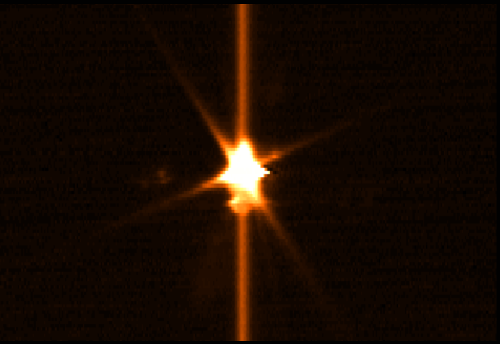
Albin F. Wrulich

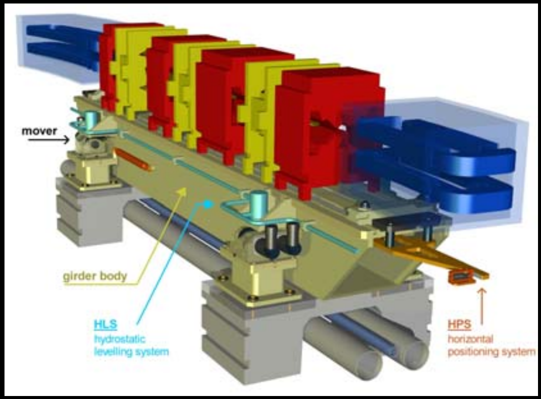
PARTICULAR FEATURES OF HIGH PERFORMANCE STORAGE RING LIGHT SOURCES

HIGH PERFORMANCE LIGHT SOURCE

FEATURES ....



ELECTRON BEAM

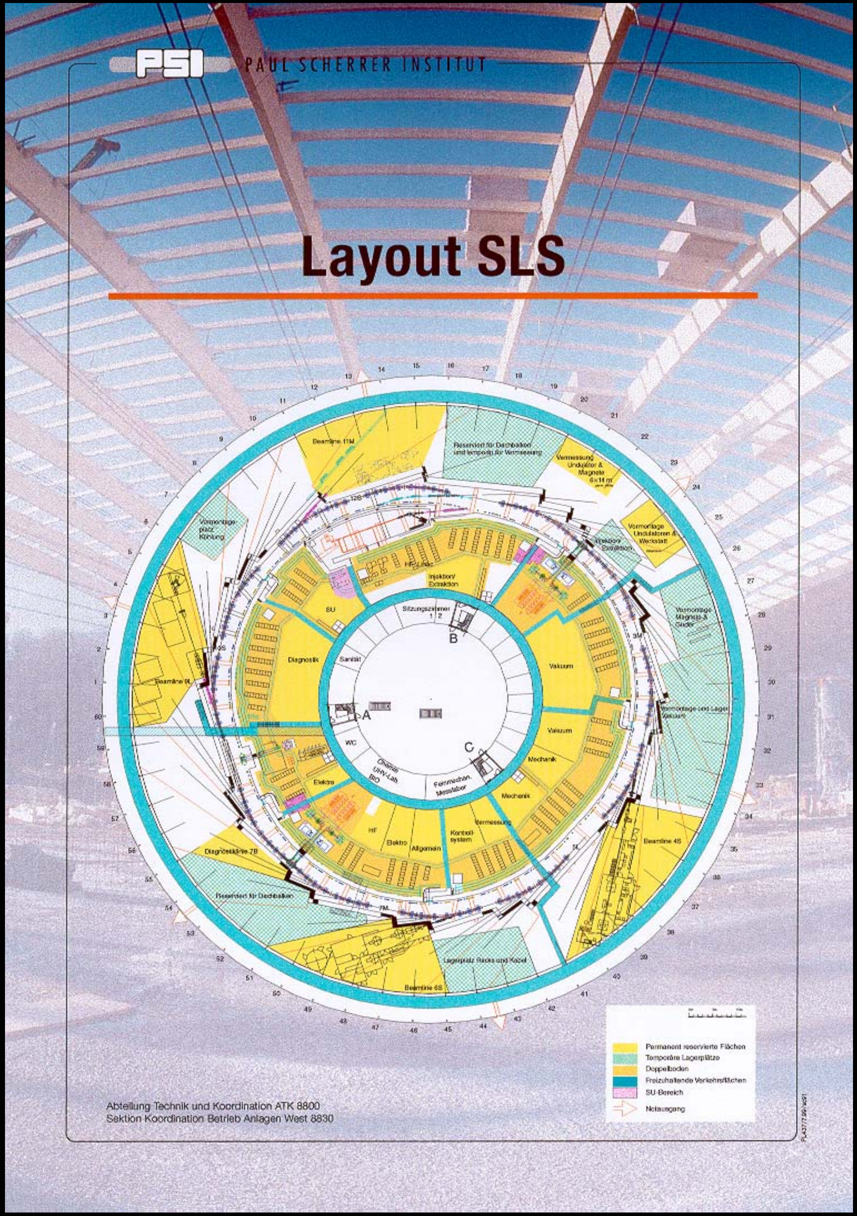


LIGHT

MAGNET STRUCTURE

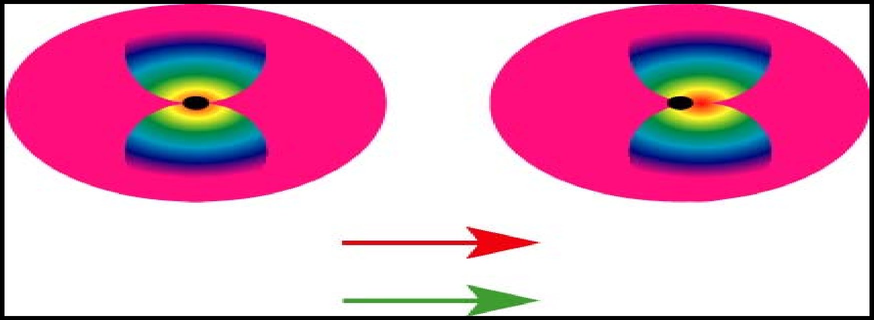
At the beginning:

SOME LIGHT SOURCE FUNDAMENTALS


PAUL SCHERRER INSTITUT
Layout SLS
Permanent reservierte Flächen
Temporäre Lagerplätze
Doppelboden
Freizuhaltende Verkehrsflächen
SU-Bereich
Notausgang
Abteilung Technik und Koordination ATK 8800
Sektion Koordination Betrieb Anlagen West 8830

1898 Liénard:

$$\underline{P} = \frac{2}{3} \frac{e^2 \gamma^6}{4\pi \varepsilon_o c} \left[\dot{\vec{\beta}}^2 - \left(\vec{\beta} \times \dot{\vec{\beta}} \right)^2 \right]$$

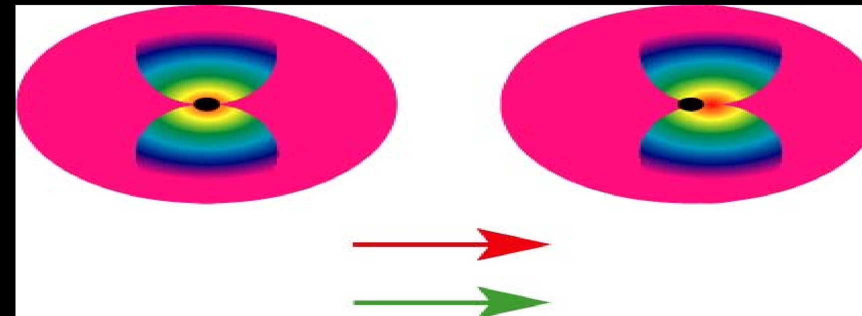


LONGITUDINAL:

Radiation field cannot separate itself from the Coulomb field

1898 Liénard:

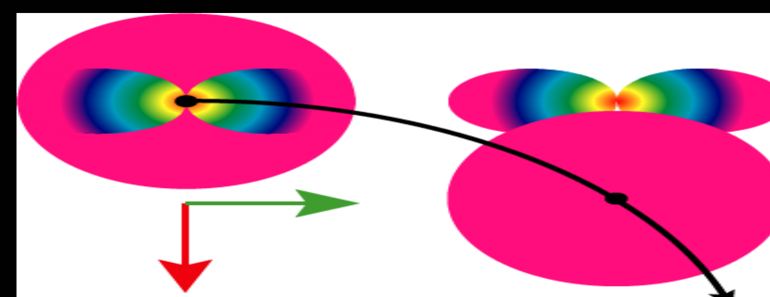
$$\underline{P} = \frac{2}{3}\frac{e^2\gamma^6}{4\pi\varepsilon_o c}\left[\dot{\vec{\beta}}^2 - \left(\vec{\beta}\times\dot{\vec{\beta}}\right)^2\right]$$



LONGITUDINAL:

Radiation field cannot separate itself from the Coulomb field

$$P \sim \frac{\gamma^4}{\rho^2}$$



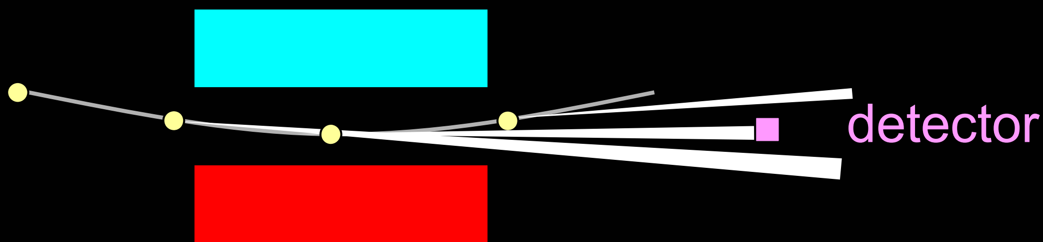
a

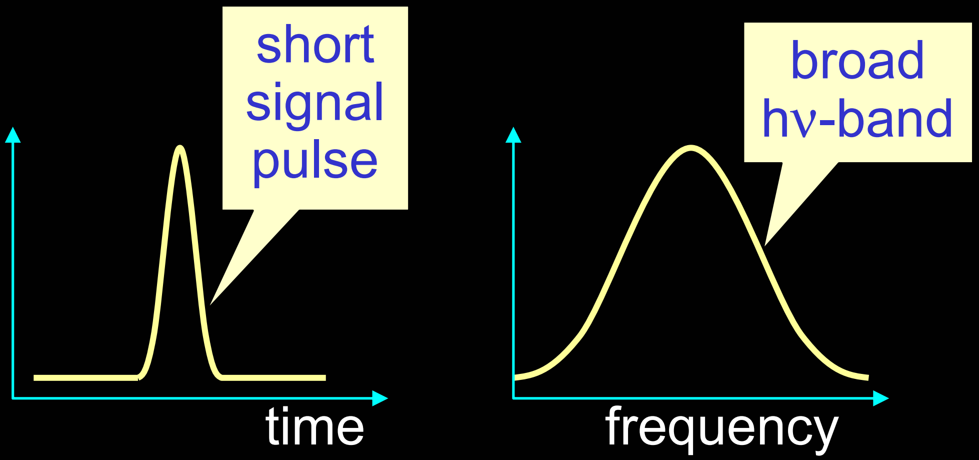
TRANSVERSE:

Radiation field quickly separates itself from the Coulomb field

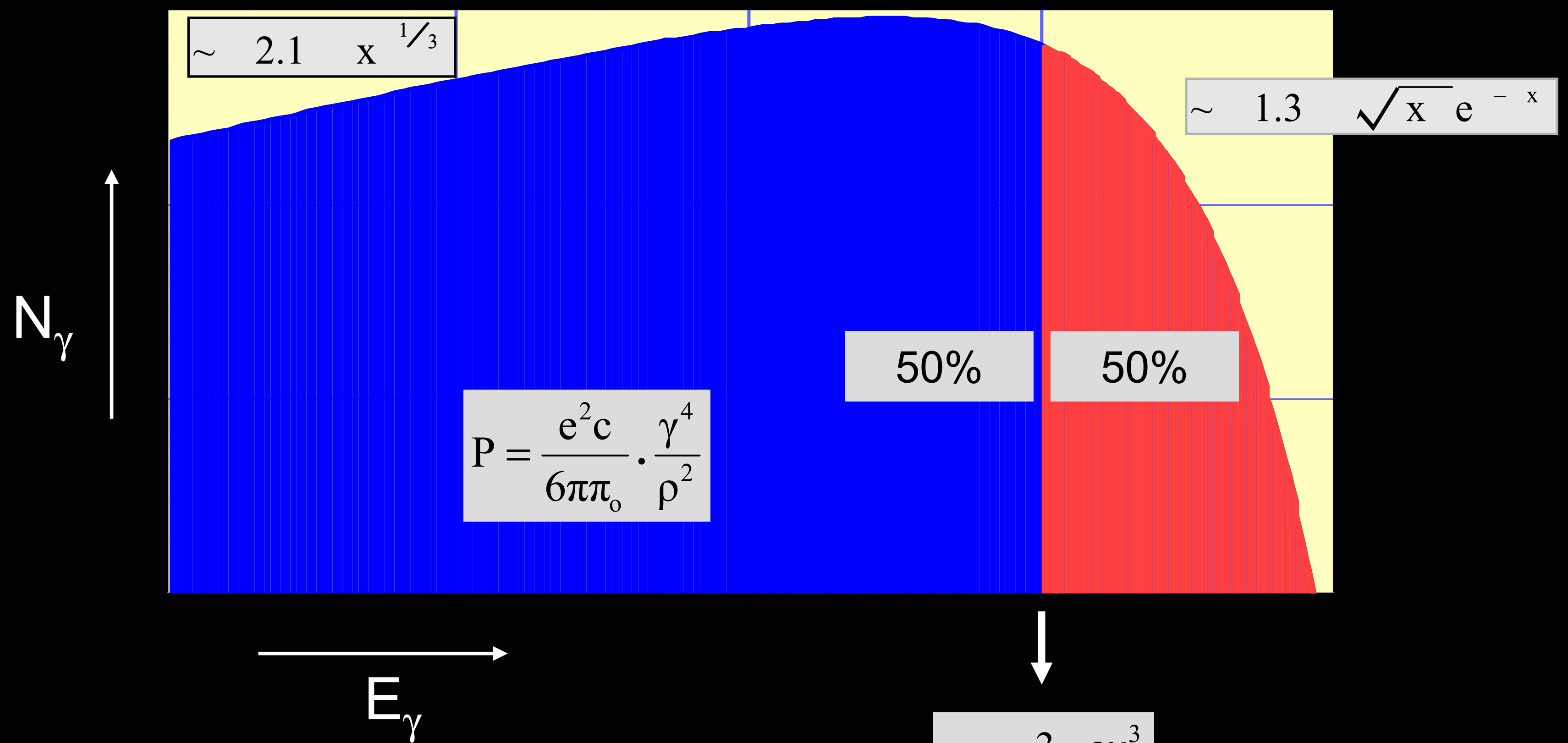
THERE ARE 3 TYPES OF DEVICES PROVIDING LIGHT FROM A STORAGE RING

1 BENDING MAGNETS: $B \sim N_e$





SYNCHROTRON RADIATION FROM A BENDING MAGNET

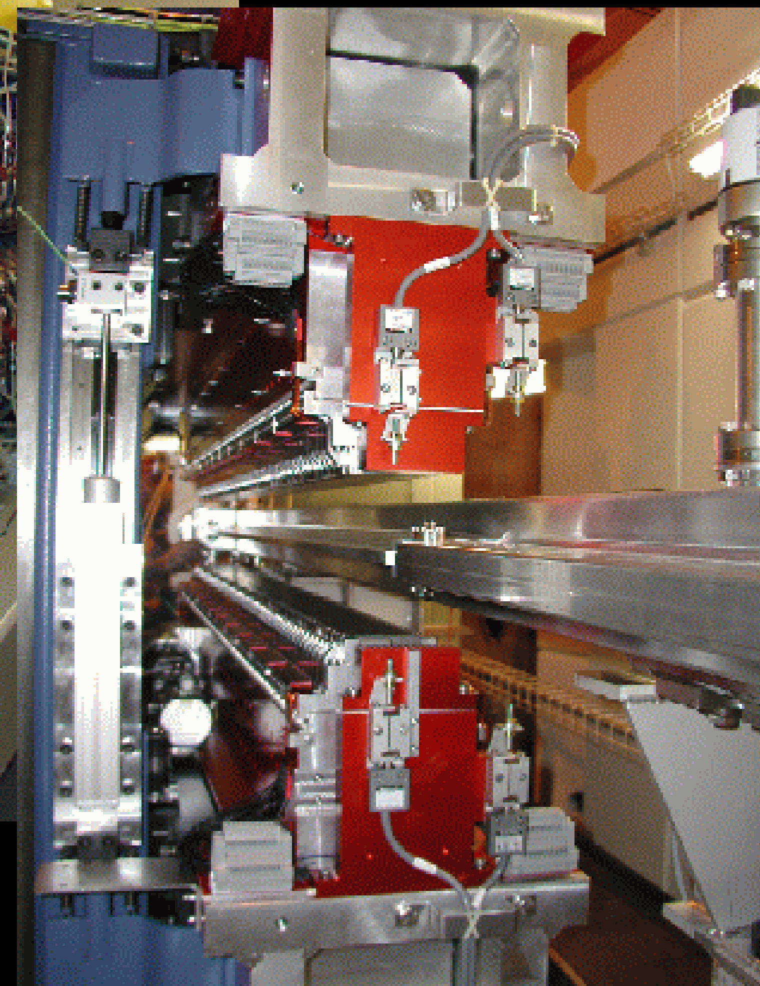


$$P = \frac{e^2 c}{6\pi\pi_o} \cdot \frac{\gamma^4}{\rho^2}$$

$$\omega_c = \frac{3}{2} \cdot \frac{c\gamma^3}{\rho}$$

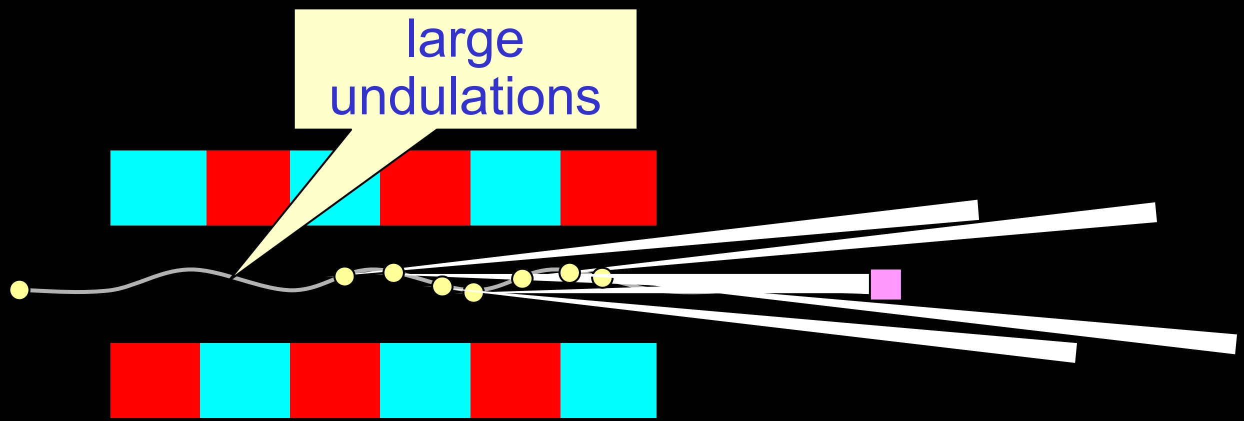
1949 - On the classical radiation of accelerated electrons / J.S. Schwinger

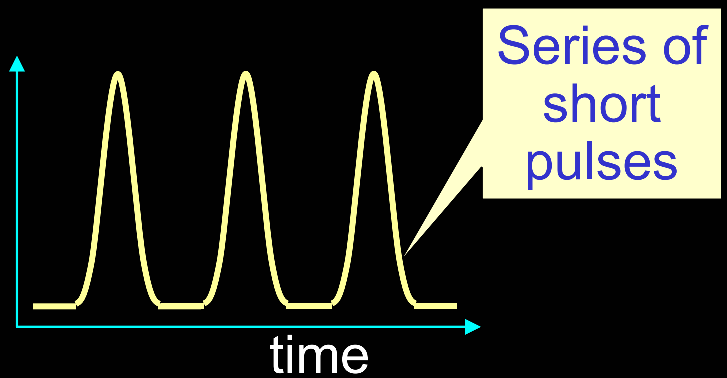
$$\lambda = \frac{\lambda_o}{\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

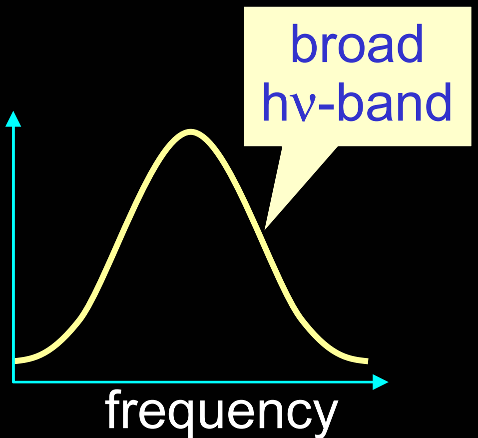


INSERTION DEVICE

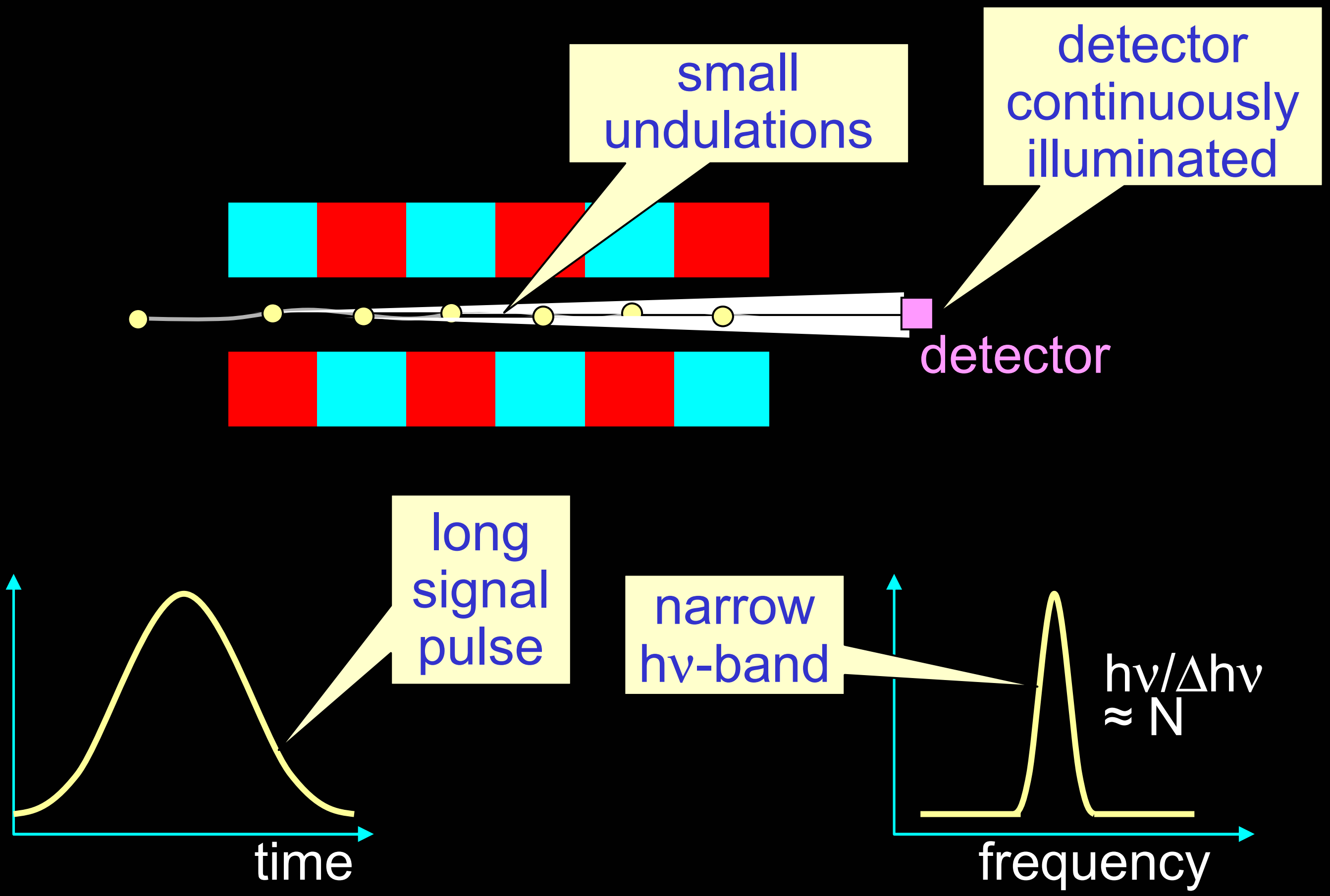
2 WIGGLERS: $B \sim N_e N_w$ x10



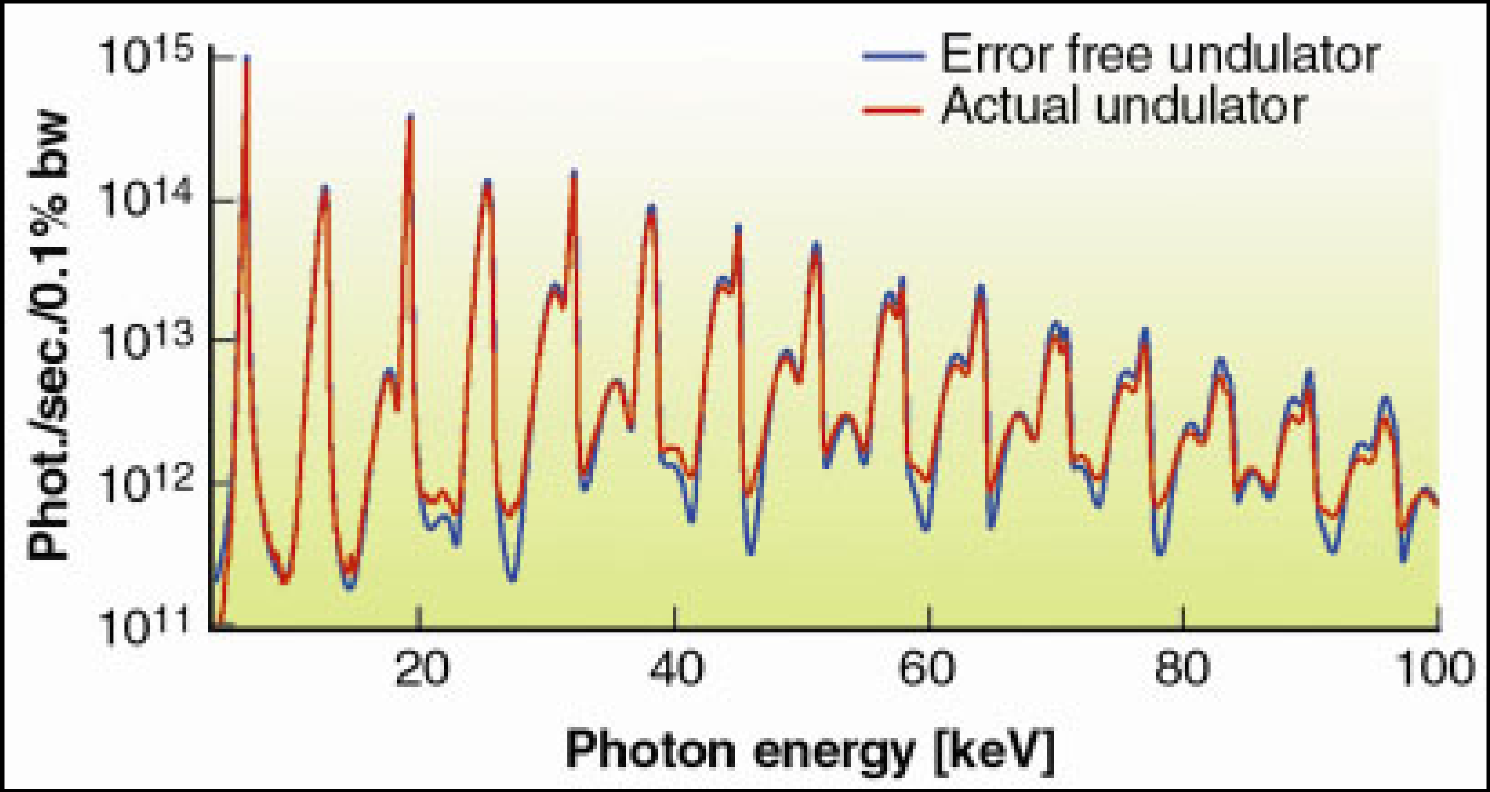




3 UNDULATORS: $B \sim N_e N^2_u$ x10³



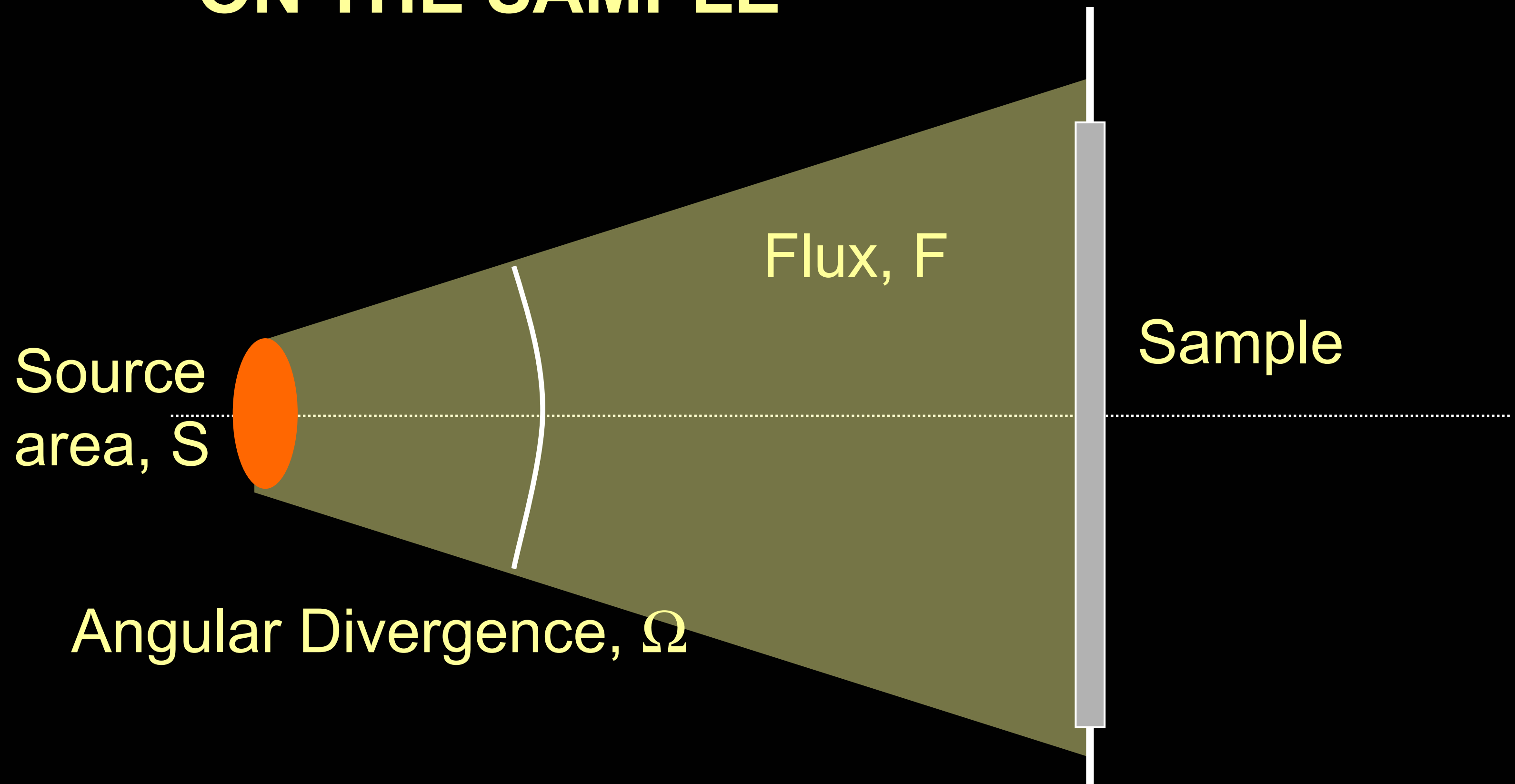
EXAMPLE: UNDULATOR RADIATION



P. Elleaume, ESRF

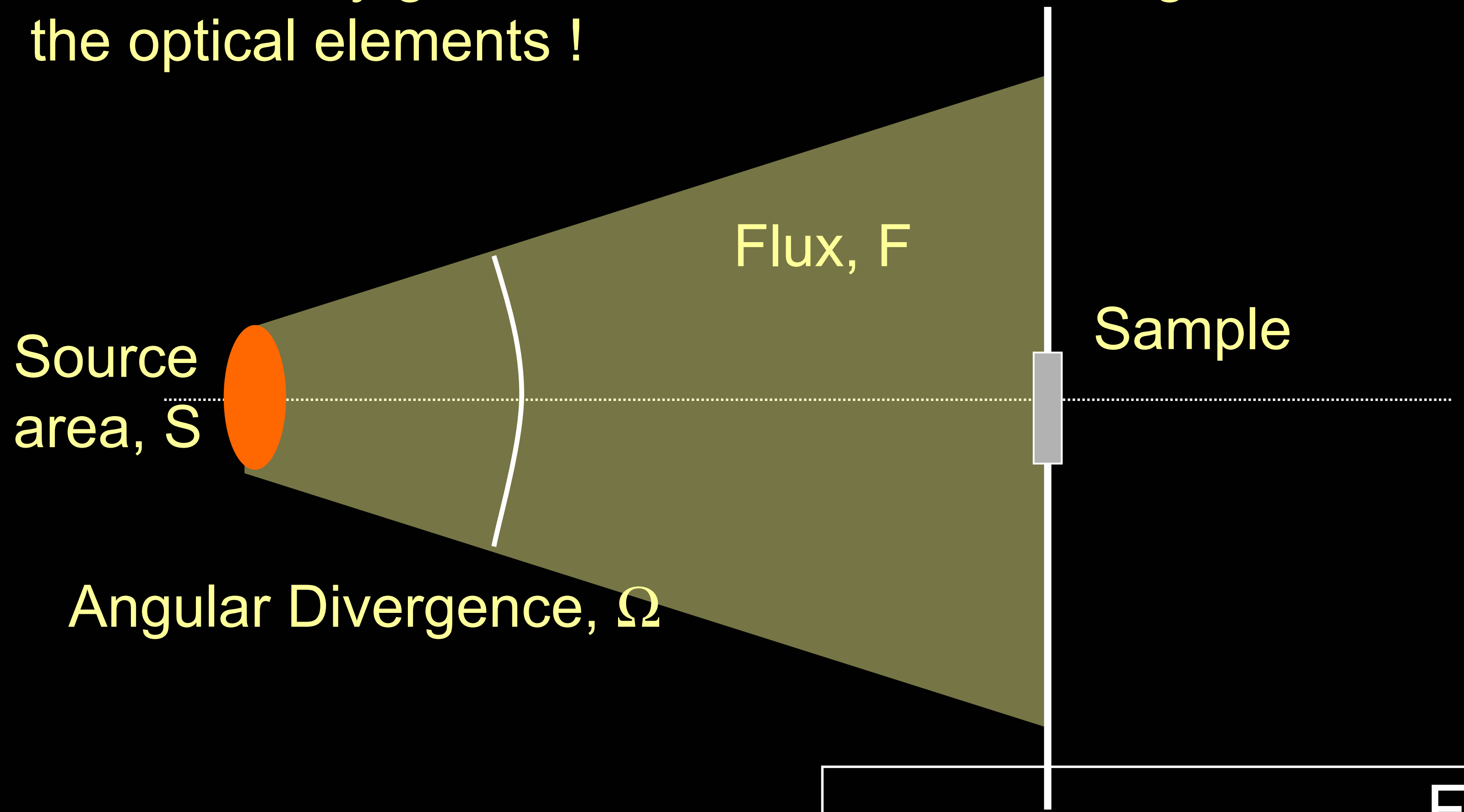
WHAT IS REQUIRED FROM A HIGH PERFORMANCE LIGHT SOURCE ?

A LARGE NUMBER OF PHOTONS ON THE SAMPLE



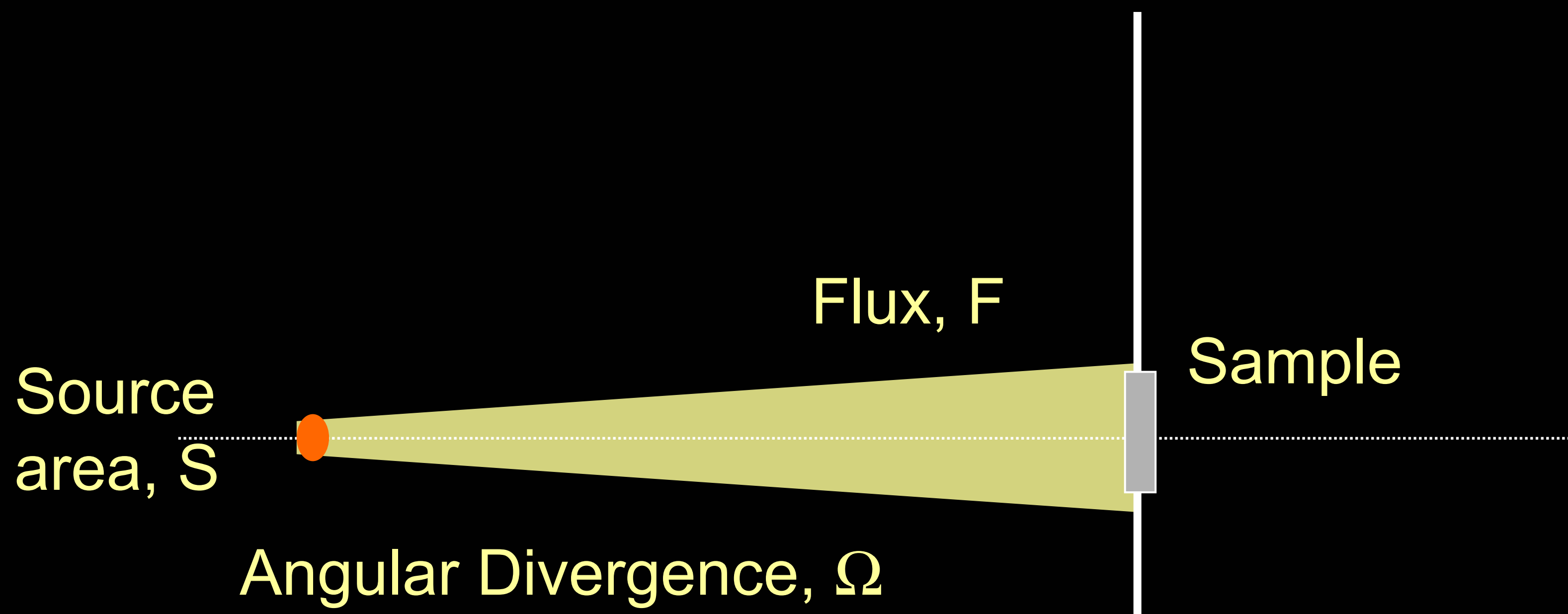
$$\textbf{Brilliance} = \textbf{const.} \frac{F}{S \cdot \Omega}$$

For smaller sample size most of the photons are wasted. They generate an unwanted heating of the optical elements !



$$\text{Brilliance} = \text{const.}\ \frac{F}{S \cdot \Omega}$$

To overcome this probleme: decrease source size and divergence, i.e. increase the brilliance



$$\text{Brilliance} = \text{const.}\,\frac{F}{S \cdot \Omega}$$

More precisely ......

FIGURE OF MERIT

$$S \rightarrow \Sigma_x \Sigma_y \qquad \Omega \rightarrow \Sigma_{x'} \Sigma_{y'}$$

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

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

$$\sigma_\gamma' = \sqrt{\frac{\lambda}{L}} \quad \sigma_\gamma = \frac{\sqrt{\lambda L}}{4\pi}$$ → photon beam sizes (undulator)

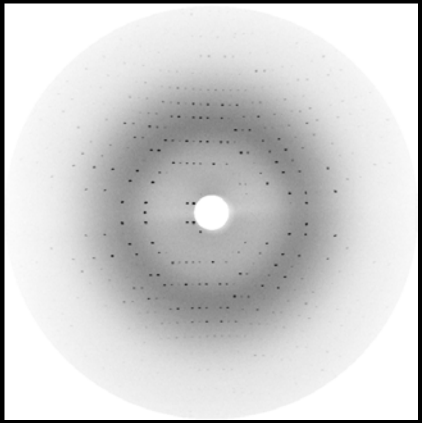
$$\Sigma_x \Sigma_{x'} \approx \sigma_x \sigma_x' \sim \varepsilon_x$$ → far away from diffraction limit

Why is high brilliance (large number of photons on the sample) needed ?

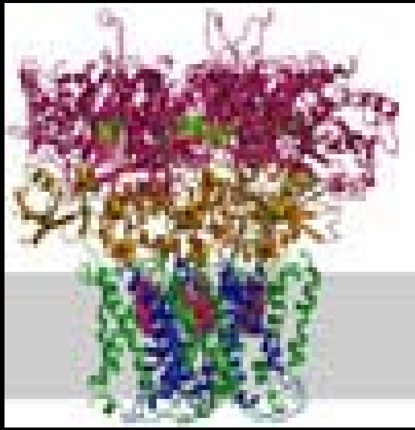
EXAMPLE:

Siccinat-Dehydrogenase

➔

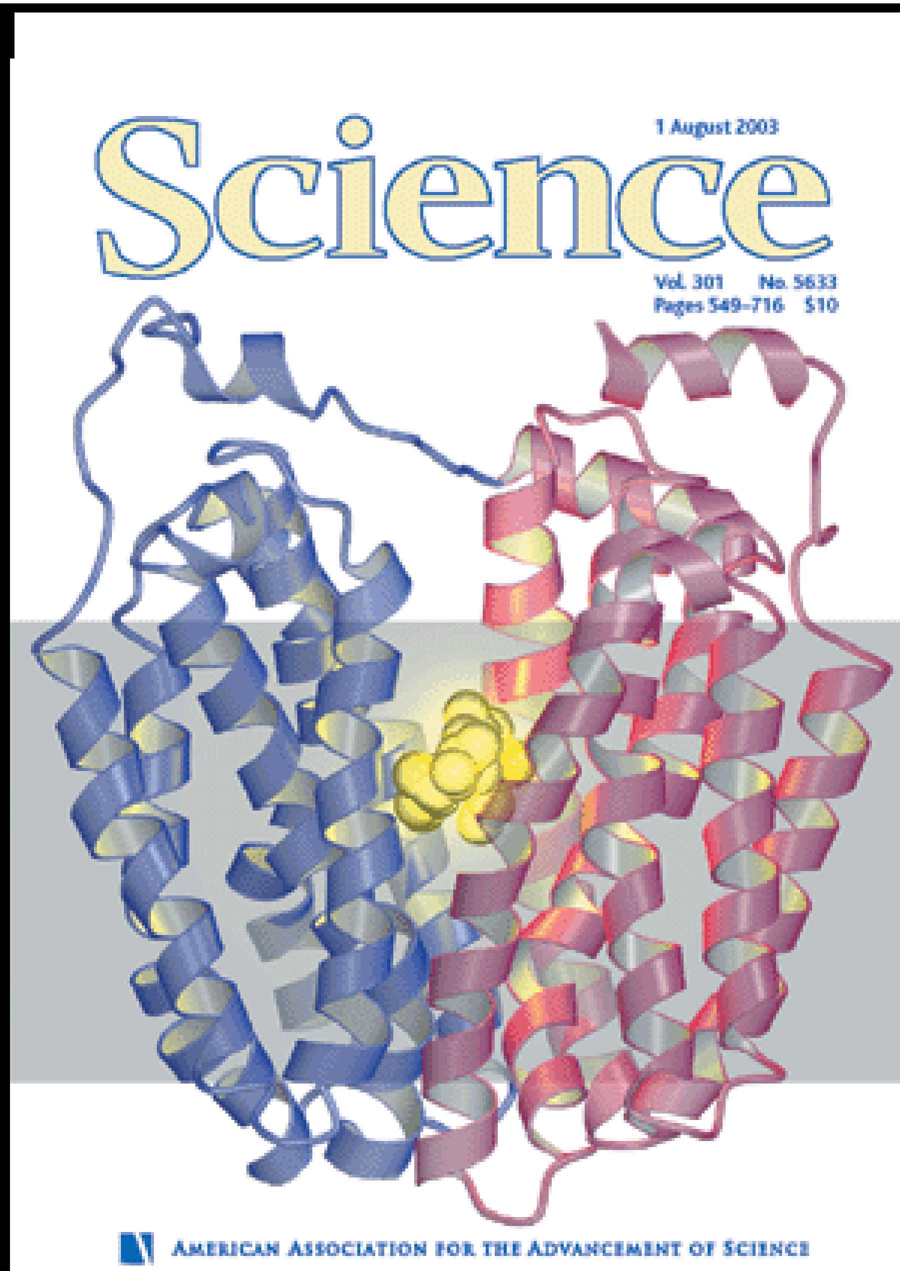


➔

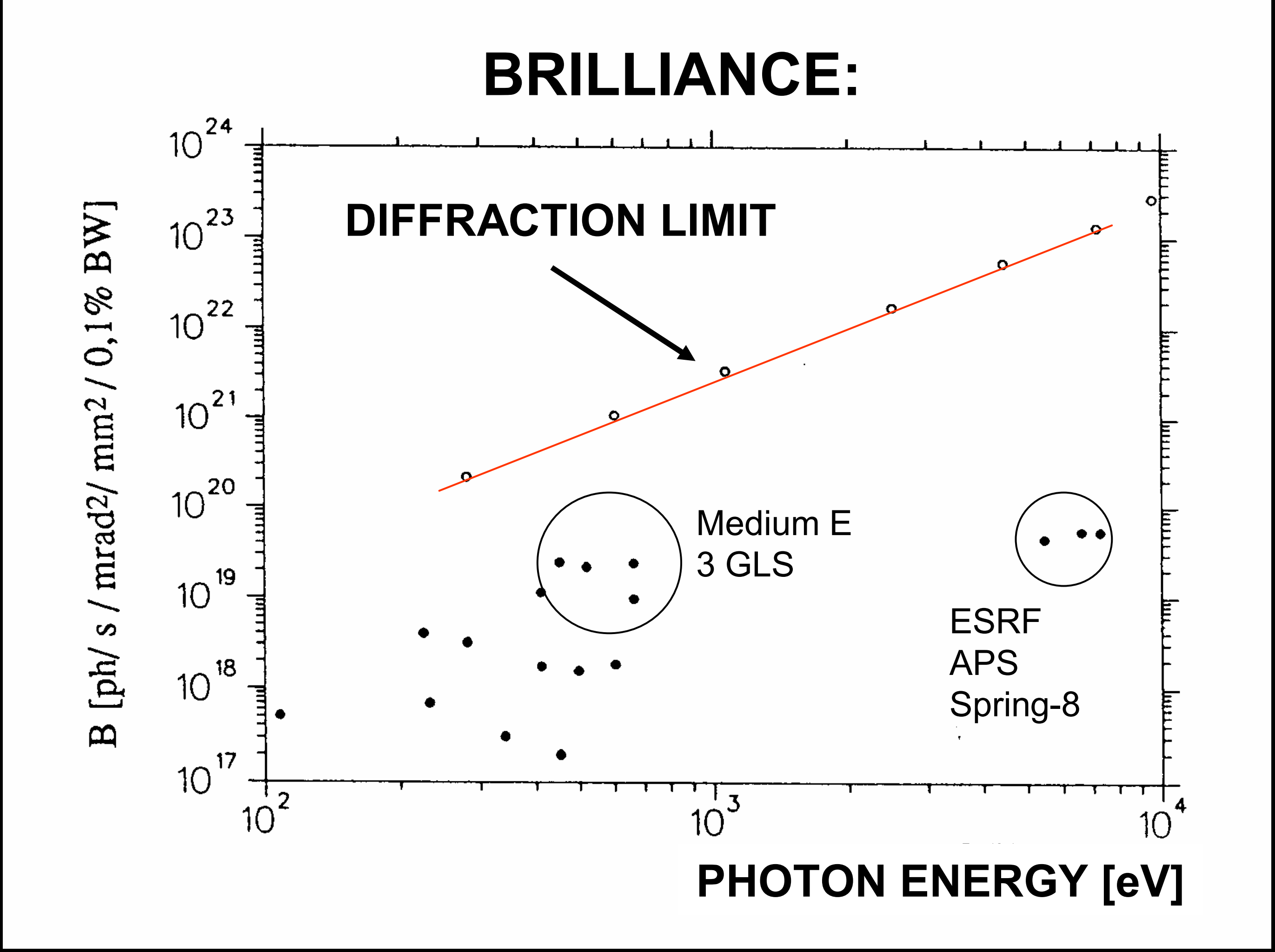


N. Ban, S. Iwata, U. Baumnan et al.

… to get some flux into sample acceptance phase space


1 August 2003
Science
Vol. 301 No. 5633
Pages 549–716 $10
American Association for the Advancement of Science

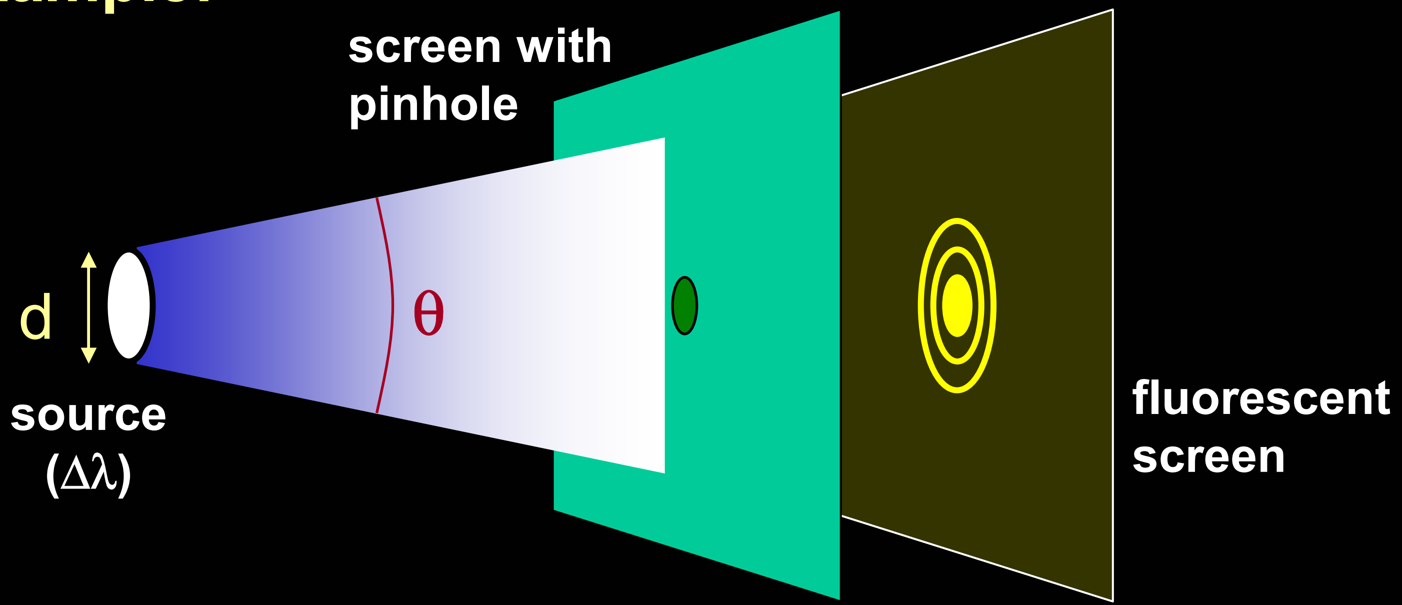
PERFORMANCE OF 3th GENERATION LIGHT SOURCES



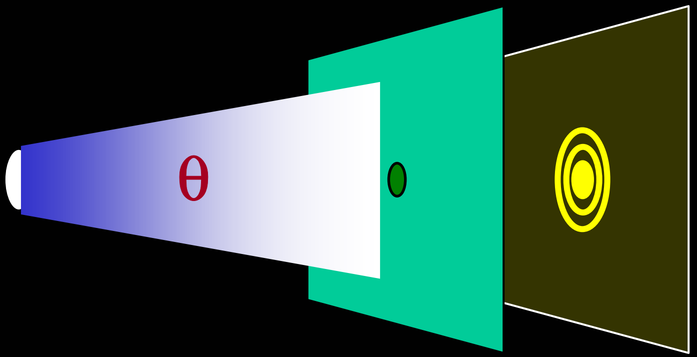
COHERENCE

→ the property that enables a wave to produce visible diffraction and interference effects”

Example:



When do we get diffraction patterns ?



- Pointlike monochromatic source

  → always

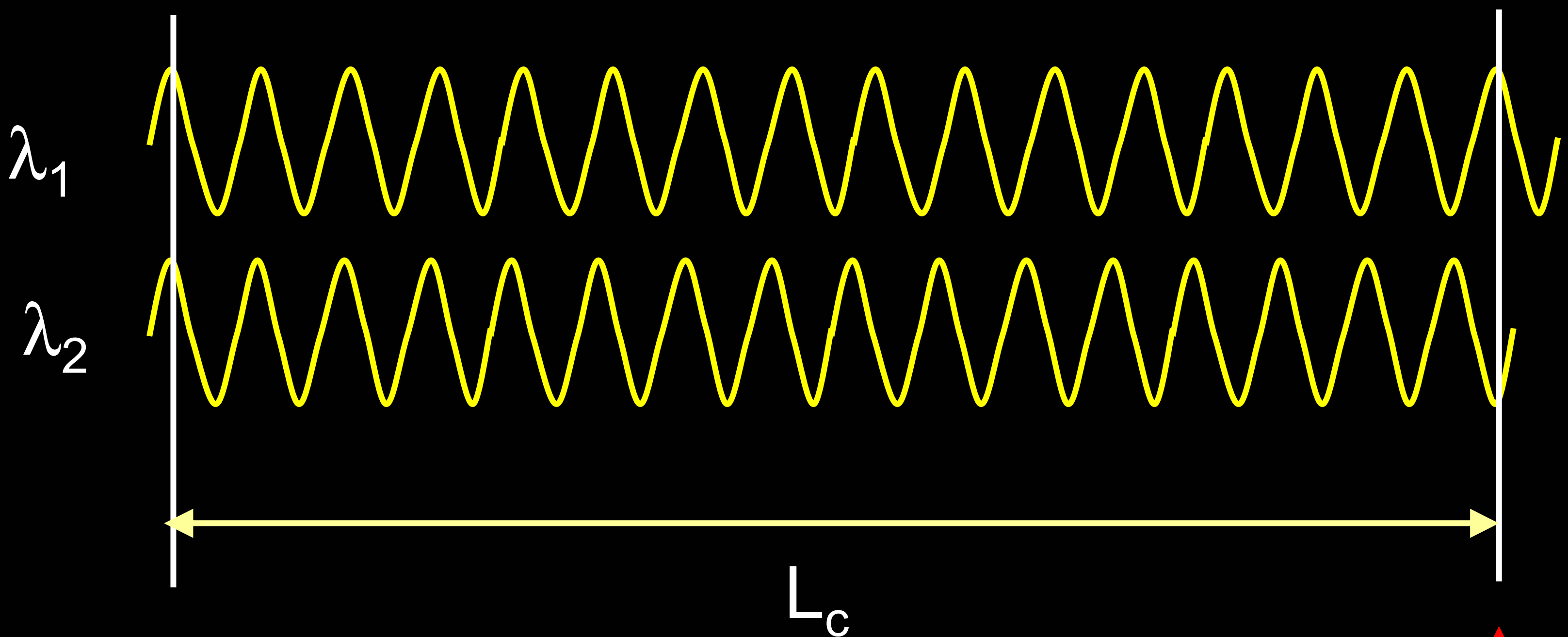
- Pointlike source with Δλ bandwith

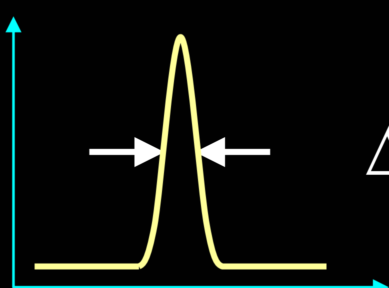
  → $\Delta\lambda/\lambda < 1$ or $L_c > \lambda$

$$L_c = \frac{\lambda}{\Delta\lambda/\lambda}$$

COHERENT LENGTH

Longitudinal coherence

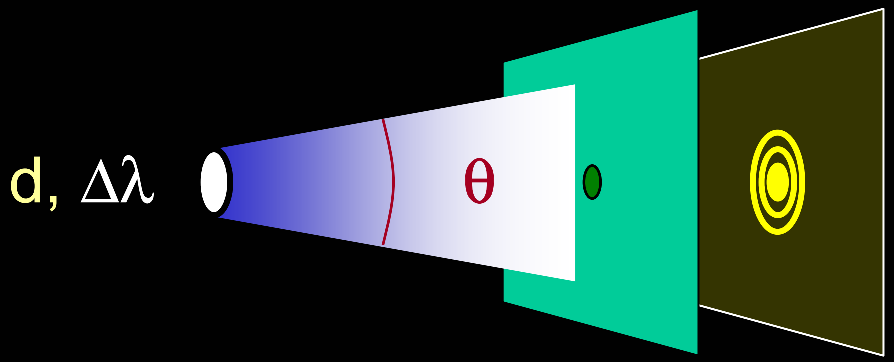




$$\Delta\lambda = \lambda_2 - \lambda_1 \qquad L_c = \frac{\lambda}{\Delta\lambda/\lambda}$$

180 °
out of phase

When do we get diffraction patterns ?



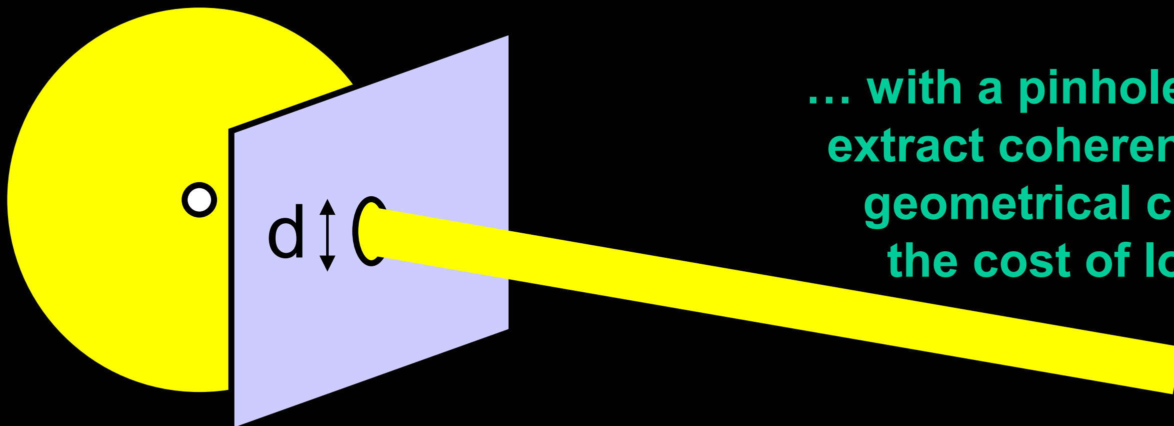
- Extended monochromatic source

  → d θ = 2λ (full lateral coherence)

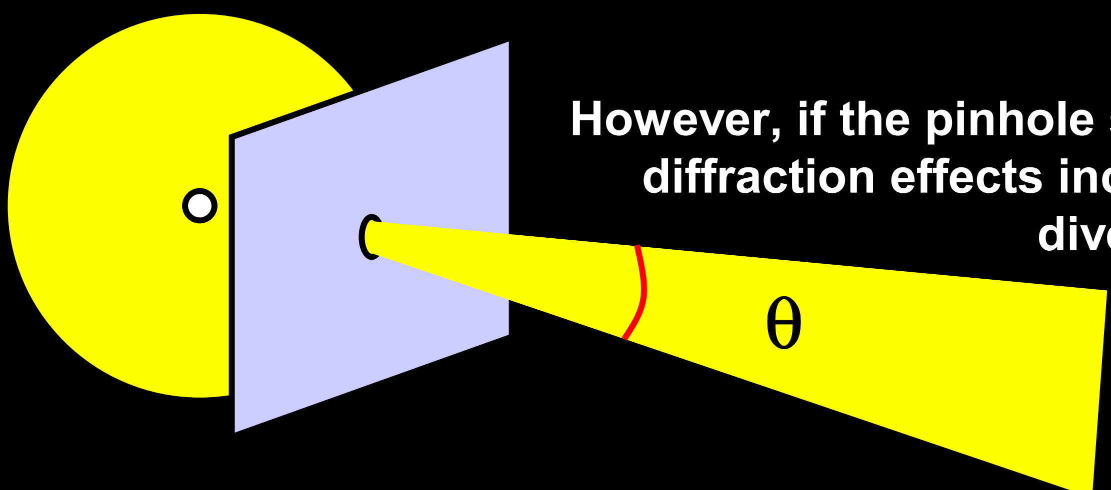
$$\boxed{\left(\frac{2\lambda}{d\theta}\right)^2}$$

~ COHERENCE

Increasing the coherence with a pinhole →



… with a pinhole (size S), 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:

$$d\theta > \lambda$$

NO SOURCE GEOMETRY BEATS THE DIFFRACTION LIMIT !

More precisely …… $(d\theta)^2 \rightarrow \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}$

What counts is the coherent flux:

$$F_c = \left(\frac{\lambda}{2}\right)^2 \frac{F}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} = \left(\frac{\lambda}{2}\right)^2 B$$

$$\varepsilon \leq \frac{\lambda}{4\pi}$$

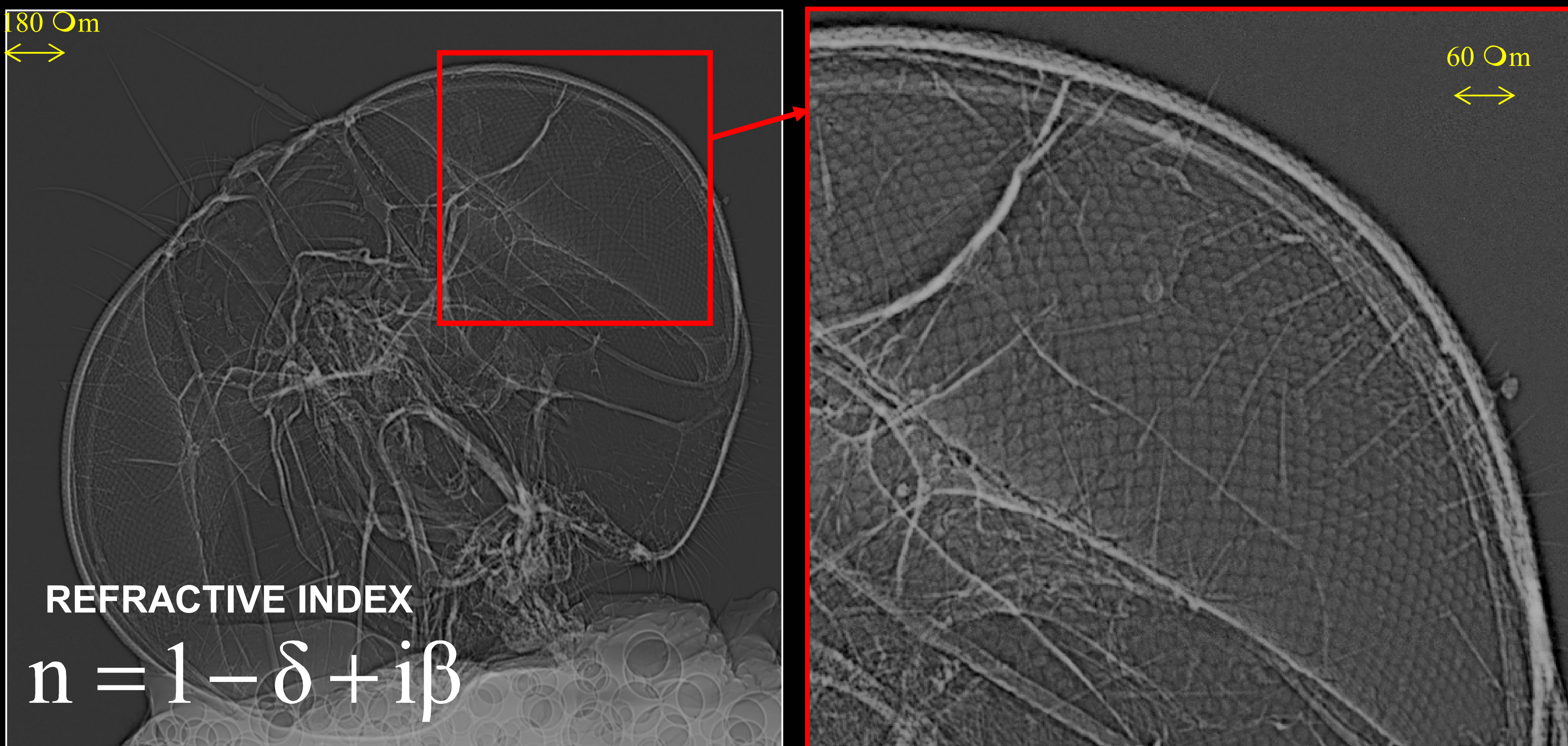
→ diffraction limited beam (full transverse coherence)

COHERENCE is needed for …..

EXAMPLES:

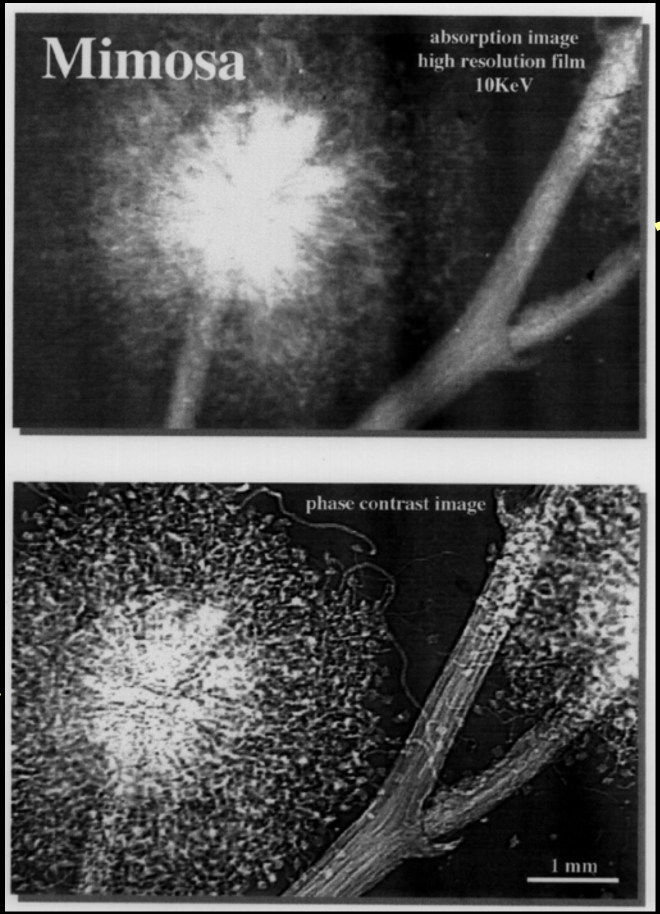
- PHASE CONTRAST IMAGING
- SPECKLE INTERFEROMETRY
- HOLOGRAPHY

EYE OF A FLY



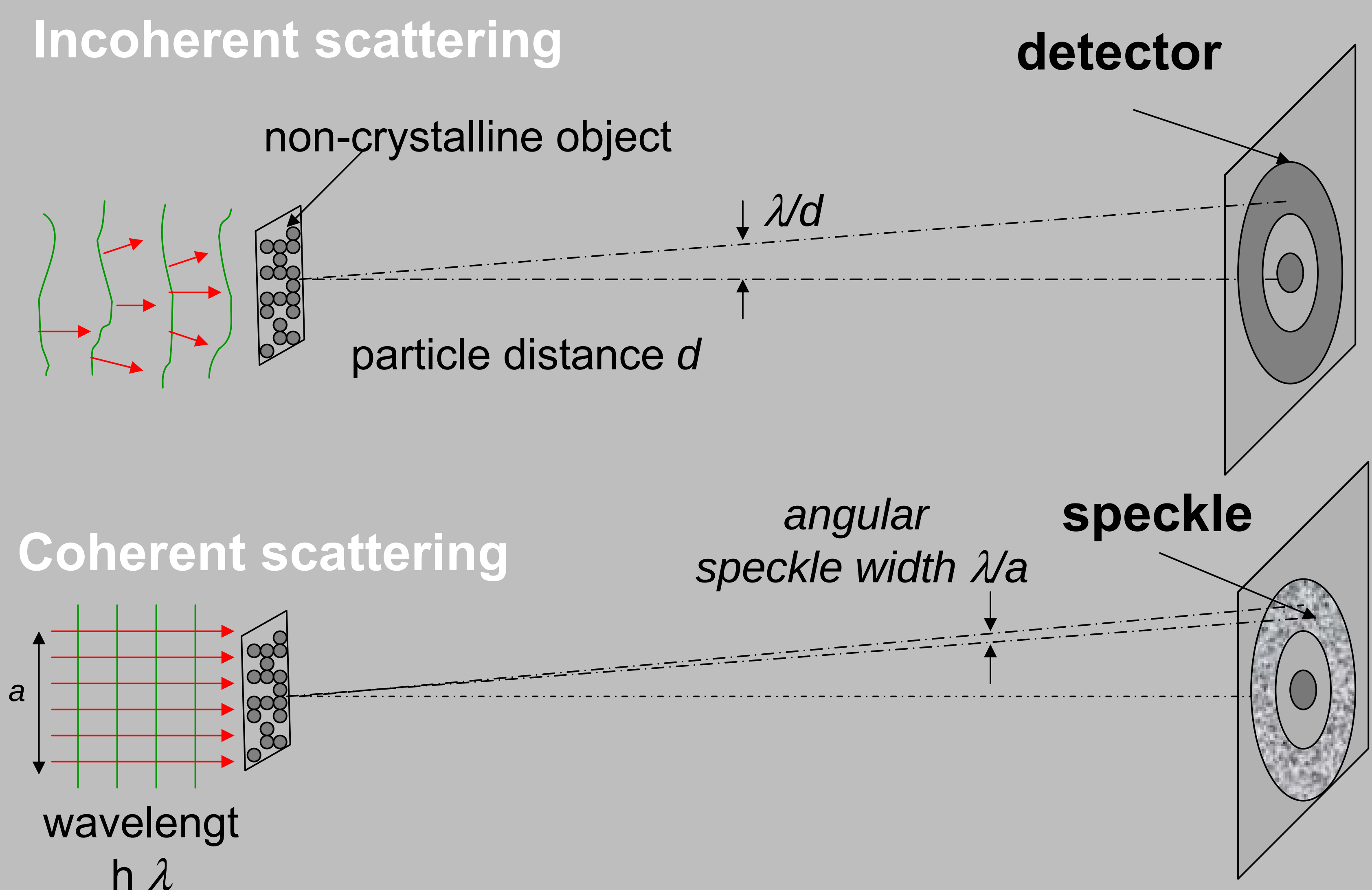
MATERIAL SCIENCE BEAMLINE: Marco Stampanoni, Rafael Abela

CONVENTIONAL RADIOLOGY

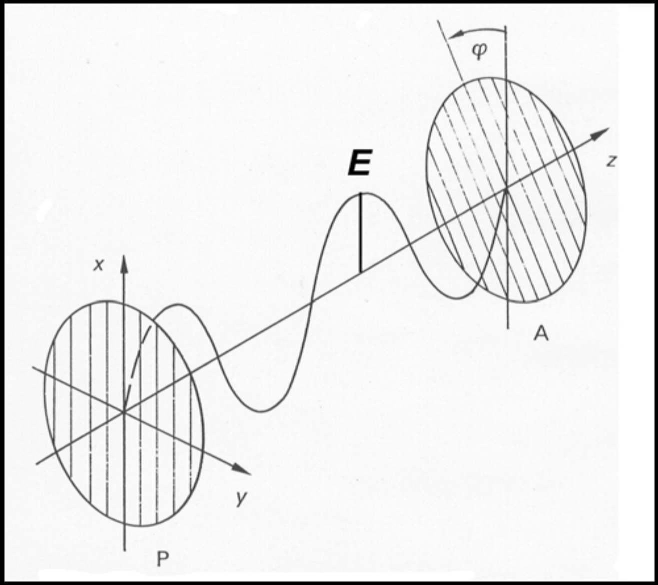


COHERENCE BASED RADIOLOGY

Using the partial coherence of an X-ray beam



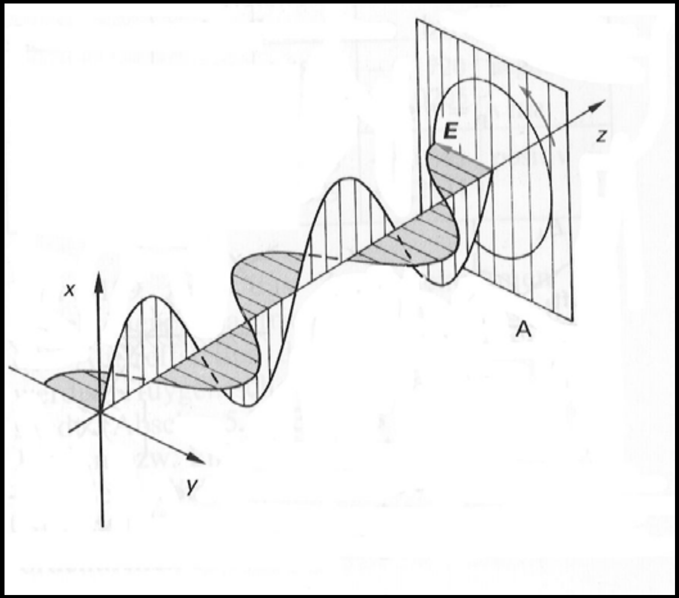
POLARISATION OF THE LIGHT



LINEAR

CIRCULAR

▼

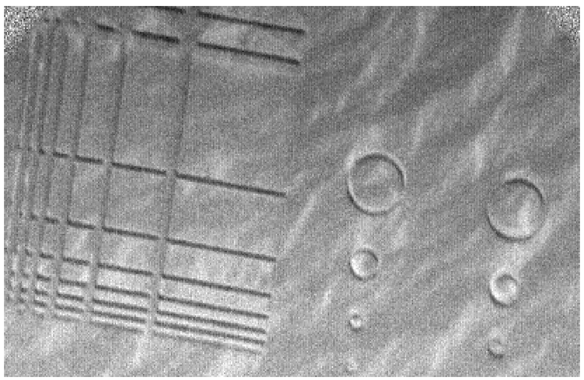


POLARISATION is needed for …..

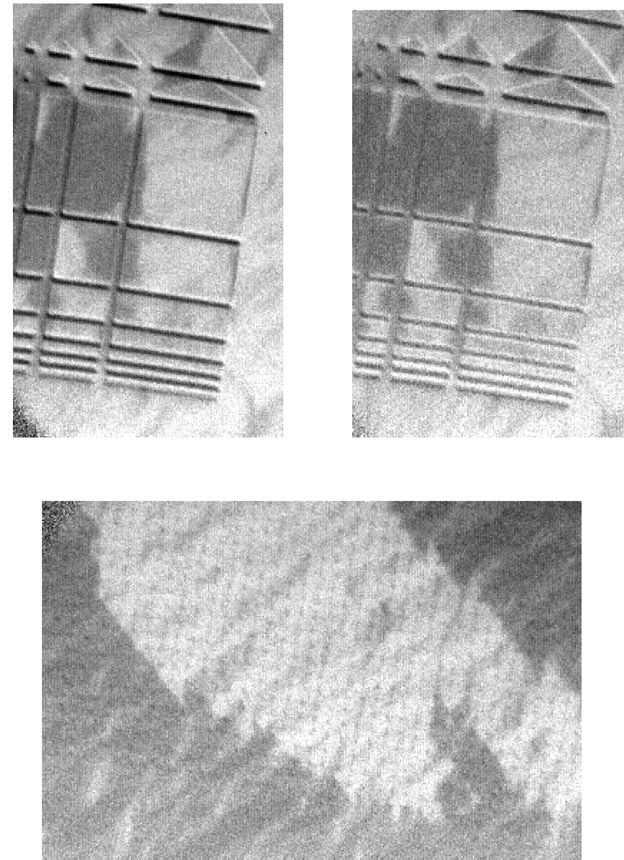
EXAMPLES:

- ORIENTATION OF MOLECULES
- MAGNETIC CIRCULAR DICHROISM

PEEM INVESTIGATION OF NANOPATTERNED MAGNETOSTRICTIVE SYSTEMS



Magnetic ripple in as-grown cobalt-Terfenol sandwich film on pre-patterned Si substrate.



XMCD images of magnetic domains following demagnetisation

TUNABILITY

(the right energy for the experiment)

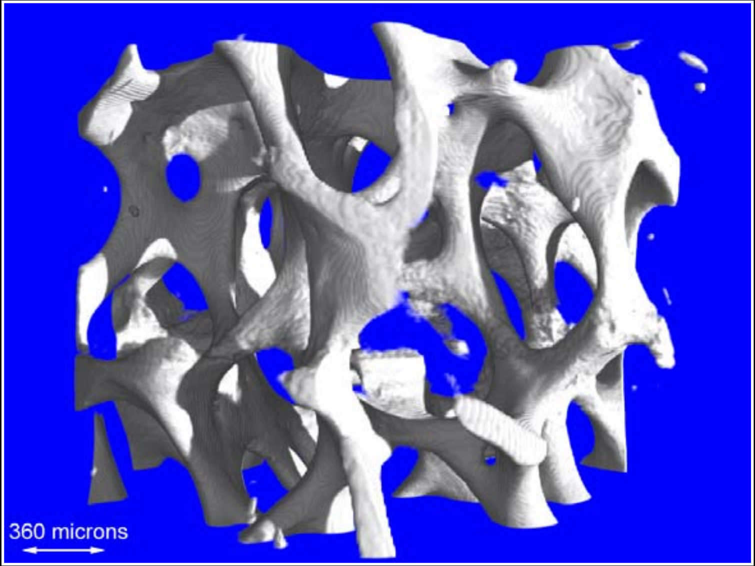
EXAMPLES:

- DIFFRACTION
- TOMOGRAPHY (absorption edge)
- SURFACE PHYSICS
- Ecc.

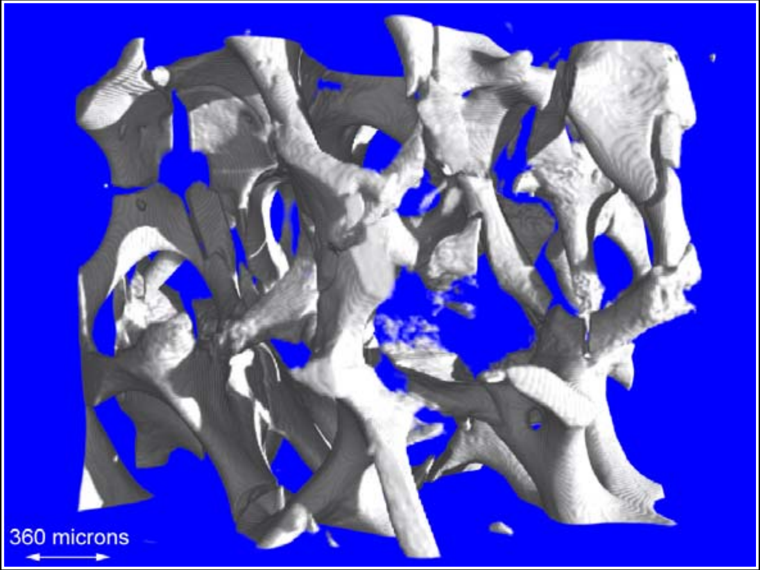
ABSORPTION TOMOGRAPHY

MATERIAL SCIENCE BEAMLINE

Bone sample damage



Sample before load.



Sample after 5% static compression and 2.5 % dynamic deformation, 1000 cycles

uni | eth | zürich
Institute for Biomedical Engineering

EMPA

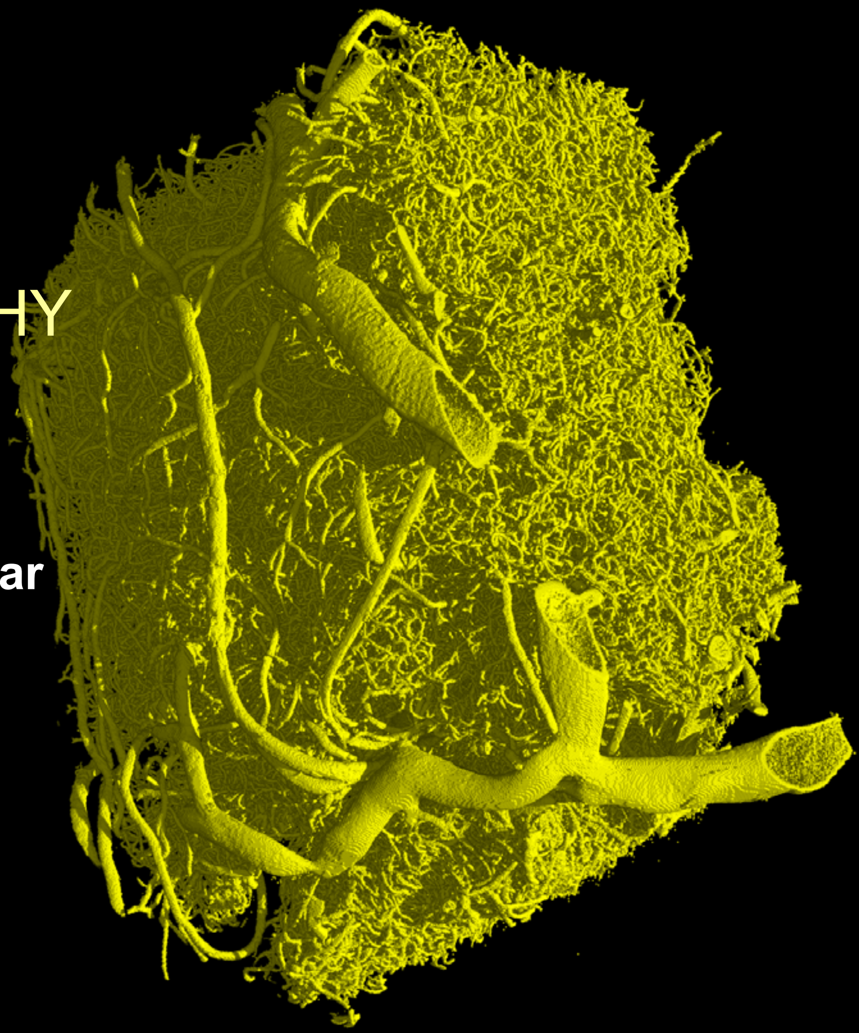
Philipp Thurner, EMPA and IBT, Marco Stampanoni, SLS

uni | eth | zürich

Institute for Biomedical Engineering

SLS Swiss Light Source

PHASE CONTRAST TOMOGRAPHY

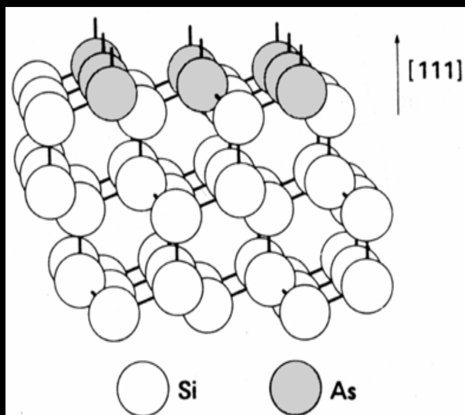


MATERIAL SCIENCE BEAMLINE

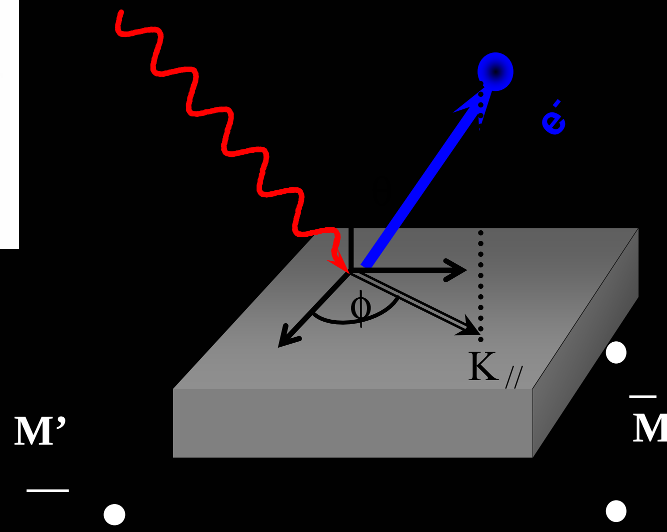
3-dimensional reconstruction of the vesicular distribution in mouse brains“

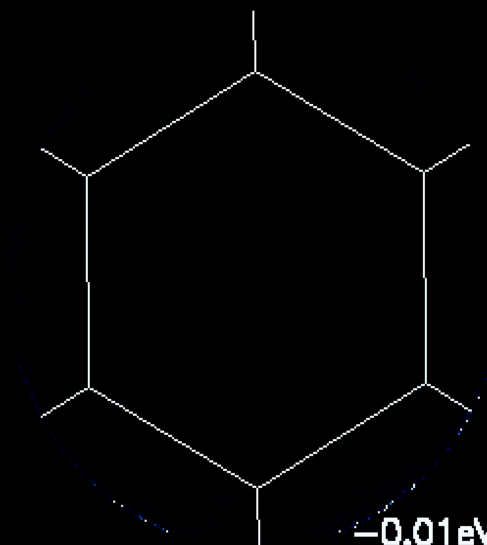
Size ~ 1 mm^3
Resolution ~ 1 μm

PHOTO ELECTRON EMISSION



ELECTRONIC STRUCTURES OF SURFACES





ANGLE DISTRIBUTION OF EMITTED ELECTRONS

C. Quitmann, F. Nolting

STABILITY

Intensity: change in background conditions and thermal load on beamline optics and machine components (→ position stability!)

Position: dilution of the emittance (reduced brilliance), intensity fluctuations

Energy: shift of the radiation harmonics from an undulator (intensity fluctuations); broadning of the lines

WHAT IS REQUIRED FROM A HIGH PERFORMANCE LIGHT SOURCE ?

SUMMARY

- High Brilliance
- Coherence
- Polarisation
- Tunability
- Stability

LIGHT SOURCE REQUIREMENTS → ACCELERATOR FEATURES

- **High Brilliance** → A. Streun
- Coherence
- Polarisation
- Tunability
- Stability

HIGH BRILLIANCE *requires* →

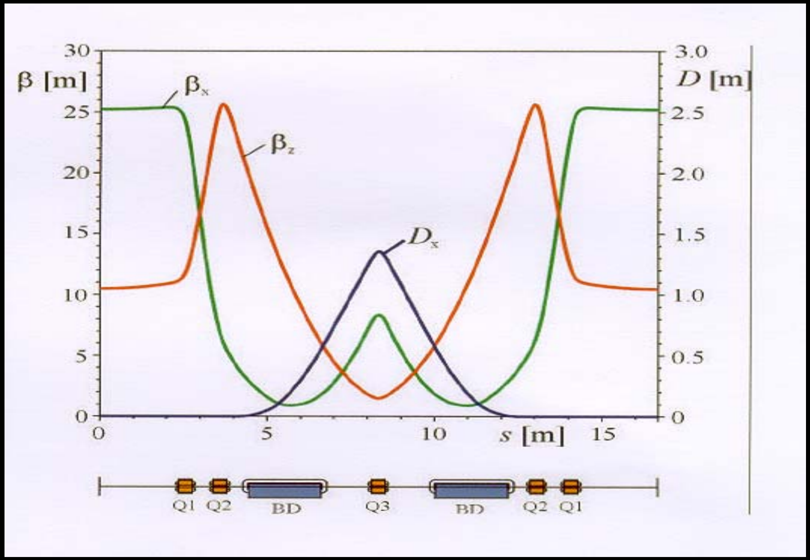
- HIGH CURRENT

- LOW EMITTANCE $$\varepsilon_x = \frac{C_q \gamma^2}{J_x} \cdot \left\langle \frac{H}{\rho} \right\rangle$$

$$H = D_x^2 \gamma_x + 2 D_x D'_x \alpha_x + D'^2_x \beta_x$$

- UNDULATORS INSTALLED IN LATTICE STRAIGHTS

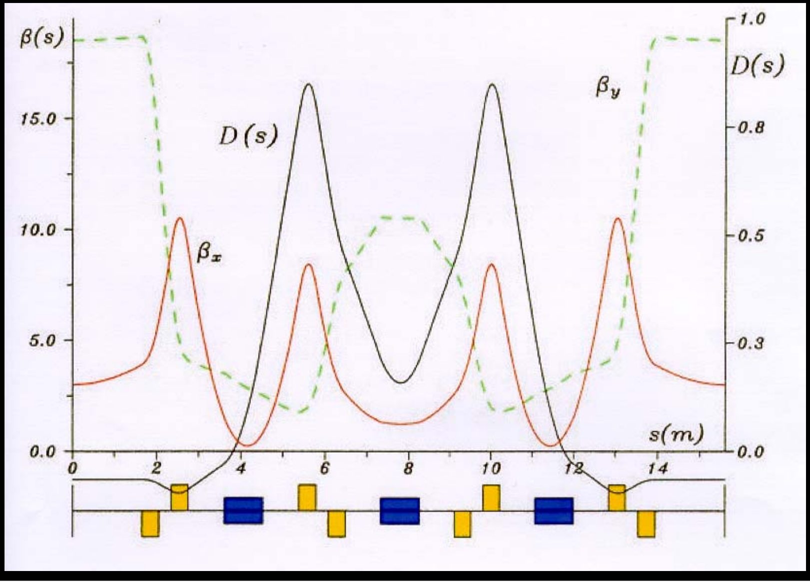
→ ACHROMAT STRUCTURES, TYPICALLY:



DBA /
Double Bend Achromat

$$K = \frac{1}{4\sqrt{15}} \approx 6{,}5 \cdot 10^{-2}$$

$$\varepsilon_x = \frac{c_q \gamma^2}{J_x} \cdot K \cdot \Phi_B^3$$

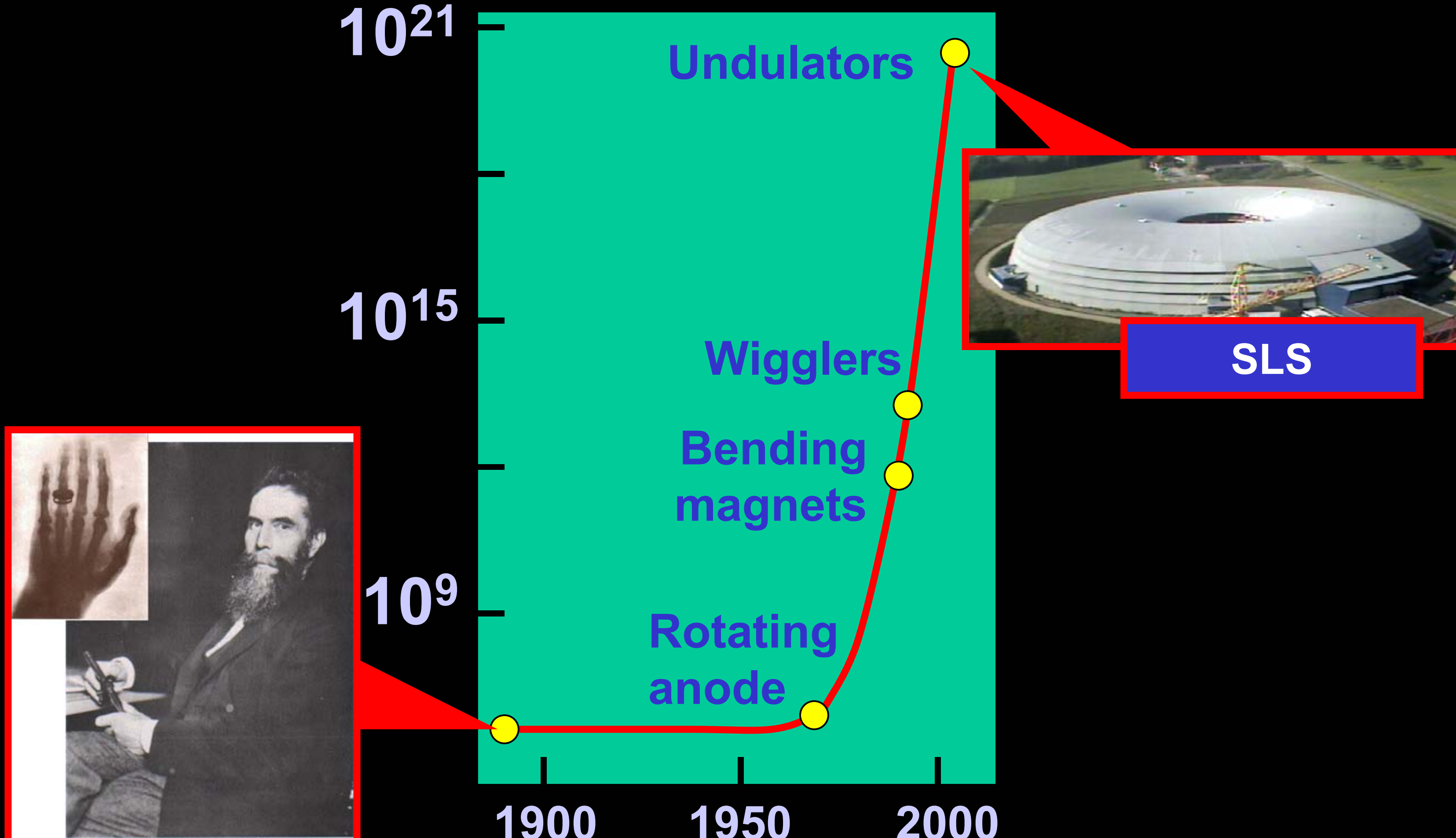


TBA /
Triple Bend Achromat

$$K = \frac{7}{36\sqrt{15}} \approx 5 \cdot 10^{-2}$$

Steep rise in brightness/brilliance

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

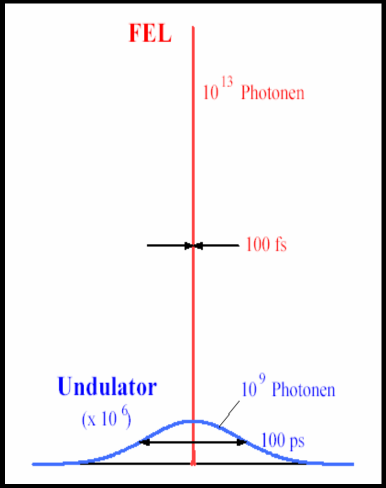


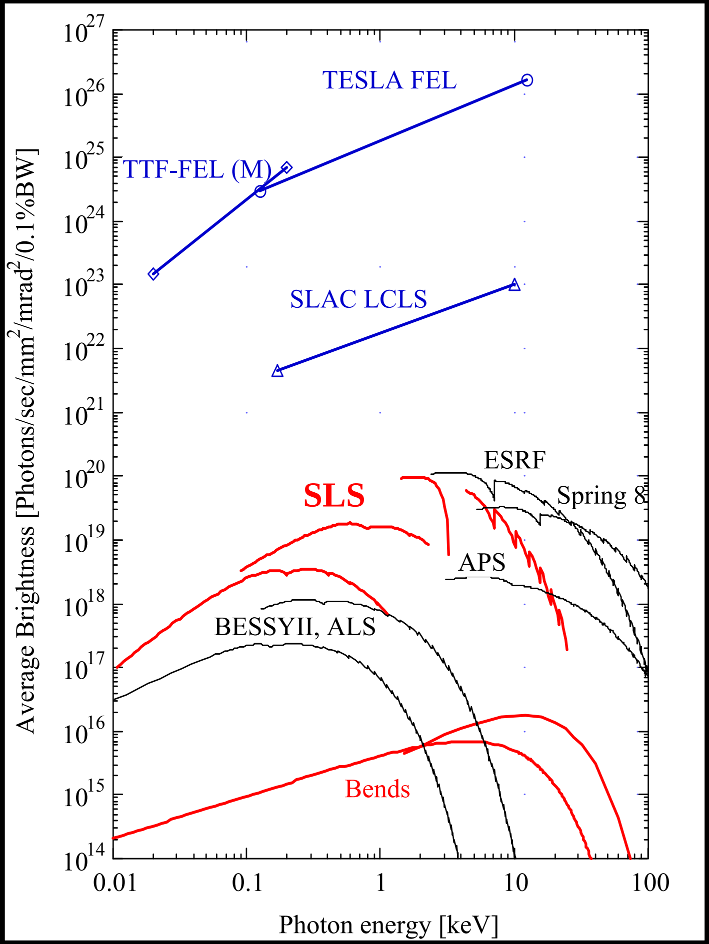
------------------------------INSERT------------------------------

FUTURE LIGHT SOURCES

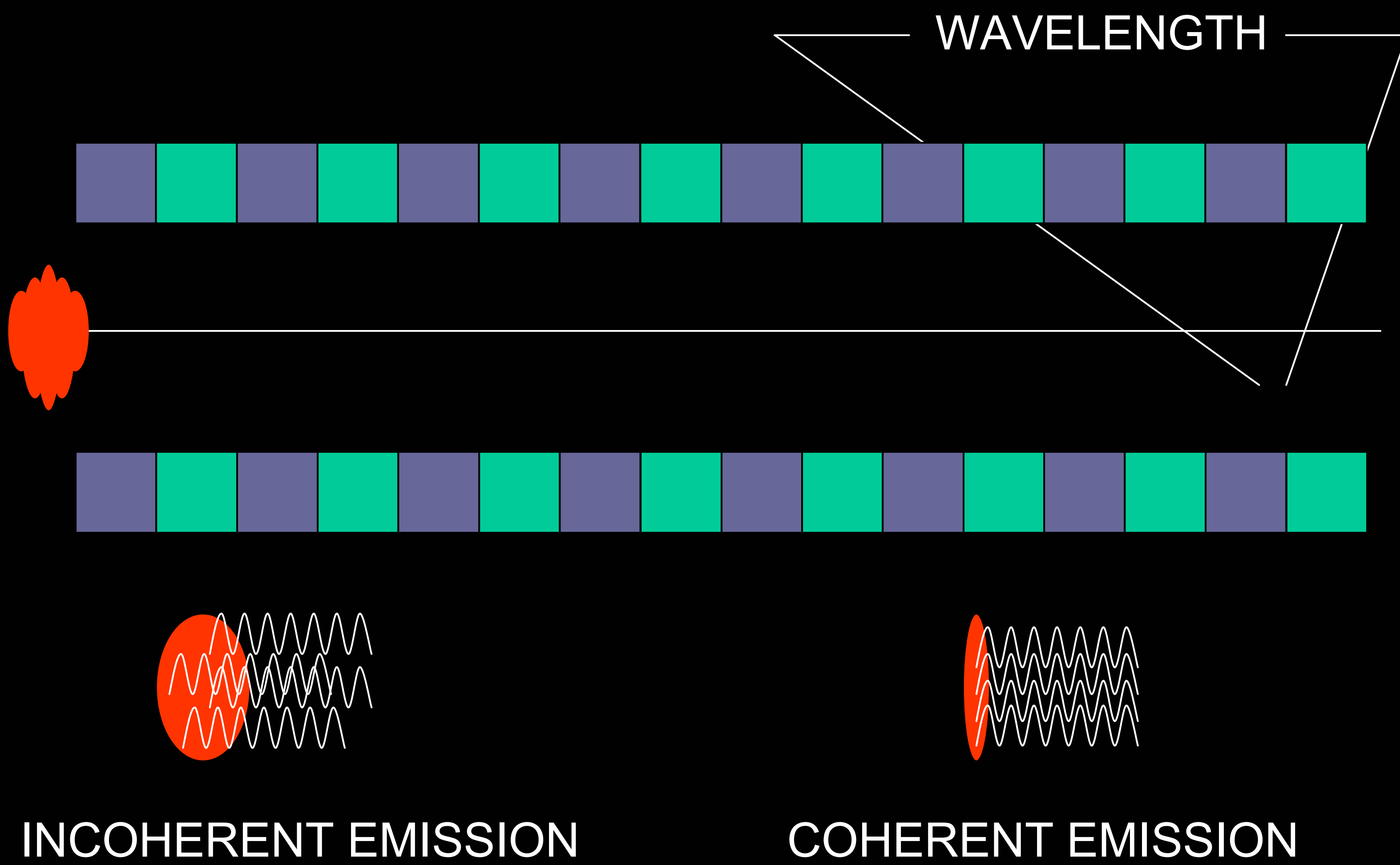
SASE FREE ELECTRON LASERS

- UNBEATABLE PEAK AND AVERAGE BRILLIANCE (10^{30} - 10^{33})
- SHORT PULSES (1 ps – 50 fs)
- SMALL BANDWIDTH

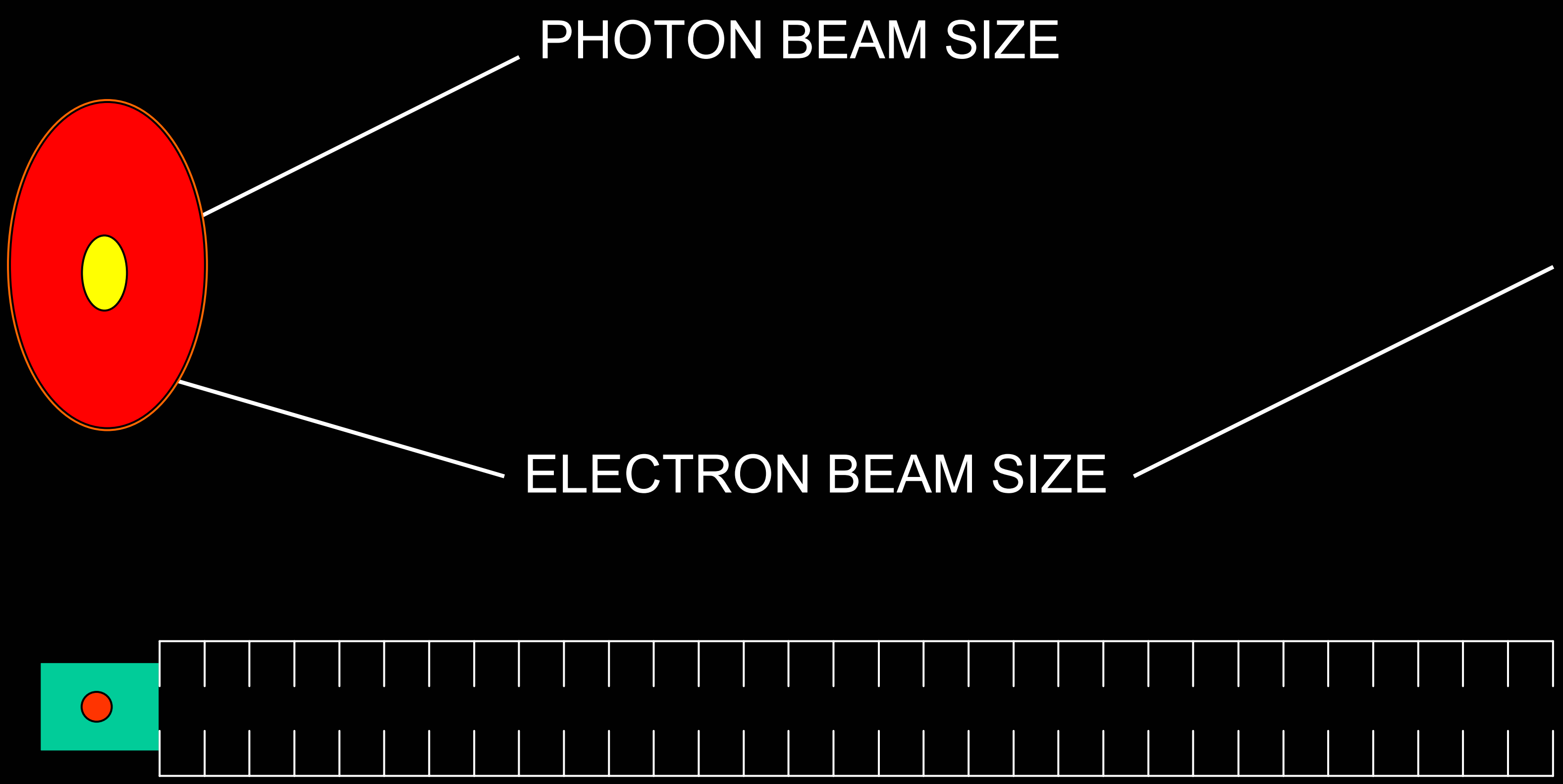




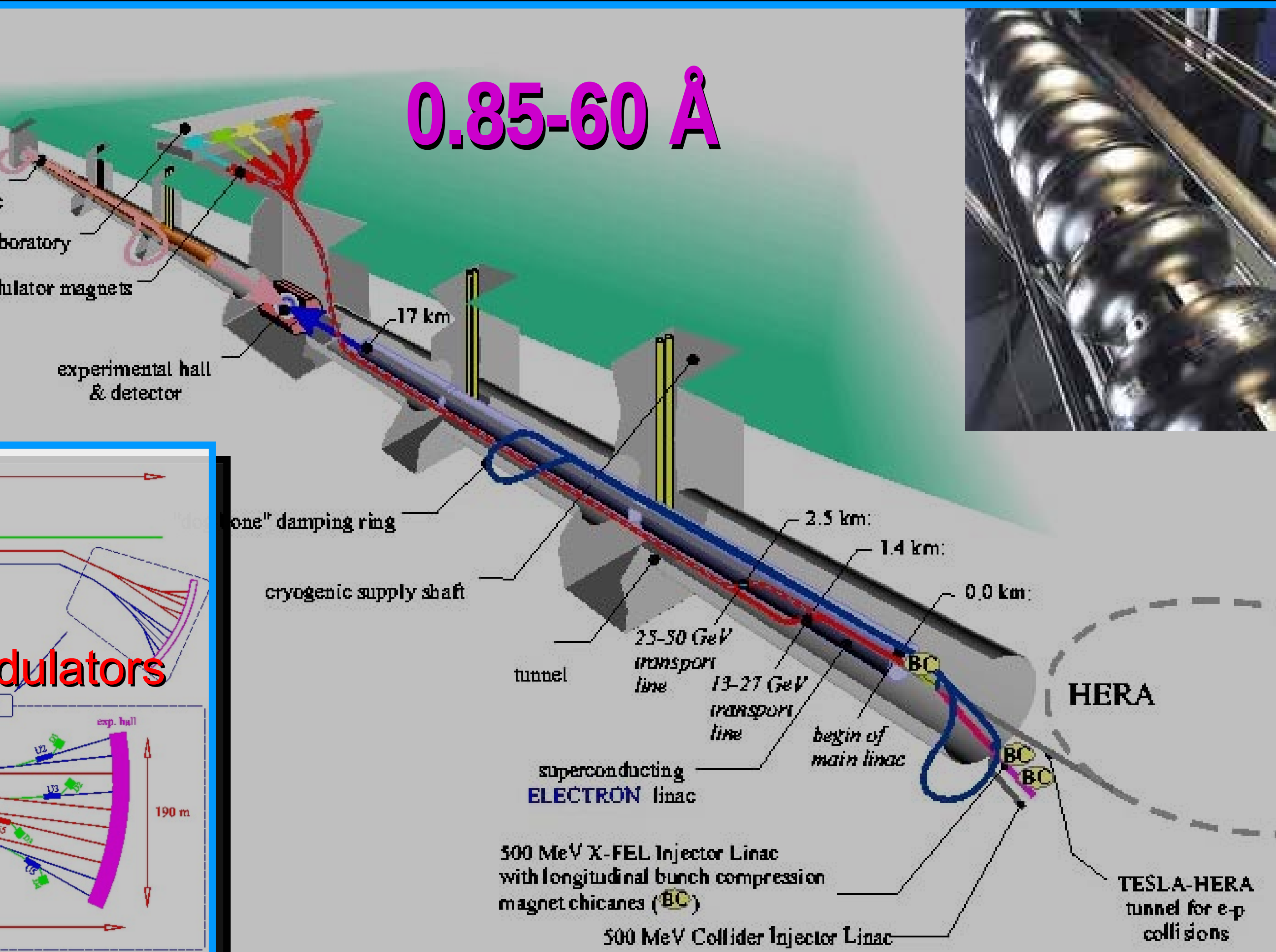
SASE PRINCIPLE:

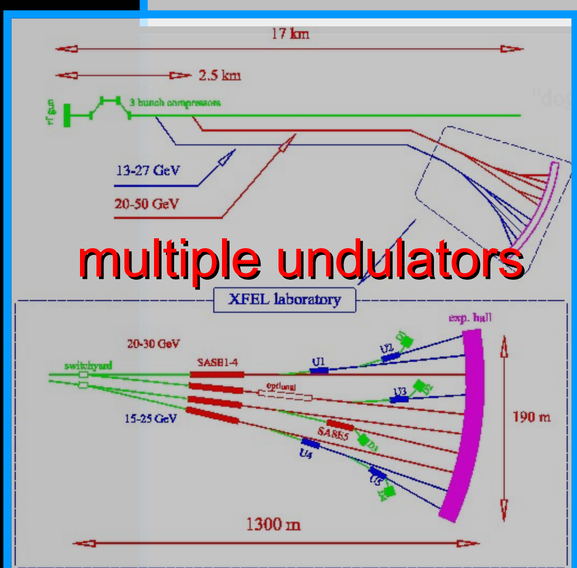


REQUIRES AN EXTREMELY SMALL ELECTRON BEAM !



TESLA X - FEL at DESY

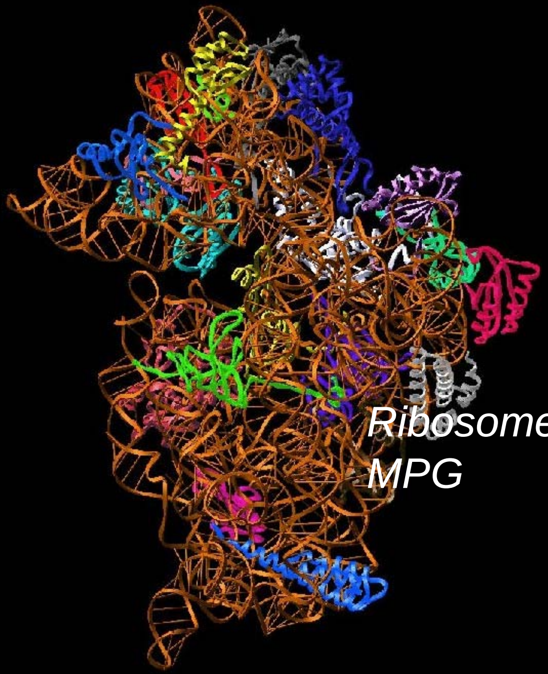




USERS DREAM WILL THEN BECOME REALITY →

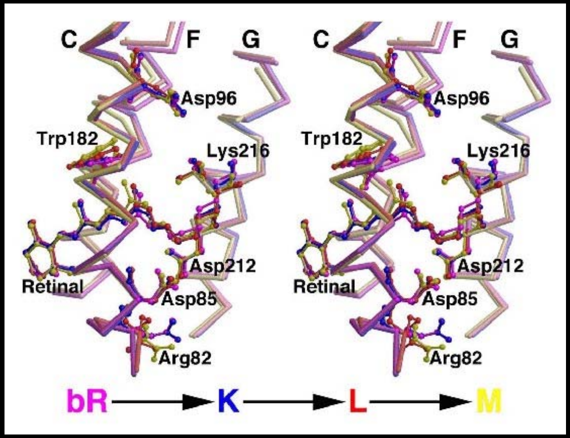
Single shot imaging of
single biomolecular complexes

NEEDS MANY PHOTONS ON THE SAMPLE !



Ribosome
MPG

LYSOZYME MOLEKUEL



Light induced structural changes during photocycle

and time resolved studies of structural processes during chemical and bilogical reactions

NEEDS VERY SHORT PULSES !

-----------------------------END INSERT-----------------------------

LIGHT SOURCE REQUIREMENTS → ACCELERATOR FEATURES

- High Brilliance → A. Streun
- **Coherence**
- Polarisation
- Tunability
- Stability

LATERAL COHERENCE

- is increasing with brilliance

LONGITUDINAL COHERENCE

- needs light emitted in a small bandwidth

UNDULATOR: $$\frac{\Delta\lambda}{\lambda} = \frac{1}{2N}$$ N … number of magnet poles

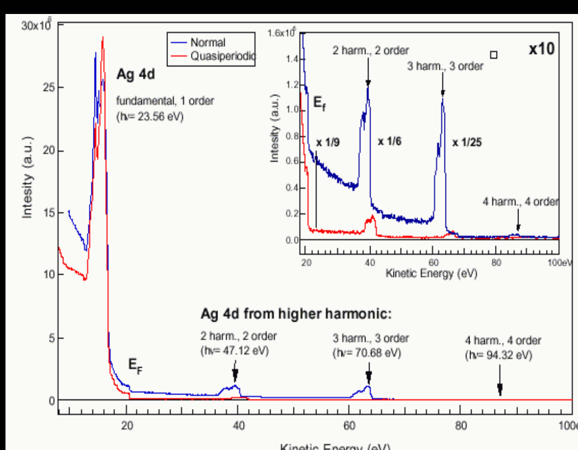
→ use long undulators to increase the longitudinal coherence (suggested for some RECIRCULATOR projects)

LIGHT SOURCE REQUIREMENTS → ACCELERATOR FEATURES

- High Brilliance → A. Streun
- Coherence → related to brilliance
- **Polarisation** → ID talk
- Tunability
- Stability

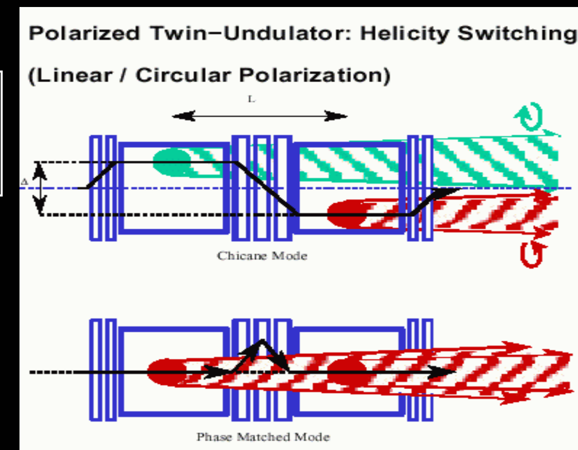
TWIN UNDULATORS FOR POLARIZED LIGHT

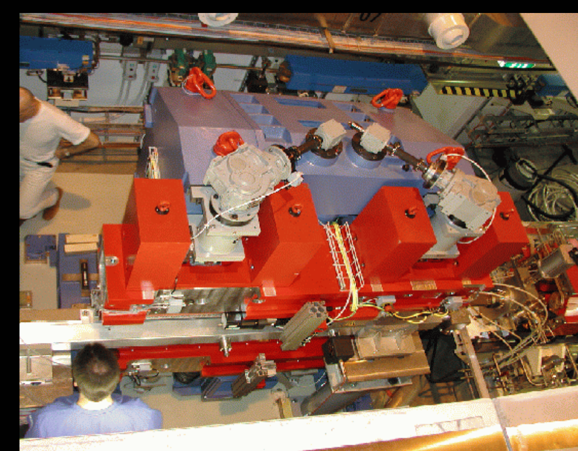
ELECTROMAGNETIC UE212 (8-800 eV)



Helicity switching

Harmonic suppression



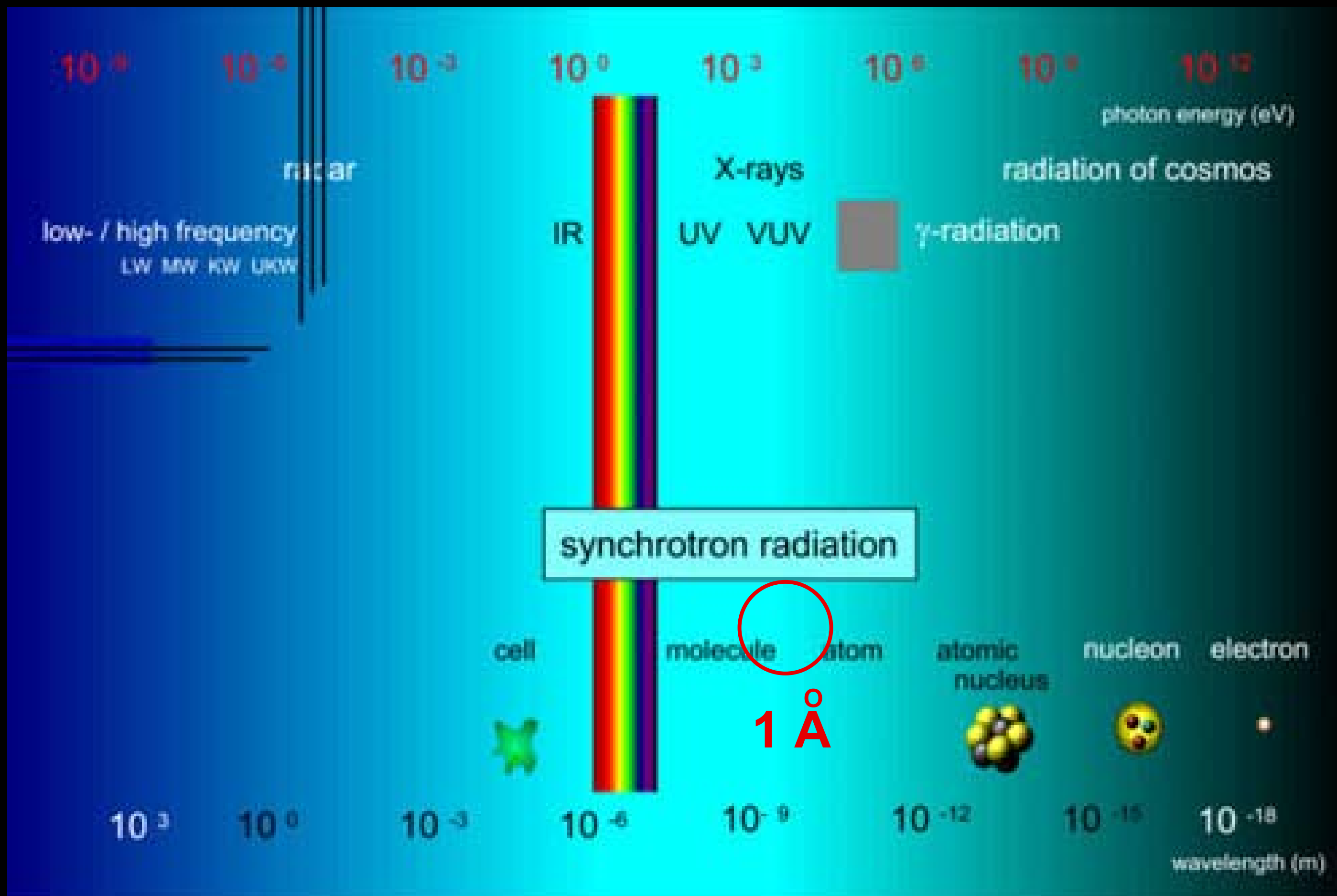


APPLE II TYPE UE56 (90 eV–3 keV)

LIGHT SOURCE REQUIREMENTS → ACCELERATOR FEATURES

- High Brilliance → A. Streun
- Coherence → related to brilliance
- Polarisation → ID Vortrag
- **Tunability**
- Stability

FOR ATOMIC RESOLUTION → X-RAYS ARE NEEDED

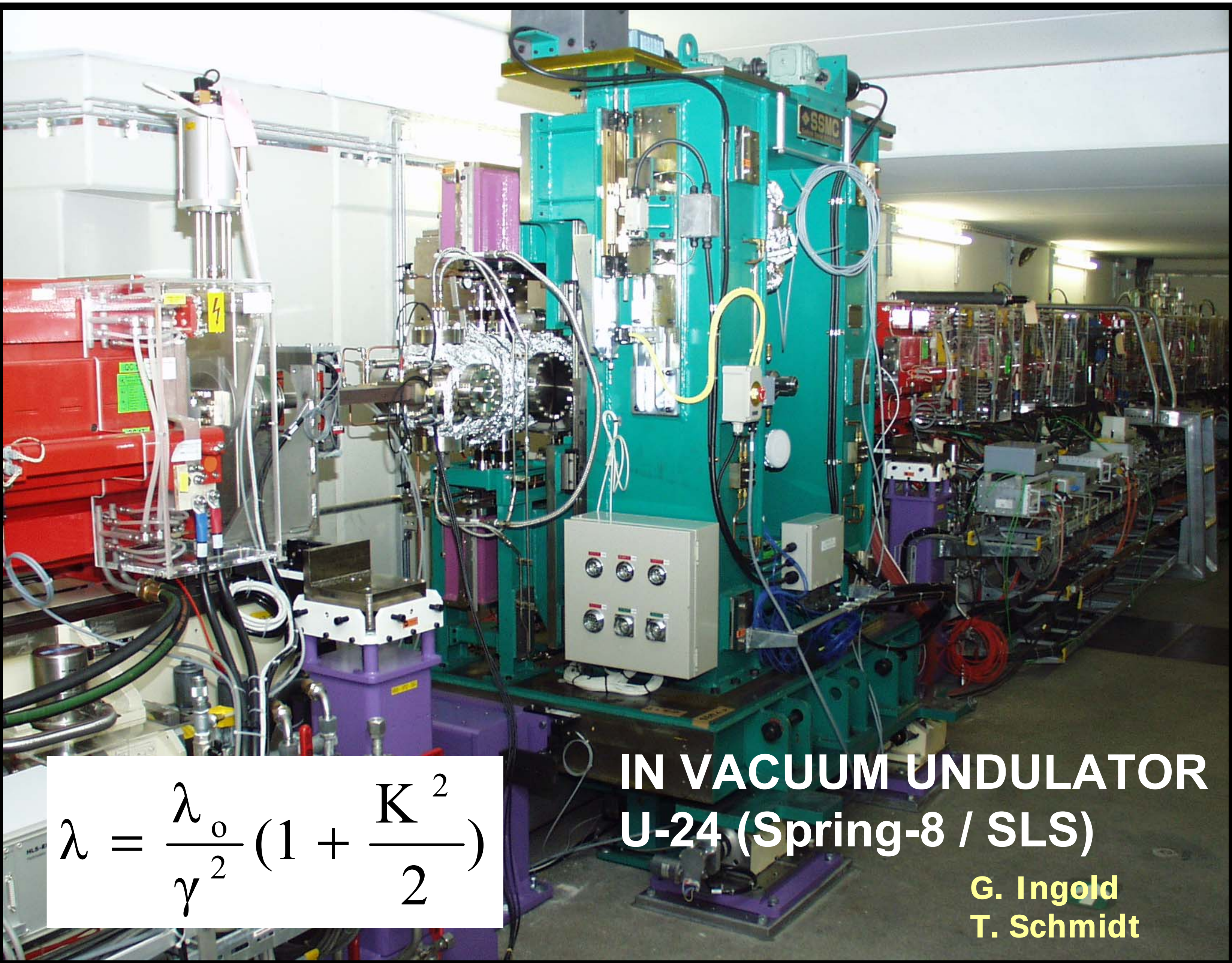


THERE IS AN INCREASING NEED FOR HIGHER PHOTON ENERGIES !

Medium energy machines can only get there by:

- SMALL PERIOD (LOW GAP) UNDULATORS
- THE USE OF HIGHER HARMONICS

SB / IPEP / LPAP - Laboratory for Particle Accelerator Physics



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

IN VACUUM UNDULATOR
U-24 (Spring-8 / SLS)

G. Ingold
T. Schmidt

THIS OPERATION MODE CREATES A SERIES OF ADVERSE EFFECTS THAT MUST BE CURED:

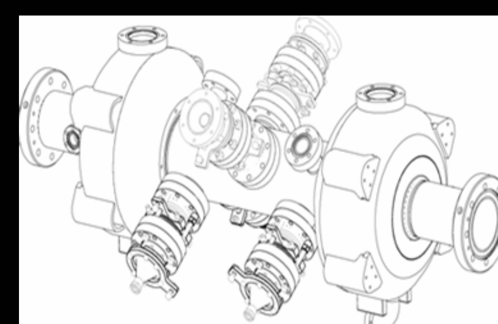
- SMALL GAPS
  → enhanced beam gas scattering
  (and also Touschek scattering!)
  [higher harmonic cavity, sophisticated vacuum system]

- HIGHER HARMONICS
  → Are destroyed if the energy spread is blown up needs therefore perfect cure of multi-bunch instabilities
  [mode shifting, temperature tuning, feedback systems, higher harmonic cavity]

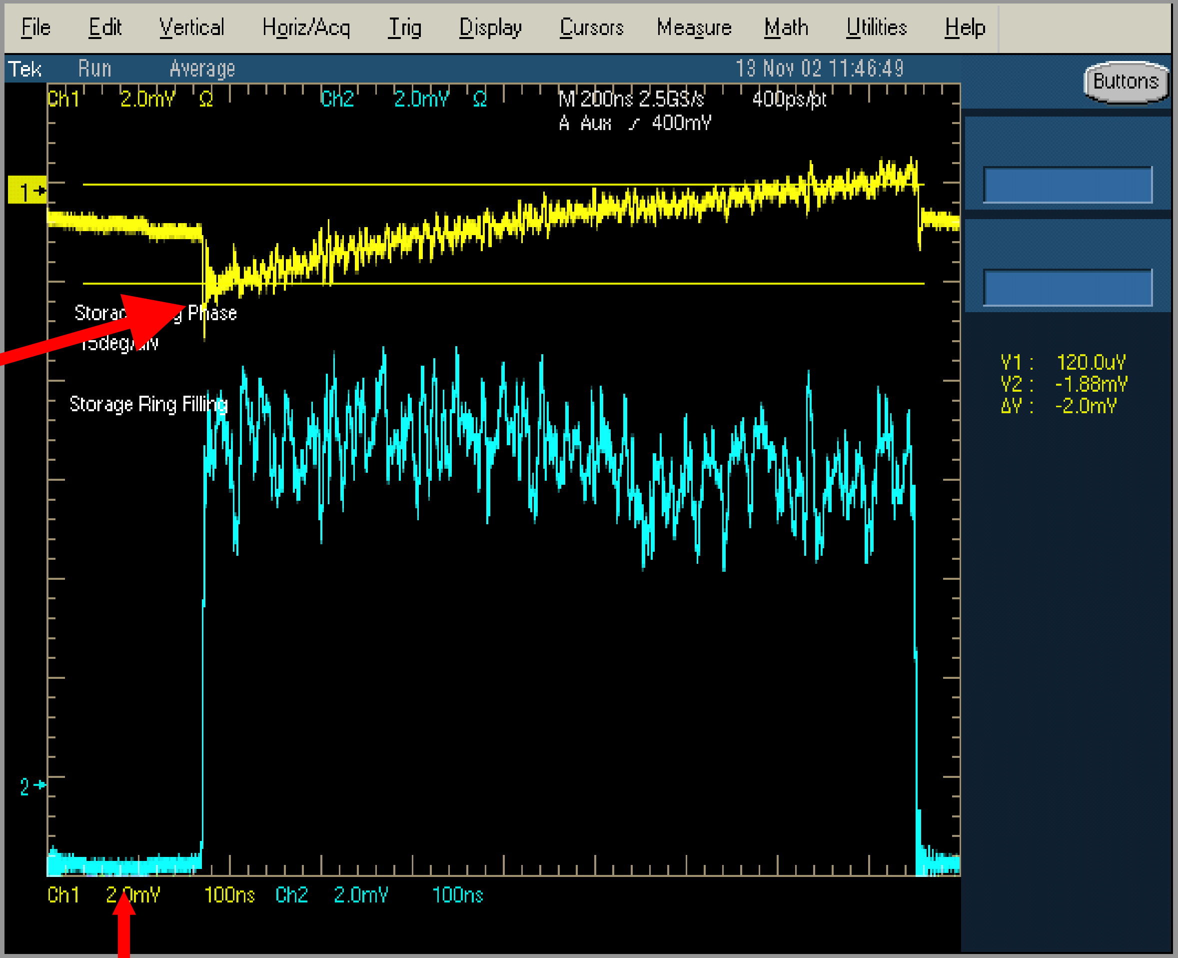
SC HIGHER HARMONIC CAVITY

3HC COLLABORATION

- CEA (Saclay)
- CERN
- Sincrotrone Trieste
- PSI



Top up with 300 mA and s.c. cavity

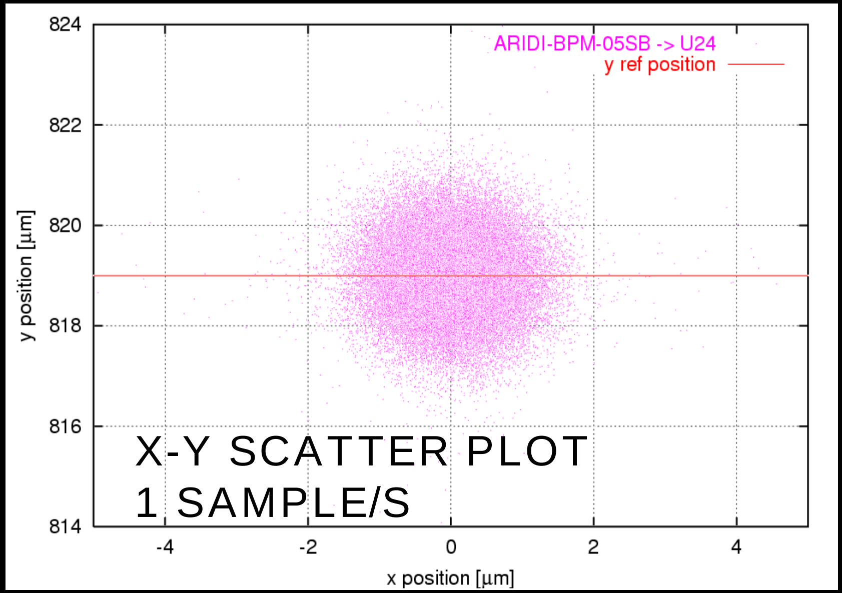


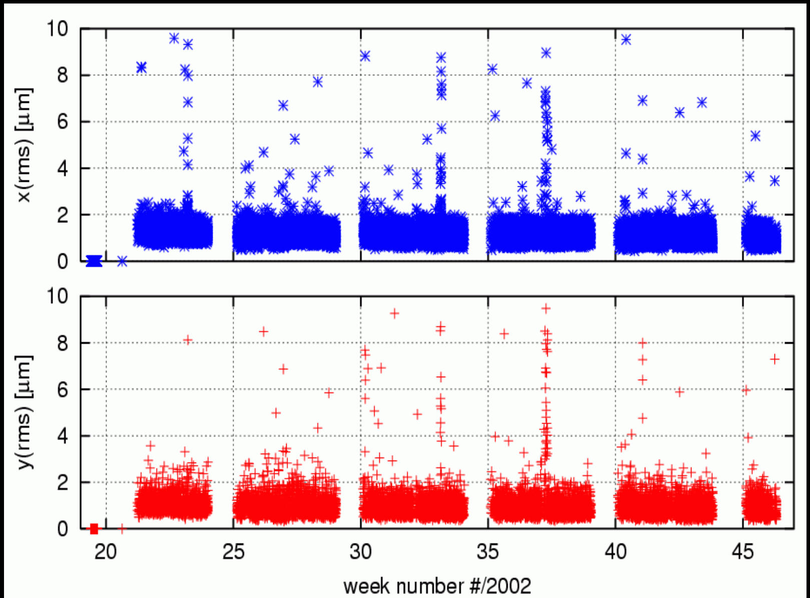
Phase ramp along the bunch train ~ 15° total

Gap in fill pattern

LIGHT SOURCE REQUIREMENTS → ACCELERATOR FEATURES

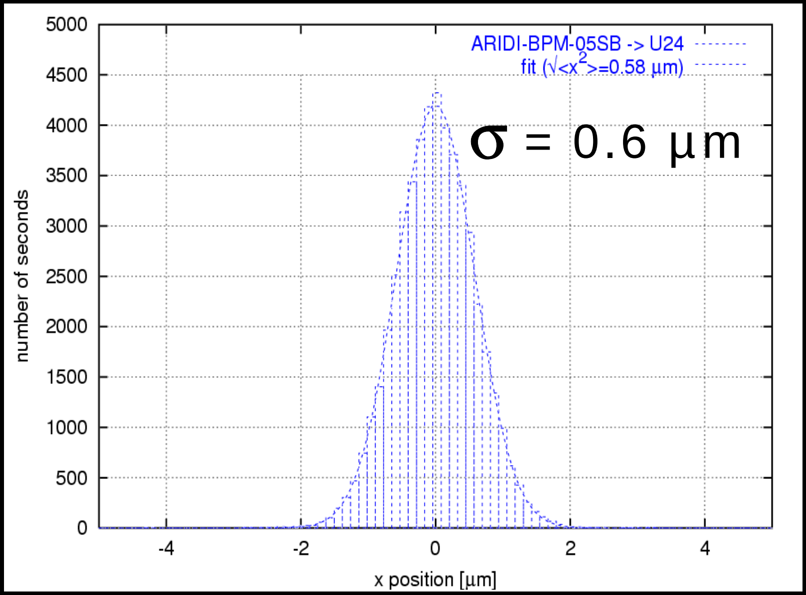
- High Brilliance → A. Streun
- Coherence → related to brilliance
- Polarisation → ID Vortrag
- Tunability
- **Stability**



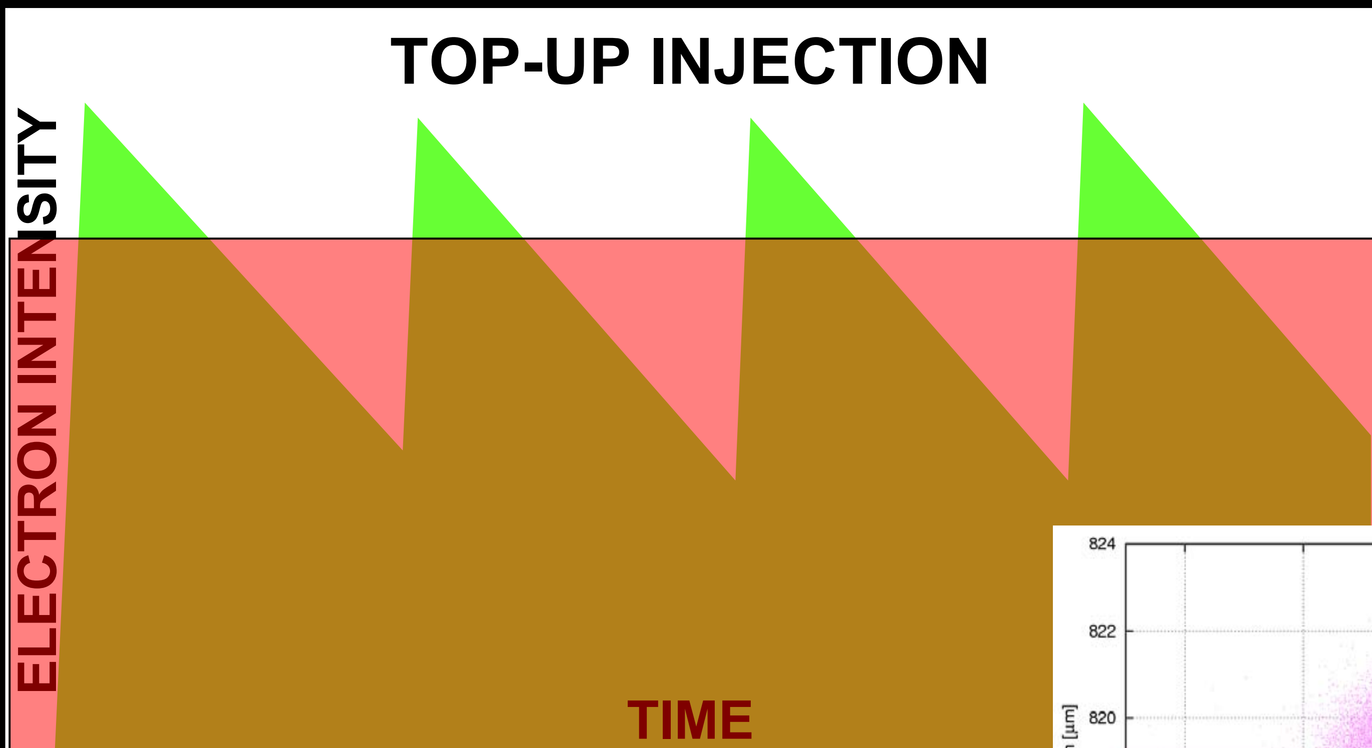


POSITION STABILITY / SLS:

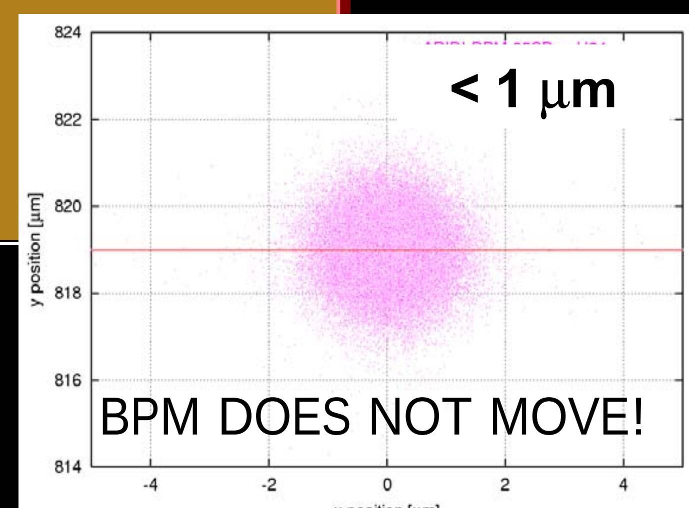
100 s	30 nm
20 days	0.5 µm
1 year	1-2 µm



INTENSITY STABILITY

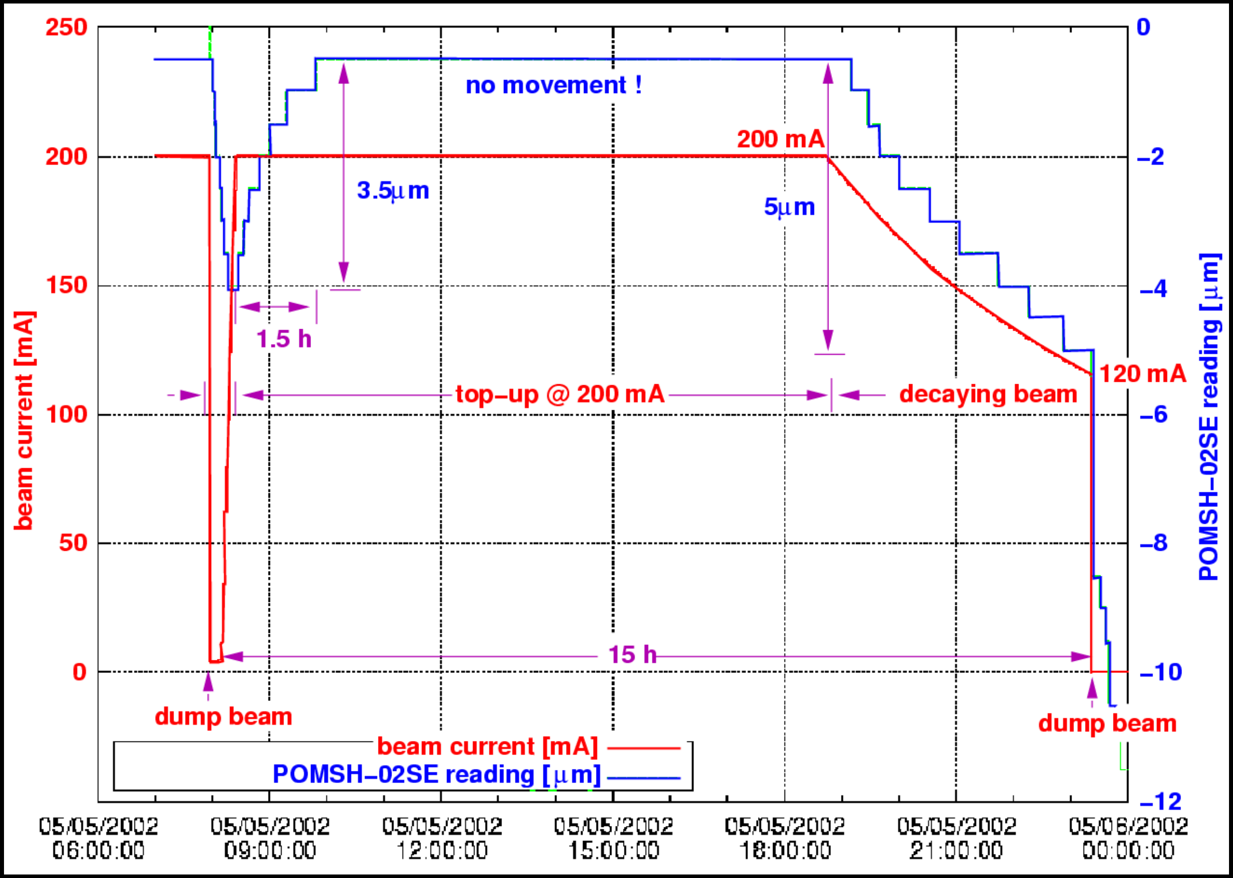


POSITION



STEADY STATE GLOW AT THE SWISS LIGHT SOURCE

TOP UP → POSITION STABILITY !



TOP UP REQUIRES A PROPER INJECTION CHAIN

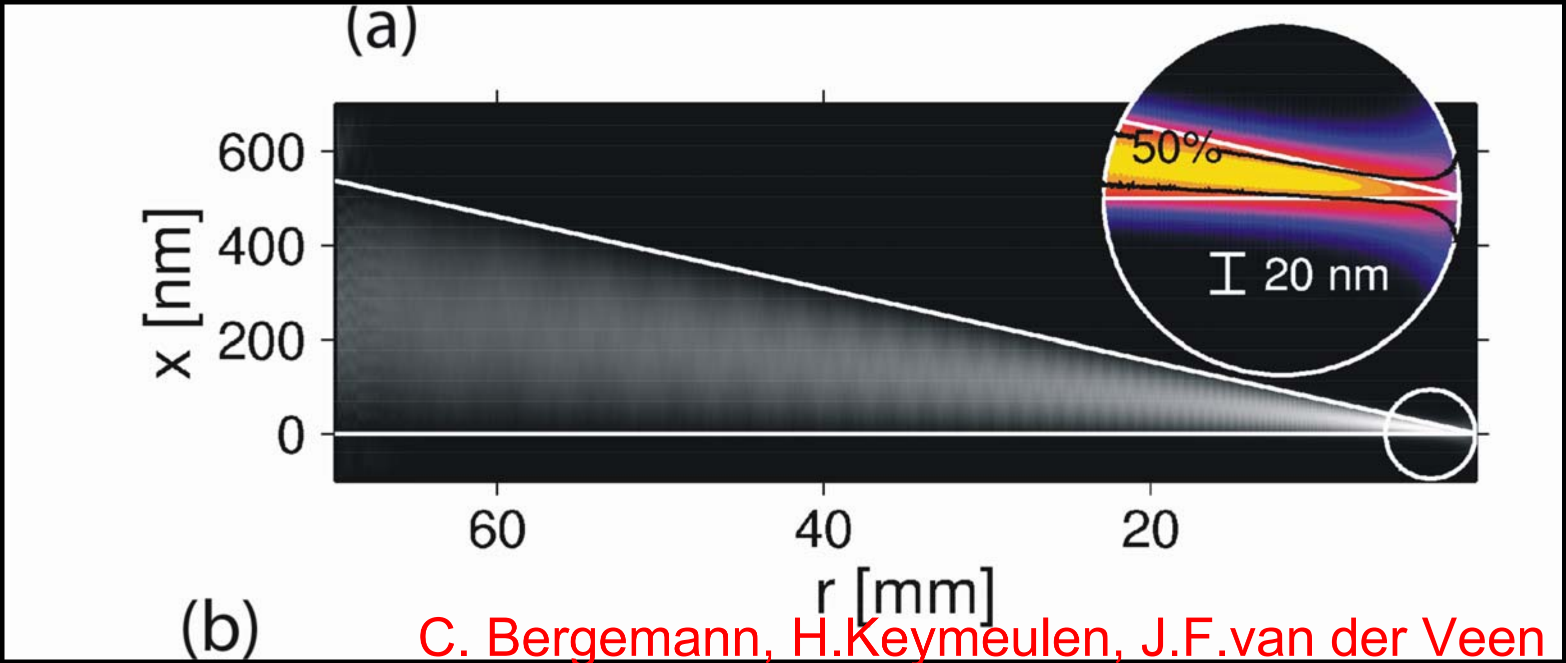
- reliable
- low power consumption
- small injected beam size

<u>SLS-BOOSTER</u>

ε = 9 nm (2.4 GeV)

P_{mag} = 200 kW

What is the smallest possible spot size ?



C. Bergemann, H.Keymeulen, J.F.van der Veen

Minimum spot size (FWHM):
Δx_{min}=0.64 W_c,

$$W_c = \frac{\lambda}{2\theta_c} = \frac{1}{2} \cdot \sqrt{\frac{\pi}{r_0 n_e}}$$

…this limit on spot size appears to hold also for other X-ray focusing devices.

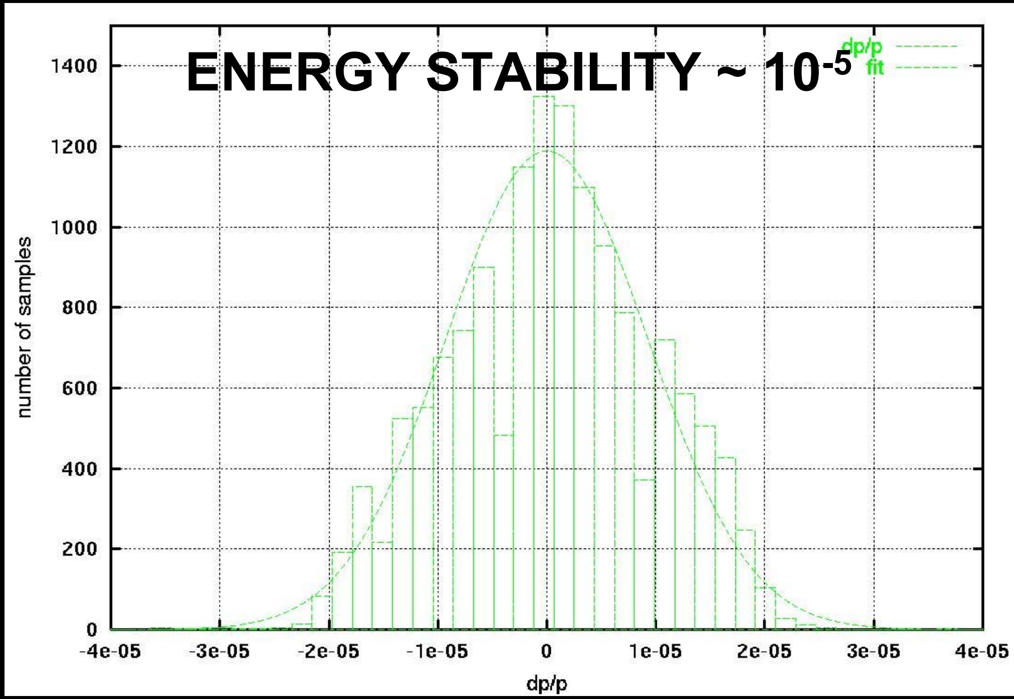
SiO_2: Δx_{min} = 13 nm
Au: Δx_{min} = 5 nm

ENERGY STABILITY ~ 10^{-5}

CORRECTING THE AVERAGE HORIZONTAL ORBIT BY ADJUSTING THE RF FREQUENCY AND THUS ADJUSTING THE ELECTRON ENERGY

HIGH INTENSITY STABILITY OF MONOCHROMATOR OUTPUT

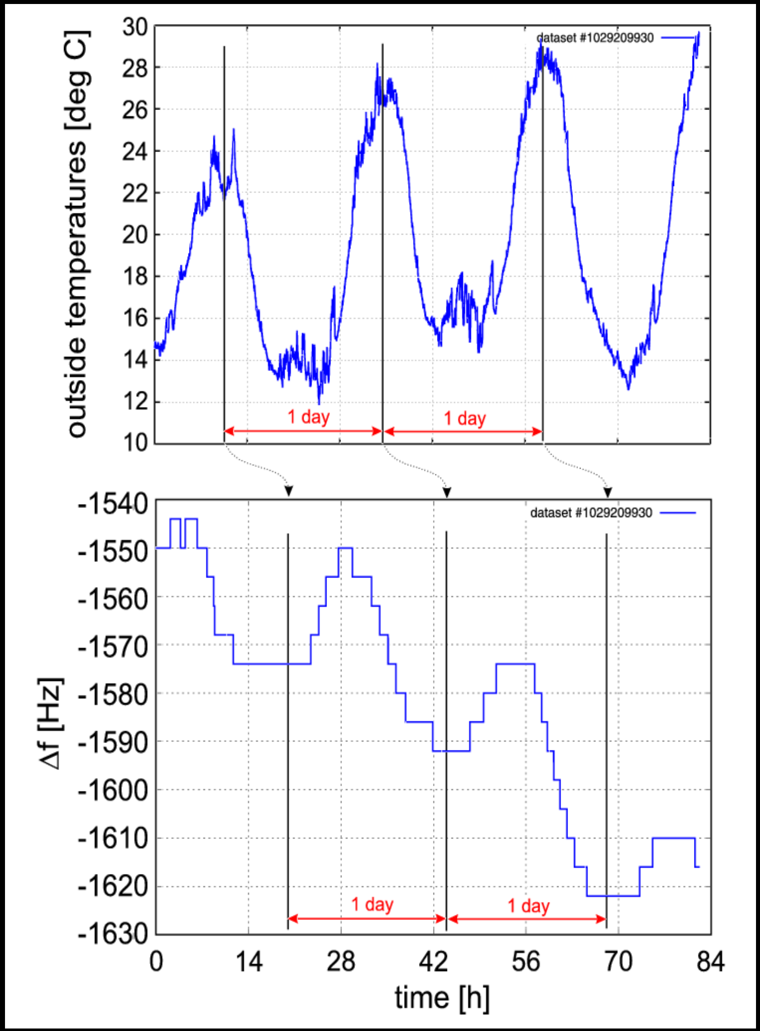
$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



DAY / NIGHT TEMPERATURE VARIATIONS

CIRCUMFERENCE OF THE SLS RING CHANGES WITH OUTSIDE TEMPERATURE

RF FREQUENCY IS ADJUSTED TO COMPENSATE FOR THESE CHANGES



SUMMARY (1)

FEATURES OF A HIGH PERFORMANCE LIGHT SOURCE

- HIGH BRILLIANCE
  - → high beam current
  - → low emittance lattice
  - → use of undulators
- HIGH COHERENCE
  - → high brilliance (lateral coherence)
  - → narrow bandwith (temporal coherence)
    - - long undulators
    - - waiting for next light source generation

SUMMARY (2)

FEATURES OF A HIGH PERFORMANCE LIGHT SOURCE

- THE PROPER PHOTON ENERGY (TUNABILITY)
  - → low gap undulators
    - - top-up injection
    - - proper injection chain
    - - bunch lengthening cavity
  - → use of higher harmonics
    - - energy spread stability
    - - multi-bunch feedback sysetms
    - - bunch lengthening cavity

SUMMARY(3)

FEATURES OF A HIGH PERFORMANCE LIGHT SOURCE

- HIGH STABILITY

  INTENSITY

  → top-up injection

  - proper injection chain

  ENERGY

  → RF frequency correction

  POSITION

  → top-up injection

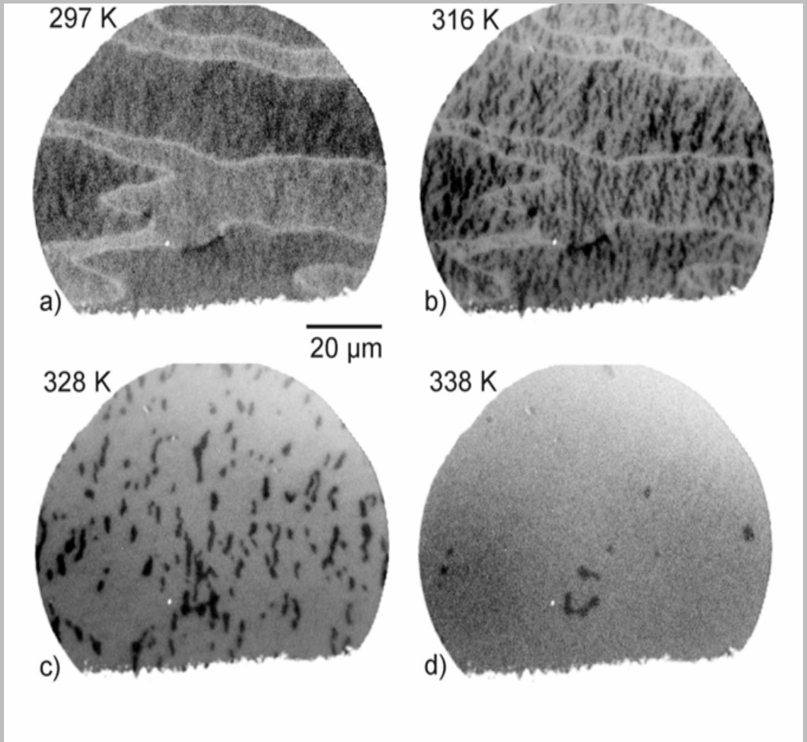
  → fast BPM system

  → orbit FB system

  → proper foundation, magnets support system, etc...

THE END

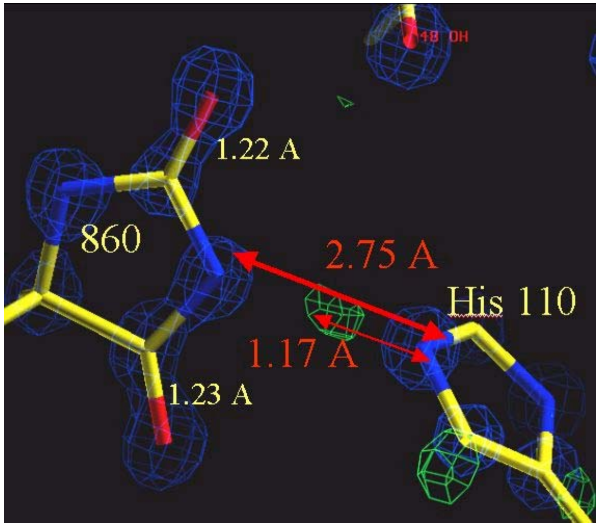
X-PEEM studies of Temperature induced Spin Reorientation Transition in Fe/Gd multilayers



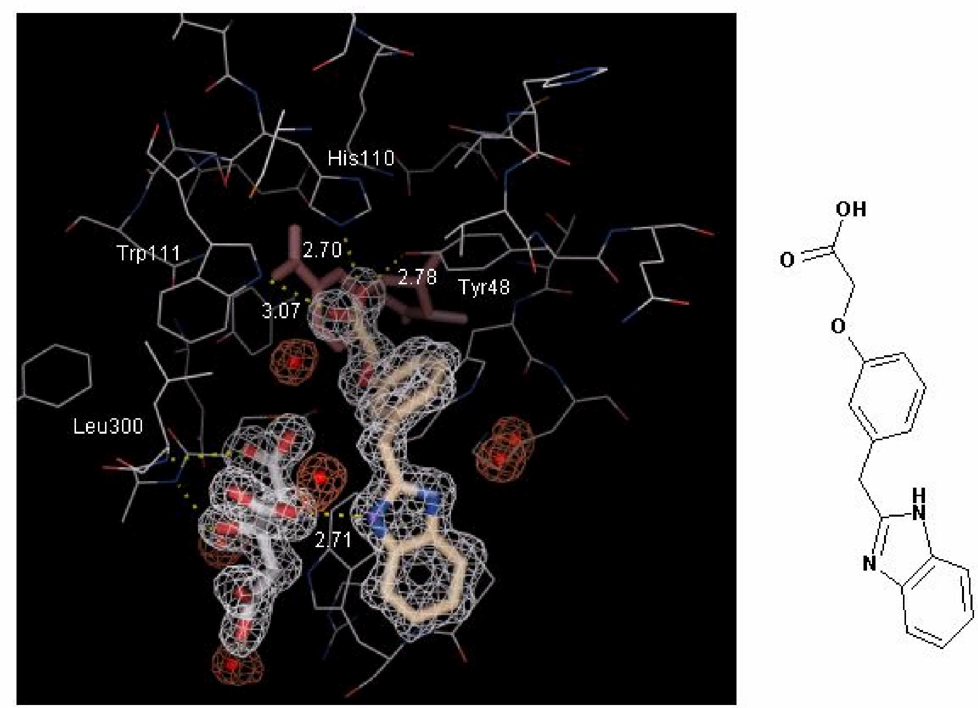
Domain pattern during a spin reorientation transition
from in-plane to out-of-plane magnetization.

Trying to understand possible ways of treating Diabetes Mellitus

- **Podjarny et al IGBMC-CNRS**
- **PX team SLS**

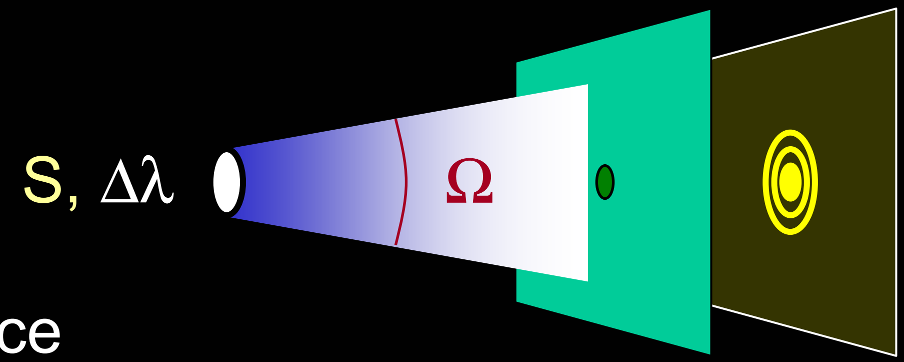


Protonation state of hydantoin head



Inhibitor HD04 in active site of Aldose Reductase

When do we get diffraction patterns ?



- Pointlike monochromatic source
  → always

- Pointlike source with $\Delta\lambda$ bandwith
  → $\Delta\lambda/\lambda < 1$ or $L_c > \lambda$

COHERENT LENGTH

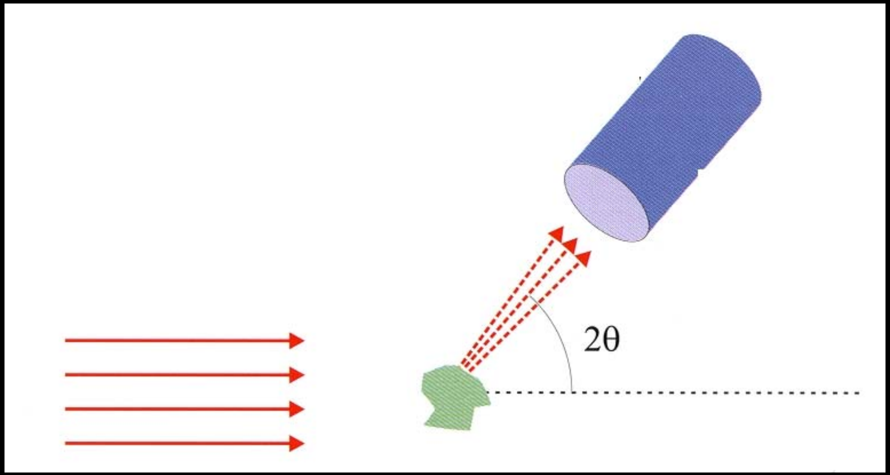
$$L_c = \frac{\lambda}{\Delta\lambda/\lambda}$$

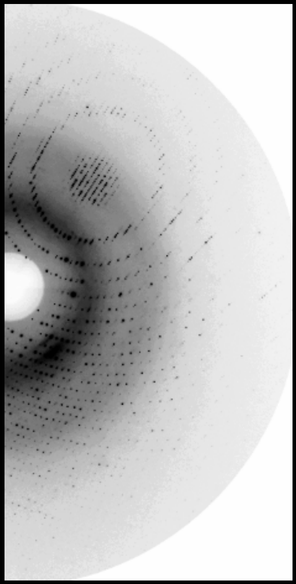
- Extended monochromatic source
  → $S\Omega = 2\lambda$ (full lateral coherence)

$$\left(\frac{2\lambda}{S\Omega}\right)^2$$

COHERENT POWER

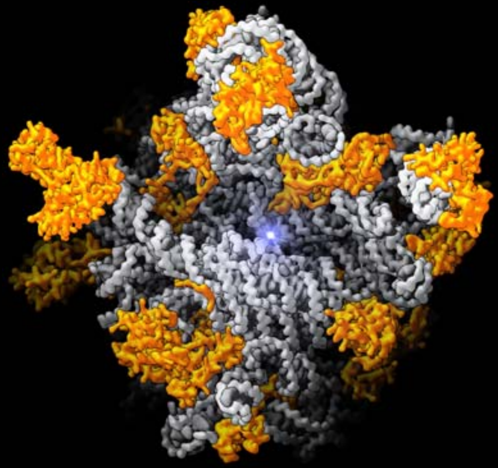
PROTEIN STRUCTURE





Diffraction pattern

Part of a Ribosome



Typical crystal size: 50 μm by 50 μm
High resolution requires low divergence
(e.g. 0.2 x 0.2 mrad)

NEEDS HIGH BRILLIANCE TO GET SOME FLUX INTO THE SAMPLE ACCEPTANCE PHASE SPACE !

N. Barn et. al.

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 LINEWIDTH

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

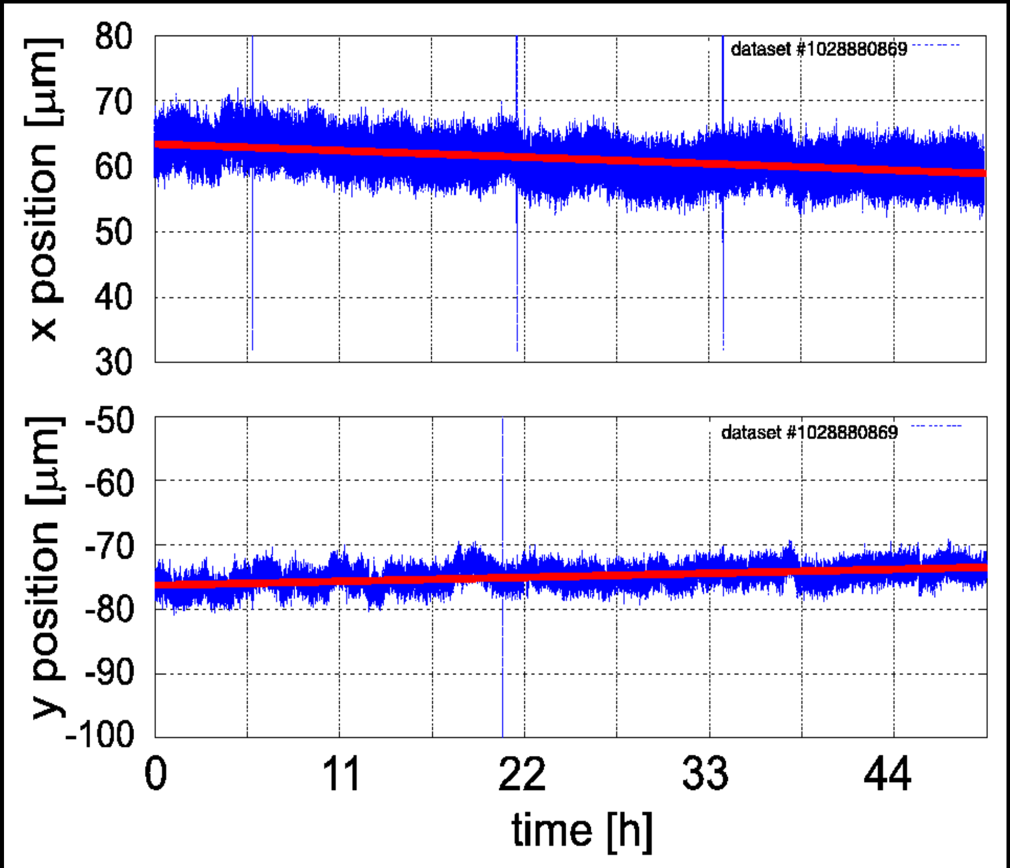
Due to the electron energy spread $\frac{\Delta\lambda}{\lambda} = 2\frac{\sigma_E}{E}$

X-BPM

Daily drifts

- hor. 2.3 microns
- vert. 1.7 microns

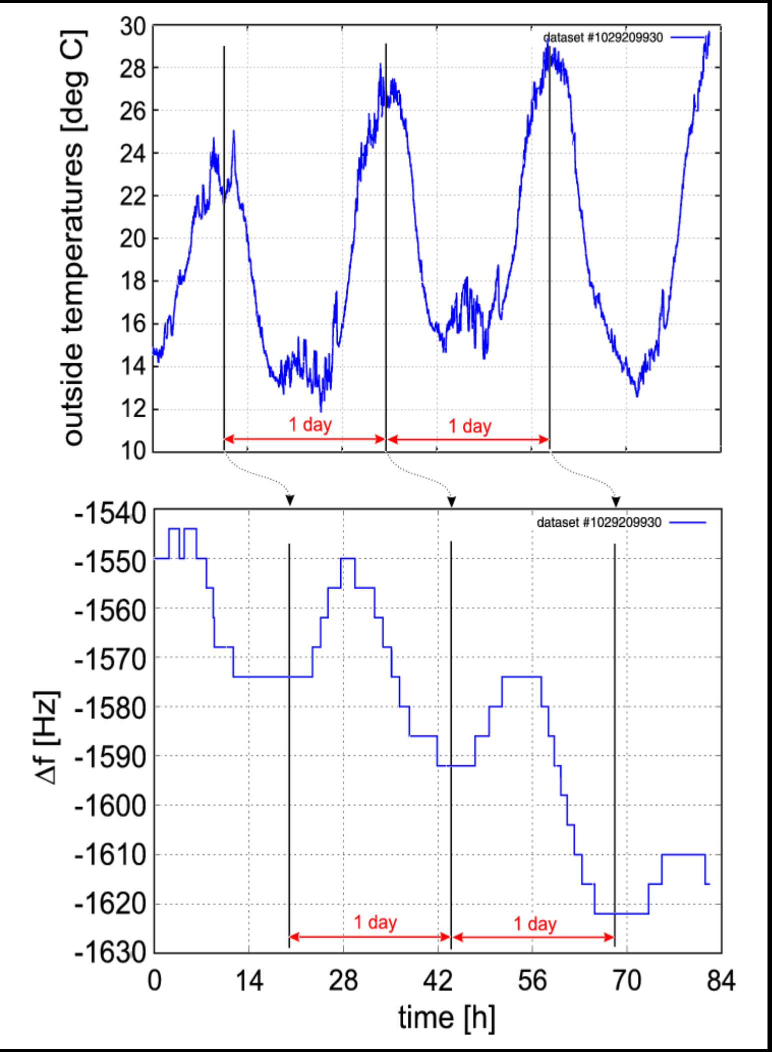
Position fluctuations are in agreement with the electron BPM data



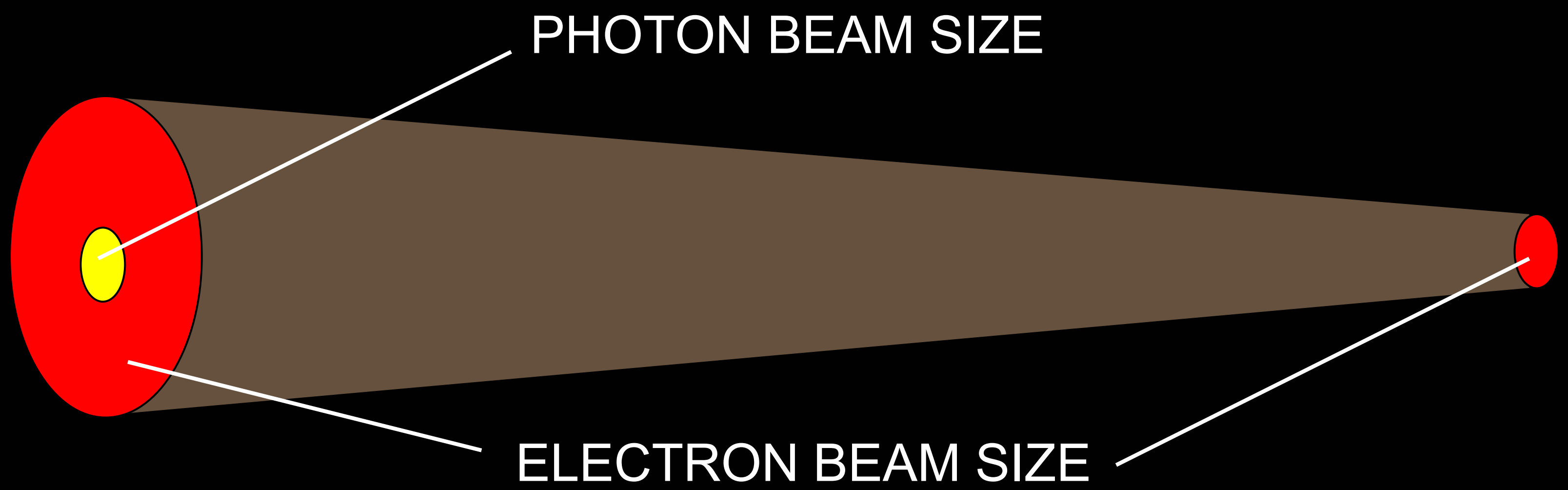
DAY-NIGHT TEMPERATURE FLUCTUATIONS

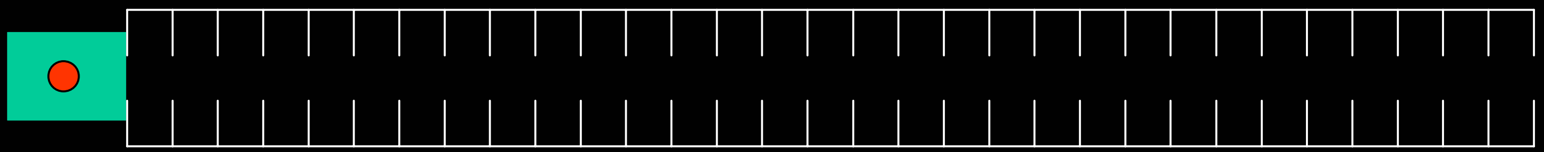
Circumference of the SLS ring changes with outside temperature

RF frequency is adjusted to compensate for these changes



REQUIRES AN EXTREMELY SMALL ELECTRON BEAM !





Other uses of coherence

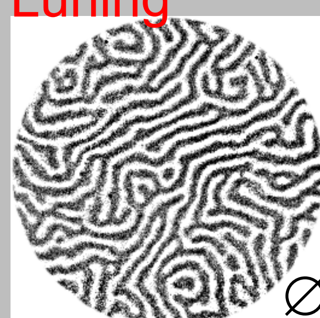
X-ray photon correlation spectroscopy
Studies of dynamics of (soft) condensed matter
A. Madsen. G. Grübel et al

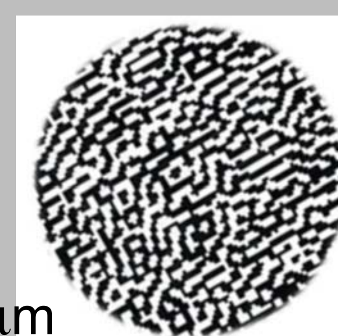
Phase contrast imaging, interferometry
Many projects at the long beamlines of SPring-8, T. Ichikawa et al
X-ray Fabry-Pérot for, e.g., metrology: Y. Shyd'ko

Coherent resonant magnetic scattering in soft X-ray range
J. Lüning, J.B. Goedkoop

Phase problem can be solved by "oversampling" of speckle image
S. Eisebitt, J. Lüning

Transmission X-ray Microscope

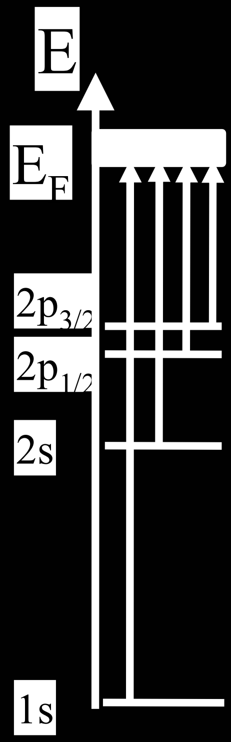


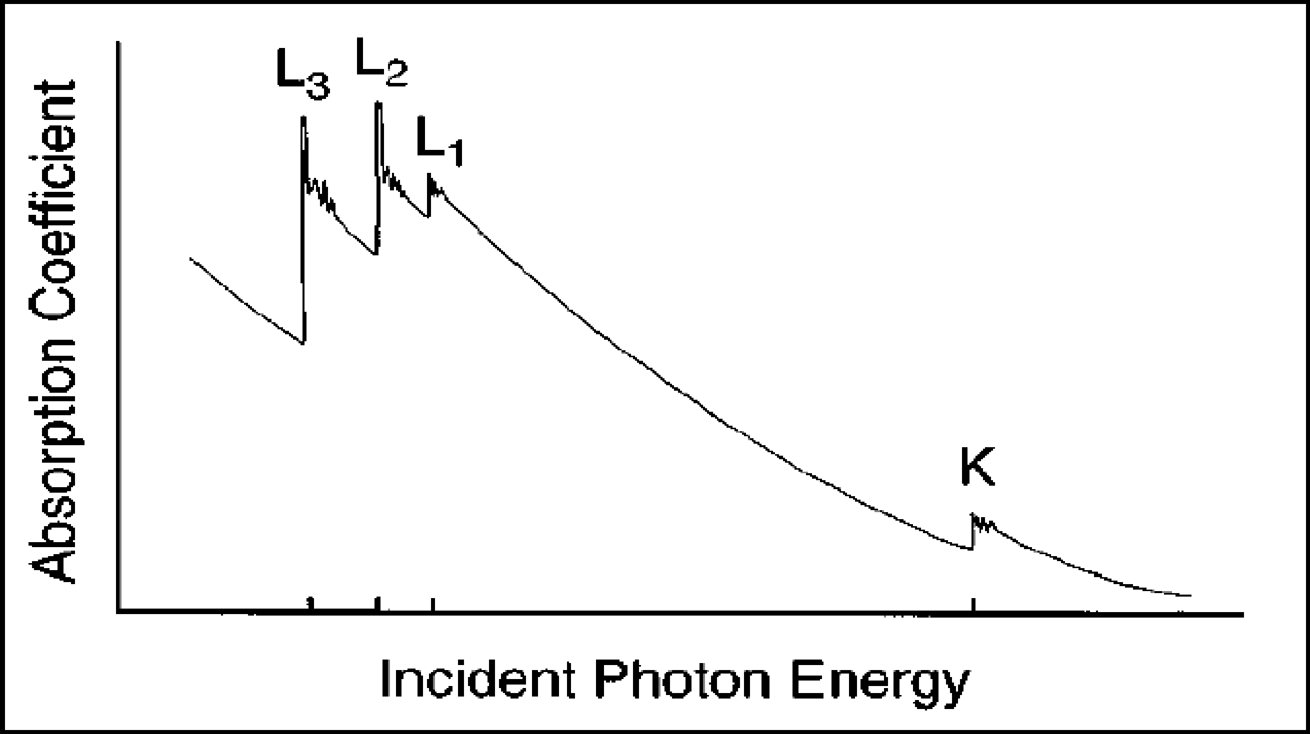


"Best" Reconstruction from Speckle Intensities

∅ 5 μm (different areas)

X-Ray ABSORPTION

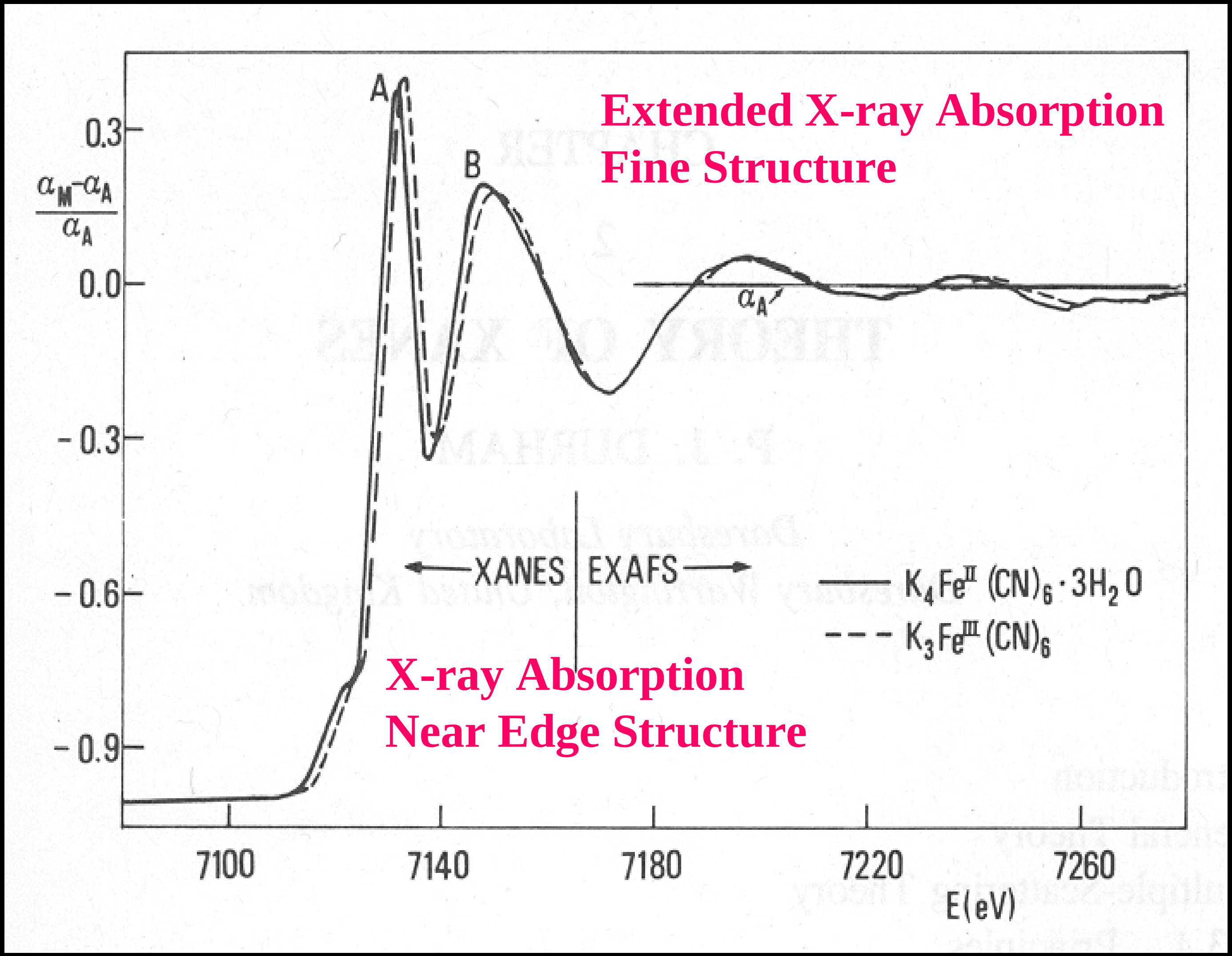




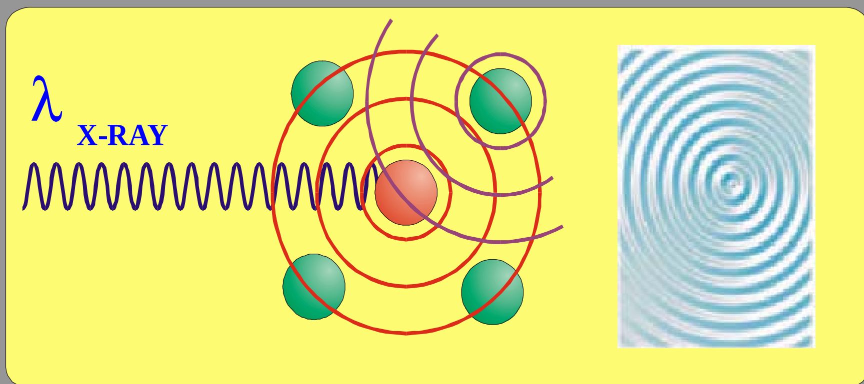
X-rays excite from core state to unoccupied state

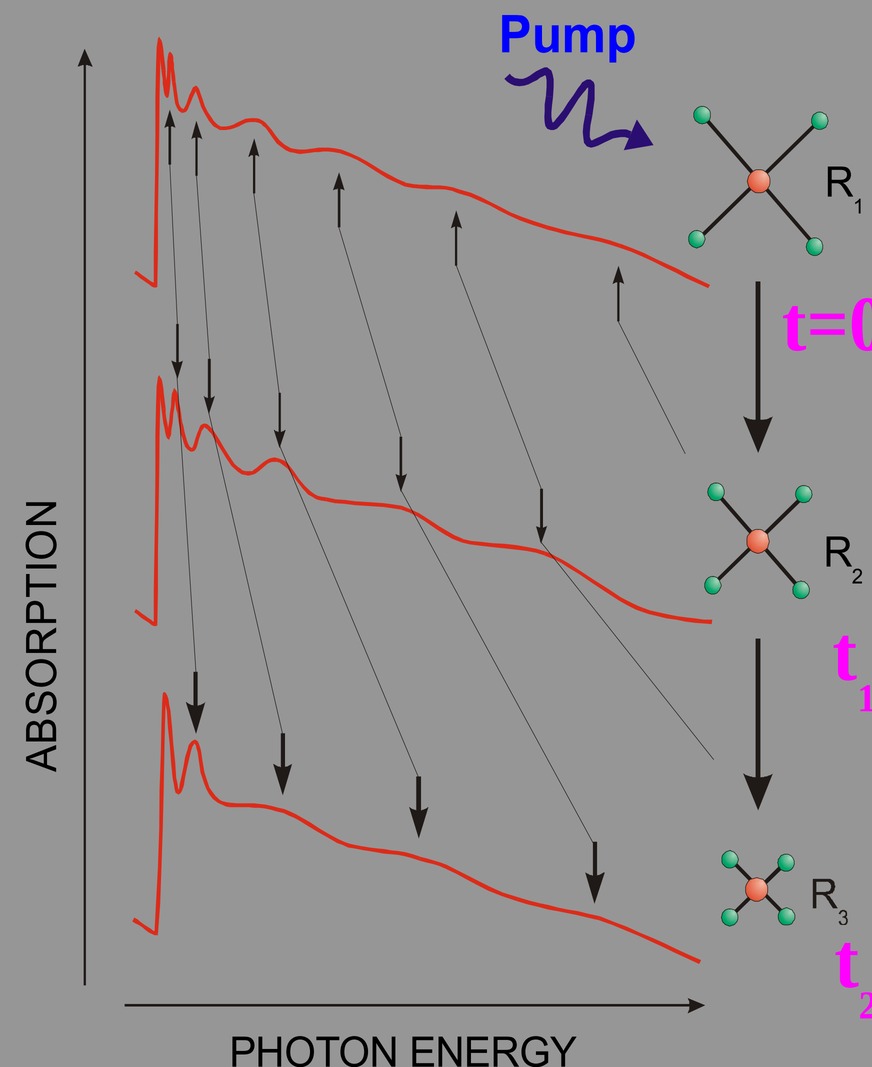
Near edge absorption related to angular momentum projected

X-Ray ABSORPTION



Structural Information via X-Ray Absorption (EXAFS)





- Local structure
- Disordered media
- Biological systems