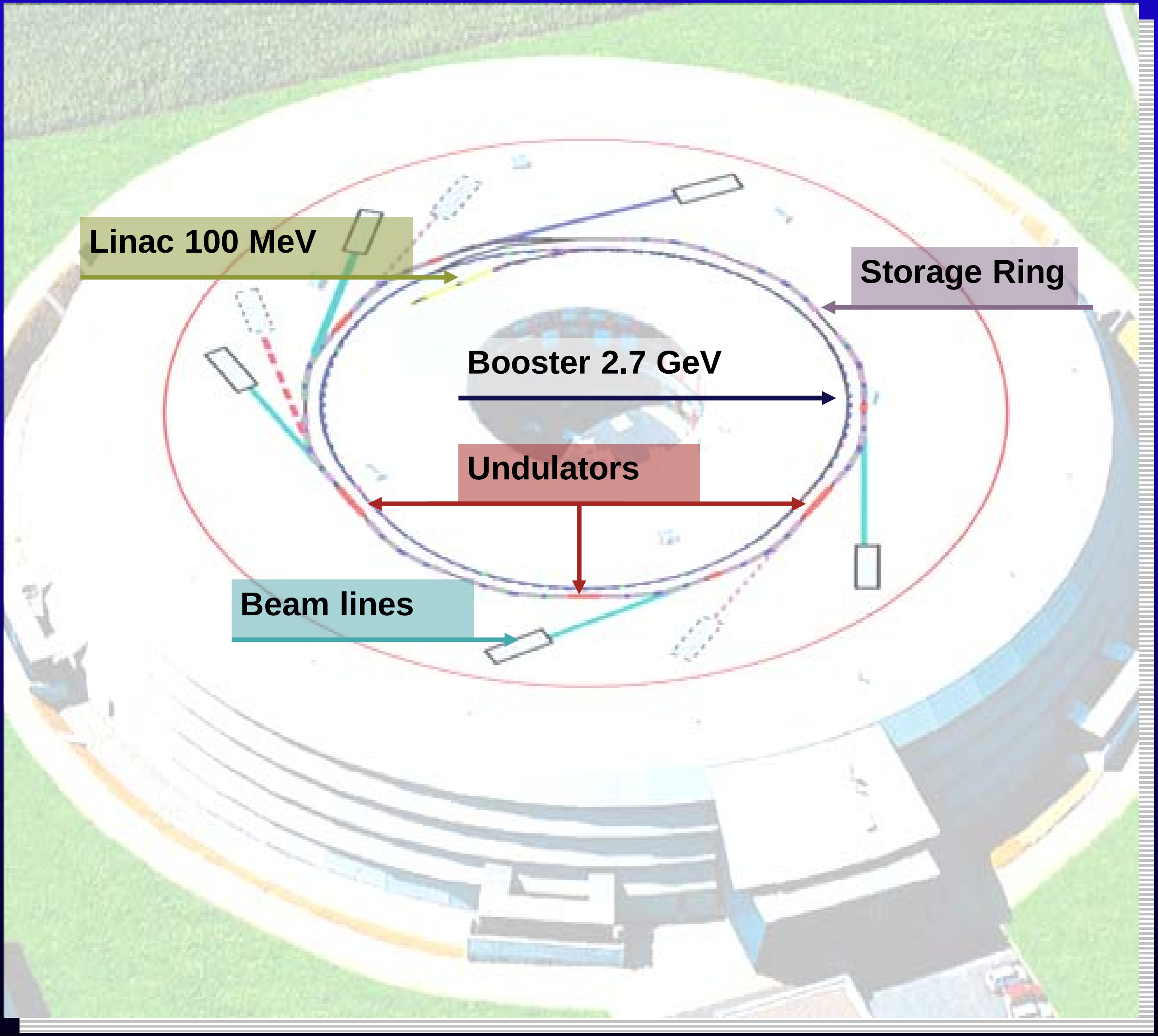
$B \sim N_e N_u^2 \quad \times 10^3$


long signal pulse


narrow hν-band

$h\nu/\Delta h\nu \approx N$

Anatomy of a light source



Linac 100 MeV

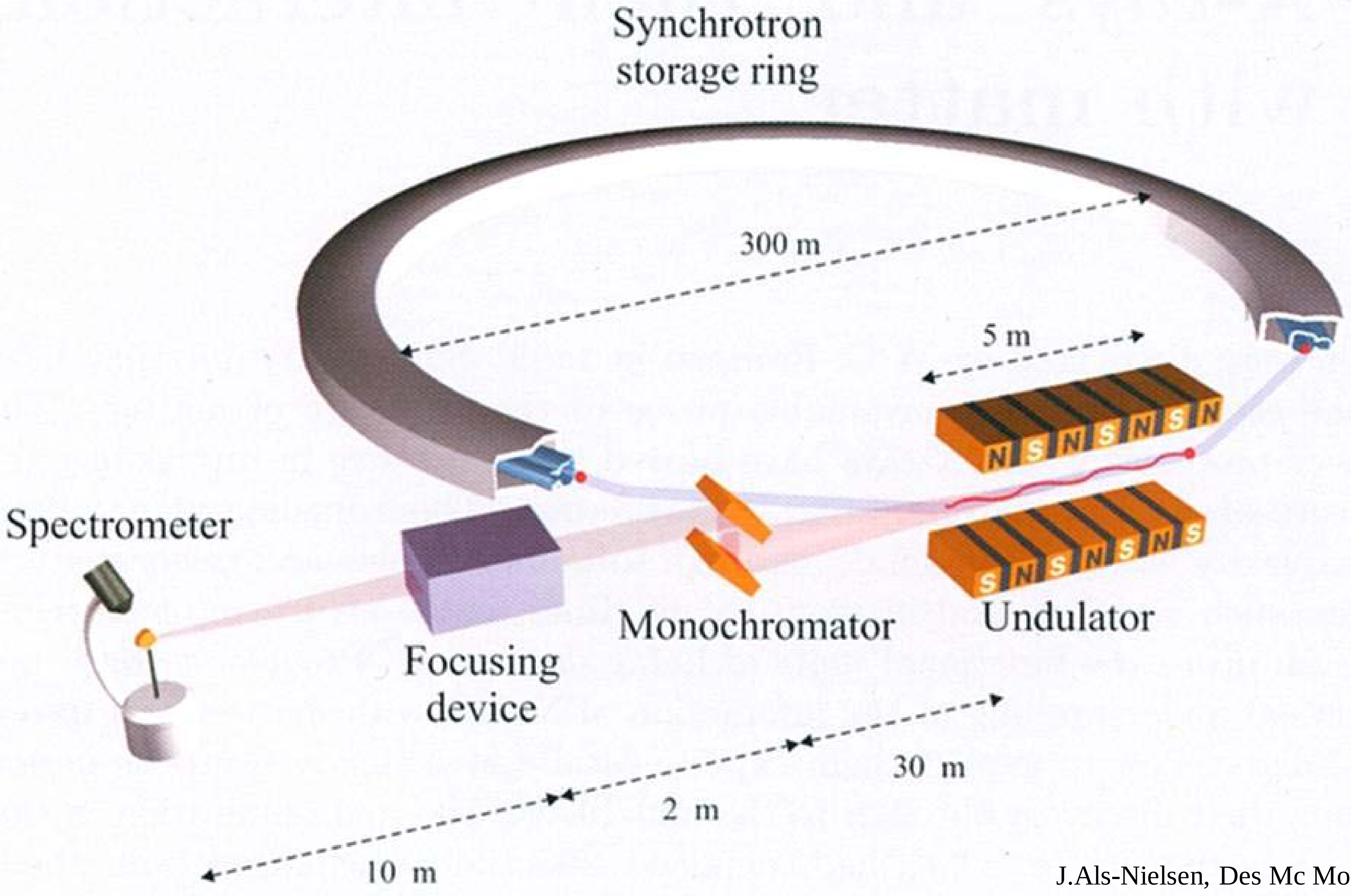
Storage Ring

Booster 2.7 GeV

Undulators

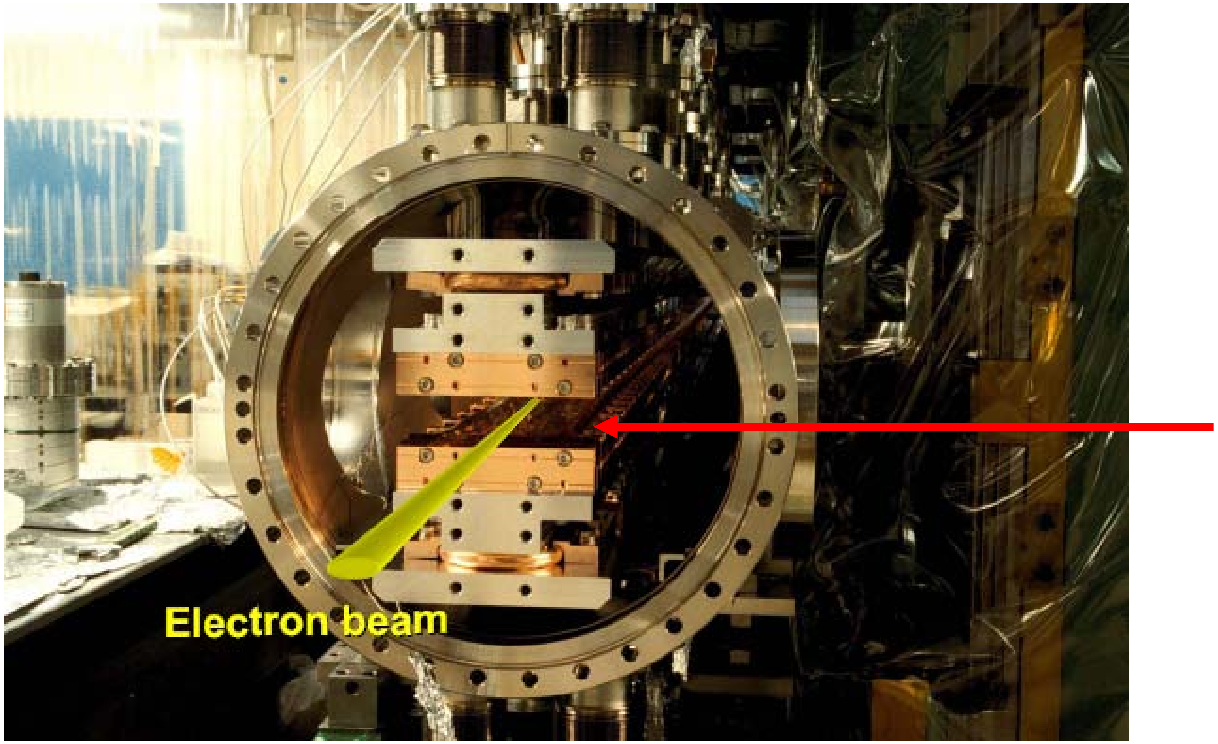
Beam lines

About 60 ring sources world-wide



J.Als-Nielsen, Des Mc Morrow

In–vacuum undulators / s.c. undulators

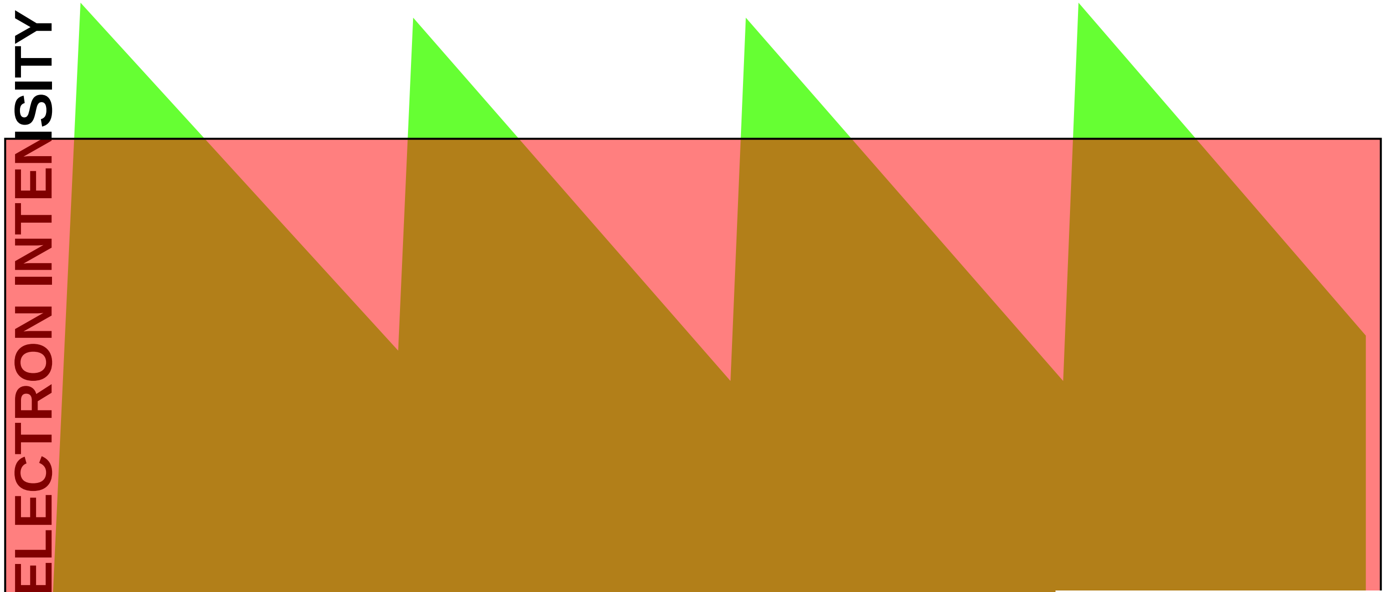


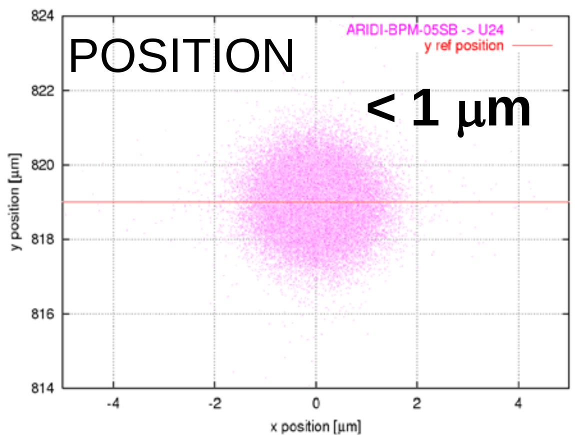
Gaps
down
to
3 mm

Third Generation Light Sources in Operation

Top-up injection: key to stability

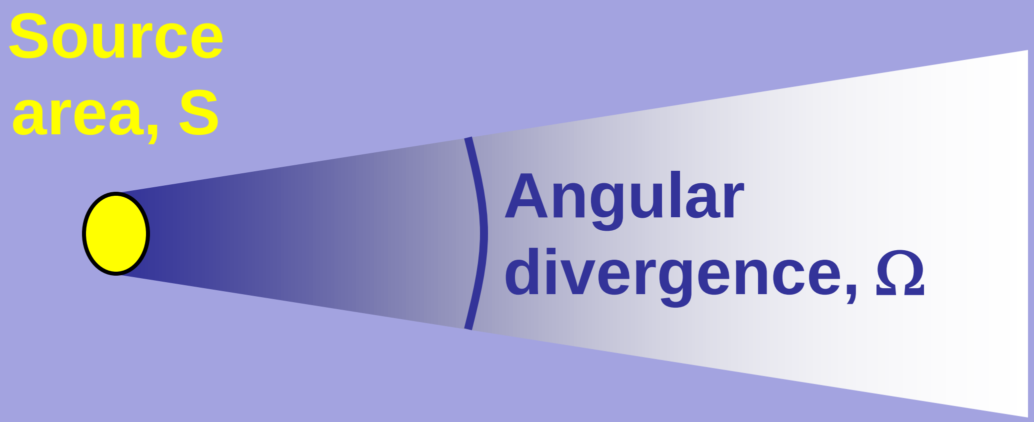
TOP-UP INJECTION





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

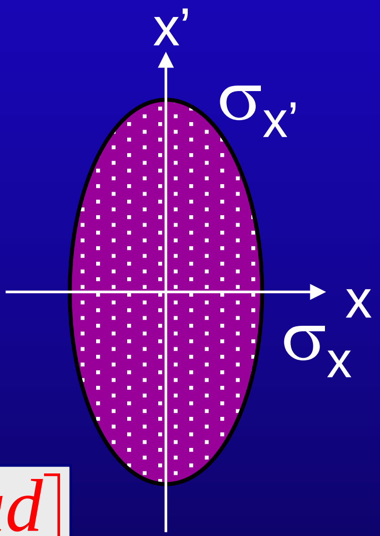
$$\text{Area} = \pi \cdot \varepsilon$$

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 $[m \cdot rad]$

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

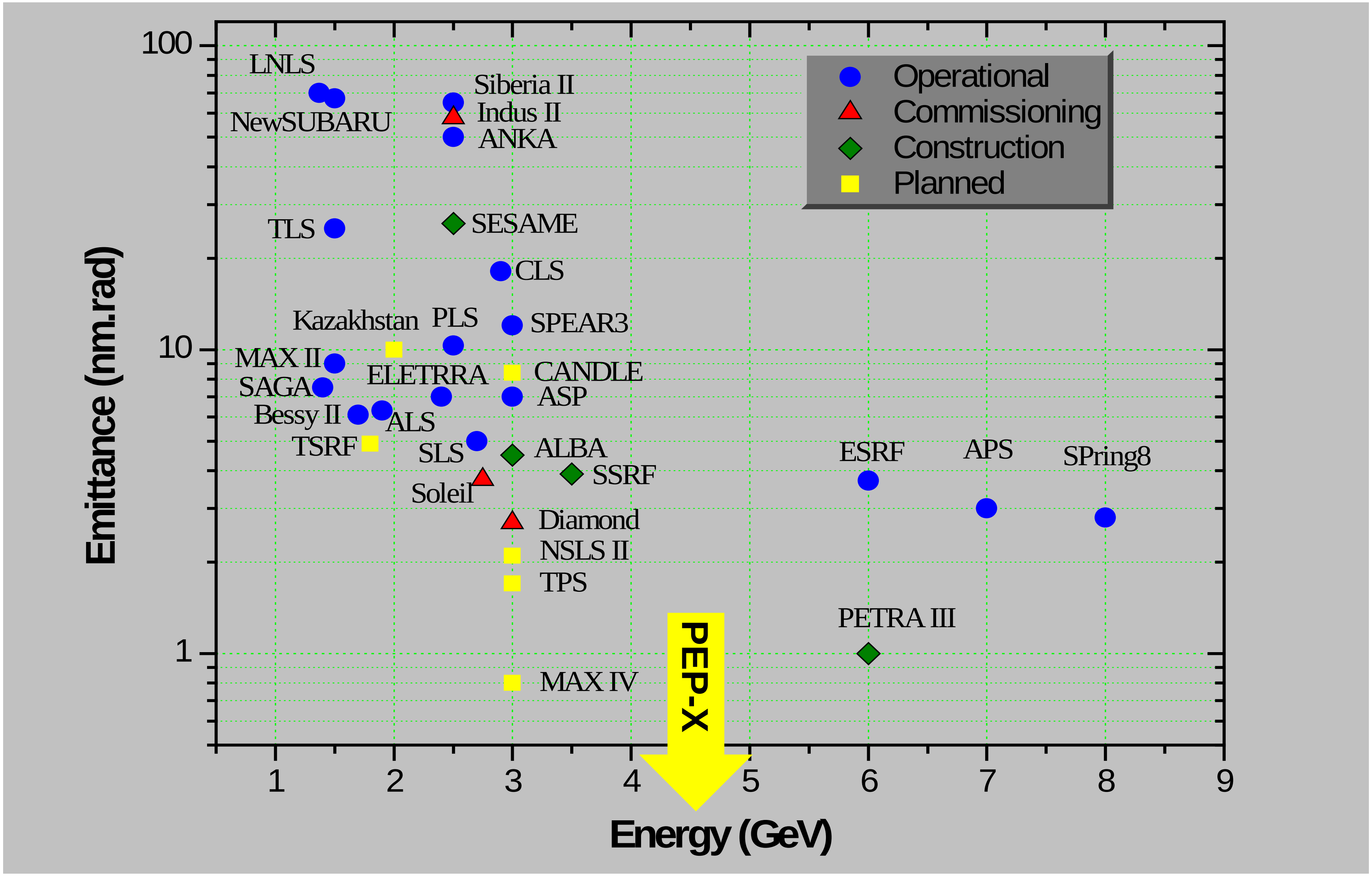
$$\varepsilon = \sigma_x \cdot \sigma_{x'}$$

$$\sigma_x = \sqrt{\varepsilon \beta}$$

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

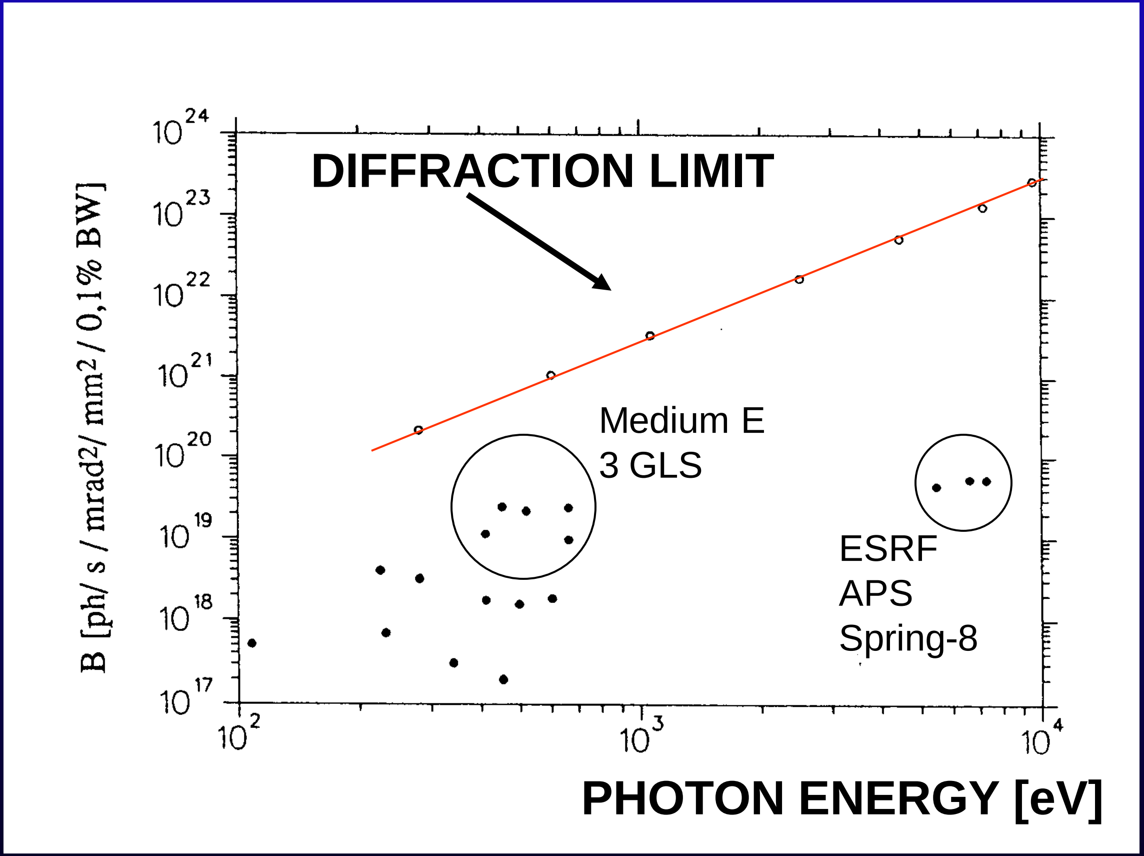
$$\beta = \frac{\sigma_x}{\sigma_{x'}}$$

Third Generation Light Sources



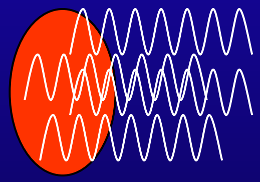
PERFORMANCE OF 3th GENERATION LIGHT SOURCES

BRIGHTNESS:



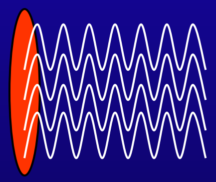
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$



INCOHERENT EMISSION

Intensity $\propto N^2$



COHERENT EMISSION

FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

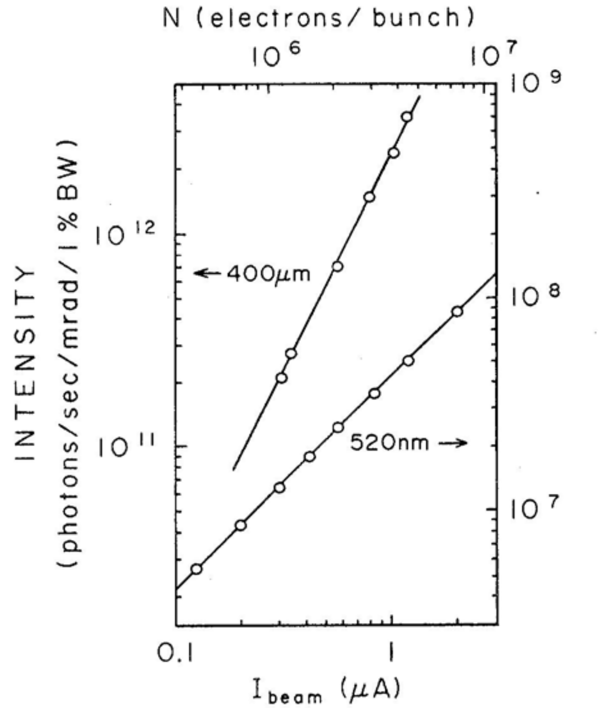


Fig. 4. Dependence of SR intensity on the beam current at $\lambda = 400$ μm and $\lambda = 520$ nm for the long pulse/short bunch beam. The ordinate is given on the left-hand side for $\lambda = 400$ μm and on the right for $\lambda = 520$ nm. The two lines show the linear and quadratic relations to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

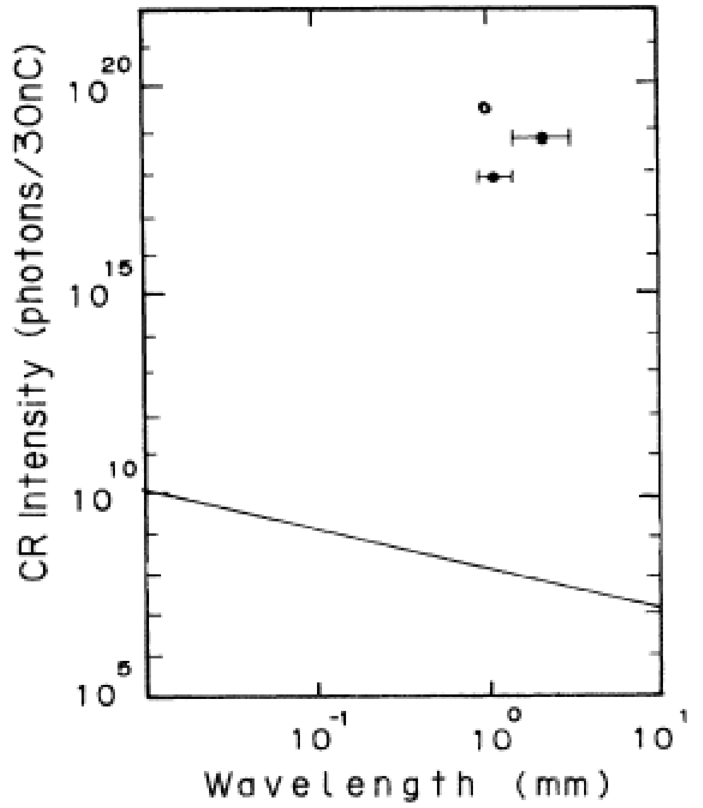


FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

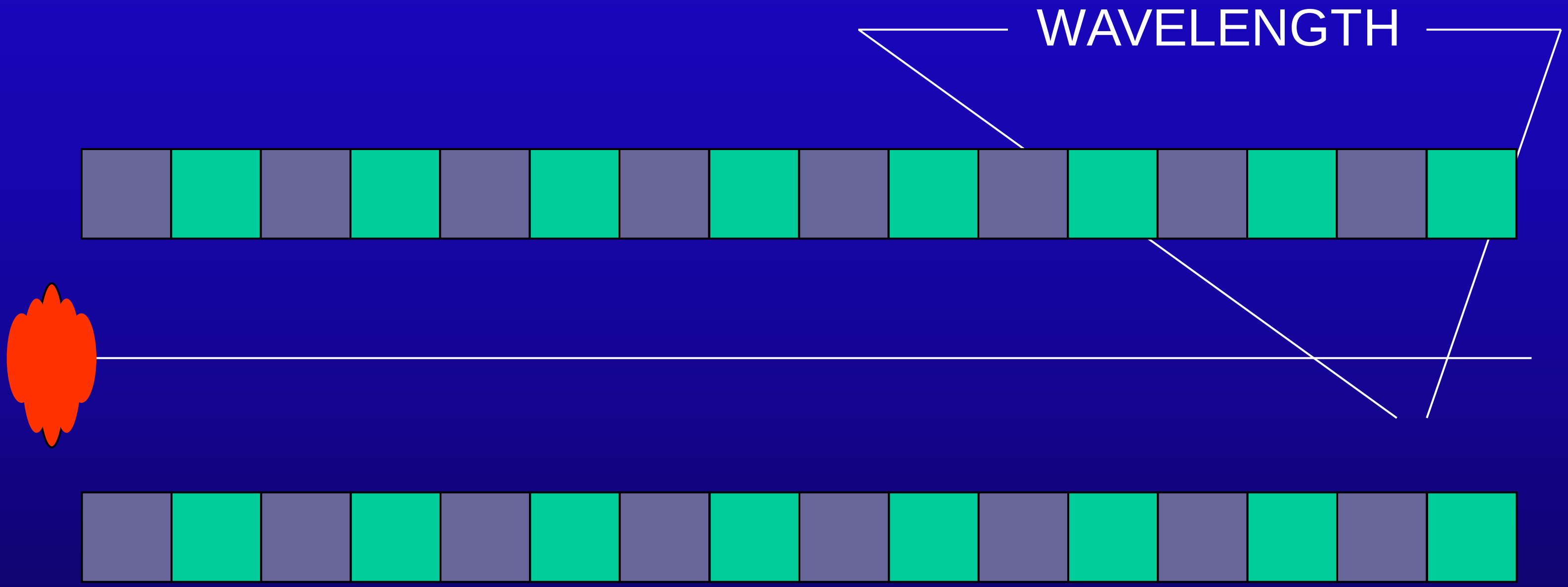
180 MeV electrons

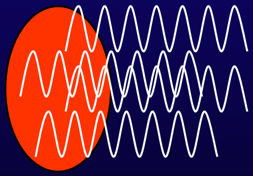
T. Nakazato et al., Tohoku University, Japan

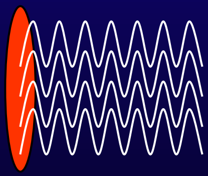
30 MeV electrons

J. Ohkuma et al., Osaka University, Japan

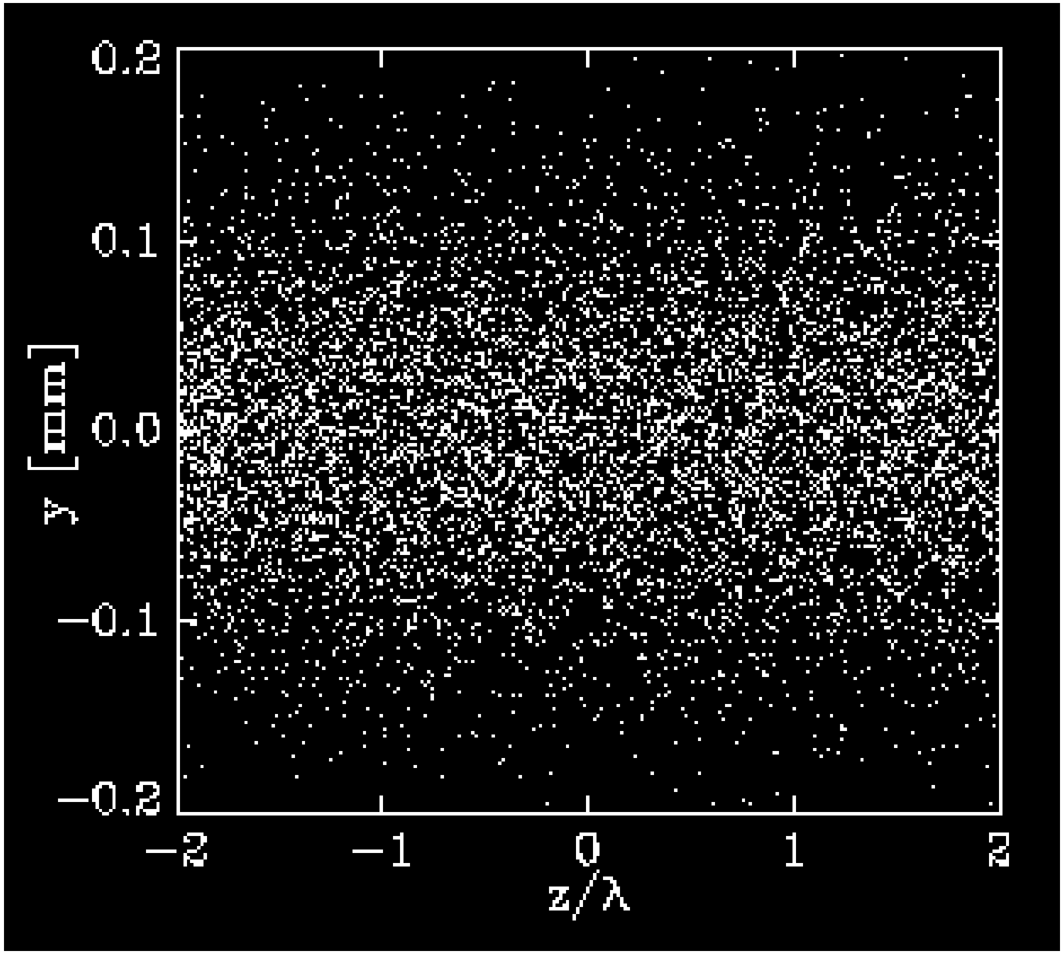
MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE


WAVELENGTH

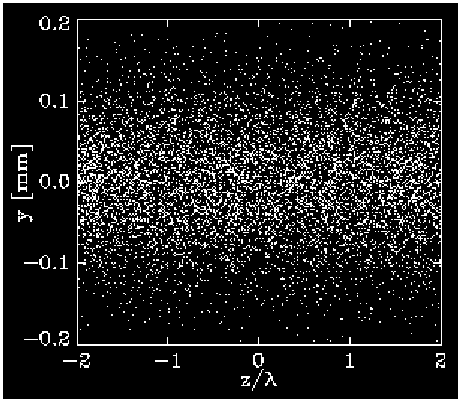

INCOHERENT EMISSION


COHERENT EMISSION

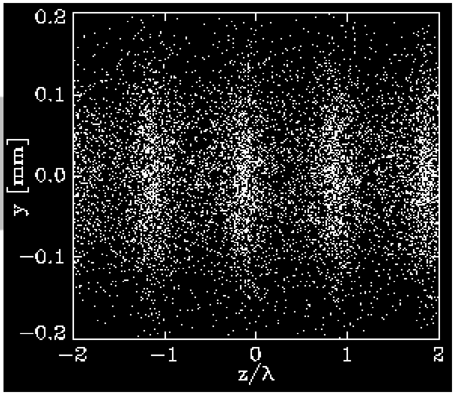
Microbunching through SASE Process



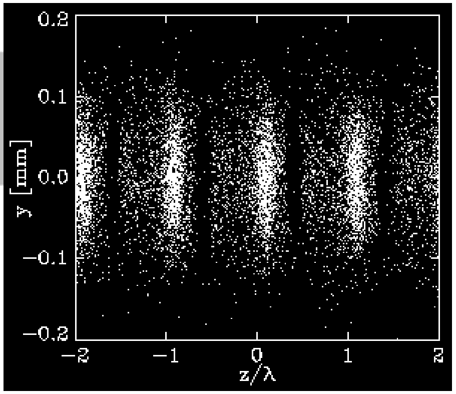
undulator entrance



half-way saturation



full saturation



GENESIS **- simulation for TTF parameters**

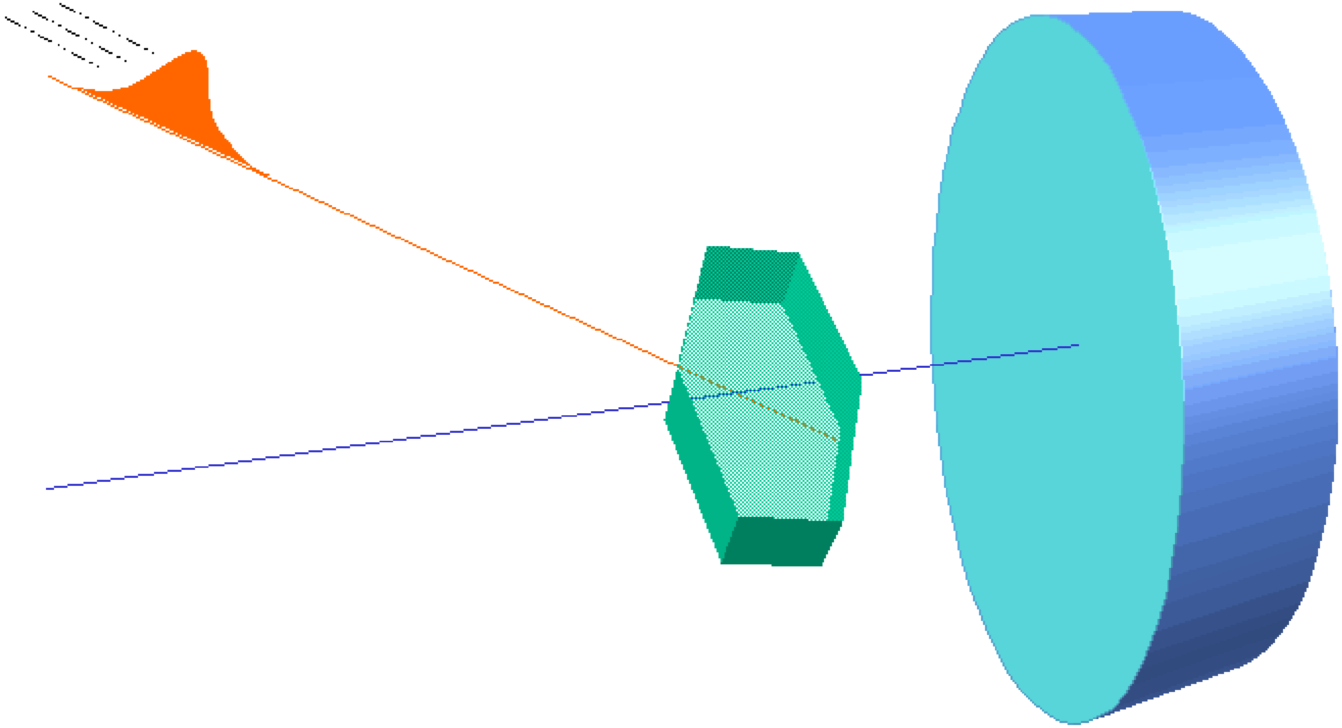
Courtesy - Sven Reiche (PSI)

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

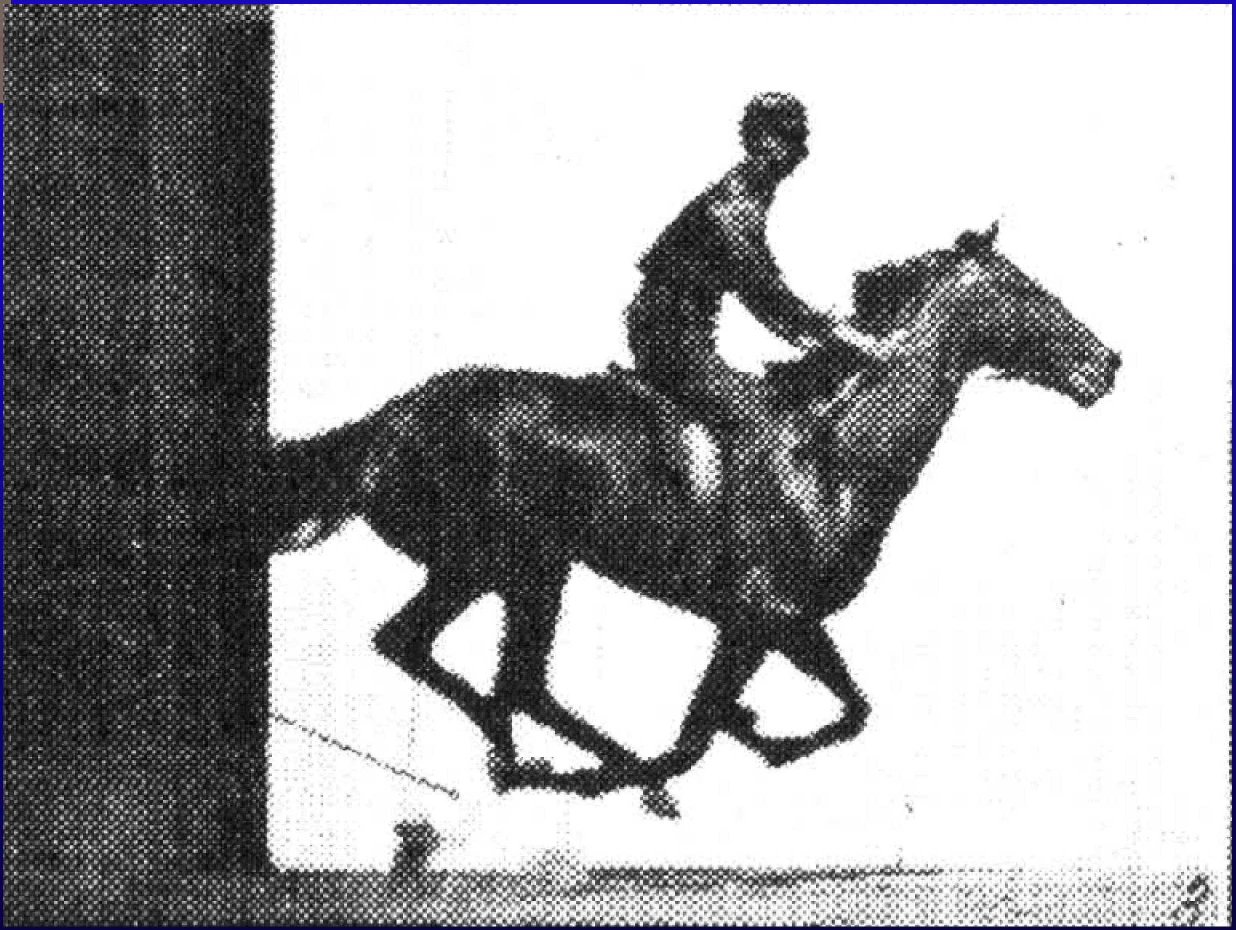


Laser pump / X-ray probe

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

E. Muybridge

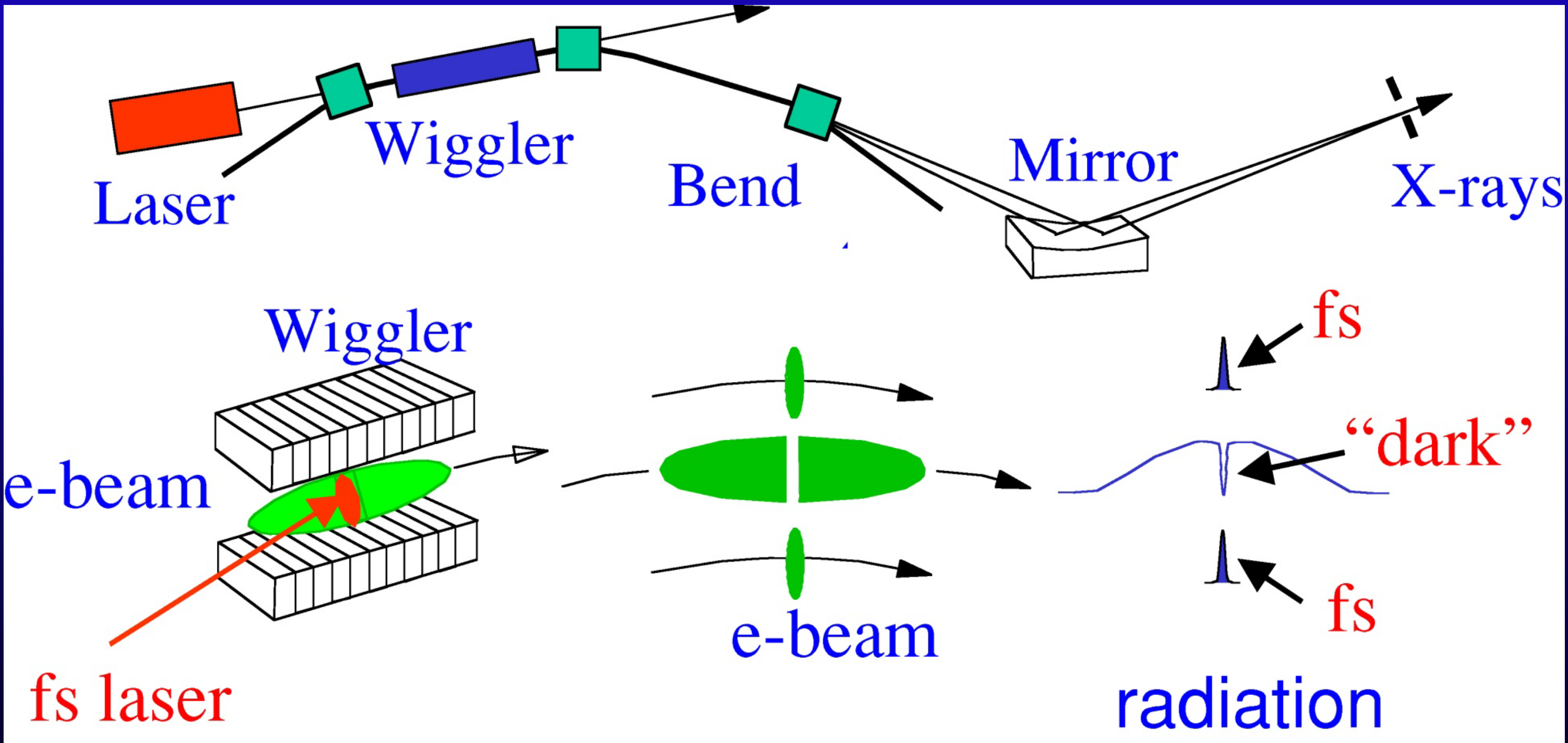


L. Stanford

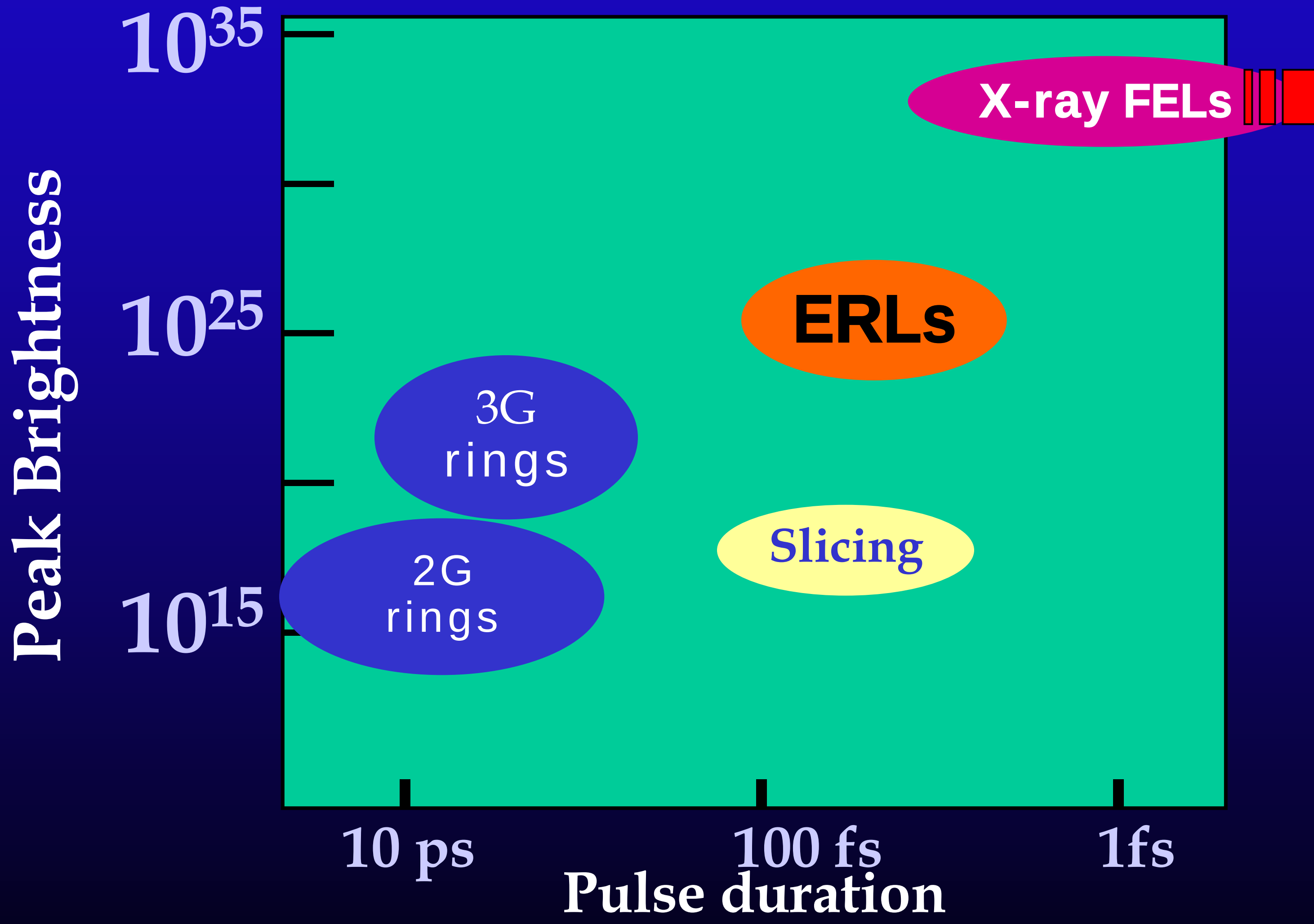
Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

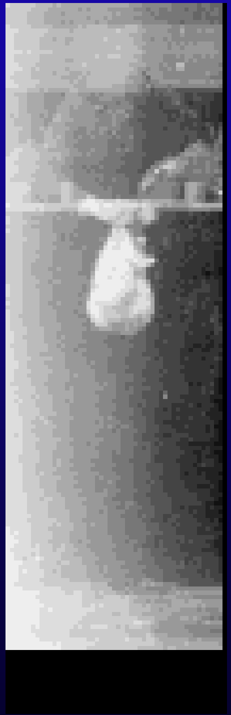
E. Muybridge, *Animals in Motion*, ed. by L. S. Brown (Dover Pub. Co., New York 1957).

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