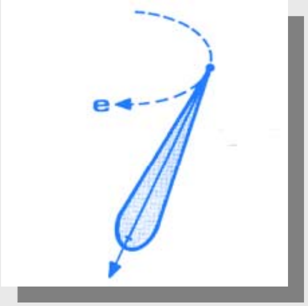


X-RAY SOURCES

Lenny Rivkin

Ecole Polythechnique Federale de Lausanne (EPFL)

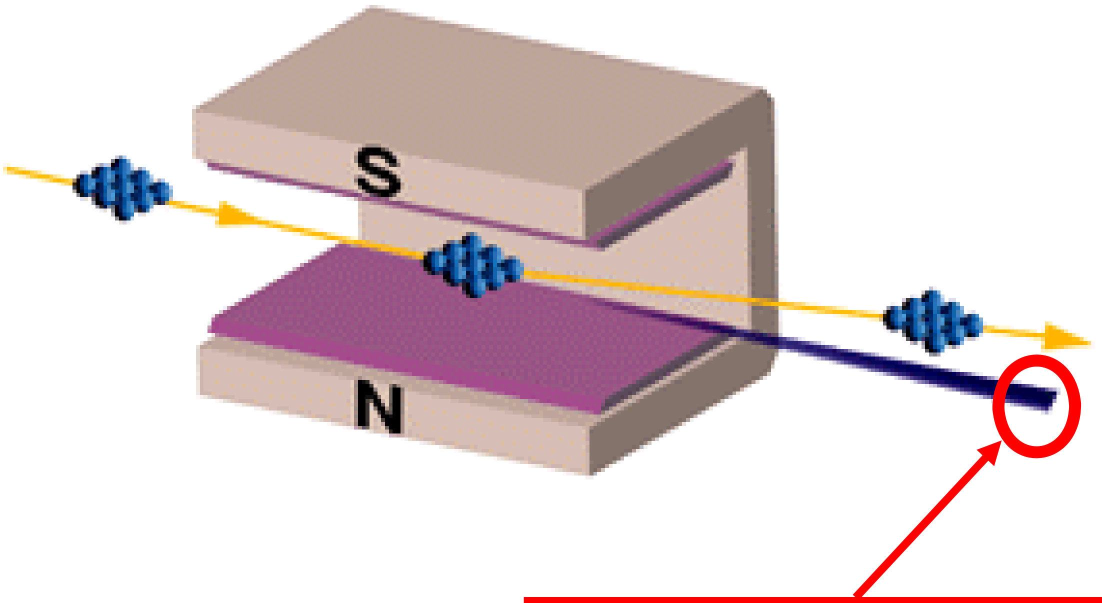
and Paul Scherrer Institute (PSI), Switzerland

Introduction to Accelerator Physics Course

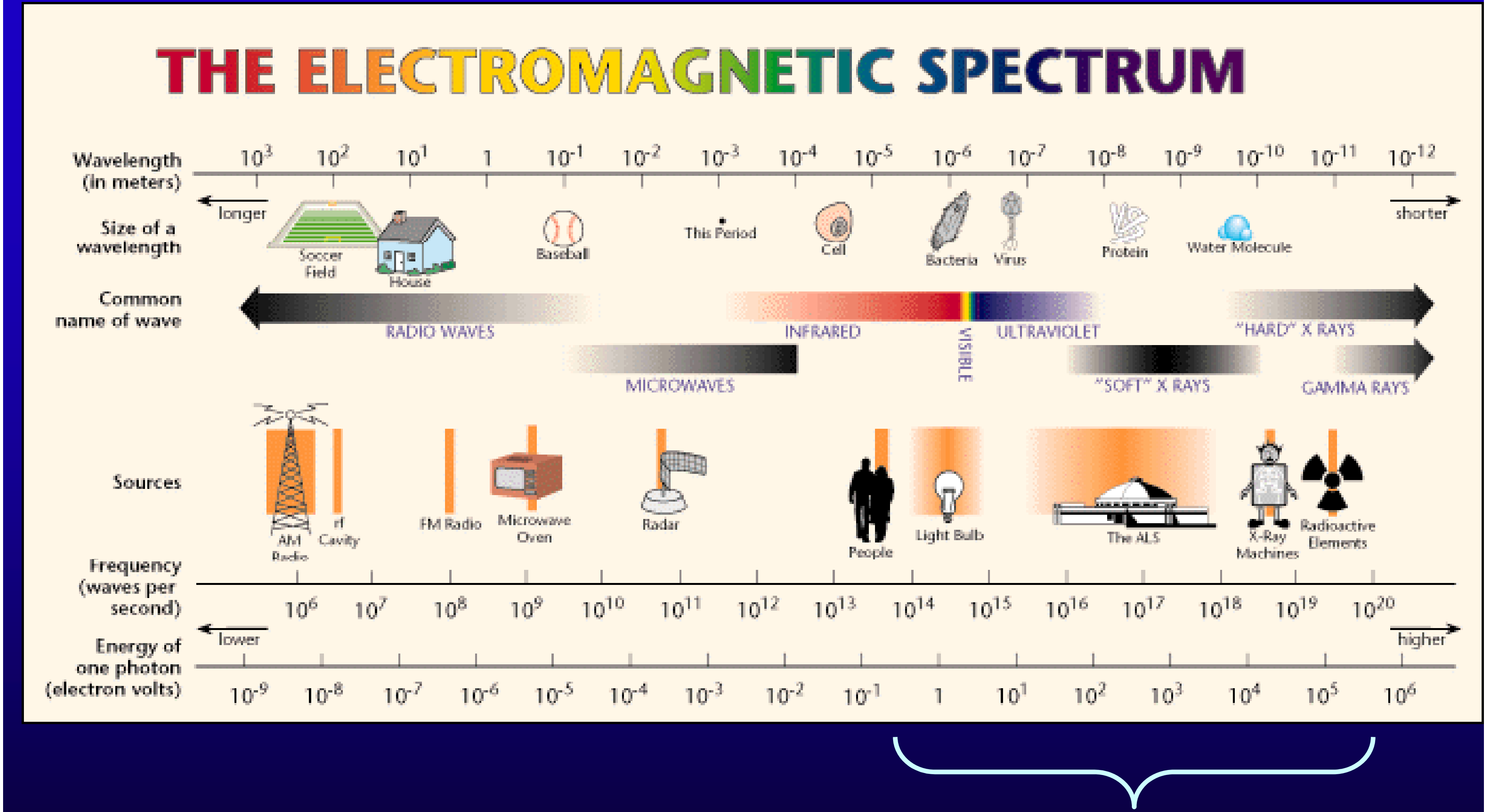
CERN Accelerator School, Frascati, Italy

2 – 14 November 2008

Curved orbit of electrons in magnetic field



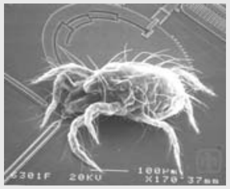
Accelerated charge → Electromagnetic radiation



Wavelength continuously tunable !

The Scale of Things – Nanometers and More

Things Natural



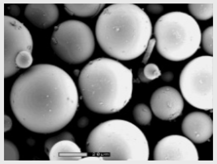
Dust mite

↔

200 µm

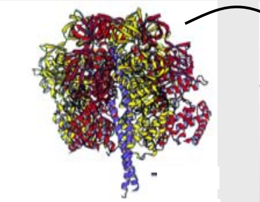
Ant
~ 5 mm

Human hair
~ 60-120 µm wide

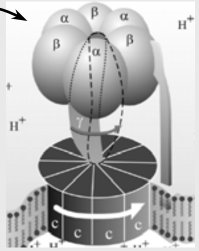


Fly ash
~ 10-20 µm

Red blood cells
(~7-8 µm)

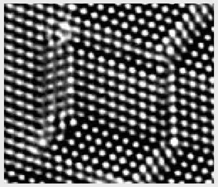


~10 nm diameter



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)

10^{-4} m — 0.1 mm
100 µm

10^{-5} m — 0.01 mm
10 µm

10^{-6} m — 1,000 nanometers = 1 micrometer (µm)

10^{-7} m — 0.1 µm
100 nm

10^{-8} m — 0.01 µm
10 nm

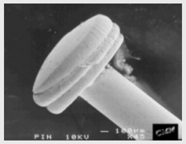
10^{-9} m — 1 nanometer (nm)

10^{-10} m — 0.1 nm

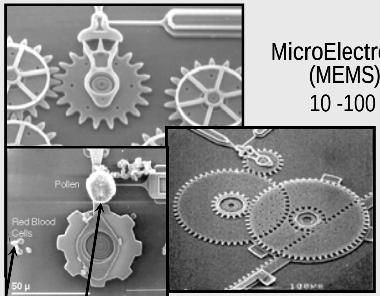
↑ Microworld ↓

↑ Nanoworld ↓

Things Manmade

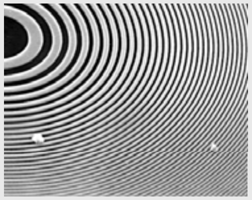


Head of a pin
1-2 mm

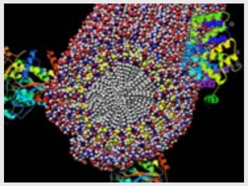


MicroElectroMechanical
(MEMS) devices
10 -100 µm wide

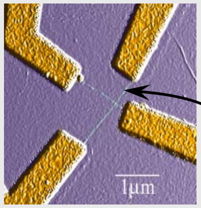
Pollen grain
Red blood cells



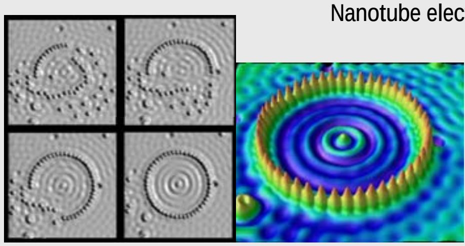
Zone plate x-ray “lens”
Outer ring spacing ~35 nm



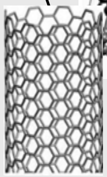
Self-assembled,
Nature-inspired structure
Many 10s of nm



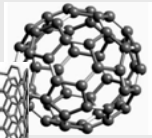
Nanotube electrode



Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm



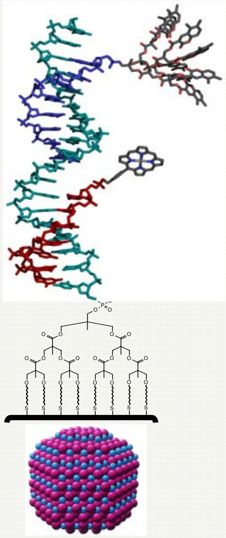
Carbon nanotube
~1.3 nm diameter



Carbon
buckyball

~1 nm
diameter

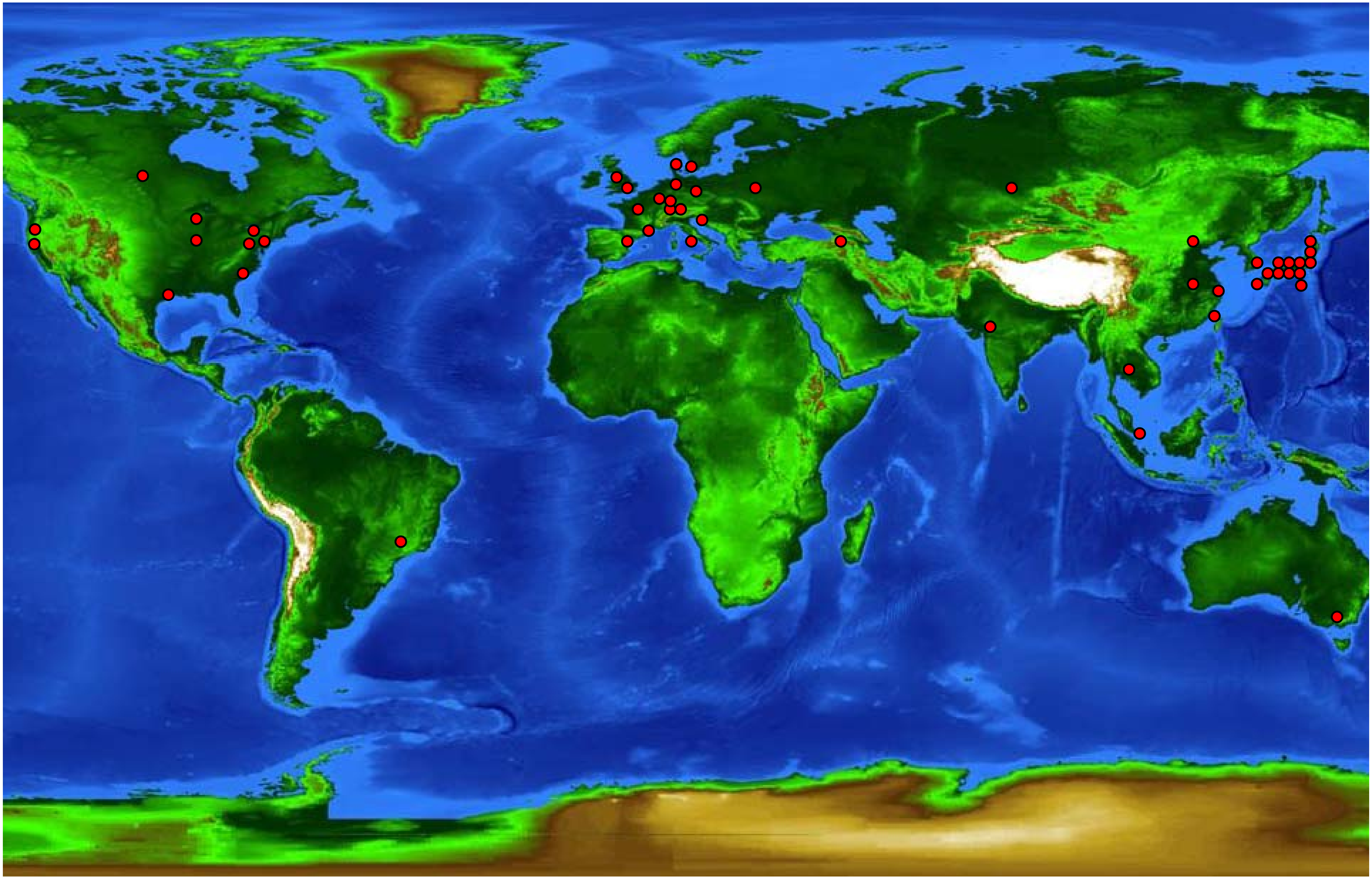
The Challenge



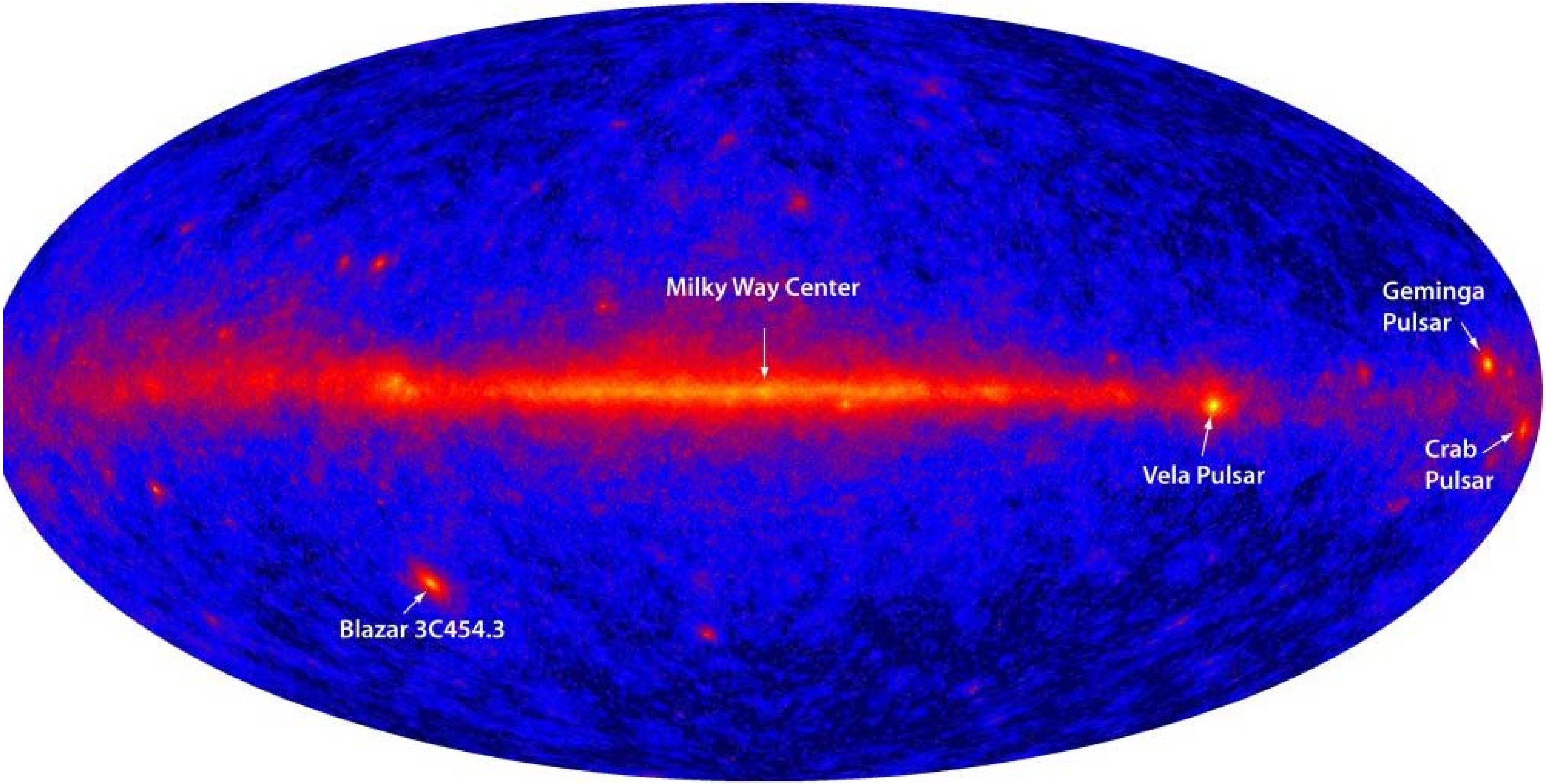
Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.

Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 01-18-05, pmd

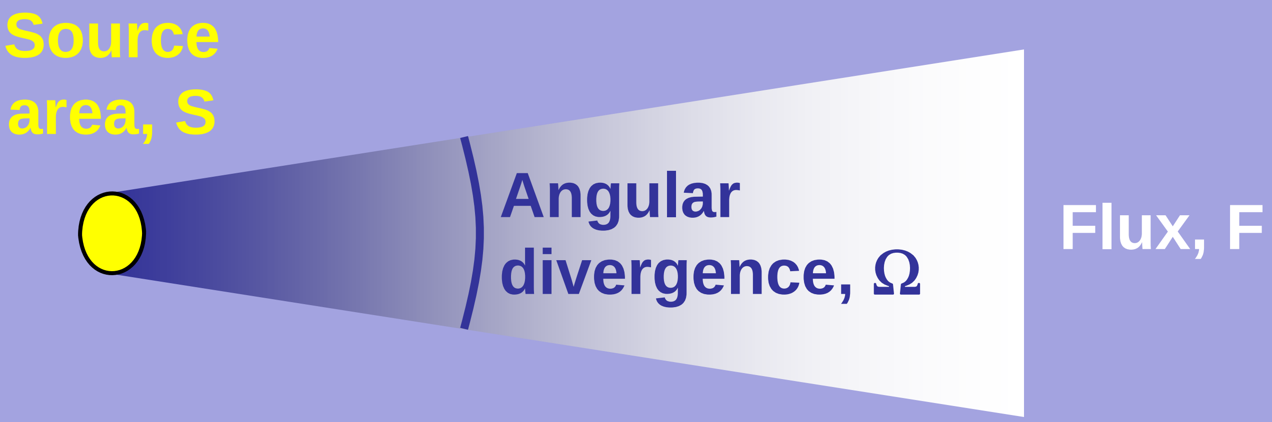
60‘000 users world-wide



A larger view



The "brightness" of a light source:



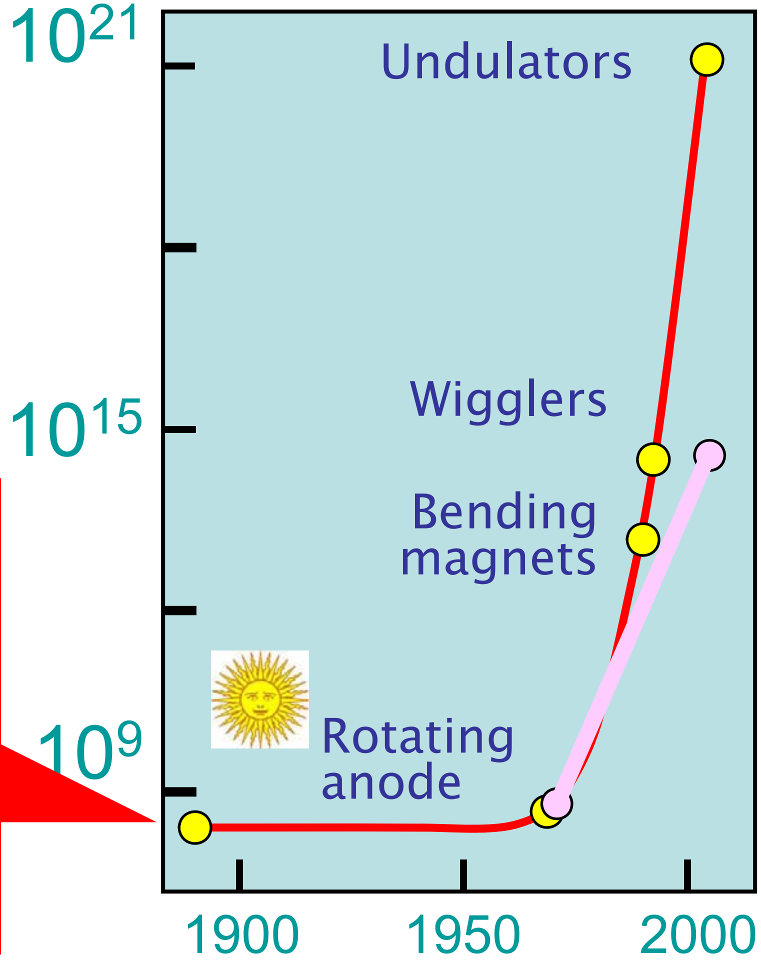
$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

G. Margaritondo

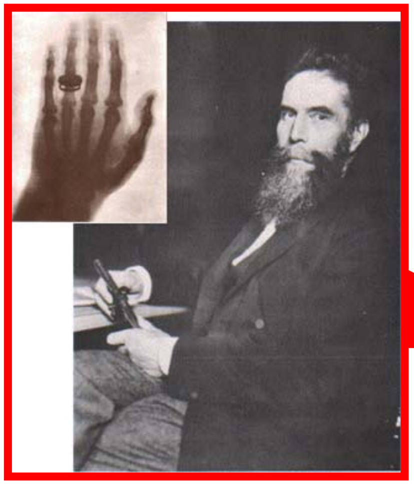
Steep rise in brightness

the second wave

XFEL



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)

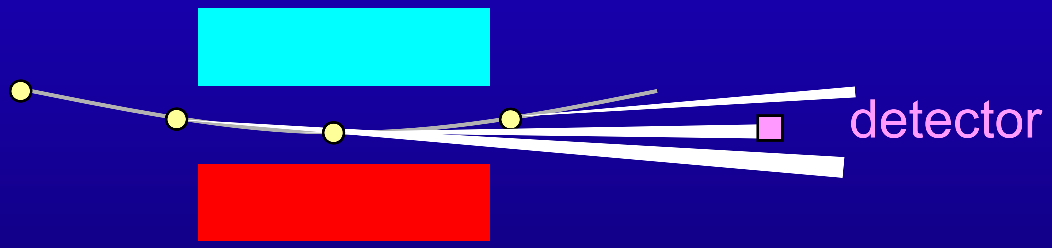
- small divergence:
  - compact mirrors, optics elements
  - minimized aberrations

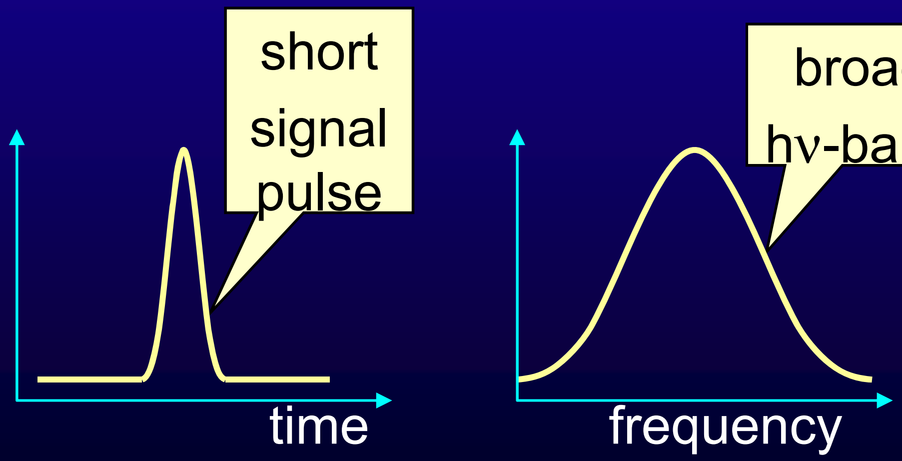
- short measurement times

- high transverse coherence
  - phase contrast imaging

3 types of storage ring sources:

1. Bending magnets: $B \sim N_e$

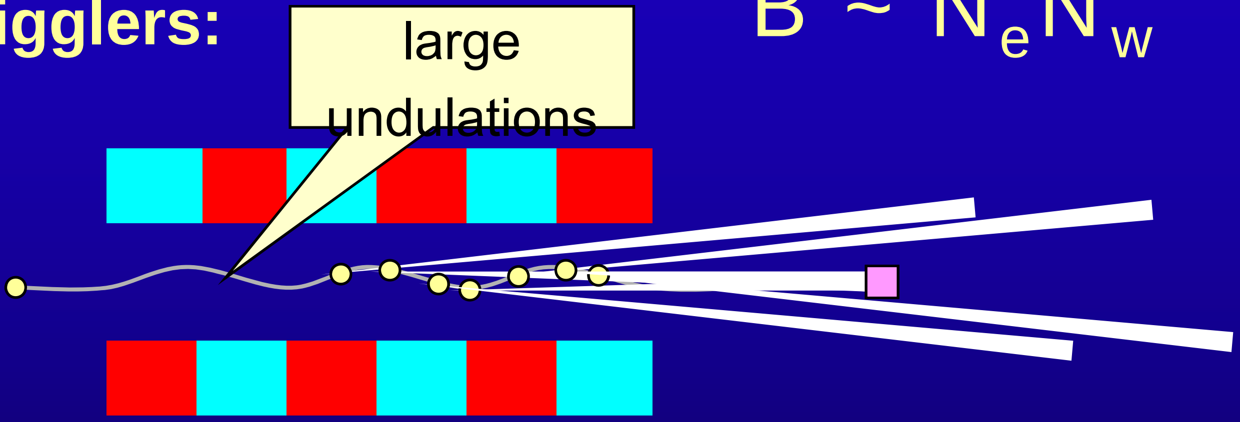


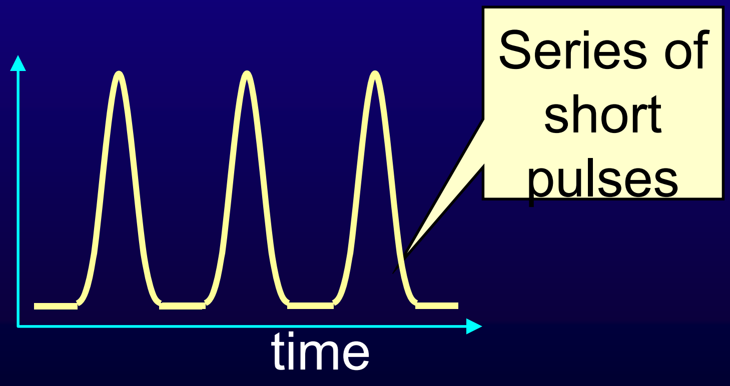


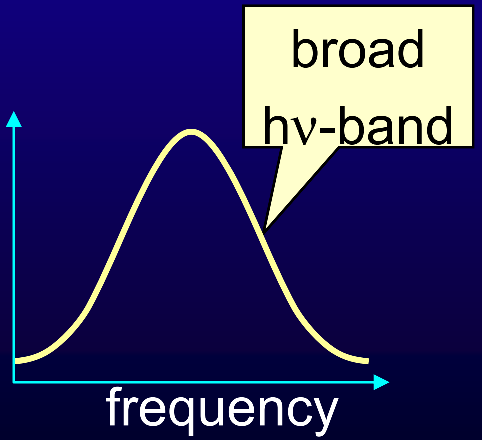
3 types of storage ring sources:

2. Wigglers:

$B \sim N_e N_w$ x10

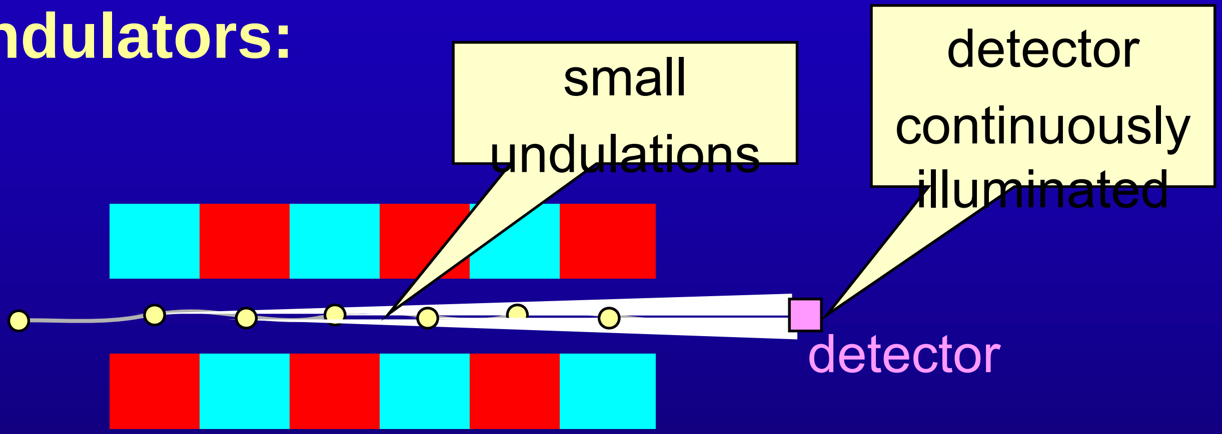

large undulations


Series of short pulses


broad hν-band

3 types of storage ring sources:

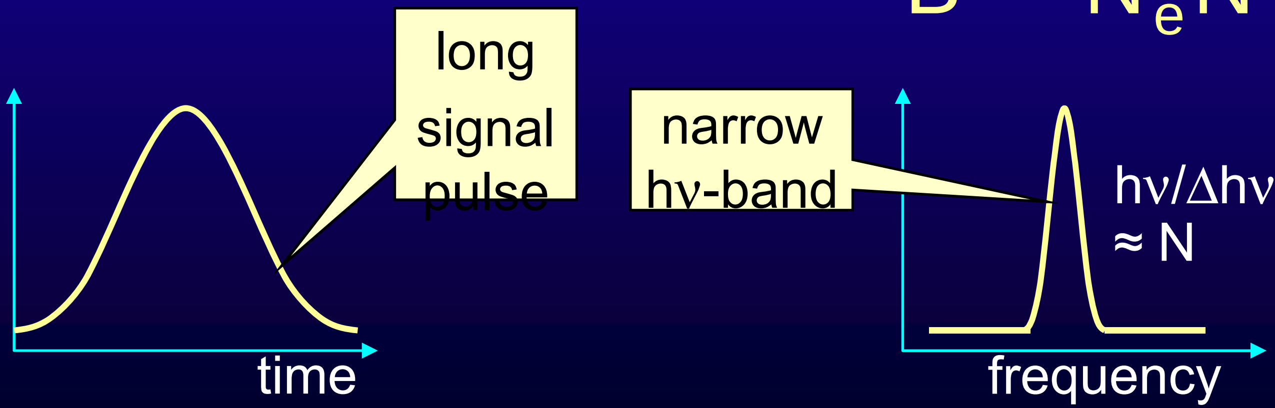
3. Undulators:



small undulations

detector continuously illuminated

$$B \sim N_e N^2_u \quad x10^3$$

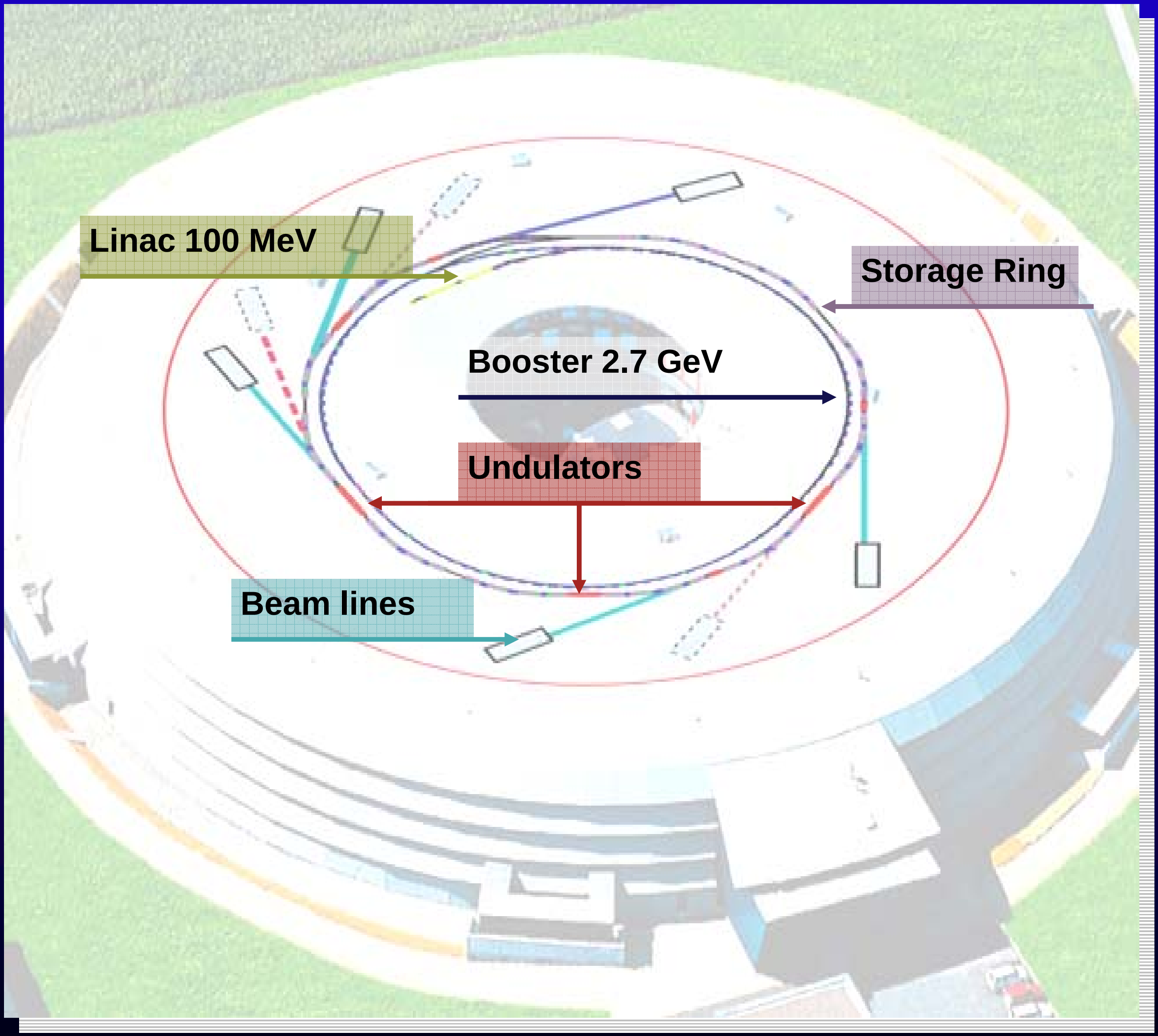


long signal pulse

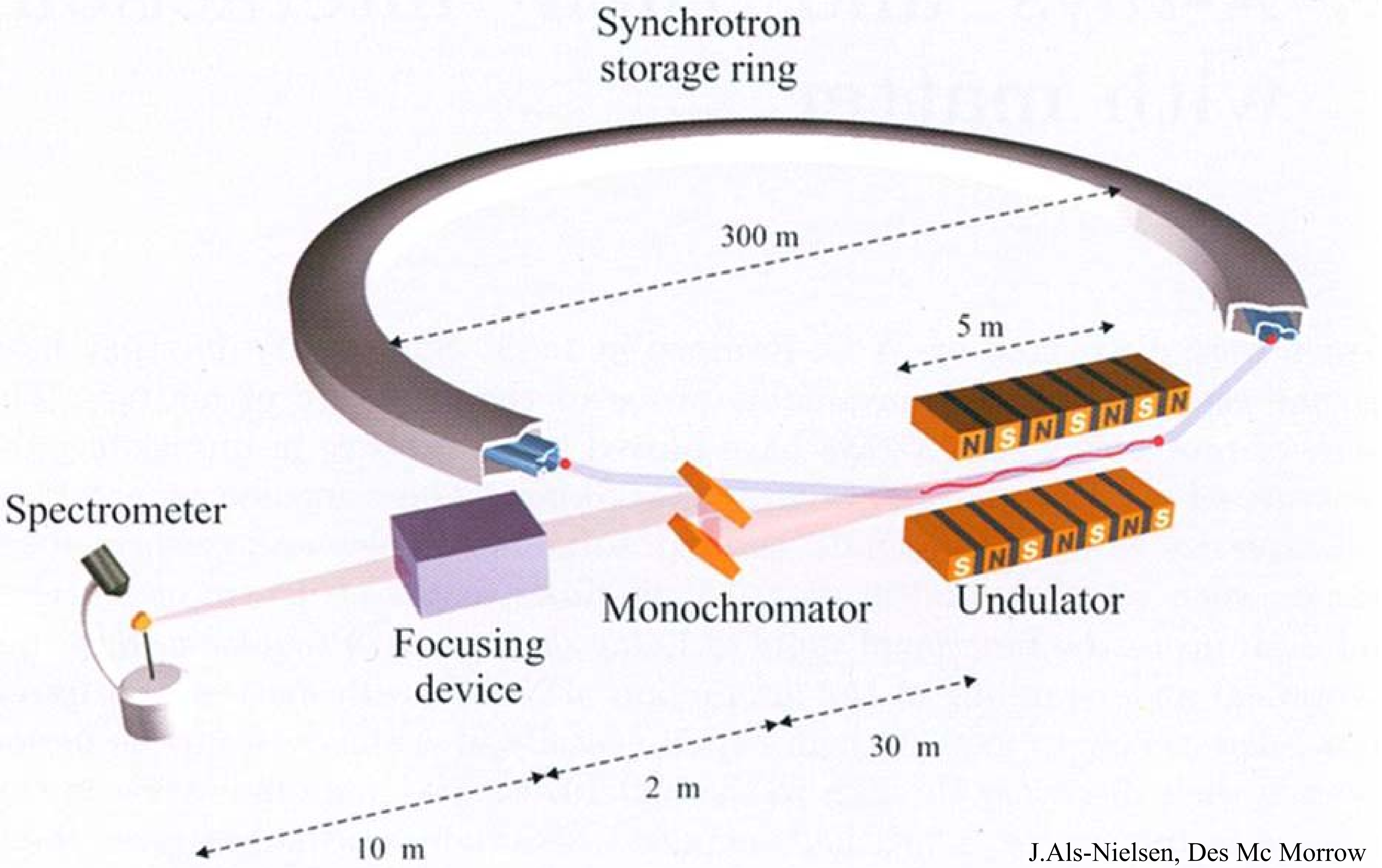
narrow hν-band

hν/Δhν ≈ N

Anatomy of a light source

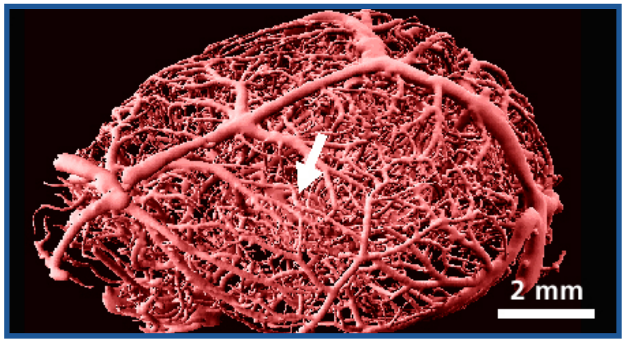


About 60 ring sources world-wide

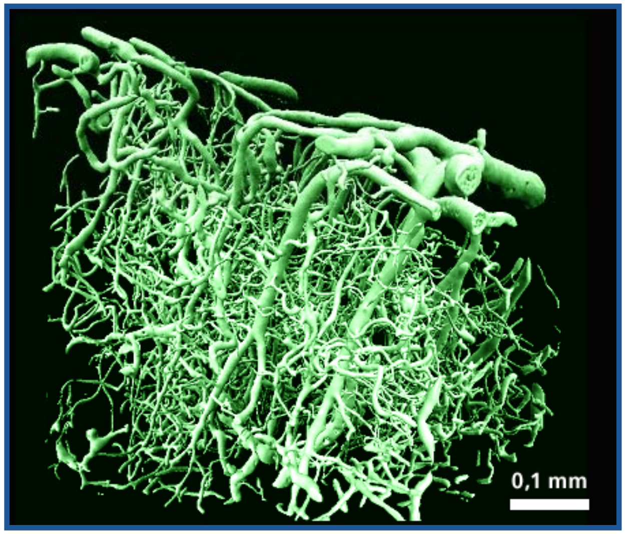


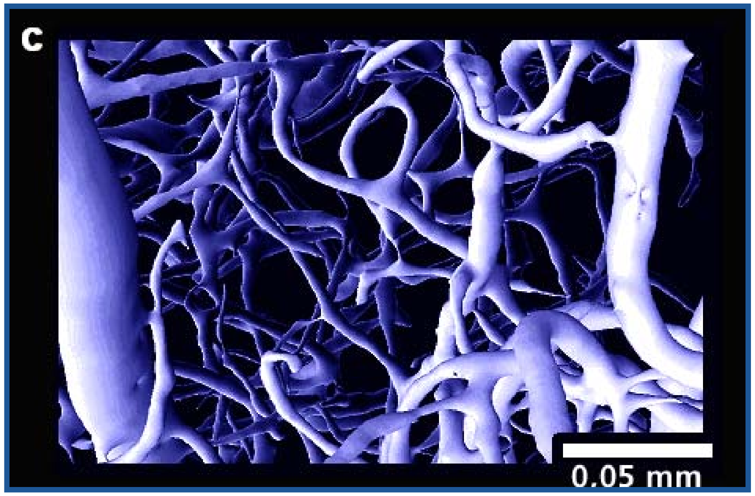
J.Als-Nielsen, Des Mc Morrow

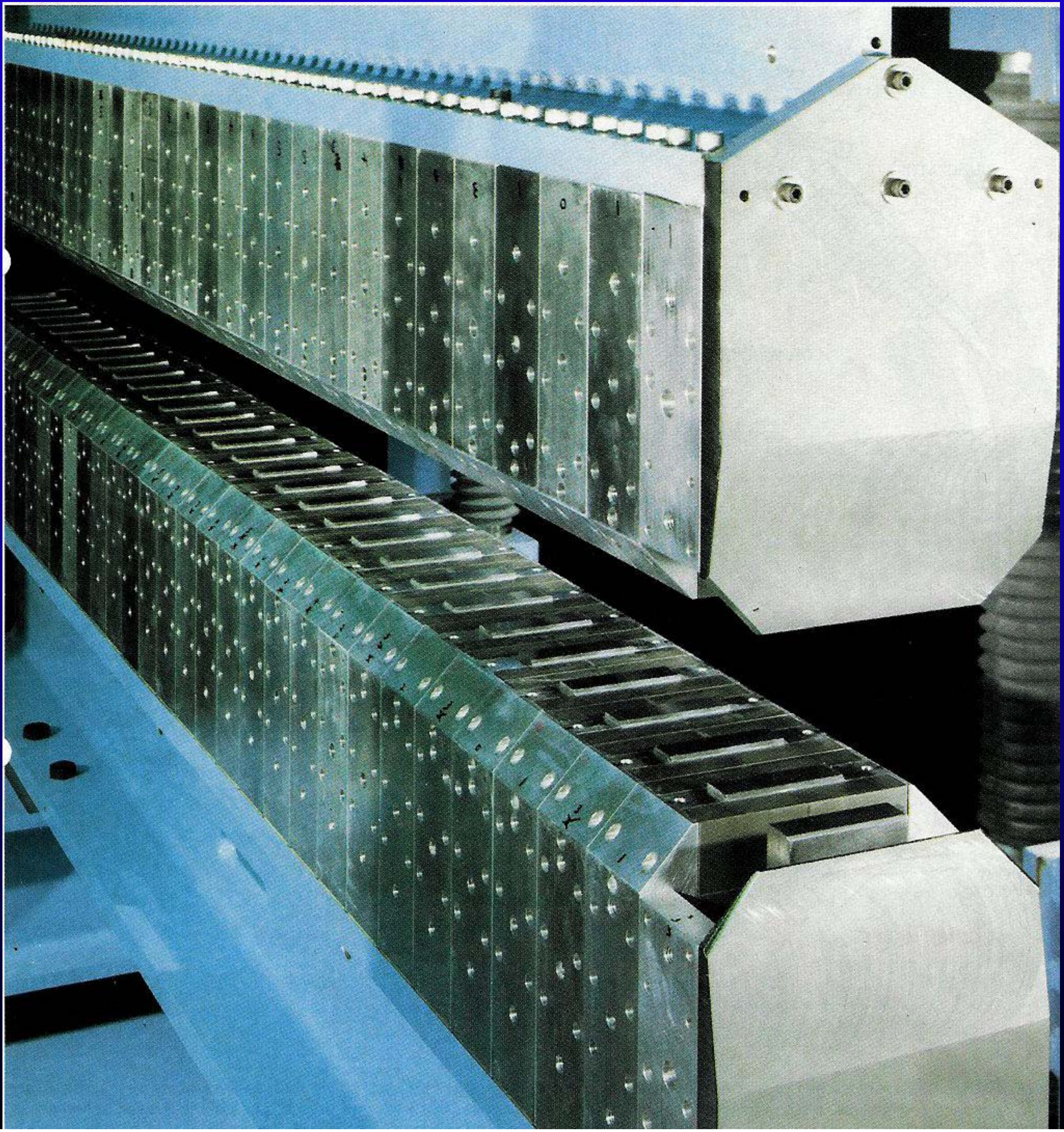
Microtomography



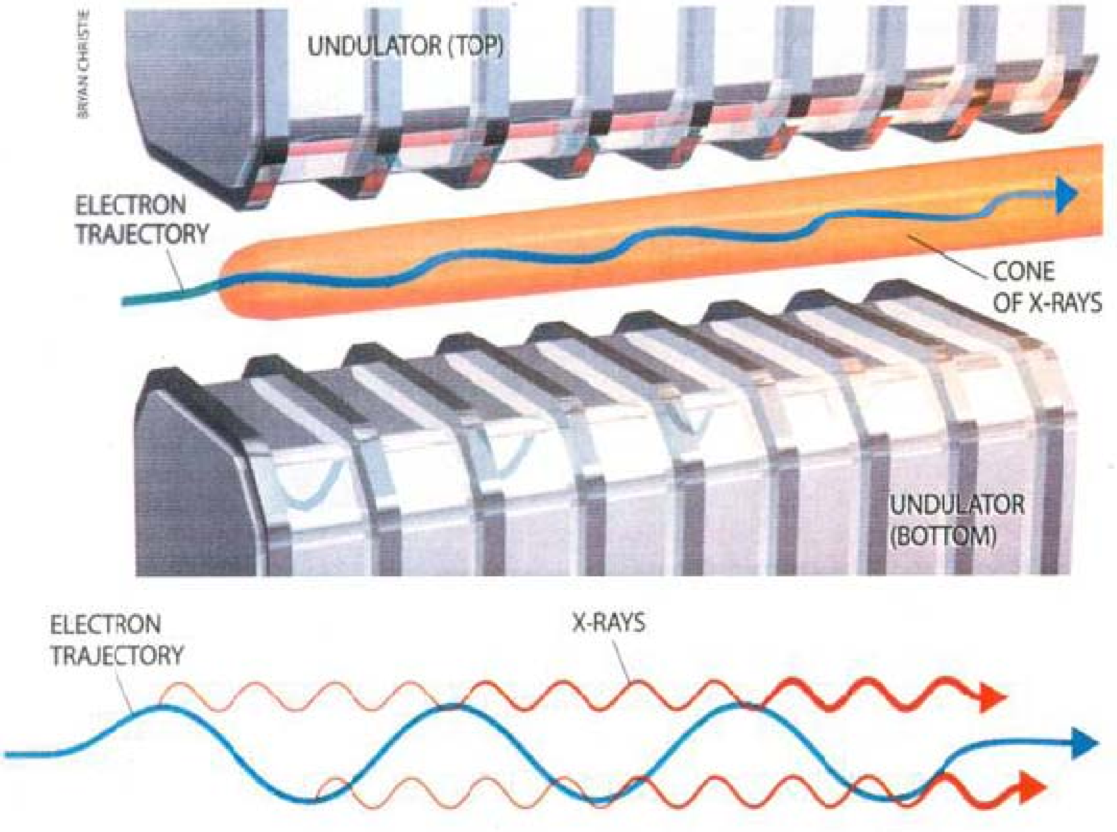
Brain blood vessels in a mouse with Alzheimer







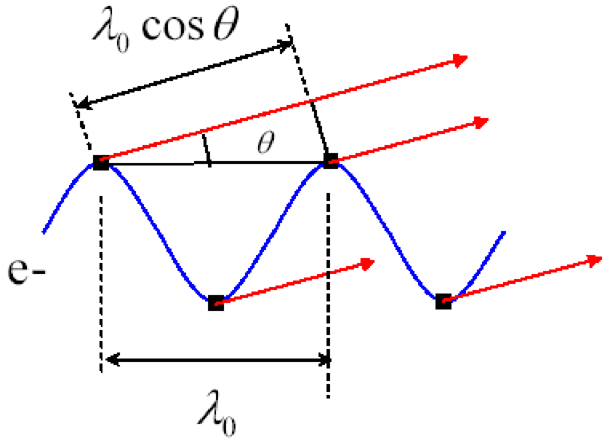
Undulators



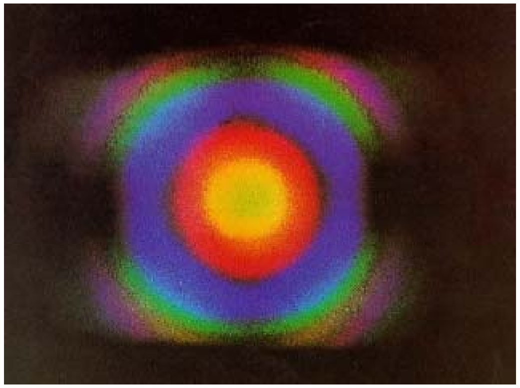
$$T_{obs} = T_{emit}(1-\beta)$$

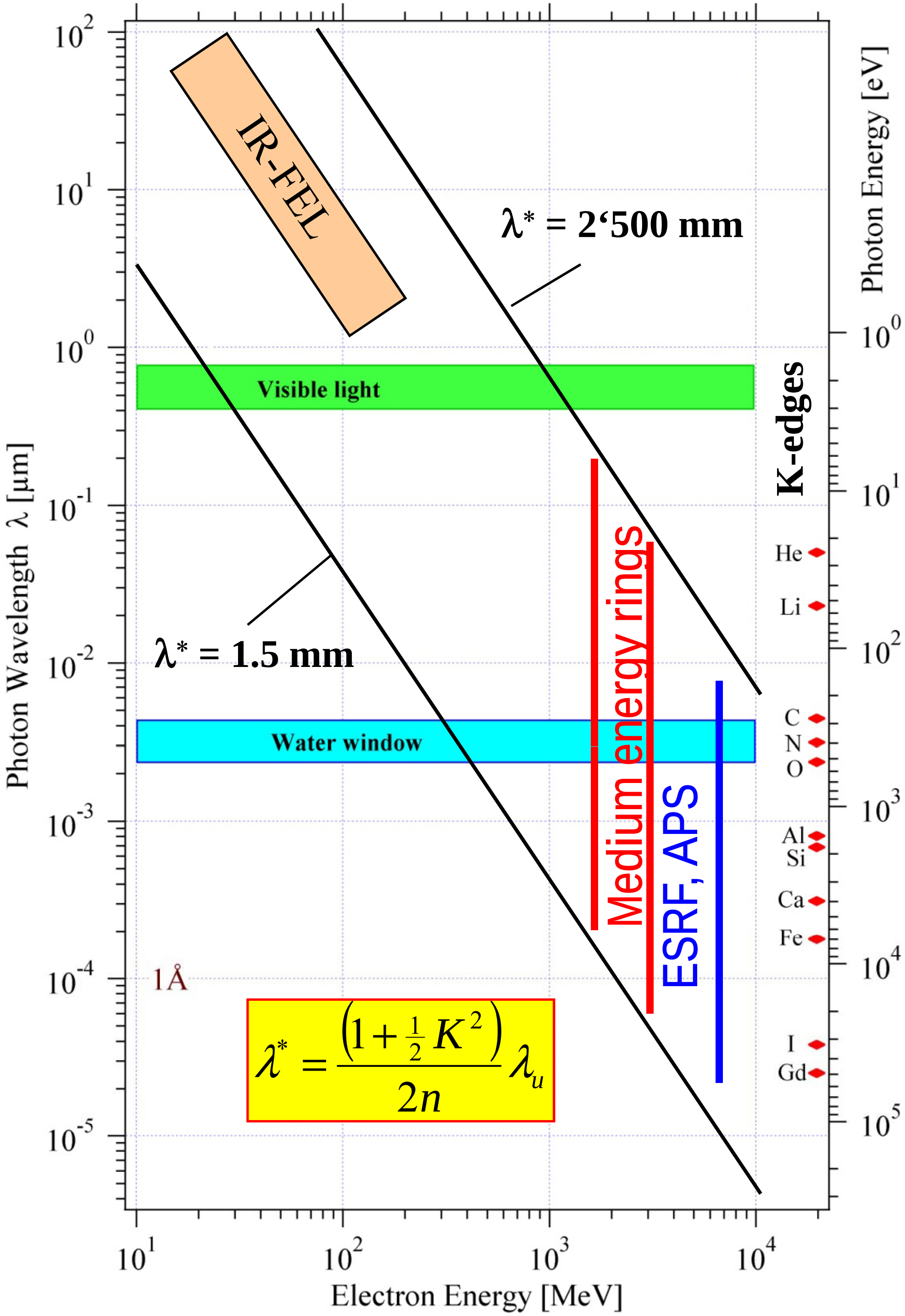
$$\boxed{\lambda_{light} \approx \frac{\lambda_u}{2\gamma^2}}$$

Undulator radiation

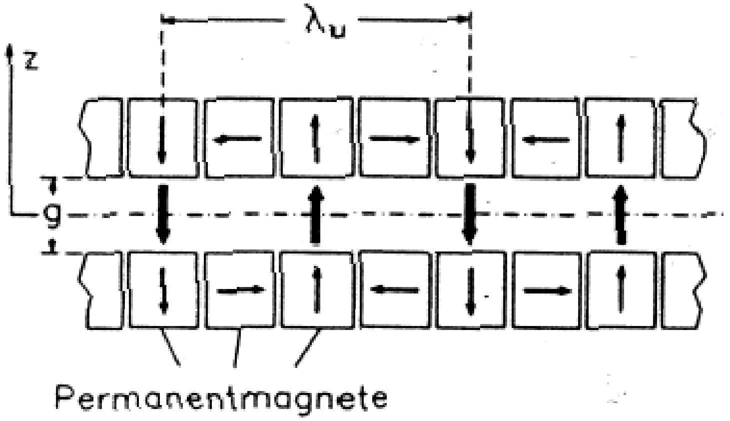


$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$





Permanent magnet undu

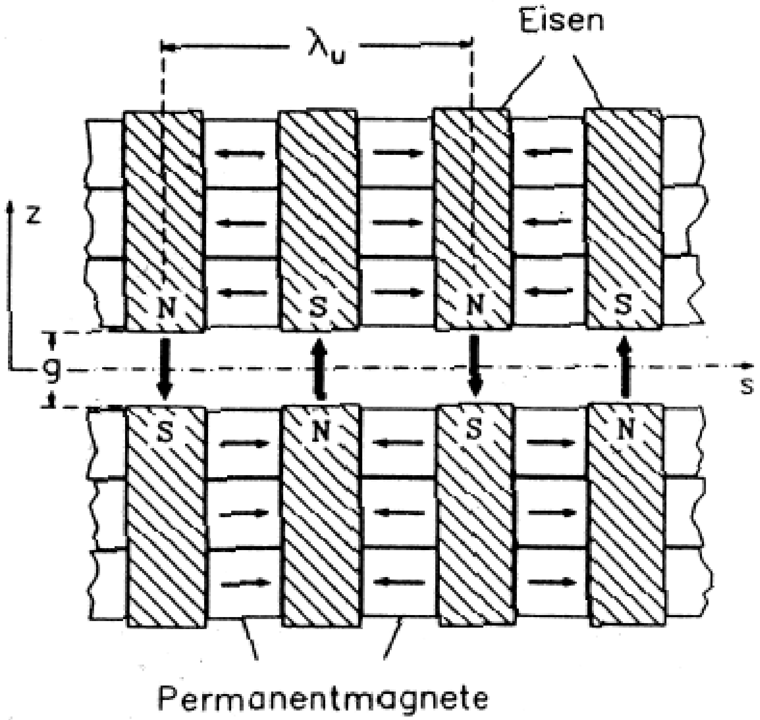


Permanent magnet materials: SmCo$_5$, NdFeB

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

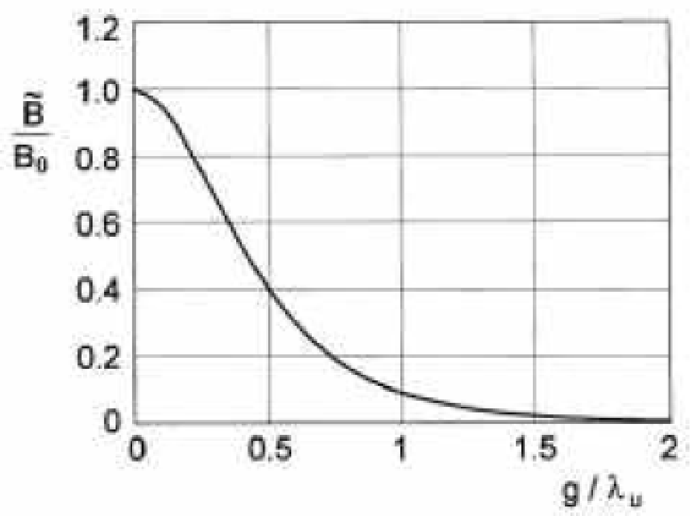
Hybrid undulator:

permanent magnets and iron



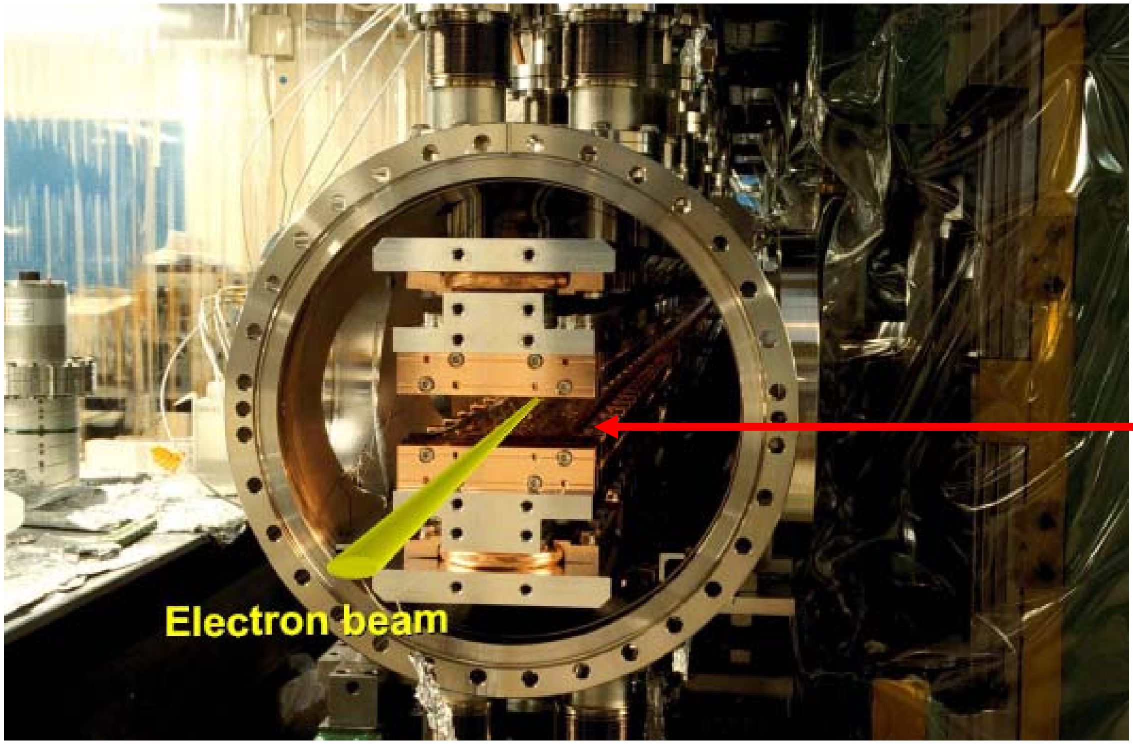
Field tuning with gap

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



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

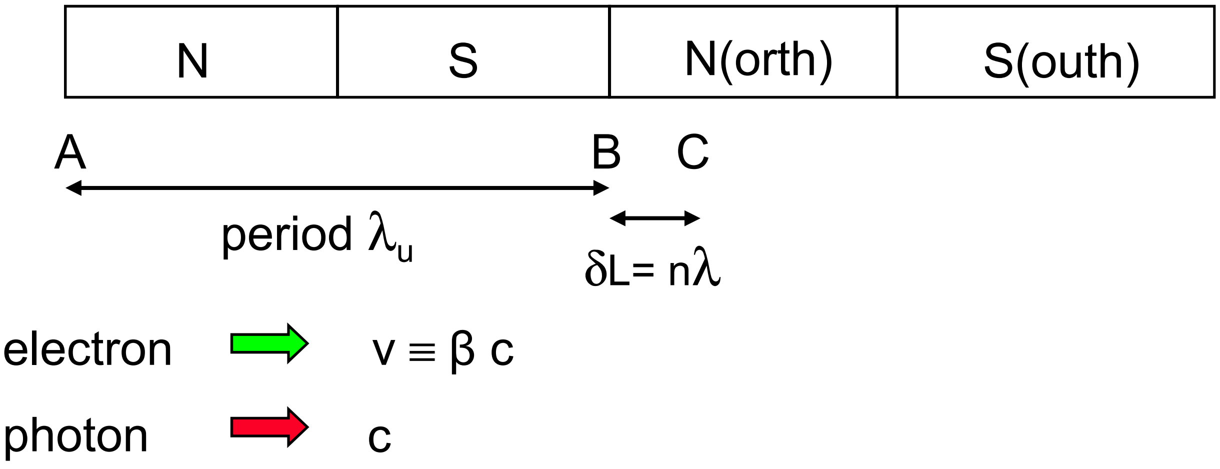
In-vacuum undulators / s.c. undulators



Gaps down to 3 mm

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

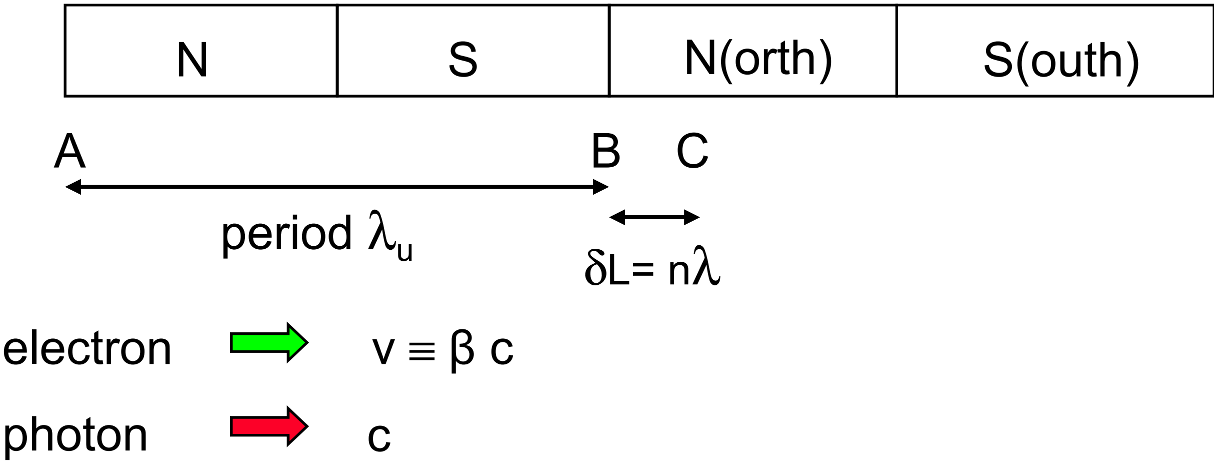
$\delta L = n\lambda$

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


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

A B C

period λ_u

$\delta L = n\lambda$

electron $v \equiv \beta c$

photon c

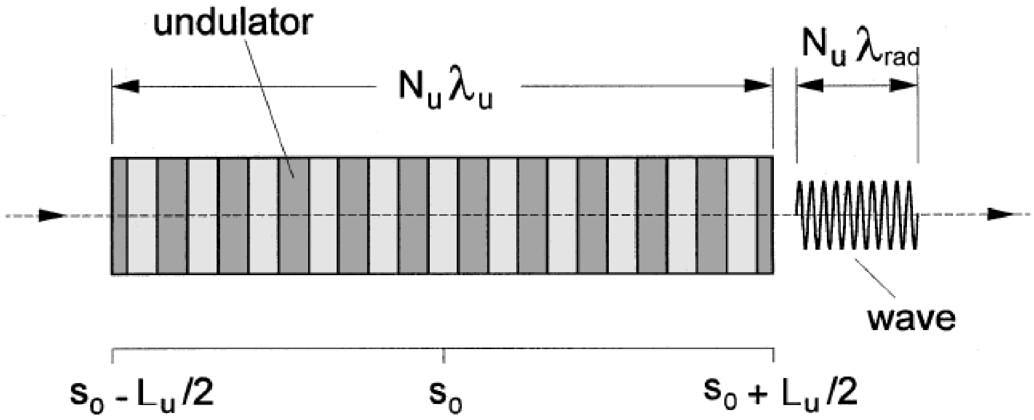
The path difference $\delta L \equiv n\lambda \approx (1-\beta)\lambda_u \,, \quad 1-\beta \approx \dfrac{1}{2\gamma^2}$

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

detour through slalom

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

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 based sources

Brightness

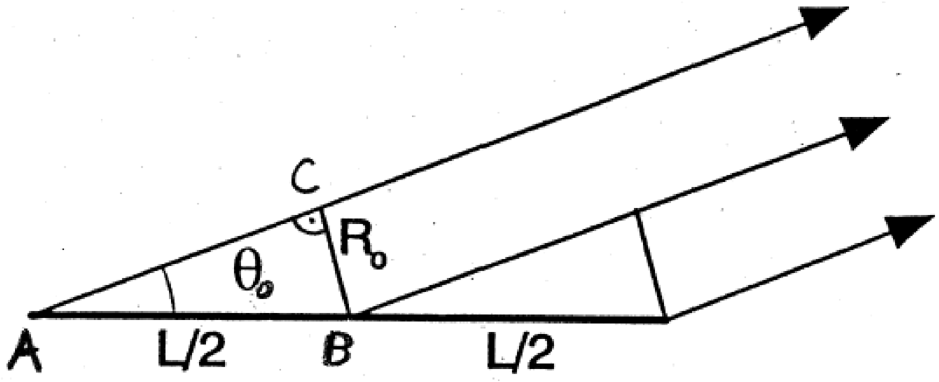
$$B = \frac{N_{ph}}{\Delta t} \cdot \frac{1}{\Delta S \cdot \Delta \Omega} \cdot \frac{1}{\Delta\lambda/\lambda}$$

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 $B \sim N_u^2$

Radiation cone of an undulator



Undulator radiates from the 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 $\Delta L = \frac{\lambda}{2}$

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

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

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

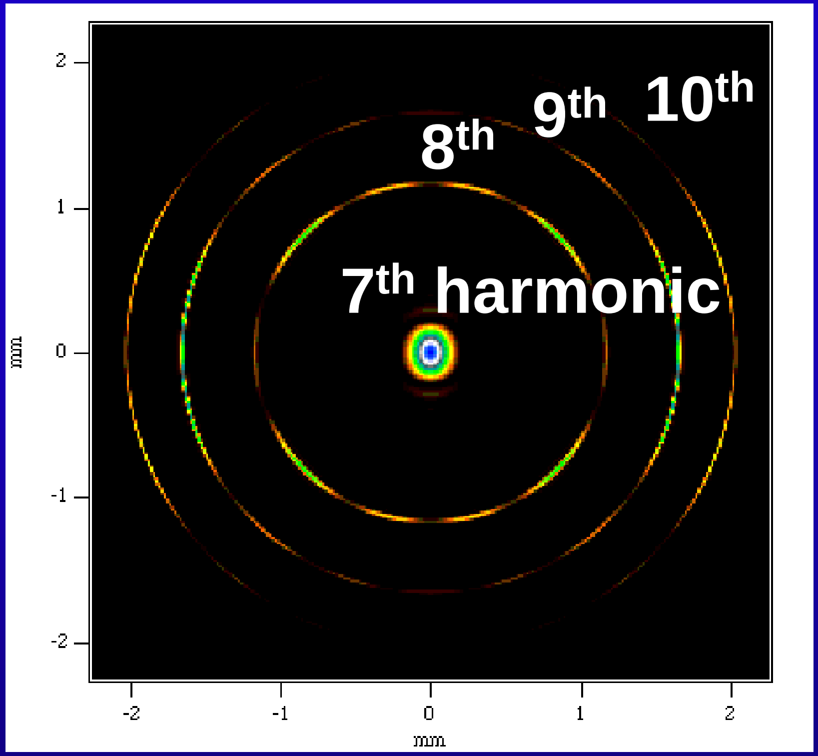
$$\Sigma_x \Sigma_{x'} \approx \sigma_x \sigma_x' \sim \varepsilon_x$$

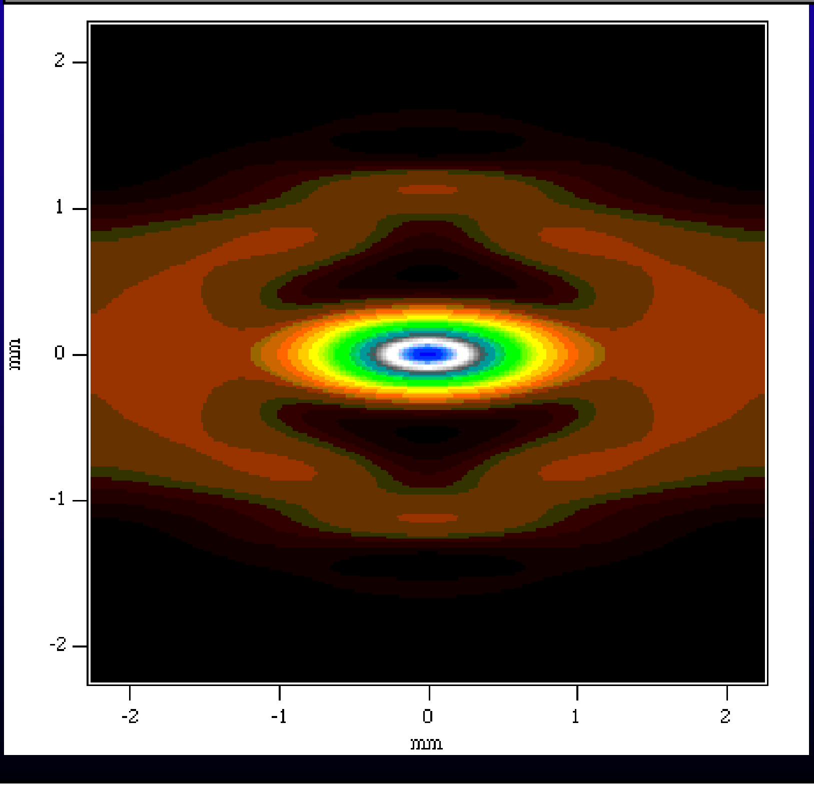
Photon beam size (U):

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

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

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





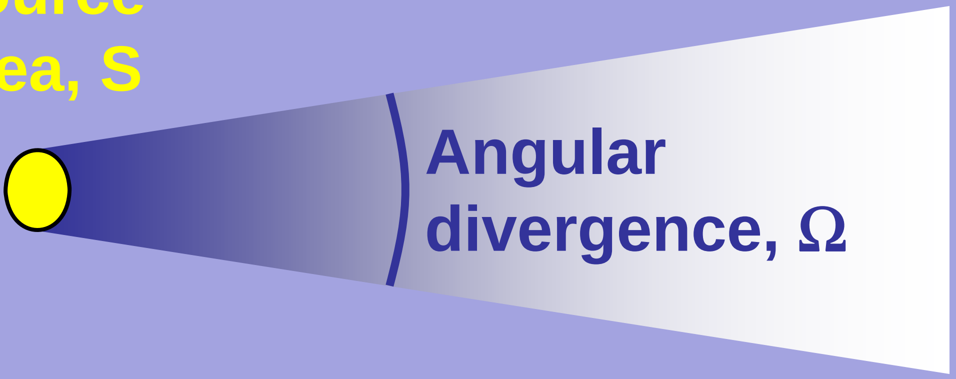
Emittance 4 nm·rad, 1% coupling, finite energy spread

Third Generation Light Sources in Operation

Third Generation Light Sources in Operation

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm.rad)	Current (mA)	Straight Section	Status
ESRF	6.0	844.4	3.7	200	32×6.3m	Operational(1993)
APS	7.0	1104	3.0	100	40×6.7m	Operational(1996)
SPring-8	8.0	1436	2.8	100	44×6.6m, 4×30m	Operational(1997)
ALS	1.9	196.8	6.3	400	12×6.7m	Operational(1993)
TLS	1.5	120	25	240	6×6m	Operational(1993)
ELETTRA	2.0/2.4	259	7	300	12×6.1m	Operational(1994)
PLS	2.5	280.56	10.3	200	12×6.8m	Operational(1995)
LNLS	1.37	93.2	70	250	6×3m	Operational(1997)
MAX-II	1.5	90	9.0	200	10×3.2m	Operational(1997)
BESSY-II	1.7	240	6.1	200	8×5.7m, 8×4.9m	Operational(1999)
Siberia-II	2.5	124	65	200	12×3m	Operational(1999)
NewSUBARU	1.5	118.7	38	500	2×14m, 4×4m	Operational(2000)
SLS	2.4-2.7	288	5	400	3×11.7m, 3×7m, 6×4m	Operational(2001)
ANKA	2.5	110.4	50	200	4×5.6m, 4×2.2m	Operational(2002)
CLS	2.9	170.88	18.1	500	12×5.2m	Operational(2003)
SPEAR-3	3.0	234	12	500	2×7.6m,4×4.8m,12×3.1m	Operational(2004)
SAGA-LS	1.4	75.6	7.5	300	8×2.93m	Operational(2005)

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

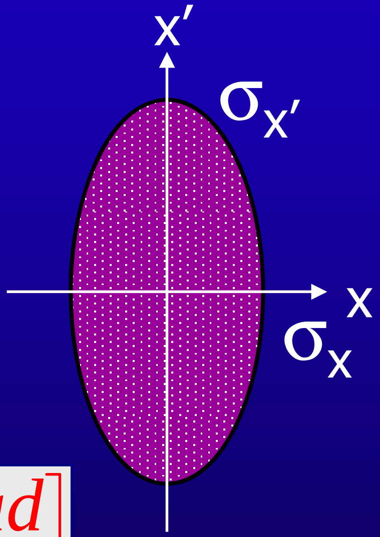
$$\text{Area} = \pi \cdot \varepsilon$$

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 $[m \cdot rad]$

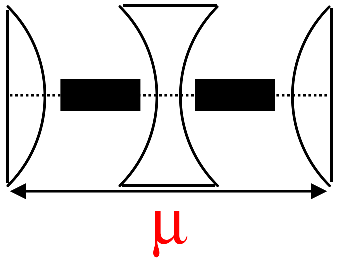
$$\text{Emittance} \equiv \frac{\sigma_x^2}{\beta}$$

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

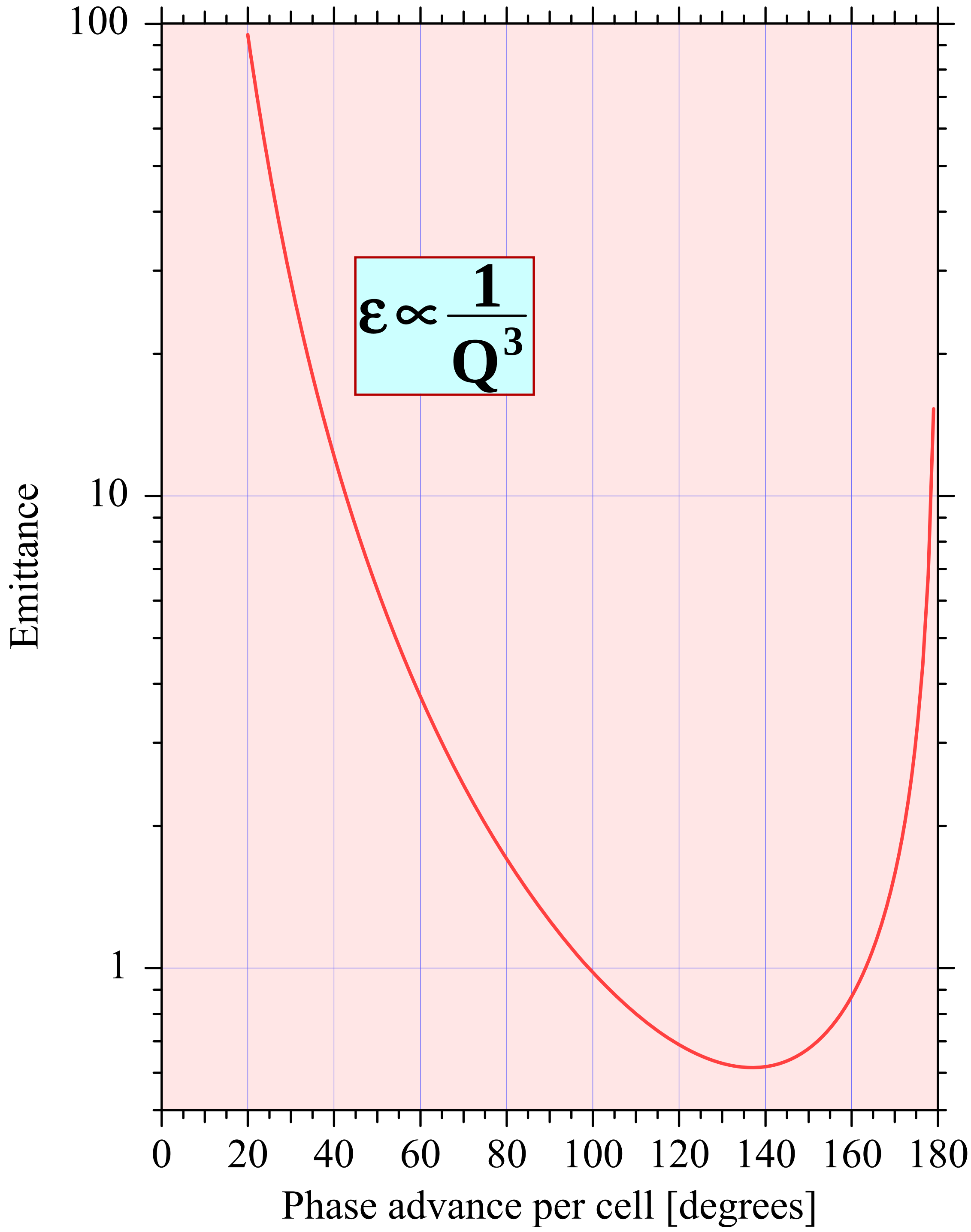
$$\sigma_x = \sqrt{\varepsilon\,\beta}$$
$$\sigma_{x'} = \sqrt{\varepsilon / \beta}$$

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

FODO Lattice emittance



$$\varepsilon \propto \frac{E^2}{J_x}\theta^3 F_{FODO}(\mu)$$



$$\varepsilon \propto \frac{1}{Q^3}$$

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

$$\mathcal{H} = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

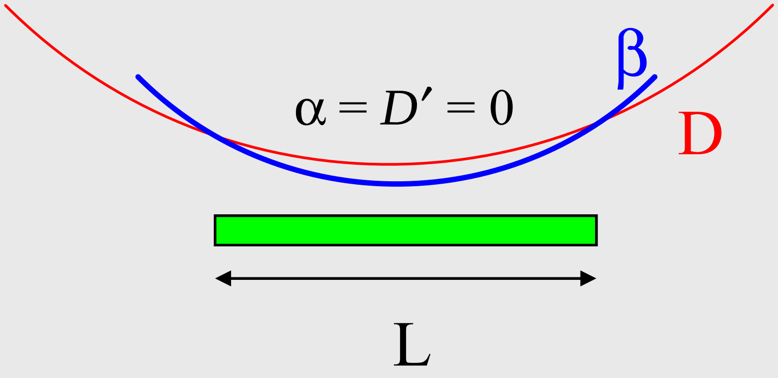
- the equilibrium emittance can be written as:

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

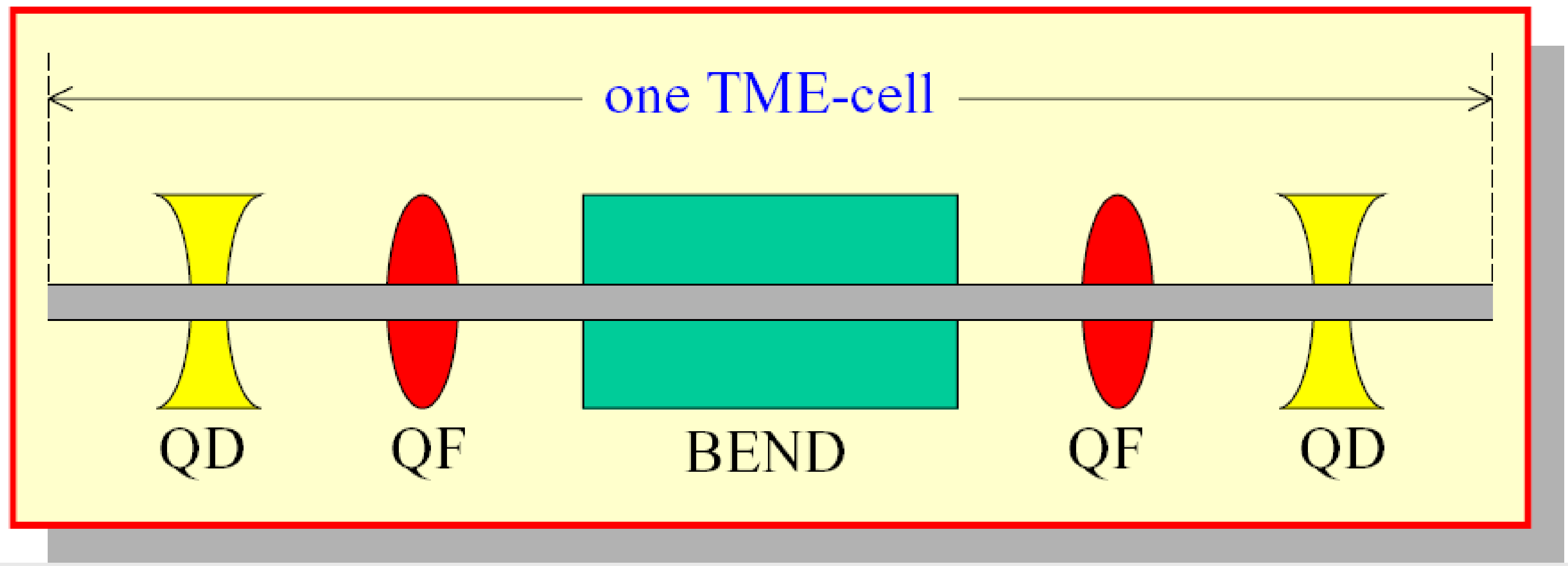
$$\mathrm{F}_{\min} = \frac{1}{12\sqrt{15}}$$

there exists a minimum

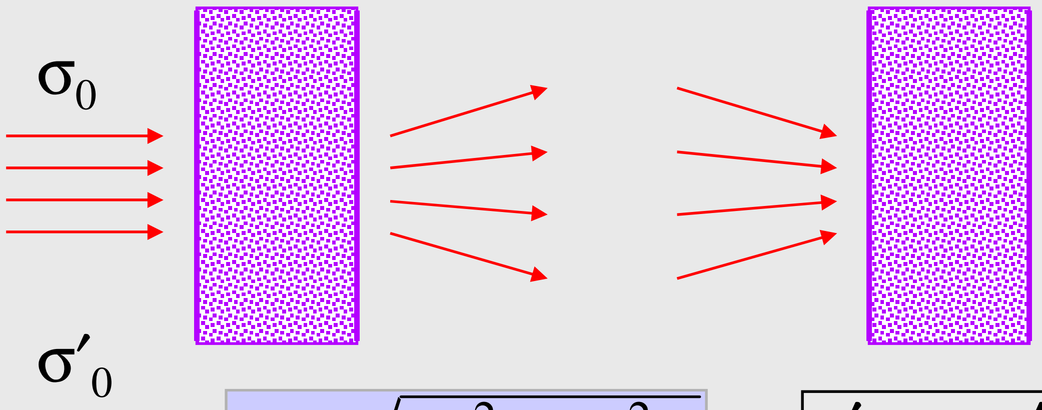
$$\beta^* = \frac{L}{2\sqrt{15}}, \quad D^* = \frac{L\theta}{24}$$



Theoretical minimum emittance



Ring equilibrium emittance



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

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

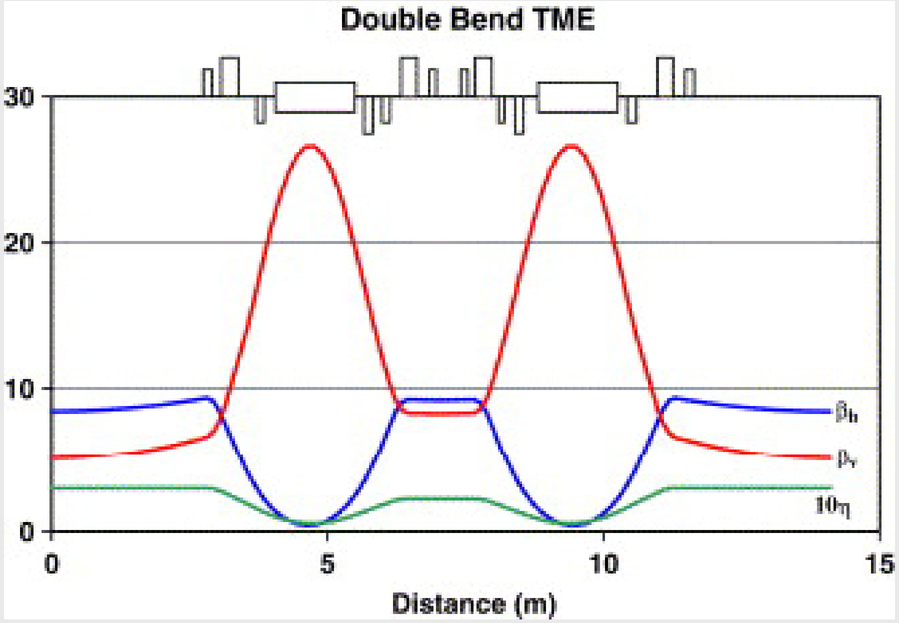
to minimize the blow up due to multiple

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

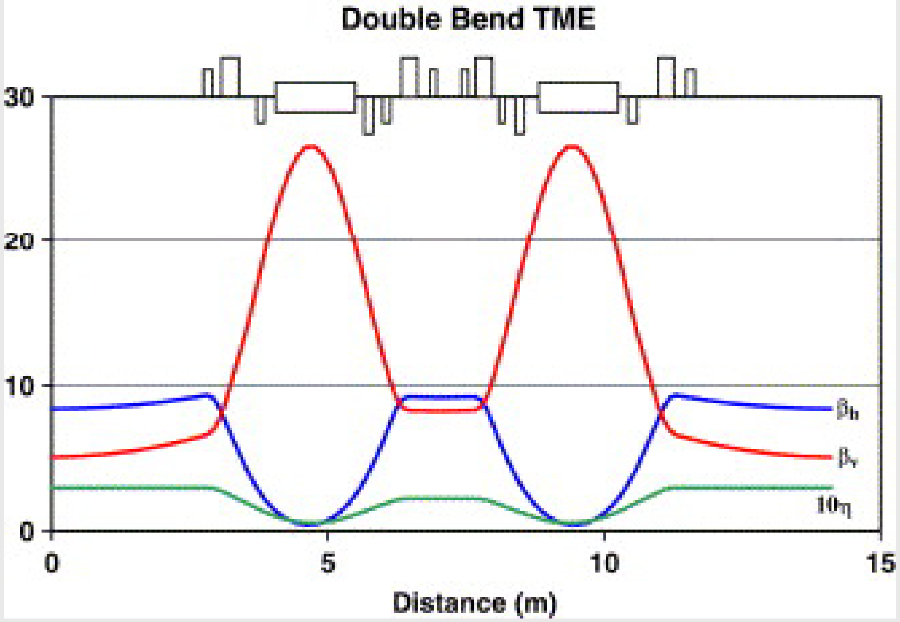
Theoretical **M**inimum **E**mittance lattice

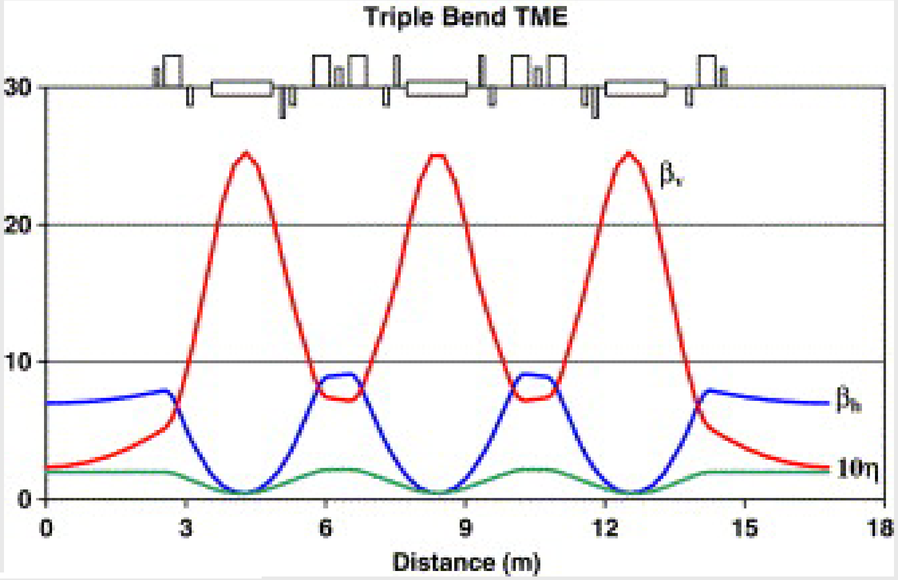
$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot \mathrm{F}_{\mathrm{latt}}$$

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

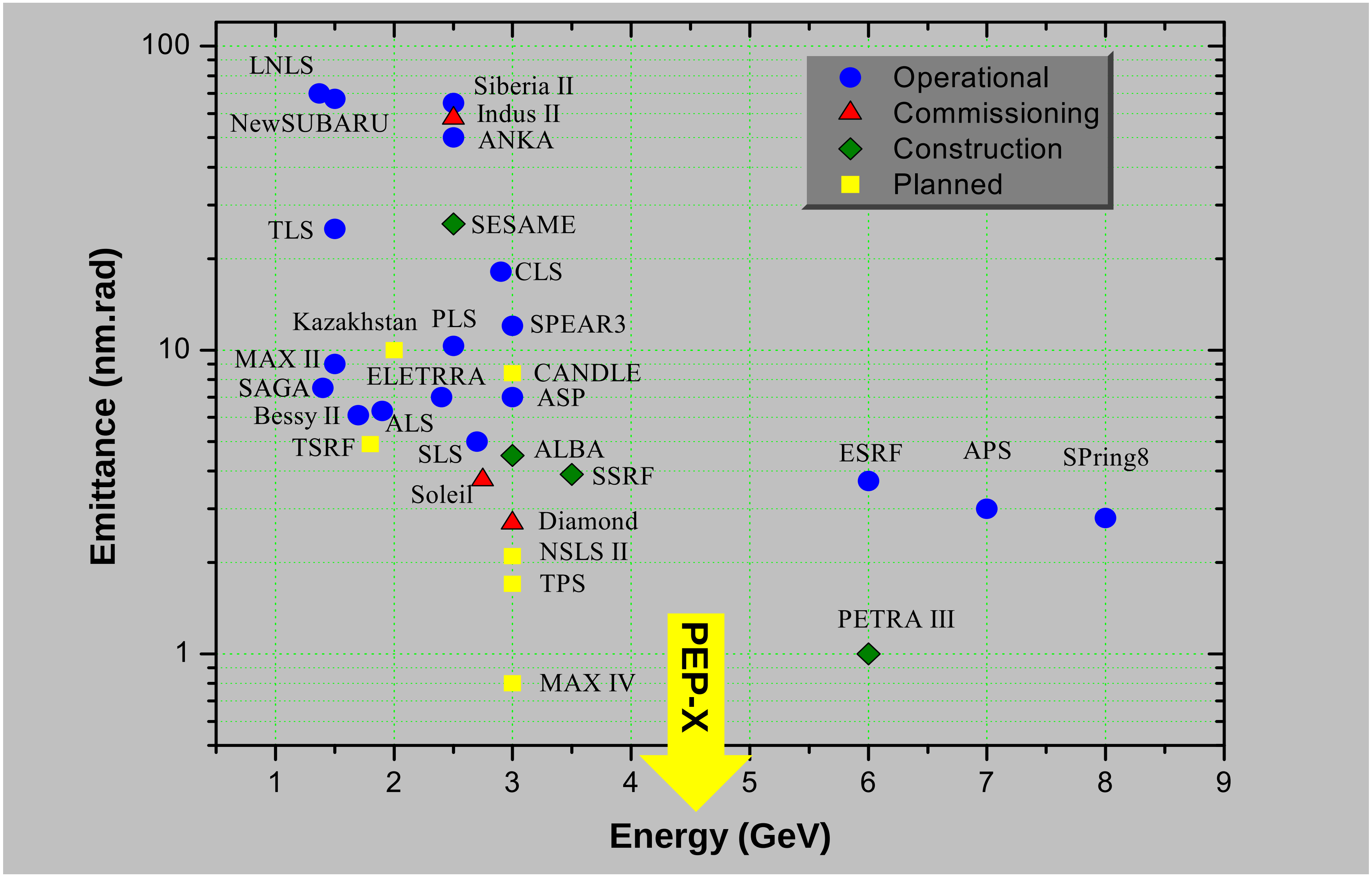


Low emittance lattice examples



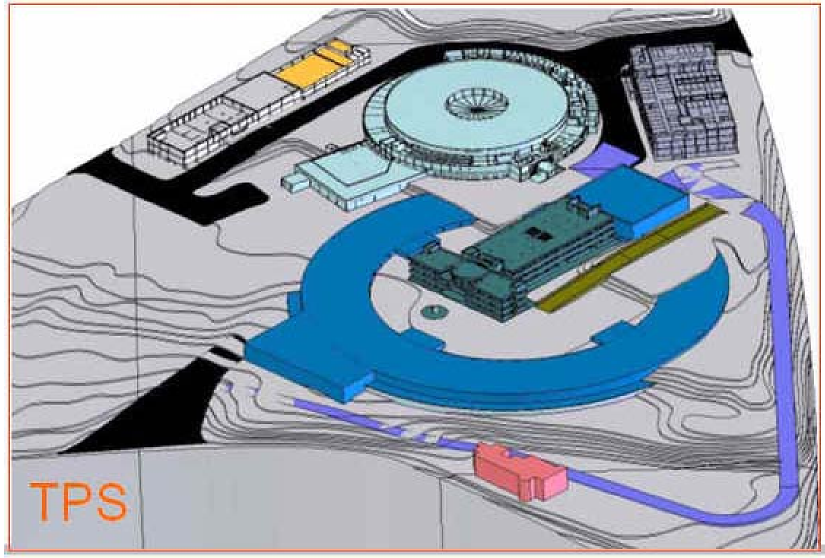


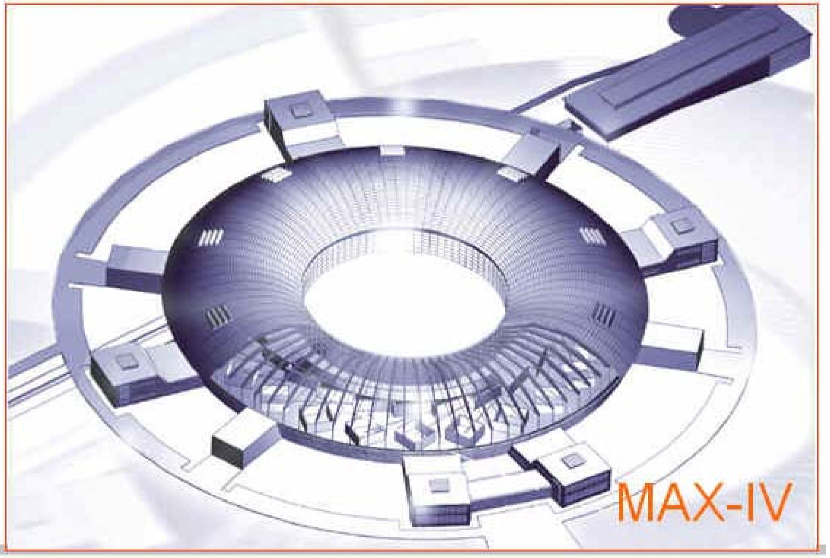
Third Generation Light Sources



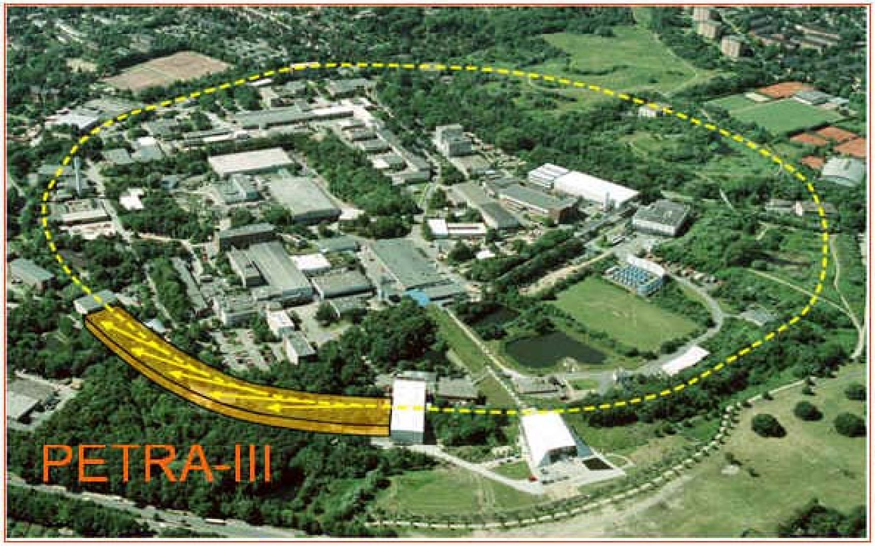
New Synchrotron Radiation Facilities

New Synchrotron Radiation Facilities

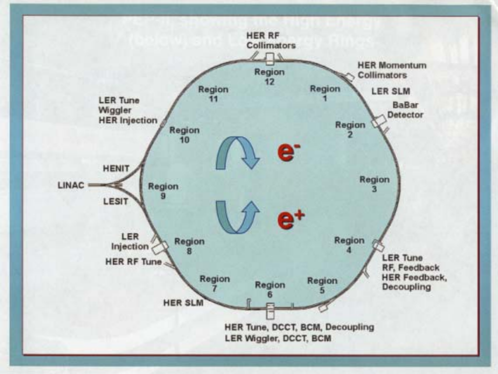




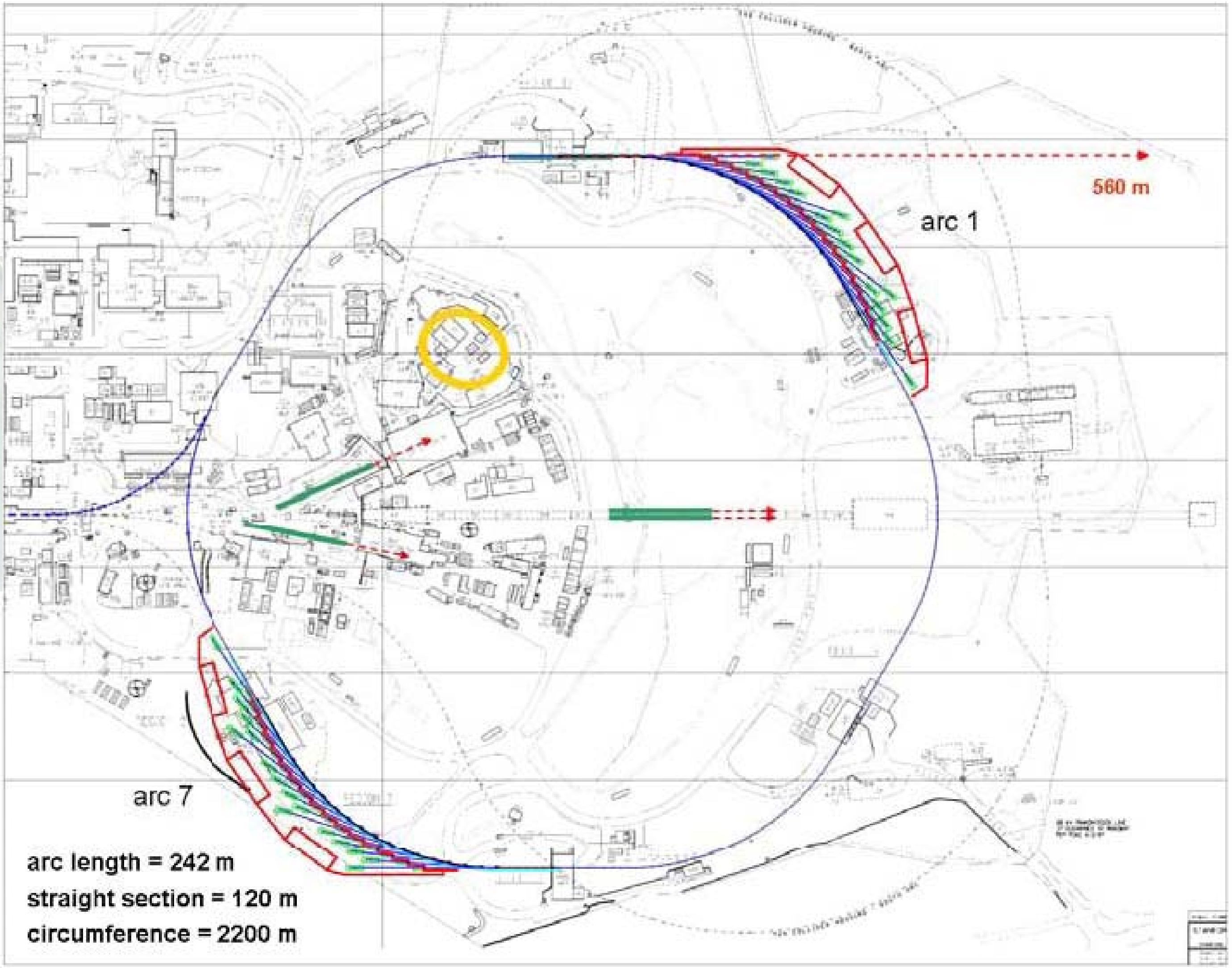
New Synchrotron Radiation Facilities



From PEP–II



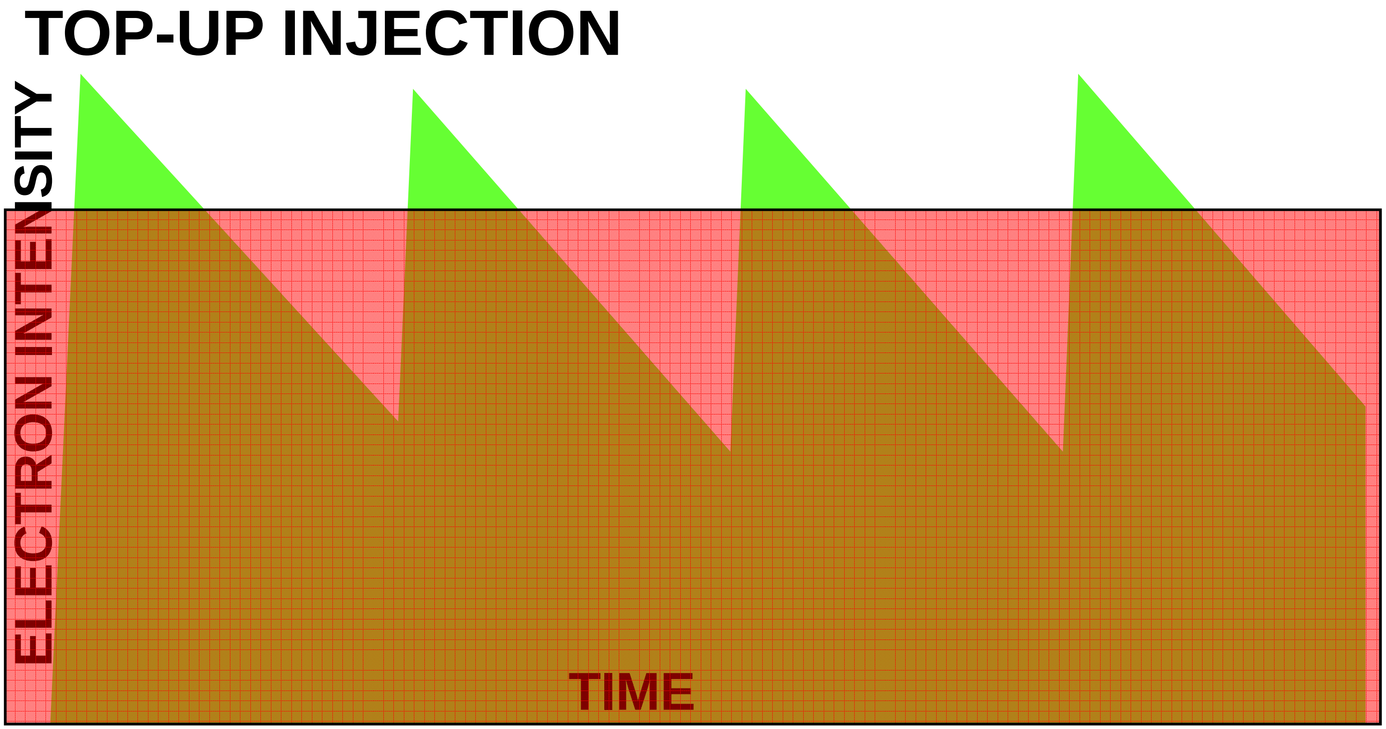
to PEP–X



Use of damping wigglers as in PETRA III to reach 0.1 nm.rad

CERN's 27 km 'tunnel with a future'

Top-up injection: key to stability



also Trickle Charge cont. Injection at PEP-II, KEKB

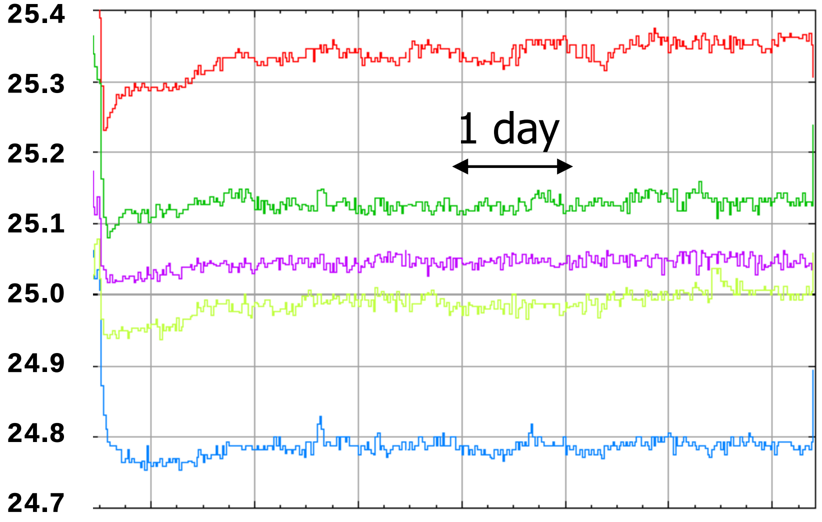
Top-up is key to the source stability

Constant thermal load on:

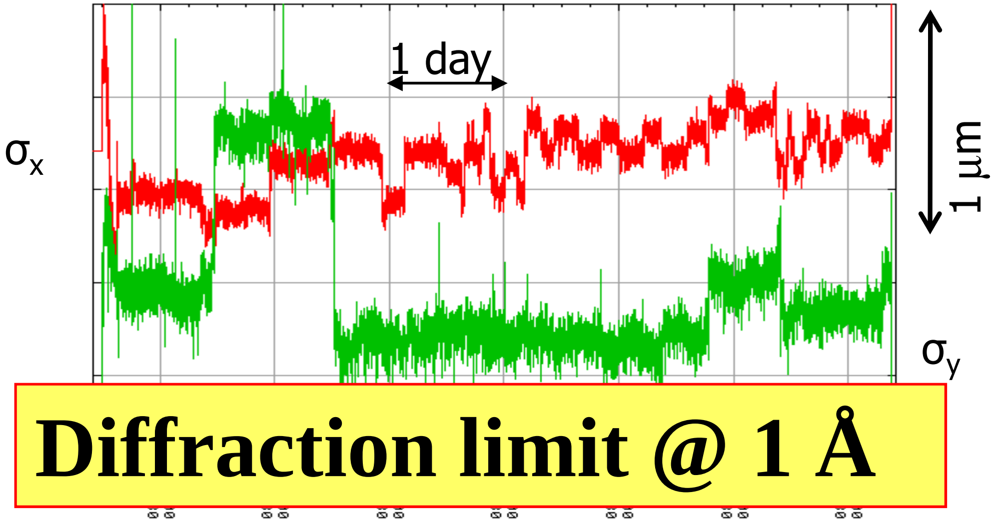
- Beam line optics
- Accelerator components (BPMs, vacuum chamber…)

Beam lifetime ~7h, not relevant! Injection every 1.5 min

Tunnel Temperature [^{0}C] 25 ± 0.03



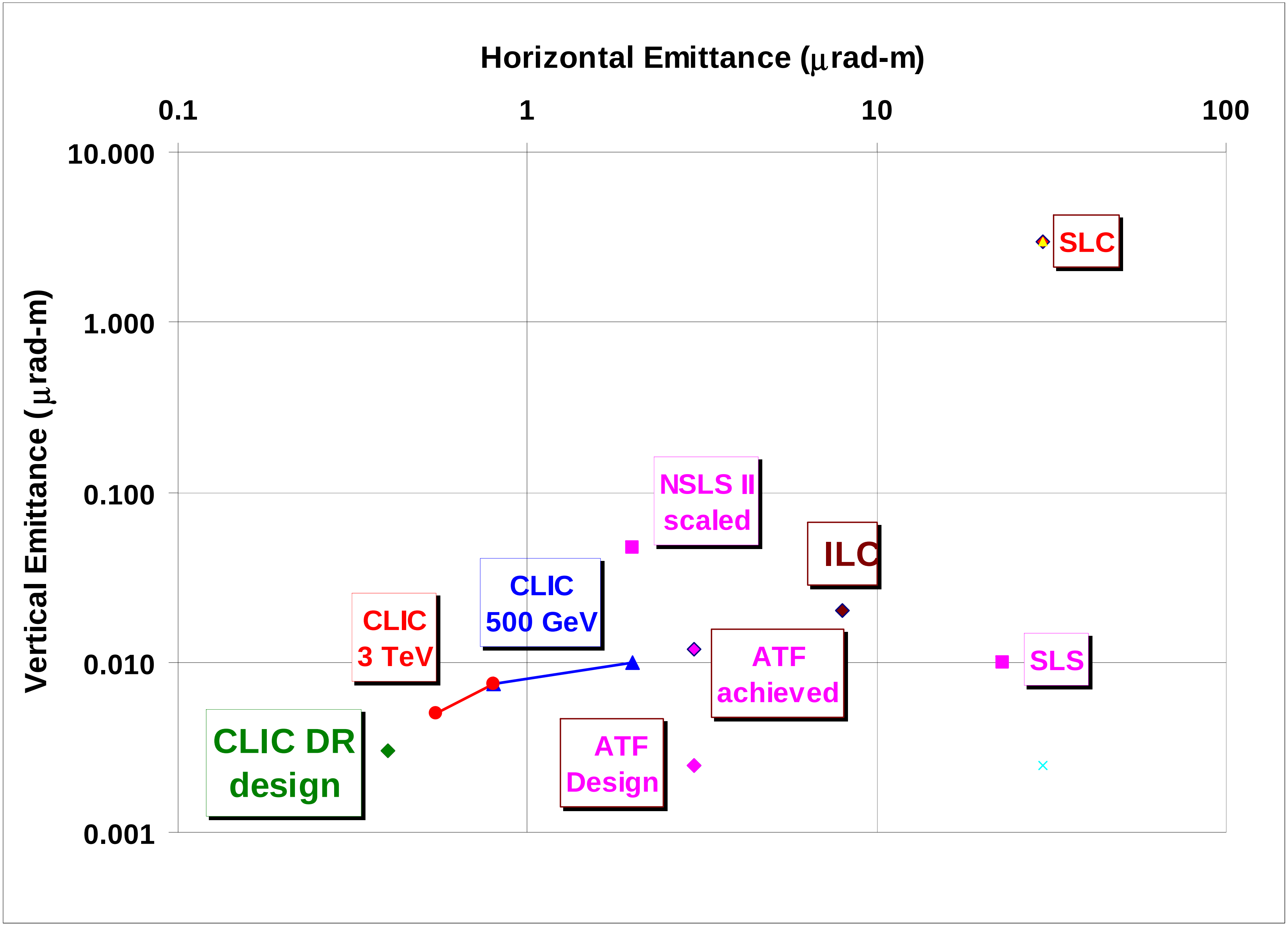
Beamsizes σ_x σ_y [μm]



Diffraction limit @ 1 Å

Vertical emittance $\varepsilon_y \rightarrow$ 4 pm-rad; coupling $\varepsilon_y/\varepsilon_x \sim 0.08\%$

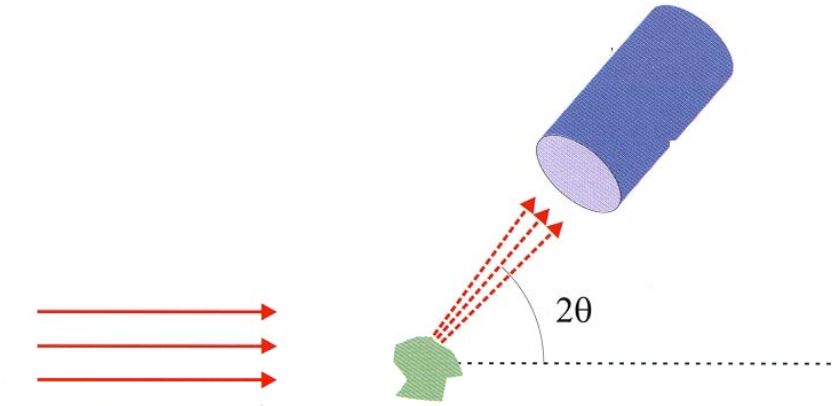
Damping Rings beam emittances

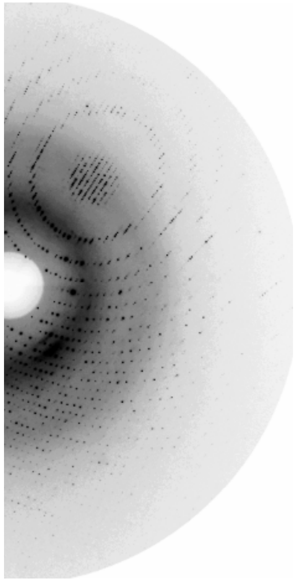


APPLICATIONS

e.g. Protein Crystallography

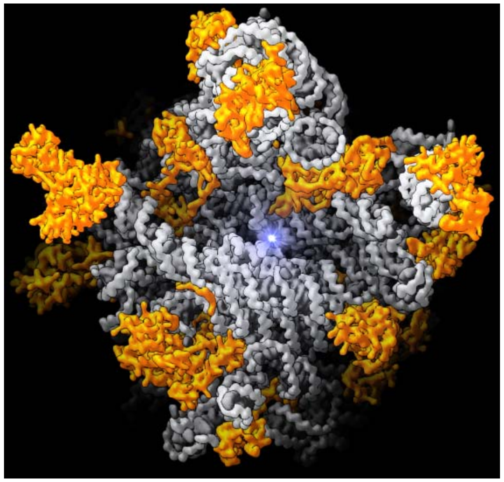
Protein structure





Diffraction pattern

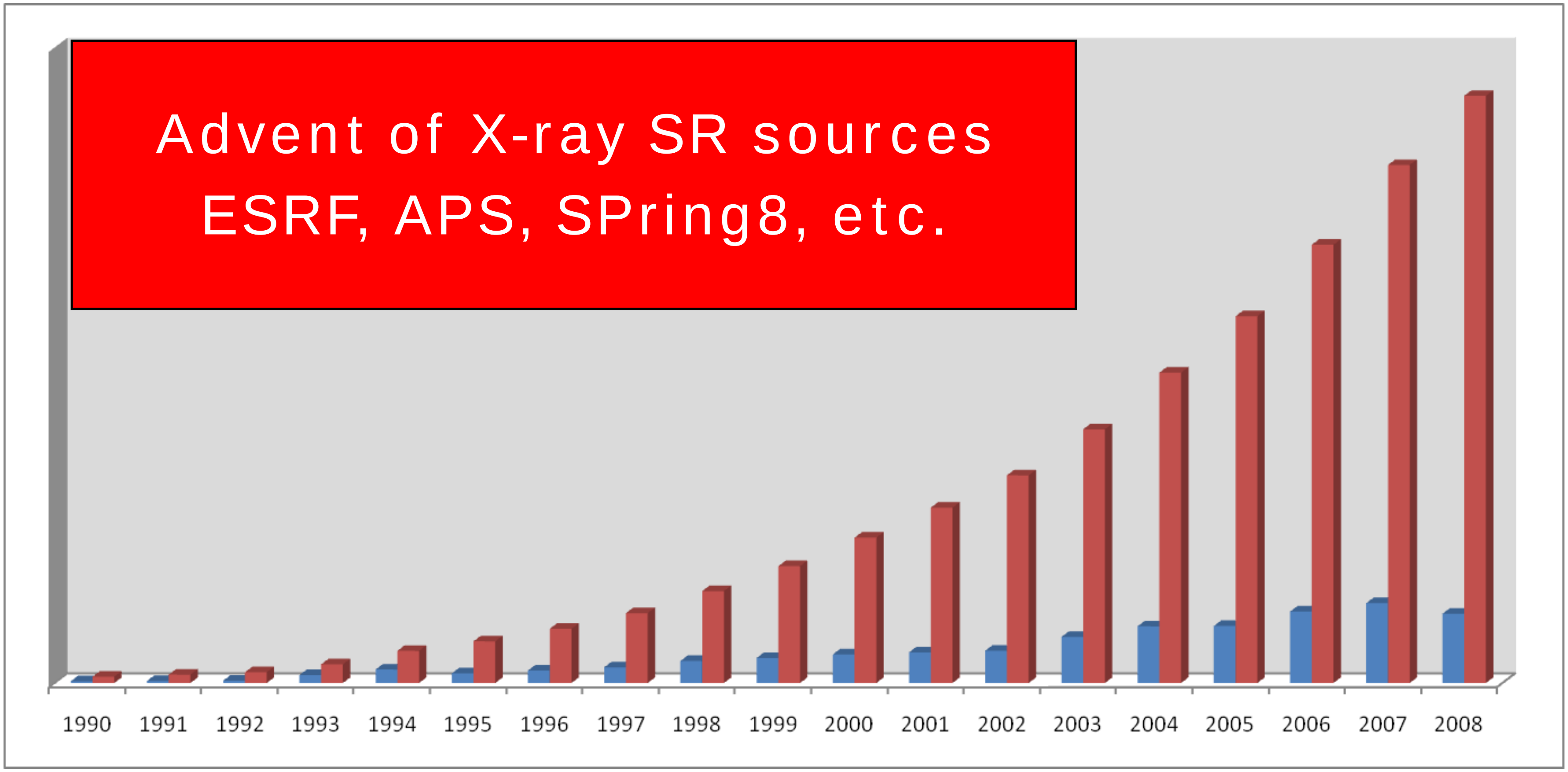
Part of a Ribosome



N. Ban et. al.

Spectacular growth of structural biology

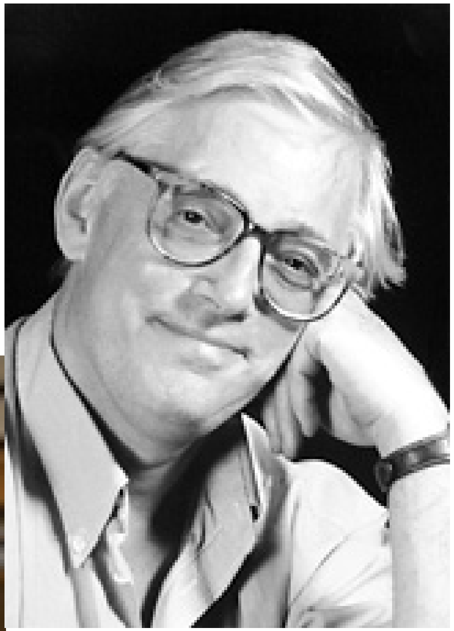
50’000


Advent of X-ray SR sources
ESRF, APS, SPring8, etc.

Nobel Prizes in Chemistry to Synchrotron Radiation Work in Protein Crystallography

1997 John E. Walker

Structure of F1-ATPase



2003 Roderick McKinnon

Structure of Cellular Ion Channels

2006 Roger D. Kronberg

Structure of RNA polimerase

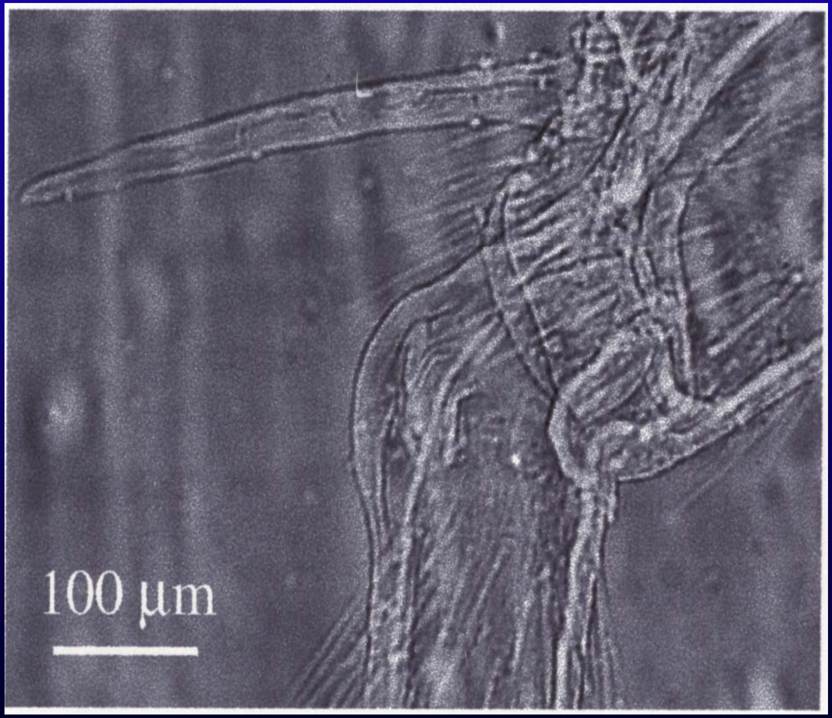
Transverse coherence

- High brightness gives coherence

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

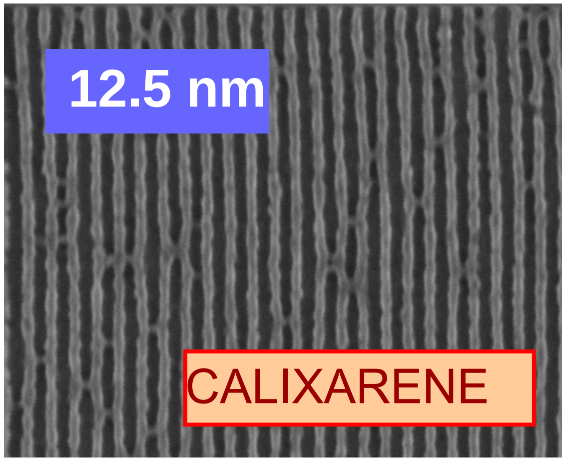
- Holography

The knee of a spider



phase contrast imaging

Lithographic Performance



EIPBN 06, Solak *et al*

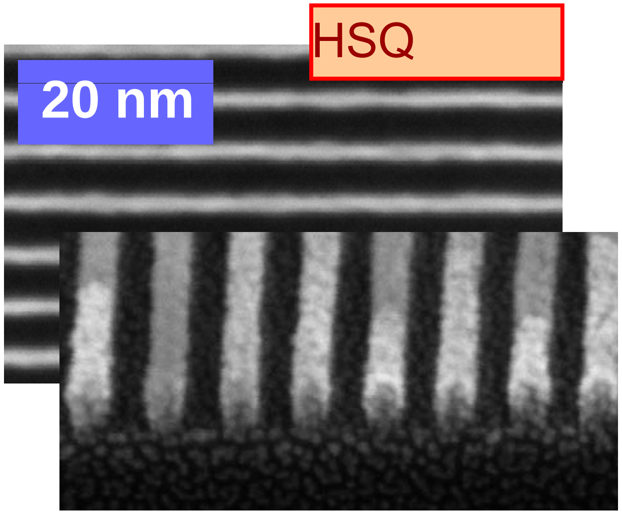
- Worldwide highest resolution in photon-based lithography
- Field size: up to 2x2 mm^2 (Achromatic Talbot)
- High throughput: ~10’000x e-beam
- Quality, reproducibility: enabling industrial operation

Fundamentals:

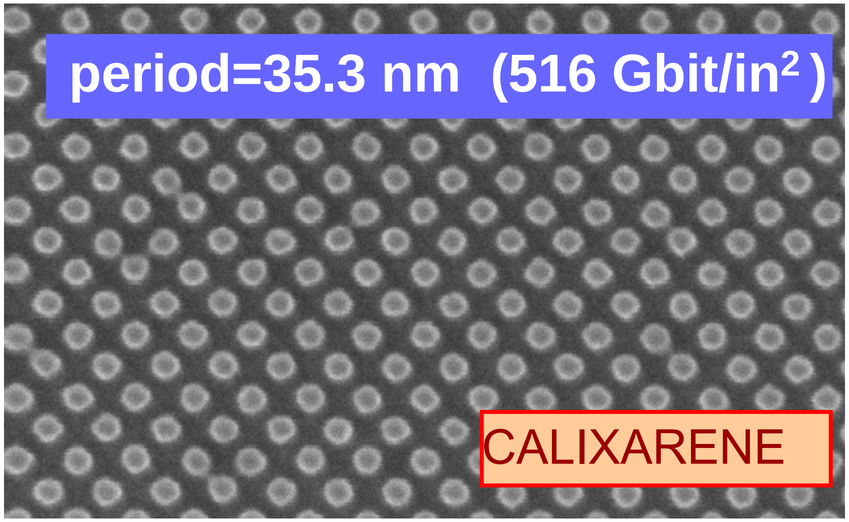
Stable, coherent source

Short wavelength (13.5 nm)

No proximity effect (electron mean free path <1 nm)



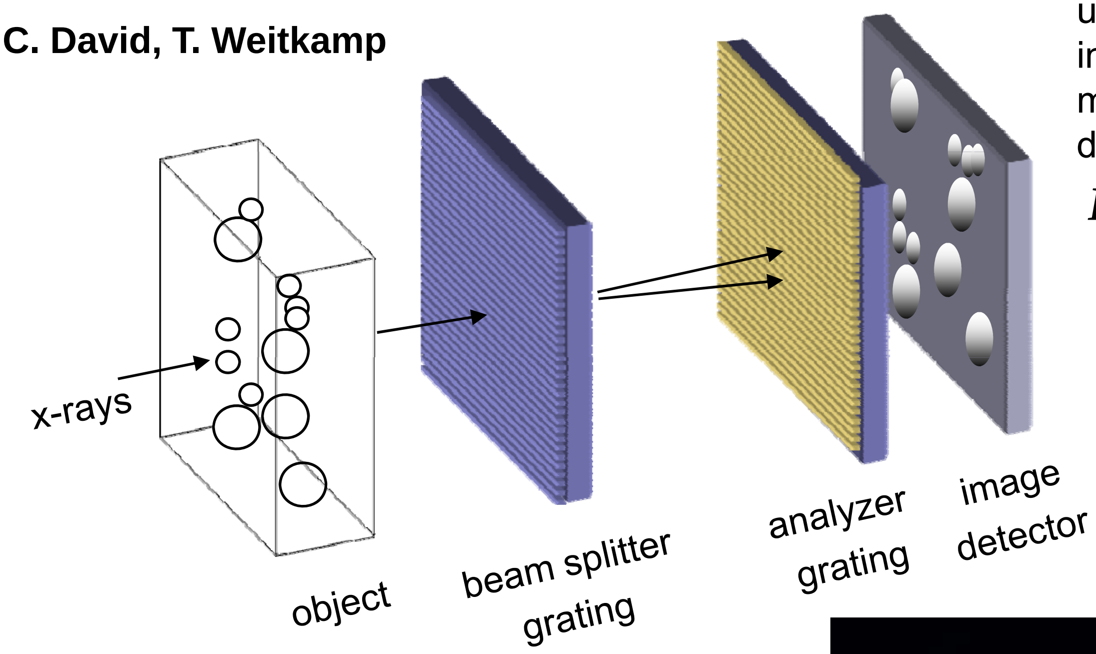
MNE 06, Ekinci *et al*



EIPBN 07, Solak *et al*

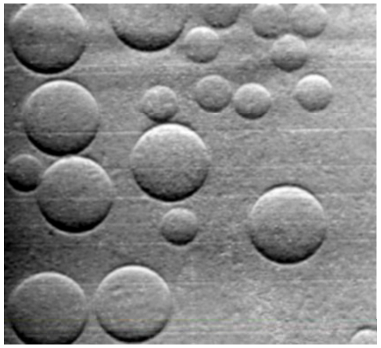
X-ray phase contrast imaging

C. David, T. Weitkamp



using a shearing interferometer based on microfabricated silicon diffraction gratings

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

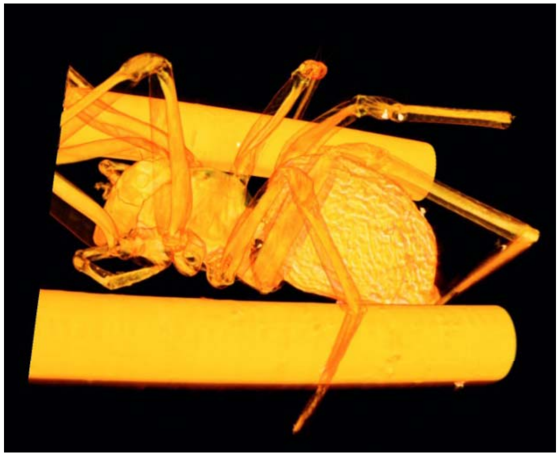


Phase-object example:

100µm and 200µm styrene beads

Advantages:

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



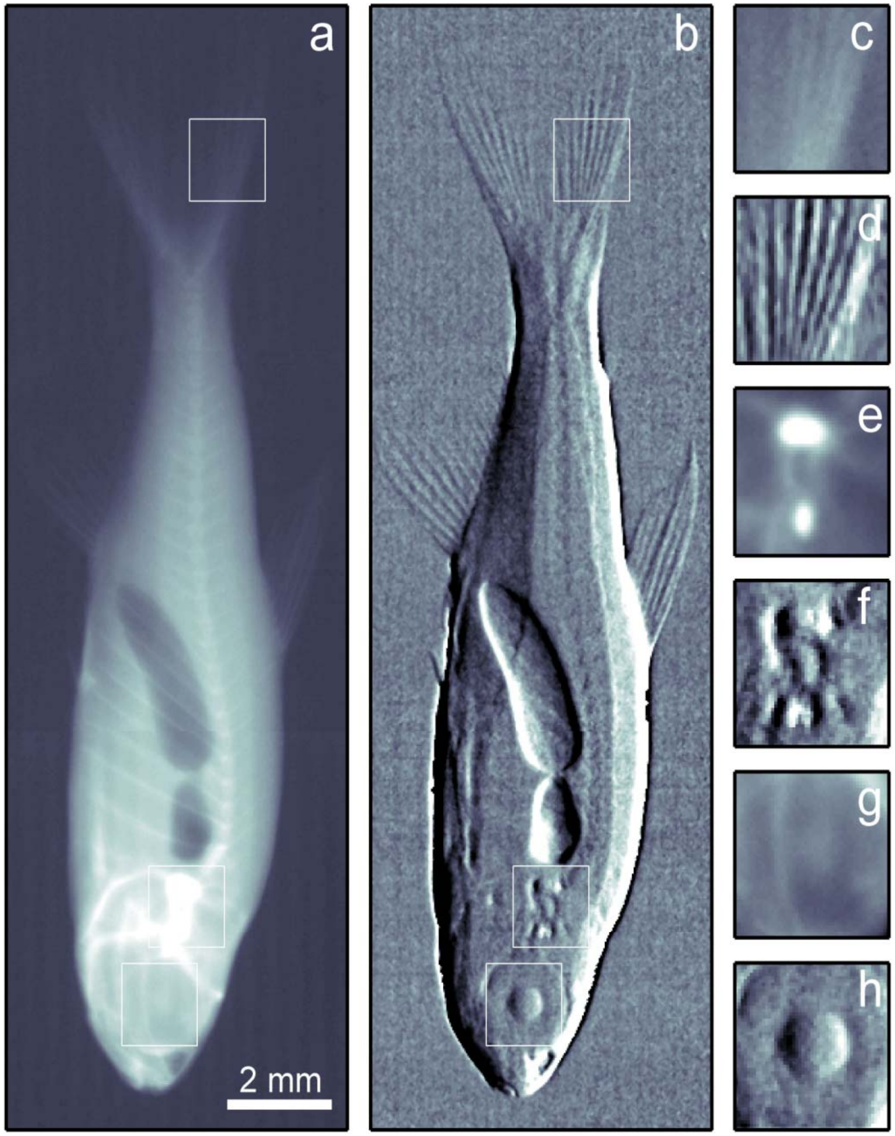
Tomographic phase reconstruction of a spider

X-ray Radiography of a fish

conventional

Absorption a

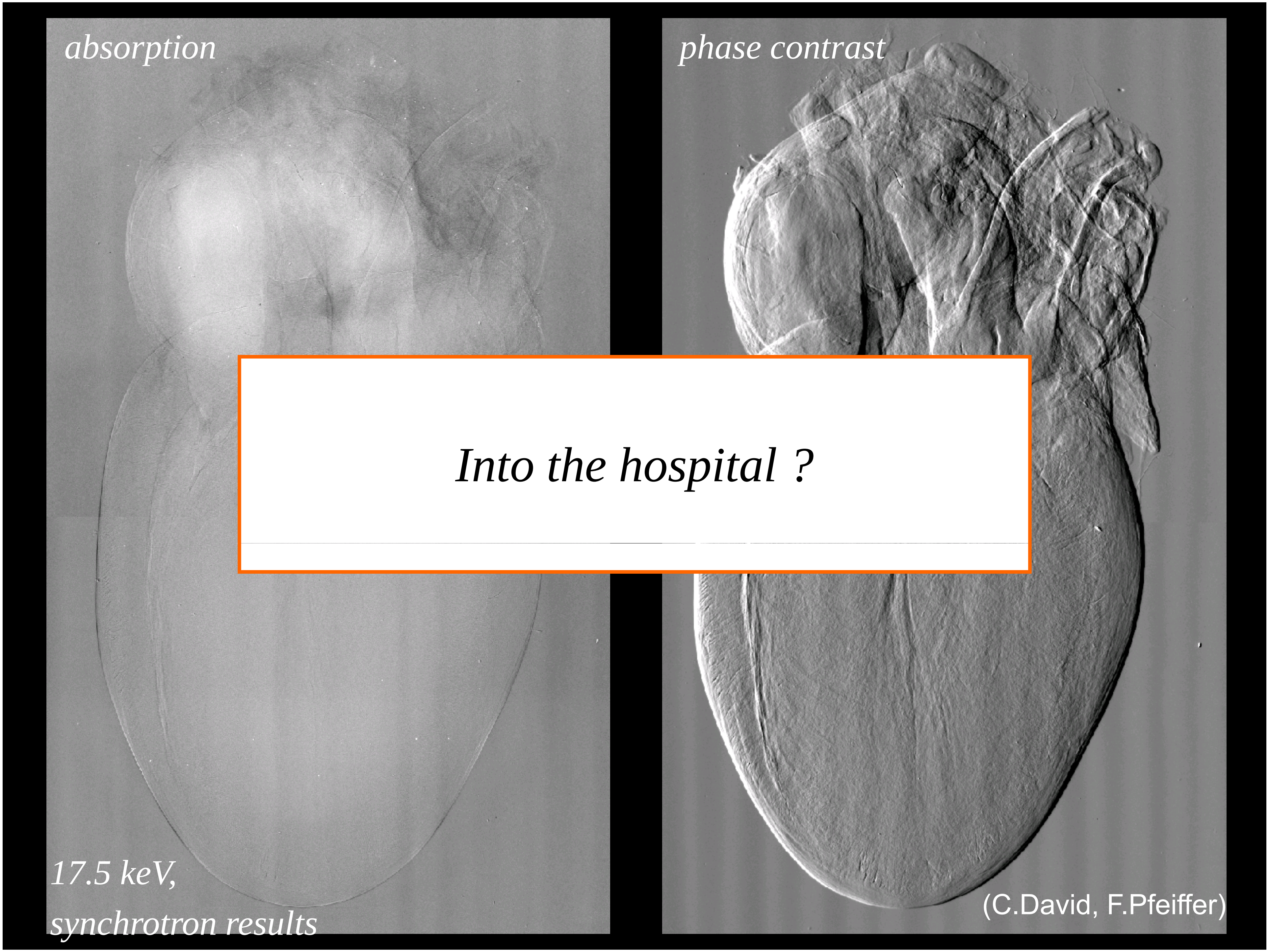
(+ details c , e, g)



Phase contrast Microscopy b

(+ details d, f, h)

(F.Pfeiffer)



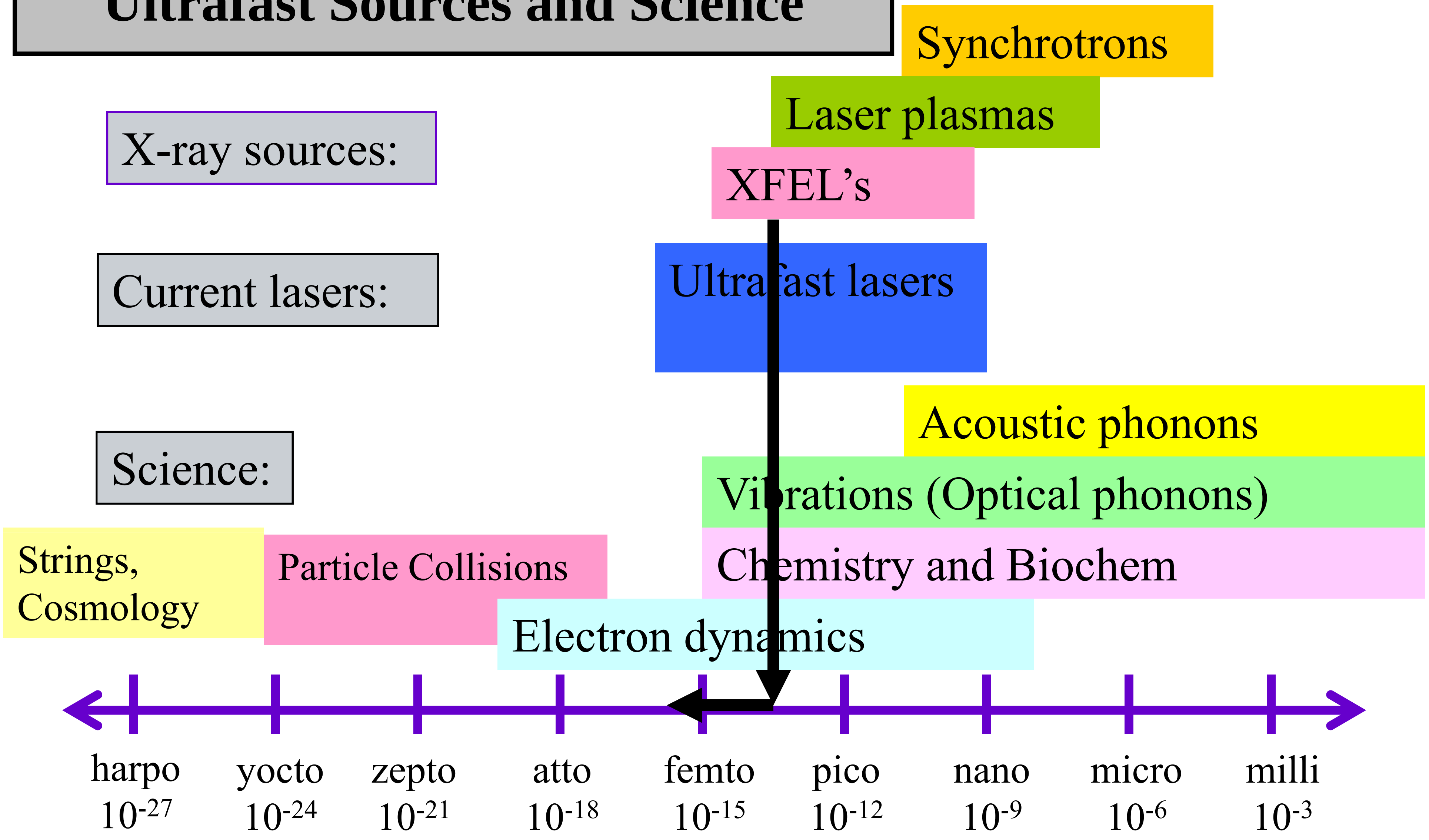
Into the hospital ?

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

Ultrafast Sources and Science



X-ray sources:

Synchrotrons

Laser plasmas

XFEL's

Current lasers:

Ultrafast lasers

Science:

Acoustic phonons

Vibrations (Optical phonons)

Chemistry and Biochem

Strings, Cosmology

Particle Collisions

Electron dynamics

harpo 10^{-27}

yocto 10^{-24}

zepto 10^{-21}

atto 10^{-18}

femto 10^{-15}

pico 10^{-12}

nano 10^{-9}

micro 10^{-6}

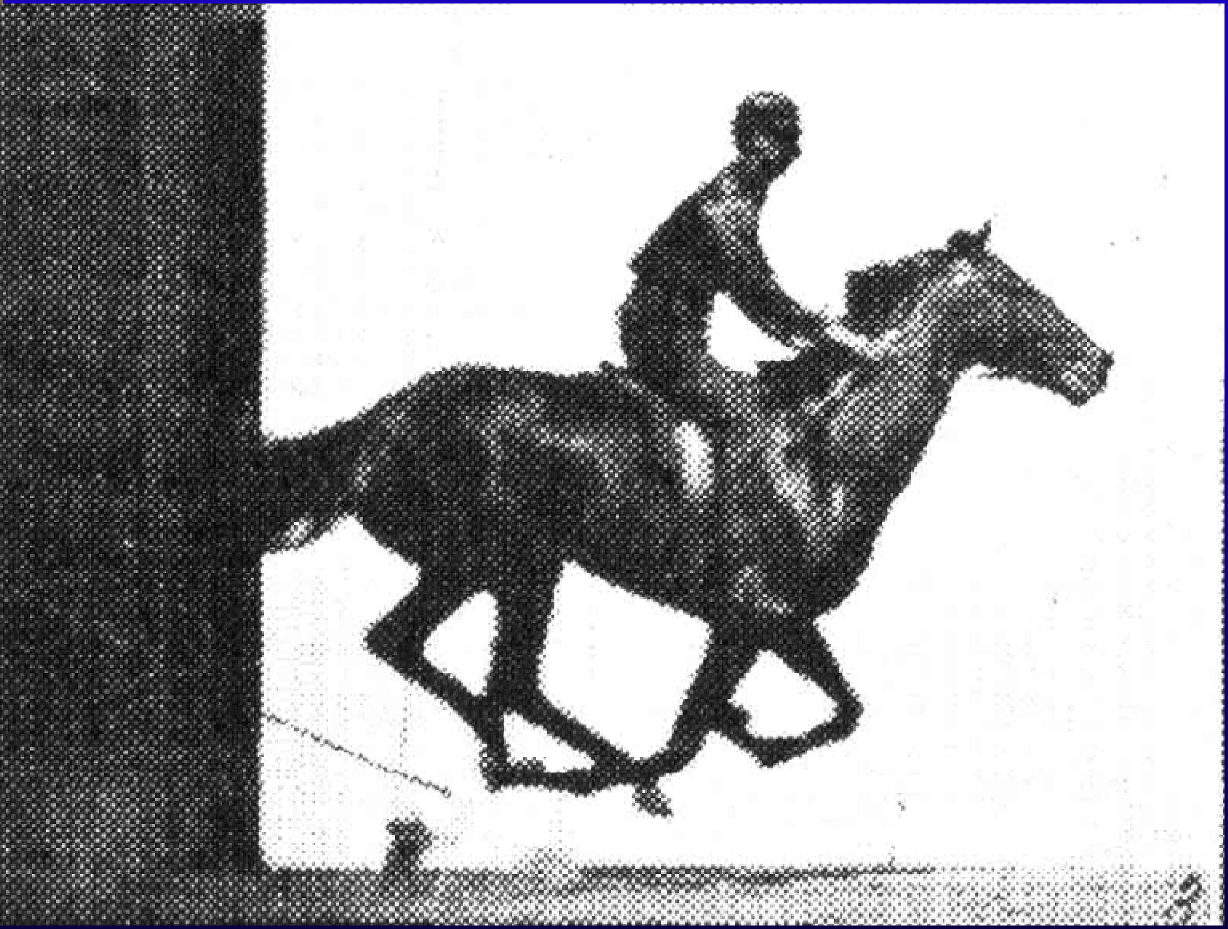
milli 10^{-3}

J. Hastings

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography


E. Muybridge

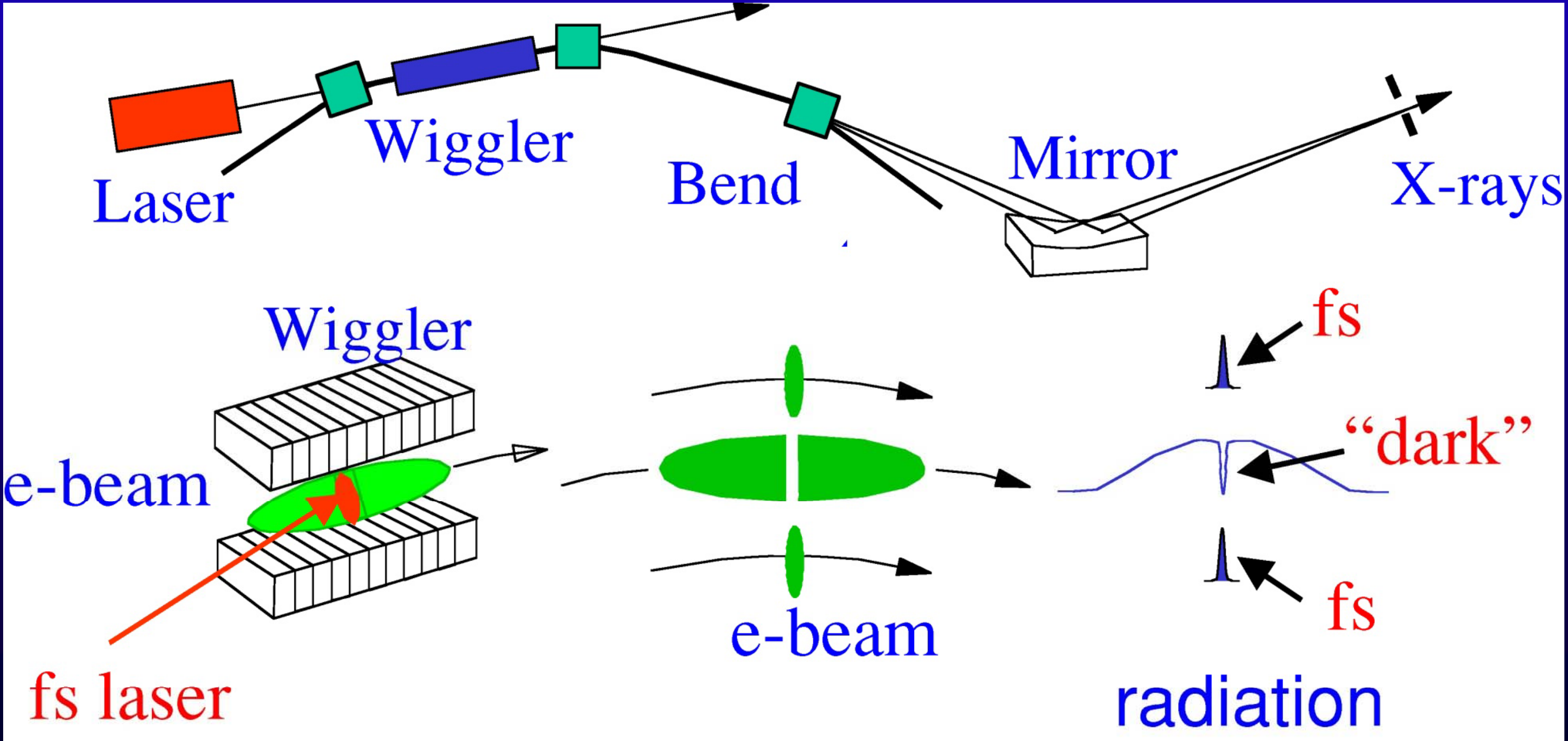



L. Stanford

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

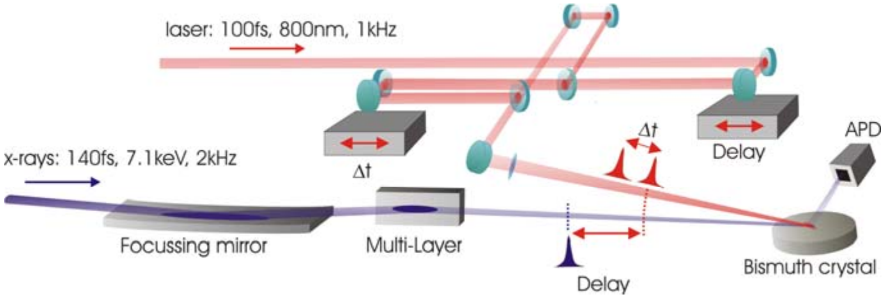
E. Muybridge, *Animals in Motion*, ed. by L. S. Brown (Dover Pub. Co., New York 1957).

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



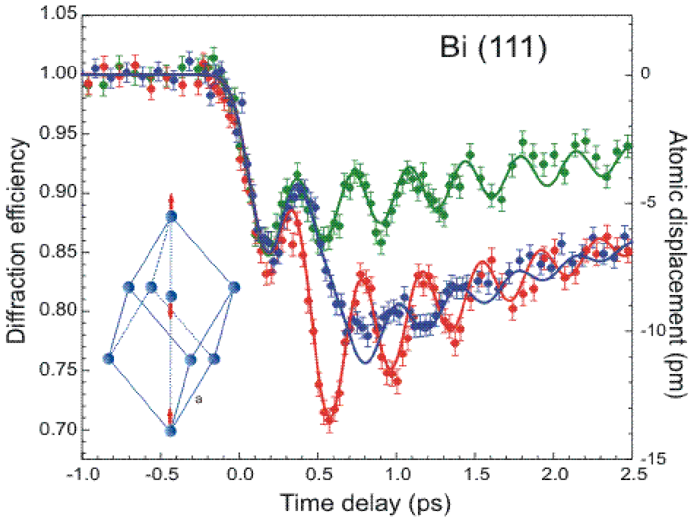
Dynamics on atomic scale visible with ultra-short X-ray pulses

FEMTO



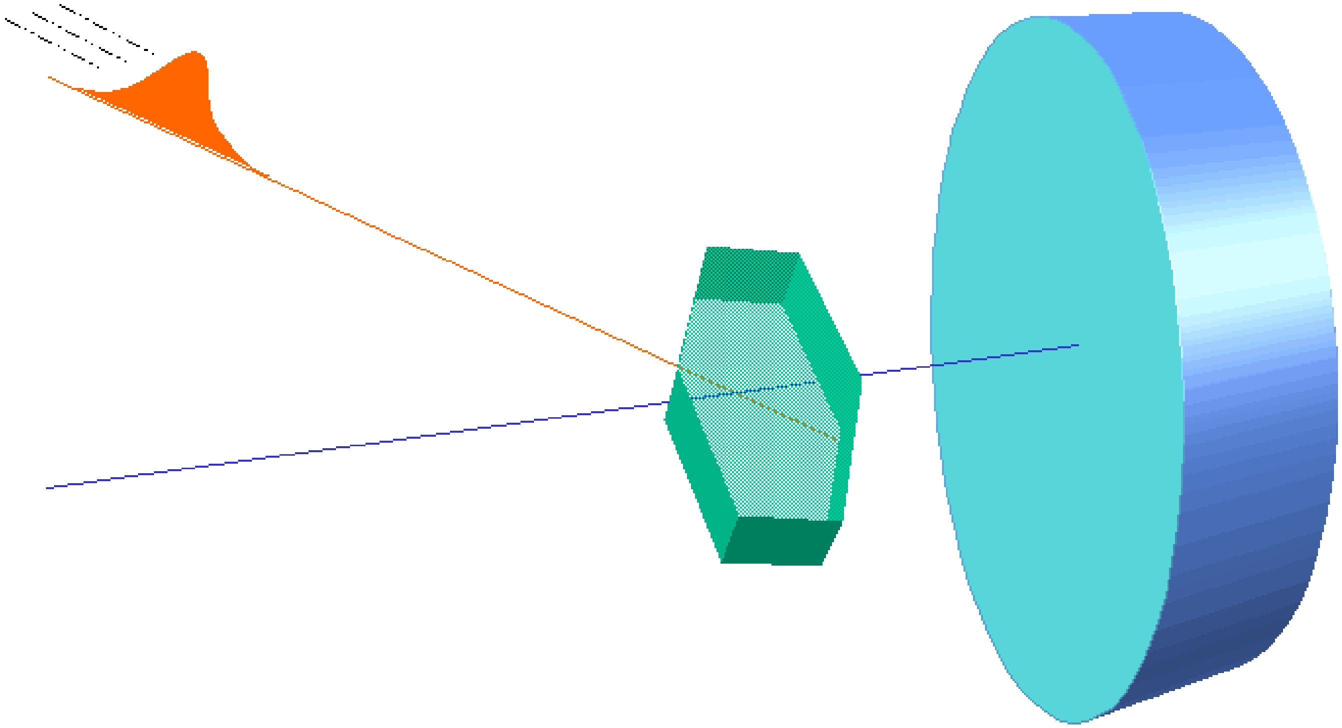
First optical experiment with atomic resolution:

Amplification and damping of lattice vibrations



Phys. Rev. Lett. 99, 174801 (2007)

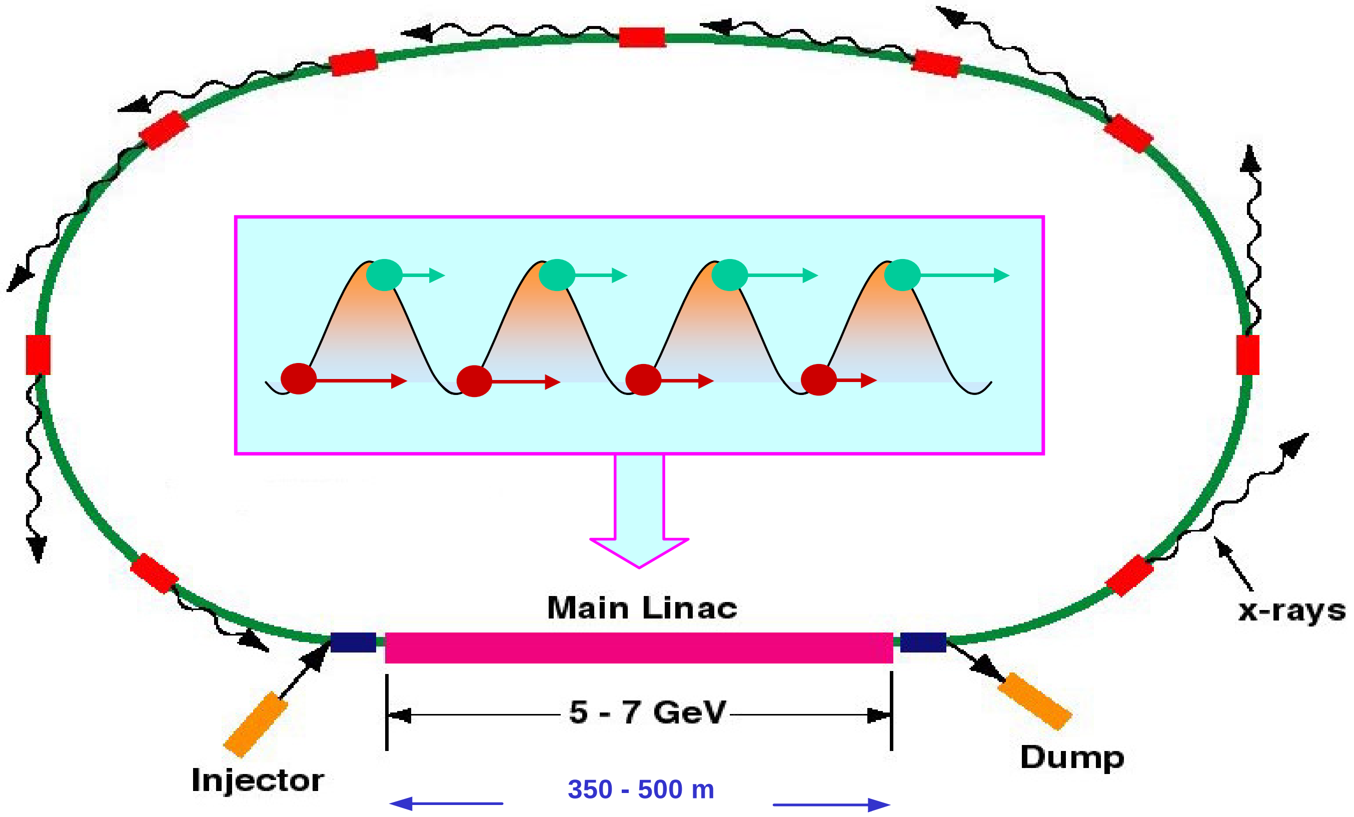
Fast processes and short pulses



Laser pump / X-ray probe

Energy Recovery Linac Schematic

Single pass: emittance and energy spread are determined by injector, can be much smaller than in storage ring

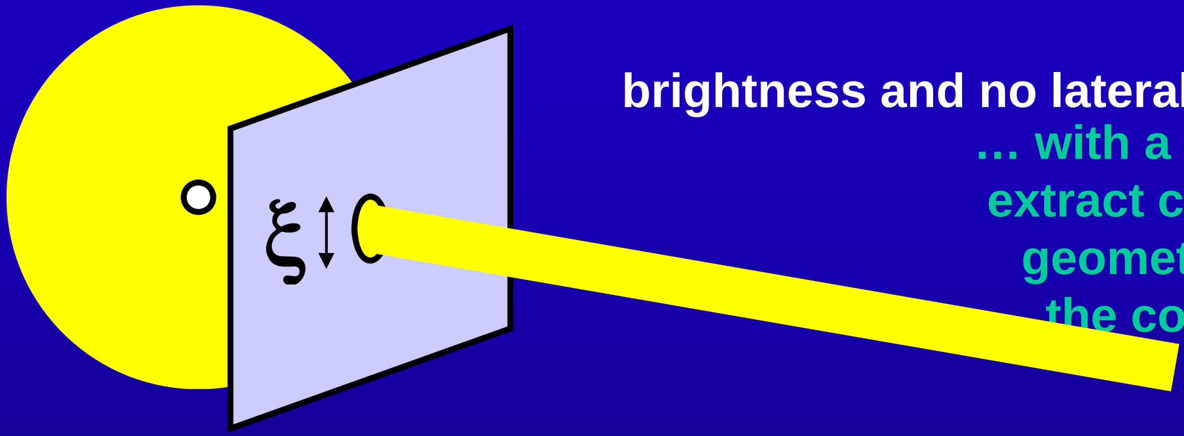


M Tigner, Cornell

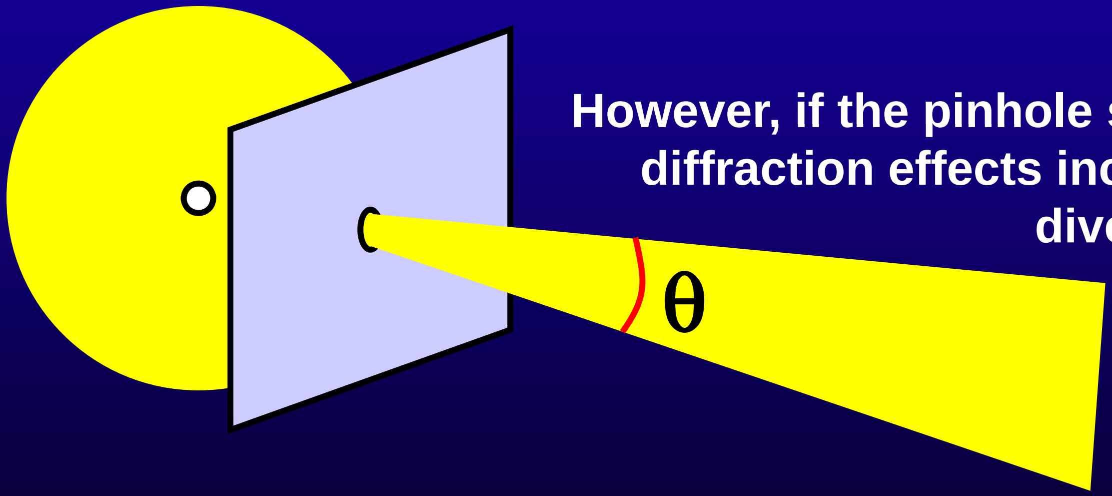
FREE ELECTRON LASERS

Take a standard photon source with limited

brightness and no lateral coherence …



… with a pinhole (size ξ), we can extract coherent light with good geometrical characteristics (at the cost of losing most of the emission)



However, if the pinhole size is too small diffraction effects increase the beam divergence so that:

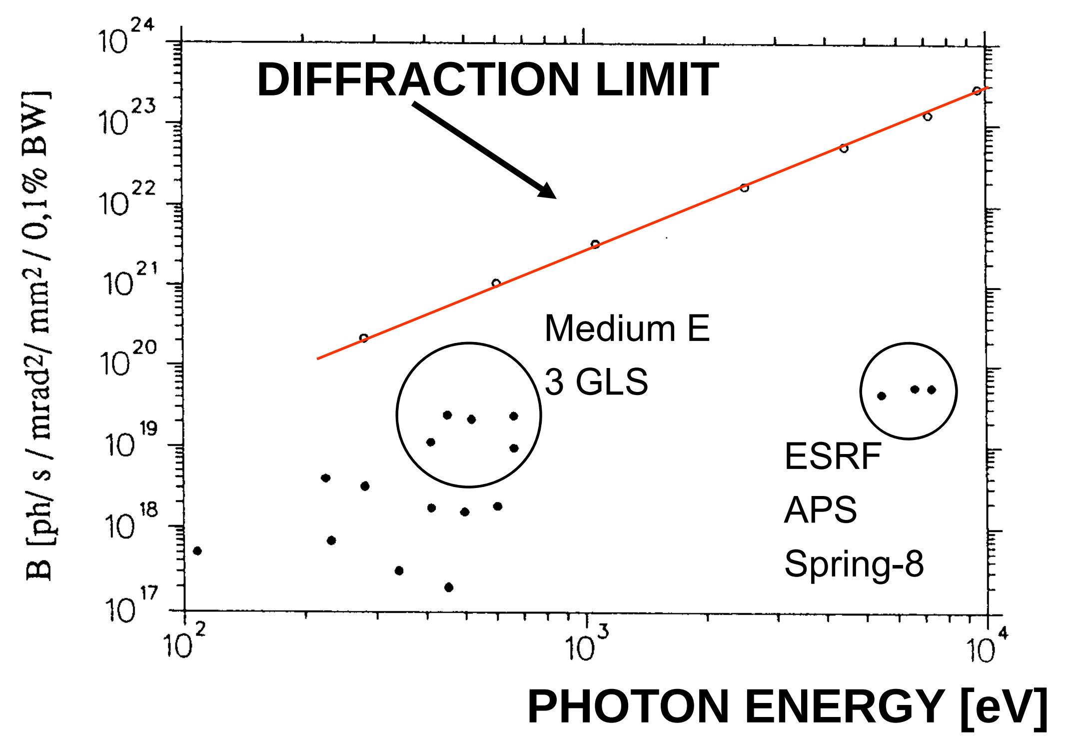
$$\xi \cdot \theta > \lambda$$

No source geometry beats this diffraction limit

G. Margaritondo

PERFORMANCE OF 3th GENERATION LIGHT SOURCES

BRIGHTNESS:

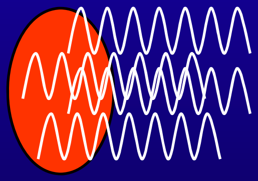


BRIGHTNESS OF SYNCHROTRON RADIATION

	electrons	*periods*		
Bending magnet	$\sim N_e$		⬬	
Wiggler	$\sim N_e$	$\sim N$	⬬	10
Undulator	$\sim N_e$	$\sim N^2$	⬬	10^4
FEL	$\sim N^2_{\mu\text{-}b}$	$\sim N^2$	▥	10^{10}
Superradiance	$\sim N_e^2$	$\sim N^2$	●	10^{12}

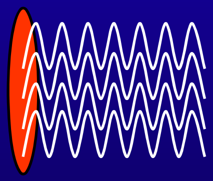
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto$ N



INCOHERENT EMISSION

Intensity $\propto$ N ^{2}



COHERENT EMISSION

FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

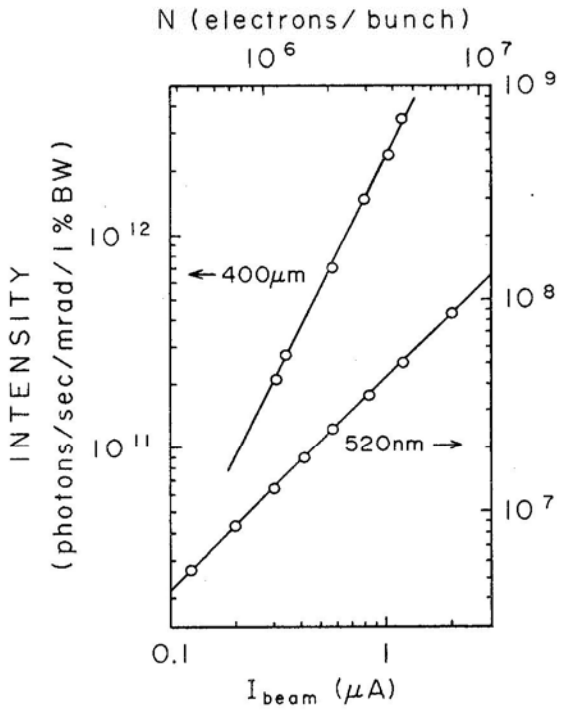


Fig. 4. Dependence of SR intensity on the beam current at λ = 400 μm and λ = 520 nm for the long pulse/short bunch beam. The ordinate is given on the left-hand side for λ = 400 μm and on the right for λ = 520 nm. The two lines show the linear and quadratic relations to the beam current. The beam current 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

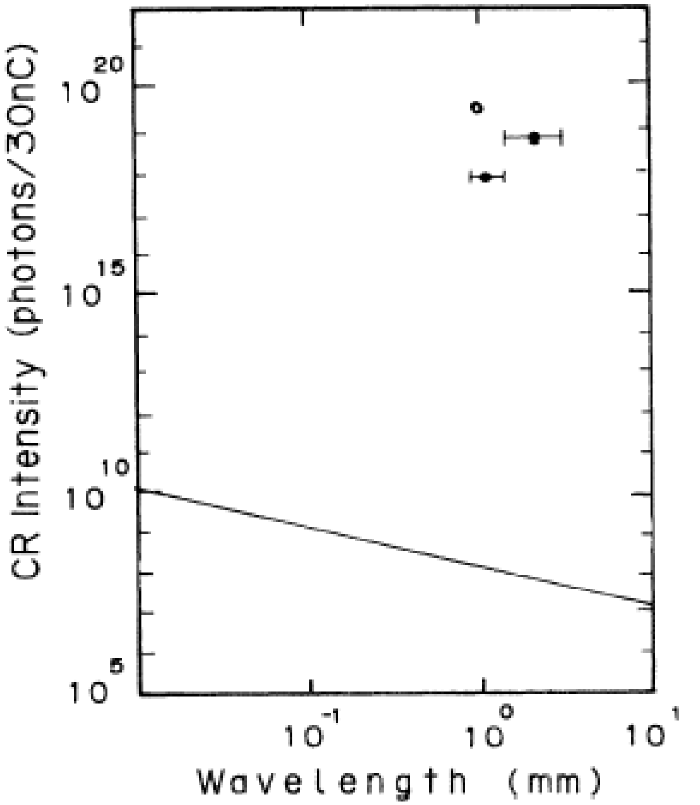
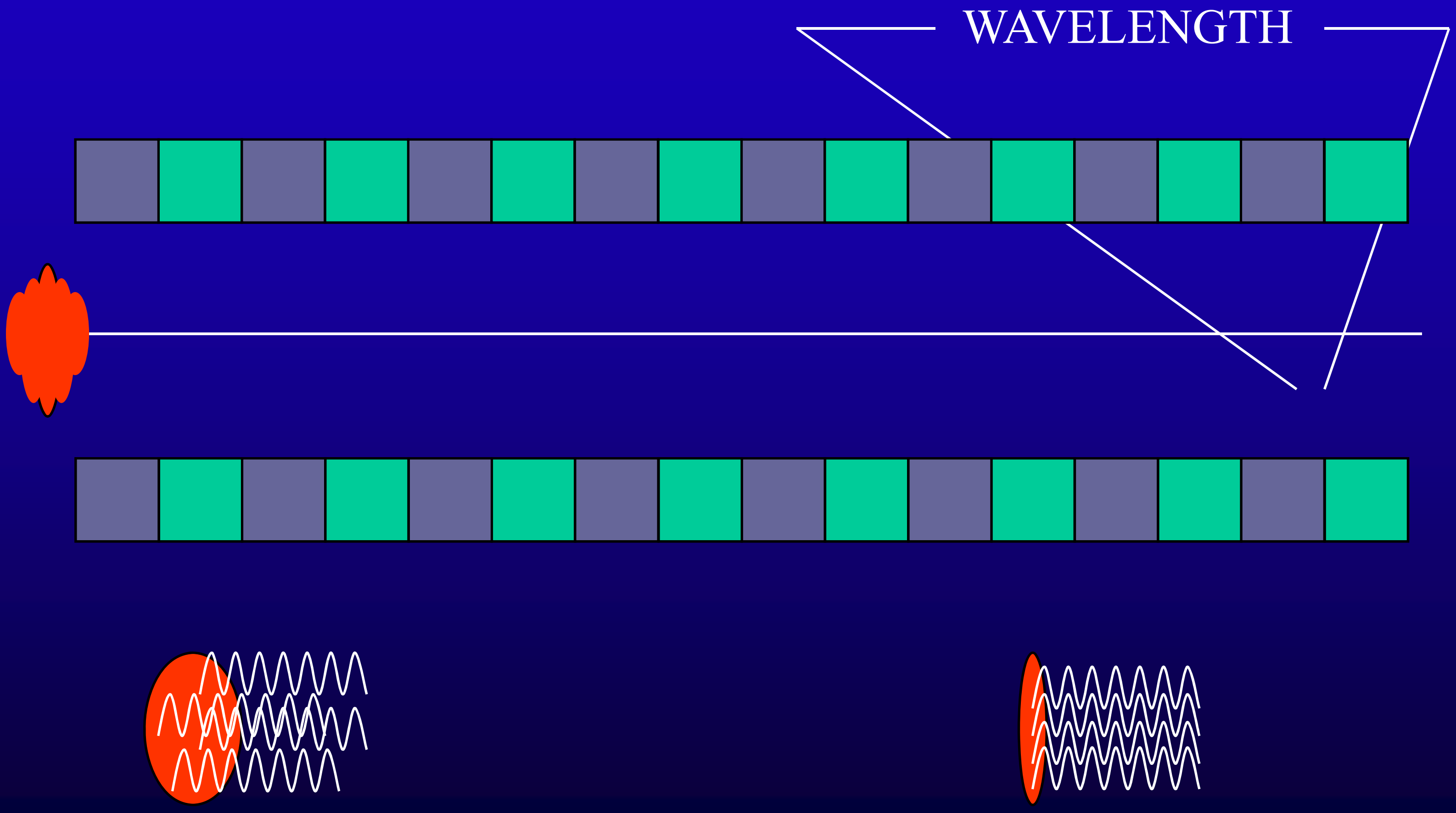


FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

30 MeV electrons

J. Ohkuma et al., Osaka University, Japan

MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE



INCOHERENT EMISSION

COHERENT EMISSION

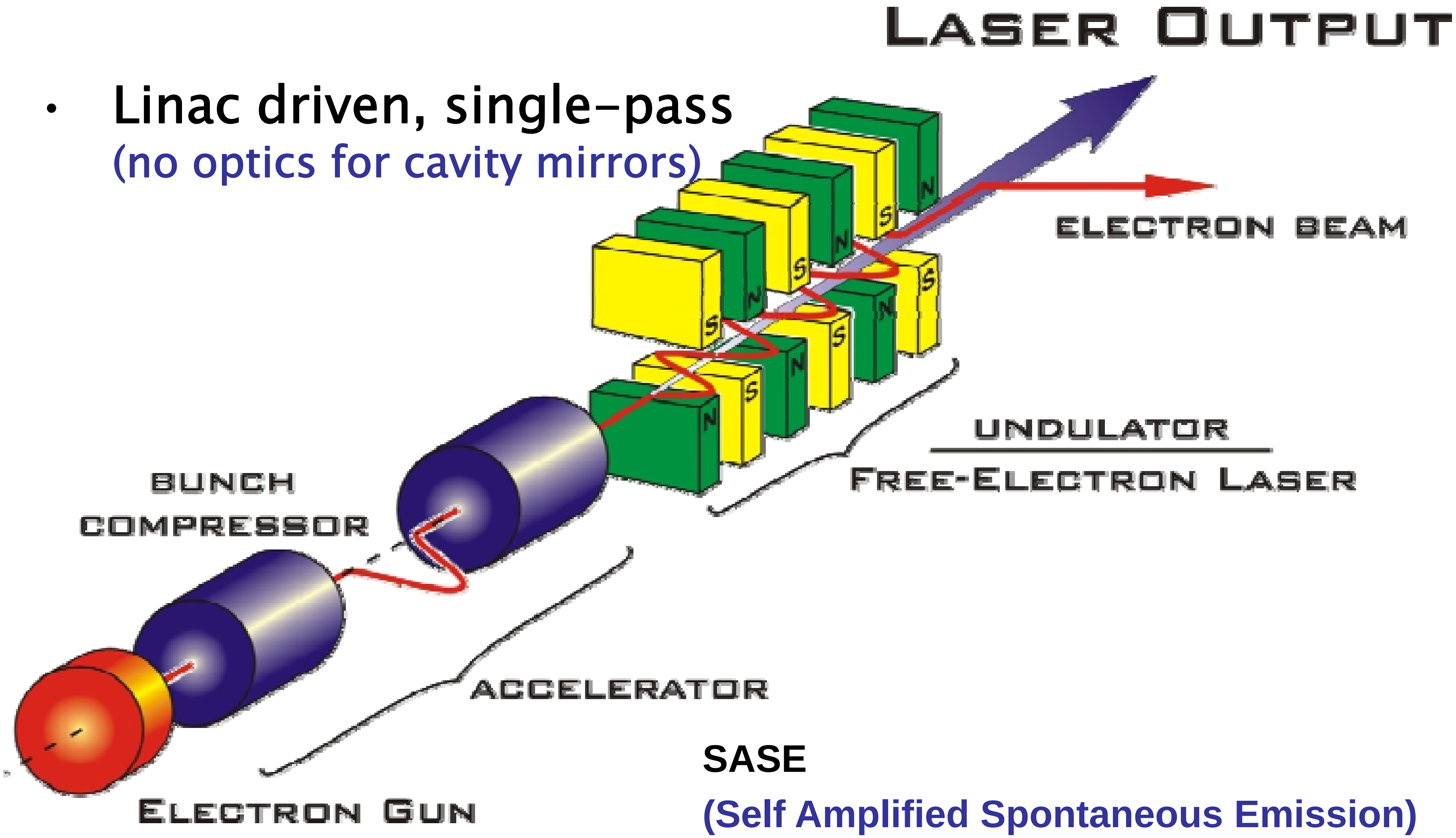
From rings to linear accelerators

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

- Fewer beamlines
- Very short pulses, single shot measurements
- High peak brightness

Free Electron Laser Keywords:

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



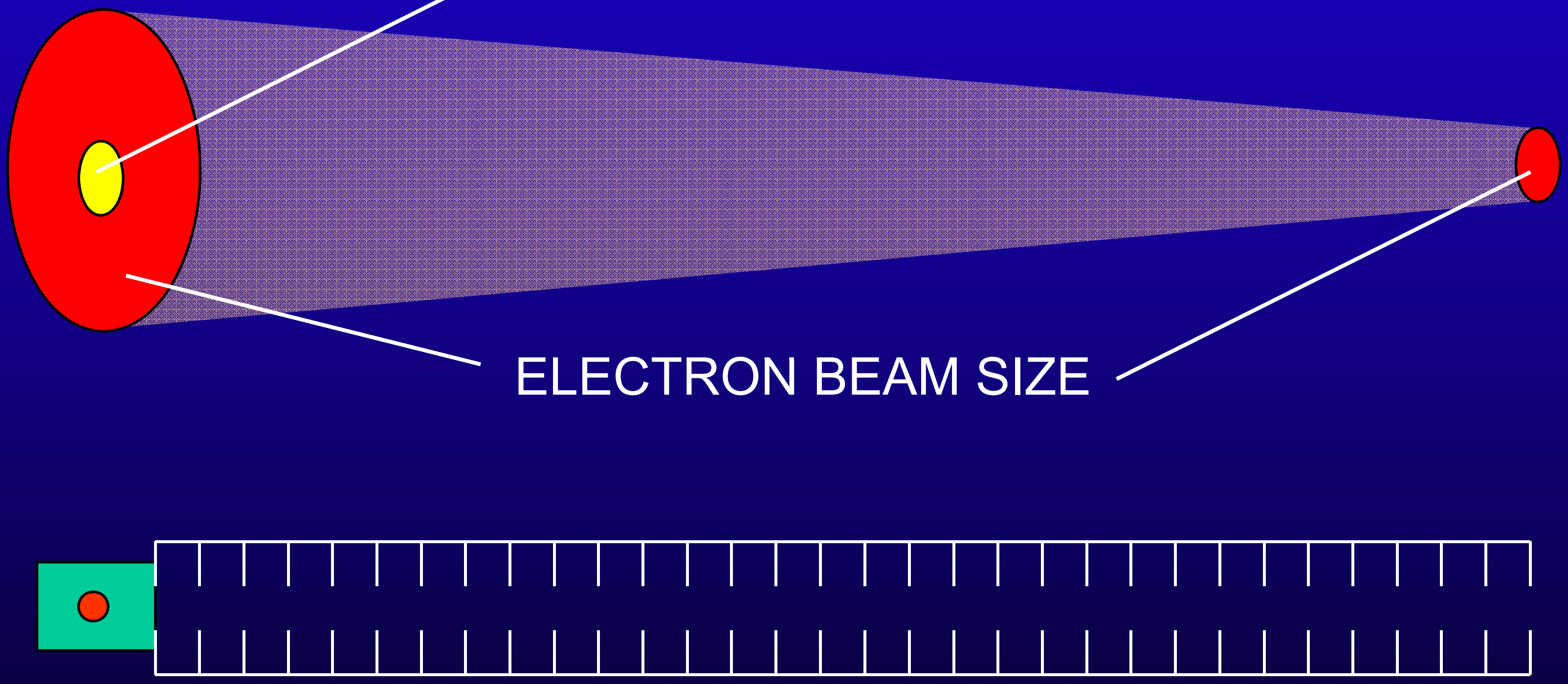
SASE

(Self Amplified Spontaneous Emission)

i.e., startup from noise

R. Bakker

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



PHOTON BEAM SIZE

ELECTRON BEAM SIZE

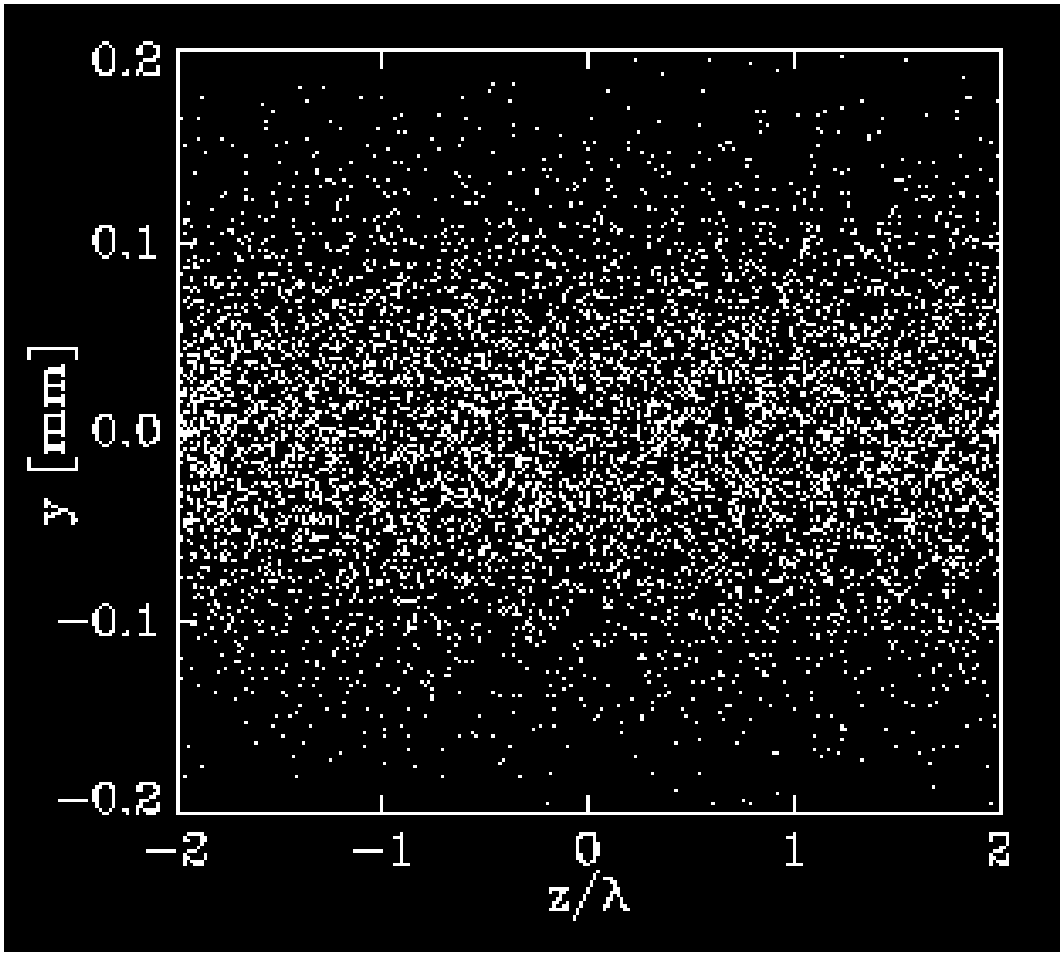
X-FEL facilities

European XFEL
DESY 2013

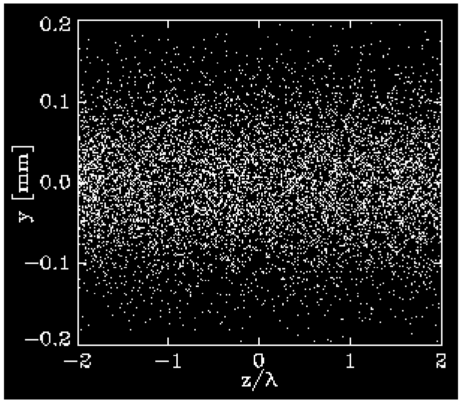
Japan
SCSS – SPring8 2010

USA
LCLS – SLAC 2009

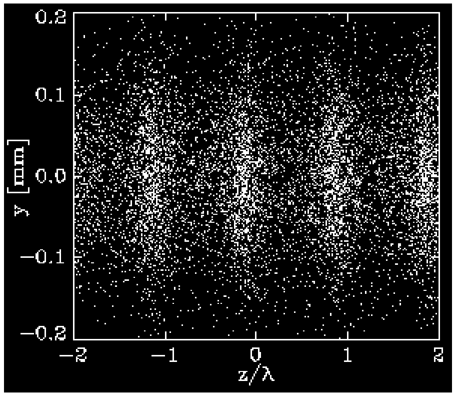
Microbunching through SASE Process



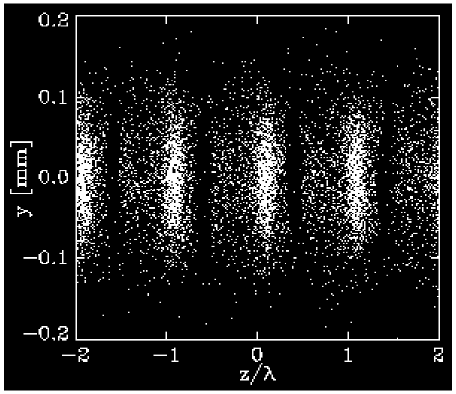
undulator entrance



half-way saturation



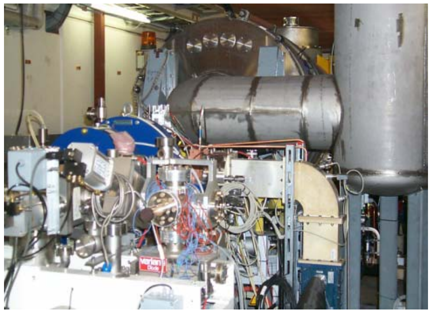
full saturation

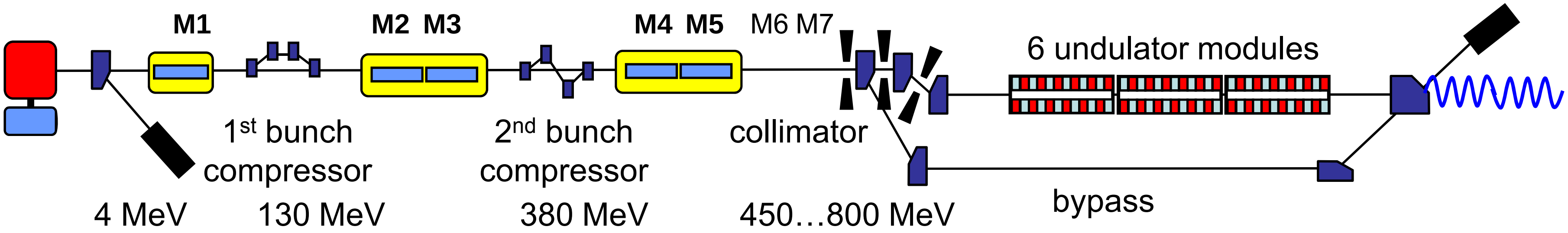


***GENESIS* - simulation for TTF parameters**

Courtesy - Sven Reiche (PSI)

FLASH: Free Electron LASer in Hamburg



M1

M2 M3

M4 M5

M6 M7

6 undulator modules

1st bunch compressor

2nd bunch compressor

collimator

bypass

4 MeV

130 MeV

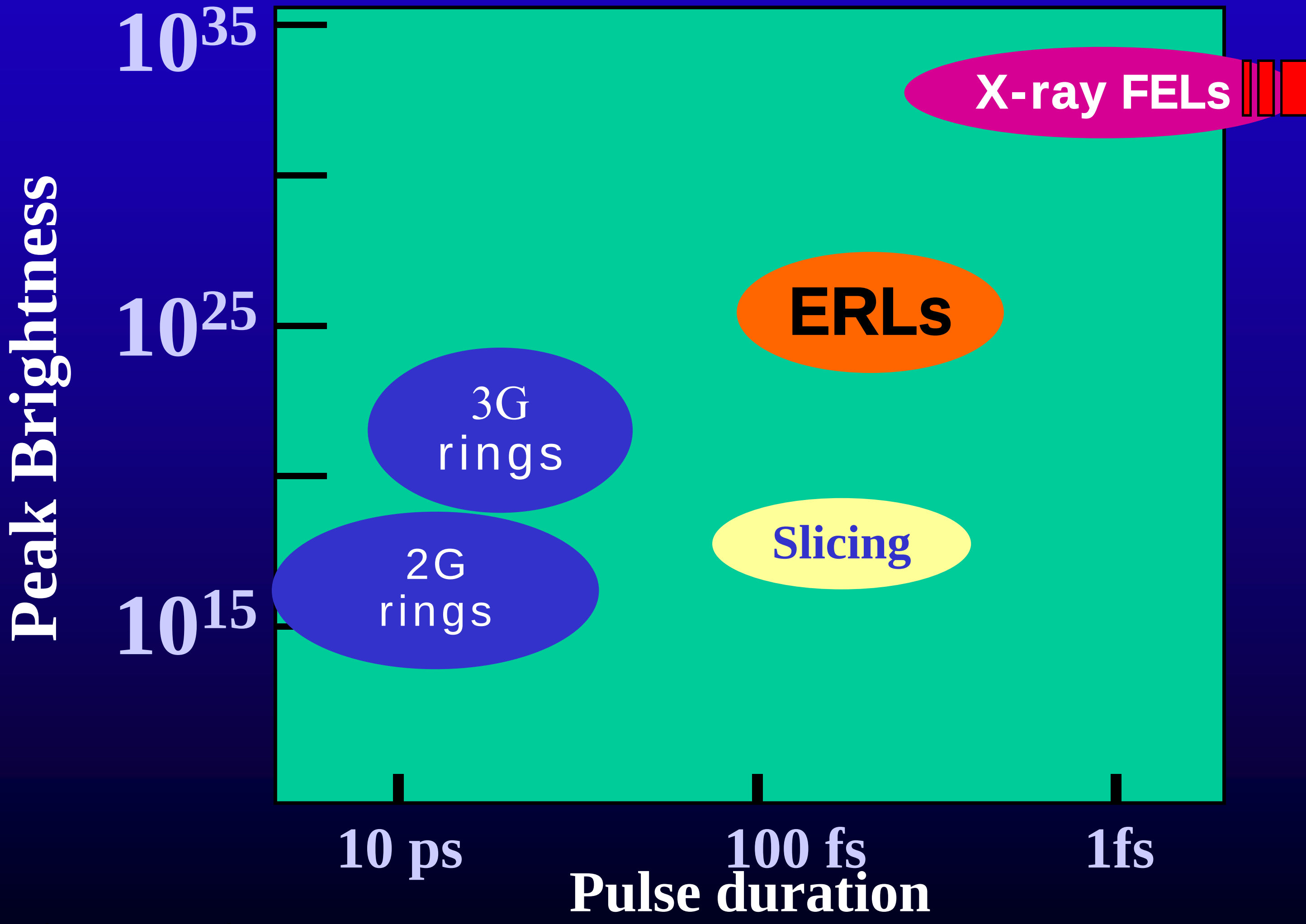
380 MeV

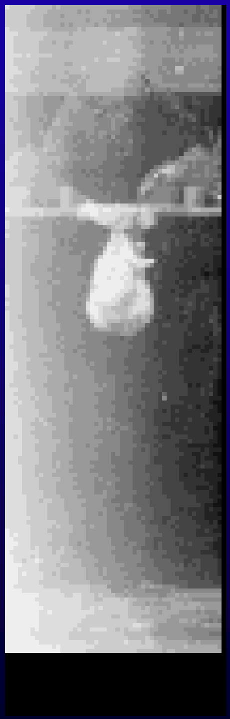
450…800 MeV




250 m

FELs and ERLs COMPLEMENT the Ring sources

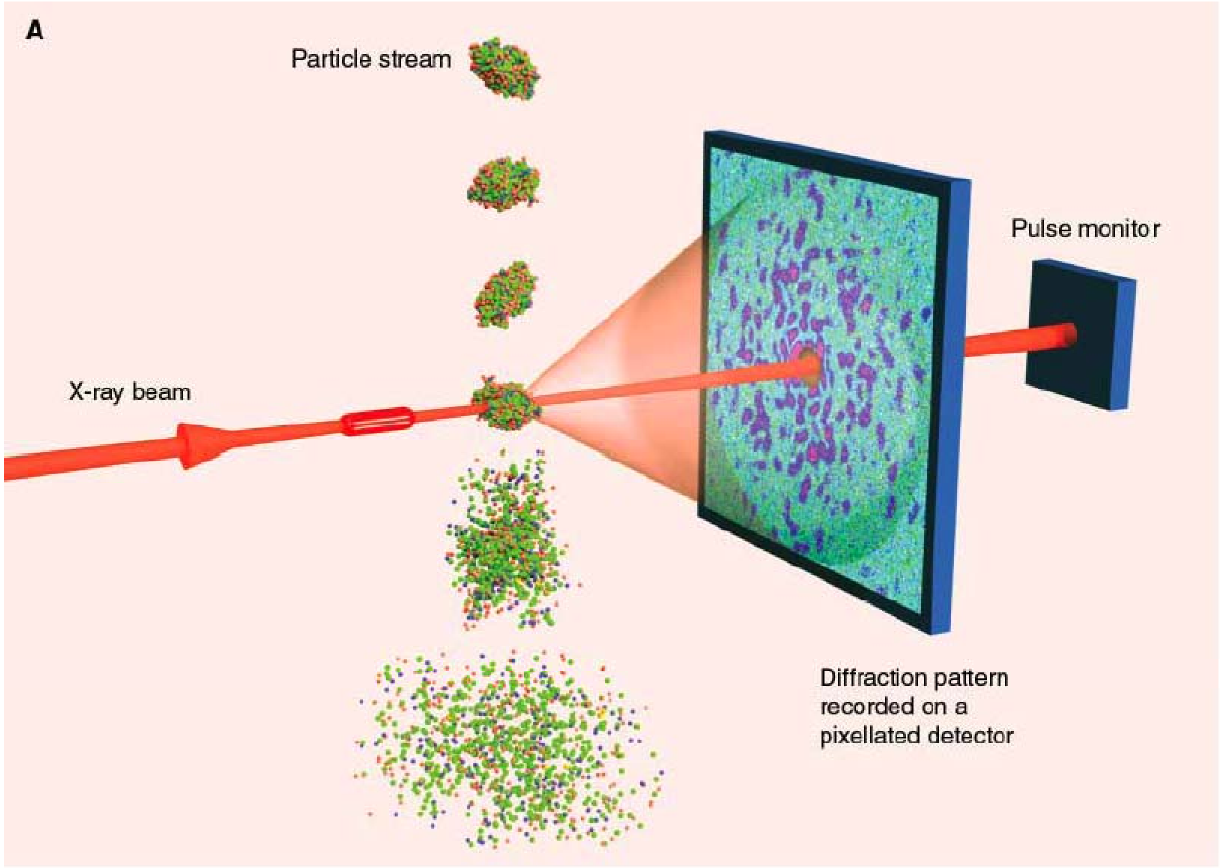


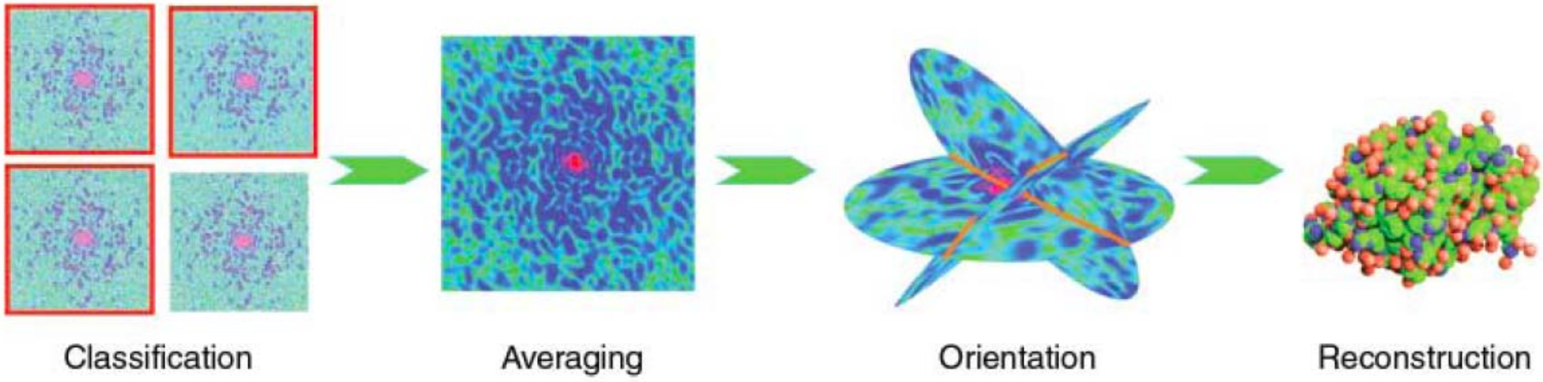


H.-D. Nuhn, H. Winick

After H.-D. Nuhn, H. Winick

Structure determination of single molecules before the Coulomb explosion

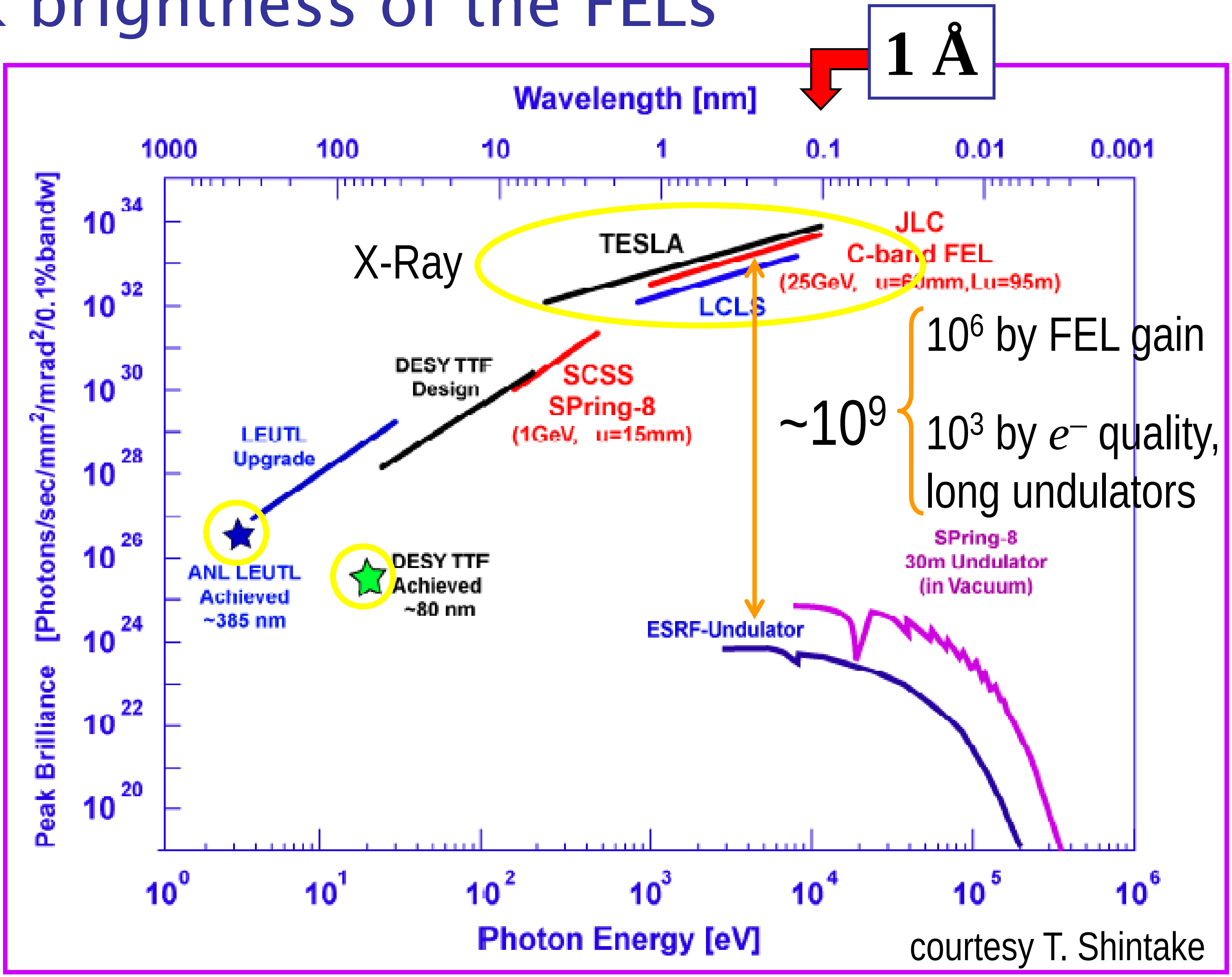




H. Chapman
(2007)

Peak brightness of the FELs

photons
per
phase-
space
volume
per band-
width



1 Å

X-Ray

10^6 by FEL gain

$\sim 10^9$

10^3 by e^- quality,
long undulators

courtesy T. Shintake

END